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Lightweight ballistic composites

Edited by Ashok Bhatnagar

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Lightweight ballistic composites

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Lightweight ballistic composites

Military and law-enforcement applications

Edited by
Ashok Bhatnagar

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This book is dedicated to all the law-enforcement and military personnel who put their lives at risk on a daily basis to save civilian lives.

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1

Introduction

L WAGNER, Honeywell International Inc., USA

1.1 History

With the invention of explosive powder, the dynamics of the battlefield have changed and from the American Civil War era to the current war on terrorism, mankind has been exposed to high speed projectiles, namely bullets fired from a handgun or rifle, fragments of hardened steel from a hand grenade, or massive explosions of artillery shells or homemade bombs. During the First and Second World Wars knowledge about personnel protective gear was limited to the use of steel. However, due to the heavy weight of the steel armor and lack of flexibility, it was used only on slow moving, heavily armored vehicles. Personnel protection was completely missing.

The earliest use of a head-protecting helmet was attempted during the First World War by the French army. This helmet was a modified metal cap to protect soldiers from head-related injuries and was used by a number of armies. During the same war Germany introduced heavy breastplates, the British lighter breastplates, and Italy armored waistcoats.

For personnel protection, flak jackets were used during the Vietnam era. However, these jackets were heavy, bulky and provided limited protection from high speed projectiles.

During the last two to three decades scientists and engineers at various industries, universities, and government laboratories have conducted research work on ballistic materials and their interaction with high-speed projectiles. A majority of these detailed studies are written for an audience whose knowledge is limited. Ballistic information which reaches end-users is in the form of condensed literature from brochures, experience by users, and from standards published by military and law enforcement agencies.

It is hoped that this book will bring some of the recent advances in the area of ballistic protection to light in simplified form. The book is divided into chapters to cover lightweight high performance ballistic fibers – the backbone of an armor system – as well as ballistic woven and non-woven materials. The book has chapters on specifications of armor from around the world; subjects include details of common bullets and fragments, deformation of bullets, ballistic testing, modeling of ballistic materials, current ballistic applications related to personnel protection, armored vehicles, and, finally, a chapter covering the future of high performance, lightweight, fiber-reinforced composite armor for personnel protection. Some new lightweight ballistic materials currently in the pipeline are also highlighted in the last chapter of this book.

The chapters in this book should help readers from a wide spectrum understand current lightweight materials and the trade-off in relation to performance of protective armor, its cost and availability.

1.2 Ballistic fibers

High performance, man-made ballistic fibers have unique properties which set them apart from other man-made fibers used for industrial applications. The tensile strength and modulus of the ballistic fibers are significantly higher and fiber elongation is lower. These fibers can be woven on fabric looms more easily than brittle fibers such as fiberglass and graphite fibers. The ballistic fibers also show inherent resistance to a number of chemicals, industrial solvents and lubricants used by automotive and aerospace industries.

Each high performance ballistic fiber has a certain unique property because of the polymer used to manufacture the fiber and the unique spinning process. The tensile properties of these ballistic fibers are determined by their structural characteristics at a molecular orientation about the spinning direction, and the effective cross-section area occupied by single chain which is related to the degree of chain linearity. The manufacturing process controls both the microscopic structure and chain orientation in a ballistic fiber. However, another equally important aspect is the economy of fiber manufacturing which may or may not give the highest theoretical properties of ballistic fibers, but help manufacturers to produce large quantities of fibers at a reasonable cost structure. Balancing the two is not simple, but after running a pilot plant for a few years and selling the ballistic fiber, most manufacturing companies figure out how to sell their fibers in applications which will utilize the unique fiber properties.

Current success of the lightweight fiber-reinforced armor did not happen overnight, the development started in the early 1970s. For the first fifteen years the understanding was limited to a few fibers and a limited type of weaves which provided a decent level of ballistic protection in the vest and to a greater extent when combined with a thermoset resin and molded under heat and pressure. Since there was practically no competition, incentive for improvement was practically non-existent. As new lightweight ballistic fibers started moving out from bench scale to full-scale production, competition increased and customers started demanding lower weight and higher ballistic protection.

A comparison of high performance ballistic fibers is shown below in Table

Table 1.1 Properties of high performance ballistic fibers

	HMPE		ARAMID		PBO	
	900	1000	LM	HM	AS	HM
Tenacity, G/D	30	35	22	26	42	42
Modulus, G/D	1400	2000	488	976	1300	2000
Elongation, %	3.5	2.7	3.6	2.8	3.5	2.5
Density (g/cc)	0.97	0.97	1.44	1.44	1.54	1.56

1.1. The High Modulus Polyethylene (HMPE) was introduced in the mid-1980s and PBO was introduced in the late 1990s.

Along with the new more efficient fibers other technologies were also developed. One of the most significant technologies combines new higher performance ballistic fibers into a (0, 90) network without going through the traditional fiber twist and weaving technology. This technology revolutionized the entire dynamics of lightweight armor. Soft armor became lighter and more comfortable and molded armor not only became lighter than water but could also stop rifle bullets.

Some European countries not only experimented with new materials but also adopted them, in some cases practically overnight, for peacekeeping and military missions.

Fine tuning of new armor technologies and traditional technologies continues to improve in terms of weight saving and higher performance. Due to continuous improvement in high performance fibers, weaving technology and non-woven cross-plied unidirectional technologies, weight reduction of lightweight armor is between 10 and 20% every ten years.

1.2.1 Aramid fibers

In the late 1960s a technology breakthrough occurred in the field of polymers. Dupont scientists developed a family of fibers three times as strong as nylon with a far higher modulus. The fiber was so fine that a woven fabric could be made which had flexibility and drapability. The new fiber was named as PRD-49 and then commercialized as Kevlar®29. These fibers were much tougher and lighter than fiberglass fibers and replaced nylon in flexible and rigid armor used by law enforcement agencies and the military. The helmets and flexible vests made with aramid fibers could stop fragments and bullets at a much lower weight than the nylon fibers. However, the fiber-reinforced composites could not stop all bullets fired from a rifle. With ceramic tiles and aramid composite backing, a new lightweight material was developed which could stop a rifle bullet in comparison to ceramic backed with fiberglass composites.

Law enforcement also showed interest in aramid fiber due to its protective properties against handgun bullets. The weight of an aramid vest was much lower than the nylon vest.

1.2.2 HMPE fibers

With the invention of gel-spun HMPE fiber manufacturing technology, fibers were commercialized by Honeywell (Allied Fibers) which were 10 times stronger than steel, but lighter than water and showed non-linear viscoelastic properties. Due to the chemistry of the HMPE fibers, the surface of the fiber is practically inert to a host of chemicals exposed to law enforcement agencies and also faced by military personnel on the battlefield.

Along with the HMPE fiber technology Honeywell introduced another equally important technology in the late 1990s. In this technology, fibers-to-high velocity projectiles interaction was dramatically increased by utilizing uni-directional, cross-plied non-woven technology. The technology utilizes untwisted fibers, which are spread out at macro level and held in a predetermined orientation by a binder.

A third technology, invented in the mid-1990s, was molding technology. In this technology high pressure is utilized to consolidate the fiber packing density in the molded product. With higher fiber pack density, along with the viscoelastic properties of the HMPE fiber technology, a rifle M80 ball bullet can be stopped at about 15 kg/m^2 which is almost a 50% weight reduction for armor molded to stop the same bullet only a few years before. The molded products consist of 100% HMPE fiber-reinforced composite, only with no ceramic facing.

The French military was the first to use molded HMPE plate kits in Bosnia. The vest consisted of four molded plates inserted into a flexible vest covering front, back, groin and collar. Since then a number of European and Asian countries have adopted similar armor for stopping high energy bullets fired from rifles.

1.2.3 PBO fibers

PBO fibers are relatively new high performance fibers for the ballistic vest. Although these fibers are more expensive and have limited supply, the remarkable ballistic-resistant qualities of these fibers have helped to set a new level of soft armor performance. At the moment, limited long-term performance data is available. A number of vest manufacturing companies in the United States have commercialized vests using PBO woven fabric and non-woven cross-plied unidirectional ballistic materials.

1.3 Fiber-reinforced ballistic armor

Fiber-reinforced ballistic armor is the generic term for a group of related yet individual materials. Some of the groups utilize only high performance fibers converted into woven materials or by combing high performance fibers and a binder and converting into non-woven cross-plied unidirectional materials. These materials are used for soft armor.

Some groups deal with rigid moldable armor systems. This is achieved by combining a relatively weak polymer with high strength ballistic fiber reinforcement. A proper ratio of polymer to ballistic fiber shows overall higher ballistic properties which are unequalled by any single material. The resulting material containing reinforced armor fibers and matrix is called a prepreg. The prepreg could be made of a woven material combined with a matrix or a cross-plied unidirectional material that may inherently contain a matrix. Utilizing a prepreg, ballistic products can be molded into a variety of simple and complex shapes under heat and pressure using a molding tool.

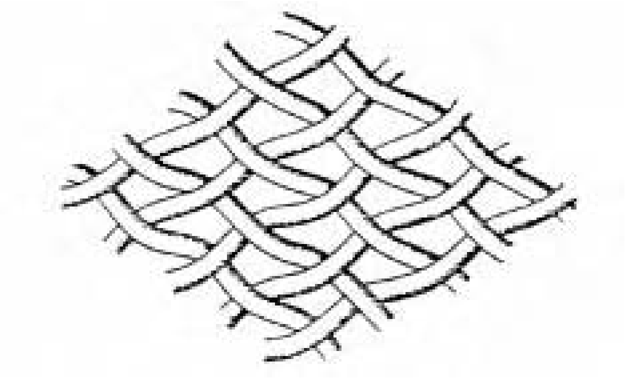
The fiber-reinforced ballistic armor provides the designer, fabricator, and end-user with sufficient flexibility to meet the demands presented by ballistic threats faced by police and military in the field. The goal in creating a lightweight high performance ballistic product is to combine one or more than one high performance ballistic material in order to defeat more than one type of ballistic threat as well as any other special requirement. Since lightweight fiber-reinforced ballistic composites can be designed to provide an almost unlimited selection of products to defeat low energy handgun bullets and high powered, high energy rifle bullets, these composites are employed globally by all the armor industries. The armor manufacturer utilizes fiber-reinforced ballistic armor to produce a variety of flexible and hard molded armors which are economical, highly efficient, and fairly sophisticated.

1.4 Woven ballistic materials

Weaving fibers into a woven fabric is a technology developed in the early stages of human civilization. However, this technology has improved with high-speed automated looms. The fiber damage in the weaving operation is minimized due to a number of modifications made at each stage where fiber comes into contact with the loom. Despite all these advances, fibers are usually twisted and some amount of fiber is also damaged during weaving operation.

In a typical weaving operation, the fibers are twisted before weaving. The twisting of the fiber reduces fiber-to-fiber entanglement, thus maintaining the physical properties of the fibers. However, twisting also reduces the projectile engagement with individual fibers in a bundle of fiber tow.

The woven fabrics for certain flexible armor applications are further processed to remove any impurity picked up as a result of the weaving operation.



1.1 Typical woven armor fabric.

This process is called the ‘scouring’ of the woven fabric. Once the fabric is scoured, a water-repellent coating may be applied. This is essential for aramid fabric so that moisture does not penetrate and reduce the ballistic resistance of the fabric. Ballistic and textile engineers are teaming up to achieve higher ballistic performance from woven armor materials. The higher performance of a woven armor material can be increased by using a variety of low deniers, limiting or eliminating fiber twist, new fabric construction, and stitching fibers into fabric type armor material.

A simple fabric is shown in Fig. 1.1. It consists of a number of yarns in the warp direction and a number of yarns in the weft or fills direction. The warp yarn is the yarn lying in the length-wise (machine) direction of the fabric, whereas the weft or filling yarn is lying in the cross-wise direction of the fabric.

There are varieties of weave style that can be used to interlace the warp yarns and weft yarns so as to form a suitable ballistic fabric. The ballistic performance of a fabric depends upon:

1. Physical properties of the ballistic fibers.
2. Denier of the fibers in warp and weft direction.
3. Level of twist in the yarn.
4. Weave design of the fabric.
5. Damage to yarn during weaving operation.
6. Post weaving operations.

Recently, a new dimension was added to enhance the ballistic performance of woven fabrics. In this technology a low amount of adhesive is introduced to increase projectile-to-fabric interaction and in some cases adding additional steps of calendering the fabric either with or without laminating with a thin film.

1.5 Non-woven lightweight armor materials

The evolution of lightweight ballistic materials in the last ten to fifteen years was propelled by the invention of lighter and stronger man-made fibers and combing these fibers in a unique orientation by avoiding twisting and crimp added to the fiber during the weaving operation.

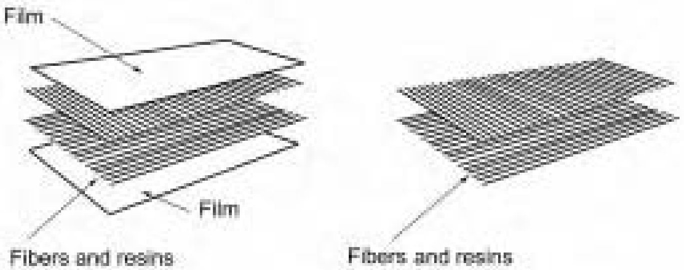
There are a number of new technologies being developed in the field of traditional woven ballistic materials which are processed further to increase the projectile interaction with the ballistic materials. However, non-woven lightweight armor materials manufactured with Honeywell's unique patented technologies have higher ballistic performance in comparison to woven fabrics.

In this patented technology process the ballistic fibers are aligned parallel to each other, similar to the beaming operation in woven fabric, and then a binder or resin is applied to form into a continuous web of aligned fibers. The web holds the fiber spacing for further processing. A web of similarly aligned fibers is applied (see Fig. 1.2) at 90 degrees to form a continuous roll. The 0 degree and 90 degree webs are further consolidated to form a unidirectional cross-plied roll product. The roll product developed by this technology is applicable to all types of continuous high performance ballistic fibers such as HMPE fibers, aramid fibers and PBO fibers.

A thin film is laminated on some of the non-woven consolidate products for soft armor applications.

The ballistic performance of non-woven, cross-plied unidirectional ballistic materials depends upon:

1. Physical properties of the ballistic fibers.
2. Denier of the fibers.
3. Amount of intermingling of fiber within a yarn bundle.
4. Fiber spreading at macro level.
5. Type of resin.
6. Quantity of resin.
7. Bond between resin and fiber.



1.2 Non-woven, cross-plied, and unidirectional armor materials.

The armor products can be engineered now to use 100% non-woven cross-plied material or 100% woven armor materials or combining more than one type of material to defeat the ballistic threat at the lowest weight while maintaining other features.

Another type of non-woven ballistic material is in the form of chopped ballistic materials converted into a felt configuration. The felt materials and technologies in other fields are fairly advanced, but new research related to felt makes it a strong candidate for lightweight ballistic materials.

1.6 Prepregs and coatings

The advances in prepreg, coating and resin film technologies, coupled with rapid development of resin formulation technologies, have led to many new ballistic products that are more uniform and have lower defects levels. This results in higher yields, lower costs and consistent ballistic performance. Quality levels that were acceptable only a few years ago are no longer acceptable and the future will be more demanding. Environmental needs and the resulting economic considerations also become more stringent and require that a much higher proportion of the starting materials end up as usable product, rather than scrap to be buried in a landfill or by incineration.

While all prepreg, coated and resin film laminated products are different in terms of their formulation and many different processes are used, the underlying science is similar. Many defects in different products have similar causes and similar cures. The principles developed from the elimination of bubbles in low viscosity resins apply also to the coating of a low viscosity resin on the woven and non-woven ballistic materials.

A wide variety of different coating application methods can apply a coating to a fabric or unidirectional fiber web. However, the successful processes are those that are defect-free over a wide range of operating conditions and industrial environments. Coating persons spend a significant amount of their time eliminating defects and trying to make the process defect-free. Prepreg companies have observed that while coating personnel may be trained in the basic science, there is very little formal training in troubleshooting or problem solving, even though it is one of the main functions of industrial personnel. The basic procedures and tools used or to problem-solve are similar for a wide variety of different defects and problems.

1.7 Hard and soft armor

Police, law enforcement agencies and military wear two types of personal body protection. These are broadly classified as ‘soft’ and ‘hard’ armor. The soft armors for police and law enforcement agencies are relatively flexible and can be tailored to conform to the body contour of the person wearing the body armor.

The flexible armor is commonly designed to stop handgun bullets and is usually inconspicuous. However, for military and peacekeepers it also designed to stop fragments from explosions and as well as bullets from handguns and is usually large and visible.

Lightweight high performance hard armor is generally molded to maintain a certain shape. A typical example of hard armor is a military and police ballistic helmet.

1.7.1 Soft armor

Most of the law enforcement officers in the US and other countries wear a flexible soft concealable undershirt called a vest. Such vests are designed for protection from handgun bullets, but not from rifle bullets or sharp pointed weapons such as icepicks and knives. These undergarments or vests are also sometimes called ‘bulletproof vests’ but no garment will certainly stop all bullets. Statistically, there is a very small probability that bullets will penetrate these vests. A better way of describing these vests is that they are ‘bullet resistant’. Another misconception is that such a vest will protect the wearer’s upper body. In fact, the vest protects only the critical organs; it will not protect hands, neck, head and legs of the person wearing the concealable vest.

The first commercial flexible vests based on high performance aramids ballistic fibers were developed and used by police in the late 1970s. Earlier versions of such vests were heavy, bulky and had poor tailoring. Frequently police departments had to ask their staff to use these vests. However, with the advancement of aramid fiber technology and introduction of High Modulus Polyethylene (HMPE) in the mid-1980s, the vests have undergone dramatic changes. Current ballistic vests are thinner, lightweight, and tailored for comfort. They utilize hybrid ballistic materials based on a number of patented technologies.

There is no simple method to test a new or used vest. The vest manufacturers are required to have a proper label identifying the vest. The label describes the result of a destructive test under controlled ballistic conditions on an identical vest. This test is recommended by the local Department of Justice and issued as a standard for the police or law enforcement agency. The standard specifies general procedure and specific types of bullets and velocities to be used in tests. Again, this is a strictly controlled test and there is no correlation to the risk of bullet penetration in field conditions.

The latest test standard issued by the US Department of Justice is NIJ Standard 0101.04. This standard, like its predecessors and other international standards in Europe and other parts of the world, is the result of an implicit trade-off among simplicity, economy, realism, reproducibility, and risk to the vest wearer.

Soft armor is also frequently used for non-personal safety applications. These applications are for protecting military or peacekeepers traveling in a vehicle.

The soft armor covers the floor and the walls of the vehicle. In such applications it is desirable to have a foldable or rollover type of soft armor in the shape of a blanket. Similarly, bomb blankets generally consist of soft armor and are used to stop fragments from bombs or other explosive devices.

Another soft armor application is for protecting airplane engines from the broken engine blades traveling at fairly high speed.

1.7.2 Hard armor

Hard armor for police and law enforcement agencies is often added to the soft armor vest. It is designed for special operations where there is a risk of bullets fired from a rifle. It may be inconspicuous but is often quite distinctive. The hard armor includes steel or titanium panels, ceramic backed with other types of materials, and molded cross-plied HMPE ballistic plates. There may be at least two hard armors inserted in a military vest to cover vital organs from front and back, and in some vests as many as five inserts covering neck and groin area.

A hard armor insert should be properly labeled for the bullets it has been tested with, with or without a soft armor vest behind it. The information will mention the test standard and the type of rifle bullets it is designed to defeat.

Other applications of hard armor are military and police ballistic helmets, military vehicles, hand-held riot shields, helicopter, military cargo planes, and civilian vehicles. A number of such applications with pictures are covered in detail in Chapter 13.

1.7.3 Ranking of armor

Current specification and test standards do not provide ranking of soft armor which stops bullets in terms of a 1 to 10 ranking. The test method usually specifies complete stopping of all the bullets. Once all the specified bullets are stopped and the specified deformation under various temperature and moisture conditions met, the armor is certified.

Similarly, the hard armor used for military and law enforcement has a pass and fail test under a host of environmental conditions.

One way to rank armor is testing for a V_{50} ballistic limit – the velocity at which the test bullet has a 50% chance of penetration. Once a V_{50} is determined, Specific Energy Absorption of Target (SEAT) is calculated. The SEAT is calculated based on the fragment mass and weight of the target which will be tested against the projectile. Such tests are currently limited to testing against fragments.

1.7.4 Life expectancy of hard and soft armor

Since the early armors were made with steel, the concept of life expectancy was missing from armor design and testing. Current lightweight armor is made with a number of materials and it is possible that certain materials may age with the passage of time. Both the soft vest and hard armor also show wear and tear with routine day-to-day activities. However, neither police nor military have specified short-term or accelerated aging tests that can predict the long-term performance of the armor materials. Limited data on aging of such armor material is obtained by using accelerated aging techniques, where the exposure conditions are deliberately more severe than those encountered in the field. With these exposures, the damage to armor material could be obtained in a relatively short time. However, it is difficult to correlate the data obtained from short accelerated aging with the field aging under normal wear and tear.

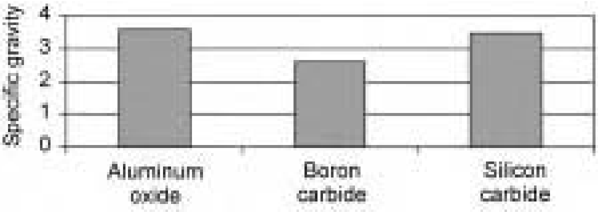
During the last few years a number of government agencies, such as NIST, vest manufacturing companies, fiber manufacturers and universities have started accelerated aging of high performance armor manufactured with ballistic fibers. Some of these tests are based on accelerated testing conducted by automotive industries. High temperature and high moisture conditions are used in a number of such tests. A few tests also cover the cycling nature of hot and cold exposure of armor, similar to some extreme field conditions.

It will be a few years before results from this testing will appear in symposium and in the textile journals. However, the entire ballistic industry is aware of the lack of this information and therefore taking precautions, including adding additional armor material to new products that will be commercialized in the coming years. Instruction labels are also added to new armor vests specifying the proper precautions during the life of the armor to limit aging in the field.

1.8 Ceramic-faced lightweight composite armor

Since the Second World War there has been a demand to develop lightweight armor systems to stop rifle bullets. The material which met this demand during that period was steel. However, with the development of fiberglass composites in early 1960s a material lighter than steel was invented. This material was developed by combining a hard surface consisting of aluminum oxide ceramic and backed with a fiberglass reinforced composite. The hard ceramic surface shatters the bullet and fragmented bullet and ceramic pieces are contained in the fiberglass backing. The material is relatively cheap and easy to manufacture. The total areal density of this composite material was in excess of 60 kg/m^2.

With the technology advancement in the area of ceramics, a new lower weight ceramic was developed based on boron carbide. The boron carbide ceramics are about 20% lower in density but with a hardness surpassing the aluminum oxide. However, two problems associated with the boron carbide slowed down adoption by the military. These problems are (a) steep cost compared to aluminum oxide ceramic and (b) difficulty in maintaining consistent quality of boron carbide ceramics. A change in composition and manufacturing



1.3 Ceramic specific gravity.

methods resulted in a hot pressed boron carbide ceramic. This change has also increased the reliability and reduced the cost of the ceramics.

Ceramic materials are known to be stiff, brittle, very hard, and stronger in compression than in tension. Such properties are desirable to blunt and break bullets that have a steel or tungsten penetrator inside the bullet's casing. However, ceramics are heavy compared with lightweight high-performance ballistic material. Lightweight ballistic materials are not stiff or brittle and are strong in tension but poor in compression. The combination of ceramic facing with lightweight composite armor material backing makes the best of both materials to defeat armor-piecing bullets at the lowest weight.

Aluminum oxide (specific gravity 3.43) was the first hard-faced ceramic to be exploited for large volume protection against armor-piercing rifle bullets (Fig. 1.3). Other higher performance ceramics are silicon carbide (specific gravity 3.20) ceramics and boron carbide (specific gravity 2.48).

1.9 Fabrication processes

The goal in creating a lightweight ballistic material is to combine high performance fibers with or without any other material in such a configuration that will provide highest flexibility (for flexible body armor vests) and maximum protection at the lowest weight. Similarly, for hard and rigid armor the goal is to fabricate durable, thin, dent-resistant armor with the highest ballistic protection at the lowest weight.

The fabrication processes, both for soft and hard armors, influence the ballistic performance of the lightweight ballistic products. In the case of soft armor, maintaining fiber orientation, proper tailoring and proper layer sequence are the essential elements in achieving the maximum performance of vests and other such applications.

Chapter 11 covers the molding processes of hard armor using relatively low pressure processes such as autoclaves and high pressure processes such as compression molding. Details are presented for a number of processes and the ballistic performance of each process is discussed. Parameters which influence the ballistic performance are the curing cycle, the equipment and tooling, and variation associated with which determines to a large measure the chemical, physical and mechanical properties. Storage conditions and handling of materials can also influence ballistic and other properties of the molded armor composites. Tests therefore are necessary to evaluate the parameters associated with the processing and handling.

1.10 Testing of ballistic materials

Tests are conducted to determine the suitability of the ballistic materials, processes and design for defeating the intended ballistic threat. Tests of lightweight soft and hard armor are conducted as per the test specified by the purchasing authority. In the US law enforcement agencies follow the NIJ Test Standard 0101.04 for testing against handgun and rifle bullets. The tests are performed against the specified threats listed in the NIJ Standard. Similarly, military procurement of soft armor and hard armor are as per the specification issued by the military.

Testing of ballistic materials is especially important because the properties and concomitant performance are subject to significant variations associated with the raw materials, processing, and design parameters.

Standardized and/or special tests are necessary to aid in materials selection, process development, design, and quality control. Tests for ballistic materials must be consistent of both non-destructive and destructive conditions. The tests on ballistic fibers are conducted by breaking the fibers under controlled conditions in the lab. Non-destructive testing takes place during the weaving or cross-plying process and assembling or molding of the finished vest or molded component.

Quality control plays an important role in the production of lightweight ballistic raw materials and finished products. Reproducibility and uniformity are necessary to ensure that the entire batch of finished product will perform uniformly during ballistic testing in the ballistic lab and also in the field. To meet this goal, it is desirable to control the quality of all constituents' materials to the extent possible or practical, to control the quality of the product while in the process of assembly or in the process of molding, and to evaluate the quality of the end point.

Knowledge of batch-to-batch variation and possibly variation during assembling and molding is important for maintaining the short-term and long-term ballistic performance of finished ballistic products. To avoid any other surprises, material qualification and batch acceptance tests are frequently required. Qualification for military applications usually requires a very extensive series of tests to ensure compliance to meet the product performance over a large period in a variety of harsh field conditions. Acceptance may involve a few ballistic tests, most likely selected from the qualification test series, that are considered adequate to ensure essentially equivalent ballistic performance.

In many cases, the end item may be subjected to extensive tests, destructive and non-destructive, as a requirement for qualification and acceptance.

Frequently, such tests are necessary during development of the product to determine how the product will respond to anticipated ballistic threats and environments. Depending upon the results, the design may be modified accordingly.

Qualification tests often are required to ensure that the end product manufactured with the selected materials, and in accordance with specified manufacturing procedures, will provide the desired response and the ability to withstand required operational conditions. Having qualified the product, subsequent units are subject to acceptance testing for consistent quality and reproducibility. Whereas the qualification tests may be quite extensive in scope, acceptance testing is generally limited to one or a few tests selected so as to evaluate quality and performance, consistent with cost and schedule. In some cases, a limited number of units from each lot may be tested to destruction during ballistic testing. Frequently, shoot packs or molded test panels are prepared along with the end item. Such shoot packs or molded panels may either be tested right away or tested after a lapse of time, in case product may not perform as designed during field trials.

The major causes of a ballistic armor failure both for law enforcement and military are due to:

1. Testing against wrong ballistic threats and not paying attention to clamping and clay conditions.
2. Ballistic design without considering the material and ballistic test fluctuation.
3. Inadequate controls of materials.
4. Poorly controlled ballistic fiber, weaving or cross-plying manufacturing techniques.
5. Wrong application of ballistic materials.

1.11 Ballistic threats

A ballistic threat consists of bullets and fragments generated from explosions. Bullets come in many different styles, shapes, and materials. Some are solid lead bullets. A number of other bullets consist of lead or steel core and a covering called a jacket. Fragments in a military conflict are generated in all kinds of shapes and sizes traveling at fairly high velocities. However, for testing fragment resistance against fragments in the lab, Fragment Simulated Projectile (FSP) and Right Circular Cylinder (RCC) fragments consisting of hardened steel are used.

1.11.1 Guns and bullets

Understanding of guns, projectiles (both bullet and fragments) and projectile deformation is important for designing ballistic materials which will defeat the high speed projectiles at the lowest weight. However, understanding projectile penetration in a lightweight ballistic material can be a frustrating area of science. The entire event of projectile firing and stopping in the lightweight ballistic material is over in a fraction of second. There are so many variables that it is almost impossible to use formulas that are based on known laws of physics without also including information from actual tests.

Chapter 2 shows the composition of a number of bullets and fragments along with photographs of the some of the frequently encountered bullets and lab fragments. Handgun bullets, rifle bullets and lab fragments are described in terms of weight, size, shape, and muzzle velocity. Chapter 2 also goes over the bullet deformation parameters such as the fiber physical properties, fiber orientation, woven and non-woven ballistic material, effects of coating and lamination, and so on.

1.11.2 Projectile deformation

Projectile deformation while penetrating a lightweight high performance fiber-reinforced armor, both soft and hard molded armor, is a complex phenomenon. Understanding projectile deformation is important during the designing of an armor system to defeat the projectile. A full metal covered jacket has higher penetrating possibility but usually has lower back face trauma. On the other hand, a lead bullet with little or no metal coverage will have less penetrating possibilities but it will generate higher back face trauma. Handgun bullets and some rifle bullets start deforming as soon as they penetrate the first layer of fiber-reinforced armor. The shape and hardness of the steel penetrator and the velocity of the bullet usually dominate deformation of bullets with a steel penetrator.

Deformation of fragments is limited to the tip of the fragment and in many instances it is so small that it is difficult to quantify without use of a magnification glass or a microscope.

There are a number of other factors which influence the deformation of projectiles in a lightweight high performance fiber-reinforced ballistic armor. The factors are interdependent, and it is difficult to separate out the influence of these parameters. However, a few parameters have major affects. These parameters are: type of high performance fibers, fiber orientation with respect to adjacent fibers and with respect to bullet, mechanical or chemical bond between fibers, number of layers in the armor and process of layers consolidation of such materials.

Each possible parameter is covered in Chapter 2.

1.12 Design of ballistic products

Designing of lightweight fiber-reinforced armor products is not straightforward due to a number of reasons. Some of the reasons are:

1. Finished ballistic products are ‘built-up’ from a number of individual layers, each oriented in a given direction.
2. Understanding of ballistic materials varies from ballistic threat to ballistic threat.
3. Limited data at high strain level encountered during projectile penetration.
4. Mathematical models are in early stages of evolution from linear materials to non-linear viscoelastic materials.
5. Hybrid materials make it difficult to calculate contribution of each material in defeating projectiles.
6. Bullet deformation is a complex phenomenon and all the parameters are not fully understood.
7. The contribution of product supporting conditions influence ballistic performance.
8. The contribution of Plastilina clay supporting vest is unknown.

Due to these factors the design of vest is usually based on:

1. Past vest design experience.
2. Understanding material ballistic performance fluctuation.
3. Ballistic data under standard threats.
4. Trial and error method, mixing and matching known and unknown materials.
5. Understanding influence of moisture, UV and temperature exposure on ballistic material.

1.13 Specifications and standards

Specifications are the documents that specify the performance of the armor to satisfy the need of the buying agency. Specifications are a mission-specific document, or a generic, fairly broad type of document covering a wide range of ballistic and other requirements. Since the late 1980s, a number of countries including the US military have moved away from product-based specification to performance-based specifications. This move has helped the military increase the performance of ballistic vests, helmets and breastplates. Similar moves by the French and other European military have helped to upgrade the coverage area and at the same time keep reducing the weight and cost of the military helmets and breastplate kits.

The Standards, such as National Institute of Technology (NIJ) 0101.04, are technical documents that specify the performance requirement that a soft or hard molded armor should meet to satisfy the needs of a law enforcement agency. The standard is designed to provide a precise and detailed test method. Compliance with the requirements of this standard is tested by an independent laboratory or guaranteed by the vendor. Personal body armor covered by the standard is classified into types of vest based on the level of ballistic performance. A certified armor will have a minimum performance against the threat specified in the test standard.

A number of countries outside the US have adopted NIJ standards. Some have adopted the NIJ standard as it is, some have modified the standard and some have come out with an entirely new standard based on local ballistic threats and the requirements of the police.

1.14 Numerical modeling of armor

Numerical models for predicting the performance of fiber-reinforced lightweight composites have been a subject of keen interest by the government agencies and commercial organizations for a number of years. Theoretical and finite-elements modeling (FEM) are cost-effective alternatives to determine their influence on ballistic response. A good model, which can predict the ballistic performance of lightweight armor, can cut down design time, cost of material and testing cost.

The ballistic response and energy absorption characteristics of woven and non-woven armor materials under high speed projectile loading are dependent upon a number of factors. Some of the factors are simple to quantify, but a number of others are difficult to measure or predict.

Construction parameters such as fabric type, fabric construction, areal density, projectile shape, projectile deformation characteristics, and ballistic impact conditions such as striking velocity and boundary conditions of the armor material are relatively easy to quantify.

Earlier armor performance prediction numerical models were based on an empirical or semi-empirical approach to formulate a material constitutive relation for armor fabrics and then used finite-elements to predict the ballistic behavior under the high speed impact from the projectile. In other models each finite-element was assigned the equivalent mechanical properties of armor fabrics using a rate-dependent model. A number of such models have used static properties of the fabric, which might have contributed to the limited use of the models.

Another set of models used the fiber properties to be linear elastic up to the point of failure under impact loading. The dynamic Young's modulus and fracture strain of the fibers were used and the model used a correction factor to calculate the wave velocity in the woven armor as a function of wave velocity in a single yarn, in order to account for the increase in density at the yarn crossovers.

DYNA3D, Material Type 19 is a strain rate-dependent isotropic elastic-plastic model. The model offers the option of representing Young's modulus, failure stress, yield stress and tangent modulus to be specified as a function of strain rate in form of stress–strain curves. The dependents of elastic modulus and failure stress on strain rate essentially constitute the viscoelastic characteristics of fabric material.

A recent model has assumed armor as a membrane element. Limited data was generated using relatively smaller fabric and impacting it with a spherical projectile. Both the fabric and sphere were modeled in full to simulate the stress wave propagation in the fabric from the point of impact. A semi-empirical approach was adopted to formulate a material constitutive relationship for aramid fabric. A three-element system of two Hookean springs and a Newtonian dashpot are used to model the viscoelastic behavior of armor fabric. The model predicts the behavior of fabric within the limited scope of simplified assumptions.

Chapter 4 of this book will go over some of the numerical analysis and empirical modeling of armor highlighting the trade-off of such numerical work.

1.15 Applications

Lightweight, high performance fiber-reinforced armor materials have shown dramatic growth in the last decade. High performance armors are becoming a standard item for militaries all over the world. Police and other law enforcement agencies in the US and other parts of the world buy large quantities of concealable body armor for their officers. In the US, federal government funded programs have encouraged police departments to buy higher cost, higher performance, state of the art soft and flexible vests which are 20 to 30% lighter than vests with similar bullet stopping performance.

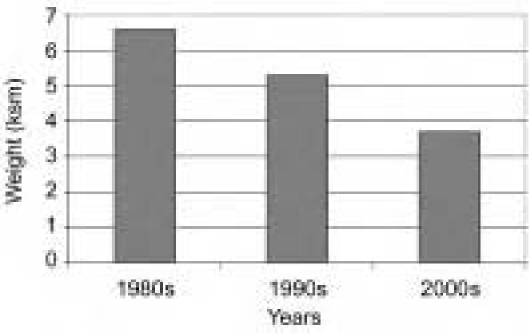
Most common applications of lightweight armor are listed below:

- *Personnel protection*
  (a) Soft flexible vest.
  (b) Rigid molded breastplates (with and without ceramic facing).
  (c) Ballistic helmets.
- *Vehicle armor*
  (a) Ground vehicles.
  (b) Sea vehicles.
  (c) Aircraft and helicopters.

1.15.1 Soft flexible vest

The commercial success of the soft flexible vest has greatly increased in the last fifteen years due to a number of factors:

- New lower denier high strength ballistic aramid fibers.
- Introduction of HMPE fibers.
- Non-woven cross-plied armor materials using aramid fibers, HMPE fibers and recently PBO fibers.
- Thinner, lighter and flexible vests.
- US government funded Vest Partnership Act.



1.4 Technological advances in soft armor vests.

Combined effects of all these factors have dramatically reduced the weight (see Fig. 1.4) and increased the flexibility of the vests worn by police and military personnel.

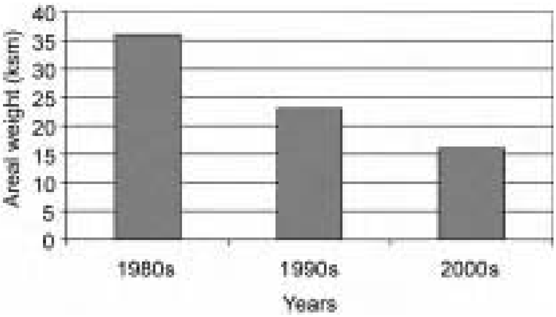
1.15.2 Rigid molded breastplates

Rigid molded breastplates are an essential part of a ballistic vest for military and special forces conducting missions that involve high energy rifle bullets from the enemy. Only ten years ago composite breastplates fabricated with ceramic backed with molded layers of aramid prepreg layers were fairly heavy. The breastplates were fabricated using an autoclave process and the reject rate was high due to a number of factors involving the quality of ceramic and development of macro gaps between ceramics tiles due to the movement of tiles during the autoclave process.

With the introduction of HMPE fibers and non-woven technology, the fabrication and performance of breastplates has changed dramatically. Predetermined layers of non-woven HMPE are molded in a heated match die mold under a high clamp pressure for a short duration. Resultant breastplates are almost half the weight and stop a number of high-energy rifle bullets. The reject rate has been dramatically reduced and durability has increased substantially. Figure 1.5 shows the reduction in weight over the years.

1.15.3 Ballistic helmets

Historically, ballistic helmets were an essential gear for military. During the First and Second World Wars, all sides of the conflicts used steel helmets. These helmets provided only low speed impact protection. During the Vietnam conflict the US army experimented with aramid inserts inside the steel helmet. This increased the ballistic protection from less than 300 mps to almost 450 mps.



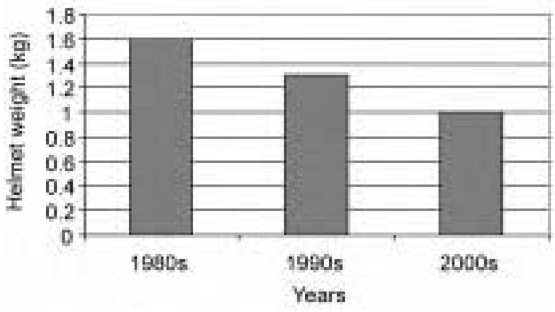
1.5 Technological advances in breast plates for M80 ball bullet.

With the R&D conducted by US military, the first all-composite military helmet was introduced in the early 1980s. The helmet consisted of woven aramid fabric prepreg, and the performance was increased to 600 mps. With the introduction of HMPE fibers and fabric, the performance was further increased in terms of reduced helmet weight by almost 20% (Fig. 1.6). With the introduction of non-woven technology for all the ballistic fibers the weight of helmets was further dropped by another 10%.

Currently, the US army is planning to buy next generation helmets, which can provide protection from a number of threats such as fragments and 9 mm FMJ bullets at a substantially lower weight than the present helmets.

1.16 Vehicle armor

A number of countries are working jointly to figure out how to reduce the weight of armor used in military vehicles. Current material of choice is hardened steel. Steel has a long history for armoring military vehicles. It is the cheapest metal and availability is good. However, steel is one the heaviest metals. There are a



1.6 Material advances in military helmets.

number of other lighter and/or stronger metals, however, the weight reduction is not significant.

One of the first attempts, called ‘Composite Infantry Fighting Vehicle’ (CIFV), demonstrated how to reduce weight by using S-2 glass and E-glass polyester based hand-lay-up and prepregs and this has also helped to reduce the number of parts required to manufacture armor vehicles.

Recently (2002) a new demonstration vehicle, called the ‘Composite Armored Vehicle Advanced Technology Demonstrator’ (CAV-ATD), provided a significant step forward in developing lighter weight, more lethal, more survivable platforms. The CAV-ATD incorporates ceramic-composite armor at an areal density of about 27 psf (5.5 ksm) and shows a 35% weight saving over traditional metallic structure with armor. The current target for an advanced armored vehicle, based on 50 caliber AP threat, is about 10 psf (2 ksm).

On the other hand, air vehicles, such as helicopters and other cargo airplanes are using state-of-the art boron and silicon carbide ceramics with either HMPE fiber composites or aramid fiber composites backing for lighter ballistic threats such as 30 caliber AP bullets and 50 caliber Fragment Simulating Projectiles (FSP).

A number of lightweight armor applications are included in Chapter 13.

1.17 Future growth of fiber-reinforced armor

History of armor materials development shows the evolution of ballistic materials, shapes and design. A review of armor design using limited material over the past few thousand years can prove very useful in providing innovation ideas for modern armor. A study of the ballistic materials used throughout history not only shows the much greater range available today, but also shows some cyclic aspects with flexible materials such as fabrics and felt materials being used years ago and appearing frequently throughout history but never being fully exploited.

The primary backbones of current lightweight ballistic materials are the lightweight high performance ballistic fibers. These fibers are man-made after extensive R&D and the spending of millions of dollars. Two common ballistic fibers highlighted throughout this book are aramids and High Modulus Polyethylene (HMPE). Thermoplastic (urethane, synthetic rubber and polyethylene) and thermoset (phenolics and vinylester) are the resins used most often for lightweight ballistic composite materials.

Another recently introduced ballistic fiber is PBO fiber. However, limited production volume and lack of long-term performance has hindered the extensive use of these fibers in ballistic application. A new ballistic fiber on the horizon is M5 fiber. Currently only theoretical ballistic data are available.

1.18 Raw materials suppliers–converter partnership

In this era of advances in lightweight ballistic composite materials technology, raw materials suppliers and converters of ballistic products have maintained a strong technology base to provide the critically necessary information that will allow both current products, and, more importantly, new products to be profitable. The required levels of this technology and to what extent it is necessary are, of course, directly related to the type of business and competitive situation of each individual company.

The task of producing high performance ballistic products that are profitable is complex enough to require a unique managerial organization if success is to be achieved. The broadest possible understanding of a variety of disciplines – including the physical science and technology – is required. It appears that most of the new advances in the area of high performance armor materials will be in the area of higher performance ballistic fibers. For hard armor, the matrix (resin) component has not yet progressed to the stage at which the full potential of armor materials can be utilized.

1.19 Rapid growth of armor materials

When reviewing modern trends in lightweight ballistic material technology, it is obvious that the overall composite industry will continue to have a rapid growth. The annual average growth rate for the overall industry as a whole has been less than 5%. Growth has been 10% for the composite industry, but more than 25% (since 2000) for the ballistic industry.

Greater demands for increased efficiency on a cost-to-performance basis continue to grow as ballistic products inevitably move to larger-volume markets such as the armored vehicle market, which emphasize durability under different environmental conditions. Furthermore, as knowledge and confidence in the area of the long-term durability of ballistic products continue to expand, their use in both flexible and rigid armor will gain even wider acceptance.

The use of lightweight high performance armor in aircraft is increasing, especially in aircraft being used for military operations in the hostile areas of the world. The pay-off in such applications is greatest for the industries involved in armoring cargo planes such as the C 130, a number of helicopters, and unmanned aircraft. Potential applications are limited only by the current shortage of high performance ballistic fibers. The main disadvantages of present lightweight armor is relatively high cost, limited repair data under field conditions, lack of extensive performance history under extreme conditions and the lack of possibility of recycling each component.

1.20 Integration and mergers of the armor industry

In recent years, the lightweight composite ballistic industry, similar to the load bearing composite industry towards the end of the Cold War in late 1980s, has been involved in integration, mergers, and regrouping. At present, it appears that there will be much more of this type of activity at a global level. For some markets, particularly the larger ballistic product converter markets, the integration approach permits a company to progress from smaller volume to fairly large products more efficiently. Acquisitions have also been a real boom for many organizations, allowing them to expand in-house capability in highly specialized fiber and prepreg manufacturing. Companies that recognized the potential of the ballistic industry in its infancy and prepared for expansion are still on the rise.

There are many possible roadblocks associated with the current explosive growth of the ballistic market. These must be overcome before the ballistic industry is accepted and widely used as a replacement to armor steel in vehicles used by the military. In general, the lack of total confidence on the part of the vehicle designer can be attributed to cost considerations and the reliability of the design data. Understanding the product and molding process reliability in primary vehicle applications is influenced by quality control evaluation procedures, particularly the ballistic field testing.

There are ballistic engineers who are exposed to metal only and they simply do not understand lightweight ballistic composites, probably due to the limited amount of time they have available to research the applications. However, since lightweight ballistic applications are continuing to expand, data will eventually be available in handbooks, standards, and on websites. In the meantime government agencies, industries, societies, and associations are making continued efforts to update and develop new specification standards and testing methods.

Past and present performance, as well as the current era of R&D, has laid the groundwork for the future growth of the lightweight ballistic industry. Effective exploitation of future opportunities is the key to the potential large-scale market penetration and consequent profitability of the high performance lightweight ballistic industry.

Both soft and hard armor should find expanding use in protecting law enforcement, military, and homeland security personnel. Although monumental technology breakthroughs are unlikely in the next five to ten years, growth will continue to be manifested in steady, incremental advances limited not by technology, but by economics. The real industrial breakthrough could occur as a result of greater use of lightweight ballistic armor in lighter and better personnel protection and vehicle armor. A fundamentally sound understanding of the mechanics of projectile interaction with the lightweight ballistic composites will soon provide increased opportunities for numerous applications. New armor products that utilize ballistic fibers of increased strength and higher modulus of elasticity in a suitable matrix will substantially reduce the weight of ballistic products currently being utilized. In the usual pattern, the requirements of military and law enforcement will continue to provide the impetus for R&D, thus creating new and better materials that eventually find application in other related commercial and military markets.

Development of lighter and better protective armor is due to a continuous desire to reduce casualties in the battlefield, or during peacekeeping and law enforcement. Other factors that play major roles in armor development are the reduction of weight of personal protective gear and lessening of the barrier posed by armor during body movement. This reduction in weight reduces the heat burden experienced by the wearer during each activity reducing sweat evaporation from the individual and ensuring that protective gear does not pose a barrier to the efficient accomplishment of the wearer's mission.

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Part I

Material requirements and testing

2

Bullets, fragments and bullet deformation

A BHATNAGAR, Honeywell International Inc., USA

2.1 Introduction

For centuries humans have been exposed to bullets and fragments generated from artillery shells and bomb explosions. Over the years as technology has advanced in the areas of explosive powders, bullets, guns, rifles, and highly efficient delivery systems for bombs, the ballistic threat for police and military has increased. In certain parts of the world, lower cost rifles and bullets are available in open markets for anyone at a negligible cost. Both police (and other law enforcement officers) and military (including peacekeepers) face these types of threats, both as part of their training and in real-life situations.

It is difficult to cover all the types of bullets sold legally, illegally and those available to terrorists. This chapter will cover only the common bullets identified by police and military including international agencies working for the safety of police and law enforcement agencies. Similarly, this chapter will focus on the type of fragments used in laboratory testing in the US and other parts of the world.

The chapter will not cover interior ballistics, which take place inside the firearm such as gun powder ignition, bore friction and pressure build-up before the firing action. Nor will it cover the exterior ballistics, which involve the projectile's flight and its impact. However, the later part of the chapter will briefly cover terminal ballistics, covering factors that contribute to interaction between projectile and ballistic fiber-reinforced materials. The second half of this chapter will also cover deformation of bullets and fragments penetrating lightweight ballistic materials. Although the deformation of projectiles penetrating either soft armor or hard molded armor is a complex phenomenon, factors are identified which contribute to the deformation of projectile penetrating fiber-reinforced ballistic materials at high speed.

2.2 Handguns and rifles

Handguns and rifles are used to fire bullets used by law enforcement, peacekeepers, military, and also groups of people working against these agencies.

Handguns and rifles are classified according to the length of barrel as handguns or long guns; the latter include rifles and shotguns. The handguns and rifles are generally designated by their 'caliber' and by the nature of their firing action.

The caliber is the inside diameter of the barrel. Thus, a 22-caliber handgun or rifle will have an inside diameter of 0.22 inch, and that of a 9 mm will have an inside barrel diameter of 9 millimeters. Anomalously, a .38 Special has a barrel with the same inside diameter as that of a .357-caliber revolver: 0.357 inches. While the .38 Special cannot fire the longer or 'magnum' .357 ammunition, the .357 revolver can fire .38 ammunition. The designated '.380' is used for automatics firing .38 caliber bullets from specialized cartridges.

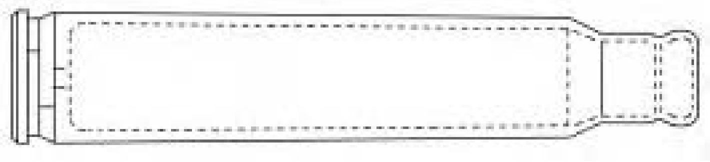
Actions are often designated 'full automatic', 'automatic', 'semi-automatic', 'auto-loading', 'double action', 'single action' , 'bolt action', 'lever action' and 'pump'. These terms divide the weapons according to what the gun holder must do to fire repeat shots. 'Full automatic' weapons will fire continuously as long as the trigger is pulled back, until they run out of ammunition. 'Semi-automatic', 'double action' and 'auto-loading' weapons require a separate trigger pull for each shot. 'Single action' weapons require 'cocking' between shots. 'Bolt action', 'lever action' and 'pump' rifles and shotguns require operation of their bolt, lever or pump between shots.

The terms 'automatic' and 'semi-automatic' are not always correctly used or understood. Regarding handguns, 'automatics' are used in contradistinction to 'revolver': the Colt .45 M1911 a1 (familiar for decades as the US military's sidearm) is an automatic whereas the Colt .45 Peacemaker (of cowboy fame) is a revolver. 'Automatic' handguns fire in the manner called 'semi-automatic' for other guns: shots can be fired in rapid succession by repeatedly pulling the trigger, without any other action such as operating a bolt or pump. These guns will continue to fire as long as the trigger is depressed. Otherwise, 'automatic' is properly used to describe a 'full automatic' gun, i.e. machine guns that will continue to fire as long as the trigger is depressed. Most such guns have a 'selective-fire switch' allowing the user to toggle between full automatic and semi-automatic modes of operation.

A submachine gun is a machine gun that fires pistol ammunition. A 'carbine' is a compact rifle. The 'assault rifle' differs from other semi-automatic carbines largely through styling, not functioning.

2.3 Handgun bullets

Handgun ammunition is described in terms of the diameter of the bullet, the length of cartridge, and the shape and composition of the bullet. Shotgun ammunition is described in terms of the diameter of gun barrel for which it is designed, and by which it contains a single bullet-like 'slug' or, if not, by the size of the shot or pellets it contains.



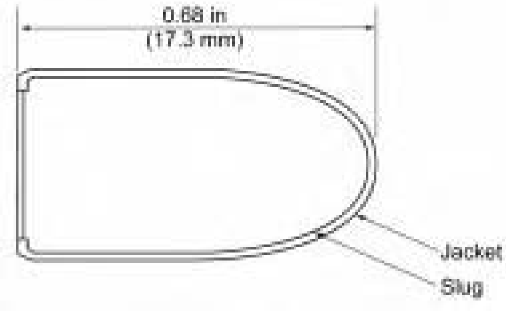
2.1 Bullets' cartridges.

Bullet diameters are the same as the inside diameters of the gun barrels from which they are fired. The length of cartridge has a direct bearing on the amount of gunpowder it can contain and thus on the velocity with which the bullet can be propelled. 'Magnum' cartridges are longer than standard cartridges so that they may contain more gunpowder. Similarly, many handguns are chambered for .22 Long Rifle cartridges, which contain more powder than .22 'Shorts' (Fig. 2.1).

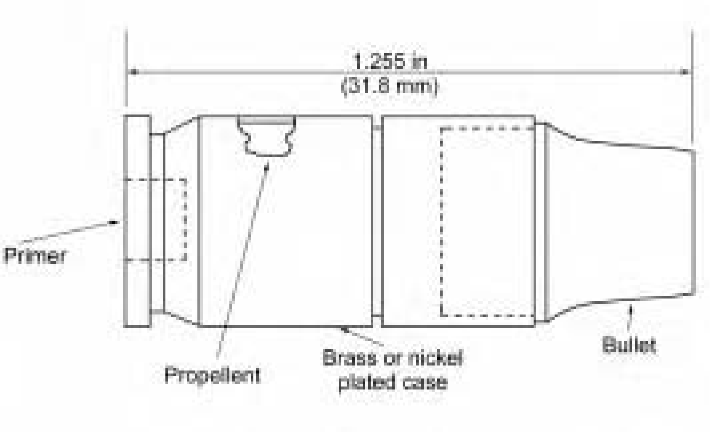
Bullets vary in shape, construction, and composition. In general all the bullets have an aerodynamic shape. The aerodynamic shape of a bullet helps it to maintain speed when fired from a distance. Although air can offer a high drag to slow down the bullet, due to its aerodynamic shape bullets lose little velocity (Fig. 2.2).

Within the aerodynamic form, the shape may range from the relatively pointed 'spear' bullet, no longer used in body armor testing, to the cylindrical 'wad cutter' bullet optimized for clear punching of circular holes in paper targets. The 'semi-wad cutter' shape is a compromise between the wad cutter and the typical aerodynamic bullet shape (Fig. 2.3).

'Hollow-point' bullets feature a small cavity in the nose to create mushrooming after impact. Some controversy surrounds the question of whether nominally identical bullets differ sufficiently in shape to affect the outcome of armor tests. The bullet can have full or partial metal jackets. A partial jacket, typically found on a hollow-point bullet, leaves the nose of the bullet exposed. The jacket is typically made of copper. Due to the copper properties, it offers



2.2 Aerodynamic shape of lead-filled bullet covered with a thin metal jacket.



2.3 Wad cutter.

sufficient strength and durability, but at the same time offers little damage to the barrel of the handgun or rifle during repeated firing. A ‘gas check’ is a copper shield on the base of the bullet to keep the burning gunpowder from melting the base while the bullet is still in the gun.

Jackets and gas checks aside, bullets are normally made out of lead. The lead is a fairly soft material and therefore deforms easily under the minor resistance offered by human flesh and muscles. Due to this deformation it can generate severe damage to the human body. The hardness of lead is governed by the degree to which it is alloyed with other metals.

Some bullets contain harder metals, either in form of machined mild steel penetrate, or in the extreme case hardened steel or tungsten pin or a hardened steel or tungsten core. These bullets are designated ‘armor piercing’. The rare Teflon-coated bullets made of machined steel, brass, or tungsten have gained notoriety far out of proportion to their number. These bullets will penetrate soft body armor. The Teflon in itself confers no special armor-piercing properties, and is used merely to lessen the extreme barrel wear that would otherwise be caused by bullets made of such hard materials.

Shotgun loads range from birdshot loads containing hundreds of small pellets to the slug load, composed of a single bullet-like ‘slug’. Buckshot lies between these extremes, with a shell containing a dozen or so pellets, depending upon the size of the buckshot. To make up for the lack of rifle in most shotgun barrels, slugs themselves are typically cast with slanted grooves on their sides to impart aerodynamically the spin needed for stability.

2.4 Fragments

Fragments are generated when a bomb, grenade or artillery shell explodes in a battlefield during a military conflict. Since these explosive devices are made of hardened steel, fragments generated from explosions have a variety of shapes and sizes and travel at different velocities respectively. Since it is practically impossible to test each shape and size of a fragment traveling at various velocities, the US military recommend five sizes of fragments which simulate a variety of shapes and sizes of the fragments in the battlefield.

As per the US military specification MIL-P-4659A (ORD) the simulated fragment projectiles are classified as follows:

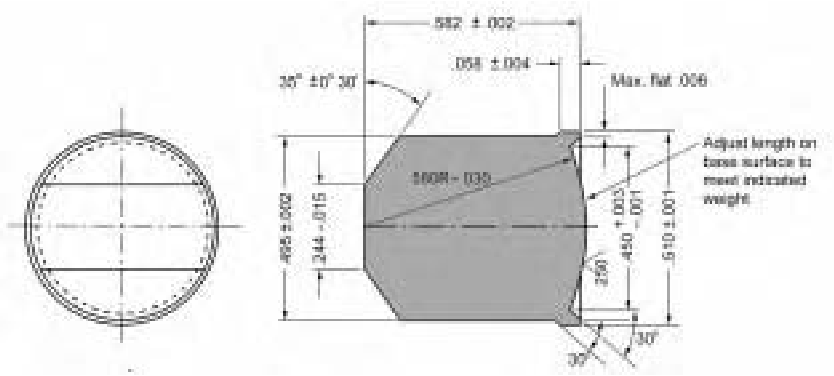
Caliber-.22 Type 1 (projectile for armor plates)
Caliber-.22 Type 2 (projectile for body armor)
Caliber-.30
Caliber-.50
20 mm.

2.4.1 Fragment Simulating Projectile (FSP) composition

As the name indicates, fragment simulating projectiles 'simulate' a variety of features of fragments. These features are shape, size, geometry, cutting, penetrating, and entanglement properties of large, medium, and small fragments generated when a hardened cast or hardened steel device explodes in a military conflict. The flat nose with sharp edges simulates cutting and penetration action, the back skirt provides the entanglement simulation (Fig. 2.4).

The following FSPs are manufactured from cold rolled, annealed steel conforming to composition 4337H and 4340H:

Caliber-.22 Type 1
Caliber-.22 Type 2
Caliber-.30
Caliber-.50
20 mm.



2.4 Shape of a Fragment Simulating Projectile (FSP) fragment.

Table 2.1 Hardness of Fragment Simulating Projectiles

FSP	Rockwell hardness
Caliber- .22 Type 1	30 ± 1
Caliber- .22 Type 2	27 ± 1
Caliber- .30	30 ± 1
Caliber- .50	30 ± 1
20 mm	30 ± 1

The composition of Caliber-.22 Type 2 FSP may have the same steel as other steels capable of hardness uniformity within the hardness values indicated in Table 2.1.

2.4.2 Hardness of Fragment Simulating Projectile (FSP)

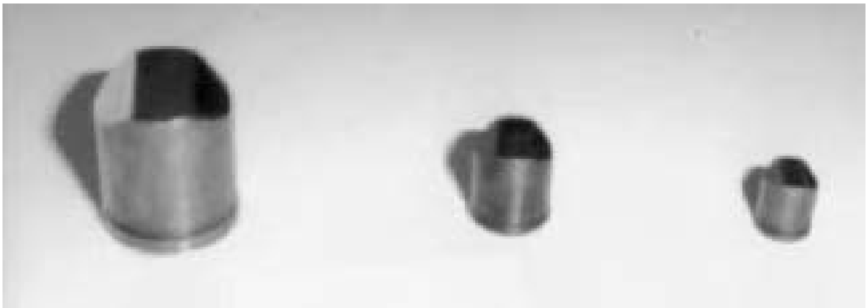
The FSP is fully quenched and tempered to a Rockwell hardness value shown in Table 2.1.

2.4.3 Weight of Fragment Simulating Projectile (FSP)

The weights of FSP are as shown in Table 2.2. For surface finish and dimension refer to MIL-P-46593A (ORD) (see Fig. 2.5).

Table 2.2 Weight for Fragment Simulating Projectiles

FSP	Weight in grains
Caliber- .22 Type 1	17.0 ± 0.5
Caliber- .22 Type 2	17.0 ± 0.5
Caliber- .30	44.0 ± 0.5
Caliber- .50	207.0 ± 0.5
20 mm	830.0 ± 0.5



2.5 50 caliber, 30 caliber and 22 caliber Fragment Simulating Projectiles.

2.4.4 Right Circular Cylinder (RCC) fragments composition

The following RCC fragments are manufactured from cold rolled, annealed steel conforming to composition 4337H and 4340H:

2 grain RCC
4 grain RCC
16 grain RCC
64 grain RCC
128 grain RCC

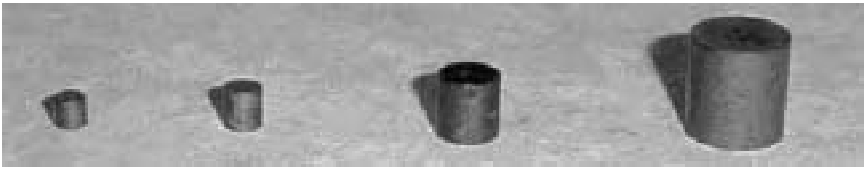
The composition of the above RCCs may have the same steel as other steels capable of hardness uniformity within the hardness values indicated in Table 2.3.

Table 2.3 Hardness of 2 grain, 4 grain, 16 grain, 64 grain and 128 grain Right Circular Cylinder fragments

RCC	Rockwell hardness
2 grain RCC	30 ± 1
4 grain RCC	30 ± 1
16 grain RCC	30 ± 1
64 grain RCC	30 ± 1
128 grain RCC	30 ± 1

2.4.5 Right Circular Cylinder (RCC) hardness

The RCC is fully quenched and tempered to a Rockwell hardness value shown in Table 2.3 (see Fig. 2.6).



2.6 2, 4, 16, and 64 grain Right Circular Cylinder (RCC) fragments, length/diameter = 1.

2.5 Small arms bullets

Small arms bullets come in many different styles, shapes and materials. Some are solid lead, many are assemblies with a lead or steel core and a covering jacket. The jacket may be gilding metal, gilding metal clad steel or copper plated steel. Some military caliber .30 and 7.62 mm frangible bullets are molded from powdered lead and friable plastics which pulverize into dust on impact with the target. The bullet normally consists of a metal jacket and a lead slug. The .50 caliber ball bullet and 7.62 mm, Ball M59 bullet contain soft steel cores.

Bullets fired from rifles lose velocity and energy as the range increases; both are required for proper expansion and penetration of a target. If a bullet does not expand well before hitting the target, the larger calibers have an advantage because the hole they make is larger. A little more weight and velocity is important if the target is located at 300 meters. A 30-06 and 7 mm bullet has an advantage for such distant targets. During penetration of a target high velocity gives more expansion but less penetration. It is important for flat trajectory and long-range hits, but if the target is not at long range, perhaps a flat trajectory is not as important. Many flat shooting small arms lose too much energy at longer-range targets.

The bullet weight, velocity, and expansion properties are in proportion to the range, size, and penetration resistance of the target. Military targets with light armor need bullets with strong penetration capability and less expansion capability. For such target penetration the preference is usually for a heavy bullet, moving slowly. Increasing a bullet's velocity may or may not increase the resistance to target penetration.

At longer range a small error, as small as 10% in estimation of the range, can almost guarantee a miss. At a shorter range, for example 200 meters, an error of 20% with an NATO (M80) bullet may be a problem, but would not be with a 30-06 bullet. Gravity pulls the bullet down the same amount per second of the flight. For small arm projectiles the time of flight is important, as is range and velocity. Velocity and energy losses at long range are major considerations for small arms. Five hundred meters is about the maximum range a small target should be fired upon. Cold weather will increase air density and therefore air resistance and drag. Cold weather also slows powder ignition, but will be by such a small amount that it is usually not considered. A projectile's flight through drizzle will also make no difference. While rain usually indicates a lower barometric pressure, it is not enough of a change to be noticeable.

Ammunition does not deteriorate with storage time duration as might be expected. Cartridges as old as ten years should not make any difference.

Some of the common small arm bullets used by the military and police are described below.

2.5.1 7.62 × 25 mm Soviet pistol

Synonyms

7.62 mm Tokarev

Development

The cartridge began as a 7.63 mm Mauser automatic pistol cartridge. Russian forces used it in the early 1900s. For manufacturing convenience the barrel of the Tokarev was 7.62 mm caliber, thus the Soviet cartridge lost its Mauser designation and became known as the 7.62 mm Tokarev. The current cartridge has been manufactured in China and other former Warsaw Pact countries using the Soviet specification. The Chinese pattern was started for automatic pistol Type 54 and Type 80 and for the Type 79 light submachinegun.

Specifications

Ball Type P
Round length: 34.55 mm
Round weight: 10.65 g
Case length: 25.14 mm
Rim diameter: 9.91 mm
Bullet diameter: 7.82 mm
Bullet weight: 5.57 g
Muzzle velocity: 505 mps
Muzzle energy: 709 J

2.5.2 7.62 × 39 mm Soviet M1943 (AK 47)

Synonyms

7.62 × 39 mm; 7.62 mm Kalashnikov; 7.62 mm obr 43 g

Development

Soviet development of an intermediate rifle cartridge had begun in the late 1930s, paralleled with similar work in Finland, Germany, and Switzerland, but dropped in 1939. In 1943 the development restarted. A design attributed to N.M. Elizarov and B.V. Semin was approved in late 1943 and applied to an experimental carbine by Simonov which later became the SKS. However, the major adoption of the cartridge came with the AK 47 Kalashnikov rifle, after which it became the standard rifle and light machinegun round for the Warsaw Pact and was widely adopted by other countries obtaining arms from the Soviet Union.

Specifications

Ball 57N231
Round length: 55.8 mm

2.7 AK 47 bullet and its mild steel penetrator.

Case length: 38.65 mm
Rim diameter: 7.9 mm
Bullet diameter: 7.9 mm
Bullet weight: 7.97 g
Nominal charge: 1.6 g SSNF 50 powder
Muzzle velocity: 710 mps
Muzzle energy: 2,010 J
(See Fig. 2.7.)

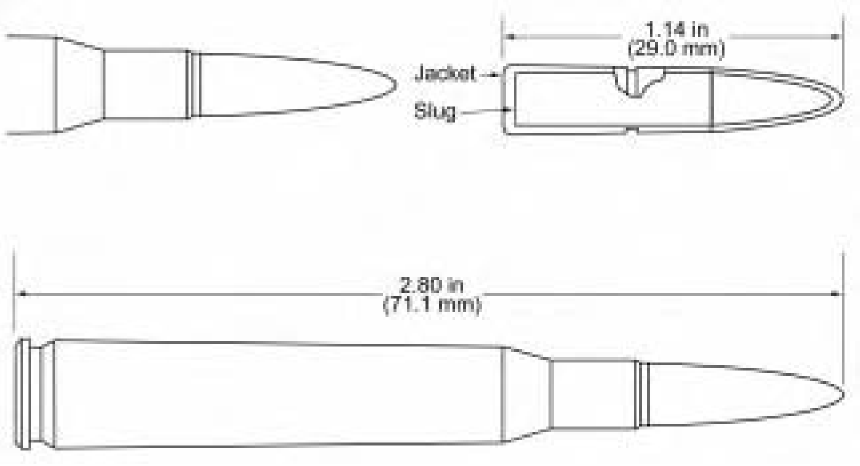
2.5.3 7.62 mm NATO Ball

Synonyms

7.62 × 51 mm

Development

The 7.62 × 51 mm cartridge was devised in the early 1950s as a compromise between full-sized 30-06 and a proposed British 7 mm round. It is little more



2.8 M80 ball bullet.

than the 30-06 with a shortened case. Since NATO adopted this bullet in January 1954 it has become widely distributed. Production has taken place at one time or another in more than 50 countries and even manufactured in RFAS for competition shooting.

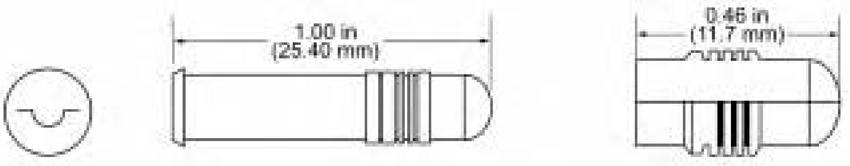
Specifications

US M80
Round length: 69.85 mm
Case length: 51.05 mm
Rim diameter: 11.94 mm
Bullet diameter: 7.79 mm
Bullet weight: 9.65 g
Muzzle velocity: 854 mps
Muzzle energy: 3,519 J
(See Fig. 2.8.)

2.5.4 0.22 in Long Rifle

Armament

All .22 rifles and pistols except those specifically chambered for .22 Short cartridges.



2.9 .22 Caliber Long Rifle bullet.

Development

In 1887 the J. Stevens Arms & Tool Company of the US developed the 0.22 Long Rifle rim fire cartridge by taking the existing .22 Long cartridge and fitting it with a 0.324 g powder charge and a 2.59 g lead bullet instead of the conventional 1.88 g bullets (Fig. 2.9). The Union Metallic Cartridge Company in 1888 was probably the first to manufacture it commercially. Remington developed the first velocity loading in 1930. Over the years it has become the most highly developed and accurate of all rim fire cartridges. Generally, it has either 2.59 g solid lead or 2.4 g hollow-point bullets, although there are many other variations. The military usually uses it for training purposes, but it has been used when low signature and accuracy were specifically required.

Specifications

Round length: 24.76 mm
Case length: 15.11 mm
Rim diameter: 6.98 mm
Bullet diameter: 5.66 mm
Bullet weight: 2.6 g
Muzzle velocity: 348 mps
Muzzle energy: 157 J

2.5.5 7.62 × 54R Mosin-Nagant

Synonyms

7.62 × 54R; 7.63 mm Soviet Rimmed; 7.62 mm obr 1891

Development

It was introduced into Russian service in 1891 with the Mosin-Nagant ‘Three-Line’ rifle and it is the oldest cartridge still in first-line services. Originally, it was adopted with a round-nose bullet. It has been kept in use for machine guns and sniper rifles because it has a superior long-range performance to the 7.62 × 39 mm cartridge. It is found where the Soviets had influence and distributed weapons and in other countries using Russian weapons, such as China and Finland.

Specifications

Heavy Ball D
Round length: 77.16 mm
Case length: 53.6 mm
Rim diameter: 14.48 mm
Bullet diameter: 7.87 mm
Bullet length: 31.3 mm
Bullet weight: 11.98 g
Muzzle velocity: 818 mps
Muzzle energy: 4,008 J

2.5.6 0.357 Magnum

Synonyms

0.357 Smith & Wesson Magnum

Development

In the United States, it became the standard law enforcement round introduced in 1935 by Smith & Wesson. The caliber is the same as the normal 0.38 cartridge, but it was changed to 0.357 to distinguish it as a more powerful round. The case is 2.5 mm longer than other 0.38 cases, which prevents it from being chambered in older revolvers, which are not strong enough to withstand the extra pressure.

Specifications

Round length: 38.5 mm (depending upon bullet)
Case length: 32.76 mm
Rim diameter: 11.17 mm
Bullet diameter: 9.0 7mm
Bullet weight: 10.23 g
Muzzle velocity: 436 mps (in 4 in barrel)
Muzzle energy: 972 J
(See Fig. 2.10.)

2.10 357 Magnum bullet.

2.5.7 0.30-06 Springfield

Synonyms

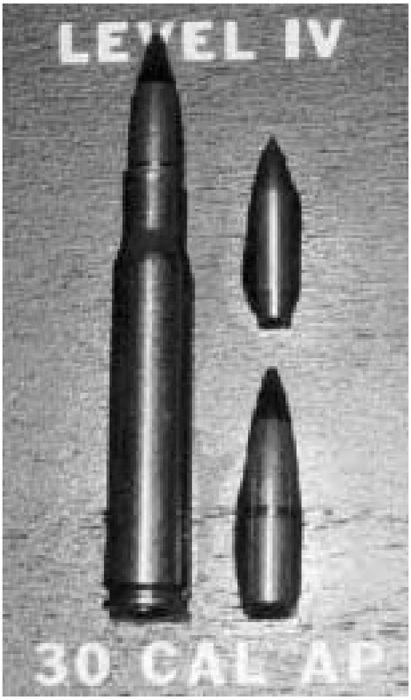
7.63 × 63 mm; 0.30 US Service; 0.30 Browning

Development

The 0.30-06 was introduced in 1906, it was a pointed round replacing the earlier round-nose 0.30-03 cartridge as the service round for the M1903 Springfield rifle. The original bullet was a 9.72 g flat-based type, but lack of range during the First World War led to the standardization of the boat tail 11.2 g M1 bullet in 1926. By 1936 complaints had arisen of the excessive safety area required for training with this bullet and of malfunction in the then new M1 Garand automatic rifle. This led to adoption of the flat-based 9.72 g M2 bullet in 1938, and this has remained the standard ever since.

Specifications

Round length: 84.8 mm
Case length: 63.2 mm
Rim diameter: 12 mm



2.11 30 Caliber armor piercing bullet.

Bullet diameter: 7.82 mm
Bullet weight: 9.72 g
(See Fig. 2.11.)

2.5.8 9 × 19 mm Parabellum

Synonyms

9 mm Parabellum; 9 × 19 mm; 9 mm Luger; 9 mm Patrone ’08

Development

It was developed by Georg Luger in order to improve the stopping power of his pistol, by opening up the mouth of the 7.62 mm Parabellum case and inserting a 9 mm bullet to meet a German Army demand. There was a tendency for it to jam in the early submachine because in its original form it used a cylindro-conoidal bullet with a flat tip. It was replaced in 1917 with an oval shaped bullet, which has remained the military standard since. The original shape bullets are still available commercially. The 9 × 19 Parabellum has been manufactured all over the world.

Specifications

British Mk 2Z
Round length: 29.28 mm
Case length: 19.35 mm
Rim diameter: 9.94 mm
Bullet diameter: 9 mm
Bullet weight: 7.45 g
Muzzle velocity: 396 mps
Muzzle energy: 584 J
(See Figs 2.12–2.16.)

2.12 9 mm, full metal jacket bullet. Cross-section shows metal jackets and lead inside the bullet.

2.5.9 5.56 × 45 mm NATO

Synonyms

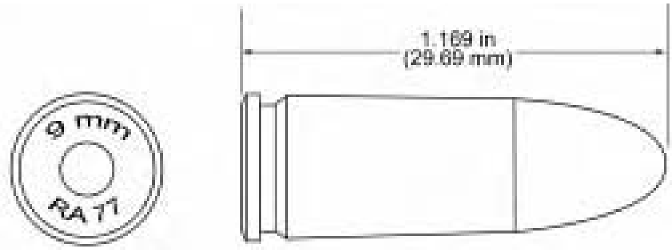
5.56 mm SS109

Development

From 1977 to 1979 NATO countries held a long series of trials to determine the next generation of small arms ammunition, as a result of which this round was adopted as NATO standard. It is essentially the M193 case with which a new

2.13 9 mm Norma bullet.

2.14 9 mm UZI bullet.



2.15 9 mm bullet with cartridge.

2.16 9 mm GECO bullet shape, size and composition.

heavier bullet developed by Fabrique Nationale of Liege is used. The trials showed that this bullet had better accuracy and penetration power, although it demanded a steeper twist of rifling to perform at its best.

Specifications

Round length: 57.4 mm
Round weight: 12.5 grain
Case length: 44.7 mm
Round diameter: 9.6 mm
Bullet diameter: 5.66 mm
Bullet weight: 4 g
Muzzle velocity: 987 mps
Muzzle energy: 1813 J
(See Figs 2.17 and 2.18.)

2.5.10 5.56 × 45 mm M193

Synonyms

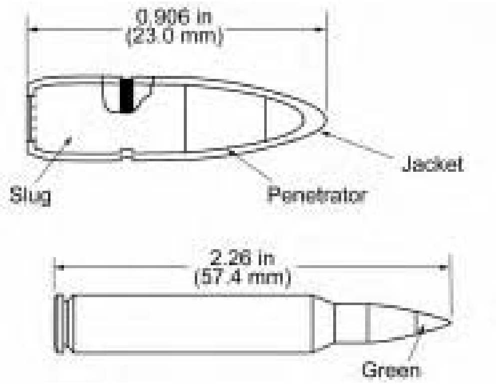
0.2333 Armalite; 0.223 Remington Special

Development

The original design was based upon the commercial 0.222 Remington cartridge, but this generated excessive pressure and a new case with slightly greater

2.17 M855 bullet, shape and size of steel penetrator.

capacity was designed, this became the 0.223 Remington Magnum. This was slightly longer than desirable, was shortened and became the 0.223 Armalite cartridge. It was finally adopted by the US military as the 'Cartridge, Ball, 5.56 mm M193' in 1964.



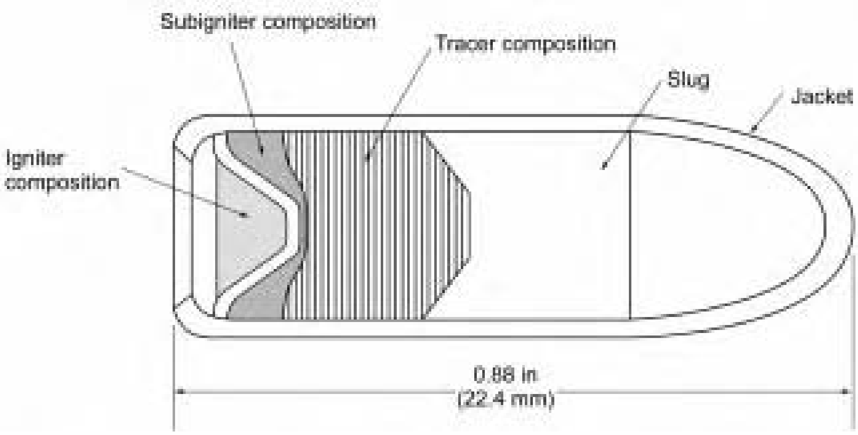
2.18 M855 ball bullet.

Specifications

Round length: 57.3 mm
Case length: 44.5 mm
Rim diameter: 9.5 mm
Head diameter: 9.5 mm
Bullet diameter: 5.66 mm
Bullet weight: 3.56 g
Neck diameter: 6.42 mm
(See Figs 2.19 and 2.20.)

2.19 M193 bullet shape and composition.

2.20 M193 7.62 mm armor piercing bullet.



2.21 Tracer bullet.

2.5.11 Tracer bullet

In flight the bullet exhibits a visible trace of full luminosity from a point not greater than 100 yards from the muzzle of the weapon to a point not less than 400 yards from the muzzle. A typical tracer bullet cross-section is shown in Fig. 2.21.

2.6 Projectile firing

Practically all rifle, carbine, pistol, revolver cartridges and lab fragments are made up of four different components:

1. The case.
2. The primer.
3. The powder.
4. The projectile.

The firing of a cartridge projectile loaded in a gun or lab universal receiver follows the following sequence:

1. The trigger of the gun is slightly pressed.
2. The firing pin strikes against the primer of the cartridge.
3. Immediately the charge explodes.
4. The sharp flash of flame ignites the powder charge in the case.
5. Chemical reaction takes place as the powder is converted into gas.
6. The tremendous gas pressure forces the projectile out of the firing barrel at high speed.

The cartridge case is often made of brass and this material is soft and elastic. As the gunpowder expands during burning, and the case becomes pressed against the barrel chamber, a good seal is achieved. This is necessary because all the gas pressure has to be used to drive the projectile. The primer is a tiny bomb in a soft metal holder. The holder contains the fulminated compound, a very highly explosive chemical mix, which can be made to explode very easily with a slight impact. This causes a sharp flash, through which the other component of the cartridge, the powder, is ignited. The powder, with which the cartridge is loaded, develops a lot of gas as it burns. It does not, therefore, explode. The burning takes place quickly and develops such a high pressure in the small space of the case that the projectile is powerfully ejected from the casing. The case itself is enclosed from all the sides except where projectile will be ejected. The gases developed due to gunpowder burning create pressure up to about 2500 bar for a 9 mm bullet. In a rifle cartridge pressure can be as much as 4000 to 7000 bar. (At about 12,000 bar a good rifle will explode and this sometimes happens.) Depending on the kind of gun, the caliber, and the powder charge, the projectile will fly for hundreds or even thousands of meters. This also generates high speed for the projectile.

2.7 Timing of firing

The entire event of pressing the trigger and the projectile hitting its target takes place in a fraction of a second. The sequence of events and timing is as follows:

1. It takes about 0.2 second before the trigger finger obeys the brain command.
2. The firing pin hits the primer of the cartridge in about 0.005 seconds.
3. The gunpowder in the cartridge is ignited within 0.0004 seconds.
4. The gas pressure build-up due to gunpowder burning takes place in about 0.004 seconds and the projectile is pushed out from the cartridge.
5. Depending upon the barrel twist level, the projectile can rotate at about 1000 revolutions per second.
6. If the target is 25 meters away, the projectile can reach it in 0.1125 seconds.
7. The total time from brain command to hitting the target takes 0.3195 seconds.
8. The shooter feels the recoil in about 0.2 seconds after the projectile has left the barrel.

Usually a new shooter, when holding and firing a gun, cannot distinguish in terms of stability, trigger mechanism, cartridge feeding, the sights, the grip, the muzzle flip, the power of recoil, and general manageability, between different guns.

2.8 Casualty reduction analysis

The interaction between a ballistic threat and hitting a target produces casualties. The extent of injury by a specified threat depends upon its mass, velocity, and target vulnerability and analysis of casualty reduction therefore requires information about the ballistic threat, the target, and the vulnerability of the target to the threat. The analysis process may vary from the interaction between a single piece of ammunition and a single target to the interaction between many pieces of ammunition and many targets.

The ballistic threat is usually fragments. Parameters are fragment delivery, its accuracy, and fragment characteristics, such as masses, velocities, and spatial distribution. Accuracy of ammunition delivery and fragmentation characteristics of the delivered ammunition affects the probability of hitting and incapacitating target elements. Accuracy is a measure of how well ammunition can be delivered to a target to inflict damage. It is measured in terms of 50% fragments hitting a probable circle. Fragment characteristics used in CSA are initial velocity, fragment distribution in an area, and mass distribution. Targets can consist of a single target or multiple targets in a specified area.

2.9 Penetration and deformation of bullets and fragments

Penetration and deformation of high speed projectiles (bullets and fragments) in a high performance fiber composite is a complex phenomenon. Due to the speed of projectile penetration, it is difficult to predict how the projectile and the penetrating material will behave under such rapid loading. There are a number of numerical models to predict the deformation based on the projectile momentum and the resistance of the material. However, each model has its limitations in terms of deformation prediction.

Based on simple force equation the smaller caliber projectile will go deeper because of the momentum of the projectile is concentrated on a smaller area. Also, the projectile with higher weight will penetrate deeper than the lower weight projectile. The bullet penetration is a function of its shape, core, jacket stiffness, and in a hollow point, the proper angle and depth.

Handgun bullets typically consist of softer, more easily deformable materials to inflict maximum damage to human tissues. The full metal jacketed (FMJ) bullets filled with lead show relatively low deformation but are known for their ability to penetrate armor. On the other hand, a full lead bullet, without any jacket, deforms easily and inflicts damage to a much larger tissue area.

The laboratory fragments are made of hardened steel with sharp edges. Based on the size and weight of the fragments, the velocities can be higher than bullets fired from handguns. Since fragments do not have an aerodynamic shape, air drag slows them down. The air drag is a function of shape, size of the fragment and the density of the air. And the air density is a function of air temperature and humidity. During the penetration of fiber-reinforced body armor and molded hard armor, fragments do not deform. However, based on the velocity of the fragment, and friction offered by the armor, the sharp edges are slightly blunted. Limited damage of such fragments can be assessed with a magnifying glass.

The weight and velocity of projectiles are the key elements responsible for the kinetic energy associated with the bullet or fragment. The kinetic energy (KE) associated is represented as:

$$\mathrm{KE} = \tfrac{1}{2} m V^2$$

where m is the mass of the projectile and V is the speed of projectile.

If two projectiles have identical mass, but one projectile is traveling at double the speed of the other, the kinetic energy associated with the faster projectile will be four times greater than the slower projectile.

2.10 Factors affecting deformation of bullets penetrating a flexible or rigid armor

2.10.1 Type of bullet

Handgun and rifle bullets are available in various weights and sizes. However, no two guns are exactly alike, nor the loads of power, bullet, primers, or anything else connected with ballistics. These variables make ballistics an imprecise science. The mathematics may be precise but the numbers fed into the equations are based on variable amounts (see Fig. 2.22).

The penetration mechanism of bullets also varies due to the composition of the jacket, inside composition and velocity of bullet, its rotation and type of ballistic material hit. A majority of bullets have aerodynamic shape to reduce

2.22 Smallest .22 caliber and largest 50 caliber AP bullets.

2.23 9 mm bullet filled with lead.

velocity loss due to air drag. Usually the bullets are covered with a metal jacket. The metal jacket not only maintains the durability and shape of the bullet but also covers and protects the material inside the bullet. Handgun bullets, such as 9 mm FMJ, are filled with lead which deforms easily and creates severe tissue damage when penetrating tissue material (see Fig. 2.23).

The rifle bullets are usually small in diameter and, based on their function, could be filled with lead or lead with a metal pin, or hardened steel.

The deformation of bullets also differs from bullet to bullet due to a number of factors such as composition, diameter, jacket or no jacket, velocity of bullet, firing gun, size of barrel, twist inside, firing distance and the composition of the target. A fiber-reinforced ballistic material may be flexible but based on reinforcing fiber and the fiber arrangement it can deform a bullet within a few layers (see Figs 2.24 and 2.25).

2.10.2 Jacketed bullet

Bullets with full metal jackets have a higher penetrating capability compared with bullets filled with lead but not covered with a metal jacket. Some of the common metal jackets of bullets are copper, brass, and steel. Copper jackets or copper-plated bullet jackets are preferred because copper does not damage the barrel of the gun when the bullets are fired. The shape and the hardness of the metal jacket helps to penetrate the target before deforming or stripping from the bullet and exposing the inside material, which could be soft and therefore

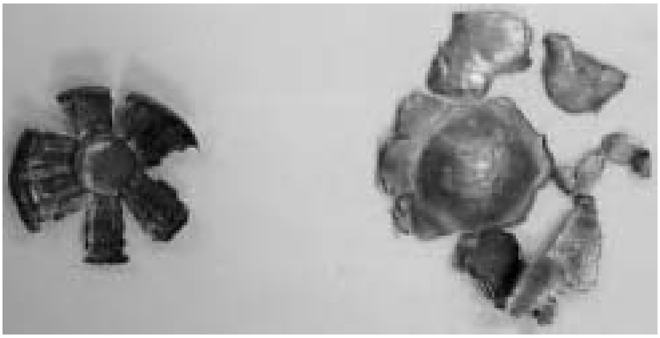
2.24 .44 Magnum bullet before and after deformation in a lightweight composite.

2.25 .357 Magnum bullet before and after deformation in a lightweight composite.

damage tissues. Some handgun and hunting bullets have no metal jacket or have partial jacket covers over the lead (see Figs 2.26 and 2.27).

2.10.3 Composition of the bullet

Compositions of the bullet jacket and inside metal influence the deformation characteristics of a bullet. The metal inside the bullet jacket could be 100% lead, or lead with a penetrator or just a penetrator. When a lead-filled bullet hits the



2.26 Deformation of .357 Magnum bullet stopped in Spectra Shield® Plus LCR material.

2.27 Deformation of .357 Magnum bullet stopped in Gold Flex® material.

target, the outer metal jacket is deformed along with the lead inside the bullet. Since lead is a softer metal, it dominates the deformation of the bullet. A picture of the deformed bullet before and after hitting the soft fabric armor is shown in Fig. 2.28.

2.28 9 mm FMJ bullet before and after deformation in a lightweight ballistic composite.

2.10.4 Stress on the bullet

The largest acceleration stress in both the firearm and the bullet occur at the peak pressure. The rear of the bullet will expand to tightly fill the bore if it is slightly undersized. The tensile strength of copper is about ten times that of lead, therefore copper, or a copper alloy, is frequently used to encase a lead bullet and assist in restraining the internal forces on the lead core. The tensile strength of steel is about 40,000 psi. The bullet can recover its shape if it is not stressed to the limit. However, lead, copper, and tins have a very low tensile strength, therefore any minor pressure or stress build-up will permanently deform the bullet. Although the peak pressure will be extremely short, the bullet will expand and deform to fit the lands and grooves of the bore.

Bullets of equal weight but of a different type and manufacture will not produce the same pressure. While the bullets' weight may be equal, the length, core weight, jacket weight, bearing length, and even to a very slight amount, the diameter, may all be different. The variations between extremes can be as high as 15%. Generally, a higher build-up of pressure will result in a higher velocity of the bullet leaving the firing barrel.

The hardness and shape of the penetrator influences the deformation of the bullet with a penetrator. If the penetrator is soft steel (AK 47, 7.62 x 39), it is easily deformed with 100% molded HMPE without a hard ceramic surface blunting the tip of the penetrator. With other types of molded composite backing, ceramic is used to blunt the penetrator. However, for a hardened steel penetrator, ceramics are used backed with lightweight molded composites to blunt the penetrator and catch the blunted penetrator and ceramic fragments in the composite backing (Fig. 2.29).

2.29 AK 47 bullet, before and after deformation in a molded lightweight composite.

2.10.5 Weight of the bullet

The weight of a bullet is a function of its diameter, length and composition of the bullet materials. The handgun and hunting bullets are usually heavy because the composition of the bullet is dominated by lead that is a relatively heavier metal. Generally rifle bullets are smaller in diameter and may not contain 100% lead inside the jacket of the bullet.

The kinetic energy associated with a bullet is linearly proportional to its weight. The heavier the bullet, the higher the kinetic energy.

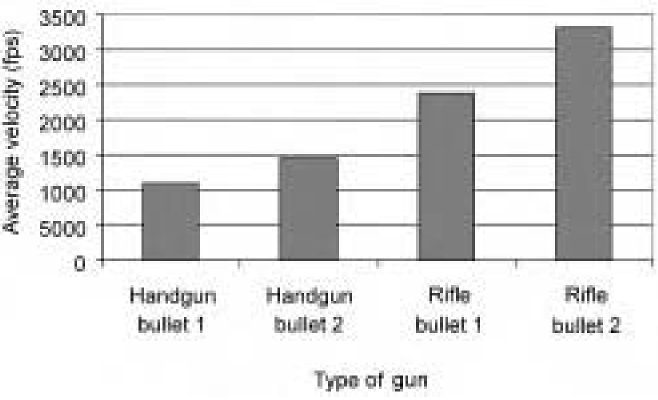
2.10.6 Velocity of the bullet

One of the major contributing factors defining the bullet deformation or penetration capability is the velocity of the bullet. The energy associated with a bullet is proportional to the square of the velocity of the bullet. If two bullets have identical geometry and weight, but one is traveling twice the speed of the other bullet, the energy associated with the bullet with higher velocity will be four times that of the slower bullet.

The handgun bullets are generally heavier, but velocities of these bullets are relatively low. This is due to the amount of gunpowder and smaller barrel size. On the other hand, rifle bullets are smaller in diameter and weight, but have much greater velocity. This is partially due to the long barrel, which can accelerate the bullet to higher velocity (see Fig. 2.30).

2.10.7 Twist in the firing barrel

Twist in the firing barrel provides the stability to the bullet when it is traveling in the air. Certain bullets wobble for a short distance after leaving the firing barrel due to the twist in the barrel. However, such bullets stabilize after traveling a



2.30 Range of handgun- and rifle-fired bullet velocities.

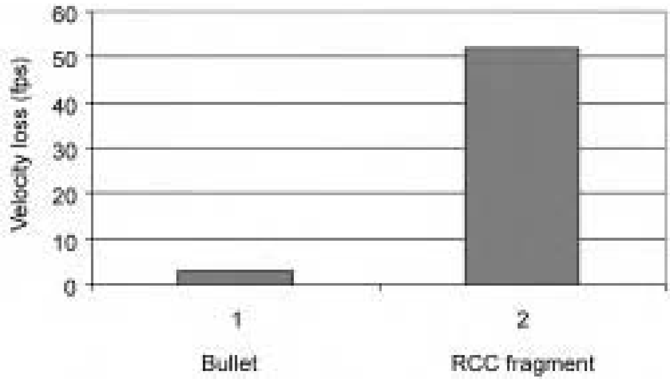
short distance. It is important for checking the quality, consistency, and ballistic performance of a vest against a bullet that is fired from a barrel which has a consistent twist.

2.10.8 Drag on projectiles

Drag is the resistance of the air to the projectile. The air drag is a function of the velocity of the projectile, its shape, size, density of air, barometric pressure of the air and temperature of the air.

Air drag reduces the velocity of a bullet fired from a handgun or rifle. However, due to the aerodynamic shape of the bullets, the loss is minimal for short firing ranges. Therefore air drag does not play an important factor in contributing to the deformation of the bullet.

The air drag is significant for fragments such as the Fragment Simulating Projectile (FSP) and the Right Circular Cylinder (RCC) fragments. Tables are available for drag loses for fragments traveling at various velocities (see Fig. 2.31).



2.31 Drag corrections for identical size 9 mm FMJ aerodynamic bullet and flat face RCC fragment at 1500 fps.

2.10.9 Kinetic energy of bullets

The kinetic energy of the bullet is the energy associated with a high velocity bullet. As soon as the speeding bullet hits the target, it dissipates its kinetic energy on the target in the form of:

- penetration of the target;
- bullet deformation;
- converting kinetic energy into heat energy.

Table 2.4 Weight, velocity and kinetic energy of handgun bullets

Bullet	Weight (grains)	Velocity (mps)	Kinetic energy (Joules)
38 Special RN lead	158	274	363
22 LRHV	40	335	139
9 mm FMJ	115	410	593
357 Magnum JSP	124	373	537
9 mm GECO	123	355	502
44 Magnum	240	441	1510
9 mm FMJ	124	441	781

The higher the kinetic energy, the higher the penetration, bullet deformation and generation of heat energy. Table 2.4 shows the kinetic energy associated with a number of handgun bullets.

2.10.10 Angle of bullet hitting the armor

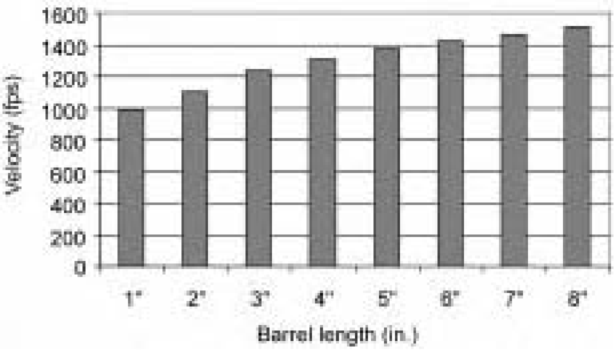
The angle of a bullet hitting the soft body armor and/or hard molded armor is another factor which influences bullet penetration and deformation during penetration. Ninety degrees or perpendicular to the armor is the most critical angle to penetrate armor. When bullets hit the armor at 90º, all the kinetic energy of the bullet is concentrated on the pointed tip of the bullet and therefore it easily penetrates the layers of the armor.

However, bullets can hit flexible armor at an angle in real life situations. Therefore a number of test standards require testing both at 90º and at 60º to the armor. The penetration mechanism of a bullet on a woven ballistic material is different from non-woven cross-plied and laminated materials. The bullet resistance (VO and /or V_{50}) at 60º on woven ballistic material is lower than at 90º. However, for non-woven ballistic material it is higher.

2.10.11 Length of firing barrel

Velocity of the bullets and fragments and stability of these projectiles depends upon the firing barrel and its internal configuration. The longer barrel length holds the projectile longer and therefore the projectile gets higher acceleration. In the case of a shorter barrel length, projectiles accelerate only when they are in the barrel. As soon it leaves the barrel, the projectile loses all the built-up pressure in the firing barrel and starts losing velocity due to air drag and gravity of the Earth.

The following velocities were measured at 20 feet from the muzzle of a .44 Remington Magnum revolver. The same gun was used each time and an inch removed. The ammunition weight was 240-grain. Ten rounds were fired at each length with the average velocity shown in Fig. 2.32.



2.32 Effect of barrel length on bullet velocity.

2.10.12 Twist in the barrel

The projectile stability depends upon the spin it picks up when accelerating inside the firing barrel due to pressure build in the firing of gun powder and the firing barrel twist level. The higher the twist levels inside the firing barrel the higher the stability of the projectile. However, twist also reduces the velocity of projectiles leaving the barrel, because part of firing energy is consumed by the friction in the barrel. Without proper twist in the barrel, the projectile will wobble while traveling in the air before hitting the target.

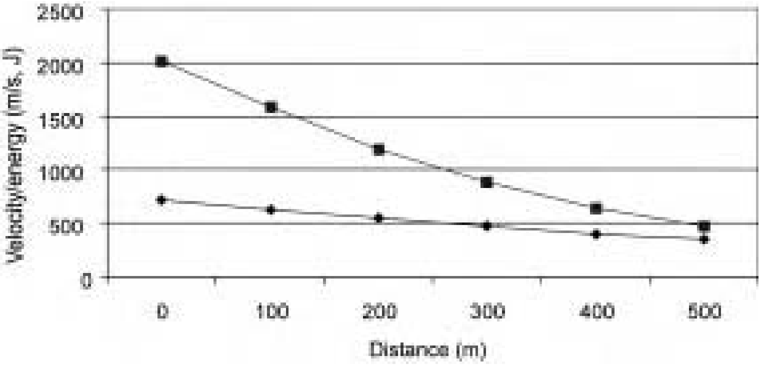
Most US-made handguns have a right-hand twist. Exceptions are Colt guns, which use a left-hand twist. The number of grooves varies, usually between 4 and 8. The depth of grooves is between 0.0035 and 0.005 inches. Most .22 caliber handguns use 14 to 20 inches per turn.

2.10.13 Distance from the muzzle

Velocity and energy association of the bullet plays a significant role during bullet penetration. Due to the aerodynamic shape of the bullet, velocity and kinetic energy associated with the bullet do not drop significantly. However, as distance significantly increases, air drag starts affecting the velocity and kinetic energy of the bullet. Figures shown in Fig. 2.33 demonstrate loss of velocity and energy as a function of distance from the muzzle.

2.10.14 Ballistic armor materials

Projectiles will not deform when fired in air or on a softer material which slows down the projectile but offers low friction and low surface and material hardness. Ballistic materials are designed to stop the projectile by resisting its penetration, and in the case of bullets, by also deforming them at the same time. The ballistic fiber by itself cannot provide sufficient surface area to engage the



2.33 Velocity and kinetic energy gradient of bullet as a function of distance.

projectile and stop it. The ballistic fiber goes through another set of processes which help to engage the bullet. One of the most common processes of converting ballistic fibers into a ballistic fabric is the weaving process (see Chapter 8). Other processes include the non-woven, cross-plied process (Chapter 9), and the chopped fiber felt process.

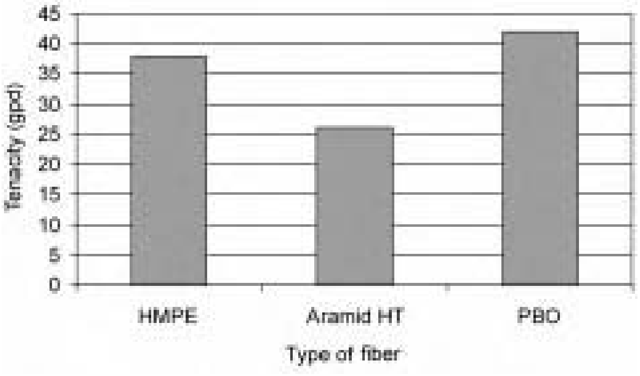
2.10.15 Type of ballistic fibers

Currently three types of ballistic fibers are available for soft flexible armor. These are aramid fibers, HMPE fibers and PBO fibers. Only aramids and HMPE fibers have been in the market for a long time and are available in a number of deniers and strengths. However, for hard armor, E-fiberglass and S-2 fiberglass are also utilized for a number of vehicle armors. The fiberglass composites offer economic armor, although with a steep weight penalty. The fiberglass composites also offer load bearing structural properties and fire barrier.

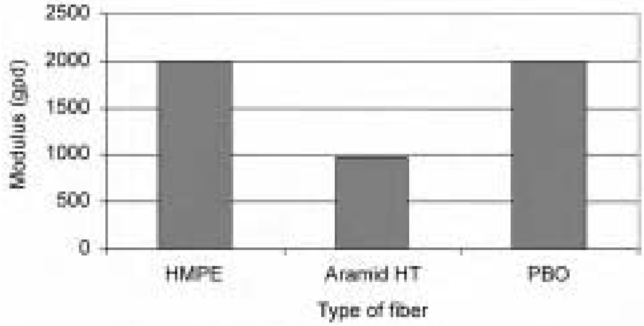
2.10.16 Strength of ballistic fibers

The projectile slowing down, deformation and stoppage depends upon the ballistic strength of reinforcing fibers. One of the most common techniques to evaluate the fiber's physical properties is to test fibers in tension mode. The strength from these tests is normally presented in terms of tenacity, modulus and ultimate elongation of the fiber (see Figs 2.34 and 2.35).

However, all fibers are not loaded in tension mode of stresses when a projectile hits a target of multiple layers of ballistic woven or non-woven material. The fibers in the first set of layers are supported underneath by further layers and therefore get sheared and transfer only a fraction of load in the fibers' axial direction. Once a projectile starts slowing down due to fiber shear resistance and in the case of bullets, by their deformation, the next set of fiber



2.34 Tenacity of high performance ballistic fibers.



2.35 Modulus of high tenacity ballistic fibers.

undergoes a mixed mode of stresses. Ultimately when the projectile is slowed down, fibers are loaded extensively in tension mode.

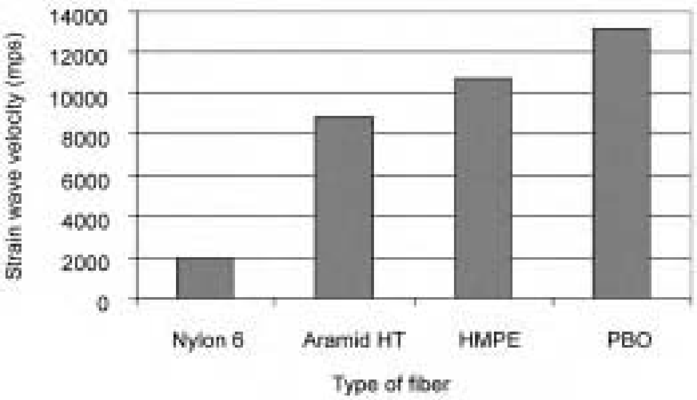
However, current test methods cannot measure shear properties of ballistic fibers when these fibers are supported by other fibers.

2.10.17 Strain velocity of ballistic fibers

The strain wave velocity of a ballistic fiber is the rate of strain dissipation through the axis of the fiber when the fiber is engaged with a high-speed projectile. The higher the strain wave velocity, the higher the ballistic energy dissipation. The strain wave velocity of a fiber can be calculated as:

$$V_s = (\text{fiber modulus/fiber density})\frac{1}{2}$$

where V_s is the strain wave velocity. (See Fig. 2.36.)



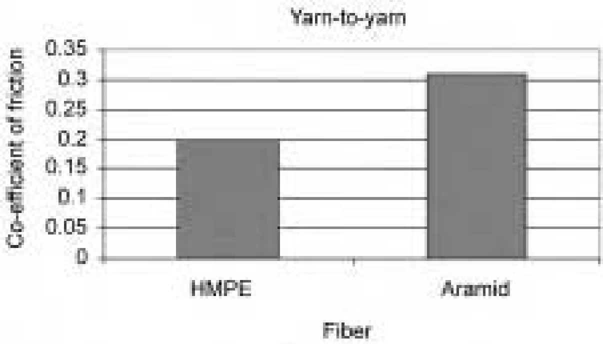
2.36 Strain wave velocity of HMPE fibers.

2.10.18 Friction between fiber and fiber

The fiber friction properties along with the fiber physical properties play an important role in slowing down the projectile. Friction also helps to strip the jackets from bullets, deform the bullet and ultimately stop the bullet. The friction properties of aramid fibers are higher compared to HMPE fibers which are slick, highly oriented, high strength and have fairly low friction. Due to the higher friction of aramid fiber, weavers can utilize higher denier, lower cost aramid fibers to achieve decent ballistic performance. There are ways to overcome lack of friction. One of these techniques is by adding a higher friction coating material to the ballistic fiber surface.

As mentioned above, high performance ballistic fibers are the backbone of a ballistic material. One factor that influences the ballistic performance of a material is the friction between fibers during bullet penetration. Controlled friction between fibers is desirable to slow down and deform the bullet. However, if friction between fibers is too high, one fiber will cut another fiber during bullet penetration and thus reduce the performance of the material. On the other hand if fiber-to-fiber friction is very low, the material will not offer any resistance to the penetrating bullet and the bullet will not slow down or be deformed.

In the current armor materials, friction is optimized by changing the fiber orientation, by applying coating on the fiber, and in many instances bonding a film on the ballistic material. Quilting is another technique to increase fiber-to-fiber friction. This technique is commonly used for woven fabric vests (see Fig. 2.37).



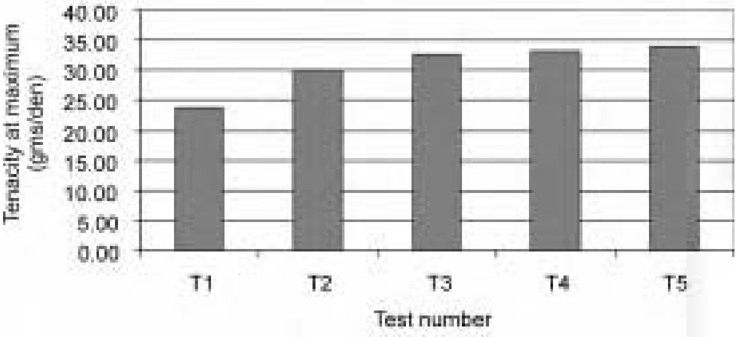
2.37 Co-efficient of friction, yarn-to-yarn.

2.10.19 Viscoelastic properties of ballistic fibers

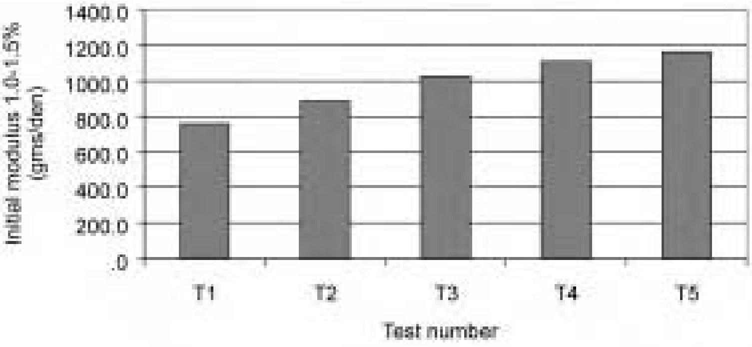
Viscoelastic properties of a fiber are defined as the properties that increase with the increased strain rate. The higher the strain levels, the higher the properties. A number of man-made fibers such as aramids, graphite, PBO and fiberglass are linear fibers. Other fibers such as HMPE, polyester and nylon fibers exhibit viscoelastic properties (see Figs 2.38 and 2.39).

2.10.20 Coating on ballistic fibers

The frictional properties and bullet-to-fiber interaction of all the high performance ballistic fibers can be engineered by adding a proper type of polymer coating in a controlled manner. Both woven and non-woven aramid and HDPE cross-plied materials have shown increased ballistic resistance for a number of projectiles. If a proper coating is not utilized it can increase the



2.38 Tenacity of HMPE fibers as a function of strain rate.
T1 = 0.01 in/min, T2 = 0.1 in/min, T3 = 1.0 in/min, T4 = 10 in/min, T5 = 20 in/min.



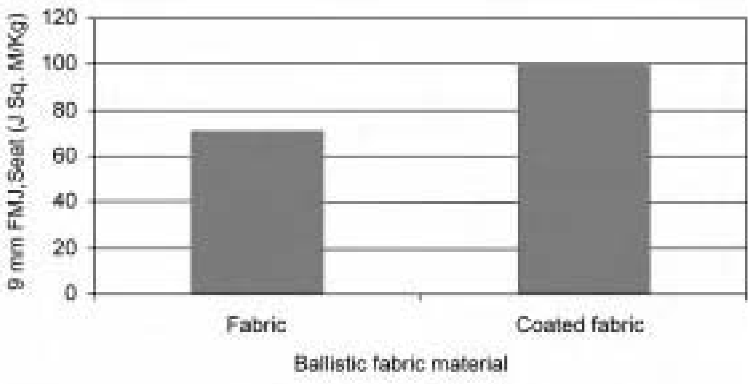
2.39 Modulus of HMPE as a function of strain rate.
T1 = 0.01 in/min, T2 = 0.1 in/min, T3 = 1.0 in/min, T4 = 10 in/min, T5 = 20 in/min.

weight and stiffness of the ballistic material. There are a number of techniques to add a coating to the ballistic fibers. These techniques are discussed in Chapter 10.

Figure 2.38 shows the effect of only 5% resin coating on HMPE fabric. The ballistic fabric shows a substantial performance increase due to the coating when tested against 9 mm FMJ (see Fig. 2.40).

2.10.21 Ballistic fiber orientation

Selecting proper orientation between adjacent ballistic fibers is important to engage the projectile with the ballistic fibers. For woven fabrics and non-woven cross-plied ballistic materials the most common orientation is fibers in two perpendicular directions held together either mechanically or bonded together with a proper binder. This is the single largest factor to achieving the highest

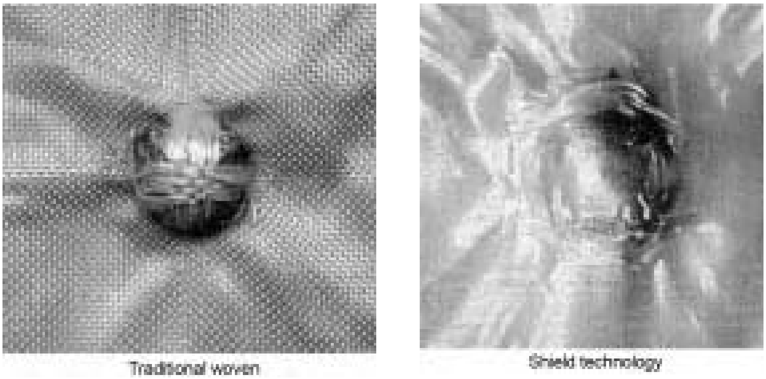


2.40 Effect of resin coating on HDPE fabric for higher ballistic performance.

ballistic resistance. However, this configuration may not be optimum for the highest material flexibility and backface deformation. To overcome this shortcoming, other fiber orientations and weave constructions such as satin weave can be used. Satin weave allows fabric stretching in certain planes.

2.10.22 Woven and non-woven materials for deforming projectiles

Woven materials are the traditional materials to engage and deform the projectile with the bundle of ballistic fibers. However, during the last few years other techniques have been developed to engage and deform a bullet at single fiber level. Where fibers are distributed at single fiber level the resultant materials are thinner and engage and deform bullets within the first layers. A detailed discussion of these techniques is available in Chapter 9 (see Fig. 2.41).



Traditional woven

Shield technology

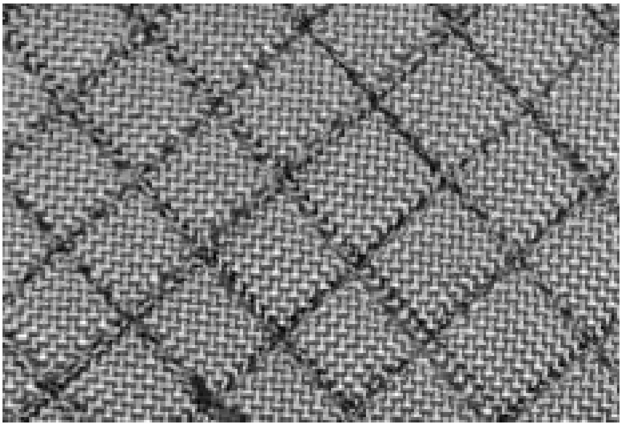
2.41 Energy dispersion on woven and cross-plied ballistic materials.

Chopped ballistic fibers converted into randomly oriented felt also engage projectiles at single fiber level. However, these materials are bulky and can soak up water and other chemicals if proper precautions are not in place.

2.10.23 Quilting

Quilting is a fairly simple technique to increase projectile engagement with the layers of woven fabrics. Quilting could be tightly or loosely spaced. Tightly spaced quilting increases the ballistic performance of the material and reduces the backface deformation, but due to its rigidity it does not conform to the shape of the person wearing the vest. A loose quilting spacing does not increase rigidity but projectile engagement is reduced and material starts bulging when projectile hits the ballistic vest (see Fig. 2.42).

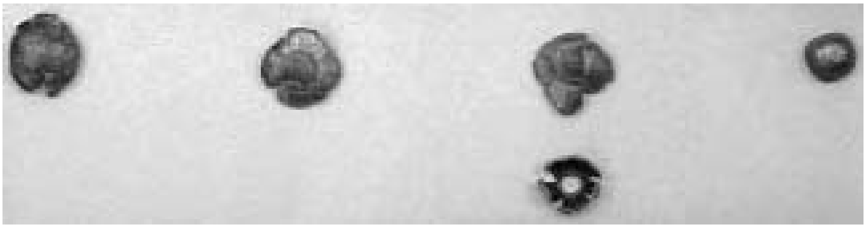
Woven ballistic materials consist of bundles of fibers woven into plain weave fabric construction. Each fiber bundle goes up and down in the fabric and gets



2.42 Quilting on soft ballistic material.

locked in a mechanical manner. However, the fibers in the bundle are not spread out similarly to cross-plied materials. When a high-speed deformable handgun bullet hits the first set of woven materials, a limited number of fibers get engaged with the bullet. However, as the bullet keeps penetrating layer after layer, more and more fibers become engaged with the bullet and start offering sufficient friction to slow it down, and at the same time start to deform the bullet. Although the bullet is completely stopped, it typically does not completely deform. The shape of the stopped bullet is similar to a mushroom.

Unlike woven materials, the unidirectional cross-plied materials are thinner, fully spread out at the micro level, and locked into (0, 90) configuration by adhesive and lamination. When a high-speed deformable bullet hits the first set of fibers, sufficient resistance is applied to start deforming the bullet from the very first layer. By the time the bullet has penetrated only a few layers, the bullet has completely deformed and stopped due to the deformed and expanded size of the bullet. The shape of the deformed bullet usually looks like a pinwheel (see Fig. 2.43).



Spectra Shield® Plus LCR material

Gold Flex® material

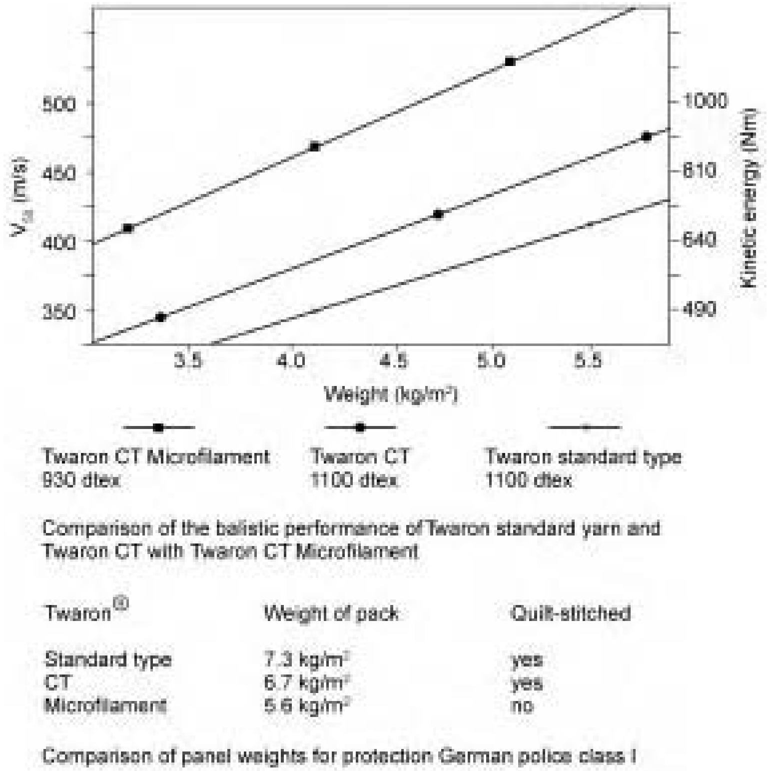
Gold Flex®/Spectra Shield® Plus LCR hybrid material

Quilt-stitched woven aramid

2.43 Deformed bullet penetrating cross-plied and quilted ballistic material.

2.10.24 Denier effect

The high performance ballistic fibers are available in various physical properties and a number of deniers. Higher denier fibers are preferred for woven and non-woven ballistic products because this results in a higher production rate with less handling compared to low denier fibers. However, as a rule of thumb low denier fibers provide lighter but higher performance ballistic materials. Higher denier fibers also have a 'bundle effect'. If the fiber bundles do not spread uniformly to engage fibers, projectile engagement and deformation of the projectile is only due to a few fibers on the outer edge of the fiber bundle. The result is poor utilization of the fibers and therefore ballistic performance is lower (see Fig. 2.44).



Comparison of the ballistic performance of Twaron standard yarn and Twaron CT with Twaron CT Microfilament

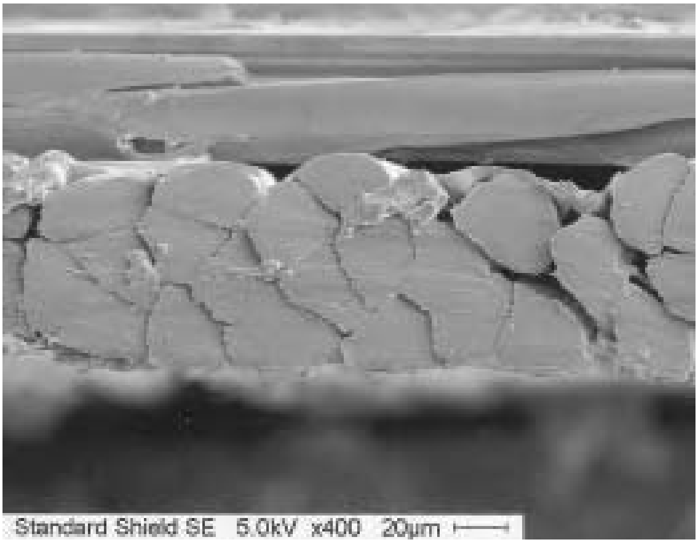
Twaron®	Weight of pack	Quilt-stitched
Standard type	7.3 kg/m²	yes
CT	6.7 kg/m²	yes
Microfilament	5.6 kg/m²	no

Comparison of panel weights for protection German police class I

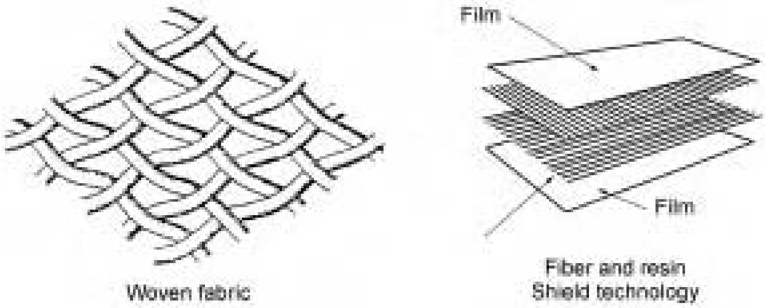
2.44 Effect of denier on ballistic performance.

2.10.25 Fiber spread-out effect

The fiber spread-out effect is opposite to the bundle effect. During the manufacturing of unitape in the non-woven process, each fiber in the filament bundle is spread out on a macro level. After cross-plying with similar unitape,



2.45 Cross-section of ballistic material showing uniform fiber spread-out.



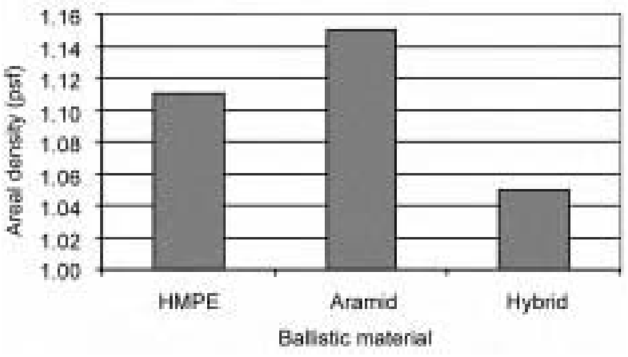
2.46 Figure showing fiber bundling and fiber spreading out.

the resultant material has a majority of fiber bundle fully spread out. This helps the projectile to engage as many fibers as possible, resulting in a thinner, flexible and more efficient ballistic material.

The fiber bundle is spread out in this technique (see Figs 2.45 and 2.46).

2.10.26 Fiber hybrid effect

Each type of high performance ballistic fiber offers certain features which are different from other fibers. For example, the aramid fibers offer higher fiber-to-fiber friction than HMPE fibers. This is a good feature to strip the bullet's outer jacket. On the other hand HMPE fibers offer non-linear viscoelastic properties which help to capture the fragmented bullet better than linear aramid fiber.



2.47 Hybrid effect for NIJ Level IIIA cross-plied vest.

Using layers of high friction material at the front and capturing fragmented bullets by HMPE offers a lighter weight solution to stop the bullet at a lower weight than either a 100% aramid or 100% HMPE fiber vest (see Fig. 2.47).

2.10.27 Type, quality and thickness of Roma Plastilina clay

The NIJ standard 0101.04 specifies that Roma Plastilina clay is used in the box holding the vest during testing. The clay is calibrated after being kept at a controlled temperature. During testing, plywood is rigidly mounted on the back of the Plastilina clay, and extensively used clay loses its texture and uniformity. Each of these conditions affects the bullet's engagement and deformation during the testing of a vest.

Similarly, clay used in Europe and Asia may not have a similar consistency, clay thickness behind the armor, box geometry holding the clay, and other factors may affect the engagement of projectile and the vest. This may influence the reliability of the test.

2.10.28 Roma Plastilina clay

Another important factor that influences bullet deformation during testing is the type, quality, compaction, and thickness of the backing Roma Plastilina clay. If the clay is not fully compacted, or kept at an elevated temperature, the ballistic material will deform due to poor backing resistance and the bullet to ballistic material interaction will be reduced. This may result in failure of the vest by bullet penetration. Similarly, if Roma Plastilina clay is kept at a low temperature, the bullet will not fully interact with the ballistic material and failure of the vest may occur due to bullet penetration. NIJ 0101.04 has recommended proper Roma Plastilina conditions and calibration before the vest is tested.

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3

Material responses to ballistic impact

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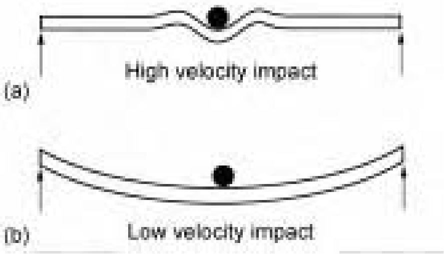
3.1 Introduction

During an impact event, the target response is a combination of global and local reactions (Pierson *et al.* 1993; Pierson 1994; Ursenbach *et al.* 1995). The relative contributions from these two reactions are generally determined by a multitude of factors including, but not limited to, strike velocity, projectile properties, target size and boundary conditions. Typically, strike velocity is considered to be the most significant factor to determine the transition between locally dominated and globally dominated response as outlined in (Cantwell and Morton 1989; Cantwell and Morton 1991; Abrate 1994; Lee and Sun 1993b; Lee and Sun 1993a). Strictly speaking, the projectile velocity itself does not provide a clear demarcation between the two types of response and other factors, e.g., the ratio of impactor to target mass (Olsson 2000; Olsson 2001) or the ratio of the local contact frequency to the structural frequency of the target (Bucinell *et al.* 1991) are more robust indicators of the nature of the impact response. However, for a given impactor and target system one may loosely use velocity as a parameter to distinguish between the local and global response. It is important to recognise that local behaviour is typically independent of target dimensions, whereas global response is inextricably linked to it. An approximate schematic representation is shown in Fig. 3.1.

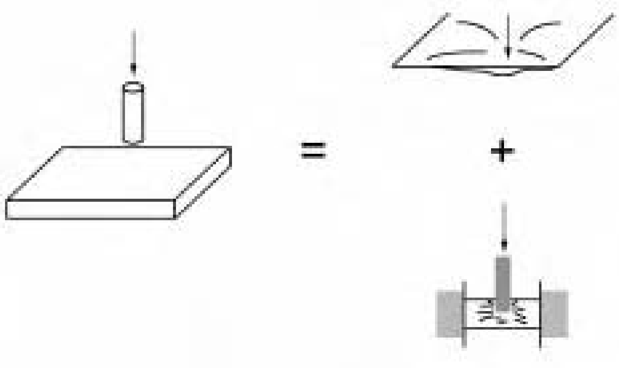
This observation is valid even during impact on single yarns. Studying the failure of high-performance yarns subjected to the impact of projectiles flying at different speeds, Carr (1999) observed that while the failure mechanism at lower velocities is of a global mode (referred to as 'transmitted stress wave'), it changes into local ('shear or plug' failure) at higher strike velocities.

The range of strike velocities from global to local dominated response covers quasi-static loading at the low end and hyper-velocity impacts at the high end, with typical behaviour being a superposition of both, as shown in Fig. 3.2 (Ursenbach 1995).

At high enough velocities, global plate deflection becomes much less important (Zhu *et al.* 1992b). In cases where damage is experienced, modes can



3.1 Schematic representation of the impact response under (a) high velocity impact loading (b) low velocity impact loading (Cantwell and Morton 1989).



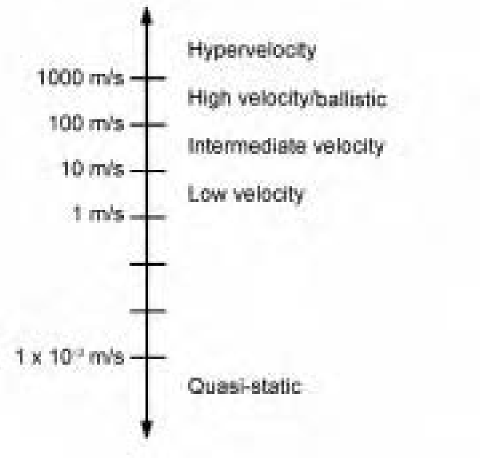
3.2 Concept of superposition for global/local response (Ursenbach 1995).

vary greatly and include indentation, matrix cracking, delamination, fibre shearing (cutting and/or punching), and fibre tensile failure (Abrate 1991; Abrate 1994; Abrate 1998). The degree to which each of these regimes is observed is a function of strike velocity, target and projectile geometry, and material properties.

3.2 Global response

Global energy absorbing mechanisms are usually dominant in low-velocity impact events, where there is ample time for the projectile energy to be transferred and spread through a large area of the target. In such cases, the impact event is long enough for the elastic waves (flexural and shear) generated in the target to propagate and reach the boundaries of the target.

The impact response of single yarns, as the basic component of fabrics and laminates, has fundamental similarities to that of fabric-based targets. One of the most comprehensive studies on this subject was presented in a series of papers by Smith *et al.* (1960). It is now generally accepted that a longitudinal strain wave, travelling at the speed of sound in the material, is generated in a fabric



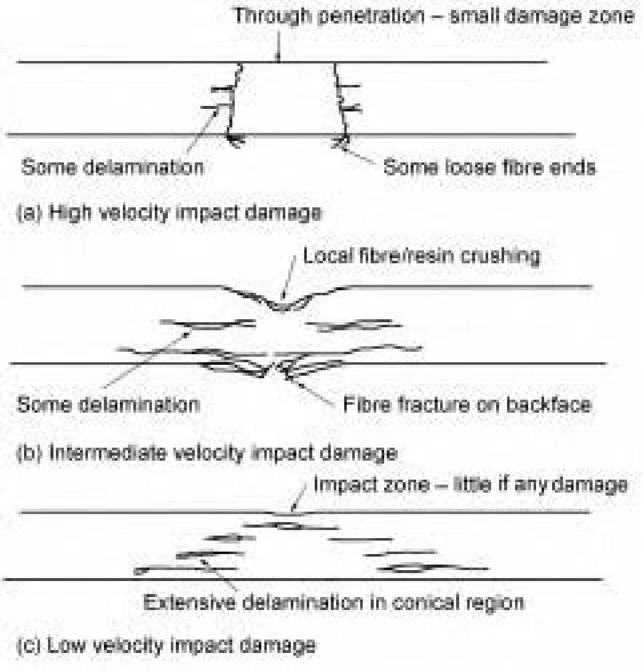
3.3 Standard velocity classifications for foreign object impacts (Ursenbach 1995).

yarn upon impact. This wave stretches the yarns and causes the material to move in-plane towards the impact point. A deformation cone is also created, with a wave front that travels at a much lower speed than the longitudinal wave. The in-plane motion of the material changes into out-of-plane at the rim of the deformation cone (Cunniff 1992; Wilde *et al.* 1973). The tent-like shape of this cone is due to the transverse deflection of the warp and weft yarns in the orthogonal directions. These two waves expand with time, increasing the energy stored in the fabric until the projectile is stopped, or the target is perforated by the projectile (Roylance *et al.* 1995; Cepus *et al.* 1999).

Strike velocities less than 100 m/s will usually elicit predominantly global response from the target (see Fig. 3.3 for the velocity classification used in this section). This is characterized by a high degree of elastic behaviour by the system (Cantwell and Morton 1989; Cantwell and Morton 1991; Delfosse *et al.* 1993). Global deflection occurs as flexural waves travel to the boundaries and back many times within the time-frame of the impact event. Generally speaking, increasing the number of reflections over the duration of the event has the effect of making the event approach a quasi-static response (Delfosse and Poursartip 1997).

Examples of quasi-static impact are tools dropped on a structural component during maintenance or runway debris strikes during take-off and landing of an aircraft. In these cases penetration or perforation is rarely experienced. However, damage can still be present and quite often will be below the surface and difficult to detect visually (Fig. 3.4) (Hoskin and Baker 1986).

More accurate definitions of quasi-static versus dynamic response are provided in Abrate (1994) where a review of research into the impact behaviour of laminated composites is provided. Generally speaking, there are three types of models that can be used to describe impact dynamics:



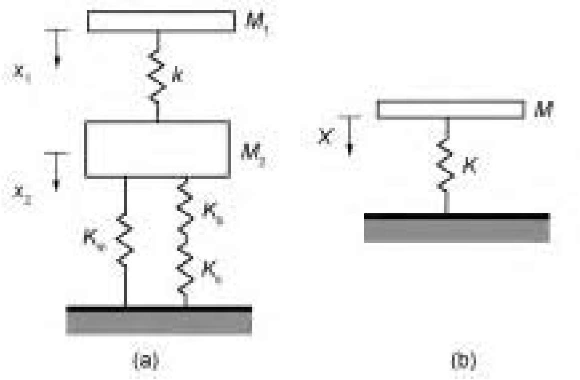
3.4 Failure modes in laminated composites resulting from various impact velocities (Hoskin and Baker 1986).

1. Energy-balance models which assume quasi-static panel behaviour and are therefore the simplest approach available.
2. Spring-mass models, such as the ones shown in Fig. 3.5, which accounts for the dynamics of the structure in a highly simplified manner.
3. Complete models where the dynamics of the structure are fully modelled.

The models are increasingly more representative of the event, with a corresponding increase in computational expense. Ideally, a range of models would be used in any given study – simple ones to gain insight, and complex ones to capture subtleties and study various parametric effects.

3.2.1 Elastic

In fabric targets, the elastic strain energy is dominantly stored in the yarns that are swept by the longitudinal strain wave. This energy is a direct function of the strain in the yarns (Ringleb 1957), and directly proportional to the volume of the strained area, which increases with time. The speed of sound in the material determines the strained area in the target, and is itself a direct function of the yarn modulus and density (Roylance *et al.* 1995). Other factors affecting the

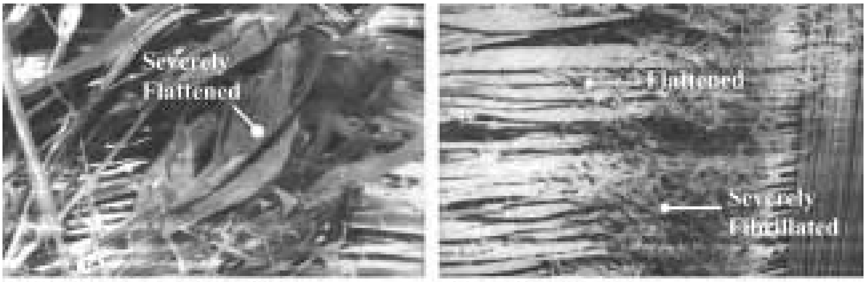


3.5 (a) Two degrees of freedom spring-mass model. (b) Single-degree-of-freedom model (Abrate 2001).

strain energy stored in the fabric, such as boundary conditions, will be discussed in later sections.

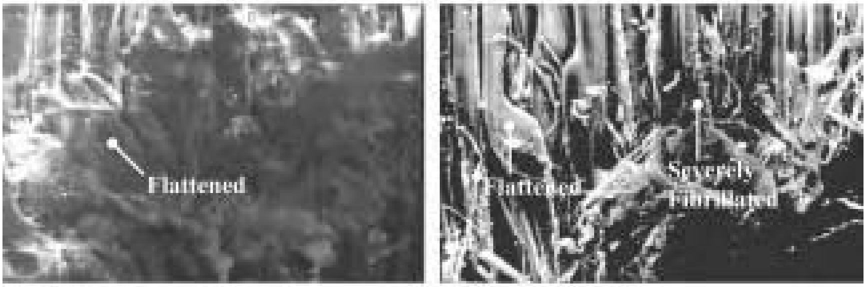
The kinetic energy transferred to a fabric target is composed of in-plane motion of the material outside the deformation cone in the wake of the strain wave front, and the out-of-plane motion of the yarns in the deformation cone. The kinetic energy of a fabric system is affected by the mass (or areal density) of the target, and the volume of the material in motion. As with the strain energy, the kinetic energy can also be affected by the boundary conditions imposed on the target.

For hard composites, the mechanisms are basically the same as would be predicted via classical elastic behaviour (Cantwell and Morton 1991; Cantwell and Morton 1989; Delfosse and Poursartip 1995; Delfosse and Poursartip 1997; Abrate 2001; Abrate 1994). By definition, the elastic energy is temporarily stored in the system and returned. In the case of an impact that induces no damage, it is the only mechanism other than system losses. A variety of models exist which attempt to address the global component of deformation and energy absorption; see the reviews by Abrate (1994; 2001). What most have in common is a means by which the global stiffness of the structure is calculated and used for predicting the elastic energy absorption as well as the global component of deflection and potential modes of vibration. For example, Pierson's work (Pierson and Vaziri 1996; Pierson *et al.* 1993) uses previously developed equations of motion (Whitney and Pagano 1970) to take into account the effects of shear deformation and rotary inertia. Projectile impact is taken as a time-varying normal force applied to the centre of the panel, and the exact response of the panel in terms of penetration resistance is determined by the amount of local damage or penetration handled separately from the global aspects. Typically, however, a finite-element method is employed to determine the elastic energy absorption (Quan 1998).



Hemispherical head impacted

Flat head impacted



Ogival head impacted

Conical head impacted

3.6 Frictional failure of fibres by projectiles of varying shapes (Tan *et al.* 2003).

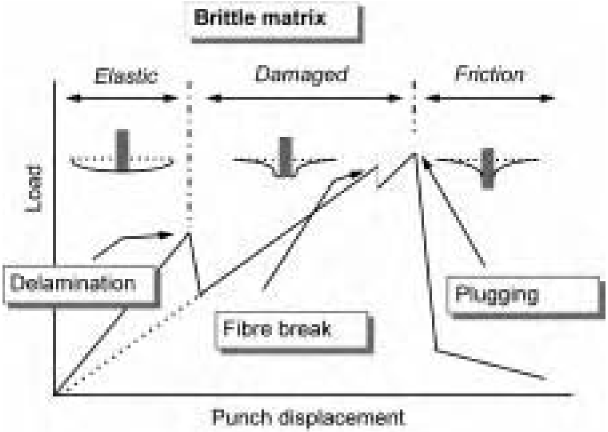
3.2.2 Dissipative

Global non-linear mechanisms observed in hard composites are typically irrecoverable and are associated with phenomena that are at least initiated locally, but can then grow to be more global. Therefore they will be discussed in more detail under local phenomena.

For fabric targets, the frictional energy dissipated during the impact event is the primary non-linear energy absorption mechanism (Fig. 3.6). Frictional mechanisms usually include frictional dissipation due to the slippage of yarns, interaction of adjacent layers, or interaction of the projectile and the target. Generally, it is thought that they make up a small portion of the overall energy absorption. Many factors will affect the magnitude of the frictional energy dissipated, including the friction coefficient between the contacting yarns, and panel boundary conditions allowing or restricting yarn motion. There is evidence, from the abrasion and fibrillation of yarns, which suggests that frictional effects are more prominent at lower impact velocities.

3.3 Local response

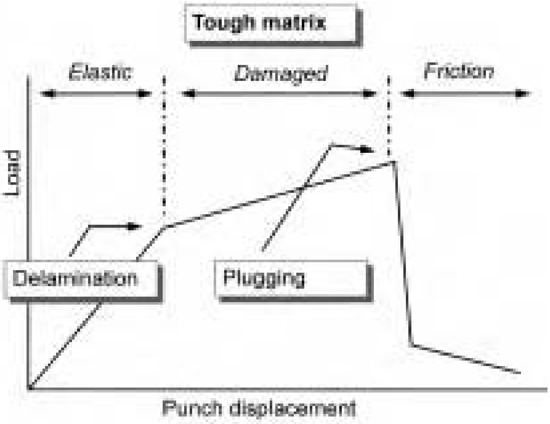
Local response refers to the behaviour of the target within close proximity to the projectile contact point. As strike velocities increase, a target panel will exhibit



3.7 Idealized load-displacement curve for brittle matrix CFRP static penetration test (Ursenbach 1995).

increasing amounts of locally dominated response. However, this does not imply that the behaviour at high velocities is necessarily different. Work by Sun and co-workers (Lee and Sun 1993b; Sun and Potti 1993) has shown that in AS4/3501-6 graphite epoxy, dynamic failure modes are very similar to quasi-static ones. Their general findings are mirrored in other studies (Zhu *et al.* 1992a; Lee and Sun 1993a; Lee and Sun 1993b; Jackson and Portanova 1996; Potti and Sun 1996).

The mechanisms discussed here often occur in stages throughout the penetration event and can be very dependent upon indentor tip-geometry (Figs 3.7 and 3.8). Discussion of what influences these mechanisms will be covered in a later section. The various mechanisms are now introduced in approximately the order in which they would occur during a penetration event.



3.8 Idealized load-displacement curve for tough matrix CFRP static penetration test (Ursenbach 1995).

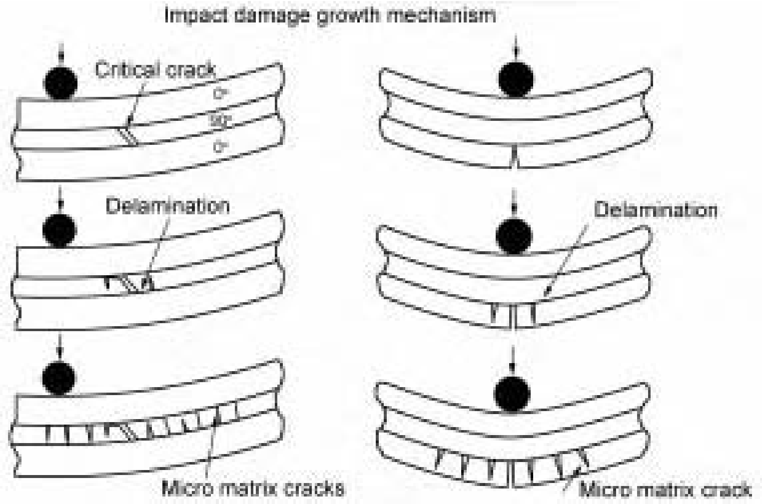
3.3.1 Matrix cracking/delamination

The majority of researchers have identified two types of matrix cracks which occur during both static and dynamic impact. In practically all cases it has been concluded that these cracks serve as the initiation mechanisms for delamination. Thus without the initiation of matrix cracks, delaminations could not occur within the plate, away from any free edges. The two types of cracks are defined as transverse shear and bending cracks (Jih and Sun 1993; Choi *et al.* 1991a; Choi and Chang 1992) as shown in Fig. 3.9.

Transverse shear cracks develop slightly away from the impact point at approximately 45°. This is due to the superposition of interlaminar shear stress and transverse normal stress – as shown in the first panel in Fig. 3.9. Figure 3.10 shows development of the cracks leading to delamination in a CFRP material. Bending cracks appear in the bottom layers of the laminate, and are caused by the high in-plane tensile stresses induced by the bending of the plate (second panel in Fig. 3.9).

It is generally believed that delaminations due to out-of-plane loading form through a combination of Mode I and II type fracture. However, there are varying opinions on the contribution of each mechanism. It has been argued that Mode II dominates and Mode I can be ignored for simplicity (Razi and Kobayashi 1993); that both modes work in approximately equal capacities (Choi *et al.* 1991b); and that Mode I is the sole mechanism responsible for crack opening (Wu and Springer 1988). It is likely that the exact modes at work vary from system to system and that a definitive statement is impossible.

What is evident is that delamination is widely accepted as a significant



3.9 Schematic description of the two types of matrix cracks seen in laminated composites (Choi *et al.* 1991a).

3.10 Cross-sectional micrograph of a delamination development in a 6.15 mm thick CFRP specimen penetrated by an indenter with 37° cone angle (Sanders 1997).

energy absorbing mechanism in laminates (Malvern *et al.* 1989; Wu and Chang 1995; Greaves 1992; Zhu *et al.* 1992a).

3.3.2 Fibre breakage/petal formation

Increased bending beyond what causes delamination ultimately results in tensile fibre breakage at the back face of the panel, also referred to as fibre fracture petal (Goldsmith *et al.* 1995), a term borrowed from metal failure modes (Thomson 1955; Taylor 1948; Zaid and Paul 1958; Johnson *et al.* 1973; Landkof and Goldsmith 1985).

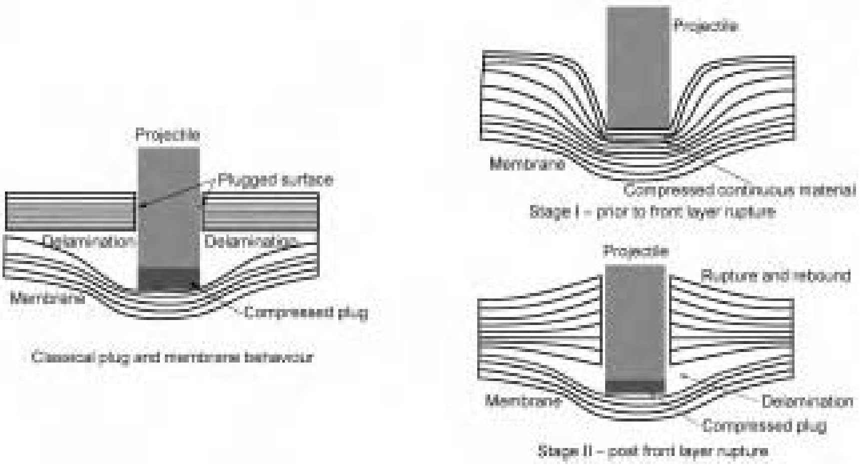
3.3.3 Shear plugging

In high velocity impact of both hard and fabric composites, the projectile usually perforates the first few layers of the target upon impact. This phenomenon, referred to as shear plugging, occurs more often with projectiles that have sharp edges, or when the initial strain in the yarns exceeds their failure threshold. The subsequent layers in the fabric or hard target are stretched and absorb the energy through membrane behaviour (Fig. 3.11) (Scott 1999). This may explain why placing the high performance layers on the distal side of the target has been suggested by some researchers (Cunniff 1999).

With blunt indenters, plugging is the final damage mechanism which occurs. Typically the plug is a circular section of material cut out in front of the indenter when perforating stiff plates. This mechanism has been reported by many researchers (Cristescu *et al.* 1975; Lee and Sun 1993b; Sun and Potti 1993) and is illustrated in Fig. 3.12.

3.3.4 Hole expansion/wedge through

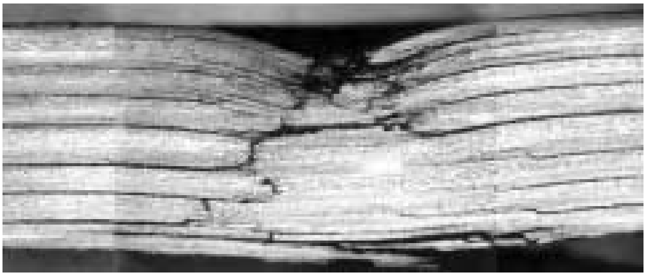
In dry fabric targets, this energy absorption mechanism occurs when the projectile perforates the layers of the target by pushing the yarns aside. In general, the hole created by the projectile upon perforation of the target is



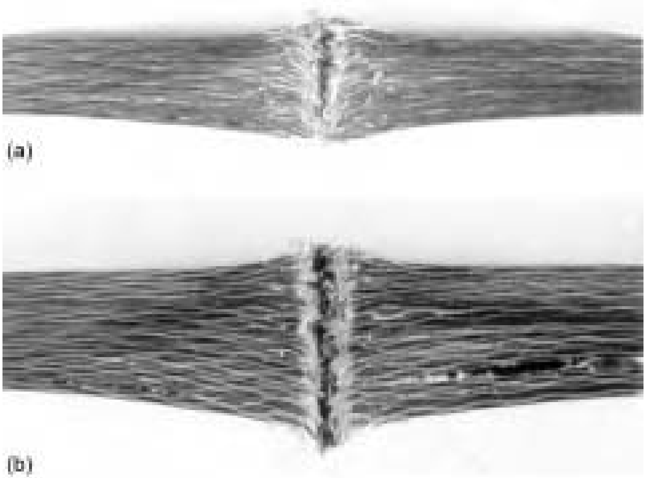
3.11 Rigid and compliant behaviour during impact (Scott 1999).

usually smaller than its diameter, reinforcing the belief that there is always a certain amount of hole expansion present during perforation (Shim *et al.* 1995). The energy absorbed through this mechanism is mainly in the form of the compression of the yarns around the projectile and the dissipated energy due to the existing friction between the yarns (Lim *et al.* 2002). However, the presence of this mode of perforation versus shear plugging in dry fabrics and laminates is highly affected by the projectile nose shape (Tan and Khoo 2005).

In cases where the resin and fibre form a tough composite, and the indenter is conically shaped or similar, a penetration mechanism (called hole expansion or enlargement in metals (Taylor 1948; Corbett *et al.* 1996; Hill 1950; Woodward 1978)) is also often witnessed with composites (Greaves 1992; Howlett and Greaves 1995; Zhu *et al.* 1992b). Examples of hole expansion in a GFRP composite are provided in Fig. 3.13 (Sanders 1997). In this mechanism, material directly ahead of the projectile is pushed aside by the projectile as it penetrates, resulting in a thickening of the panel in the vicinity of the hole.



3.12 Cross-sectional micrograph of a 6.15 mm CFRP laminate penetrated by the indenter with an included cone angle of 120°. The plug initiation site can be clearly seen (Sanders 1997).



3.13 GFRP panel showing hole-expansion and ploughing by a conical projectile of (a) 37° @ 203 m/s and (b) 120° @ 384 m/s. 13.2 g each (Sanders 1997).

3.3.5 Hole friction

The final mechanism, common to all projectile types and most material systems is friction and is simply the energy required to push the projectile through the crater created by either hole expansion or plugging. The frictional load is related to the length of penetrator in contact with the panel, the in-plane compressive stresses acting on the penetrator and the coefficient of friction between penetrator and composite.

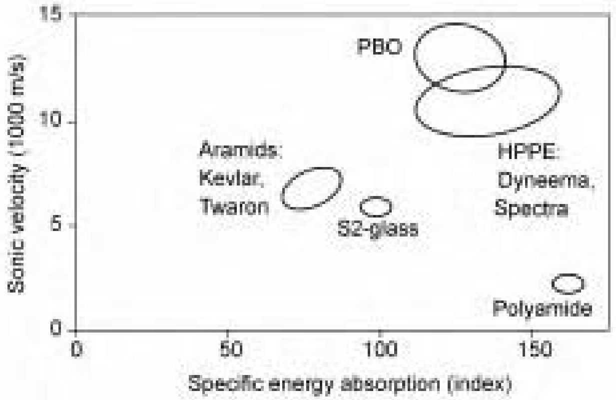
3.4 Influencing parameters

3.4.1 Material properties

Fibre type

In general, materials with high specific energy absorption characteristics (high strength and rupture strain and low density) are considered ideal, and for dry fabric targets, a high wave speed to spread the absorbed energy into a larger area is desired. High performance fibres and yarns commonly used in practice today are glass, aramid, PBO, and high-performance polyethylene fibres. For the latter, an elegant means of comparing the various yarns is shown in Fig. 3.14 (Jacobs and Van Dingenen 2001). For hard composites, fibres with higher stiffness will result in higher flexural wave speeds and more reflections during the impact event, which in turn leads to more global panel behaviour.

The transverse properties of yarns, although overlooked by many studies, play a major role in the energy absorption of fabrics. Since the yarns in a woven



3.14 Comparison of materials for ballistic application (Jacobs and Van Dingenen 2001).

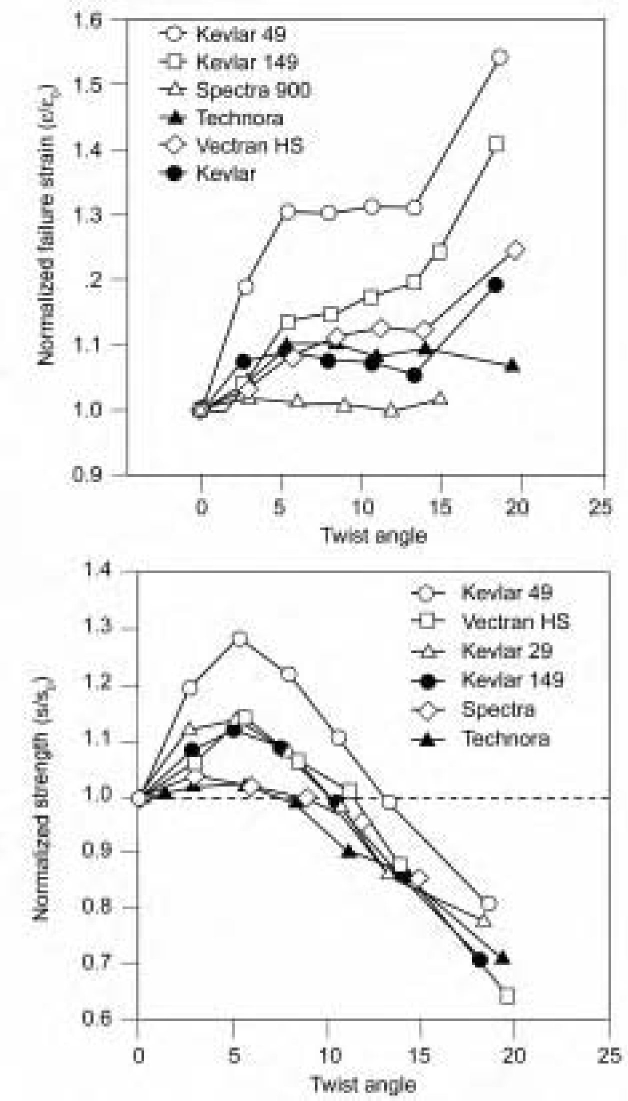
fabric interact under the applied extension, their transverse deformation determines how much the two crossing yarns can extend, leading to the emergence of various mechanisms in the target. Most studies on the transverse properties of yarns have been performed in the context of processing of textile composites (e.g. Gutowski 1985), or handling (Van Wyk 1946). These studies indicate a highly non-linear transverse response of fabrics that will greatly affect the interaction between the projectile and the target. This non-linearity has a number of sources including the complex geometry of the fibres in a yarn, the yarns in the woven fabric, and the non-linear transverse behaviour of the fibres themselves (Cheng *et al.* 2004).

Yarn structure

High performance yarns are typically made from filaments assembled together by twisting or entangling. It is known that twisting the yarns alters their modulus and strength. Rao and Farris (2000) performed a study on a number of materials and reported that there is an optimum twist angle that will maximise the strength of the yarns. This angle was found to be around 7° for all the materials that were studied by them (Fig. 3.15).

Strain rate sensitivity/temperature dependence

It is well established that the mechanical properties of high-performance polymers are sensitive to the rate of loading and temperature, owing to relaxation and creep mechanisms. As a result, many researchers have focused on the effect of loading rate on the mechanical properties of fibres in yarns and in fabrics, since the properties obtained from static or quasi-static tests are not necessarily

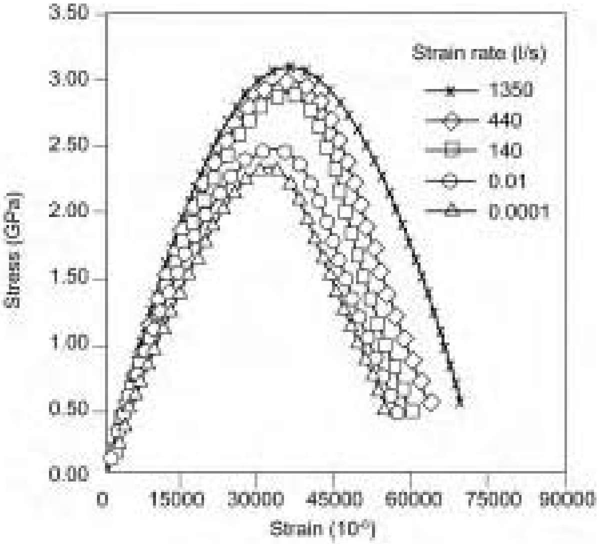


3.15 Normalized failure strain and strength versus twist angle (Rao and Farris 2000).

applicable to ballistic events. Figucia *et al.* (1971) conducted static and dynamic tests on a selection of high performance polymeric materials such as glass, nylon, and silk. They observed a clear stiffening in the stress–strain response of polymeric materials at higher rates of loading. The strength of the material increased at higher loading speeds, while the elongation-to-break decreased. Termonia and Smith (1988) developed a microscopic model for the fracture of perfectly ordered polymer fibres. They applied their model to oriented polyethylene and PPTA, and matched the experimental data which showed an increase in the tensile strength (tenacity) of the filaments with increasing strain rate. In another study, Fenstermaker and Smith (1965) used photographic data of transverse impact of polyester filaments to investigate creep and relaxation characteristics in the stress–strain response of these filaments, and represented it with a three-element spring-dashpot system. Wang and Xia (1998) developed a bi-modal Weibull distribution model to capture the strain-rate and temperature sensitivity of Kevlar® 49. Experimental results on Kevlar® 49, as seen in Fig. 3.16, show the dependence of its mechanical properties on the loading rate.

Shim *et al.* (2001) studied the strain-rate sensitivity of Twaron® fabric using split Hopkinson bar experiments. They concluded that the mechanical response of Twaron® is significantly rate sensitive, with an increase in tensile strength and modulus and decrease in strain-to-failure at higher rates. This observation incorporates both the fibre/yarn material rate sensitivity and the geometrical effects imposed by the weaving of the yarns into a fabric.

In the laminates, one of the most significant factors with respect to material properties is the strain rate sensitivity of the fibres. In the cases of glass, polyethylene and aramid, strain rate sensitivity makes it difficult to generalise target behaviour over a range of impact velocities (Harding and Welsh 1983). Similar findings by Zhu *et al.* (1992a) also found discrepancies between static and dynamic indentation tests. Even though damage progressed in the same order between velocity regimes, material parameters were found to be ineffective unless some strain rate sensitivity correction factor was used.



3.16 Stress–strain response of Kevlar® 49 at various strain rates (Wang and Xia 1998).

Conversely, carbon/graphite fibres have been shown to be strain-rate insensitive over a wide range of strain rates (Harding and Welsh 1983). Not surprisingly, carbon fibre reinforced systems are very attractive for model development.

Yarn surface finish/friction

In hard composites, fibre treatment can drastically alter the level of adhesion between the fibre and the matrix. Good fibre/matrix adhesion has been shown to result in higher damage resistance at low incident impact energies than in plates with poor adhesion (Kessler and Bledzki 1999; Kim and Sham 2000). Poor adhesion typically manifests itself as an increase in delaminations upon impact. However, at higher incident impact energies it is often advantageous to promote delamination due to its effective energy absorption properties.

As discussed previously, frictional energy dissipation is important in fabric targets. Numerous studies have focused on measuring the frictional properties of yarns and fabric. Briscoe and Motamedi (1992) looked into surface treatment of the yarns and the resulting effect on the friction coefficient. Other researchers have used fibre pull-out tests to characterise the frictional properties of the yarns in a fabric. The study by Bazhenov (1997) used the yarn pull-out technique and concluded that the addition of friction between the yarns would broaden the pull-out zone active during impact, affecting the dissipation of energy in the fabric. Martinez *et al.* (1993) measured the frictional properties of yarns using a yarn pull-out technique, as well as the friction and wear of Kevlar while in contact with metals, although they noted that it was desirable to measure behaviour at higher pressures and loading rates than they did. Kirkwood *et al.* (2004, 2005) used the frictional properties measured from quasi-static yarn pull-out to model energy absorption of the fabric due to uncrimping and translation of the yarns. Shockey *et al.* (2000) similarly used the friction coefficient obtained from such tests to simulate the response of fabrics via three-dimensional modelling of the fabrics. They found that the friction coefficient was affected by the fabric weave. Rebouillat (1998) performed a study that showed the friction coefficient is higher in fabrics with lower density yarns, possibly due to the high number of contact points along a yarn.

All the effort focused on the measurement of frictional properties of yarns emphasizes the importance of this parameter on the performance of the panels. Duan *et al.* (2005a, 2005b) used a three-dimensional model of the fabric and concluded that the frictional mechanisms are most active in panels with boundary conditions that allow extensive yarn movement upon impact. More interestingly, they observed that the presence of friction not only stabilizes the structure of the fabric in the impact zone, but it also affects the contribution of other global mechanisms such as the strain and kinetic energy components to the overall energy absorbed.

Fibre configuration

The most common fibre configuration used in hard composites is unidirectional or fabric, with (at least currently) few three-dimensional weaves. Woven fabrics exhibit enhanced interlaminar fracture toughness (Kim and Sham 2000), with two to eight-fold improvements reported. This results in reduced damage by suppressing delamination initiation. In terms of impact performance, cross-ply laminates exhibit a clear load drop after reaching maximum load, whereas woven-fabric laminates exhibit somewhat of a plateau prior to failure.

It has been found that composites containing three-dimensional weaves tend towards higher damage tolerance than their two-dimensional counterparts of the same fibre system (Chen and Jang 1995). This finding was attributed to a reduction in delaminations in the three-dimensional weave. Further support for this argument is provided by Mouritz (2001), where it was found that in blast loading the damage resistance was increased even more than in projectile impact.

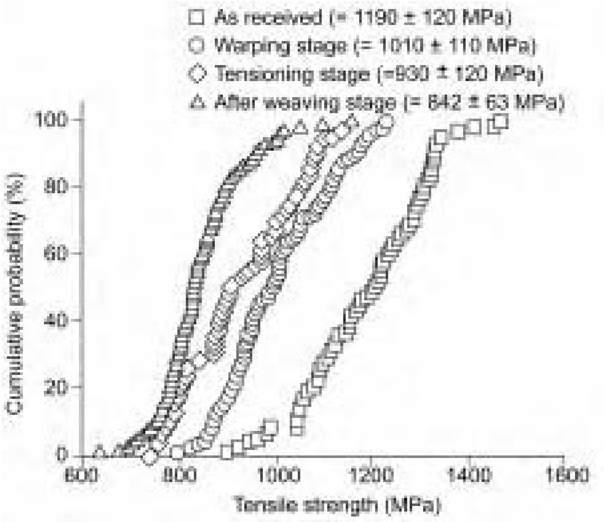
Fabric

Mechanical properties of a fabric are generally different from the yarns, due to its complex structure. Presence of crimp, friction and yarns interaction, and many other factors alters the response of a fabric to the applied loads. Cunniff (1992) discussed the loss of efficiency in going from a fibre to a yarn, from a yarn to a fabric, and from a single fabric layer to multi-layer packs. He concluded that yarn slippage may lead to the loss of efficiency and performance degradation in a loosely woven fabric or a fabric with low yarn-to-yarn friction. Considering the geometry of the weave, it has long been observed that balanced fabrics absorb more energy than non-balanced ones.

It is well known that the process of weaving degrades the properties of the yarns. In studies published by Lee *et al.* (2002) and Rudov-Clark *et al.* (2003) degradation of glass yarn properties during the weaving process of three-dimensional fabrics is discussed. Based on their findings, the weaving damage mainly influences the yarn strength, reducing it by up to 30% due to the high abrasion of the filaments (Fig. 3.17). The tensile modulus of the yarns was found to be less affected by weaving. Although these studies were conducted in the context of fabric composites, parallel conclusions can be drawn in the case of dry fabrics.

Lay-up and resin

Choi *et al.* (1991b) highlight two basic impact damage growth patterns which are dependent on lay-up. The most common difference between resin systems is their toughness and strength. The major difference between tough and brittle systems is the behaviour immediately after the onset of delamination. Brittle systems tend to experience instantaneous delamination with very little growth



3.17 Cumulative probability distribution of yarn tensile strength at various weaving stages (Lee *et al.* 2002).

afterwards, whereas tough systems experience more steady and controlled delamination growth.

3.4.2 Target details

In-plane dimensions

Target size is critical under low velocity impact as the size of the panel dictates the amount of elastic energy that can be stored.

Under high velocity impact, target size effects are diminished, and can be completely inconsequential for high enough strike velocities as damage is highly localized (Cantwell and Morton 1989; Cantwell and Morton 1991). However, at lower velocities it has been shown that small specimens are always stronger than their larger counterparts (Morton 1988), though this effect is not nearly as pronounced as thickness scaling effects (Liu *et al.* 1998). This also holds true in the case of dry fabrics. Cunniff (1992) showed that in-plane dimensions directly affect the ballistic performance of the fabric targets at strike velocities close to the ballistic limit of the fabric. This effect diminishes at higher impact velocities, where the dominance of the local mechanisms results in the choice of target boundaries to be inconsequential.

Thickness

For dry fabric targets, thickness is normally reported as the number of layers. The most common test data reported in the literature is the plot of residual velocity, V_r against strike velocity V_s. As the number of layers is increased, the specific energy absorption capability of the fabric is reduced, possibly due to the interaction of the plies and the increased transverse stress on the first layers of a multi-layer fabric system (Cunniff 1992). However, Lim *et al.* (2002) concluded from their study of two-ply targets that this is true only for flat-nosed projectiles. Other projectile shapes change the shape of the $V_s - V_r$ curves, which will be discussed in the section on the effect of projectile shape.

Prosser (1988) measured the V_{50} of fabric panels with varying numbers of layers and concluded that there is a linear relationship between the square of V_{50} and the number of layers, as long as the energy absorbing mechanism remains the same. The cause for change in the mechanism was attributed to the nature of the target and material and geometrical properties of the projectile.

Cunniff's investigation (Cunniff 1999) of fabric targets with varying number of layers lead to the conclusion that at extremely high velocities (well above V_{50}), the layers nearest the strike face have a very small effect on the overall energy absorption, since they fail almost instantly under the high initial strain.

For hard composite panels, the ratio between panel thickness and indenter diameter is an important variable in determining the dominant penetration mechanism (Cantwell and Morton 1988; Olsson 2000; Olsson 2001). Woodward (1984) proposed transitions of penetration mechanisms for conical projectiles into metallic targets, and these were found to be valid for laminates in the work of Cantwell and Morton (1990) and Quan (1998). Further supporting results can also be found in Liu *et al.* (1998). Woodward observed that:

- When the plate thickness, h, is less than the projectile diameter $2R_p$, $h < 2R_p$, dishing instead of hole expansion is the favourable penetration mechanism for metallic materials with low toughness in the through thickness direction.
- When the plate thickness, h, is less than $\sqrt{3}/2$ times the projectile diameter, $h < \sqrt{3}R_p$, ductile plug formation and ejection instead of hole expansion is the favourable penetration mechanism for metallic materials with low strength, low work-hardening, and high thermal softening rate.

It has also been observed that with thicker panels, indentation damage becomes more important due to their smaller deflections (Sutherland and Guedes Soares 2004).

3.4.3 Boundary conditions

The in-plane boundary conditions of dry fabric targets have been the focus of much research. Boundary conditions alter the energy absorption of panels upon the reflection of the longitudinal strain wave from the boundaries. This can be observed as a change in the projectile deceleration upon return of the strain wave to the impact point. Cepus *et al.* (1999) studied the energy absorptions of panels with fixed-all-around and free-all-around boundary conditions in high speed impact events. They observed that in the case of free boundary conditions, the tension in the yarns is reduced significantly after the reflection of the strain wave, since the yarns can move freely in the plane of the fabric. As a result, a large portion of the energy absorbed is in the form of kinetic energy, with little contribution from the strain energy. In contrast, the constraint applied to the yarns in panels with fixed boundary conditions significantly increases the strain in the yarns and the strain energy stored in the fabric. Furthermore, the kinetic energy stored in panels with fixed boundaries is mainly from the transverse motion of the material in the deformation cone. In practice, the finite flexibility of the test fixture and boundary slippage means that the response of a fabric target lies between the two extremes of fixed and free.

Slippage of the fabric at boundaries is almost inevitable in ballistic experiments. Cepus (2003) showed that this slippage at the boundaries can have a significant effect on the overall energy absorption of the panel. Reducing slippage at the boundaries results in a faster rate of energy absorption prior to perforation. However, the strain levels in yarns with less boundary slippage are higher, and thus perforation of the target generally occurs earlier.

For hard composites, restriction of out-of-plane motion using a rigid backing eliminates the global response completely and results in a locally dominated response, with potentially higher degrees of crushing in the volume immediately ahead of the projectile. This effect is more pronounced in blunt projectiles than in conical ones. Changing the opening size of the backing structure has less effect with increasing velocity (Cantwell and Morton 1988) since in this case the impact event becomes more localized.

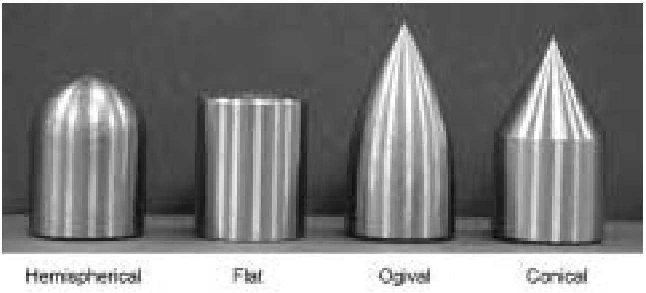
3.4.4 Projectile details

The following parameters will typically only be significant in cases where localized forms of panel response are exhibited.

Projectile shape

Projectile shape has a direct influence on the energy absorption of fabrics and the failure mechanisms of the yarns. Montgomery *et al.* (1982) studied the performance of Kevlar® 29 and Kevlar® 49 panels impacted by projectiles of varying shapes. They concluded that at lower velocities, the more pointed projectiles decelerate faster while at higher velocities the deceleration is faster for more blunt nose-shapes.

Tan *et al.* (2003) investigated the performance of single-ply Twaron® fabrics by four different projectile nose shapes: hemispherical, flat, ogival and conical (Fig. 3.18). This study showed that the flat-nosed projectile tends to shear the yarns on the contact surface, whereas the hemispherical nose-shape tends to stretch them to failure. The other two projectile shapes perforated the target in a



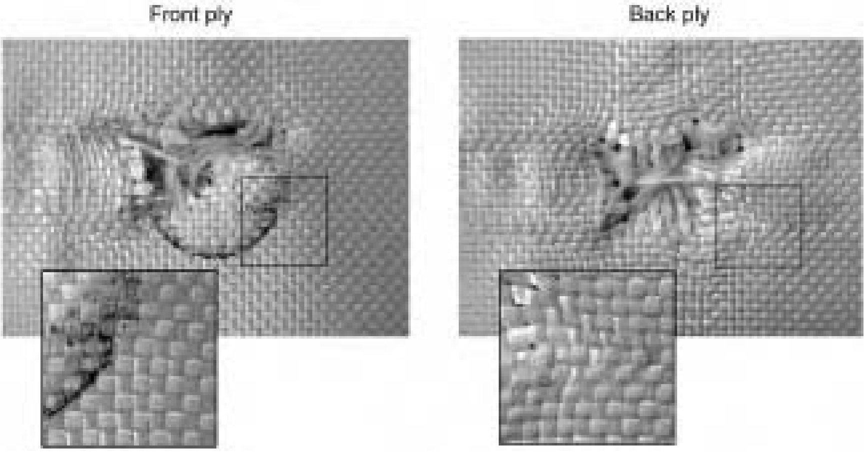
3.18 Various projectile shapes considered by Tan *et al.* (2003).

'wedge-through' fashion. Consequently, it was found that the hemispherical nose-shape leads to the highest energy loss in the projectile compared to other shapes.

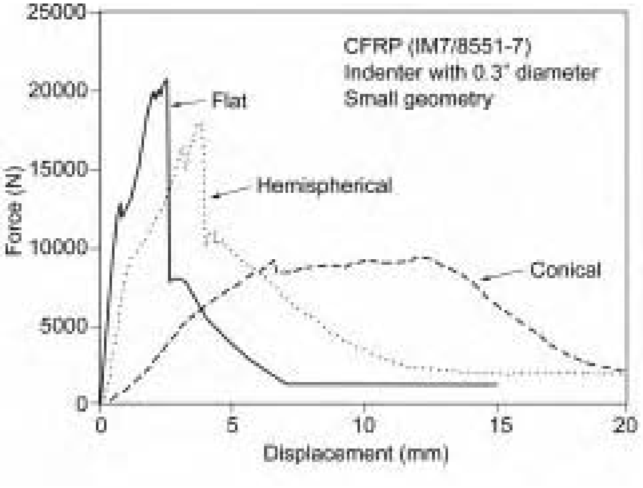
Lim *et al.* (2002) expanded the study by Tan *et al.* (2003) to two-ply fabrics impacted by the same projectile geometries. They concluded that while target performance is highly affected by the projectile nose-shape, the influence diminishes in the thicker panels. They also observed that while failure through rupture and friction is more evident on the impact face, bowing is more amplified on the back-face of the target (Fig. 3.19).

Tan and Khoo (2005) performed a similar study on the response of flexible Spectra® laminates to the four projectile nose-shapes identified in Fig. 3.18. Similar to dry fabrics, flat-nosed projectiles cut through the laminates upon perforation, while the hemispherical projectile stretched the filaments to failure.

Projectile shape also plays a dominant role during the penetration event in hard composites, as it significantly affects the damage profile (Delfosse and



3.19 Increase in bowing of the yarns on the backside of the target (Lim *et al.* 2002).



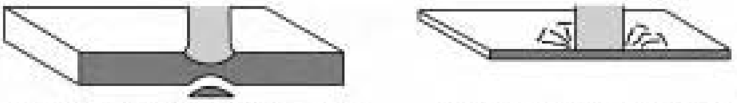
3.20 Static force-displacement curves for different nose shapes (Delfosse and Poursartip 1995).

Poursartip 1995) (Fig. 3.20). Various models (Awerbuch and Bodner 1974; Zhu *et al.* 1992a; Zhu *et al.* 1992b) were applied in an attempt to capture the penetration response of carbon fibre reinforced laminates (Pierson *et al.* 1993). In this work, flat and conical projectiles were used and required separate treatment due to the significantly different behaviour seen in each case. As a result, performance of a panel will be dictated by the projectile shape in relation to either the shear strength or in-plane compressive strength of the panel.

Generally speaking, a blunt projectile will first make an initial indentation followed by plastic shearing and the formation of a plug. It has been shown that flat-nosed response can be witnessed in conical-tipped projectiles with sufficiently large cone angles (120º) (Zhu *et al.* 1992a), but for the purposes of this discussion flat shall be assumed to be 180º. When compared with conical and hemispherical indenters of the same diameter, flat-nosed indenters yield the highest forces prior to perforation for most material systems (Delfosse and Poursartip 1995).

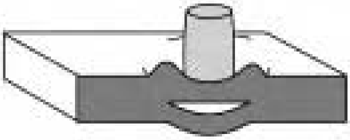
The mechanism which dominates for flat projectiles most resembles shear punching in metals (Awerbuch and Bodner 1974), shown in Fig. 3.21(d) (Corbett *et al.* 1996). However, as mentioned in Pierson (1994) and Pierson and Vaziri (1996) shearing in composites occurs via a fracture mechanism rather than plastic shearing as is found in metals, and the use of metal analogies is of limited usefulness.

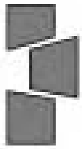
Interestingly, it has been shown that the local damage caused by quasi-static punch tests performed on composites (Lee and Sun 1993b) was very similar to that witnessed in dynamic blunt impact tests (Sun and Potti 1993; Lee and Sun 1993a; Jenq *et al.* 1994). In both cases damage was shown to progress from



(a) Fracture due to initial stress wave

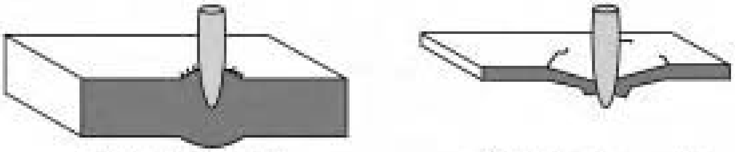
(b) Radial fracture behind initial wave in brittle target





(c) Spall failure (scabbing)

(d) Plugging



(e) Petalling (frontal)

(f) Petalling (rearwards)

(g) Fragmentation

(h) Ductile hole enlargement

3.21 Typical perforation mechanisms found in metals (Corbett *et al.* 1996).

matrix cracking to delamination and eventually plug formation as the indenter sheared though the material. From this point on in-plane friction forces needed to be overcome. The work was shown to be valid over a range of panel thicknesses from 2 mm to 8.1 mm.

Delfosse and Poursartip (1995) showed that a conical tip geometry had considerable influence on the impact event. Conical tipped projectiles encountered the least resistance with materials that possessed lower in-plane stiffness such as Kevlar™ and Spectra™. The tip was able to plough through the material in a manner analogous to hole expansion witnessed in metals (Corbett *et al.* 1996; Taylor 1948; Greaves 1992; Howlett and Greaves 1995). In the stiffer carbon and glass fibre reinforced laminates, however, the projectile met with considerably more resistance as the conical shape had to push stiff layers out of the way in order to proceed forward. Some component of compressive normal forces will exist until the entire conical tip emerges from the back. As a result, upon penetration there is a levelling off of the force-displacement curve as the projectile overcomes the friction associated with passing through the fully expanded hole. Pierson's (1994) work effectively captured a penetrating ballistic event by separating the global response from the local response, and then modelling the entire ballistic event by superposition. This approach was also suggested by Sjoblom *et al.* (1988).

Hemispherical-nosed indenter geometry typically shows behavioural characteristics of flat-nosed indenters, with slightly lower contact forces due to the slightly earlier initiation of penetration and damage.

Projectile hardness

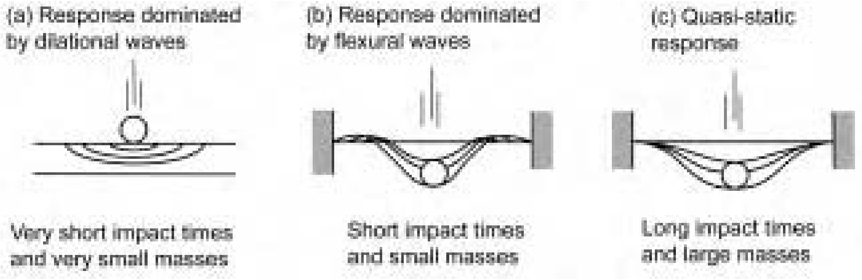
Plastic deformation of the projectile is a local energy absorption mechanism. This phenomenon occurs when the strength of the projectile is low enough to permit extensive plastic deformation upon interaction with the target. This phenomenon, also known as mushrooming of the projectile, can absorb significant amounts of energy (up to 25%) as reported by Jacobs and Van Dingenen (2001).

Although definitive evidence is lacking, the relative hardness of the projectile is likely to be more critical than the absolute hardness, and there could be a velocity dependence if either material is strain-rate sensitive. In addition, if a panel is hard enough to cause a projectile to deform and become blunt, then there will be an increase in frontal area as the event progresses, and a divergence in behaviour from a comparable non-deforming projectile.

Projectile mass

For fabric targets, the relative mass of the projectile will change the energy absorption mechanism of the fabrics. While smaller masses are easily defeated at lower velocities, their perforation mechanism at higher velocities is highly localized. On the other hand, larger masses trigger both local and global mechanisms under various strike velocities (Shahkarami *et al.* 2002).

For hard composites, the projectile to plate mass ratio is critical in determining the panel response (Olsson 2000). Olsson further expands on Cantwell and Morton's (1989) generalization of impact response types, as shown in Fig. 3.22. The response is attributed to the dominant wave forms present, based on the mass of the projectile initiating them. Very small impactor masses cause what he refers to as a *ballistic response*, where through thickness waves dominate and impact duration is generally very short (Fig. 3.22a). Moderately small impactor masses cause an eponymous *small mass response* where shear and flexural waves dominate, and load, deflection and flexural strains are out of phase (Fig. 3.22b). Impactor masses much larger than the target



3.22 Classification of response types for varying projectile velocities (Olsson 2001).

will cause a quasi-static *large mass response* where the peak load, deflection and strains are generally in phase (Fig. 3.22c). The breakdown of responses originally identified by Cantwell and Morton remains valid, and Olsson simply differentiates further between the smaller masses and shorter duration times on the extreme ends of the spectrum.

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4

Modeling ballistic impact

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4.1 Introduction

Modeling impact and penetration problems have been the subject of much interest especially for their application to defense and space technology. Due to the constant improvements of weapon technology, predicting the ballistic resistance and behavior of armor under impact by a projectile is the subject of much experimental, analytical and numerical research. Nevertheless, the problem has not yet been fully understood or solved. Ballistic experiments are crucial to further understand the complexity of penetration mechanics in order to identify key parameters defining the perforation and damage phenomenon of the armor materials. The complexity of ballistic problems caused by the high number of intervening parameters like relative velocity, shape of colliding objects, relative stiffness and masses, location of contact, dimensions and boundary conditions, material characteristics, etc., increases when composite materials are involved, due to the orthotropic properties and distinct failure modes that may occur. Designing composite material ballistic armor thus requires a very large number of experimental tests, which are time and resources consuming.[1–2]

Nowadays, there are approaches used to quantify the penetrator and armor interaction using empirical, numerical and analytical methods. The recent advances toward understanding damage mechanisms and mechanics of laminated composites[3–6] coupled with the development of advanced anisotropic material models[7–9] offer the possibility of avoiding many of the experimental tests by using ballistic impact simulation. With the development of computer hardware and decades of research in these techniques, computational simulations have become both feasible and cost effective to reduce the physical experimentations and also optimize the parameters involved in both ballistic penetration and fragmentation. However, the numerical results should be used with precaution and must always be validated by experimental tests.

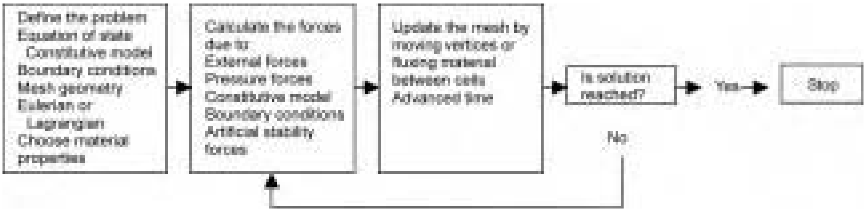
Empirical methods seek to establish simple relations between some of the parameters which define the projectile and the armor interaction including their material properties, their geometry and its velocity. These parameters and some others, experimentally measured, i.e. penetration depth, ballistic limit velocity V_{50}, etc. lead to parametric equations. This method is useful only when there are a very limited number of variables to correlate.[10–14] Analytical methods enable the study of penetration mechanics from the general continuum mechanics equations. The aim is to develop empirical models for approximating the materials behavior. In this case, a real knowledge of the physical phenomenon taking place during the penetration process is necessary in order to select the most proper parameters. Such parameters will be included in the equations governing the solids interaction during the impact. The main advantage in this approach is that it provides the solution with less computing time but at the expense of accuracy of such model compared to full numerical simulation. The analytical approaches are discussed at length in references 15–19.

Numerical methods are based on finite element or finite difference codes. Since the equations governing the impact of solids are in general, non-linear, numerical analysis of penetration mechanics allows a more correct material representation and a more precise simulation of the process. The main advantage of this approach is the wider information provided which enables a better understanding of the process and it is quite valuable for an improved design of the armor. The accuracy of such codes is mainly dependent upon definite constitutive equations used to represent the behavior of each individual material. The disadvantage of this method arises from the high computer time (CPU) involved for a single simulation process.[20] Hydrocodes or wave codes are large computer programs used to numerically simulate highly dynamic events in solid mechanics particularly include shock, by approximating a continuum in point-wise (finite difference) or piece-wise (finite element) then solving the conservation equation coupled with material models.

Our focus in this chapter, however, will be mainly on the numerical aspects of ballistic modeling. The first section of this chapter starts with a fundamental overview of hydrocode modeling and computational aspects and the second section demonstrates the ability of some candidate computer codes. Suggestions for future trends are presented and discussed.

4.2 Computational aspects

The equations governing the impact of solids are, in general, non-linear and cannot be solved analytically, thus, numerical analysis of the equations is used to determine the response. Hydrocode modeling is summarized in the flow chart in Fig. 4.1. Hydrocode modeling rests on three pillars, which are used to determine the forces acting on the mesh at each time step. These are: the Newtonian laws of motion; the equation of state; and the constitutive model.[21] The modeling of incompressible, inviscid fluid flow may be described by the Newtonian laws of motion alone, as a set of differential equations established through the principles



4.1 Flow chart summarizing the general scheme of a hydrocode.

of conservation of momentum, mass and energy from a macroscopic point of view. These equations are of the form:

Conservation of momentum
$$\frac{Dv_i}{Dt} = f_i + \frac{1}{\rho}\frac{\partial \sigma_{ji}}{\partial x_j} \tag{4.1}$$

Conservation of mass
$$\frac{D\rho}{Dt} + \rho\frac{\partial v_i}{\partial x_i} = 0 \tag{4.2}$$

Conservation of energy
$$\frac{DI}{Dt} = -\frac{p}{\rho}\frac{\partial v_i}{\partial x_i} + \frac{1}{\rho}\Pi_{ij}\dot{\epsilon}'_{ij} \tag{4.3}$$

where ρ is the material density, v_i is the velocity, I is the specific internal energy, σ_{ij} is the stress tensor, which is composed of a hydrostatic part, the pressure p, and a deviatoric part, Π_{ij}. f_{ij} is the external body forces per unit mass, and $\dot{\epsilon}'_{ij}$ is the deviatoric strain rate. The subscripts represent the standard tensorial notation, and summation is implied by repeated indices. The equation of state relates pressure to the density and internal energy. It thereby accounts for compressibility effects; that is, changes in density and irreversible thermodynamic processes such as shock heating.

Equation of state
$$p = p(\rho, I) \tag{4.4}$$

The constitutive model, relates the stress to a combination of strain ϵ $\dot{\epsilon}'_{ij}$, strain rate effects $\dot{\epsilon}'_{ij}$, internal energy I, and damage D. These describe the effect of deformation (change in shape or strength properties).

Constitutive model
$$\sigma_{ij} = g(\epsilon_{ij}, \dot{\epsilon}_{ij}, I, D) \tag{4.5}$$

Analytical solutions to equations 4.1–4.5 above are only obtainable for circumstances where certain simplifying assumptions may be invoked, reducing the number of variables to be considered. In cases of practical interest, where the variables are numerous and the problem is complex, the equations must be solved simultaneously. Computational techniques, provide the only amenable method to achieve the number of mathematical operations required for the solution. All hydrocodes utilize some form of the conservation equations; however, the usefulness of the hydrocode depends on the sophistication of the equation of state and constitutive model.

4.2.1 Spatial discretization

It is necessary in a computer analysis to replace a continuous physical system by a discretized system. In the discretization process, the continuum is replaced by a computational mesh. Three fundamental techniques exist for discretizing the differential equations: finite-element schemes, finite-difference schemes and smooth particle hydrodynamic (SPH) techniques. Essentially the three schemes offer different algorithms for solving the same problem; however, each has its benefits and weaknesses.

Finite-difference scheme

In the finite-difference method the spatial derivatives in the differential equations are replaced by difference equations. For example, for some function F the partial derivative $\partial F/\partial x$ becomes $\Delta F/\Delta x$ where the differences are computed at grid points. The first derivative of F at x_n can be represented by a variety of difference formulae:

$$\begin{aligned}
\left.\frac{\partial F}{\partial x}\right|_{x_n} &= \frac{F_{n+1} - F_n}{\Delta x} \\
\left.\frac{\partial F}{\partial x}\right|_{x_n} &= \frac{F_n - F_{n-1}}{\Delta x} \qquad (4.6) \\
\left.\frac{\partial F}{\partial x}\right|_{x_n} &= \frac{F_{n+1} - F_n - 1}{2(\Delta x)}
\end{aligned}$$

which correspond to forward, backward and central difference equations, respectively. The finite-difference method is well-founded and simple to implement. However, it does require that the grid is structured (cells arranged in rows and columns). Consequently, clever coordinate mapping techniques or adaptive meshing algorithms must be applied in order to solve problems involving complicated geometries. Furthermore, there is no straightforward way to test the accuracy of a solution, and the scheme is prone to certain types of numerical instability, which require artificial corrections. In general, the accuracy of the solution increases with decreasing cell size; however, limits on the time step mean that small cell sizes imply small time steps, leading to long run times.[22–25]

Finite-element scheme

The finite-element method was initially developed on a physical basis for the analysis of problems in structural mechanics; however, it was soon recognized that the method can be applied to a variety of problems.[26–29] Whereas the finite difference method is a point-wise discretization of the problem space, finite-element methodology divides the problem space into elements. The elements can be rectilinear or curved and, unlike the finite-difference method, need not be arranged in a structured grid. Hence, complicated problem geometries are handled better with a finite-element approach.

Interpolation functions are used to represent the variation of a variable over the element. Each element is associated with a set of nodes, whose initial locations are known. The displacement of these nodes is the basic unknown of the problem. The equations governing the displacements of these nodes are calculated on an element-to-element basis and then combined. A consequence of this fact is that finite-element codes may be parallelized as a way to reduce run time. Once combined, the system of equations relating the forces and displacements at each node is solved by inverting the 'stiffness matrix', which represents the constitutive relationship between stress and strain. One advantage of this method is that when the displacements have been derived, they can be substituted back into the original equations to check for consistency. Any inconsistency is a direct measure for the inaccuracy of the solution and can be corrected for during the simulation.

Smooth particle hydrodynamics

Smoothed particle hydrodynamics (SPH) was invented to simulate problems in astrophysics involving fluid masses moving arbitrarily in three dimensions in the absence of boundaries.[30] A typical example is the numerical simulation of the fission of a rapidly rotating star. SPH involves the motion of a set of points. At any time, the velocity and thermal energy are known at these points. A mass is also assigned to each point and, for this reason; the points are referred to as particles. In order to move the particles correctly during a time step it is necessary to construct forces which an element of fluid would experience. These forces are basically constructed using sophisticated interpolation techniques to determine properties such as density at a given point. SPH codes offer an attractive alternative to the more well-founded techniques of finite-difference and finite-element, due to the simplicity of the algorithm: most users tend to write their own SPH code. The method is inherently Lagrangian, and therefore, possesses most of the benefits of this formalism; however, SPH does not break down when large displacements are involved, because the particles are not connected.

Although currently in-vogue, and in an ever advancing state of development, SPH codes do suffer from several major short-comings. Currently, there are no robust methods for describing complicated material rheologies such as strength, elasticity, etc. Moreover, by their very nature, SPH codes do not handle certain types of boundary conditions well, further limiting their potential use. Lastly, in problems such as impact calculations where the density varies dramatically (from very dense target rock to low density vapor), SPH suffers because the low density material is represented by too few particles to simulate the problem well. SPH codes are good for fluid flow problems involving relatively small density differences and primarily inflow or outflow boundary conditions. In particular, they are good for problems involving self-gravity, such as the formation of planets and stars.

4.2.2 Time integrating methods

The time stepping methods are the heart of most structural dynamics problems. Hence there have been extensive studies,[31–34] only a brief description will be given here; there are basically two time iteration methods outside of classical closed-form solutions available to analysts: implicit and explicit formulations of the systems of equations that describe the mechanics.

The procedure for the discretized equation of motion is called *explicit* if the solution at some time $t + \Delta t$ in the computational cycle is based on the knowledge of the equilibrium condition at time t. The advantage of using the explicit method is that there is no need to calculate stiffness and mass matrices for the complete system, thus the solution can be carried out on the element level and relatively little storage is required. The drawback of the method is that it is conditionally stable in time, and the time step must be carefully chosen, the size of the time step must be sufficiently small to accurately treat the high-frequency modes that dominate the response in wave propagation problems.

Many finite-element codes employ the explicit integration scheme to solve highly transient, non-linear problems. The most widely known commercially available software is LS-DYNA, from the Lawrence Livermore National Laboratory, and its various commercial descendents, LS-DYNA, PAMCRASH, and MSC/DYNA. Another code using this method that is not a DYNA derivative is ABAQUS/EXPLICIT.

In an *implicit* scheme, the solution at any time $t + \Delta t$ is obtained with knowledge of the accelerations at the same time. Implicit methods are unconditionally stable, however, such stability is obtained at the expense of solving a set of equations at each time step. The most often mentioned implicit finite-element codes are ABAQUS, ADINA, ANSYS, NASTRAN, MARC, and NIKE. Generally, it may be said that the implicit integration method is more effective for static or low frequency problems while the explicit integration method is the best for high speed impacts.

4.2.3 Problem description

The description of the deformed body can be expressed in either Lagrangian or Eulerian coordinates.[26] In *Lagrangian* coordinates, every point in the deformed body is referred to some reference state, and any discretization, such as finite-element mesh or finite-difference zoning used in the analysis, deforms with the material. Hamouda and Hashmi[20] evaluate most of the Lagrangian and Eulerian codes as shown in Table 4.1 and Table 4.2, respectively.

In *Eulerian* coordinates, however, the points are fixed in space and the discretization does not move with the material. These two descriptions can be compared, respectively, with a traffic policeman following an automobile, and one sitting at a traffic light and watching all automobiles through the light. The Eulerian formulation has no mechanism for tracking material history, but the Lagrangian formulation follows material particle paths which permit an accurate historical description of the material. This will make it easy to incorporate history-dependent material description. To date, the most sophisticated material descriptions have been done with Lagrangian codes.

For the sake of comparison between the two approaches, Predebon *et al.*[31] simulated cylinder impact tests in Lagrangian code (HEMP) and in Eulerian code (CSQ). They found that the final dimensions of the simulated cylinder in the Lagrangian code are 2.8% higher than the one simulated using the Eulerian code.

Generally, Lagrangian formulation is most appropriate for impact of solid bodies since the surfaces of the bodies will always coincide with the discretization and are therefore well defined. The disadvantage is that the numerical mesh can become severely compressed and distorted in many problems. This has a very adverse effect on the integration time step and accuracy. These problems

Table 4.1 Evaluation of Lagrangian hydrocodes

Code	Year	Developers	Organization
HEMP	1964	M.L. Wilkins	Lawrence Livermore Laboratories
HEMP-3D	1975	M.L. Wilkins	Lawrence Livermore Laboratories
HEMP-DS	1983	M.L. Wilkins	Lawrence Livermore Laboratories
C-HEMP	1987	L. Seanman *et al.*	SRI Int.
TOODY	1967	W. Herrmann	Sandia National Laboratories
HONDO	1974	S.W. Key	Sandia National Laboratories
EPIC-2	1976	G.R. Johnson	Honeywell Inc.
EPIC-3	1977	G.R. Johnson	Honeywell Inc.
EPIC-2 (Erosion/plugging)	1987	B.E. Ringers	BRL
EPIC-3 (Erosion)	1985	T. Belytschko	BRL
DYNA 2D/3D	1976	J.O. Hallquist	Lawrence Livermore Laboratories
DYNA-2D (Erosion)	1989	J.O. Hallquist	Livermore Software Technology Corp.
DEFEL	1984	W. Flis	DYNA East Corp.
PEPSI	1984	R. Hunkler and G. Paulus	ISL, France
PRONTO 2D	1987	L.M. Taylor and D.P. Flanagan	Sandia National Laboratories
ZEUS	1987	J.A. Zukas and S.B. Segletes	Computational Mech. Conslt, Inc.

Table 4.2 Evaluation of Eulerian hydrocodes

Code	Year	Developers	Organization
PIC	1957	M. Evans and F. Harlow	Los Alamos Laboratories
SHELL	1959	W. Johnson	General Atomic Corp.
SPEAR	1963	W. Johnson	General Atomic Corp.
OIL	1965	J. Walsh and W. Johnson	General Atomic Corp.
TOIL/TRIOIL	1967	W. Johnson	General Atomic Corp.
DROF	1971	W. Johnson	Systems, Science, and Software (S-Cubed)
DROF-9	1971	W. Johnson	S-Cubed
TRIDROF	1976	W. Johnson	Computer Codes Constultant (CCC)
SOIL	1977	W. Johnson	CCC
LASOIL	1987	W. Johnson	Los Alamos Laboratories
RPM	1968	J. Daienes *et al.*	General Atomic Corp.
HELP	1971	L. Hageman and J. Walsh	S-Cubed, BRL
HELP-75	1975	L. Hageman *et al.*	S-Cubed
METRIC	1976	L. Hageman *et al.*	S-Cubed
CHART-D	1969	S.L. Thompson	Sandia National Laboratories
CSQ	1975	S.L. Thompson	Sandia National Laboratories
CSQ-II	1979	S.L. Thompson	Sandia National Laboratories
CHT	1987	J. McGlaun *et al.*	Sandia National Laboratories
HULL	1971	R. Durrett and D. Matuska	Orland Technology (OTI)
HULL-78	1978	R. Durrett and J. Osborn	OTI
EPHULL	1988	R. Bell	S-Cubed
MESA	1989	D. Mandell *et al.*	Los Alamos Laboratories

can be overcome to a certain extent through the use of *eroding sliding interface*, and *rezoning*. Another numerical technique that can be used is called the *tunnel approach*.[20] A hydrocode may employ either type of formulation to describe the situation of interest. The choice of either mode of description depends on the problem under consideration.

Coupled Eulerian Lagrangian

The Coupled Eulerian Lagrangian (CEL) technique was developed in an attempt to unite the advantages of both formulations (Lagrangian and Eulerian). The advantage of this approach is that either technique can be applied, in parallel, to different regions of a problem according to the physics being modeled. Such a description is useful for problems involving two materials, one of which is less deformable than the other. In the case of the less deformable region the problem can be modeled as Lagrangian, while regions undergoing large deformation can be modeled in Eulerian sense. The disadvantage of this technique can be the computational penalty associated with the Euler–Lagrangian interface. AUTODYN is one of the commercial codes which use the CEL approach.[35]

Arbitrary Lagrangian Eulerian

The Arbitrary Lagrangian Eulerian (ALE) technique was originally developed for fluids.[36] The ALE description treats the computational mesh as a reference frame which may be moving with an arbitrary velocity that is different from both the particle velocity (Lagrangian) and zero velocity (Eulerian). The difficulty in developing the algorithms needed for continuous rezoning has limited the use of ALE technique. Another disadvantage of ALE, is that the material interface, free surfaces, and material history are very difficult to treat with the ALE technique.[37]

4.2.4 Rezoning (re-meshing)

Rezoning is a formation of a new mesh out of the old mesh. The new mesh may be manually defined, or automatic mesh generators may be used. Mesh rezoning has more application than just fixing the distorted mesh of a Lagrangian computation. Typically, the desire is to have fine zoning for good resolution in areas where large stress variations exist from zone to zone. Rezoning is not a straightforward task because it necessitates the calculation of the new mesh quantities by interpolating from those of the old mesh without significant loss of accuracy in the response predications.

4.2.5 Mesh generation and boundary conditions

Generating a mesh to represent the geometry of interest, assigning appropriate initial material parameters, and choosing appropriate boundary conditions are the basic inputs for a hydrocode. Certain types of hydrocodes are designed for particular geometries or boundary conditions, again emphasizing the importance of choosing an appropriate hydrocode for a particular problem. 1D, 2D and 3D hydrocodes exist; however, because memory requirements scale with the number of cells, 3D hydrocodes have only recently come into mainstream usage. Frequently, simplifying assumptions are used to reduce the spatial degrees of freedom.

The types of boundary conditions implemented in a hydrocode also vary between specific codes. Common boundary conditions fall into the following categories:

- *Free surface*: This is the simplest type of boundary condition, which applies no constraints on the motion of the vertex.

- *Free slip*: For a symmetry boundary or a free slip wall, the normal wall velocities must be kept at zero throughout the calculation. If such a boundary is parallel to the coordinate axes implemented in the hydrocode, this is a simple matter of setting one of the velocity component to zero. If the wall is slanted or curved both velocity components must be adjusted.
- *No slip*: For this boundary condition both velocity components are set to zero, regardless of mesh geometry.
- *Specified outflow or inflow*: For this type of boundary condition the velocities at the boundary are specified externally. This condition is complicated, however, by the need to set not just velocities but other, cell-centered quantities such as density and internal energy.
- *Continuative outflow or inflow*: Similar to the specified flow boundary condition, the typical treatment of such conditions is to set the inflow or outflow velocities, densities, energies, etc. equal to the adjacent cell within the mesh.
- *Forcing*: This form of boundary condition applies a stress along or across the boundary. The form of this stress may be constant or time dependent.

4.2.6 Material models

A *constitutive law* or *model* represents a mathematical model that describes our ideas of the behavior of a material. In other words, a constitutive law simulates physical behavior that has been perceived mentally. The main advantage of establishing a mathematical model is to apply the ideas for solving (complex) events quantitatively.

The object of the constitutive relations is to describe the behavior of the present experiment and predict the results of the experiment not yet performed. The accuracy and predictability of the numerical calculation depend on the realistic description of the material of interest through appropriate constitutive model in the code. To quote from Hashmi and Hamouda[38]: ‘The objective of the material models is to provide a theoretical description applicable to a wide class of practical problems, but using simple idealizations of the outstanding features of the real phenomenon’. Along this line it should also be emphasized that numerical implementation of a proposed constitutive equation into a computer code is almost as an important issue as the model itself. A literature survey can easily reveal models that are mathematically very elegant, but pose overwhelming computational difficulties. It is thus believed that a constitutive model, although rigorous in theory, should also be suitable for computational use and should lend itself to efficient implementation in computer codes. Constitutive modeling of materials, in general, has been approached from one of two viewpoints, namely, *microscopic* and *macroscopic*.[20]

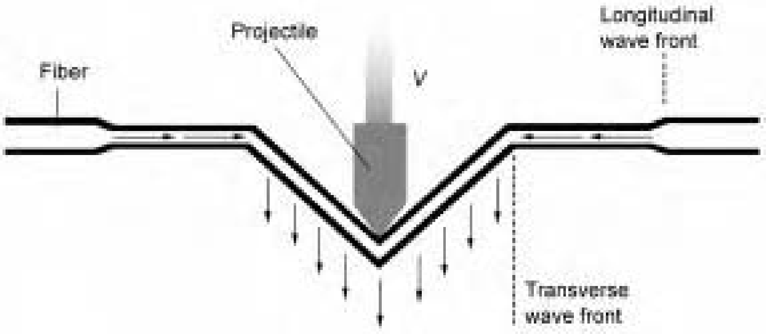
The most important characteristics and phenomena governing the behavior of composite materials under ballistic impact are: material anisotropy, shock response, coupling of volumetric and deviatoric behavior, anisotropic strength degradation, material compaction, phase changes. In the case of anisotropic materials, there is a strong coupling between the equation of state and the constitutive relations, as volumetric strain leads to deviatoric stress and similarly, deviatoric strain leads to spherical stress. An advanced material model,[39–40] specially designed to simulate the shock response of anisotropic materials has recently been implemented, and couples the non-linear constitutive relations with the equation of state. The coupling is based on the methodology proposed by Anderson *et al.*[41] The model can additionally include compaction and orthotropic brittle failure criteria to detect directional failure such as delamination. Hamouda and Hashmi[42] developed a constitute law for Metal Matrix Composite subject to impact and ballistic loading conditions.

Composite materials of polymeric matrix subjected to impact exhibit complex behavior. Experimentally, the dominant tensile material failure modes were identified as extensive delamination, due to matrix cracking and/or matrix-fiber debonding, in-plane fiber failure and punching shear failure caused by a combination of delamination and fiber failure leading to bulk failure. In the numerical model the composite material is considered to be homogeneous. Kevlar fibers and epoxy matrix are not separately modeled and the main phenomena of relevance are accounted for in a macro-mechanical model.

4.3 Ballistic computational modeling

In order to describe the impact into a fabric, the transverse impact into a single fiber is described first. When a projectile strikes a fiber, two waves, longitudinal and transverse, propagate from the point of impact, as shown in Fig. 4.2.

The longitudinal tensile wave travels down the fiber axis at the sound speed of the material. As the tensile wave propagates away from the impact point, the material behind the wave front flows toward the impact point, which has deflected in the direction of motion of the impacting projectile. This transverse



4.2 Scenario of projectile impacting into a ballistic fiber.[43]

movement of the fiber is the transverse wave, which is propagated at a velocity lower than that of the material. Noting the similarities between the transverse impact of a single ply of fabric with that of a single fiber, Cunniff[43–44] noted that when a projectile impacts the fabric, it produces a transverse deflection in the yarns that are in direct contact with the projectile (defined as principal yarns) and generates longitudinal strain waves that propagate at the sound speed of the material down the axis of the yarns. Additionally, orthogonal yarns, defined as yarns that intersect the principal yarns, are then pulled out of the original fabric plane by the principal yarns. These orthogonal yarns undergo a deformation and develop a strain wave like those observed in the principal yarns. Analogously, these orthogonal yarns then drive yarns with which they intersect. These yarn–yarn interactions, which are a function of the friction between them, produce bowing, the misalignment of the orthogonal yarns, toward the impact point. The transverse deflection proceeds until the strain at the impact point reaches a breaking strain.

Naik[45] has used analytical method to study woven fabric composites consisting of warp and fill yarns, interlaced in a regular sequence. They reported that, as the projectile impacts on to the woven fabric composite, there can be many yarns beneath the projectile. It has also been observed that, for identical ballistic impact conditions, ballistic limit is higher for E-glass/epoxy than for carbon/epoxy as shown in Table 4.3. For E-glass/epoxy, energy absorbed by secondary yarn deformation and tensile failure of primary yarn are the main energy absorbing mechanisms. For carbon/epoxy, the main energy absorbing mechanisms are the secondary yarn deformation and shear plugging. Morye *et al.*[46–47] reported on the development of a simple model for calculating the energy absorption by polymer composites upon ballistic impact. Three major components were identified as contributing to the energy lost by the projectile during ballistic impact, namely the energy absorbed in tensile failure of the composite, the energy converted into elastic deformation of the composite and the energy converted into the kinetic energy of the moving portion of the composite. These three contributions are combined in the model to determine a value for the ballistic limit of the composite. The required input parameters for the model were determined by a combination of physical characterization and from high speed photography. They reported that, the size of the deformed region, formed through shear deformation, on the backface of the composite is related directly to the in-plane shear modulus of the material. Perhaps the most surprising result was that the dominant energy absorbing mechanism was found to be the kinetic energy of the moving portion of the composites.

Ulven *et al.*[48] have investigated the influence of projectile geometry onto the damage propagation and evolution during ballistic impact to carbon/epoxy composite panels using analytical modeling. Analytical models[49–54] were adapted for the prediction of ballistic limit in each panel impacted by the four different projectiles. The models were derived from energy balance relationships.

Table 4.3 Ballistic impact test results for typical plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites, d = 5 mm, h = 2 mm

Material	Projectile mass, m_p (g)	Predicted ballistic limit, $V_m (m/s)$	Experimental ballistic limit, V_{50} (m/s)	Predicted damage size, $r_d (mm)$	Experimental damage size, $r_d (mm)$	Predicted surface radius of the cone, $r_t (mm)$
Plain wave E-glass/epoxy	2.8	159	150	9.6	10	35
Twill weave T300 carbon/epoxy	1.8	99	105	–	–	59
Twill weave T300 carbon/epoxy	2.8	83	–	–	–	61

These models are based on the assumptions that during a ballistic event, deformations are localized and that the mean pressure provided by a laminate to resist a projectile consists of two parts: quasi-static and dynamic resistive pressure.

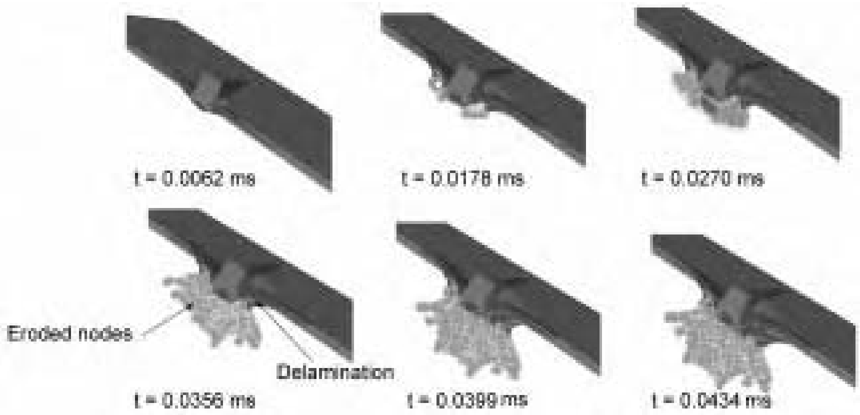
Gu[55] developed an analytical model to calculate the decrease of kinetic energy and residual velocity of projectiles penetrating targets composed of multi-layered planar plain-woven fabrics. Based on the energy conservation law, the absorbed kinetic energy of the projectile equals the kinetic energy and strain energy of the planar fabric in the impact-deformed region if deformation of the projectile and the heat generated by interaction between the projectile and the target are ignored. Then the decrease of kinetic energy and residual velocity of the projectile after the projectile perforates multi-layered planar fabric targets could be calculated. Fibers in fabric are under a high strain rate state when fabric targets are perforated by a high velocity projectile, and the mechanical properties are used to calculate the residual velocity of the projectile. It has been shown that the mechanical properties of fibers at high strain rate should be adopted in modeling rate-sensitivity materials and predictions of the residual velocities and energy absorbed by the multi-layered planar fabrics show good agreement with experimental data. Compared with other models on the same subject, the perforating time in this model can be estimated from the time during which a certain strain at a given strain rate is generated. This method of time estimation is feasible in pure theoretical modeling when the perforation time cannot be obtained from experiments or related empirical equations.

Numerical studies by Roylance and his co-workers[3,6] have shown that the majority of the kinetic energy of the projectile is transferred to the principal yarns as strain and kinetic energy, whereas, the contribution of the orthogonal yarns to energy absorption is small. Lim *et al.*[56] developed the finite-element model of ballistic impact on Twarons fabric. A non-linear, explicit, three-dimensional finite-element code DYNA3D is used to simulate the response of fabric under high-speed projectile impact. The fabric is modeled using membrane elements. Suitable material properties to account for its viscoelastic nature are obtained through mathematical manipulation of the three-element spring-dashpot model and by use of available experimental data. The ballistic limit, residual velocity, energy absorption and transverse deflection profiles of the fabric are predicted and compared with those from experiment. Recent studies by Lim and his co-workers[57–59] have included the effect of transverse yarn interactions and have found that these interactions can significantly influence the results from ballistic response models. The description of single ply fabric deformation is given to serve as an illustrative example to point out some of the fundamental physical mechanisms observed that influence the ballistic performance of fabrics. Material properties, fabric structure, projectile geometry, impact velocity, multiple ply interaction, far field boundary conditions and friction all play a role. Although many authors attempt to describe these mechanisms individually, it should be noted that many of the individual mechanisms have been reported in a coupled manner (i.e. multiple ply ballistic panels impacted by different geometry projectiles at varying velocities). As such, it is difficult to isolate each mechanism; therefore, further research in this aspect is needed.

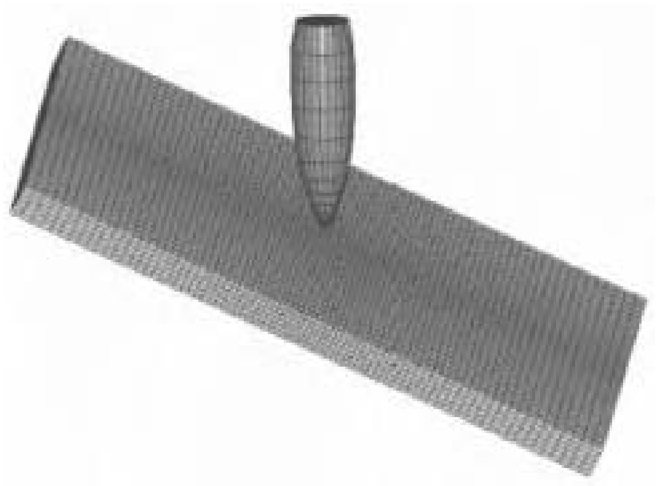
Silvaa *et al.*[60] have studied numerical simulation of ballistic impact problems on thin composite laminated plates reinforced with Kevlar 29 using AUTODYN 3D. Ballistic impact was imparted with simulated fragments on plates of different thickness. Numerical modeling was used to obtain an estimate for the limit perforation velocity V_{50} and simulate failure and damage modes. Significant evolution of the delamination, caused by excessive shear tensile stresses through thickness can be observed. Good correlation between computational simulation and experimental results was achieved, both in terms of deformation and damage of the laminates, as it can be seen from Fig. 4.3.

Mahfuz *et al.*[61] developed a finite-element model using DYNA3D to investigate the response of an integral composite armor under high-velocity impact. The 3D model consisting of the various discrete layers of the armor. The projectile is blunt ended and is made from a hardened 4340 steel rod. Stress distributions through the thickness have been determined and maximum values were found to occur at the ceramic layer. From the delamination point of view, the two interfaces across the rubber layer were found to be most critical.

Gu and Xu[62] presented the ballistic perforation test results of 4-step, 3D braided Twaron/epoxy composites, which were subjected to impact by conically cylindrical steel projectile. The finite element code LS-DYNA was used to simulate the impact interaction between projectile and inclined lamina. The material modeling was also based on this simplified model. Figure 4.4 shows a finite-element model of projectile and lamina, while the penetration process of lamina target and projectile is clearly shown in Fig. 4.5. The residual velocity of

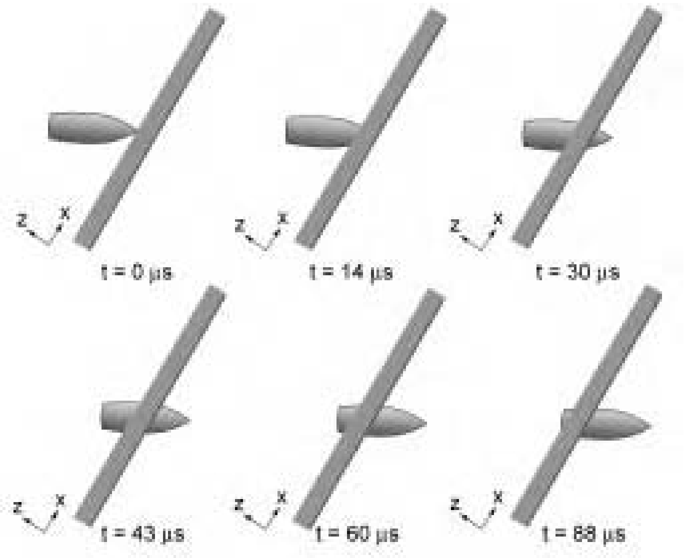


4.3 Ballistic limit – simulated damage development.[60]



4.4 Mesh scheme of finite-element model of projectile and lamina target.[62]

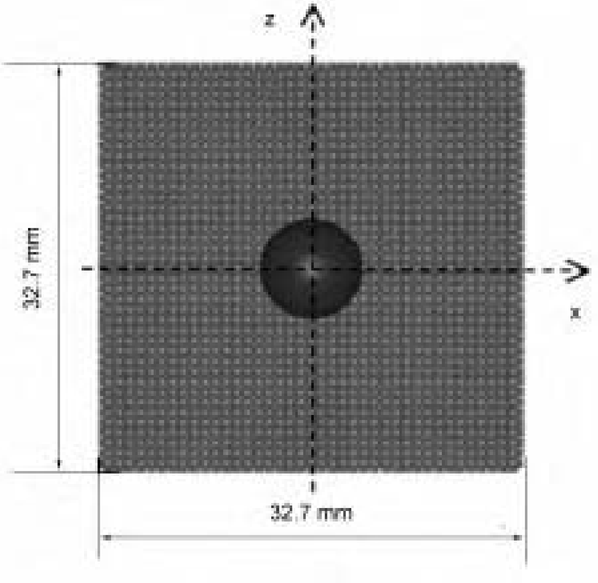
projectile perforating the entire 3D braided composite was calculated from the sum of kinetic energy loss of the projectile that obtained from the computational model. From the simulation of the ballistic penetration process and comparison between numerical results and experimental results, it shows that the analysis scheme at the quasi-microstructure level in their study is valid and reasonable. The simplified method developed in their study could be extended to model other kinds of 3D textile composites under ballistic impact.



4.5 Ballistic penetration damage of one of lamina in fiber inclination model.[62]

Taylor and Vinson[63] describe a model that treats fabric as a very flexible isotropic plate. However, this formulation ignores the directional properties of the yarns. Several authors[64–71] model the fabric as an assembly of flexible fibers interconnected at nodal points. Increasingly sophisticated models of this type have been developed that include contact between plies and slippage between yarns.[72–75]

Other researchers have used full 3D finite-elements with smeared properties.[8–9] In references 76–77 a micromechanical model that explicitly treated the deformation and failure behavior of individual yarns when the fabric was impacted is presented. To ensure the model would be true to the physical processes induced in the fabric by fragment impact, they examined yarn and fabric geometry, performed static and high-rate experiments, measured stress–strain and failure behavior, and developed empirical expressions describing the data and observations. Duan *et al.*[77] developed a finite-element model to study the influence of friction during ballistic impact of a rigid sphere onto a square fabric panel that was firmly clamped along its four edges (see Figs 4.6 and 4.7). Projectile–fabric friction and yarn–yarn friction were investigated and from the modeling result indicates that friction dramatically affects the local fabric structure at the impact region by hindering the lateral mobility of principal yarns. Reduction of lateral yarn mobility allows the projectile to load and break more yarns so that fabric possessing a high level of friction absorbs more energy than fabric with no friction. The projectile–fabric friction delays yarn breakage



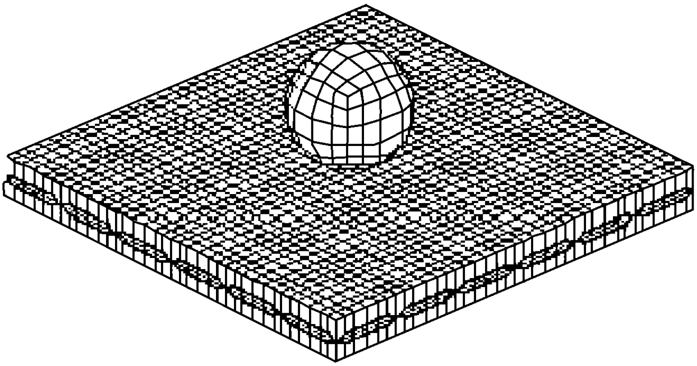
4.6 The initial geometry of the ballistic impact of a rigid sphere onto the center of a square fabric panel.[77]

4.7 Finite element mesh for the plain-woven fabric.[77]

by distributing the maximum stress along the periphery of the projectile–fabric contact zone. The delay of yarn breakage substantially increases the fabric energy absorption during the later stages of the impact. The yarn–yarn friction hinders the relative motion between yarns and thus resists de-crimping of fabric weave tightness. It induces the fabric to fail earlier during the impact process. The overall influence of projectile–fabric friction and yarn–yarn friction cannot be calculated by simply adding their individual effects. Duan *et al.*[78] reported a similar contribution from projectile–target friction in their research on low velocity impacts onto polymer disks. O'Daniel *et al.*[79] presents a detailed description of the precision impact event, and a comprehensive coverage of the validation of LS-DYNA3D for different impact events.

Shockey *et al.*[72–75] described a computational capability for designing lightweight fabric barrier systems to protect aircraft against fragments from an engine burst. A model of the deformation and failure of yarns and woven fabric under impact was developed, using data and observations from experiments. When implemented in the shell elements of the LS-DYNA3D finite-element code, the model computed residual energies of fragments accelerated against fabric targets in agreement with measurements from laboratory gas gun tests. Computational simulations with this model can assist the engineer in specifying such design variables as yarn pitch, number of fabric plies, gripping conditions, and loads applied to the supporting structure.

In the past, most polymer-based composite armors have been fabricated in the form of laminates and/or fiber-reinforced thermosets. For transparent armor applications, laminates are usually manufactured from PC, PMMA, ceramics and glass.[80–86] Though laminates improve the mechanical properties considerably and are easy to manufacture, they are prone to poor modes of failure. Often, cracks induced in the more brittle and stiffer components travel extensively, which limits structural integrity. Composite armors usually involve the

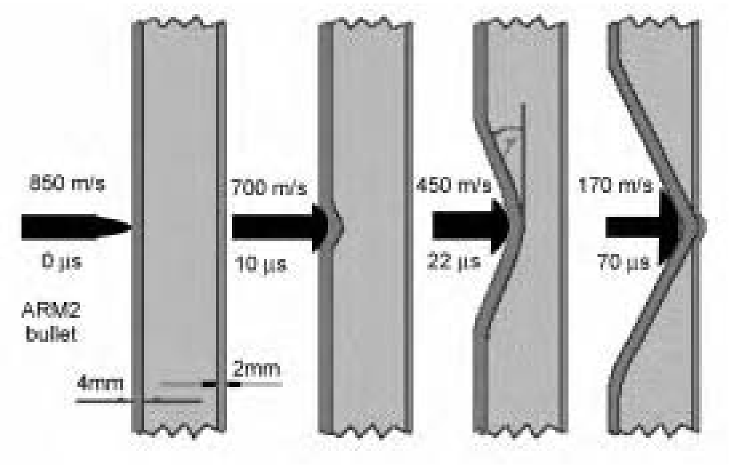


4.8 3D model of a composite armor under impact.[87]

combination of high stiffness and resilient materials. Jovicic *et al.*[87] suggested the application of the gradient design concept in armors which can offer reduction of weight and cost without significant reduction of ballistic resistance. In order to develop a precise methodology for the optimization of gradient design composite armors, an improved understanding of the relative significance of the design parameters must be developed. One way to study the relative significance of these parameters is through computational modeling. The central impact of a spherical projectile onto a polymer matrix composite plate is shown in Fig. 4.8. Computational limitations impose compromises in the modeling of both geometry and material behavior. Jovicic *et al.*[87] discussed two types of models (a) an approximate fiber/epoxy two-phase model for the backing; and (b) a damage-based, rate-dependent model for the ceramic spheres embedded in the epoxy. The development of a library of fiber architectures based on the unit cell has been initiated, which will open the possibility of the structural optimization along with simulation of the high velocity impact phenomena of advanced composites. Leigh and Porwal[12] developed an analytical model for the ballistic impact response of fibrous materials of interest in body armor applications. It focuses on an untensioned 2D membrane impacted transversely by a blunt-nosed projectile. They presented a hypothetical, body armor with multiple layers of diverse properties, and raised many fundamental questions about many long-held views on fabric system impact behavior and parameters thought to be important. Figure 4.9 illustrates a sequence of possible events that a futuristic, lightweight material system (perhaps 40% of the weight of current systems) might undergo to halt an armor-piercing bullet.

4.4 Concluding remarks and future trends

The main features of the computer codes suitable for impact calculation have been reviewed. Hydrocodes can be very useful tools in research if one



4.9 Schematic of a hypothetical layered fibrous structure envisioned to stop armor piercing APM2 bullets, yet half the weight of current, state-of-the art systems.[12]

recognizes their limitations and understands their operations. They can give detailed understanding of physical processes and can be used to perform analytical experiments. These computational experiments can be cheaper than laboratory experiments. As a demonstration, few examples of penetration problems have been presented to illustrate the capability of some commercially available computer codes.

Material deformation models for composite materials have been reviewed. Many numerical techniques have been utilized for impact and ballistic modeling. As indicated in the review, the most popular two are the finite-element and finite-difference methods, although finite-difference methods today are not as popular as they once had been. During the past two decades, finite-element methods have become the common tool for modeling impact and penetration events. More recently, boundary element methods and smooth particle hydrodynamics have appeared as promising approaches.

The question of reliability of computer simulation is one of great concern to specialists and researchers in ballistic modeling. Without some confidence in the accuracy of simulations, their value is obviously diminished. Today, remarkably accurate and reliable simulations are obtained routinely in many application areas while others are, at best, qualitative and capable of depicting only trends in physical events. This concern for reliability has led to the creation of a challenging technological area labeled simply validation and verification.

One of the major factors in increasing industrial competitiveness is the reduction in design cycle time. Such reduction hinges critically on the availability of virtual design, the ability to complete designs entirely in the computer, without making time-consuming prototypes. For Defense Department products, extreme environments, such as live-fire tests are increasingly simulated. Although great strides have been made in simulation in the past two decades, virtual prototyping is still more of an art than a science. To develop a virtual prototyping capability, many tests must be performed since many of the physical phenomena cannot be modeled on the basis of first principles today. Instead, models are tuned to tests, and the technology is not applicable to radically new designs. Specific obstacles to virtual prototyping include the inability to simulate problems with multiphysics phenomena, such as burning and change of phase, fracture and spalling, phenomena involving large disparities in scales, and behavior with significant stochastic characteristics. These capabilities are also of crucial importance to our defense. In order to make virtual design a reality in the next decade, radically new computational tools with the ability to handle multiscale phenomena, very heterogeneous materials, and discontinuous behavior, such as fracture and assessment of the range of performance and automatic guidance to improving design, must be available.

With the rapid development of new concepts of warfare and defense, new weapons and devices must be quickly designed and evaluated. Virtual design and prototyping are essential in this process. For example, with the new emphasis on the soldier and body armor, various protective devices must be evaluated. However, modeling of materials such as Kevlar and other new materials in the failure range requires a dynamic failure analysis that is beyond the state of our knowledge. These capabilities are also essential in maintaining our nuclear weapons stockpile without testing.

Ballistic modeling has become a central enabling discipline that has led to greater understanding and advances in modern science and technology. It has been the basis of numerous important developments in recent years and will continue to be crucial to industrial development and competition, to safety and security, and to understanding the diverse physical and biological systems occurring in nature and in society.

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5

Standards and specifications for lightweight ballistic materials

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5.1 Introduction

This chapter covers the test standards and specifications used by the US and a number of countries in South America, Europe and Asia for testing military and law enforcement ballistic materials and ballistic products. The test standards and specifications are essential elements for the armor designer, manufacturer, and buyer. Since lightweight ballistic materials are relatively new, both test standards and specifications in certain areas are still evolving. Similarly, although ballistic testing has been conducted on different materials for the last few decades, fine tuning of these test methods and new test techniques continues to evolve.

The main reasons for ballistic test standards and specification evaluations are:

- New and higher performance ballistic materials.
- Better understanding of short- and long-term behavior of ballistic fibers, fabrics, and non-woven felt and cross-plied materials.
- High power and more lethal ballistic threats such as Improvise Explosive Devices (IED).
- Understanding of ballistic trauma on human organs.
- Protecting upper and lower extremities.

The US standards and specifications are fairly detailed and revised on a continual basis. Some of the European, South Asian and Pacific Rim countries have test standards and specifications that are slightly different than the US, but overall there are more similarities than differences. Each test standard or specification could be fairly detailed covering every single item used in the vest or helmet or on an armored vehicle. However, this chapter will cover only the salient features of some of these standards and specifications related to lightweight ballistic materials used for flexible vests, molded breastplates, hand-held riot shields, military and police helmets and armored vehicles.

A number of countries follow or refer to the US standards as the benchmark or use them as a guideline, modifying them for local requirements. For example, the US Standard 0101.04 is a widely used test standard for testing bullet resistant vests used by law enforcement agencies. The Level IIIA in this standard calls for stopping (VO) of 9 mm FMJ and 44 Magnum bullets and limit on backface deformation (commonly referred to as 'trauma') in 44 mm. A number of countries specify the test as per Level IIIA vest but limit the test against only the 9 mm FMJ bullet. Other modifications of the test standard are in terms of speed of the bullet and much lower trauma limits.

Some of the most referred to and used test ballistic standards are:

MIL-STD-662F
NIJ Standard 0101.04 for law enforcement vests
NIJ Standard 0101.08
International Standard, ISO/FDIS 14876
STANAG 2920
PSDB

Similarly, some of the recent specifications are:

INTERCEPTOR
SAPI
SPEER

Armored vehicles such as cargo aeroplanes and helicopters use a number of specifications. However, the specification which covers the lightweight ballistic materials fabrication and testing generally follow the guidelines of MIL-L-62474B.

STANDARDS

5.2 Military standard MIL-STD-662F: V_{50} ballistic test for armor

The standard provides general guidelines for procedure, equipment, physical conditions and terminology for determining the ballistic of metallic, non-metallic, and composite armor against small arms projectiles. The ballistic test procedure described in this standard determines the V_{50} ballistic limit of armor.

5.2.1 Applications

The test standard provides the method for testing armor for acceptance and R&D of new armor material. The ballistic test method is used for testing body armor, armored seats for military aircraft, internal and external armor for aircraft, transparent armor and armor for light and heavy combat vehicles and structures.

5.2.2 Definitions

Appliqué armor

Armor that can be easily installed or removed from an armored system in kit form without adversely affecting its structural integrity or operation.

Areal density

The weight of the armor material per unit area, expressed as pounds per square foot (psf) or kilograms per square meter (ksm) of the armor surface.

Armor

A material that defeats the projectile (bullet or fragment).

Ballistic acceptance test

A test performed on a lot representing samples to determine the acceptance or rejection of a lot of armor.

Ballistic coefficient

Ballistic coefficients are the approximate formulations to determine average speed of a projectile.

Ballistic impact

Impact due to hits on the target by projectiles.

Ballistic limit

The velocity at which a projectile completely penetrates a specific armor when hit at a specified angle of obliquity.

V_{50} ballistic limit

The V_{50} is defined as the average of equal number of highest partial penetration velocities and lowest complete penetration velocity, which occur within a specified velocity spread. A minimum of two partial and two complete penetration velocities are used to complete the ballistic limit. Four, six and ten-round ballistic limits are frequently used.

Ballistic resistance

A measure of the capability of a material or component to stop or reduce the impact velocity and mass of an impacting projectile.

Ceramic armor

A type of armor, which consists of a ceramic face, bonded to a reinforced composite or metallic back plate.

Chronograph

An electronic instrument used to measure the time interval of a projectile flight between two fixed stations.

Composite armor

An armor system consisting of two or more different materials bonded to form a protective armor.

Fair hits

Fair hits apply only to ceramic armor consisting of ceramic tiles.

- Fair hit center tile – A fair hit for the center tile of the ceramic composite armor is an area within 25.4 mm radius of the center of an undamaged tile.
- Fair hit adjacent tile – A fair hit in an adjacent tile is a fair hit center tile in the tile that has an edge adjacent to a previously impacted tile whose hit was declared a fair hit.
- Fair hit at joint – A fair hit on the joint line is a hit within 3.8 mm of a single joint between two tiles, but no closer than 12.7 mm from the intersection of three or more tiles.

Fair impact

A fair impact is an impact by a projectile on an unsupported area of the target material at a specific obliquity at a distance twice the projectile diameter from any previous impact or disturbed are a resulting from an impact, or from any crack, or from an edge of the test specimen.

Fragment simulation

A projectile designed to simulate the effects of fragmenting munitions when such a fragment strikes a target.

Initial velocity

The projectile velocity at the moment that the projectile ceases to be acted upon by propelling forces. Expressed as feet or meters per second. It is also called muzzle velocity.

Integral armor

Armor material used as part of a structure to perform a load-carrying or other operational function in addition to ballistic protection. Also known as structural armor.

Lumiline screen

Photoelectric device used to activate or deactivate a chronograph on passage of a projectile.

Muzzle velocity

The velocity of the projectile with respect to the muzzle at the instant the projectile leaves the weapon. The velocity is a function of weight, firing charge of a projectile, barrel characteristics, etc.

Obliquity

The extent to which the impact of a projectile on an armor material deviates from the line normal to the target. A projectile fired perpendicular to the armor surface has 0° obliquity.

Obliquity angle

Angle between the normal to the target surface and the projectile trajectory or line of flight.

Penetration

A complete penetration occurs when the projectile or any fragment of projectile or screw from the ballistic component perforates the witness plate, resulting in a crack or hole which permits light passage when a 60-watt, 110-volt bulb is placed approximate to the witness plate.

Partial penetration

Any impact from a projectile, which is stopped in the ballistic target, shall be considered a partial penetration.

Projectile, fragment simulating

A projectile designed with special material, shape, and size for ballistic test firings so that the effect of a typical fragment can be simulated.

Propellant

A rapidly burning substance or mixture whose combustion or release produces the gas pressure that propels the projectile through the gun bore.

Sabot

Lightweight projectile carrier in which a specified caliber projectile is centered to permit firing the projectile in the larger caliber weapon. The sabot is usually discarded in flight a short distance from the muzzle, and only the sub-caliber projectile continues downrange.

Small arms

All gas-propelled, tube-type weapons firing a ballistic projectile with a diameter up to and including 20 millimeters (0.787 inches).

Small arms ammunition

All ammunition up to and including 20 millimeters (0.787 inches).

Spaced armor

Armor system having spaces between armor elements.

Spalling

The detachment or delamination of a layer of material in the area surrounding the location of impact, which may occur on either the front or rear surfaces of the armor. Spalling may be a threat mechanism even when penetration of the armor itself is not complete.

Striking velocity

The velocity of a projectile when impacted on the target.

Target baseline

The distance from a point midway between the two velocities measuring, trigger devices to the test sample.

Terminal ballistics

A branch of ballistics which is concerned with the effects of weapons on the target including penetration, fragmentation, detonation, shaped charge, blast, combustion and incendiary effect.

Test sample

An armor plate or fabricated armor section or component, which is to be ballistically tested for evaluation of ballistic protection properties.

V_{50} ballistic limits

The velocity at which the probability of penetration of an armor material is 50 percent.

Witness plate

A thin sheet located behind and parallel to the ballistic test sample which is used to detect penetrating projectiles or spall.

Yaw

Projectile yaw is the angular deviation of the longitudinal axis of the projectile from the line of flight at a point as close to the impact point on the target as is practical to measure.

5.2.3 Detailed requirements

Test conditions

Unless otherwise specified, all ballistic tests shall be performed in a standard atmosphere of 23 ± 2 °C (73 ± 4 °F) and 50 ± 5% relative humidity. Temperature and humidity will be recorded for each firing.

Equipment setup

Triggering devices

The spacing from the muzzle to the first pair of triggering devices shall be sufficient to prevent damage from muzzle blast and obscuration from the smoke in case optical devices are used. Spacing between triggering devices is a function of the expected velocity of the projectile. Physical restriction can also dictate the spacing. The last pair of triggering devices shall be placed at least 4 feet (1.22 meter) in front of the test sample and should be protected from possible damage resulting from the fragments.

Witness plate

Witness plate shall be made of 2024-T3, 2024-T4 or 5052 aluminum alloy, and shall be located 6 ± 0.5 inches (150 ± 10 mm) behind and parallel to the armor test sample. When the test sample is a helmet, the witness plate shall be rigidly mounted inside the helmet and 2 inches (51 mm) behind the area of impact and may be smaller than specified for a helmet.

Warm-up for constant velocity

Warm-up rounds are fired for a number of reasons. It could be alignment or establishing velocity or warming up the barrel to give consistent velocity. Additional rounds shall be fired as required.

Yaw checking

After mounting the test sample, the point of impact shall be located on the test sample and shall be positioned to line up with the previously determined line of flight of the projectile. Yaw shall be measured for each round by yaw cards, flash radiograph or photography. Yaw should not be greater than 5º.

First firing

For acceptance test the first firing round shall be loaded with a reference propellant charge that the striking velocity is approximately 75–100 ft/s (23 to 30 m/s) above the minimum required V_{50}. For other tests, first round shall be loaded with propellant close to the estimated V_{50}.

Examination of witness plate

The witness plate shall be examined for penetration. If the witness plate shows a big hole, it will be recorded as complete. In the event there is only a small dent, the witness plate should be examined against light to confirm whether the round has penetrated the target.

Subsequent firing

If the first round fires show a complete penetration, the propellant for the second round shall be reduced to achieve a lower velocity by 50 to 100 ft/s (15 to 30 m/s). If this results in a round stopping on the target after the propellant charge, the next round will have the propellant equal to first round plus propellant required to increase the velocity by 50 ft/s (15 m/s). A propellant increment or decrement, as applicable, for at least 50 ft/s (15 m/s) until a pair of partial and complete penetrations are achieved. After obtaining a partial and a complete penetration, the propellant increment or decrement for 50 ft/sec shall be used. Test is continued until a V_{50} is determined, using random pattern of impact sites, otherwise specified.

Calculation of the V_{50} ballistic limit

The V_{50} shall be calculated by taking the arithmetic mean of an equal number of highest partial and the lowest complete penetration within the allowable velocity spread.

5.2.4 Ballistic test report

Ballistic test reports shall contain the following information:

1. Contractor information
2. Test facility
3. Contact number
4. Lot number and quantities
5. Item specification number
6. Item specifications
7. Armor material description
8. Material identification for each test sample
9. Temperature and humidity at the test facilities
10. Date of the test
11. Personnel conducting the test and any witness
12. Weapon used
13. Projectile used
14. Projectile weight in grains
15. Type of propellant
16. Weight of propellant for each shot
17. Impact velocity used in computing V_{50}s with the highest partial penetration, lowest complete penetration, range (spread), and velocities of each rounds.
18. Witness plate characteristics, partial or complete
19. Calculation V_{50}BJ (P) ballistic limit
20. Remarks pertinent to the conduct of the test, or behavior of the material

5.2.5 Acceptance and rejection

The tested armor samples shall meet the minimum V_{50} ballistic requirement specified for the lot acceptance. Failure of any test samples to meet the minimum specified V_{50} ballistic limit shall constitute rejection of the entire lot which they represent.

5.3 National Institute of Technology: NIJ standard 0101.04

One of the widely used standards is the US National Institute of Justice (NIJ). The NIJ Standard 0.0101.04 was issued in September 2000. Since its introduction, it has been used as a reference by a number of South American, European and Asian countries. The standard establishes the minimum performance requirement and test method for the ballistic resistance of personal body armor for protecting the human torso against handgun and rifle gunfire. The standard also lays out criteria for acceptance of the armor vest in terms of labeling, test sequence, workmanship, tractability and labeling.

The ballistic resistance body armor in this standard is classified into seven levels. Type I, IIA, II and IIIA provide increasing levels of protection from handgun threats. Types III and IV armor, which protect against high-powered rifle rounds, are for use only in tactical situations.

5.3.1 Sampling of vests for testing and certification

Type I, IIA, II and IIIA

Six complete vests to fit 117–122 cm chest circumference for males and 107–112 cm chest circumference for females shall constitute the test group. Five of these vests shall be selected randomly from the group and used for ballistic testing. Four vests will be used for penetration test and backface signature testing, and one vest will be used for baseline ballistic limit determination.

Type III

Four complete samples, or panels, not smaller than 254 mm × 305 mm will be submitted for testing. Two of these samples shall be selected randomly from this group. Two samples will be tested for penetration and backface signature and one sample will be used for baseline ballistic limit determination. Any remaining will be returned.

Type IV

Nine complete samples, or panels, not smaller than 203 mm × 254 mm will be submitted for testing. Eight of these samples shall be selected at random from this group. Two samples will be tested for penetration and backface signature and six will be used for baseline ballistic limit determination. Any remaining will be returned.

5.3.2 Armor backing materials

Backing material fixture (BMF)

Minimum of three backing material fixtures filled with Plastilina #1 (clay) are required. The inside dimension of BMF shall be 610 mm × 610 mm × 140 mm deep. The backing of the fixture shall be removable and constructed of 19.1 mm thick wood or plywood.

Fixture construction

The sides of the box fixture shall be rigid wood or metal. The Plastilina #1 clay shall be worked into the fixture with as few voids as possible.

5.3.3 Test methods for penetration and backface signature (P-BFS)

Each body armor sample must successfully complete a two-part performance test series. The first test series, P-BFS, is designed to measure the overall ballistic performance of the armor according to pass/fail criteria. For the second test series, no pass/fail criteria are attached, but baseline BL determination is a test to penetrate failure and is designed to statistically measure penetration performance.

5.3.4 Ballistic penetration and backface signature test

All vest and plate armor models will undergo a series of ballistic impact tests using the bullet threats specified in Table 5.1. The tests measure two backface signatures (BFS) and record armor's pass/fail bullet capability. This test series requires the use of Plastilina #1 (clay backing material) deforming witness media held in direct contact with the back surface of the armor panel. The configuration is used to measure the BFS depression produced in the backing clay material during non-perforating threat round impacts.

5.3.5 Weight

The test weapons shall be ANSI/SAAMI unvented velocity test barrel mounted in an ANSI/SAAMI Universal Receiver. No commercial firearms will be used.

5.3.6 Velocity measurement

Velocities of bullets during testing will be determined using two independent sets of chronographs and an average velocity will be recorded as velocity of the bullet. The first chronograph start trigger screen will be placed a minimum of 2 meters from the muzzle of the test barrel, as shown in Fig. 5.1.

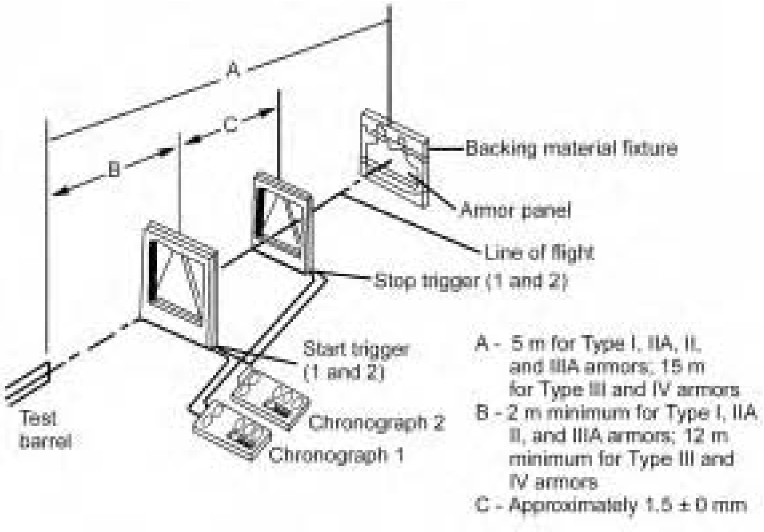
5.3.7 Sample conditioning

The vest samples for NIJ Level I, IIA, II and IIA will be tested after 12 hours storage at test range conditions (21 °C, 50% RH) and also in wet conditions as specified by NIJ Standard 0101.04.

Table 5.1 NIJ Standard 0101.04 P-BFS performance test summary

Armor type	Test round	Test bullet	Bullet weight	Reference velocity (± 30 ft/s)	Hits per armor part at 0° angle of incidence	BFS depth maximum	Hits per armor part at 30° angle of incidence	Shots per panel	Shots per sample	Shots per threat	Total shots required
I	1	.22 caliber LR LRN	2.6 g 40 gr	329 m/s (1080 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	.380 ACP FMJ RN	6.2 g 95 gr	322 m/s (1055 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
IIA	1	9 mm FMJ RN	8.0 g 124 gr	341 m/s (1120 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	40 S&W FMJ	11.7 g 180 gr	322 m/s (1055 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
II	1	9 mm FMJ RN	8.0 g 124 gr	367 m/s (1205 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	357 Mag JSP	10.2 g 158 gr	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
IIIA	1	9 mm FMJ RN	8.2 g 124 gr	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	44 Mag JHP	15.6 g 240 gr	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
III	1	7.62 mm NATO FMJ	9.6 g 148 gr	838 m/s (2780 ft/s)	6	44 mm (1.73 in)	0	6	12	12	12
IV	1	.30 caliber M2 AP	10.8 g 166 gr	869 m/s (2880 ft/s)	1	44 mm (1.73 in)	0	1	2	2	2
Special	*	*	*	*	*	44 mm (1.73 in)	*	*	*	*	*

Panel = Front or back component of typical armor sample; Sample = Full armor garment, including all component panels (F and R); Threat = Test ammunition round by caliber



5.1 Ballistic test set-up.

5.3.8 Backing material conditioning

The Plastilina #1 (clay) will be conditioned for at least three hours at temperature above 29 °C. The Plastilina #1 will be calibrated by dropping a steel ball, diameter 63.5 mm, weighing 1043 gm from a height of 2 meters. Average of five-drop depression should be 20 mm ± 3 mm.

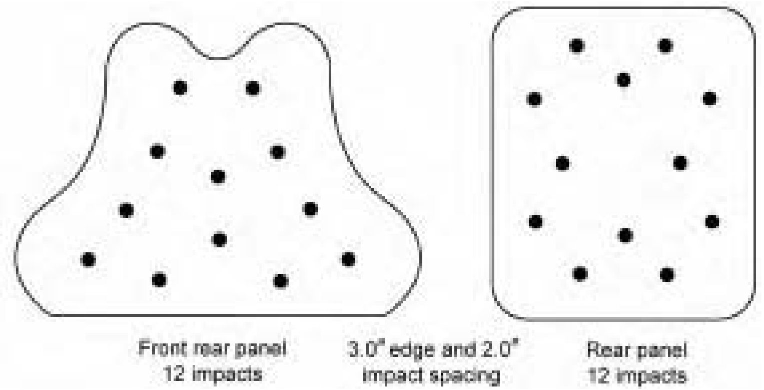
5.3.9 Testing of vest

Select the right bullet for testing and warm up the barrel by firing a few bullets. The vest will be strapped on the backing material fixture with 51 mm wide elastic straps and Velcro.

Bullet firing on vest

Four complete armor samples consisting of either a front and back set or full vest will be tested with six fair hit bullet impacts per vest. Figure 5.2 shows impact location. In all, 48 total bullets will be fired to complete the test. No bullet should pass through the vest sample. Similarly for backface deformation, a total of 16 measurements at normal obliquity will be recorded and no depth should be greater than 44 mm.

Tests on vests are also conducted at a 30° angle of incidence and under wet conditions.



5.2 Ballistic vest bullet shot pattern.

5.3.10 Ballistic limit calculations

For Level I, IIA, II, and IIIA a minimum of 12 data points are required, including five partial and five complete penetrations. However, for molded Level III and IV armor a minimum of six data points are required, consisting of three partial and three complete penetrations. Any special testing may require additional partial and complete penetration set of data points.

5.3.11 Test report

A test report will be submitted within 10 days to the NIJ CTP office reporting the outcome of testing with other related documents.

5.4 PSDB ballistic body armor standard

The PSDB ballistic body armor standard describes a test method of assessing the protection offered by commercial body armor systems against firearm threats to the United Kingdom police force.

5.4.1 General requirements

The body armor system should provide protection to vital organs such as heart, liver, spine, kidneys and spleen against bullet penetration and blunt trauma effects of the bullet while providing minimum body movement restrictions.

The ballistic insert should be removable. Similarly, a separate trauma pack must be used with the ballistic pack to meet the trauma level.

5.4.2 Other requirements

The standard covers details about both dry test and wet (after submerging for an hour) test.

Mounting of armor

For ballistic testing the body armor is placed vertically on the open face of a tray 420 mm × 350 mm × 100 mm filled with void free Roma Plastilina No. 1. The clay block is calibrated using a steel cylinder with hemispherical end.

Type of threat class, weapon, ammunition, bullet weight, firing range and velocity

These features are detailed in Table 5.2. The minimum range for HG1 and HG2 armor shall be 5 meters, and for rifle and shotgun shall be 10 meters. Shot positions are described in the test standard. Shots 1, 2, 3 and 6 will be at 90° and shots 4 and 5 will be at 60°.

Trauma limit

The maximum trauma permissible is 25 mm.

Table 5.2 Type of threat class

Threat class	Caliber	Ammunition	Bullet weight	Velocity (m/s)
HG-1 Low handgun	9 mm	9 mm FMJ Dynamit Nobel	8.0 g (124 gr)	360 ± 10
	0.357″ Magnum	Norma Soft point flat nose	10.2 g (158 gr)	385 ± 10
HG-2 High handgun/ Carbine	9 mm	9 mm FMJ Dynamit Nobel	8.0 g (124 gr)	425 ± 10
	0.357″ Magnum	Norma Soft point flat nose	10.2 g (158 gr)	450 ± 10
	0.44″ Magnum	Remington Soft point flat nose	15.6 g (240 gr)	440 ± 10
RF1 Rifle	7.62 mm	Royal Ordnance Nato ball	9.3 g (144 gr)	830 ± 15
SG1 Shotgun	Shotgun 12 gauge	Winchester 1 oz Rifled lead slug	28.4 g (437 gr)	435 ± 25

Performance assessment

For a body armor to pass the test as per the velocities shown above, no bullet should penetrate the armor and trauma shall be less than 25 mm. If tested with rigid panels, no part of the panel, metal or ceramic may be found in the Plastilina.

Results presentation

A detailed report will cover the test shot velocity, a pass/fail result and indentation depth for each shot.

5.5 NATO standardization agreement, STANAG 2920, ballistic test method for personal armors

5.5.1 Aim

The aim of this agreement is to standardize guidelines for determining the ballistic limit protection (BLP) of body armor, helmets and the materials used in manufacturing of these items.

5.5.2 General

The agreement is intended to cover testing and comparison of ballistic materials with small arms bullets or fragment simulating projectiles.

5.5.3 Test equipment

Barrel size

The projectile may be any bullet against which protection is required. However, for fragment protection, fragment simulated projectiles (FSP) are defined in US MIL-P-46593. The 5.385 mm caliber FSP A3/6723/1 (1.02 g) is preferred. An obturator skirt around the base of the projectile is recommended when shot from a rifled barrel of the same caliber as the projectile.

Velocity range

The mean velocity shall be within 80 m/s on either side of the expected ballistic limit by controlling the velocity within ±15 m/s.

Firing barrel

Bullets will be fired from the same diameter barrel as a rifle barrel. FSP may be fired either from smooth bore barrels or with the aid of a sabot.

Timing system

The timing system will consist of two chronographs. Air drag will be corrected to the velocity measured by chronographs.

Yaw card

A stiff material (such as cardboard) shall be used to check the uniformity of the circular size hole after shooting on the stiff measuring material.

Armor size and clamping

The armor materials shall be specified to the maximum extent for each material and shall be firmly bolted or clamped to a rigid framework in such a manner that the projectile will hit perpendicular to the armor surface. There shall be no backing support to the armor within 30 mm of any point of contact.

Witness system

The witness system consists of a 0.5 mm thick aluminum alloy sheet which is placed behind the armor at a distance of 15 cm.

5.5.4 Method of testing

Material conditioning

The armor material will be conditioned at 20 ± 2 °C and relative humidity of 65 ± 5% in accordance with ISO 554-1976.

Number of impacts

At least six projectiles shall be fired at the armor and their velocity shall be measured. Only fair shots will be included which hit the armor at an incident angle of less than 5° to the normal. The impact shall occur at a distance of more than 30 mm from the clamping or support points, edge, previous impact or deformation or disturbance of the material. On woven textile, no two shots shall be fired on the same yarn.

Complete and partials

Any projectile which passes through the target or perforates the witness system shall be considered a complete penetration. All other impacts shall be partial penetrations.

Ballistic limit V_{50}

The V_{50} ballistic limit for a material or armor is defined as that velocity for which the probability of penetration of the chosen projectiles is exactly 0.5. This will be achieved by an up and down firing method by changing the quantity of propellant to generate an increase or decrease in velocity of 30 m/s.

The number of shots per V_{50} shall be the three highest complete and partial set of velocity within ±40 m/s, or five highest complete and partial set of velocity within ±50 m/s, or seven highest complete and partial set of velocity within ±60 m/s.

5.5.5 Test report

A report will be prepared for the test or series of tests which must include several items. The items such as full description of material, its areal density, the thickness, identity of bullet or FSP, V_{50}, highest partial penetration velocity and lowest complete penetration velocities, and the velocity spread used in computing the V_{50} BL (P).

5.6 International standard, ISO/FDIS 14876 (draft): protective clothing – body armor

ISO (International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies).

ISO 14876-1 test Standard consists of following parts:

Part 1: General requirements
Part 2: Bullet resistance – Requirements and test methods
Part 3: Knife stab resistance – Requirements and test methods
Part 4: Needle and spike stab resistance – Requirements and test methods

This chapter will cover the summary of bullet resistance for vests only.

5.6.1 Introduction

It should be recognized that no body armor can provide complete protection from injury in all situations. However, it has been found that the incidence and severity of injuries is reduced by appropriate body armor.

5.6.2 Scope

The European Standard specifies that general requirements for body armor include the designations of types of body armor, the sizing, coverage, ergonomic and innocuousness requirement, the requirements for labeling the information. It provides test methods for body armor for torso protection.

5.6.3 Types of body armor

Body armor shall be classified into the following types:

- Type A
  The vest not protecting the top of the shoulder, and not overlapping at the sides of the torso. The lower edge is intended to be less than 70 mm above the top of the pelvic bones. Type A is only covert body armor.
- Type B
  The vest is not protective over the top of the shoulder, but closed or with an adequate overlap at the side of the torso. The lower edge is intended to be less than 20 mm above the top of the pelvic bones. Type B is normally covert, but may also be overt body armor.
- Type C
  The vest provides protection over the shoulder. Closed or with an adequate overlap at the side of the torso. The lower edge is intended to be less than 20 mm above the top of the pelvic bones (overt).
- Type D
  Similar to Type C, but lower edge is intended to be more than 40 mm below the top of the pelvic bones (overt).
- Type E
  It is a pelvic protector attached to another type of armor.
- Type F
  It is an optional collar to attach to another type of armor.
- Type G
  Type G are the armor molded plates, single or multiple, which are intended to provide a higher level of protection when worn with an appropriate Type A, B, C or D vest.

5.6.4 Size designation

Body armor sizes shall be designated to EN 340. Body armor dimensions and sizes shall be based on at least three control body dimensions for male users and four dimensions for female uses.

5.6.5 Restraints

Body armor marked with a size range shall have adjustment means that allow more than 50 mm adjustment at each side of the torso, or 100 mm in a single central adjuster. Made to measure body armor shall have at least 25 mm or 50 mm of adjustment at these points.

Body armor shall not slide up the body pinning the arms, nor shall it have a hard edge pressing on the throat or chin when a force is applied vertically upwards to a clamp attachment to the back of the neck of the garment.

Modular inserts

Inserts such as molded armor plates shall be securely attached to the body armor or contained within closed pockets in the armor carrier. The plates shall not be separated from the body armor or pulled out of pockets.

5.6.6 Ergonomic requirements

Body armor shall be designed to minimize discomfort in use. Hard edges and rough surfaces shall not contact the user during normal movements. Head, arm, torso and leg movement shall not be unduly restricted. Consideration should be made for severe thermal discomfort and the accumulation of sweat.

5.6.7 Test methods and procedures

Measuring instruments shall have error of ±2% of the pass/fail level of the characteristic being measured.

Ergonomic testing

Three sizes of each model of body armor designated for men and for women shall be supplied for ergonomics testing. The sizes shall be chosen from the smaller, medium, and large parts of the available size range.

Preconditioning of body armor

Body armor shall be cleaned five times by the method(s) specified by the vest manufacturer. Body armor will be thoroughly dried between cleaning cycles.

Penetration resistance and indentation depth

No bullet penetration will occur for any acceptable shot within an accepted sequence. The indentation depth shall not exceed 44 mm for any accepted shots except for those on the breast cups on body armor for female users for which no measurement of the indentation depth is required.

5.6.8 Performance level

Complete testing at each performance level shall be carried out with all the cartridges listed in Table 5.3 for that performance level.

5.6.9 Test specimen support frame

The backing material boxes shall contain a framework. Straps shall also be provided holding the sample on the backing material. During ballistic testing,

Table 5.3 Bullet and cartridge specification

Performance level	Ammunition	Bullet mass (g)	Bullet velocity (m/s)
1	9 × 19 mm, full metal steel jacket	8.0 ± 0.2	360 ± 10
2	9 × 19 mm, full metal steel jacket	8.0 ± 0.2	415 ± 10
3	9 × 19 mm, full steel metal jacket	8.0 ± 0.2	425 ± 10
	.357 Magnum, full metal jacket (conned bullet)	10.2 ± 0.2	430 ± 10
4	5.56 × 45 mm, M193	3.6 ± 0.2	970 ± 15
	7.62 × 51 mm, NATO Ball	9.4 ± 0.2	830 ± 15
5	7.62 × 51 mm, AP Hardened steel core	9.7 ± 0.2	820 ± 15
S	12/70 gauge, Brenneke solid lead slug	32.0 ± 0.5	425 ± 10

the straps shall be positioned for each shot so that the edges of straps are more than 50 mm from the point of impact.

5.6.10 Backing material

Backing material shall be stiff, oil and mineral powder modeling clay (Roma Plastilina No. 1). Backing material shall be replaced either after 1000 impacts or as soon as it becomes contaminated, or within two years of first use, whichever is the shorter period.

The consistency of the clay shall be measured by dropping steel ball impacts and measuring the depth on the clay.

5.6.11 Backing restoring during testing

Before second and subsequent impacts the backing material shall be restored to its initial condition. The test specimen shall be repositioned and flattened against the backing material. The test sample shall be restored as nearly as practical to its previous state, ensuring the layers are smoothed as flat as possible and are positioned relative to one another and to the carrier as in the original body armor.

5.6.12 Positions of bullet impact

Impact of bullets on the body armor mounted on the clay frame shall meet the following criteria:

- All impact positions shall be within the marked test area.
- All impact positions shall be more than 50 mm from an edge of the backing material box.

- All impact positions shall be more than 50 mm from the edge of a strap.
- Third and subsequent impact positions shall lie more than 10 mm from every straight line passing through any two previous impact positions.
- Performance level 1, 2, 3 impact positions of shot normal to the armor shall be:
  - More than 75 mm from the previous impact shot.
  - More than 75 mm from any previous impact of an angled shot.
  - More than 200 mm beyond any previous impact.
- Performance level 1, 2 and 3 impact positions of shot angled at 60° to the armor shall be:
  - More than 75 mm from the previous impact shot.
  - More than 75 mm from any previous impact of an angled shot.
  - More than 200 mm beyond any previous impact.

5.6.13 Wet performance

Body armor sealed in a waterproof container shall be immersed upright in deionized or distilled water at 15 °C to 20 °C for 60 ± 5 minutes. Test specimen shall be hung and drained for 3 ± 0.5 minutes and tested within 30 minutes.

5.6.14 Test report

The test report shall contain at least the following:

- The test sample source, identification, name or code, type, sizes supplied, batch number or equivalent and dates of manufacturing.
- The performance level(s) of testing required.
- Any additional projectiles to be included and optional tests requested.
- The date of testing and a list of tests performed.

5.7 NIJ standard, 0106.01 for ballistic helmets

The standard was last revised in December 1981. NIJ is working on a new draft. The standard establishes performance requirements and a method of ballistic testing for helmets intended for law enforcement and other agencies against handgun bullets.

5.7.1 Types of protection level

Ballistic helmets covered in this standard are classified into three types by the level of handgun protection.

Type I (22LR-38 Special)

This is the lowest level ballistic threat protection.

Type IIA

The helmet protects against lower velocity handgun bullets fired from a 357 Magnum and 9 mm FMJ gun barrel.

Type II

The helmet protects against higher speed bullets fired from a long rifle capable of firing higher speed bullets fired from 357 Magnum or 9 mm FMJ bullet.

Special type

The buyer can specify changes in the bullets for a specific situation.

In comparison to NIJ Standard 0101.04, there is no Level IIIA, III and IV standard for testing helmets. It is possible to have Level IIIA (stopping higher velocity 357 Magnum and 44 Magnum), Level III (rifle bullet protection) and Level IV (armor-piercing bullets) helmets. However, the human neck has limited rigidity and may not be able to withstand the whiplash from any of the bullets with higher kinetic energy than 100 Joules.

5.7.2 Sampling and test method

Three helmets, size 7¼ and selected random sizes, shall constitute a test sample. Some of the bullets may be hand-loaded to achieve velocities of bullets mentioned below in Table 5.4. Each submitted sample of complete helmets for Type classification will be tested as per the velocity suggested in Table 5.4.

5.7.3 Head forms

Bullet firing at vest

Each penetration test head form shall be size 7¼ and shall have the dimensions shown in the Fig. 5.3. The sagittal penetration type shall be so modified that it can rigidly hold a witness plate in the coronal plane. Conversely, the coronal penetration type shall be able to hold a witness plate in the sagittal plane. Both coronal and sagittal are shown in Fig. 5.3.

The witness plate shall be 0.5 mm (0.020 inches) thick, and shall be made of type 2024-T3 or 2024-T4 aluminum alloy.

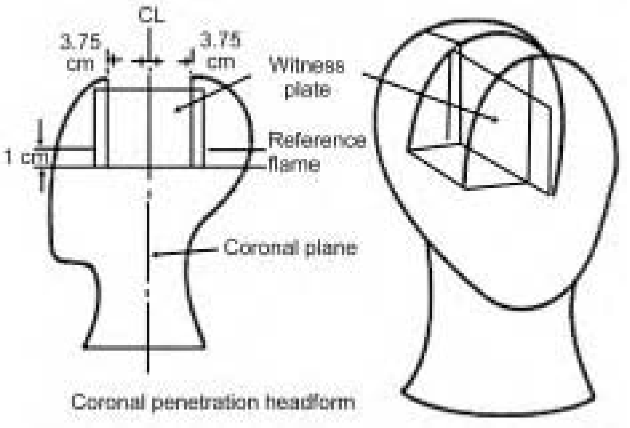
Impact test head form

The impact head form made with magnesium alloy or other suitable material, recommended in the test standard NIJ Standard 0106.01, is to record human

Table 5.4 Test summary

		Test variables		Performance requirements	
Helmet type	Test bullet	bullet mass	Nominal bullet velocity	Required fair hits per helmet	Required part penetration
I	22 LRHV Lead	2.6 g 40 gr	320 ± 12 m/s 1050 ± 40ft/s	4	0
	38 Special RN Lead	10.2 g 158 gr	259 ± 15 m/s 850 ± 50 ft/s	4	0
IIA	357 Magnum JSP	10.2 g 158 gr	381 ± 15 m/s 1250 ± 50 ft/s	4	0
	9 mm FMJ	8.0 g 124 gr	332 ± 15 m/s 1090 ± 50 ft/s	4	0
II	357 Magnum JSP	10.2 g 158 gr	425 ± 15 m/s 1395 ± 50 ft/s	4	0
	9 mm FMJ	8.0 124 gr	358 ± 15 m/s 1175 ± 50 ft/s	4	0

Abbreviations: FMJ = Full metal jacketed,
JSP = Jacketed soft point,
LRHV = Long rifle high velocity,
RN = Round nose



5.3 Head form.

head acceleration when hit by a bullet. However, due to a number of factors, currently no lab in the US is equipped to conduct this test.

5.7.4 Ballistic penetration test

Test set up is arranged as described below. The velocity measuring trigger devices are placed at a distance shown in Fig. 5.1. Fire a pre-test bullet to verify line of bullet flight.

Insert a witness plate in the sagittal penetration test head form, place the helmet under test on the head form and secure it firmly by the chin strap or by other means which will not interfere with the test. Place the helmeted head form with the desired point of bullet impact and check if helmet will be hit at 90º to the helmet surface.

Fire the first bullet in the front of the helmet. The bullet should hit no more than 90 mm (3.5 inches) above the basic plane and no more than 50 mm (2 inches) from the mid-sagitted plane. Record the velocity of the bullet. Examine the helmet and the witness plate to determine whether penetration occurred when the bullet hit at predetermined spot on the helmet. If no penetration occurred, place the helmet on the coronal penetration test head form and shoot it once on each of the four sides no more than 50 mm (2 inches) above the basic plane and no more than 75 mm (3 inches) from the coronal plane. If no penetration occurs, repeat test on a second helmet, which is preconditioned by immersion for 2 to 4 hours in water at 25 ± 5 ºC (77 ± 9 ºF).

Test reports should record details of the test helmets such as shape, size, and weight. And also the type of bullet, speed of bullet, area it has hit on the helmet and if all the bullets were stopped during the test.

5.8 Vehicle armor

The ballistic materials used by armored vehicles have similarities with the hard molded armor being used by military personnel for body armor. Therefore there are instances where the US military in Iraq has used armor material specified for one particular situation in an entirely different situation.

As materials are evolving and getting lighter, the test standards and specifications are also evolving. However, some of the vehicle armor standard written for molded panels of woven aramid prepreg materials (when only lightweight materials were based on aramid fibers) can be used for new materials. This is achieved by fine tuning the fabrication process based on chemistry of reinforcing fibers and prepreg resin.

Autoclaves and high-pressure match die molding are widely used for molding large and small hard panels irrespective of the ballistic raw material.

5.9 National Institute of Justice, NIJ 0108 – ballistic resistant protective materials

A number of lightweight ballistic armor materials are now available that are designed to protect against small-caliber handguns and high-powered rifles. This includes hand-held riot shields, armored clipboards used by police, armored

Table 5.5 Hard armor classification

Armor type	Test ammunition	Bullet mass** gram (grain)	Barrel length	Bullet velocity Fps (mps)
I	22 LRHV Lead	2.6 g (40 gr)	15–16.5 cm (6–6.5 in)	320 ± 12 m/s 1050 ± 40 ft/s
	38 Special RN Lead	10.2 g (158 gr)	15–16.5 cm (6–6.5 in)	320 ± 12 m/s 1050 ± 40 ft/s
IIA	357 Magnum JSP	10.2 g (158 gr)	10–12 cm (4–4.75 in)	381 ± 15 m/s 1250 ± 50 ft/s
	9 mm FMJ	8.0 g (124 gr)	10–12 cm (4–4.75 in)	332 ± 12 m/s 1250 ± 40 ft/s
II	357 Magnum JSP	10.2 g (158 gr)	15–16.5 cm (6–6.5 in)	425 ± 15 m/s 1395 ± 50 ft/s
	9 mm FMJ	8.0 g (124 gr)	15–16.5 cm (6–6.5 in)	358 ± 12 m/s 1175 ± 40 ft/s
IIIA	44 Magnum SWC	15.55 g (240 gr)	14–16 cm (5.5–6.25 in)	426 ± 15 m/s 1400 ± 50 ft/s
	9 mm FMJ	8.0 g (124 gr)	24–26 cm (9.5–10.25 in)	426 ± 15 m/s 1400 ± 50 ft/s
IV	7.62 mm 308 Winchester FMJ	9.7 g (150 gr)	56 cm (22 in)	838 ± 15 m/s 2750 ± 50 ft/s
V	30-06 AP	10.8 g (166 gr)	56 cm (22 in)	868 ± 15 m/s 2850 ± 50 ft/s
Special	As specified	As specified	As specified	As specified

** Five bullets per test for Type I, Type IIA, Type II, Type IIIA and Type IV except one bullet for Type V armor.

Abbreviations

AP	Armor piercing
FMJ	Full metal jacket
JSP	Jacketed soft point
LRHV	Long rifle high velocity
RN	Round nose
SWC	Semi-wadcutter

buildings for security guards, police checkposts and temporary housing for military and peacekeepers and occupants of a vehicle.

Such armored materials can be fabricated by metals, ceramics, transparent glazing, fabrics, felts and fiber-reinforced composites.

5.9.1 Classification

Ballistic-resistant protective materials covered by this standard are classified into the following types by level of ballistic performance:

- Type I (22 I.R; 38 Special)
- Type IIA (9 mm FMJ, 357 Magnum)
- Type II (9 mm FMJ, 357 Magnum)
- Type IIIA (9 mm FMJ, 44 Magnum)
- Type III (M80 ball)
- Type IV (30-06 AP)
- Type Special

(See Table 5.5.)

5.9.2 Ballistic testing of armor

Once the proper test weapon is supported, leveled and positioned, fire a few pre-test rounds through the witness plate to determine the point of impact.

Place the test armor specimen 5 m (16 ft) from the test weapon in the support fixture. Then place a witness plate 15 cm (6 inch) beyond the test specimen. Fire the first round and record the velocity of the bullet as measured by the chronograph. Examine the witness plate to determine penetration, and examine the specimen to see if the bullet made a fair hit.

If no penetration occurred, reposition the test specimen and repeat the procedure with additional test rounds until the test is complete. Space the bullet hits as evenly as possible so that every portion of the test specimen is subjected to test.

SPECIFICATIONS

5.10 Multiple threat body armor 'Interceptor'

The Interceptor is a multiple threat body armor system consisting of a base vest and modular components for tailoring protection level to defeat multiple hazards across the battlefield continuum and manage armor weight. Interceptor is functionally integrated with Modular Lightweight Load Equipment (MOLLE).

5.10.1 Components

- Base vest
- Collar
- Throat protector
- Groin protector
- Small Arms Protective Inserts (SAPI)

5.10.2 Sizes

X-Small, Small, Medium, Large and X-Large. Throat protector has one size only.

5.10.3 Salient features

Ballistic protection level

Interceptor provides protection from multi-hit from a variety of fragments, handgun bullets and rifle bullets.

- NATO 7.62 x 51 mm M-80 Ball
- Soviet 7.62 mm x 54 R Ball Type LPS
- US 5.56 mm M855 Ball

Functional integration

All Interceptor components shall be integrated for functional and physical interface for any Interceptor system configuration. All components within a size shall be fully interchangeable, with every other system of the same size with no degradation of performance.

Removal and insertion of inserts

Molded ballistic inserts (SAPI) must be able to be inserted easily into the vest carrier and groin protector. The gap/ease between carrier and insert shall be no greater than the ease allowed within the baseline pattern.

Donn/doffing

The Interceptor system shall be easily configured, donned, and adjusted to fit within 30 seconds (maximum) required/15 seconds by the wearer, unassisted.

Collar donn/doff

The collar shall not be readily removed during troop movement. The collar attachment shall be easy yet require a dedicated act to attach and detach. The

Table 5.6 Finished coverage and weight

Finished component	Area coverage (sq. in. (min))	Weight (lb (max))
Base vest and collar	755	8.50
Throat protector	18	0.25
Groin protector	70	0.70

collar remains secure when attached to stay in position when worn and when the vest is carried by the neck edge and/or collar.

5.10.4 Coverage and weight (size medium)

See Table 5.6 for details of coverage and weight

5.10.5 Environmental conditions

All Interceptor materials forming the Interceptor system shall be functional and durable in all climate categories during day and night. No parts of the system shall show degradation of performance requirements specified in the Interceptor document. Climates include hot-dry, hot-humid, constant high humidity, variable humidity, basic hot, basic cold, cold, severe cold, and fungus resistance.

Wet conditions

Seawater shall be utilized for wet test conditions. The ballistic material will be completely submerged in seawater kept at 70 ± 5 ºF for 24 hours. Excess water will be drained from the specimen by hanging vertically for 60 seconds and tested within 5 minutes.

Accelerated aging

The ballistic samples are exposed to a 100% oxygen atmosphere and kept in a chamber at 300 ± 10 psi for 16–96 hours. Visual inspection should not show appreciable change to the original state of the sample.

Industrial fluid contamination

The ballistic material system specimen shall be submerged in each of the following fluids: motor oil, gasoline, weapon lubricants for 24 hours at room temperature. The specimen shall be hung vertically to drip dry for three minutes, excess oil shall be wiped from the surface to facilitate handling and the specimen shall be immediately ballistically tested.

Other requirements

Service life

The system shall have a service life of 10 years of continuous use in all types of typical field use if not hit by ballistic projectiles and 15 years including intermittant storage periods from one month to five years maximum duration.

Reliability

The Interceptor system shows no operational mission failure in 120 continuous days of use. All repairs required within the first two years of continuous use must be accomplished by the individual.

Camouflage

The camouflage will be for multi-terrain environments to reduce visual and infrared (both near and far IR) signatures to an acceptable level.

Abrasion resistance

Any adjacent layers within the ballistic material system shall demonstrate abrasion resistance against each other for a minimum of 2000 cycles with no broken surface characteristic or delamination of the abraded area.

5.11 Small Arms Protective Inserts (SAPI)

The Small Arms Protective Inserts (SAPI) are armor plates that when inserted into the Interceptor Outer Tactical Vest (OTV) (fragment protective vest) provide protection from certain high power rifle bullets. The SAPI is part of a protective system, which includes a soft fragmentation and handgun tactical vest. The SAPI is used in conjunction with the soft under garment as a total armor.

5.11.1 SAPI construction

The SAPI shall consist of double curvature monolithic high performance ceramic (silicon carbide or boron carbide) glued with molded layers of SPECTRA Shield PCR layers on the back of the ceramic. The backing material is molded to the same curvature as the monolithic ceramic.

5.11.2 SAPI molding process

The monolithic ceramics for SAPI have the factory finished double curvature meeting the SAPI shape and size specification. These ceramics are used as is, or in certain cases, reinforced with fiber-reinforced composite materials. Either an autoclave or match die molding process is used to consolidate the layers of SPECTRA Shield which contain a thermoplastic resin.

An adhesive is used to glue the ceramic with the consolidated layers of SPECTRA Shield.

5.11.3 Weight

All SAPI sizes will have a finished uniform nominal areal density.

5.11.4 Thickness

All SAPI will have uniform thickness throughout the entire plate surface.

5.12 Pacific rim countries breastplates

The ballistic hard armor inserts or hard armor plates when inserted into the Small Arms Protective outer vest shall provide protection from certain high power rifle bullets. The specification lists the minimum performance of hard armor plates.

5.12.1 Shape of the breastplates

The front breastplate will be curved. However, the back plate could be flat or curved. Both the front and back plates are to be marked clearly.

5.12.2 Size of plates

The front and back plates shall be 300 mm × 250 mm.

5.12.3 Thickness of plates

The plates shall have uniform thickness of 18 mm maximum.

5.12.4 Weight of each plate

Weight of each finished plate shall not exceed 1.6 kg.

5.12.5 Ballistic threat

The ballistic plates shall defeat multiple strikes from a variety of handgun and rifle bullets.

5.12.6 First article

Before the contractor starts production, six pre-production samples representing the production lot of breastplates will be used for qualification.

5.12.7 Ballistic testing

The testing will be carried out by an independent ballistic lab authorized by the contracting authority either in the country or outside the country.

Three to five sets of breastplates are tested from each lot of breastplates. Any failure from a particular batch will result in rejecting the entire batch.

5.13 European vest

European military vests are designed for a number of operations which the military may have to undertake. The operations could be a military conflict in European or African or Asian countries, or conflict in desert areas, or a peacekeeping mission under UN, or a Red Cross-type mission. For each operation, the military requires a different camouflage color vest.

5.13.1 Type of military vest

- Military green Camouflage
- Desert color Camouflage
- UN Blue
- Red cross white.

5.13.2 Size of vest

Three sizes of vest shall be procured: Small, Medium, and Large.

5.13.3 Outer jacket

The flexible vest shall consist of water resistant cotton-polyester fabric.

5.13.4 Ballistic threat

For a 9 mm copper covered lead bullet fired at 430 m/s deformation on clay backing should be less than 30 mm.

5.13.5 Ballistic layers

The ballistic materials layers will consist of water repellent treated woven aramid fabric consisting of 1100 dtex, weighing 190 gsm. The ballistic layers shall be quilted at an angle. The grid size is generally specified. Each flexible vest shall have pockets for hard armor molded plates to defeat rifle bullets.

5.13.6 Number of plates

As many as five molded plates per ballistic kit.

5.13.7 Size of hard armor plates

- Curved front plate, size 250 mm × 300 mm
- Flat back plate, 300 mm × 250 mm
- Groin plate 150 mm × 250 mm
- Collar plate 200 mm × 165 mm.

5.13.8 Areal density of ballistic kit

Areal density of the plates shall be uniform in the range of 17 to 20 kg/sq.m.

5.13.9 Thickness

The thickness of molded plates of the kit shall not to exceed 22 mm.

5.13.10 Ballistic threats for hard molded plates

Table 5.7 provides the details for testing each component of the soft vest and inserted molded plates.

5.13.11 Marking

Each vest shall have proper marking showing the size, washing and other instructions related to the maintenance of the vest.

5.14 Asian ballistic vest

For a number of years South Asian countries were buying ballistic vests from outside the country, mainly from the UK. However, some of the countries have started manufacturing such vests in their own countries. Only raw materials are bought from outside countries for the flexible vest. Molded hard armor plates are generally bought from outside the country.

The following summary is based on the key features of the specifications.

Table 5.7 Ballistic threats and deformation for European military vest

Configuration	Bullet caliber	Velocity of bullet (mps)	Distance from barrel (m)	Stopped bullet location	Maximum deformation
Soft vest	9 mm	430	7.65	Soft vest	30 mm
Front molded plate + soft vest	7.62 mm	865	7.65	Molded plate	30 mm
Front molded plate + soft vest	5.56	1000	7.65	Molded plate	30 mm
Back molded plate + soft vest	7.62	865	7.65	Molded plate	30 mm
Back molded plate + soft vest	5.56	1000	7.65	Molded plate	30 mm
Molded pelvic plate + soft vest	7.62	865	7.65	Molded plate	No measurement
Molded collar	7.62	865	7.65	Molded plate	No measurement

5.14.1 Ballistic threats for breastplates

- NATO 7.62 mm ball ammunition fired on the vest from a distance of 10 meters.
- AK 47 bullet with mild steel core fired from 10 meter range.

5.14.2 Size of plate

305 mm × 254 mm.

5.14.3 Number of plates per vest

Curved plate, one in the front and one in the back.

5.14.4 Ballistic material of the plates

High modulus polyethylene fiber molded into hard molded panels.

5.14.5 Weight of each hard armor plate

- 1.5 kg maximum
- Collar
- Groin
- Shoulders.

5.14.6 Total area of coverage

The body coverage area to be covered by flexible vest, including front and back, shall not be less than 0.55 sq.m.

5.14.7 Sizes

Two sizes: Medium and Large.

5.14.8 Outer cover for the flexible vest

High strength heavy-duty nylon coated with water repellent resin.

5.14.9 Ballistic material for flexible vest

Layers of plain weave-woven aramid fabric treated with water repellent. Quilting is required to reduce the material bulging during ballistic testing.

5.14.10 Ballistic performance

The flexible vest will be tested as per the NIJ Standard NIJ 0101.04 against 9 mm bullets at a velocity of 430 mps.

5.14.11 Trauma material

Trauma material is allowed in the flexible vest to reduce the backface trauma.

5.14.12 Trauma limit

Twenty-five mm trauma on the Plastilina when tested as per the NIJ 0101.04.

5.14.13 Total weight of soft and hard armor per vest

Total weight of flexible and hard armor should not exceed 6.3 kg for a Medium vest and 6.6 kg for a Large vest.

5.14.14 Other features

Minimum life of the vest shall be 10 years. Both flexible vest and hard molded plate should maintain ballistic performance at:

- −50 °C to +50 °C.
- Humid and hot atmosphere of 95% humidity and 40 °C temperature.

5.15 Military helmet specifications

MIL-H-44099A, title Military Specification: Helmet, Ground Troops and Parachutists. This specification was released on December 22, 1986, superseding MIL-H-44099, dated March 23, 1983. Millions of helmets made for the Department of Defense in the US and around the world followed this specification as it is, and also in modified versions. The PASGT (Personnel Armor System Ground Troop) shape of helmet used to meet this specification was adopted by a number of countries such as France, Brazil, Taiwan, and Saudi Arabia.

The specification is a detailed document covering the manufacturing and testing of the military helmets. Only the specification part relating to lightweight composite helmets will be covered in this chapter. Other parts of the specification, such as suspension assembly, head band and chin strap, first article test and packing will not be covered in this summary of the military helmet specification.

5.15.1 Sizes of helmets

The helmet assembly shall be one type in the following sizes: X-Small, Small, Medium, and Large.

5.15.2 Helmet shell

Helmet shell material

The helmet shell material will be aramid ballistic cloth conforming to MIL-C-44050 coated with catalyzed system composed of 50% phenol formaldehyde and 50% polyvinyl resin. The resin shall be pigmented to match the military green color. The resin content of the coated reinforced material shall be 15% to 18% solid by weight.

Helmet shell performing

The pinwheel patterns or combination of pinwheel and rectangular patterns shall be cut from the coated aramid fabric. The individual preform layers shall be superimposed over each other such that the gaps of any two adjacent layers are offset by a minimum of half an inch. The panels shall be laid up so that there are not less than 19 layers of coated fabric, including the inner and outer pinwheel layers, throughout any cross-sectional area of the shell.

Molding of helmet shell

The helmet shell is molded in a single cycle using a match die compression mold by applying heat and pressure. The shell shall not be remolded after this molding cycle. Delamination and blisters as well as evidence of delaminations and blisters are not acceptable.

5.15.3 Finishing of helmet

The molded shell will be drilled first, followed by applying rubber edging on thoroughly cleaned and abraided edges using an adhesive. Once adhesive has dried, the outside surface of the shell will be prepared by filling any gaps and pits with epoxy resin, and then the outer surface will be thoroughly cleaned and prepared for painting. A suitable primer will be applied followed by a final coat of paint containing the texturing aggregate. Finally, suspension assembly, chin strap and head band will be installed in the helmet

5.15.4 Performance tests

The finish helmet will go through the tests listed below:

Weight

The maximum weight of the finished helmet assembly with suspension assembly and chin strap shall be as follows:

Size	Weight (ounces)
X-Small	50
Small	51
Medium	53
Large	57

Water immersion test

The helmet shall be immersed in tap water at 60 ºF to 80 ºF for 16 hours followed by air drying for 12 hours. The coating on the outside surface of the helmet shall be examined for any failure such as evidence of softening, blistering, or peeling.

Ballistic resistance test

The helmet will be stored in the test chamber for no less than 24 hours prior to testing. The helmet shall be subdivided into five clearly marked sections, a top 50 mm circle, and four equal side sections. The ballistic resistance test shall be conducted in accordance with MIL-STD-662 using .22 caliber fragments conforming to MIL-P-46593. The helmet will be rigidly mounted and a minimum of two randomly placed fair impacts, at least 37 mm apart, shall be fired in each of the five marked sections. Each impact will be normal to the line of fire.

The V_{50} ballistic limit for each helmet shall be no less than 2000 feet per second (610 mps).

5.16 MIL-L-62474B (AT): Laminate aramid-fabric-reinforced plastics

The specification was revised on June 25, 1984 for use by the US Army Tank-Automotive Command, Department of the Army, and is available for use by all Departments and Agencies of the Department of Defense.

The specification covers an aramid fabric-reinforced laminate for use in the composite armor system.

5.16.1 Classification

Laminates shall be of the type and class specified:

- Type 1 Flat
- Type 2 Molded
- Class A Yarn used, nominal 1500 Denier, 1000 filaments
- Class B Yarn used, nominal 3000 Denier, 1333 filaments.

5.16.2 Requirements

First article

The first article units are furnished for inspection and testing before the large-scale production starts. All subsequent laminates delivered to the government shall conform to these samples in all of their pertinent physical and performance attributes. Any change in the manufacturing, method of fabric weave, laminating resin or laminate construction shall require a first article.

Materials

Referenced ballistic material shall be free of defects that adversely affect performance or serviceability of the finished product.

Qualified products

The contractor shall be responsible for using materials from qualified product lists when applicable.

Aramid fabrics

- Class A laminate: woven aramid of nominal 1500 denier, 42 × 42 basket weave fabric with zero yarn twist.
- Class B laminate: woven aramid of nominal 3000 denier, 21 × 21 basket weave fabric with zero yarn twist.

The aramid fabrics for Class A and Class B will be scoured weighing 16.25 ± 0.75 oz/yd (551 ± 25 g/m), with maximum 5% moisture by weight.

Laminating resin

The resin system will be a catalyzed mixture of phenol formaldehyde and polyvinyl butyral resin. The total resin content shall be 16 to 20 weight percent solid, with moisture content less than 2%.

5.16.3 Fabrication

The laminates shall consist of a specified number of plies of resin-coated aramid fabric fabricated in a single molding step under heat and pressure.

5.16.4 Thickness and flatness variation

The thickness variation shall not be more than ±0.015 inches (0.38 mm) for type I laminate and ±0.030 inches (0.76 mm) for type II laminates. Variation from flatness panel shall not exceed 0.06 inches per foot (5.00 mm/m).

5.16.5 Weights

The areal density (1 ply = 0.127–0.152 psf, or 0.62–0.74 ksm) of the finished laminates shall fall within the range established by the standard.

5.16.6 Lamination process

The following conditions shall prevail during the lamination process:

1. (a) Type I laminates shall be molded in a press at 200 ± 10 psi (1380 ± 70 kPa).
   (b) Type II laminates shall be molded in a press at 200 ± 10 psi (1380 ± 70 kPa) or molded in an autoclave at minimum 50 psi pressure.

Molding pressure indicated above shall be maintained until the following stages have been completed:

2. Type I and II (press molded)
   (a) Press platen temperature increased to 330 ± 10 °F (166 ± 6 °C).

Table 5.8 Laminating dwell times

Laminate plies (number)	Dwell time (minutes)
1–10	30
11–20	45
21–30	60

(b) Dwell in accordance with schedule of table II with platens at 330 ± 10 °F (166 ± 6 °C).
(c) Cool down platen temperature to 180 °F (82 °C) before laminate removal.

3. Type II (Autoclave)
   (a) Autoclave temperature increase to 330 ± 10 °F (166 ± 6 °C).
   (b) Dwell in accordance with schedule of table II with platens at 330 ± 10 °F (166 ± 6 °C).
   (c) Cool down platen temperature to 150 °F (66 °C) before laminate removal.

(See Table 5.8.)

5.16.7 Finishing laminates

The finished laminates shall be sandwiched between single peel-plies that can be incorporated during the molding process. All cutting and machining of laminate panels shall be done with the peel-ply intact. Wet cutting and machining procedures shall be followed by a drying process using forced draft at 200 ± 10 °F (93 ± 6 °C). The finished laminate shall have an epoxy resin sealed surface on all cut, trimmed or drilled hole edges which is applied after the drying process. The epoxy resin shall conform to MIL-R-9300. The epoxy resin used shall have a surface temperature of no less than 250 °F (121 °C).

5.16.8 Performance of laminates

The peel-ply should be removed by hand without requiring heat or solvents.

Temperature resistance

The laminates shall not show evidence of delamination following a two-cycle exposure to a temperature range of −65 °F to 250 °F (−54 °C to 121 °C).

Ballistic resistance

The .30 caliber (44-grain) Fragment Simulating Projectile conforming to MIL-P-46593 shall be used for conducting a V_{50} protection limit test. The test shall be conducted as per the MIL-STD-662 on two separate 20 inches × 20 inches (508 mm × 508 mm) size laminates consisting of twenty-six plies each. The average V_{50} shall not be less than 2250 fps.

Workmanship

The laminate shall satisfy visual acceptance Level I of ASTM D2563 for following defects: (1) Blisters, (2) Burned, (3) Crack, (4) Crack Surface, (5) Crazing, (6) Edge Delamination (7) Internal Delamination, (8) Dry spot, (9) Lack of filling, and (10) Wrinkles. Fabric layers shall be free of tears, reasonably straight, and perpendicular wrap-to-fill.

5.17 Bibliography

International Standard, ISO/FDIS 14876-1, final draft, 2002.

Military Standard, MIL-L-62474B (AT), title ‘Laminate: Aramid-Fabric-Reinforcement, Plastics’, 25 June 1984.

Military Standard, MIL-H- 44099A, title ‘Military Specification: Helmet, Ground Troops and Parachutists’, 22 December 1986.

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6

Testing lightweight ballistic materials

D R DUNN, H P White Laboratory Inc., USA

6.1 Armor general

Armor is a protective cover. Ballistic armor, as used herein, is a cover, which is intended to protect against the impacts of kinetic energy (inert materials) projectiles. Through popular usage, stab resistant, personal armor is frequently included in the broad category of ballistic armor as are materials intended to resist penetration by wind-borne debris (hurricanes) and the accidental or maliciously intended impacts of a broad range of projectiles (rocks, birds, bricks, etc.) with high speed vehicles (aircraft, trains, etc.) and structures. Finally, ballistic resistant materials are often found in commercial application of fragmentation containment such as might occur in the disintegration of high velocity, rotary machinery and engines.

Monolithic armors are generally thought of as a single, rigid, layer of homogenous material. Composite armor is generally thought of as multiple plies of the same or differing materials, which may be either rigid or flexible in nature.

6.2 Armor penetration

The mass and impact velocity of the threat determines the kinetic energy of the threat to the armor. If the target deflects the threat, only a portion of that energy is absorbed and dissipated in the target. Similarly, if the threat completely penetrates the target and continues down range only a portion of the impact energy, proportionate to the velocity lost in penetrating the target, is absorbed and dissipated by the threat. However, if the threat remains with the target, all of its energy must be absorbed and dissipated within the target. The latter places the most severe demand on an armor's performance and how effectively the armor absorbs and dissipates that energy is the measure of its performance.

Armors are designed as a material overmatch to the material of the threat causing the threat to be broken apart or distorted upon impact, spreading the energy of the threat over an enlarged area of the target. The distorted threat must, thereby, engage an enlarged area of the target and overcome the increased resistance of the enlarged engagement area.

If the threat resists deformation and concentrates its energy on as small an area as possible, the likelihood of its successful penetration is increased.

Conversely, if the threat is destabilized and distorted, to the extent that the cumulative resistance of the area of the target engaged exceeds the energy of the threat, the target will have successfully resisted penetration. Monolithic armors present an overmatching of its face hardness with the softer material of the perceived threat to induce a maximum distortion of the threat upon impact.

The multiple plies of composite armors and tensile strength of those plies are used to distort the threat (tensile strength) and dissipate the energy of the threat over an enlarged area (multi-plies). The threat must stretch each ply to the limits of its tensile strength, before the ply will fail. Thus, as each ply is penetrated the threat becomes increasingly distorted and its energy progressively reduced.

6.3 Armor protection

Vehicular and structural armors are intended to resist penetrations and the internal damage that that penetration will produce. However, even non-penetrations of personal armor with ballistic threats may induce blunt trauma or biomechanical injuries. Today's personal armors are designed to prevent wounding from penetration and deformation (blunt trauma), but do not address the biomechanical threat. The energy of a non-penetrating ballistic impact must either be deflected and dissipated down-range or absorbed and dissipated within the target. Little definitive data is available which conclusively defines the limits of energy, which can be safely endured by the human body. In fact, the variables of the human body with respect to weight, muscle tone, general health and differing susceptibilities of differing parts of the body are infinite and do not lend themselves to standardization. In any case, personal armor testing does not adequately address problems such as brain and neck injuries from non-penetrating, helmet impacts and have only recently addressed the problems of non-penetrating blunt trauma injuries from torso (vest) impacts.

6.4 Armor testing

All performance testing is either non-destructive or destructive in nature. Non-destructive testing is generally conducted to confirm the satisfactory performance of a specific sample, which is then returned to service. Destructive testing is most often conducted with a statistically representative sampling of a larger population to establish the probability of satisfactory performance of the population from which the sampling was drawn.

The size of the test sampling (number of samples selected) is determined by two factors: the size of the parent population and the level of confidence that the performance of the test sampling accurately represents the performance of the entire population from which the sampling was drawn. This process has been reduced to tabular form which may be found in ANSI/ASQC Z1.4-1993, *Sampling Procedures and Tables for Inspection by Attributes*.

To ensure the sampling is representative of the entire population from which it is drawn, the sampling must be random and be representative of the time span and locations of production, changes in batches, lots and suppliers of raw materials used in that production and changes in processes or personnel which may have occurred during that production.

6.5 Ballistic threats

Ballistic threat ammunition fired from hand- and shoulder-fired weapons are designed for sporting or military/law enforcement purposes. How the kinetic energy of the bullets of this ammunition is to be expended upon impact (terminal effect) is a function of the design of the bullet. Bullets intended to penetrate light armor with sufficient residual velocity to inflict wounds and/or damage to that, which the armor is protecting, are designed to concentrate their kinetic energy in order to perforate the armor. Bullets intended to inflict wounds on unarmored targets are designed to transfer all of their energy to the target, i.e., complete penetration with the attendant down-range; residual velocity is a waste of its kinetic energy.

To maximize penetration characteristics, military ammunition is loaded with bullets known as armor piercing, which have a hard, non-deforming core. Other military ammunition intended for use against unarmored targets is loaded with deformable, lead cores with thin copper jackets and are frequently termed as ‘ball’ ammunition from the lead balls of early, smooth bored, musketry.

Commercial ammunition, intended to maximize the wounding of wild game, is loaded with bullets similar to military ball ammunition. The bullets of this type of ammunition may have exposed, soft, lead tips which maximize deformation upon impact, creating larger wound cavities than the same fully jacketed bullets. International conventions disallow this soft point, expanding bullet from all military applications.

A special category of projectile is found only in testing laboratories for use in evaluating the fragmentation resistance of armors and is intended to be more consistent in materials and configuration than fielded bullets thereby producing more reproducible test results. The first of these, relatively hard, steel projectiles known, as Fragment Simulating Projectiles (FSPs) were developed to evaluate light personal armors and heavier, vehicular armors. MIL-P-46593A specifies four sizes/weights of FSPs – caliber .22/17 grain, caliber .30/44 grain, caliber .50/207 grain and 20 mm/830 grain.

More recently, steel, right cylindrical fragment simulators known (redundantly) as Right Circular Cylinder Fragment Simulators (RCCs) were developed to evaluate the casualty reduction performance of personal armors. The most frequently encountered weights of RCCs are 2, 4, 16 and 64 grains. While the use of RCCs is widely invoked by a broad range of procurement and engineering documents, there is no generally accepted standardization of RCCs except HPW-010-02-01.

Neither FSPs nor RCCs are intended to replicate a specific field threat but both are intended to be *representative* of a broad range of fragments produced by fragmenting munitions. The use of FSPs has been accepted in many areas of the commercial world as representative of the fragmentation threat from disintegrating machine tools, racing engines, etc.

6.6 Test methodologies

Ballistic armor performance may be determined by either of two evaluation methodologies – Ballistic Resistance Testing or Ballistic Limit Testing. Ballistic resistance testing evaluates the performance with respect to predetermined performance requirements. Ballistic limit (V_{50}) testing determines the limits of performance. The selection of which type of test is to be employed is determined by the purpose for conducting the test. In either case, the detailed procedures of the test are what insure the reliability and repeatability of results of testing.

The performance of stab resistant armor is determined by testing to predetermined performance requirements. As with ballistic performance testing, the details of the test are what ensure the reliability and repeatability of the results of testing.

6.7 Ballistic resistance methodologies

Ballistic resistance testing of armor is testing conducted to evaluate the pass/fail performance of an armor with respect to predetermined performance specifications/requirements. This type of testing will *not* determine the margin by which a sampling passes those requirements, nor, if it fails, the margin of failure. The basic procedures for ballistic testing are the same whether the target is a bulleted or fragmentation threat. As a minimum the procedures of ballistic resistance testing must include:

1. Description of the test sampling material coupon versus operational assembly, the number and size(s) of the test samples in the sampling.
2. The distribution of the samples over the full spectrum of tests of the standard.
3. The ballistic threat to be used in testing – caliber, bullet type/construction, bullet weight, impact obliquity and velocity of the impact of that threat with the sample.
4. Pre-test conditioning of test sample.

5. Test environmental conditions.
6. Sample backing (if any) and its calibration.
7. Acceptable limit of bullet stability (yaw).
8. Acceptable limits of obliquity of impact.
9. Definition of fair/unfair shots.
10. Required number and location of fair shots on each sample.
11. Whether re-fixturing of sample between shots is permitted.
12. Range set-up including mounting of the sample.
13. Methodology of velocity determinations.
14. Precise definition of penetration including methodology for determinations of penetrations.
15. Statement whether spall constitutes penetration.
16. Precise definition of deformation including methodology for determinations of deformation.
17. Level of acceptable post-test operability of an assembly.
18. Data and reporting requirements.
19. Ownership and disposition of tested samples.

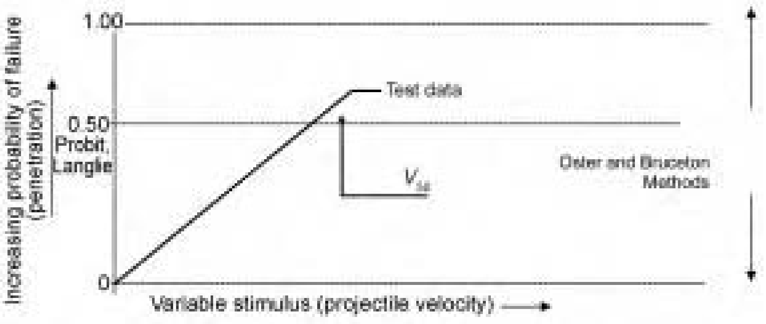
Ballistic resistance testing is well suited to any material coupon or assembly evaluation requiring only a pass/fail conclusion – product demonstrations, marketing, field demonstrations, lot acceptance, etc.

Because its findings are limited to pass/fail conclusions, ballistic resistance testing is of limited (if any) value in comparing the performance of differing designs or changes in the same design. For these quantitative purposes, ballistic limit (V_{50}) testing is better suited.

6.8 Ballistic limit (V_{50}) testing

V_{50} testing is one of four similar testing methods used to determine the probability of penetration of ballistically resistant materials, all of which were derived for the testing of devices – not necessarily armor – which are consumed in a single test trial of a non-quantifiable reaction to a variable stimulus; i.e., a match ignites or does not, a fuse functions or does not, etc. A multiplicity of identical test samples are subjected to a variable stimulus, the 'go/no-go' results of which are used to establish a curve of the go/no-go results with respect to the full range of the variations of the stimulus. The differences in the four methods are procedural and, while the results of each are similar, the reliability of those results are a reflection of the complexity and sophistication of the procedure. These methods are frequently used to establish the probability of penetration of an armor as a function of projectile velocity (Fig. 6.1).

Adapting these methods to the evaluation of ballistically resistant materials is, in the main, impractical and of academic value only. The control of the stimulus – in the case of armor testing that stimulus is projectile velocity – to



6.1 Armor penetration versus projectile velocity.

precisely, predetermined values is a requirement which cannot be achieved in armor testing without excessive and costly expenditures in ammunition and armor samples.

6.8.1 Probit method

Ten firings are conducted at each pre-selected narrow velocity range. The results of each group of ten firings are analyzed to determine the number of penetrations which, when expressed as a percentage, is used to establish a point of the curve. The number of points necessary to establish the curve is a reflection of the required level of confidence and the range of velocities and/or penetration probabilities to be examined.

6.8.2 Langlie method

This method was derived to produce the entire range of results (curve) with a minimum of trials; however, when adapted to armor testing this is largely illusionary, inasmuch as many firings are not usable due to non-compliance with velocity requirements. The initial firing is conducted at the mid-point of the velocities of predicted 100% and 0% probabilities of penetration. Subsequent firings are conducted at precise, mathematically predetermined velocities based on an analysis of results of firings to that point. Firings continue until a pre-selected stopping point is reached, usually 20 usable firings and/or 5 shot-to-shot reversals within a predetermined zone of mixed results. Measuring the velocity with the required precision is difficult, resulting in many unusable firings.

6.8.3 OSTR method

The One Shot Test Response method is a more sophisticated variation of the Langlie method requiring more than one trial at the same velocity as the Langlie method, which requires only one usable shot at each velocity. All of the negative considerations of the Langlie method – excessive ammunition and armor costs and procedural and analysis complexity – are amplified by this method; however, the results are more highly refined.

6.8.4 Bruceton method

This method may be used to develop the full range of results, but is the least suitable for that purpose, inasmuch as it was derived to focus on the area of 50% probability of penetration. The procedures are less complex and projectile velocities need not be controlled with the same precision as the other methods. The initial firing is conducted at the expected velocity to produce a 50% probability of penetration. All subsequent firings vary by a fixed amount until an even number of trials (2, 4, 6, 8 or 10) are obtained within a predetermined total velocity variation (usually 60, 90 or 125 fps), one half of which (50% probably) are penetrations. The practicality, low cost and usefulness of this method are the basis for the extensive, universal use of the MIL-SD-662 V_{50} method of armor testing, which is a specialized case of the Bruceton method.

For a more complete discussion of these methods, their procedures, strengths and weaknesses consult MIL-STD-331A, *Military Standard, Fuse and Fuse Components, Environmental and Performance Tests for*, 10 October 1987.

Ballistic limit (V_{50}) testing, as widely used to evaluate the limits of armor performance, is an adaptation of the Bruceton method which was originally derived for the testing of devices – not necessarily armor – which are consumed in a single test trial of a non-quantifiable reaction to a variable stimulus.

Testing standard, MIL-STD-662F, V_{50} *Ballistic Test for Armor*, dated 18 December 1997, is the most comprehensive adaptation of the Bruceton Method to armor testing. The requirements of MIL-STD-662F define the procedures to be followed to establish the limits of performance of a sample of armor in terms of the precise velocity of impact, which will produce 50% penetrations. The shot-to-shot velocities of the test are intentionally varied (increased and decreased) until an equal number of penetrations and non-penetrations are produced within a narrow overall range of velocity. The average of the velocities of these equal numbers of penetrations and non-penetrations is termed the V_{50} of that sample.

When properly conducted and reported a V_{50} test is at once a measure of the performance of the armor, is self-evaluating and a reflection of the physical consistency of the test sample.

The confidence level of the V_{50} is inversely related to the narrowness of the range of the velocities used to compute the V_{50}. A 9 mm bullet at 2 fps, which would not penetrate a sheet of paper, averaged with the same bullet of a second, penetrating shot at 5000 fps would yield a V_{50} of 2500 fps. Disallowing extreme velocity variations – 5000 fps in this example eliminates distortions of this nature. Depending on the required confidence level, maximum allowable velocity variations of 60, 90, 125 and 150 fps are frequently specified. However, if the sample lacks homogeneity, those inconsistencies may render attainment of a V_{50} within the specified range of velocities, impossible. In such cases the results are termed inconclusive and ignored. The range of velocities used to compute the V_{50} is often reported as 'Range-of-results'.

Variations within the test sample such as thickness or hardness may produce apparent inversions in logic if a lesser velocity shot penetrates when a higher velocity shot does not. When this occurs, the lower velocity of the penetrating shot is subtracted from the higher velocity of the non-penetrating shot and the difference reported as 'Range-of-mixed-results'. Often ignored, the Range-of-mixed-results is a reflection of the consistency of the make-up of the test sample. For example, should a high velocity shot impact a harder location and not penetrate, while a lower velocity shot impacts a softer spot and does penetrate, the magnitude of the Range-of-mixed-results provides a measure of this inconsistency.

As a minimum the procedures of a V_{50} test must include:

1. Descriptions of the test sample – size and number of the material coupon. Note: V_{50} testing of armor assemblies is rarely conducted inasmuch as variations in configuration conflict with the sample homogeneity, which is an assumption of V_{50} testing.
2. The distribution of the samples over the full spectrum of tests of the standard.
3. The ballistic threat to be used in testing – caliber, bullet type/construction and bullet weight.
4. Pre-test conditioning of samples.
5. Test environmental conditions.
6. Backing (if any) of the test sample and its calibration.
7. Acceptable limits of bullet stability (yaw).
8. Acceptable limits of obliquity of impact.
9. Definition of fair/unfair shots.
10. Required minimum number of penetrations and non-penetrating velocities to be used in computation of V_{50}.
11. Whether re-fixturing between shots is permitted.
12. Maximum allowable variation in velocities used to compute V_{50}.
13. Maximum number of shots allowable on one sample.
14. Range set-up including mounting of the sample.
15. Methodology of velocity determinations.
16. Precise definition of penetrations including methodology for penetration determinations.
17. Statement whether spall constitutes penetration.
18. Statement whether residual velocities of penetrations are to be determined.

19. Data to be recorded and reported.
20. Ownership and disposition of tested samples.

V_{50} testing is best suited to any purpose requiring a comparative evaluation such as engineering and development, comparing the performance limits of two or more differing armoring materials or the effect of environmental extremes or modifications of the same armoring material.

Because the procedures of V_{50} testing are based on the assumption that the test sample is homogenous, V_{50} testing is of limited value in evaluating the performance of armored assemblies with configuration variations – seams, weldments, subassemblies, etc. – for which ballistic resistance testing is well suited.

6.9 Stab resistance methodologies

Stab resistance testing is similar to ballistic resistance testing inasmuch as this testing is conducted to evaluate the pass/fail performance of the armor with respect to predetermined performance specifications/requirements. This type of testing will *not*, without modification, determine the margin by which a sampling of stab armor passes those requirements nor, if it fails, the margin of failure. However, the delivered energy of the stab test threats are frequently increased and decreased to determine these margins of performance.

Stab resistance testing is conducted with one of two predetermined types of threat – pointed implement (spike) or edged (knife), but the procedures are otherwise the same and must include:

1. Description of the test sampling – material coupon or final assembly (vest), the number and size(s) of the test samples in the sampling.
2. The distribution of the samples over the full spectrum of tests of the standard.
3. The stab threat to be used in testing – spike or edge, and their precise configuration and material.
4. Fixturing used to deliver the threat – projected (airgun) of gravity (drop fixture).
5. Velocity and momentum of the impact – do not use energy since equal energies of differing combinations of mass and velocity will produce differing results.
6. The number, location and obliquity of required impacts.
7. Definition of fair/unfair impacts.
8. Acceptable limits of obliquity of impacts
9. Test set-up including mounting and backing of the test sample.
10. Methodology of velocity determination.
11. Precise definition of penetration including methodology for determination of penetrations.

12. Precise definition of deformation including methodology for determination of deformation.
13. Pre-test condition of the test samples.
14. Test environmental condition.
15. Data and reporting requirements.
16. Ownership and disposition of the tested samples.
17. Methodology of verification/calibration of the edge sharpness and point of test implement and the test life of those implements.
18. Is re-fixturing of sample between impacts permitted?

6.10 Composite versus monolithic armor

The basic methodologies for the ballistic or stab testing of *rigid* forms of composite armors are no different from the methodologies for testing monolithic armor except that due to the tendency for laminated composites to delaminate, the disturbed area of each impact is generally larger than the disturbed area of monolithic armors and methodologies for rigid, composite armors will frequently specify a larger spacing between shots.

Flexible forms of composite armor test methodologies should recognize several phenomena of flexible armor not found in rigid armors and include procedures to accommodate those phenomena when they are encountered. Most flexible armors are personal armors, which should offer protection from blunt trauma injuries as well as penetration injuries. Evaluation of the blunt trauma protection is provided by backing the armor with an easily deformable material with which to measure the backface deformation of the armor. This function is usually provided by non-hardening, modeling clay of a specific deformability, which is calibrated before and after testing.

Impacting of multi-ply, flexible armor tends to draw the plies of armor into the location of the impact exposing the periphery of the protected area. This phenomenon, frequently termed ‘bunching’, will invariably result in subsequent penetration. Manufacturers use quilt stitching in their armors, which prevents slippage between plies and prevents this bunching, but may reduce the flexibility of the armor. Test procedures used to evaluate flexible armor should address this phenomenon by either specifically requiring, or denying, smoothing between shots.

Finally, the ballistic impact of woven forms of flexible armor stretches and stresses the full length of the fibers emanating, horizontally and vertically, from the point of impact. Test procedures used to evaluate flexible armor should address this phenomenon by either specifically requiring, or denying, staggering of the shots to avoid two or more impacts on the horizontal or vertical strands of the weave.

6.11 Miscellaneous considerations

6.11.1 Velocity determinations

The most critical parameter of any ballistic or stab resistance test is the accuracy and reliability of the determination of projectile/implement velocity. The most accepted means of assuring this accuracy is periodic calibration of the instrumentation. If the instrumentation velocity is suspected the test should be suspended until the accuracy of the instrumentation can be reconfirmed. However, reliance on a single instrumental velocity for each shot can lead to continuing, undetected, erroneous velocity determinations if, and when, that instrumentation falls out of calibration. Duplicate, independent determinations all but eliminate undetected, erroneous determinations, since two independent systems would have to malfunction at precisely the same time, by precisely the same magnitude and in the same direction (high or low readings) for the faulty determination to go undetected.

6.11.2 Energy

The use of kinetic energy to specify the impact requirements of stab resistance testing can be misleading unless the implement velocity of the implement is also a requirement. Experience has shown equal energy impacts of differing masses and velocities will produce markedly differing stab test results. Stab impacts should, therefore, be characterized by specific mass and velocity requirements.

6.11.3 Target distance

Muzzle exit of a bullet is always accompanied by some degree of bullet instability induced by the exiting burning gases, which cause the bullet to wobble. The degree of this instability is a function of the volume of the burning powder expelled behind the bullet. This instability is resolved within a short distance of the muzzle. The distance at which the bullet is stabilized varies, but experience has shown that bullets from handguns are stabilized at 10–12 feet while the greater volume of gas and higher velocities of rifle caliber may require 30–35 feet. In order to insure bullet stability at impact during armor testing, the armor should be at not less than 15 feet when testing with handgun threats and 40 feet when testing with rifle or larger caliber ballistic threats. In order to minimize the difference between instrumental and impact velocities, the distance from the impact to the velocity instrumentation should be minimized.

6.11.4 Helmet testing methodologies

Ballistic resistance testing of helmets is currently conducted with either bulleted threats (military and law enforcement) or fragmentation (military). Bulleted testing is normally with the ballistic resistance form of testing and fragmentation testing with the ballistic limit (V_{50}) form of testing.

Fragmentation, V_{50} testing is normally conducted on helmet shells with the shells rigidly mounted to an articulating fixture, capable of maintaining zero degree obliquity impacts.

Bulleted, ballistic resistance testing of helmets is normally conducted on helmet assemblies, including suspension systems, on a headform and restrained only by the chin strap/suspension system. Some lay-ups of the construction of laminated composite helmets present an inherent weakness of the crown and the suspension system mounting, usually through screws or rivets; these are potential weaknesses of all helmets. Bulleted testing of helmet assemblies should always include shots to impact these areas, but many procedures do not.

All helmet testing procedures should specify the minimum shot-to-edge and shot-to-shot distances and provide for the inclusion of the five principal areas of the helmet – front, rear, crown, right and left sides. There are no known, broadly accepted procedures used to evaluate the blunt trauma protection, nor biomechanical protection of helmets. Helmet testing is almost exclusively intended to evaluate the penetration characteristics.

All forms of helmet testing employ a witness panel to confirm penetrations. The witness panels are usually 0.020 inches thick, 2024T3 aluminum positioned a short distance behind the impact surface of the helmet (2 inches typically) which, if perforated, is termed ‘penetration’.

6.11.5 Visor, goggle testing methodologies

Ballistic resistance testing of transparent, personal armors differs from personal opaque armors (vest and helmets) only to reflect the proximity of the eyes to this armor.

Inasmuch as the eyes are likely to be injured by far lower levels of threat than other parts of the body, testing procedures of transparent armor specify more demanding criteria for penetration.

Test samples of eye protection armor are mounted either on a headform (goggles) or on a representation of the host helmet (visors). Penetrations are determined by the perforation of a witness panel (usually 0.002 inches thick aluminum foil) positioned a short distance (typically 2 inches) behind the armor. Personal, transparent armor testing procedures will frequently include additional acceptance criterion such as cracking or fragmenting of the test sample.

6.11.6 Vest testing methodologies

Ballistic resistance testing of body armor (vests) is currently conducted with either bulleted threats (law enforcement and military) or fragmentation threats (military). Bullet testing is usually with the ballistic resistance form of testing and fragmentation testing with the ballistic limit (V_{50}) form of testing, although testing with either threat is frequently conducted with the ballistic limit (V_{50}) form of testing.

Bulleted and fragmentation testing are conducted on complete vest assemblies or coupons of the ballistic materials of the vest and testing of either type of sampling with either form of testing may be conducted with a variety of sample mountings including:

- Framed with the framing rigidly fixtured and the sample unbacked.
- Framed with the framing suspended from its upper edge and a weight attached to its lower edge.
- Strapped to a clay backing material.

The requirements for fragmentation testing of body armor may include procedures for additional firings at velocities known to produce penetrations and the determination of the residual velocities of those penetrations as a measure of the casualty reduction characteristics of the armor. Residual velocity testing is only conducted on unbacked test samples.

Body armor testing should, in addition to the general requirements of Section 6.7 and Section 6.8.4, include specific directions with respect to impacting of specific features of the armor, i.e., seams, closures, fasteners, pockets, pouches, etc.

Procedures, which require clay-backing material, do so to measure the extent to which non-penetrating shots deform the backface of the armor. Frequently termed transient deformation, this deformation will be used to evaluate the blunt trauma protection of the armor. A typical non-penetration impact will create a depression in the clay, which will be surrounded by a raised area around its rim referred to as the ‘cratering effect’. The measurement of the depth of the depression must disregard this raised edge and be made from the undisturbed surface of the clay to the deepest point of the depression. In addition to the depth of the depression, some procedures require the volume of the depression be determined as well. This determination is usually made by casting the depression with a quick setting medium and measuring the displacement of casting in water.

6.11.7 Body armor insert testing methodologies

Frequently flexible body armors will include front and/or back pouches to accommodate the addition of rigid inserts which increase the level protection from handgun or fragmentation levels to rifle levels of protection. Body armor inserts of this nature may be intended only to augment the flexible armor and require the insert be used with the flexible armor, or as a standalone armor capable of resisting the specified threat without the added resistance of the flexible armor.

If the insert is ‘augmentary’ it must be tested in conjunction with the flexible armor or a surrogate representation of the flexible armor frequently referred to as a ‘shoot pack’.

Often an insert may be intended to resist only a limited number of ballistic impacts, which will require a multiplicity of samples to conduct V_{50} testing. The total number of shots required by the V_{50} test is then spread over several samples and the results used to calculate the V_{50}. The use of a multiplicity of samples to develop a single V_{50} is sometimes termed a ‘constructed V_{50}’.

The physical properties of the material used to fabricate inserts may require special, pre-test conditioning. For example, ceramics, which are often used in inserts, are extremely brittle and may be easily damaged by abusive, day-to-day handling. Accordingly, some test procedures require the inserts be mechanically impacted prior to ballistic testing.

6.11.8 Vehicular/structural armor testing

No distinction is usually made between vehicular as opposed to structural armor. This is probably based on the perception that neither will be in contact with the body (personal armor) and the mass and inertia of both are ballistically the same (rigidity and immovable).

Ballistic testing of this armor differs from personal armor only in that the mounting of the test sample is always rigid and the acceptable performance does not include a measure of its deformation.

When tested as an assembly, vehicular and structural armors require all features of the assembly be tested as well as the base materials and will include seams between doors and their framing, hinges, locks, weldments, fasteners and the convoluted passages of deal trays and speak-through devices. The acceptance criteria of these procedures should include the post-test operability of subassemblies. For example, the successful ballistic resistance of a door lock which is ‘unlocked’ by the ballistic impact may be unacceptable.

6.11.9 Fragmentation containment devices

Materials and devices intended to contain fragmentation are normally tested as assemblies and may include bomb containment blankets, bomb containment canisters and blankets or rigid assemblies intended to protect from high velocity, disintegration of industrial machinery and racing engines. These threats are of three types – fragmentation, blast and a combination of fragmentation *and* blast.

Fragmentation containment testing is identical to the fragmentation testing for person and vehicular armors.

Blast and fragmentation/blast containment testing present problems, which fragmentation threats alone, do not. Pressures from the blast portion of threats must be vented in a manner, which renders them harmless. This is normally accomplished by dissipation of this energy with cooling baffles, or by venting into a predetermined safe area. Bomb containment canisters will frequently be of high strength materials to contain the fragmentation and blast pressures except for a weakened area, which directs and vents blast pressures upward. Since the gas pressures of the blast are directly related to the temperature of those gases, baffles with large surface areas are frequently added to cool those gases as rapidly as possible. However, if the strength of the blast is misestimated, the blast may destroy the containment armor adding to the fragmentation threat.

Blanket configurations of blast containment have not proven to be particularly effective since the blast usually lifts the blanket causing the blast pressures to be directed laterally under the lifted blanket.

Specific procedures for testing these devices are generally non-existent and are tailored to each specific device. Generally these tailored procedures will employ an array of free air pressure sensors to assess the dissipation of blast pressure with respect to the distance from the explosive initiation point and an array of witness panels to assess the fragmentation hazard at those same locations.

6.11.10 Bullet resistant body armor test procedures

Responding to appeals from the US Law Enforcement Community in March 1972, the US National Institute of Justice (NIJ) conducted a study and developed test procedures for evaluating bullet resistant body armor. Prior to that time the body armor industry could, and did, market body armor with an infinite number of claims which were largely unsupported by scientific, reliable, dependable testing. NIJ-STD-0101.00 provided order to this chaos. Since 1972 the procedures have been revised several times, the most current revision being NIJ-STD-0101.04, June 2001.

The US Law Enforcement Community's acceptance of NIJ-STD-0101 has been overwhelming to the extent that little, if any, body armor is marketed in the United States, which has not been certified by NIJ. In addition, the procedures of NIJ-STD-0101, with and without minor variations, are used to evaluate armor worldwide. To that extent, NIJ-STD-0101.04 has come closer to being accepted as an international standard than any other body armor test procedure.

Manufacturing and marketing compliance with NIJ-STD-0101 has always been voluntary, and in order to encourage that compliance and develop a level of confidence in the reliability of the performance of body armor, NIJ developed a process for certification of compliance of body armor with the voluntary requirements of NIJ-STD-0101. The certification process is also voluntary, but manufacturers cannot claim compliance unless they agree to comply with the requirements of the certification process.

Participation in the NIJ, body armor certification process requires the manufacture to submit samples of the model of armor to be certified to NIJ who inspects the sampling to:

1. Ensure the armor is indelibly identified with a unique model number/name.
2. Ensure compliance with minimum levels of workmanship and labeling.

Armors found non-compliant with workmanship and labeling requirements upon receipt by NIJ will be returned, without ballistic testing, to the manufacturer. Compliant armors are forwarded by NIJ to an NIJ approved, testing facility for ballistic testing in accordance with the requirements of NIJ-STD-0101.04. While the manufacturer is responsible for the cost of this testing, copies of the test report *and* the tested samples are returned to NIJ which retains the tested samples for future reference and issues a letter certifying compliance of the model (if appropriate) to the manufacturer.

Models of armor which survive the NIJ labeling and workmanship inspection are ballistically tested for compliance with the requirements of NIJ-STD-0101.04 for the level of protection claimed – Levels I, IIA, II, IIIA, III or IV. While not specified by NIJ-STD-0101.04, it is assumed that compliance with a higher level of protection includes all lower levels of protection, *except* compliance with the single shot requirements of Level IV protection *does not include* compliance with *any* lower level of multi-shot protection.

Levels I through IIIA are known as ‘handgun levels’ of threat and are tested with two calibers of ballistic threat one known to have superior penetration characteristics and one which delivers high levels of impact energy. Level III, often referred to as a ‘rifle’ level of threat is tested only with the basic, NATO, rifle caliber of ammunition – 7.62 x 51mm, M80, Ball. Level IV, the ‘rifle armor piercing’ threat, is tested only with caliber .30-06, AP (armor piercing), M2 ammunition from the US Military arsenal of ammunition.

NIJ certification testing includes two procedures for each level of protection – one which confirms or denies compliance with protection level requirements and one which establishes the ballistic performance limit of models which pass protection level requirements for use in the resolution of post-certification anomalies.

To be certified by NIJ, a model of armor must comply only with the protection level requirement testing which is denied to any model of armor, which is penetrated *or* excessively deformed by a non-penetrating shot.

Only models of armor, which successfully demonstrate compliance with level of protection requirements, are tested to establish a performance baseline for comparison with future, post-certification performance. This testing, known as ballistic limit (V_{50}) testing, scientifically establishes the projectile velocity which will have a 50% probability of penetrating the certified model of armor at the time that model was certified. The results of the baseline V_{50} testing have no significance in the NIJ certification process of a model of armor and are only used to evaluate long-term, performance changes of the production of that model.

The ballistic resistance (BR) testing of NIJ-STD-0101.04 for Levels I through IIIA protection requires that two vests of each model be tested with each of the two calibers of ammunition specified for the claimed level of protection (four vests total). All BR testing is conducted after wet conditioning of the test samples and with the test samples backed with non-hardening modeling clay. The pliability of the clay backing material must be tested, before and after, each panel is tested. Each panel of armor is tested at each of six specified locations with a maximum of two additional shots (eight in total) should one or two of the required shots be unfair, i.e., high or low velocity, insufficient spacing between shots or too close to an edge of the panel. Any shot of the 48 required fair shots which perforates the rear surface of the armor or creates a backface clay deformation exceeding 44 mm in depth, fails the model. After BR testing each of the test samples are destructively inspected to certify the construction of each of the eight panels. Any variation in construction fails the model, even though the model may have passed BR testing. After BR testing and the post-test construction inspection, baseline ballistic limit (V_{50}) testing of the front and back panels of models which have satisfied the level of protection requirements *and* construction requirements, are developed.

All baseline V_{50} testing of Level I through IIIA armor is conducted on dry, clay backed panels with 9 mm, 124 grain, FMJ ammunition regardless of the protection level (I through IIIA) of the model of armor. The V_{50}s are developed independent of one another, i.e., one V_{50} for the front panel and one for the back panel, and neither may be used to deny the basic certification of the model.

The BR testing of Levels III and IV armor are conducted with one caliber of threat only, 7.62 × 51 mm, NATO, M80 and .30-06 AP, M2, respectively. BR testing of both levels are conducted with four panels of the armor, but Level III is conducted with six shots per panel (24 total) while Level IV is conducted with one shot per panel (four in total).

Ballistic V_{50} testing of Level III armor is conducted with 7.62 × 51 mm, M80 and Level IV armor with .30-06, AP, M2 providing the model of armor has satisfied the BR and construction requirements for their respective level of protection.

6.11.11 Used versus new condition armor

The result of testing of any material is only valid insofar as the tested sample accurately represents the full range of the population from which the sampling was drawn. Ballistic materials are manufactured under demanding controls intended to minimize variations within the entire population of the production and test samplings of this uniform population are, generally, representative of the entire population.

However, after armor has been in service, its usage and environmental exposures may induce changes in the properties of the material affecting its ballistic performance. Samples of identical armor may, after differing environmental exposures, no longer produce identical ballistic performances. In no other form of armor is this more evident than in body armor, which may be vulnerable to changes when exposed to a broad range of environmental conditions including sunlight, moisture, heat and a broad range of common household products. Therefore, a sampling of the population of armor which has been in service (used armor) is not representative of the entire population and the performance of each armor within that population must be evaluated independent of all others.

Paradoxically, current body armor evaluations methodology is destructive in nature, and precludes returning satisfactory armor to service. This paradox cannot be circumvented until non-destructive methodologies are developed with which to evaluate the ballistic resistance of armor.

Part II

Types of material and their application

7

High performance ballistic fibers

T TAM and A BHATNAGAR, Honeywell International Inc., USA

7.1 Introduction

High performance fibers (HPF) are engineered for specific end uses that require exceptional strength, heat resistance and/or chemical resistance. They are generally niche products, such as lightweight composite materials for aircraft, ballistic fibers and bullet resistant vest or body armor, protective gear for fire officers, and cut or stab resistant articles. On the lighter side, examples are fishing line, bowstring, and marine rope and sail cloths such as those used in the Americas Cup race.

7.2 Classical high performance fibers

7.2.1 Glass fibers

The oldest, and most familiar, high performance fiber is glass. Glass fibers were relatively inflexible and not suitable for many textile applications. However, they can be found in a wide range of end uses, such as insulation, fire resistant fabrics, and reinforcing materials for plastic composites. In recent years optical quality fiberglass has revolutionized the communications industry.

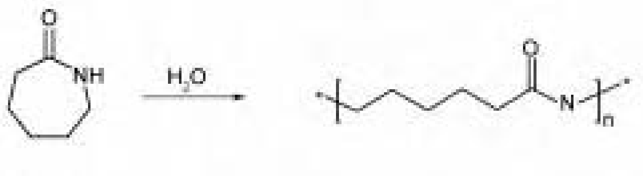
7.2.2 Carbon fibers

The next classic HPF is carbon fiber which can be engineered for strength and stiffness to reinforce composite; or can, in various forms, improve the electrical conductivity, thermal and chemical resistance of textile materials. The primary factors governing its physical properties are degree of carbonization and orientation of the layered carbon planes. Carbon fibers are made from specially purified rayon or top quality acrylics (PAN), or pitch fibers from liquid crystal (for reinforcement and other applications). The almost perfect carbon fiber is graphite.

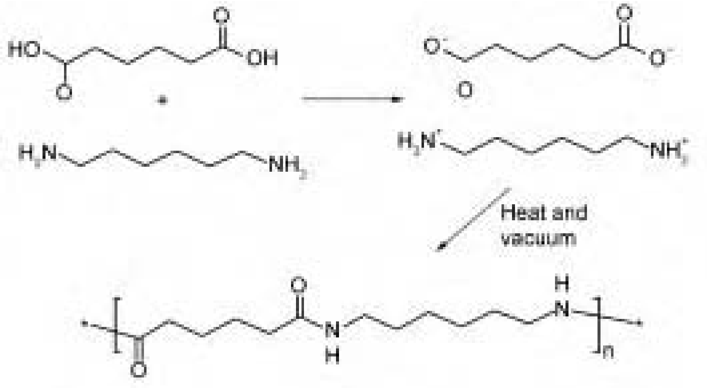
7.3 Rigid chain aromatic high performance fibers

The best known high performance, synthetic, organic fibers are aramids, which like nylons are polyamides derived from aromatic acids and amines. Figures 7.1 and 7.2 are nylon 6, and nylon 66 which have a flexible chain between the amide group whereas Fig. 7.3 is Nomex which has an aromatic chain between the amide group that gives its unique properties.

Because of the stability of the aromatic rings and the added strength of the amide linkages, due to conjugation with the aromatic structures, aramids exhibit higher tensile strength and thermal resistance than the aliphatic polyamides (nylons). The para-aramids (trade name Kevlar and Twaron) based on terephthalic acid and p-phenylene diamine, or p-aminobenzoic acid, exhibit higher strength and thermal resistance than that (trade name Nomex) with the linkages in meta positions on the benzene rings. The greater degree of conjugation and more linear geometry of the para linkages, combined with the



7.1 Structure of nylon 6.



7.2 Structure of nylon 66.

7.3 Nomex structure.

7.4 Structure of aramid fiber.

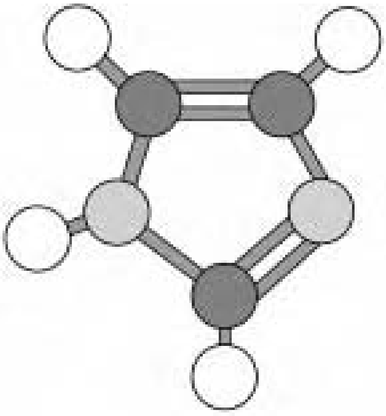
greater chain orientation derived from this linearity, are primarily responsible for the increased strength. The high impact resistance of the para-aramids makes them popular for first generation bullet-resistant body armor. Aramid fiber (Fig. 7.4) can be chopped into staple form to make felt. Applications such as chain saw protective garments may be blended with other fibers for other end uses. Aramid fiber is lyotropic. It is solution spun and it melts at a lower temperture than a thermotropic liquid crystal fiber.

7.4 High temperature performance fibers

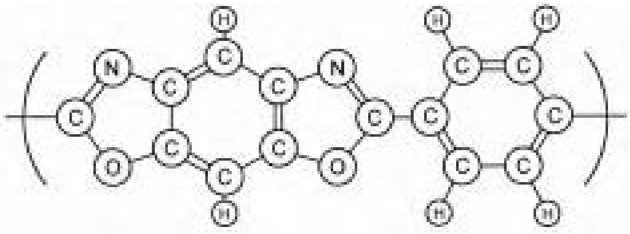
7.4.1 PBI fiber

PBI (polybenzimidazole) (Fig. 7.5) is another fiber that takes advantage of the high stability of conjugated aromatic structures to produce high thermal resistance.

The ladder-like structure of the polymer further increases the thermal stability. PBI® was first discovered in the 1950s. In the 1960s, Celanese developed a dry spinning and polymerization process for a high temperature resistant PBI® polymer. Following a fire in an Apollo spaceship in 1967, NASA cooperated with Celanese to develop PBI® textiles. The fibers were launched in 1983. PBI is noted for its high cost, due both to high raw material costs and a demanding manufacturing process. The PBI fiber has a yellow color (PBIgold) but with high moisture regain (7–8%). When converted into fabric, it yields a



7.5 The chemical structure of PBI.



7.6 PBO fiber structure.

soft hand and feels comfortable (due to high moisture regain). Blending with other high temperature resistant fibers such as aramid to reduce cost and/or increase fabric strength may optimize the utilization of PBI.

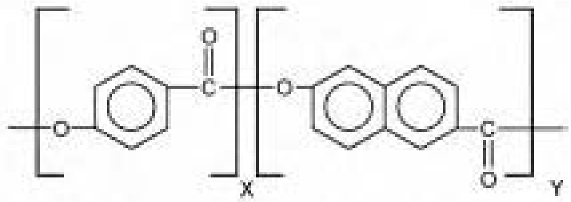
7.4.2 PBO fiber

PBO (polyphenylenebenzobisozazole) is another high temperature fiber based on repeating aromatic structures which is a recent addition to the market (see Fig. 7.6). PBO exhibits very good tensile strength and high modulus, which are useful in reinforcing applications. Currently, Toyobo's commercial rigid-rod chain molecules of poly (p-phenylene-2, 6-benzobisoxazole) (PBO) is called Zylon.

7.5 High performance thermoplastic fibers

7.5.1 Liquid crystal fiber

Liquid crystal fiber (Fig. 7.7) is a melt spun fiber made by high temperature melting and spinning liquid crystal polymer. Vectran® is the only commercially available melt spun LCP fiber in the world. The lightweight Vectran® reinforcement fibers and matrix fibers have exceptional strength and rigidity, which make them a very good alternative to steel: pound for pound, Vectran® is five times stronger than steel. Its cross-section shape and distribution make it ideal for high temperature filtration applications. It is sometimes blended with aramid or other performance fibers to increase final fabric strength.[1]



7.7 Structure of liquid crystal fiber.

7.5.2 HMPE

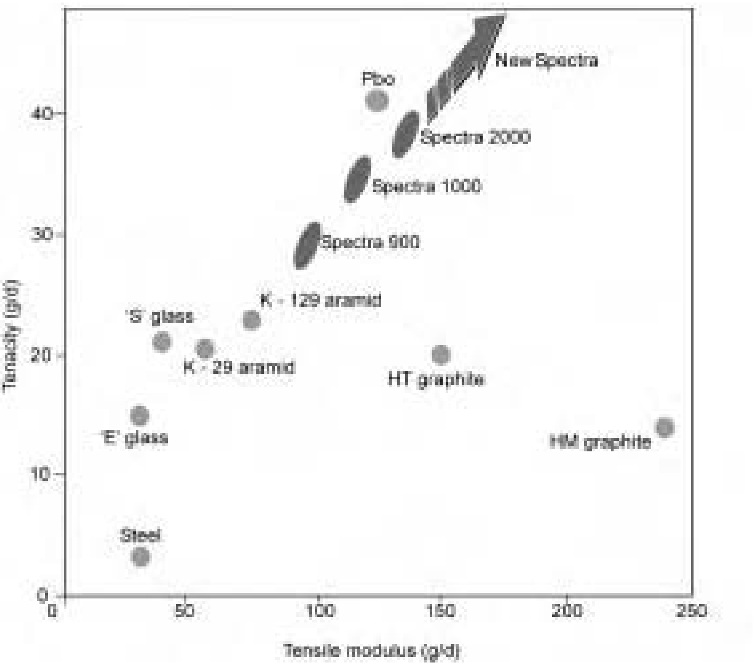
HMPE (ultra high molecular weight polyethylene) can be extruded using special gel spun technology to produce very high molecular orientation. The resulting fiber combines high strength, chemical resistance and good wear properties with light weight, making it highly desirable for applications ranging from cut-proof protective gear to marine ropes. Since it is lighter than water, ropes made of HMPE float. Pound for pound, gel spun HMPE fiber (Spectra®) is ten times stronger than steel. Its primary drawback is its low softening and melting temperature, as well as its tendency to creep under high load.

7.6 Physical properties comparison

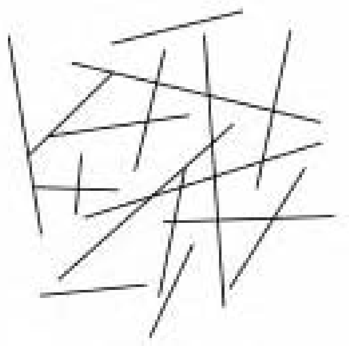
Graphical comparisons of representative high performance fibers are illustrated in Fig. 7.8.

7.7 Requirements for high performance fiber

In order to achieve high performance fiber with exceptional tenacity and modulus properties, there are at least three necessary requirements.



7.8 Modulus versus tenacity of commercial high performance fibers.[5]



7.9 Random rods of polymers.

1. The molecule must be highly oriented in the fiber axis direction.
2. The molecular weight or the molecular chain length must be very high.
3. The fiber must be highly crystalline with few defects.

There are generally two approaches in manufacturing high performance fibers to meet the above criteria. One can start with a highly oriented but relatively low molecular weight, rigid chain and rod-like polymer (Fig. 7.9) such as an aramid (lyotropic) or liquid crystal (thermotropic) polymer.[2,3] This can then be spun into fiber and given a high molecular weight by drawing and/or annealing processes. Aramid spinning will be used as an example for this approach.

On the other hand, one can start with an ultra high molecular weight, flexible long chain randomly coiled polymer like ultra high molecular weight polyethylene (HMPE)[2,3] (see Fig. 7.10). Since the ultra high molecular weight polymer can not be melt spun (polymer will decompose before it will flow at the melting temperature), one must spin this polymer with a dilute solution in the range from 2 to 30% concentration. In this dilute solution, the ultra high molecular weight polymeric chain will 'uncoil' and form a network called a gel. By this 'gel spinning' method, a long molecular chain xerogel fiber with a

7.10 Random coils of polymers.

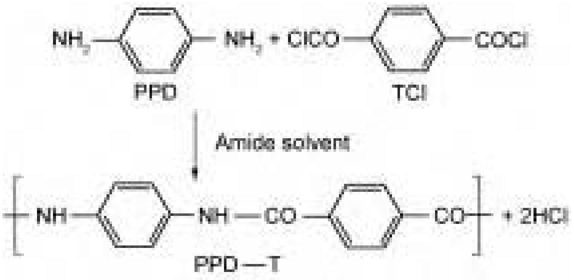
loosely connected network can be made. The xerogel fiber can be drawn to a highly oriented, highly crystalline high performance fiber via specially developed drawing techniques. High performance HMPE fibers like Spectra® or Dyneema® will be used to illustrate these processes. A more in-depth discussion of these fibers will follow.

7.8 Aramid fibers

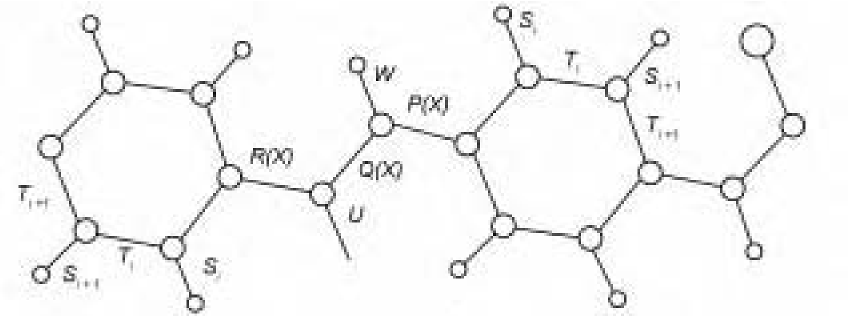
An aramid fiber is based on poly (p-phenylene terephthalamide) (PPD-T) polymer: a classical polycondensation of PPD (p-phenylene diamine) and terephthaloyl chloride (TCI) in amide solvent. The condensation polymerization is described below[2,3] (see Fig. 7.11).

While the PPD-T polymer is not soluble in conventional solvent like most of the para-oriented aromatic polyamides, the rod-like aramid fiber can be dissolved in strong sulfuric acid[2,3] (see Fig. 7.12).

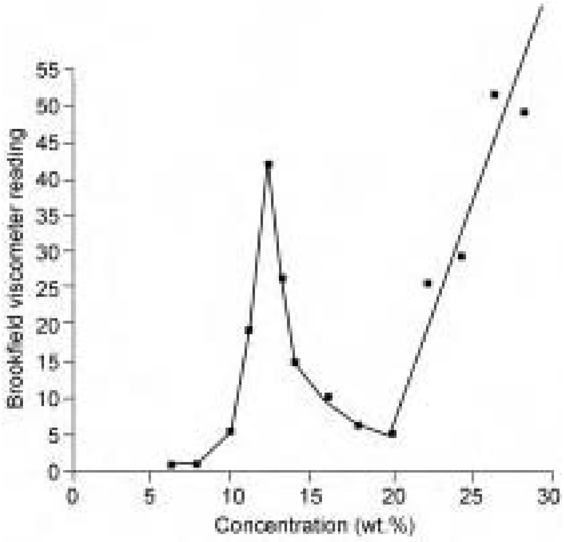
The degree of molecular order of aramid in solution depends on the concentration as in Fig. 7.13.[2,3] As the polymer concentration increases from 5 to about 12%, the solution viscosity increases as expected. The rod-like molecule will take a form as in Fig. 7.14.



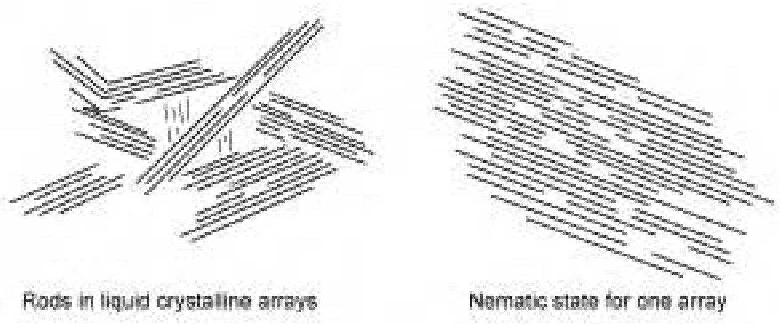
7.11 Condensation polymerization.



7.12 Aramid in sulfuric acid.



7.13 Viscosity versus polymer concentration in sulfuric acid solution.

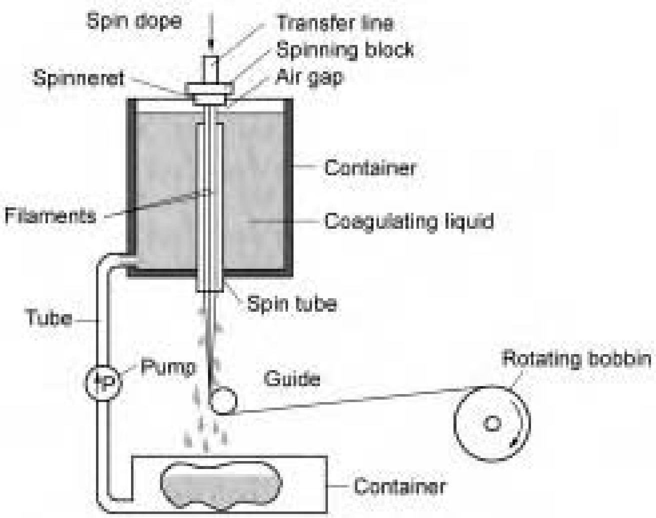


7.14 Distribution of rod-like structures in diluted solvent.

However, as the concentration increases further, the rod-like polymer will form a nematic state with high degree of orientation. As a result, the solution viscosity will drop instead of increase as shown in Fig. 7.13. When this highly anisotropic solution is under shear, or elongation flow like fiber spinning process, the molecule of the extrudate will further align with the fiber axis to give the resulting fiber its orientation.

7.8.1 Dry-jet wet aramid fiber spinning

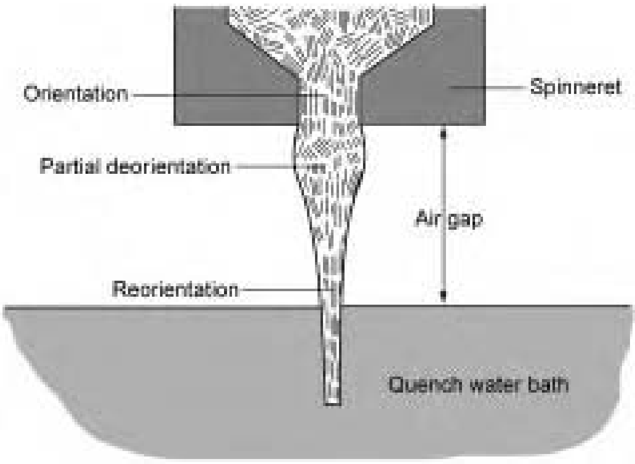
The aramid solution is spun by a process called the dry-jet wet spinning (Fig. 7.15). In this process, an anisotropic solution of PPD-T is extruded through the



7.15 Schematic diagram of the dry-jet wet spinning process for aramids.

air gap into a coagulated bath as shown in Fig. 7.15. The resultant yarn after coagulation is washed and dried.[2,3]

The keys for the dry-jet wet spinning method to orient the anisotropy molecule are both shear orientation and elongation flow, through the spinneret's capillary, and this is represented graphically in Fig. 7.16. In addition, the 'relaxation' of the molecule after the exit of the capillary is kept to a minimum by filament tension or attenuation in the air gap and through the coagulate bath as the filament precipitates into the highly oriented crystalline fiber. This fiber is



7.16 Orientation through the capillary die: elongation and shear flow.

Table 7.1 Typical properties of aramid yarns

Yarn property	Ballistic fiber	High modulus fibers
Tensile strength		
gpd	23.0–26.5	18.0–26.5
Kpsi	420–485	340–420
Initial modulus		
gpd	550–750	950–1100
Mpsi	10.3–14	17.4–21
Elongation, %	3.6–4.4	1.5–2.8
Density		
g/cm^3	1.44	1.44
Moisture regain, % 25 °C, 65% RH	6	1.5–4.3

also heat treated under tension to increase its modulus. Various properties of the Kevlar fibers are listed in Table 7.1.[2,3]

7.8.2 Aramid fiber structure and morphology

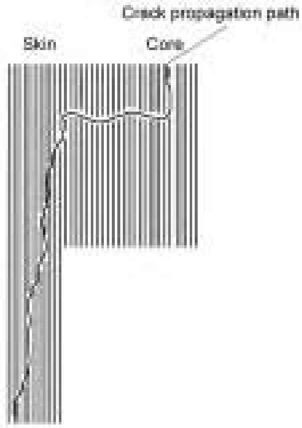
Aramid fibers contain several levels of microscopic and macroscopic morphology. A brief discussion of each is described below using the individual fiber as a starting point.

Skin core fibril structure

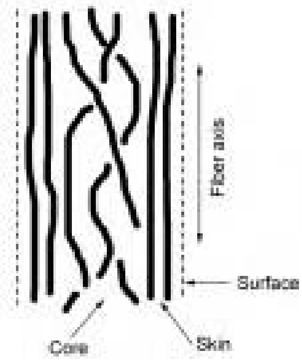
When aramid fiber is subjected to tensile testing, its typical fracture modes are generally a fibrillated type failure. This fracture mode represents a highly ordered lateral fiber structure (see Figs 7.17 and 7.18).

Fiber fibrillar structure

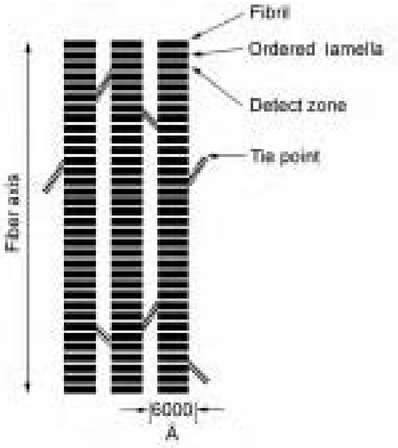
Aramid fiber fibrillates easily upon abrasion especially in the perpendicular direction to the fiber axis. In fact, almost all highly oriented fibers like UHMWPE (such as Spectra® fiber) are easily fibrillated. It is because the macro-molecules were only held together by the van der Waals force, and/or the hydrogen bond force. Figure 7.19 is a proposed model of the fibrillar structures for most of the highly oriented performance fibers. The individual fibrils are the load-bearing elements for the fiber whereas the tie molecule is the load-bearing element for the conventional fibers. The widths of the fibril are about 600 nm and the lengths up to several cms.[2,3]



7.17 Crack in fiber.



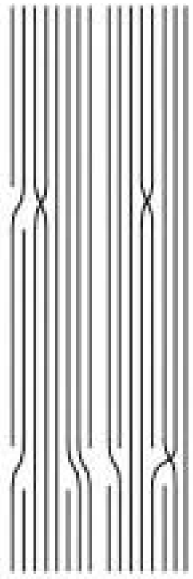
7.18 Skin and core of fiber.



7.19 Fibrillar structure model of aramid fiber.

7.8.3 Aramid fiber morphology and orientation

Figure 7.20 illustrates a fibril. On each fibril, the straight line represents the PPD-T molecular chain. Some of these chains contain breaks or bends. These defects or amorphous layers are the weak links in the fiber structure. However, some of the PPD-T chain can be oriented and extended to bridge several 'amorphous' or defect layers. This unique 'extended chain tie molecule' should give satisfactory fiber strength as shown in Fig. 7.20.

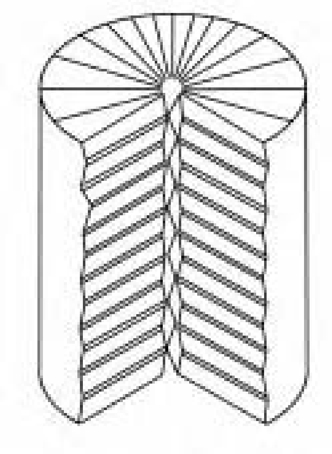


7.20 Crystalline structure model of aramid fiber.

7.8.4 Pleat structure

Aramid fiber has a unique feature when observed under a cross-polarized microscope light field, in that it displays transverse bands. However, these transverse bands diminish when the filament is under tension.[2,3] This leads to the hypothesis that aramid fiber has a pleated structure as in Fig. 7.21. The occurrence of a pleat sheet structure in aramid is not well understood.

For the formation of the pleated structure it has been hypothesized that during the coagulation of the aramid fiber, the skin is first formed and is subjected to attenuation stress on a spinning filament. This allows the 'core' fiber to relax and form pleats at a uniform[2,3] periodicity. The formation of the pleat structure gives the fiber an inherent elongation or elasticity. That may be the reason why when Kevlar fiber is under stress, the transverse bands diminish as observed under the microscope.



7.21 The pleat structure model of aramid fiber.

7.8.5 Crystalline structure

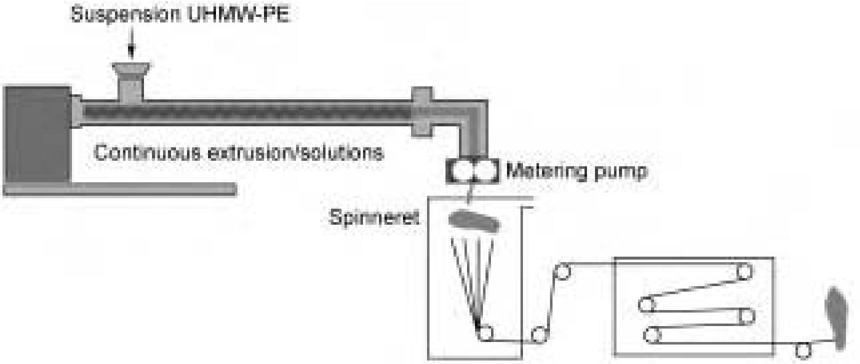
Aramid fiber has a highly crystalline, highly ordered molecular structure. Wide angle X-ray diffraction shows no amorphous halo indicating a highly crystalline fiber. There is a pair of sharp rings in the equatorial scan indicating that the fiber may contain a few percent of unoriented crystals.

7.9 Gel spinning of HMPE fiber

The process of making the high performance HMPE fiber, based on the simplest and flexible polyethylene, is another extreme spectrum of processing methods for high performance fibers. While the chemical structure of the HMPE is identical to the normal high or low density polyethylene (HDPE, LDPE) such as those found in engineering plastics, the HMPE is not melt spinnable due to its extreme high melt viscosity. In addition, because of the very high degree of entanglement in the flexible molecular chain, the drawing for high tenacity yarn HMPE is almost impossible even at a slow drawing rate.

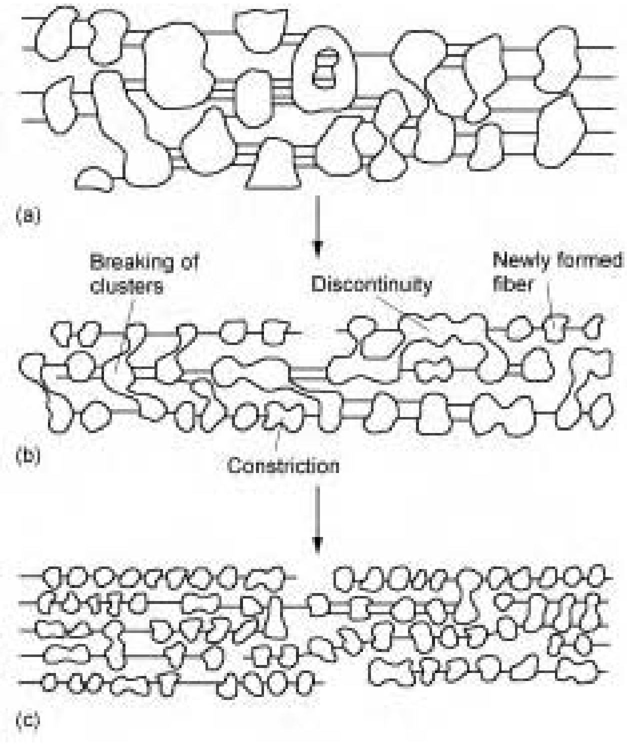
The key to achieve high strength, high modulus properties of the HMPE is by the gel spinning process. In this process, the long, flexible and entangled molecules are dissolved in a solvent from 2–15% concentrations (depending on the molecular weight) and mixed thoroughly via an extruder, helicon mixer or other mixing means as shown Fig. 7.22.

In the solution, the molecules become disentangled and form a loosely connected network called gel. The gel is then spun through a spinneret just like a conventional melt spinning process. After quenching or cooling of the gel fiber, the loosely entangled molecule fiber can be drawn at a very high draw ratio to a highly oriented, long chain crystalline high performance fiber. The solvent to

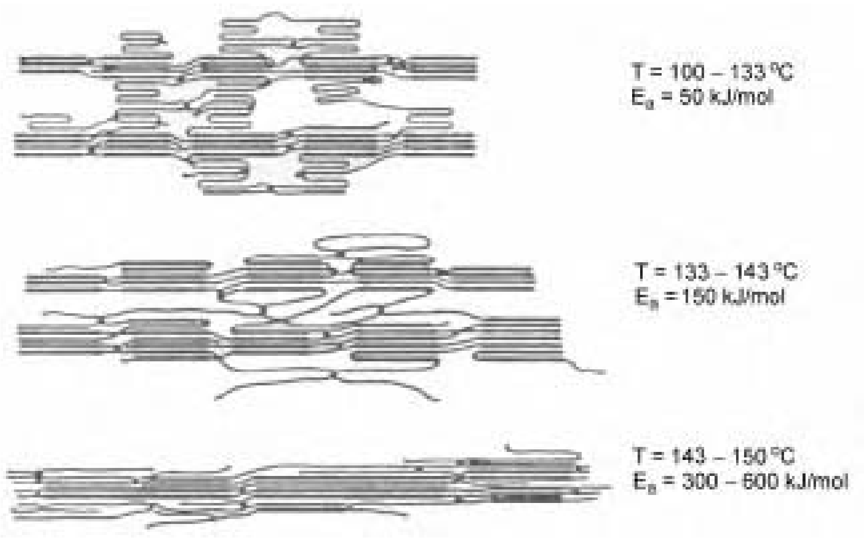


7.22 Schematic of gel spinning process.[6]

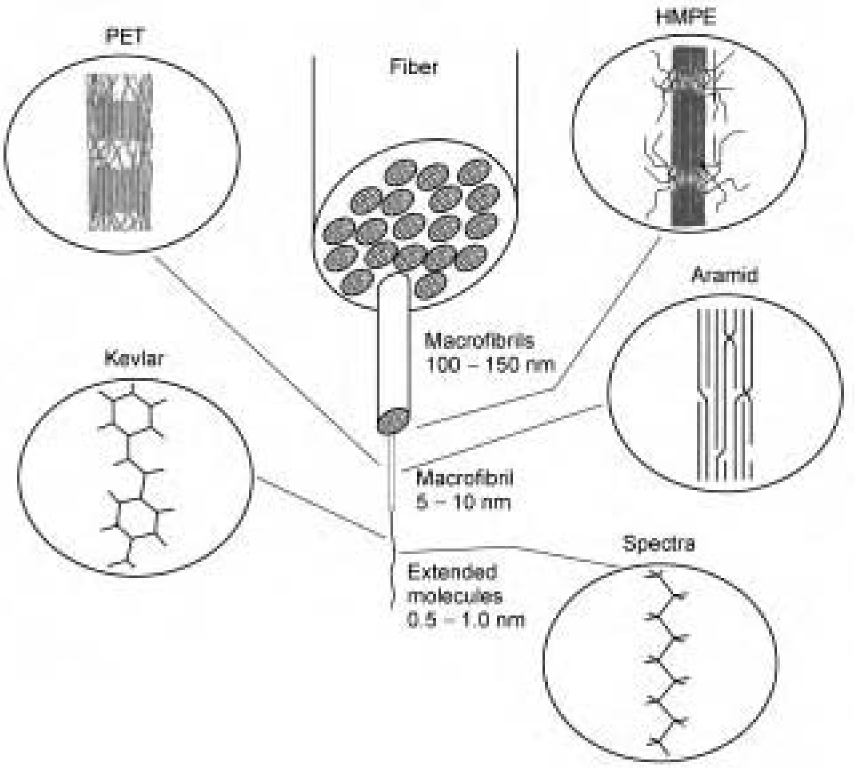
dissolve or disentangle the HMPE can be volatile or non-volatile but the principle of the gel spinning will be the same. The schematics shown in Figs 7.22, 7.23 and 7.24 were proposed by Pennings and colleagues from spinning of the gel to drawing into high performance fiber.[4]



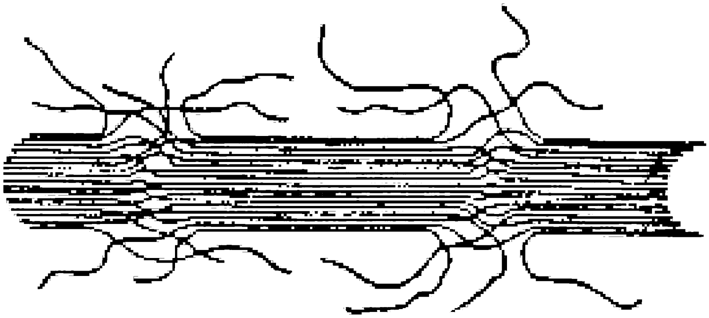
7.23 Deformation stages of gel fiber with solvent.



7.24 Deformation mechanism during hot drawing of HMPE.



7.25 Micro and macro fibrillar structure of PET, aramid and HMPE fibers.



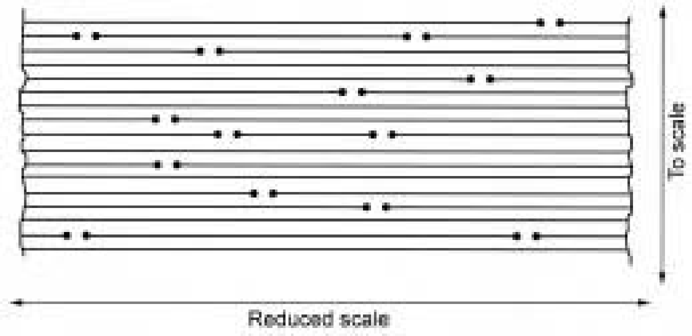
7.26 Micro fibrillars of HMPE fiber.

7.9.1 The morphology of the HMPE fiber

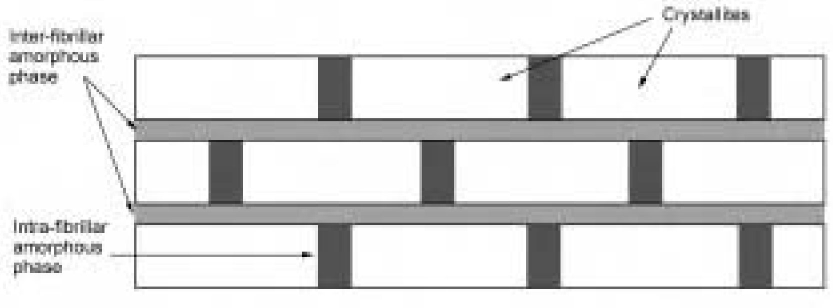
Similar to aramid fibers, ultra high strength HMPE fiber also contains microscopic and macroscopic fiber morphology. The SEM picture shows regular micro and macro structures. Figure 7.25 is a representation of the current model consisting of micro and macro fibrils. The longitudinal structure consists of micro fibrils which have a proposed structure in which nearly perfect crystals are covalently linked through a relatively small amorphous domain (see Fig. 7.26). This micro fibril structure is far from the perfect uniaxial fiber structure and thus the strength of the HMPE fiber, while ten times stronger than steel, is still far from the theoretical strength of the covalent C–C bond (see Fig. 7.27).

It is speculated that an increase the number of 'extended chain' molecules that span the amorphous domain would increase both strength and modulus. The potential is certainly there to further advance the properties of the HMPE fibers (see Fig. 7.27).

Figure 7.28 represents a proposed model for the macro fibrils. Because amphorous matter also exists between the micro fibrils, the structure appears to be a composite of near perfect oriental crystalline micro fibrils imbedded in an



7.27 Proposed longitudinal structure of HMPE micro fibrils.



7.28 Characterisitcs and properties of high performance HMPE fiber showing macro and micro fibrillar.

amorphous matrix. This model appears to be similar to the aramid model discussed earlier. However, the aramid model suggests that a strong inter-macrofil linkage exists because of hydrogen bonding of the polyamide molecules. Figure 7.28 shows a 'clear cut' amorphous and crystalline region.[5] However, there are extended chain molecules that can bridge through several layers of 'amorphous' region. It is speculated that the more of this type of 'bridging' molecule, or a new term called the extended chain tie molecule, the higher strength and more dimensionally stable the HMPE fiber will be.

The typical HMPE fiber's properties are listed in Table 7.2.[6] As the gel spinning and drawing technology mature, fiber properties improve to meet different end uses. As a result, there are different grades of Spectra fibers such as S-900, S-1000 and S-2000 or in case of DSM, SK 75 and SK 76. In short, the new generation product tends to be in lower denier per filament (dpf), higher tenacity and higher modulus.

Table 7.2 Properties of HMPE fibers

Yarn property	Standard fiber	High strength fibers
Tensile strength		
gpd	25.5–30.5	37.5–41.0
Gpa	420–485	3.21–3.61
Initial modulus		
gpd	775–920	1320–1450
Gpa	66–79	113–124
Elongation, %	3.6–4.4	1.9–3.6
Density		
g/cm^3	0.97	0.97

7.10 Poly(p-phenylenebenzobisoxazole) fiber

Synthetic fibers for ballistic applications have been getting stronger and more effective to defeat ballistic threats since the first development of nylon fiber, followed by aramid fiber, HMPE fiber and PBO fiber is the latest commercial fiber in this field.

High performance properties of PBO are originated from the rod-like nature of the polymer chain which also makes the processing of fiber from polymer fairly difficult. The development of production technology on PBO fiber spinning took a long time due to the difficult nature of the rod-like structure. In 1991 Dow Chemical decided to work with Toyobo. Their joint development resulted in a unique spinning technology, opening the way to the industrial production of PBO fiber.

Toyobo received a license from Dow Chemical and has worked on further development. The pilot plant for PBO fiber production was completed in early 1995. The commercial production started in 1998.

7.10.1 Polymerization and spinning

PBO is polymerized from diaminorescocinol dihydrochloride (DAR 2HCl) and terephtharic acid (TA) in polyphosphoric acid (PPA). Current PBO fiber is spun from spinning dope with phosphoric acid solution using air-gap wet spinning technology. On a coagulation process, fiber structure formation through phase separation should occur. The first filaments extruded from a spinneret transform to a swollen micro fibrillar network when the nematic rigid-rod solution touches a coagulant. Passing through the coagulation process, the network loses their open spaces and forms dense fibrillar structure. The coagulated fiber is subsequently washed and dried.

As-spun PBO shows the tenacity of 42 g/d (5.7 GPa) or more and the modulus of 1300 g/d (175 GPa) or more. By heat treatment at around 600 ºC, the as-spun fiber achieves the increase of modulus up to 2000 g/d (275 GPa) without tenacity loss.

7.10.2 Micro fibril and void

Scanning electron micrographs taken on a fractured surface of high modulus PBO fiber show that the fiber is formed from assembly of fibrils, the diameter of which varied from 10 to 50 nanometers. On such fractography, however, careful analysis should be performed to elucidate structural entities, because there may exist some artificial structures generated in the fracturing process.

In PBO fiber, streak-like scattering patterns, which would come from elongated micro voids to the fiber direction, appears on the equator. During the heat treatment process this streak disappears and the four-point pattern, similar to the shape of a butterfly, appears. This kind of striation was reported on PPTA fibers, It is interesting that current high modulus fiber, even stronger than former fibers in tenacity, gives us the same pattern. In the case of high strength polyethylene fiber, this periodic density fluctuation acts as a weak point on tensile strength.

To estimate the cross-sectional diameter of micro voids of PBO fiber intensity profile along the equator was taken from a two-dimensional small-angle X-ray scattering SAXS pattern. The logarithm of the intensity after background correction is plotted against the square of the scattering vector. The data exhibits linearity and the slope gives the average diameter of the micro voids which is measured as 24 A.

7.10.3 Fiber structure and physical properties

Structure

Structure of PBO fiber formation is through coagulation, washing and drying. Since 86% of PPA is extracted from the dope, the structure of as-spun filaments has a fibrillar nature with a capillary void of diameter of around 20 Å which is determined from the plot of small-angle X-ray scattering (SAXS). As-spun fiber has an extended chain structure which is confirmed by the lattice image of electron micrograph and its inverse FT image.

The crystal size of the as-spun fiber is about 100 Å and increase up to 200 Å by heat treatment. SAXS pattern of as-spun fiber shows a four-point pattern. This four-point pattern disappears with heat treatment.

The standard PBO fiber is formed from micro fibrils (preliminary 10–50 nm in diameter) and contains many capillary-like micro voids, which exist between micro fibrils before drying. These micro voids are connected with each other through cracks or openings between micro fibrils. There is a void-free region in the very surface of the fiber. The micro fibril is made of extended PBO molecules, highly oriented to the fiber axis. The Hermann's orientation function measured by WAXS is estimated to be over 0.95. The preferential orientation exists and the a-axis of the PBO crystal aligned radically in the cross-section of the fiber. In the case of higher modulus PBO fiber, the Hermann's orientation function value becomes 0.99 or higher.

Properties of PBO fibers

Tenacity, modulus, heat resistance and flame resistance are the four main physical attributes of the PBO fiber. PBO is the first organic fiber which exceeds steel and even carbon fiber in strength per cross-sectional area. The theoretical modulus of polymers can be easily calculated due to the recent remarkable progress in computer chemistry. The PBO-HM from the Toyobo pilot plant

Table 7.3 Properties of PBO fibers

Filament denier		1.5	1.5
Density	g/cm^3	1.54	1.56
Tensile strength	g/d	42	42
	GPa	5.8	5.8
Tensile modulus	g/d	1300	2000
	GPa	180	280
Elongation break	%	3.5	2.5
Moisture gain	%	2.0	0.6
Decomposition temp.	°C	650	650

shows only the 60% of crystalline modulus of PBO. Fiber modulus of many super fibers achieved crystalline modulus. When PBO fiber achieves the crystalline modulus value, no other fiber from linear polymer will exceed PBO, which is the ultimate fiber in terms of modulus.

The heat resistant property of PBO is about 100 °C higher than p-Aramids. Flame resistance (limiting oxygen index (LOI)) is surprisingly higher than other FR organic fibers such as PBI (LOI 41), which is the former record holder, and p-Aramid (LOI 29).

Thermal stability

PBO fiber shows very high heat resistance. Temperature dependence of physical properties are also very small as compared to other organic fibers. The temperature dependence of crystalline modulus does not change up to 400 °C. Fiber modulus also does not show significant loss even at high temperature. Only 20% loss of modulus is observed at 400 °C. Tenacity at high temperature is also superior to p-Aramid. 15 g/d of tenacity of fiber still remains at 500 °C.

Other properties

Moisture regain is very low, 0.6 wt% for PBO-HM and 2.0 wt% for PBO-AS at 25 °C and 65RH condition. Dimensional stability against moisture and temperature is excellent. Creep rate is about half of that for p-Aramid in the same stress ratio to breaking stress. Chemical resistance against organic solvents and alkaline is excellent and no loss of strength is observed. As for bleach, PBO is superior to other organic super fibers. In acidic conditions, PBO is not as strong as in alkaline, but still is stronger than p-Aramids (Table 7.3).

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8

Fabrics and composites for ballistic protection of personnel

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8.1 Introduction

The recognition of lightweight fibrous material-based armor as a superior system for personnel protection compared to metallic armor occurred during the Second World War.[1–3] This advantage was further confirmed during the Korean War through the observation of significantly reduced incidence and severity of chest wounds with the use of 12-ply nylon fabric vest.[4,5] There are several reasons for the emergence of the fibrous armor for personnel protection. First, fibrous materials in the form of dry or resin-coated fabric are flexible. When the body armor needs to be worn for protection during combat, flexibility is an essential parameter. Second, the anisotropic nature and the shape of the fibers provide the highest modulus and strength at least in the axial direction with a given composition of each material. This is mainly due to the molecular orientation in the axial direction of the fibrous materials produced by the drawing or spinning process. Thanks to a variety of novel means of molecular orientation, a series of high-strength, high-modulus fibers are available including the ones developed specifically for impact or ballistic-resistant applications.

Finally, fibers are excellent reinforcing materials for polymers. When a small amount of polymeric resin is added to the fibers or fabrics, they form a reasonably stiff composite material and can be mass-produced through the molding process. These molded items are more compliant than steel but stiff enough to be shaped into certain fixed forms such as helmets as protection against fragments from exploding munitions. But they are lighter and stronger than steel due to the lower density of both fibers and polymeric resins and the excellent axial properties of fibers. As will be discussed later, resin-lean (usually less than 20% by weight) composites are typically fabricated for both soft and hard personnel armor systems, such as body armor or protective helmets, to achieve most efficient utilization of unique stress–strain behavior of the armor grade fibers.

8.1.1 Armor-grade fibers

The efforts for the development of fibrous armor were accelerated with the introduction of the first successful example of rigid-rod type liquid-crystalline-polymer fibers by DuPont Inc. in the 1970s.[6] This fiber, now known as Kevlar® aramid fiber, and its various derivations, are currently used in many different applications including not only body armor systems for the military as well as law enforcement organizations but also load-bearing structures. Following the Kevlar fibers in the US market, a Dutch firm, Akzo Nobel Inc., introduced the same family of fibers under the trade name of Twaron® in the European market. For the Asian market, the same type of aramid fiber was also commercialized by a Japanese firm, Teijin Inc., under the identical trade name. In addition, Teijin introduced an aramid copolymer fiber under the trade name of Technora®, which exhibits equivalent strength with improved resistance to chemicals and fatigue failure.

In addition to aramid fibers, highly-extended ultra high-molecular-weight polyethylene (UHMWPE) fibers are currently used in various armor systems throughout the world. Since the birth of the synthetic fiber in the 1930s,[7] theoreticians and experimentalists have been suggesting that the absolute maximum values for elastic modulus of straight-chain hydrocarbon polymers are considerably higher than those measured for commercially available textile fibers.[8–14] Mark predicted that the modulus of a straight-chain polyethylene should approach 250 GPa if the molecules were aligned in a planar zigzag conformation.[8] Later, Sakurada[9–11] calculated a modulus value of fully crystalline polyethylene that was close to Mark's predicted value. Works by other investigators in the 1970s showed that the theoretical limit of modulus of polyethylene was between 300 and 400 GPa.[12–14] The laboratory curiosity of achieving the theoretical maximum properties became a reality in the early 1980s when UHMWPE fiber was introduced.[15–23] Currently three companies manufacture this polymer using a similar processing technique. Allied-Signal Inc. (now Honeywell) first marketed Spectra® fiber in the US, while DSM Inc., a Dutch firm, introduced Dyneema® fiber in the European market. Mitsui Petrochemical Inc., a Japanese firm, produced Tekmilon® fiber for the Asian market.

Poly(p-phenylenebenzobisoxazole) (PBO) is another high-strength, high-modulus polymer of rigid-rod type that has high potential for armor applications. This fiber is a product of the US Air Force Materials Laboratory-funded research program, which started in the late 1960s. The patents on the composition and processing were issued in the 1980s.[24–26] A Japanese firm, Toyobo Inc., commercialized this fiber under the trade name of Zylon®.

The majority of the data to be presented throughout this chapter are mainly based on Kevlar, Spectra and Zylon fibers as representatives of aramid, UHMWPE and PBO families, respectively. Although there will be differences in

Table 8.1 Tensile properties of typical armor-grade fibers

Fiber type	Density	Tensile strength		Tensile strain at break	Initial tensile modulus	
	(g/cc)	(g/d)*	(MPa)	(%)	(g/d)*	(GPa)
Nylon-66	1.14	10	1006	18.2	45	5
Kevlar-29	1.44	22	2794	3.5	525	67
Kevlar-129	1.44	27	3429	3.3	755	96
Kevlar-KM2	1.44	27	3429	4.3	500	64
Spectra-900	0.97	31	2610	3.6	920	79
Spectra-1000	0.97	38	3250	2.9	1320	113
Spectra-2000	0.97	41	3510	2.9	1450	124
Zylon-AS	1.54	43	5800	3.5	1325	180
Zylon-HM	1.56	42	5800	2.5	1962	270

* Unit g/d (gram force per denier) is unique for textile materials. Denier is the linear density that is used to describe the thickness of fibers. One-gram mass per 9000 m length of the fiber is one denier. The cross-sectional area (A) of a fiber can be obtained by the following relationship: $A = \text{Denier}/(900000 \text{ cm} \times \rho)$, where ρ is density of the fiber in g/cm^3. For example, assuming the cross sectional area of Kevlar fiber is circular, the diameter of 1.5 denier Kevlar fiber is 12 μm.
Conversion from g/d to Pa is: $\text{Pa} = (8.82 \times 10^7)\ (\text{g/d})\ (\rho)$

processing parameters between different trade names in the same family, chemical composition and physical properties are basically same in most cases and the mechanical as well as ballistic properties are expected to be similar among the fibers of the same family. The density and tensile properties of aforementioned armor grade fibers are listed in Table 8.1.

As shown in the Table 8.1, there is a dramatic jump in tensile properties from melt spun, semi-crystalline polymer of Nylon-66 to Kevlar-29® which is the first commercialized rigid-rod type liquid-crystalline polymer fiber. The variations in physical properties of Kevlar, Spectra and Zylon fibers are mainly due to the post-processing steps, such as drawing, heat setting, etc. The post-processing conditions often alter the morphology of crystal formation as well as the molecular orientation, which will greatly affect the mechanical properties such as modulus and elongation.

8.1.2 Fabric structures

Both non-woven and woven fabric structures of various types are being used either with or without resin matrices for ballistic applications. Typical non-woven fabrics are 'felts', which is constructed by mechanically orienting and interlocking the fibers of a spunbonded or carded web. Another commonly used non-woven structure is the unidirectional 'shield', which is constructed by layering successive arrays of the continuous unidirectional filaments collimated at a specific angle in each layer. In contrast, woven fabrics are constructed through interlacing yarns in two- or three-dimensional patterns. Depending on specific patterns deployed, two-dimensional woven structures are further subdivided into 'plain', 'twill' and 'satin' weaves. In addition to weaving, three-dimensional fabrics are also created by 'braiding'.

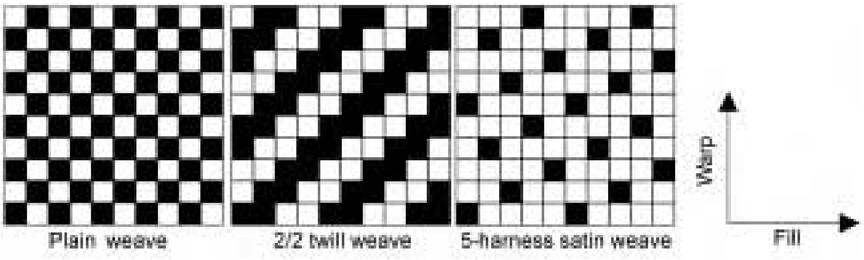
Two-dimensional woven fabrics

Two-dimensional (2-D) woven fabrics constructed through interlacing of yarns at 90° angle are the most common structures for ballistic applications. As shown in Fig. 8.1, basic two-dimensional woven structures are 'plain', 'twill' and 'satin' weaves. Among them, the plain weave fabric exhibits the highest level of yarn-interlacing-density or weave-crimp-density, followed by twill and then satin weave. Therefore, the dimensional stability of plain weave is the highest among these three basic structures.

However, weave crimp created from interlacing of the yarns reduces the efficiency of the reinforcement significantly when the performance of woven fabric composites is compared to that of unidirectional shield composites without crimp. Previous studies on the effect of fabric type suggest that the structures with fewer interlacing yarns show better ballistic performance due to the reduced interference of the strain wave propagation upon ballistic impact.[28] It was also found was that the fabrics constructed of finer yarns performed better than the fabrics constructed of thicker yarns. This result indicates that the detrimental effect of crimp can be overcome by increasing the number of yarns involved in the resistance to projectile penetration. Apparently, the chance to have effective fiber breakage upon ballistic impact, which is the major source of kinetic energy absorption, is greater with fine yarn-based fabric systems than thick yarn-based systems.

Following is a summary of physical characteristics of typical fabric structures used in high strength composites including armor and aerospace applications.[29]

Plain weave is the most common weave style. It is formed by weaving the warp and fill yarn in an over-one-under-one fashion. Plain weaves will be very open and easy to wet-out. On the other hand, the open weaves will require a higher resin content to fill in the gaps in the weave pattern. In addition to woven fabric, woven roving can be produced in a plain weave and is usually flatter.



8.1 Three typical basic weave structures of fabric.

Basket weave is similar to a plain weave, but two or more yarns are grouped together in both warp and fill directions and alternately interlaced over and under each other. Basket weave is flatter and more pliable than plain weave. Basket weaves have less problem of pre-buckling because the yarns do not alternate over-and-under as often as plain weave. Basket weaves are often used to weave thick, heavy reinforcements.

Twill weave is somewhat like a basket weave where the yarns are woven over-two-and-under-two; however, only one yarn at a time is woven instead of two. A 2 × 2 twill weave is when a single yarn is woven over-two-under-two. The weave increment can be increased as in the case of 4 × 4 twill, where a single yarn twill is passed over-four-under-four. Twills are characterized by the diagonal pattern that is formed by the weave. This optical illusion often confuses fabricators into laying-up the material 45° off the desired fiber orientation. Twill weave is more pliable than plain weave and has better drapeability while maintaining more fabric stability compared to four- or eight-harness satin weaves. Twill weaves are often used for fabrication of complex shaped composite structures in both vacuum-bagged and wet lay-up processes. Carbon fiber twill material is often chosen for its aesthetic appearance.

Crowfoot weave is the first weave in a family of what are called satin weaves patterns. The crowfoot weave is actually a 4-harness satin. The yarns are woven under-one-over-three, or that the yarn is woven under every fourth yarn. Hence the term 4-harness satin is used.

5-harness satin weave: In the quest for more straight yarn, a 5-harness satin can be used. Here the yarn passes under every fifth yarn or an over-four-under-one pattern. 5-harness satin is a common weave used in aerospace manufacturing when parts with complex shapes need to have very high strength and light weight.

8-harness satin weave: The yarns are woven under-one-over-seven or under every eighth yarn. This is the weave pattern for thin fiberglass reinforcement fabric that is commonly used throughout the aerospace industry.

Three-dimensional fabrics

Three-dimensional (3-D) fabrics are constructed by interlacing the yarns in the network-forming fashion while introducing the third dimension other than the planar dimension. Various types of 3-D fabrics are available based on the orientation of the yarns. Typical structures are 3-D 'braiding' and 3-D 'weaving'. The main advantage of a 3-D structure is reinforcement in through-the-thickness direction; hence the dimensional stability of 3-D structures is much greater than that of 2-D structures.

As a result, 3-D reinforced composites exhibit excellent damage tolerance upon ballistic impact by showing more localized damage.[30–32] On the other hand, 3-D reinforced composites are often less advantageous than 2-D counterparts in the effectiveness of kinetic energy absorption of the relatively thin structures that are used in body armor systems, such as, helmets.[32] The difference can be attributed to either higher resin content of 3-D reinforced composites at a given thickness or the change of failure modes such as suppression of the delamination process.

Selection of optimal system

Currently the most commonly used fabric structures for ballistic applications are *plain weave*, *basket weave*, and *unidirectional shields*. In determining the fabric structures, yarn size, the tightness of the weave, surface treatment, such as scouring, water-repellent finishing for proper adhesion of resin matrices as well as moisture absorption are additional parameters to consider for the optimum conditions for fiber reinforcement. Tables 8.2 and 8.3 show the various fabric structures of Kevlar and Spectra fabrics, respectively, that are currently used in various ballistic applications.[29]

8.1.3 Resin matrices

One of the first matrix material systems qualified for ballistic protective body armors was phenolic resin blended with polyvinylbutyral (PVB) resin. This polyblend resin system was originally developed by DeBell & Richardson Inc. for nylon helmet liners in the early 1960s.[33] The resin is typically formed by mixing phthalic anhydride-catalyzed phenol formaldehyde and PVB with the 1:1 ratio of two components by weight. Carswell[34] reported that the phenolic/PVB system exhibits superior properties to either the PVB (themoplastic) alone or the phenolic (thermoset) alone. In the final phenolic/PVB blend system, the toughness, flexibility and elasticity of the thermoplastic (PVB) is retained, while the presence of phenolic resin phase reduces the susceptibility of materials to heat or solvent. The ballistic resistance level was found to be acceptable when this resin was combined with various reinforcing materials, such as nylon,[35] Kevlar[36,37] or glass fibers.[38]

The phenolic/PVB resin is widely used as matrices, especially, for Kevlar fiber composite armors and has demonstrated superior peel strength compared to other resins such as phenolic-vinylacetal polyblend.[39] From the studies on the effect of various compositions of phenolic/PVB systems, Song *et al.*[40,41] reported that the 40 to 60% PVB gives higher interfacial bonding strength than other compositions. Furthermore, they reported that the ballistic impact resistance of composites was also found to be the optimum in the 40–60% PVB region. Kevlar fiber-reinforced composite specimens with the matrix resins of lower PVB composition (0 to 20%) exhibited a brittle shear failure with inferior ballistic performance.

As optimum matrix resin systems for Spectra polyethylene fabric composites, two top choices are vinylester (VE) (Derakane® derivatives by Dow Chemical Company) and thermoplastic polyurethane (PU) (Dispercol® by Mobay Chemical

Table 8.2 Various Kevlar fabric structures and constructions

Weave	Yarn denier Warp × filling	Construction Warp × filling	Thickness (mm)	Weight (g/m^2)	Breaking strength (kg/cm) Warp × filling
Kevlar-29 and -129					
Plain	840 × 840	31 × 31	0.3048	220.59	161 × 170
Plain	1500 × 1500	24 × 24	0.4318	319.00	197 × 214
Plain	1000 × 1000	31 × 31	0.3810	281.67	161 × 166
Plain	840 × 840	26 × 26	0.2540	196.83	134 × 143
Plain	1500 × 1500	17 × 17	0.3048	223.98	139 × 145
Plain	1420 × 1420	17 × 17	0.2794	220.59	152 × 152
Plain	1000 × 1000	22 × 22	0.2540	281.67	116 × 130
Plain	400 × 400	32 × 32	0.1524	108.60	80 × 77
2 × 2 basket	1500 × 1500	35 × 35	0.5842	468.32	322 × 325
2 × 2 basket	1420 × 1420	35 × 35	0.5842	464.93	349 × 357
Plain	200 × 200	40 × 40	0.1270	71.27	60 × 58
Plain	3000 × 3000	17 × 17	0.6096	461.53	286 × 322
8 × 8 basket	1500 × 1500	48 × 48	0.8128	638.00	393 × 411
4 × 4 basket	3000 × 3000	21 × 21	0.7620	546.37	357 × 357
4 × 4 basket	3000 × 3000	24 × 24	0.7620	610.85	416 × 447
Kevlar-LT					
Plain	400 × 400	36 × 36	0.1778	122.17	98 × 100
Kevlar-KM2					
Plain	850 × 850	31 × 31	0.3048	230.77	157 × 170
Kevlar-49					
Plain	1420 × 1420	17 × 17	0.3048	217.19	125 × 134
Crowfoot	195 × 195	34 × 34	0.0762	57.69	38 × 38
8H satin	380 × 380	50 × 50	0.2032	166.29	118 × 116
Plain	195 × 195	34 × 34	0.0762	57.69	46 × 46
Plain	380 × 380	22 × 22	0.1016	74.66	53 × 53
Plain	1140 × 1140	17 × 17	0.2540	169.68	112 × 115
Crowfoot	1140 × 1140	17 × 17	0.2286	169.68	111 × 114
Plain	1420 × 1420	13 × 13	0.2540	162.89	102 × 107
4 × 4 basket	1420 × 1420	28 × 28	0.4826	363.12	243 × 232
4 × 4 basket	2130 × 2130	27 × 22	0.6350	461.53	326 × 263
8 × 8 basket	1420 × 1420	40 × 40	0.6604	509.04	327 × 320

Company).[42–48] A blend of VE and PU as well as other resin systems such as melamine-formaldehyde, polyvinylalcohol and modified phenolic/PVB systems were also considered.[45] Detailed study based on Spectra fabric-reinforced composites with VE versus PU resin matrices[42] confirmed that the penetration failure resistance of composite armors is inherently limited by the stiffness and volume content of resin matrix. These two factors control the degree of reinforcement movement thereby influencing the ‘energy absorption characteristics’ and

Table 8.3 Various Spectra fabric structures and constructions

Weave	Yarn denier Warp × filling	Construction Warp × filling	Thickness (mm)	Weight (g/m^2)	Breaking strength (kg/cm) Warp × filling
Spectra-900 fabrics					
Plain	1200 × 1200	10 × 10	0.305	101.72	89 × 89
Plain	1200 × 1200	17 × 17	0.457	186.48	160 × 152
Plain	1200 × 1200	21 × 21	0.508	237.34	196 × 178
Plain	650 × 650	34 × 34	0.432	213.60	169 × 160
8 × 8 basket	1200 × 1200	48 × 48	0.965	525.53	446 × 410
8H satin	1200 × 1200	21 × 23	0.457	247.51	196 × 214
Spectra-1000 fabrics					
Plain	215	45 × 45	0.152	88.15	98 × 85
Plain	650	17 × 17	0.279	94.93	107 × 98
Plain	650	34 × 34	0.432	203.43	196 × 187
Plain	215	56 × 56	0.178	108.50	125 × 116
Plain	375	32 × 32	0.178	108.50	107 × 98
8H satin	650	32 × 32	0.355	186.48	187 × 178
Plain	375	32 × 32	0.178	108.50	107 × 98
Spectra-2000 fabrics					
Plain	180	49 × 49	0.007	2.45	440 × 440

'deceleration time of projectile' during penetration. The same study showed that stiffer VE resin matrix tends to restrain the yarn movement to a greater degree thereby enhancing the ballistic energy absorption capacity of composites.

Despite their advantages in terms of stiffness, heat resistance or solvent resistance, there are growing environmental concerns about thermoset resin systems, including phenolic and VE resins, due to the solvents used and hazardous fumes generated during the prepreg processing. Another major disadvantage of thermoset resin system in general is their limited shelf life due to the continuous cross-linking reactions of the resin during the storage period. In addition, thermoset resins are not recyclable and the fiber-reinforced composites with thermoset resin matrices cannot be easily repaired.

In this respect, thermoplastic resins are potential alternate matrices over thermoset resins for many armor-grade composite structures.[49] Thermoplastic matrix composites offer significant improvements in terms of the durability and the processing costs over conventional thermoset resin matrices. The inherent toughness and chemical resistance of these polymers make them well suited for composites. Of course, a reasonably high level of strength and creep resistance should be maintained under harsh environments. Since thermoplastics are melt-processable, they offer potential ease of fabrication and quick field repair based on resin remelting.

Aside from the above-cited case of thermoplastic polyurethane (Dispercol) matrix resin for Spectra fabric composites, styrene-butadiene-styrene diblock copolymer (Kraton® from Shell Chemical Company) has been used as a matrix material for commercially available composite shields based on UHMWPE fibers, such as Spectra and Dyneema. Thermoplastic resin systems such as low-density polyethylene (LDPE) and linear-low-density polyethylene (LLDPE) are also used in Kevlar fabric composites.

8.1.4 Armor-grade composites

Lightweight composite structures for ballistic protection utilize outstanding impact resistance of high-modulus, high-strength polymeric fibers such as Kevlar®, Spectra®, Zylon® fibers.[27,39–52] These fibers in the form of collimated continuous filaments or woven fabrics are embedded in the resin matrix forming a unique class of fiber-reinforced composites, the so-called 'armor-grade' composites. As discussed earlier, the armor-grade composites are constructed with a very low resin content (less than 20% by weight) to achieve maximum utilization of the inherently high resistance of fibers to the transverse impact.

As a result of very low resin content, these composites are relatively flexible unless a structure of considerable thickness is constructed. Armor-grade composite laminates are widely used in hard personnel armor systems, such as protective helmets, against fragments from exploding munitions.[27,40–48,52,53] The increasing use of aramid or UHMWPE fiber composites for ballistic protection is also found in lightweight armored shelters.[51]

For the aforementioned applications, the most important parameter in evaluating the ballistic impact resistance of materials is a critical level of projectile velocity or kinetic energy applied to the system below which no full perforation occurs.[28,46] The property is referred as 'ballistic limit' V_C or V_{50} in which 50 means 50/50 chance of full penetration in probability plot. Also important are the residual strength and damage tolerance characteristics of the materials with partially penetrated projectiles or surface damage, which determine the long-term survivability of the protective systems.

Past experience clearly indicates that the tensile stress–strain properties of the fibers are the most important parameters in predicting the ballistic performance of armor-grade composites. Apparently the major source of kinetic energy absorption upon ballistic impact is fiber straining despite the fact that the phenomenon is complicated by its highly dynamic nature of loading. Of course, it is impossible to apply the tensile properties of the fibers as universal parameters to predict ballistic performance of all candidate materials, mainly because of their differences in physical and thermal characteristics.

However, for the same materials with slight difference in post-processing conditions, it is possible to correlate their quasi-static tensile properties to the highly dynamic ballistic properties. In Table 8.4, Riewald *et al.*[27] illustrated how

Table 8.4 The ballistic limit (V_{50}) and ballistic efficiency (V_{50}/shell weight) of helmets produced with two typical aramid fibers (Kevlar-29 and Kevlar-KM2)

Fiber	Yarn denier	Shell wt (kg)	V_{50} (m/s)	V_{50}/wt (m/s/kg)	Tensile toughness (MPa)	Tensile strength (MPa)	Tensile strain at failure (m/m)	Tensile modulus (GPa)
Kevlar-29	1500	1.34	686	511.94	51	2794	0.033	67
Kevlar-KM2	1500	1.13	697	616.81	72	3429	0.043	64
% difference		−15.67	1.60	20.48	41.18	22.73	30.30	−4.69

the basic tensile properties of the fibers or yarns affect the ballistic performance of the final product of the protective helmet. For more direct correlation, tensile properties obtained from the yarns are also listed in Table 8.4. For both composite helmet systems under evaluation, the same resin of phenolic/PVB blend was used as matrices. The fabric structure of Kevlar-29 was 2 × 2 basket weave while Kevlar-KM2 was constructed with plain weave structure. The areal density of these two different woven structures was same at 0.36 kg/m^2 (14 oz/yd^2).

As shown in the Table 8.4, there is no significant difference in tensile modulus values of these yarns. The initial slope of the curve is straight in both cases until it breaks without exhibiting the yield region. However, significant differences exist between two types of yarns in the cases of tensile strength, tensile strain at failure and tensile toughness, i.e. the area under the stress–strain curve. The data clearly indicate that the significantly increased strength (more than 20%) and higher failure strain (more than 30%) of Kevlar-KM2 yarn are responsible for significant improvement of ballistic performance efficiency (more than 20%) of resulting composites. Also the same ballistic performance of composites was observed for KM2 reinforced composites with more than 15% lighter weight compared to Kevlar-29 counterpart. This illustration demonstrates the importance of basic tensile properties of fiber for the prediction of materials behavior even in a highly dynamic phenomenon such as ballistic impact.

8.2 Impact testing

The impact resistance of fibrous materials was investigated extensively for a variety of applications including fabric armors,[65,66] fiber-reinforced composite armors,[27,44,50,56] hard ceramic-faced composite armors,[54,55] as well as aircraft/aerospace composite structure.[57–60] These applications have demanded a thorough understanding of their mechanical behavior when subjected to transverse impact loading.

The impact loading conditions can be classified into the following groups according to the striking velocity and the penetrator mass: (a) low-velocity impact,[61,62] and (b) ballistic impact.[63–66] As a reference condition for comparison with these impact loadings, the quasi-static puncture[67–69] test is often performed in the laboratory by applying simple transverse loading at a low enough strain rate that dynamic effects are negligible. Quasi-static puncture loading is machine driven at a constant velocity, which simulates a penetrator with infinite mass since no deceleration occurs during testing.

Low-velocity impact[61,62] occurs in situations such as automobile accidents and falling debris impact with relatively low initial heights. Low-velocity impact testing can be performed in a drop-weight configuration (in which the penetrator is driven by gravity), or a hydraulic test machine. While the drop-weight impact test configuration involves a variable velocity, the hydraulic test machine allows constant velocity of the penetrator.

In contrast to low-velocity impact, ballistic impact is a highly dynamic event involving a transient stress wave propagation.[63–66] In many cases, the impacted material will fail before the stress waves reflect from the material boundaries.[64] As the name suggests, ballistic impact is generally caused by bullets or fragments from exploding ammunitions. The mass is, therefore, usually much smaller than that of low-velocity impact, and the impacting velocity is much greater than that of low-velocity impact. In ballistic testing, the high penetrator velocity is often accomplished using an actual gun or a pressurized gas gun system. As in drop-weight impact testing, ballistic impact involves a variable impacting velocity since the penetrator decelerates during the event.

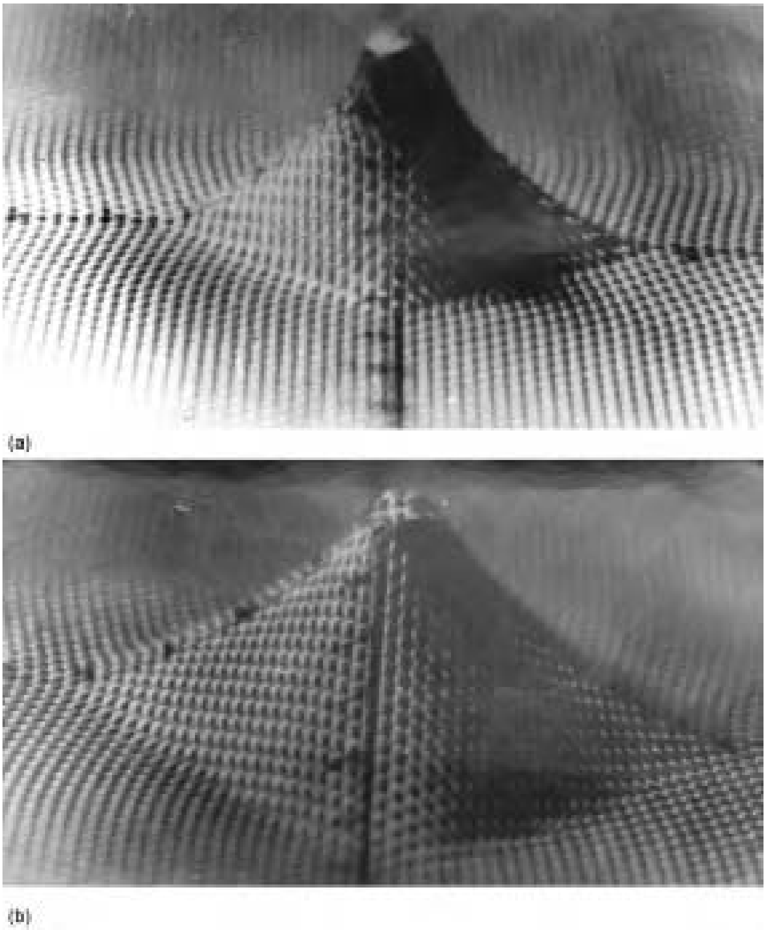
8.3 Penetration failure mechanisms of fabric and composite armors

Numerous experimental and analytical investigations have been undertaken to uncover the penetration failure mechanisms of the composites under impact.[42,44,48,50,54–58,60–62] In contrast to the case of more rigid composites designed for typical aerospace structures, the dominant energy absorption mechanism of relatively flexible armor-grade composites of very low resin content appears to be the fiber straining effect.[42,70] However, resin matrix properties were found to have some influence on the overall ballistic performance of flexible composites.[42,70] This effect of a small amount of resin matrix has not been fully characterized, particularly with regard to the effect of yarn-to-yarn coupling with the presence of a small amount of resin. Past investigations have also focused on the response of dry textile fabrics with no resin matrix against ballistic impact.[65,66] Here the complicated decrimping mechanisms occur during the final stages of penetration failure.

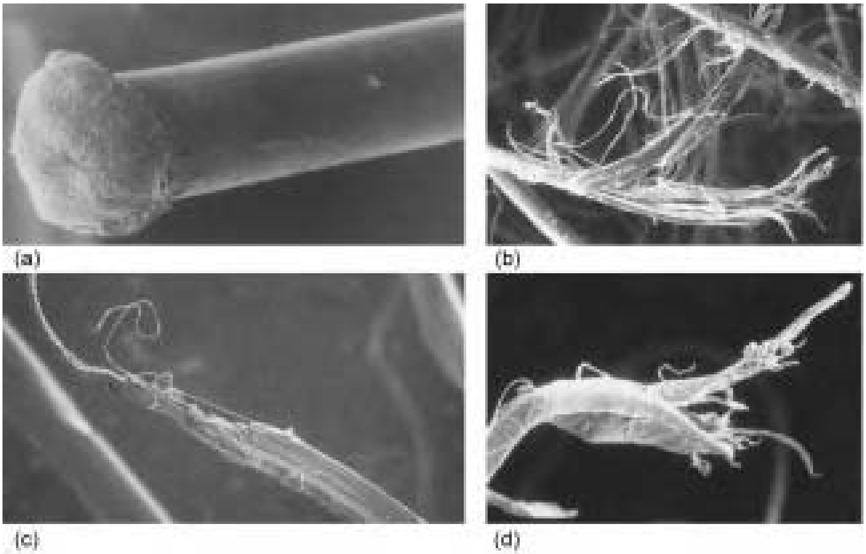
8.3.1 Fabric armor

Figure 8.2 illustrates a typical penetration mode observed in Nylon-66 and Kevlar-29 fabrics upon ballistic impact.[71] In both cases, the cone shapes were formed due to the wave propagation mainly along the orthogonally oriented yarns from the impact point. Since Kevlar-29 has a significantly higher modulus than Nylon-66, a noticeably larger cone is formed with Kevar 29 than Nylon-66 (see Fig. 8.2). This clearly indicates that the Kevlar-29 absorbs more kinetic energy than Nylon-66 fabric upon ballistic impact.

As discussed earlier, a major source of kinetic energy absorption by the armor system upon ballistic impact is fiber breakage through tensile straining of fibers. Hansen[72] nicely described the penetration mechanism of fabric armor under ballistic impact. He stated that the initial step in the ballistic process of the fabric armor systems is the development of strain in the impacted yarns as a result of displacement under impact. The distended yarns then intersect others, and at these cross-over points two significant and opposing events appear to occur. The yarns originally impacted share some of the strain with the fibers intersected and thus ‘unload’ themselves. At the same time, the yarn intersection results in a reflection of some of the energy in the strain wave back toward the impact point. This increases the strain at the impact point and unless the projectile significantly slowed the process (with resultant loss of kinetic energy), the strain will eventually exceed the yarn fracture strain, and penetration occurs.



8.2 Cone formation observed on Nylon-66 (a) and Kevlar-29 (b) fabrics upon ballistic impact. The fabric structure (2 × 2 Basket weave), the areal density of the fabrics (14 oz/yd^2) as well as mpact velocity (200 m/s) are identical. Projectile used is 17-grain fragment simulating projectile (FSP).



8.3 Fiber failure upon ballistic penetration of Nylon-66 (a), Kevlar-29 (b), Spectra (c) and Zylon (d).

Resultant failures of fibers under ballistic penetration are shown in Fig. 8.3.[73] The failure modes of Kevlar fiber are splitting and severe fibrillation. PBO fiber also shows similar behavior as Kevlar. Nylon-66 fiber exhibits the evidence of melting. The UHMWPE fiber, such as Spectra fiber, exhibits the fiber straining, kinking due to the strain as well as snap-back of fibers after breakage. The evidence of melting was also observed in the case of Spectra fiber. To explain this phenomenon, the following two opposing views were reported: (a) the melting is due to the heat generated from the friction between target and projectile during the penetration; and (b) adiabatic heating effect after the penetration.[44,74]

Failure modes of fibers are also influenced by other factors, such as yarn denier, weave structures, degree of twist and yarn orientation. Figucia[75] examined the effect of a number of fabric constructions on ballistic impact resistance. According to his results, the satin weave fabric having more floating yarns (see Fig. 8.1) shows superior performance over basket or plain weave fabric in both single and multi-ply systems. This report also indicated that the fabrics constructed with the finer denier yarn are more efficient energy absorbers than the fabric constructed with the coarse yarn, on an equal areal density basis. Similar conclusions appear to be valid in the composites. The studies on Spectra fiber composites revealed that, with less fiber interlacing, angle-plied laminate of unidirectional tapes performed significantly better than plain weave fabric composites.[42]

8.3.2 Composite armor

Hansen[72] reported that the basic failure mechanisms in Kevlar and glass fiber composites under ballistic impact are delamination, shear deformation in the resin, and straining of the fibers. In their detailed studies on the failure mechanisms of glass/epoxy composites upon ballistic impact, Malvern *et al.*[76–78] concluded that the penetration-induced fiber breakage is one of the major damage modes in high-velocity impact. In case of low-velocity impact, however, delamination accompanied by matrix cracking was found to be an equally important damage mode.

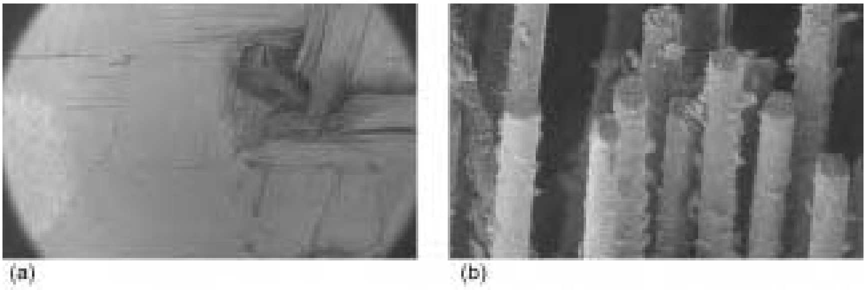
In the studies of failure mechanisms of Kevlar-29 and S-2 glass fiber composites with thermoset resin matrices, Song and Egglestone[79] confirmed that the fiber breakage is the major source of the kinetic energy absorption. Furthermore, the fiber breakage due to the straining resulted from the wave propagation along the fiber axis is the most preferable failure mode for the optimum ballistic resistance. Figure 8.4 clearly shows severe straining at the impact point for Kevlar-29 composites. Matrix cracking and fiber-matrix debonding were also observed reasonably far away from the impact point, presumably due to wave propagation and reflection along the fiber axis from the impact point. Wave propagation and reflection is also believed to contribute to the process of fiber fibrillation at the impact point.

On the other hand, S-2 glass fiber composites showed shear failure (see Fig. 8.5) with minimal disturbance of fibers immediately away from the impact point. Unless they undergo severe fiber motion as shown in Fig. 8.4, the contribution of delamination in ballistic impact energy absorption process is minimal.

The UHMWPE fibers, such as Spectra and Dyneema, have totally different thermal and physical characteristics. Unlike other armor-grade fibers, UHMWPE fibers melt at a relatively low temperature (around 150 °C) and their glass transition temperature is significantly below room temperature (around -120 °C). In contrast, other high strength fibers described earlier are thermally stable until they reach their decomposition temperatures, which are usually greater than 400 °C. Therefore, UHMWPE composites deserve some attention on their failure modes under ballistic impact.

Lee *et al.*[42,48] reported close examinations of ballistic penetration failure modes of Spectra fabric- as well as Spectrashield-reinforced composites. In Spectra fabric-based composites, fibers apparently fail due to the shear or fiber cutting in the plies close to the striking surface and by clear tension failure at the rear of a completely penetrated panel. Lateral movement during the penetration is similar to the cases of other fabric composites by showing the delamination in a symmetrical, out-of-plane cone shape around the impact point. As shown in Fig. 8.6, shear failure at the striking surface and tension failure at the rear portion of the target were also observed in Spectrashield angle-ply composites.

8.4 Ballistic failures observed on five ply Kevlar-29 composites. As marking shown here, the trace of the wave propagation and matrix cracking and fiber–matrix debonding are shown. 17-grain FSP projectile was used.



8.5 Ballistic failures observed on five ply S-2 glass composites. (a) Front view of the panel. (b) Close look of failed fibers. 17-grain FSP projectile was used.

(a) (b)

8.6 Ballistic failures observed on Spectrashield composites. (a) Front view of the panel. (b) Rear view of the panel. 17-grain FSP projectile was used.

However, the delamination pattern of the Spectrashield angle-ply composites appears to be different from the case of fabric-reinforced composites.

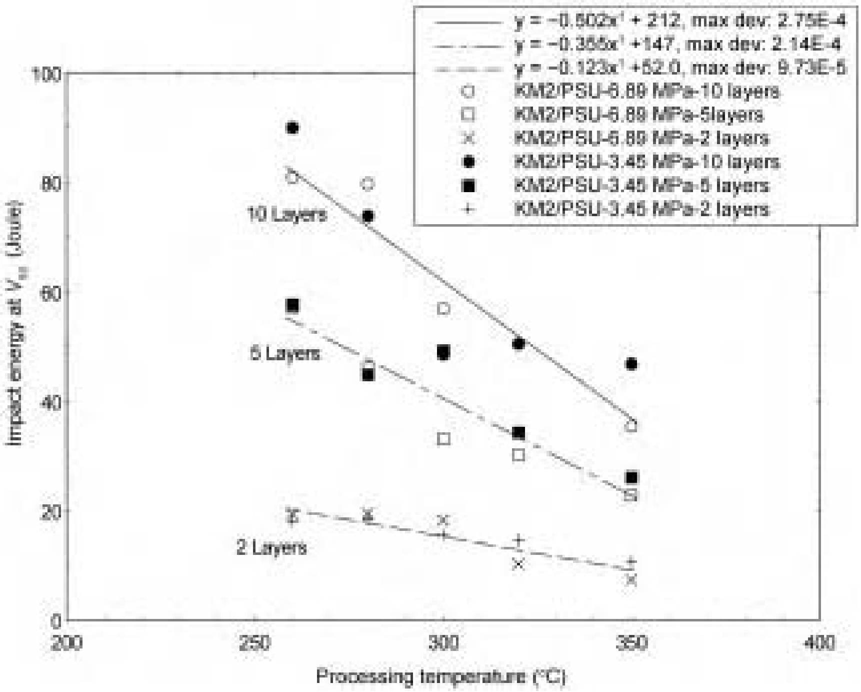
The delamination in Spectrashield angle-ply composites more closely resembles the generation strip phenomenon observed by Cristescu *et al.*[77] on their studies of glass/epoxy composite systems. Upon impact, the projectile pushes a strip of the first ply of the laminate. This first strip of the laminate, in turn, applies a transverse load to the second ply and generates delamination successively through the remaining plies of the laminate until complete penetration occurs or the projectile is stopped. The length of the strip is considered to be somewhat dependent upon the amount of the time required for the projectile to cut through the first ply and the width of the strip usually correlates to the diameter of the projectile. In angle-ply Spectrashield, the generator strip configurations tend to follow the angle of the respective fiber orientation in the panel.

The contribution of fiber failure to the kinetic energy absorption during the penetration of the projectile can be estimated by observing the broken fibers of the target materials after penetration. Hsieh *et al.*[70] examined the performance of Kevlar and Spectra dry fabrics and their fabric composites under low velocity and ballistic impact. For both cases, composites outperformed the dry fabrics. Postmortem examination of the specimens revealed that more fibers were broken in the composites than in the fabrics.

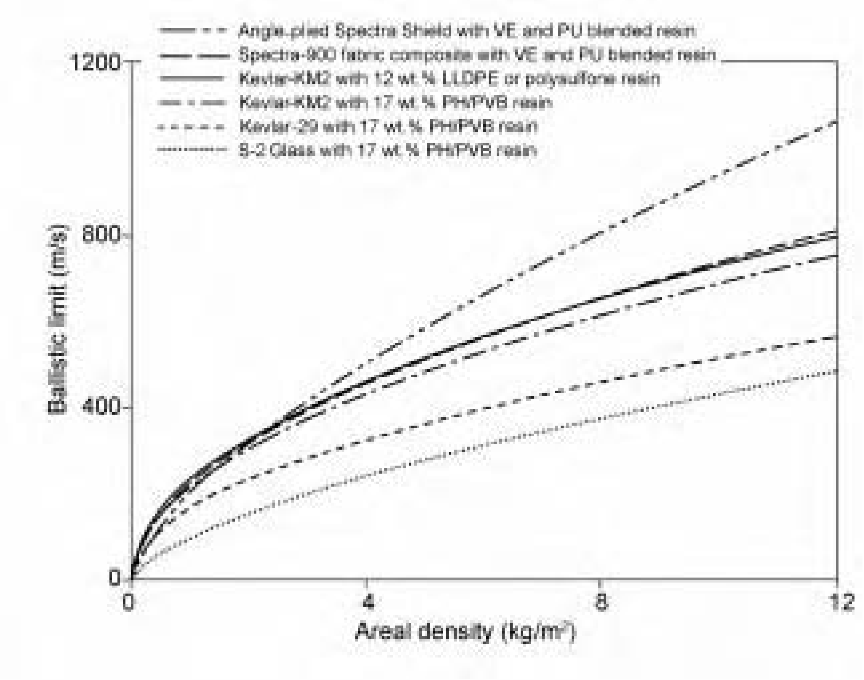
Lee *et al.*[48] also observed higher kinetic energy absorption of Spectra-900 fabric composites over the same configuration Spectra-900 dry fabrics. Restricting the fiber movement by applying a small amount (<20% by weight) of resin resulted in more fibers involved in breakage than the dry fabric, which allows considerable yarn slippage during the projectile penetration. They also studied the effect of resin systems of Spectra fabric composites by examining the broken fibers after penetration. The Spectra fabric composite with vinylester (VE) resin system showed more broken fibers than Spectra fabric composite with polyurethane (PU) resin system. The resultant ballistic performance in terms of kinetic energy absorption was better for Spectra/VE composite than Spectra/PU composite. The stiff nature of the VE resin system seems to be more effectively constraining the fiber and resulted in more fiber breakage during projectile penetration than in the ductile PU resin system.

As indicated in the discussion above, although the contribution might not be as significant as fiber types, resin types also directly or indirectly contribute in absorbing kinetic energy upon ballistic impact. Resin property changes due to processing could be another factor affecting kinetic energy absorption of the composites. This is especially the case for the thermoplastic resin systems, since the thermoplastic resins could have larger processing windows than thermoset resin systems. In the studies on thermoplastic composites for ballistic applications, Song[80] reported the significant influence of the resin properties on ballistic performance, especially, on the amorphous polymers, such as polycarbonate (PC) and polysulfone (PSU). As shown in Fig. 8.7, the impact energy absorbed by the Kevlar-KM2/PSU composites was significantly reduced by increasing the processing temperature.

By increasing the processing temperatures, stiffness of the Kevlar-KM2/PSU composites increased due to improved wetting of the composite as well as morphological conformation changes of the resin systems. Apparently, the



8.7 Impact energy absorbed at the ballistic limit, V_{50}, by the Kevlar-KM2/PSU composites as functions of processing conditions.



8.8 Ballistic performance of relatively thin composites with various fiber reinforcements, resin systems and resin contents. Data shown are obtained using 17-grain Fragment Simulating Projectile (FSP).

stiffness of the Kevlar-KM2/PSU composites was inversely proportional to the ballistic energy absorption. The postmortem evaluation revealed the evidence of shear failure of the fibers on higher-temperature-processed Kevlar-KM2/PSU composites.

The effects of fiber reinforcement, resin types, resin content and fiber configurations of relatively thin composites used in ballistic protective body armor applications are shown in Fig. 8.8 to illustrate the relative importance of these complicated parameters.

The empirical relationship of $V_c = \gamma(A_d)^{\delta}$, which can be found in Reference 41 and illustrated in the next section, was used to fit these curves. Here V_c is the ballistic limit, A_d is areal density of the composites, γ and δ are the constants. The values of the constants γ and δ are listed in Table 8.5. Similar relationships were also found in thickness variations.[48]

Although the data shown in Fig. 8.8 are the result of a complicated mixture of various parameters, Fig. 8.8 illustrates the relative importance of those parameters that are important for optimization of the composite systems. As mentioned above, angle-plied unidirectional Spectrashield composite showed significantly better performance than Spectra fabric composite. This result,

Table 8.5 The values of the constants γ and δ

	S-2 Glass/ PH/PVB	Kevlar-29/ PH/PVB	Kevlar-KM2/ PH/PVB	Kevlar-KM2/ LLDPE or PSU	Spectra-900	Spectra-shield
γ	98.81	157.69	216	234	223	200
δ	0.64	0.56	0.502	0.492	0.518	0.67

mainly, illustrates the importance of the effect of the configuration of reinforcement fibers. The difference between Kevlar-29/Phenolic-PVB, Kevlar-KM2/Phenolic-PVB and S-2 Glass/Phenolic-PVB composites clearly shows the effect of fiber types. The effect of resin types and resin contents are also shown in the Kevlar-KM2 composites.

8.4 Analytical models predicting penetration failure and ballistic limit

One of the most important issues encountered in the study of penetration mechanics under ballistic impact is the determination of a critical velocity below which a projectile will perforate a target. This particular property is commonly termed as a *ballistic limit* and is of prime importance in the design of protective systems against ballistic impact. A comprehensive review of the ballistic penetration mechanics of conventional metallic materials can be found in References 81 and 82. Many attempts have been made to relate striking velocity and residual velocity of the projectile to the ballistic limit for a variety of materials.[46,56,59,66,69,81–89] Due to the complex nature of the ballistic penetration process, most of the studies on penetration modeling are empirical or semi-empirical.

Awerbuch and Bodner[88] proposed the three interconnected stages of target metal plate perforation under ballistic impact with plug formation and ejection being the principal mechanism. Here the plug means the material separated from the body of the target in front of the projectile. In the first stage, the forces acting on the projectile are (a) an inertial force, due to the acceleration of the mass of the target material in contact with the projectile in the direction of motion, and (b) a compressive force, due to compressive strength of the target material in contact with the projectile. The second stage of penetration is the onset of through-the-thickness shearing of a plug from the target plate. The third stage starts when the plug is fully developed. The plug and projectile move together as a rigid body with shearing force acting on the plug's circumference along its whole length.

For the prediction of the ballistic limit velocity, Recht and Ipson[85] considered the ballistic impact penetration of a blunt-headed projectile, which was assumed to be the non-deformable projectile. The penetration process is modeled as the inelastic impact of two free cylinders, the projectile and the plug separated from the body of the target material in front of the projectile. Since the impact is considered completely inelastic, the final velocity of the projectile and the plug is the same. Momentum must be conserved; hence,

$$V_r = \left[\frac{m_p}{m_p + m_s}\right] V_s \tag{8.1}$$

where V_r and V_s are residual and initial or striking velocity, respectively, and m_p and m_s are masses of the projectile and the plug, respectively.

The energy lost to deformation and heat during this impact (E) is the difference between the initial and final kinetic energy,

$$E = \frac{1}{2} m_p V_s^2 - \left[\frac{m_p}{m_p + m_s}\right] \frac{1}{2} m_p V_s^2$$

or

$$E = \left[\frac{m_s}{m_p + m_s}\right] \frac{1}{2} m_p V_s^2 \tag{8.2}$$

Additional kinetic energy will also be lost through the shear deformation during the perforation due to the presence of the circumferential shear area, denoted as W, then the perfectly valid energy balance can be written:

$$\frac{1}{2} m_p V_s^2 = E + W + \frac{1}{2}(m_p + m_s) V_r^2 \tag{8.3}$$

At the critical velocity of ballistic limit (V_c), which is the highest velocity for $V_r = 0$ or the lowest velocity to penetrate the target, i.e. $V_s = V_c$ where $V_r = 0$, hence

$$W_c = \left[\frac{m_p}{m_p + m_s}\right] \frac{1}{2} m_p V_c^2 \tag{8.4}$$

where W_c is the value of W at $V_s = V_c$.

For a given target element and projectile, the kinetic energy loss due to the presence of the circumferential shear area at critical velocity, W_c, is assumed to be constant. Incorporating equations 8.2 and 8.4 into equation 8.3 and solving for V_r gives the following expression.

$$V_r = \frac{m_p}{m_p + m_s} \sqrt{V_s^2 - V_c^2} \tag{8.5}$$

Using the same approach based on the conservation of energy and momentum, Lambert[84] derived an equation of more generalized form than the Recht–Ipson equation discussed earlier.

$$V_r = a(V_s^p - V_c^p)^{1/p} \qquad \text{for } V_s > V_c \tag{8.6}$$

Here $a = \dfrac{m_p}{m_p + h m_s}$ and the empirically determined $h = 1/3$. a and p are parameters to be optimized for a given situation.

Equation 8.6 forms the basis of the Jonas–Lambert model, which can incorporate the Recht–Ipson equation (8.5) as a special case. For a non-deformable rigid projectile, p is equal to 2. Then:

$$V_r^2 = A(V_s^2 - V_c^2) \qquad \text{for } V_s > V_c \tag{8.7}$$

By definition, the critical velocity, V_c, is the highest velocity for $V_r = 0$ or the lowest velocity to penetrate the target. Therefore, V_c is a constant for a given target material and type of projectile. Therefore, equation 8.7 can be written as a hyperbolic form:

$$V_r^2 = AV_r^2 - B \qquad \text{for } V_s > V_c \tag{8.8}$$

where $B = AV_c^2$ is the intercept of a linear regression of V_s^2 versus V_r^2 plot. Hence,

$$V_c = \sqrt{\frac{B}{A}} \tag{8.9}$$

Zhu *et al.*[56] proposed the three stages of penetration of fiber-reinforced composites, which is similar to the three stages of the penetration on the metallic plate proposed by Awerbuch and Bodner.[88] The first stage is indentation. Like the metallic plate, this indentation is caused by the compression force acting on the projectile. The indentation stage terminates when fiber failure first occurs. The second stage is perforation, which is similar to the plug formation in the metallic plate. In this stage, further penetration increases the contact area, which enhances the resistance to penetration of the laminate. On the other hand, successive fiber failure reduces the penetration resistance. Fiber failure dominates the resistance of composites. The final stage is the exit of the projectile. Similar to the third stage of a metallic target described above, friction is the only resistance to further motion of the projectile.

As an alternative, Vinson *et al.*[90–92] proposed the conical shell model. Upon impact of the ballistic projectile into the composite material structure, a conical shell forms and proceeds to develop until either the projectile penetrates the target or its velocity is reduced to zero. This conical shell is primarily in a state of membrane stress and strain, and the resistance to penetration is almost exclusively due to the membrane strain energy. Through an iterative method, at a given striking velocity, the velocity changes with time as does the ultimate strain to failure at $V_r = 0$, which is the strain at critical velocity, V_c. The relationship between ultimate strain and striking velocity showed a linear relationship for the given target and projectile type, which can be used to predict the V_c for the given V_s.

For the case of dry fabric, Cunniff[66,83] considered the exchange of total energy during the penetration with strain energy (E_{se}) and kinetic energy (E_{ke}) such that:

$$\frac{1}{2}m_{\mathrm{p}}(V_{\mathrm{s}}^{2}-V_{\mathrm{r}}^{2})=E_{\mathrm{se}}+E_{\mathrm{ke}} \tag{8.10}$$

At the instant of the critical velocity (i.e., $V_{\mathrm{s}}=V_{\mathrm{c}}$ where $V_{\mathrm{r}}=0$), where the projectile and target are at rest, the energy partition at that instant is all in the form of strain energy.

$$E_{\mathrm{se}}=\frac{1}{2}m_{\mathrm{p}}V_{\mathrm{c}}^{2} \qquad \text{for } V_{\mathrm{s}}=V_{\mathrm{c}} \tag{8.11}$$

Above the critical velocity, the strain energy function is a strictly decreasing function and expressed as an exponential decay function to fit the data as follows:

$$E_{\mathrm{se}}=\frac{1}{2}m_{\mathrm{p}}V_{\mathrm{c}}^{2}\mathrm{e}^{-K_{1}\left(\frac{V_{\mathrm{s}}-V_{\mathrm{c}}}{V_{\mathrm{c}}}\right)K_{2}} \qquad \text{for } V_{\mathrm{s}}>V_{\mathrm{c}} \tag{8.12}$$

Here K_1 and K_2 are the regression constants. For $V_{\mathrm{s}}>V_{\mathrm{c}}$ or after completion of penetration, kinetic energy of the projectile takes over while strain energy is negligible.

$$E_{\mathrm{ke}}=\frac{1}{2}K_{3}A_{\mathrm{d}}A_{\mathrm{p}}V_{\mathrm{r}}^{2} \qquad \text{for } V_{\mathrm{s}}\geq V_{\mathrm{c}} \tag{8.13}$$

K_3 is another regression constant, A_{d} and A_{p} are the areal density of the target and the presented area of the projectile, respectively. Note that $A_{\mathrm{d}}A_{\mathrm{p}}$ is equal to that mass of a plug of target material immediately in front of the projectile.

From their extensive experimental studies on Kevlar, Spectra and glass fiber reinforced composites, Lin *et al.*[46] found the relationship between the energy lost to deformation and heat at the critical velocity of ballistic limit, E_{c}, and the projectile diameter, D, as $E_{\mathrm{c}}=\alpha D^{\beta}$ where α and β are regression constants. Equation 8.8 can then be expressed as

$$V_{\mathrm{r}}=\sqrt{A\left(V_{\mathrm{s}}^{2}-\frac{2}{m_{\mathrm{p}}}\alpha D^{\beta}\right)} \tag{8.14}$$

From their studies on graphite/epoxy composites, Lee and Sun[59,69] calculated the ballistic limit by predicting the *residual* velocity from the static punch data using the following relationship:

$$E_{\mathrm{r}}=\frac{m_{\mathrm{p}}}{2}V_{\mathrm{r}}^{2}=\frac{m_{\mathrm{p}}}{2}V_{\mathrm{C}}^{2}-F_{\mathrm{E}}(b+h) \tag{8.15}$$

where b and h are the length of the projectile and the thickness of the laminate, respectively. V_{C} is the velocity at the point C in a force–displacement trace during the static punch-through test, where the sudden drop of force occurred.[69] At this point the plugging is initiated. The whole plug is assumed to form instantly. F_{E} is the stationary friction force at point E, which is the point where the plug is being pushed out of the specimen.

The ballistic limit, V_{c}, was calculated by incorporating V_{r} from equation 8.15 into equation 8.16 below.

$$V_c = \sqrt{V_s^2 - V_r^2} \qquad \text{for } V_r > 0 \tag{8.16}$$

Later, Sun and Potti[87] proposed a simple model to predict the residual velocity as

$$V_{RS} = \sqrt{V_s^2 - \frac{2}{m_p} E_{DP}} \tag{8.17}$$

where V_{RS} is predicted residual velocity and E_{DP} is dynamic penetration energy. Assuming the dynamic penetration energy is constant for a range of incident velocities, the dynamic penetration energy was estimated by the energy balance equation

$$E_{DP} = \frac{1}{2} m_p (V_s^2 - V_r^2) \qquad \text{for } V_r > 0 \tag{8.18}$$

where V_r is the experimentally measured residual velocity at a particular incident velocity V_s for the particular specimen and projectile.

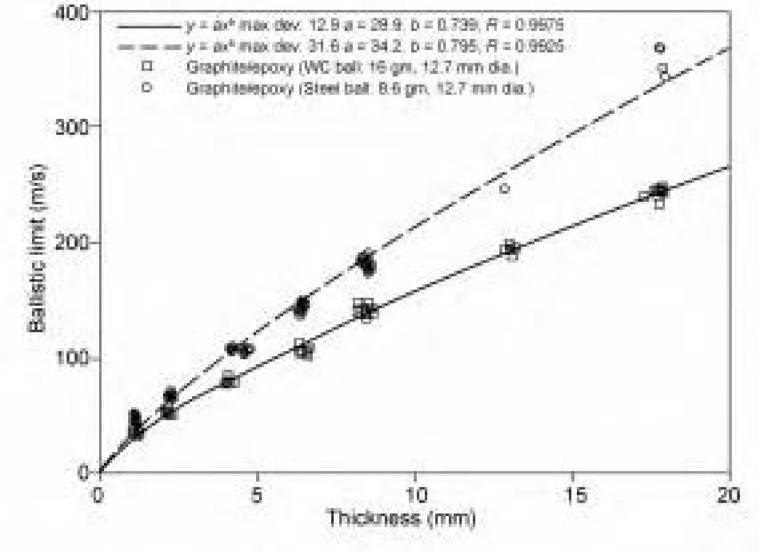
As amply confirmed by the field experience, the increase of target thickness raises the ballistic limit velocity V_c.[41,52,56,70] For example, Segal[52] reported that the ballistic limit is proportional to the areal density. For the case of relatively thin plates of graphite/epoxy composites, Hsieh *et al.*[70] reported that the energy absorbed, which is proportional to V_c^2, increases linearly with the number of layers in the laminate and that strain rate effects are minimal. In other words, the exponent value of a power law correlation between V_c and the thickness should be 1/2. However, in their study covering extra thick laminates of graphite/epoxy composites up to 18 mm, Lee and Patts observed that the exponent value of a power law correlation is no longer 0.5.[48,93,94]

The same study including a comparative evaluation of aluminum, polycarbonate and polymer composites demonstrated that the nature of failure mechanisms of target materials under ballistic impact can be related to the exponent value of a power law correlation between the thickness and the ballistic limit velocity V_c. As a result of additional mechanisms of energy absorption during the penetration failure (such as delamination, interfiber cracks and fiber fracture), the exponent depicting the thickness dependence of V_c was found to be 0.74 to 0.80 instead of 0.5, in the case of graphite fiber/epoxy resin composite (Fig. 8.9).

In similar vein, as discussed earlier in this chapter, Song and Egglestone[41] derived a complex relationship between the ballistic limit and areal density of relatively thin flexible composites in the following equation:

$$V_c = \gamma (A_d)^\delta \tag{8.19}$$

where A_d is areal density of the laminate and γ and δ are constants that are closely related to the material properties as well as the laminate configurations of target.



8.9 Ballistic performance of graphite/epoxy composites with various thicknesses.

Finally, for a special situation of personnel armor with hybrid material composition, Florence[95] established a simple analytical model that consists of one very hard, inflexible surface backed by flexible composites. When a projectile strikes the hard ceramic facing of the composite, most of the momentum is spread over a circular area the diameter of which is dependent on the mechanical and geometrical properties of the projectile and the ceramic facing. Experimental observations indicate that, for much of the motion, the backing remains bonded to the ceramic facing outside the circular area thus confining most of the kinetic energy absorption to the backing within the circular area. Consequently, the backing can be analyzed as a circular membrane or plate fixed at the circular boundary and having an initial mass and velocity distribution.

The following empirical relationship was proposed:

$$V_{\mathrm{c}} = \left[\frac{\epsilon S}{0.91\, m_{\mathrm{p}} f(a)}\right]^{1/2} \tag{8.20}$$

and

$$f(a) = \left(\frac{m_{\mathrm{p}}}{m_{\mathrm{p}} + (m_{\mathrm{c}} + m_{\mathrm{b}})\pi R^2}\right)\pi R^2$$

where ϵ is the maximum strain of the backing material, S is the constant tension on the backing material, m_{c} and m_{b} are the mass of the ceramic and the backing material, respectively, and R is the radius of the circular area on the surface of the backing material, which was involved in the failure and energy absorption process.

The aforementioned analytical models are a list of various approaches to predict the ballistic limits from the penetration mechanics of the target materials and the systematic experimental studies. Although the penetration mechanisms of fiber-reinforced composites are more complex than homogeneous metallic plate, the models based on the penetration mechanics of a metallic plate appear to provide reasonable guidelines for fiber-reinforced composites.

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9

Non-woven ballistic composites

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9.1 Introduction

Humans have used forms of protective armor in combat for at least five millennia. At first animal skins and furs were the only protection both in combat and in cold weather. Ancient civilizations used leather as a form of protection beginning in roughly 3000 BC. The use of leather has continued as a means of various types of body protection. Some 700 years later, ancient cultures such as those in Egypt learned to alter leather by boiling and tanning it. Leather was very effective in warding off blows from bludgeoning weapons and can be found serving this role in some cultures and subcultures up to the present day.[1]

The first fabricated weapons of note in warfare were swords and spears, so more advanced armor was at first designed specifically to address these threats. The Egyptians were using armor to protect from slashing and cutting weapons as early as 1500 BC. The first forms of armor were probably cloth garments with bronze scales or plates sewn mounted on them. The Assyrians apparently developed lamellar armor between 900 and 600 BC by mounting small rectangular plates upon a garment in parallel rows. Later, the Greeks made armor from bronze plates that not only fitted over the individual parts of the body, but were shaped to fit over the part of the body where it would be carried. Chain mail seems to have been invented by the Celts in Europe, but it was quickly adopted by the Romans and many subsequent civilizations afterward.[1]

By the end of the sixteenth century and with the advent of firearms, armor had to withstand and absorb impact from large caliber projectiles. The weight of armor increased up to about 50 kg, which was a burden on the wearer. The leather garment originally created to be worn under armor was used alone, because it gave the wearer mobility. A debate began then about what was more important, optimum protection or comfort and mobility.

> As early as the 14th century, armor was given a proof rating which guaranteed its protective qualities against weapons of the time. By the 17th century ballistic testing was required for proofing protective gear. Some surviving armor shows marks of ballistic testing.

During all of the armor developments of the ancient and medieval cultures, the greatest threats to soldiers and their armor were the ballistic weapons. Of these, the bow and the crossbow first posed the most dangerous challenges to survival on the battlefield.

Standard bows were able to penetrate many armors at ranges of 30–50 yards in early warfare, but the wooden or metal overlaid wooden shield was able to effectively defeat most of these weapons. The Celts apparently were the military technologists who again changed warfare by introducing the longbow by the 13th century A.D. This devastating projectile weapon was, in a sense, the first hint of the effectiveness of the later repeating rifles on battlefields. The longbow could put up to six arrows in the air simultaneously and accurately at targets 200 yards away before the first arrow in the volley hit. In continental Europe, crossbows became so effective against armor that the Church actually banned their use in warfare for a time.

Eventually, armor for nobles became thick and heavy enough to withstand most hits by even longbows or crossbows, so a further development in lethality was needed. This step came in the form of the gun.

Guns and gunpowder were introduced to Europe from China, where such weapons were in widespread use by the 12th century. Early guns were no more effective against royal armor than bows, but they eventually became powerful enough to render the use of any armor of the times ineffective. Thus it seemed that the struggle between weapons and armor had been won by the weapons until the reappearance of a new and practical concept in the Second World War.[2]

9.1.1 Modern armor

The British Royal Air Force and the US Army Air Corps created and issued protective vests to flight personnel beginning early in the Second World War. These early ballistic resistant armors were known as ‘flak’ jackets because German Anti-Aircraft Artillery was known as FLAK (Fliegerabwehrkanonen). Thus, flak jackets are ballistic resistant garments intended solely for the purpose of defending a body from shrapnel, or explosion fragments, and not from bullets. These first flak vests contained steel plates carried in multiple plies of nylon fabric that protected against relatively low velocity shrapnel.[3]

During the period of the 1950s through early 1960s, the various military branches began to define levels of protection they believed would represent the real threats to service personnel from combat weapons.[4] (See Fig. 9.1.)

9.1.2 Scientific armor studies begin

By the Vietnam War, combat infantrymen were wearing ceramic and/or ballistic nylon vests to protect themselves against both fragment and lower speed projectile threats.

Early Military Standards

- US Army
  - range = 5 feet
  - witness plate 6 inches behind armor target
  - penetration of armor + plate = fail
  - no plate penetration = pass
  - determine max velocity at which pass occurs
- US Navy
  - range = 5 feet
  - no witness plate
  - target penetration = fail
  - no penetration by a projectile = pass
  - fragment penetration without projectile penetration = pass

9.1 Test protocols from early military standards determinations.

Today it is common practice for both combat personnel and military police to use ballistic protection fabrics and plates to defend against fragments and some small arms threats. The military standards which were used to rate the effectiveness of these materials varied according to end use and even according to the military service branch which was testing them, but in general, the stopping power of the material was evaluated based on its ability to completely stop a penetrating projectile (see Fig. 9.1). Some military standards also evaluated the material deformation and target deformation after impact.

Despite its obvious lack of sophistication by present standards, it quickly became apparent in such testing that no material or combination of materials could withstand the entire spectrum of ballistic objects or magnitudes of velocity of such objects and remain intact or protect the wearer/user.

The most common major standards for civilian and police ballistic threats that are used by the market's suppliers of fabrics and fibers to compare performance of products are those in the USA and in the European Union. The US Standard is from the National Institute of Justice (NIJ) and identifies four levels of threat plus two subparts. These levels range from rather low velocity or low mass projectiles at Level I to very high velocity, high mass projectiles at Level IV. The NIJ standard in current use is 0101.04, although the older 0101.03 standard can still be found in application for body armors produced when that part was in effect and will be in use until their lifespan has been exceeded (see Tables 9.1 and 9.2).

In both of these NIJ standards, armor is tested using Roma Plastilina #1 modeling clay as a test backing to determine how much impact is transferred to the body after the bullet is stopped. The US standard is 44 mm (1.73 inches) of indenting into the clay after bullet stop (Fig. 9.2).

The various classes within the standard represent the energy threats and penetration power of various bullets and bullet types. If armor is present, the total energy a bullet delivers to its target is not as important as how well it

Table 9.1 NIJ Standard 0101.03 for protection classes

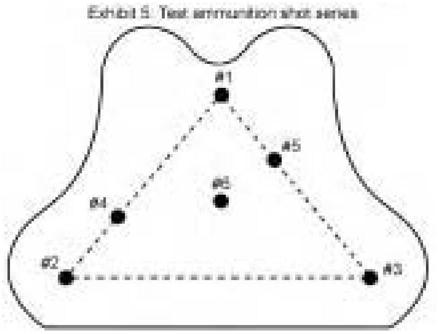
Threat level	Caliber	Projectile description	Mass (g)	Velocity (m/s)
I	.22 Long rifle	Lead	2.6	320
I	.38 Special	Rounded, lead	10.2	259
IIA	9 mm	Full metal jacket	8.0	332
IIA	.357 Magnum	Jacketed soft point	10.2	381
II	9 mm	Full metal jacket	8.0	358
II	.357 Magnum	Jacketed soft point	10.2	425
IIIA	9 mm	Full metal jacket	8.0	426
IIIA	.44 Magnum	Lead semi-wadcutter	15.55	426
III	7.62 mm Winchester	Full metal jacket	9.7	838
IV	.30-06	Armor piercing	10.8	868

Table 9.2 NIJ 0101.04 (http://www.nlectc.org/pdffiles/0101.04RevA.pdf)

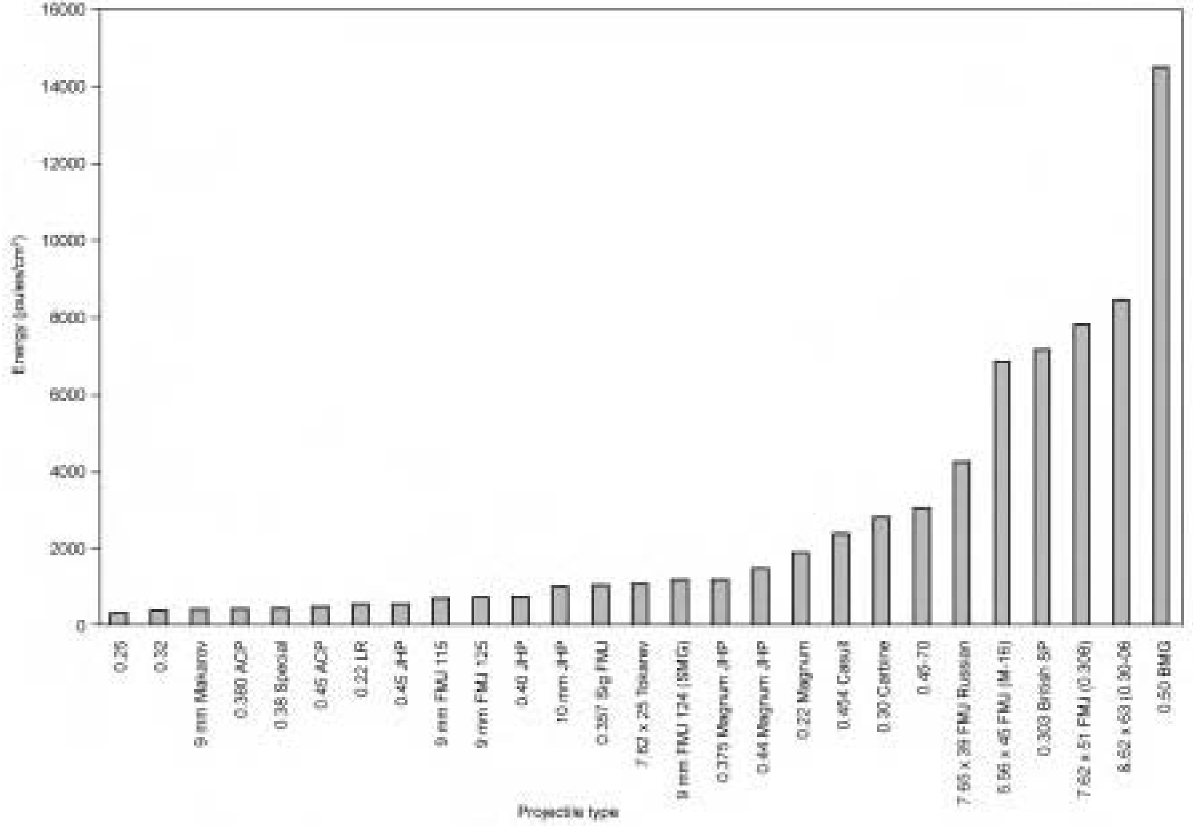
Threat level	Caliber	Projectile description	Weight g (gr)	Velocity m/s (ft/s)
I	.22 Long rifle	Lead	2.6 (40)	329 (1080)
I	.380 ACP	Full metal jacket	6.2 (95)	322 (1055)
IIA	9 mm	Full metal jacket	8.0 (124)	341 (1120)
IIA	.40 S&W	Full metal jacket	11.7 (180)	322 (1055)
II	9 mm	Full metal jacket	8.0 (124)	367 (1205)
II	.357 Magnum	Jacketed soft point	10.2 (158)	436 (1430)
IIIA	9 mm	Full metal jacket	8.0 (124)	436 (1430)
IIIA	.44 Magnum	Jacketed hollow point	15.6 (240)	436 (1430)
III	7.62 mm NATO	Full metal jacket	9.6 (148)	847 (2780)
IV	.30-06	Armor piercing	10.8 (166)	878 (2880)

Scheme of recommended target strikes

- Level I, IIa, II, and IIIa require two shots at 30 degrees and four at 90 degrees
- Level III ('high powered' rifle tests) require six shots at 90°
- Level IV (armor piercing rifle) tests require one shot at 90°
- All targets are tested for deformation against Roma Plastilena modeling clay backing, 24″ × 24″ × 4″ in dimension



9.2 Recommended ballistic testing procedure for National Institute of Justice standards. Graphic courtesy of National Institute of Justice (NIJ Standard 0101.03, p. 10, method "A").



9.3 Energy delivered to a target by various ammunitions.

penetrates the target. The smaller the bullet, the more energy per square inch (or square centimeter), and the greater the penetrating power exists (Fig. 9.3).

When blunt tipped, hollow point or bullets are the projectile threat, the energy is released much more quickly than when ballistically optimized bullets are present. Metal jacketed bullets stay together longer and penetrate farther than soft lead or hollow point bullets do, therefore they are a greater threat to ballistic resistant armors. Large quantities of energy, released quickly onto an armor that successfully stops the bullet, can still be very serious unless the armor system can absorb the energy of impact.

As an example of what this means, the following illustration is offered: if a police officer is on duty and a criminal shoots at him/her, the officer wants the best possible armor to stop the penetration of the bullet first. After that, the officer wants low impact to the body from the bullet's energy when it is stopped. Some highly touted bullet types, like the .38 Special JHP, the .45 ACP, and the .40 S&W deliver a lot of energy quickly into a soft target (a body) to bring it down. For this very same reason, they are very ineffective against body armor, and they are the easiest bullets to stop with modern armor. On the other hand, the 9 mm FMJ, the .357 magnum JHP and the .44 magnum JHP/SJHP are very dangerous. The magnum rounds deliver penetrating power followed instantly by a massive blow even if the bullet is stopped.

Worse yet for blunt impact force than the magnum handguns are the shotguns. Although most soft body armor above Level IIA can stop the pellets, or even a slug, the energy of impact from a slug or from 00 or 000 buckshot can still permanently injure or kill the wearer. For this reason, new efforts are being made to reduce the impact from weapons after bullet termination.

Bullets like the 7.62 x 25 mm and the 5.7 mm FN are very small, but they can go through most soft body armor without problem. They have what may be described as a 'high energy density', that is, high velocity, notable mass and a very small area of impact into which they concentrate all their deadly penetrative energy. These weapons are far more dangerous than the slower, thicker .45 ACP or .40 S&W projectiles for this reason. Rifles above .22 magnum caliber require rigid, or 'hard', armor. Such armor types may consist of either metal, ceramic, pressed hard plastic or combinations thereof to stop anything from a .30 caliber M-1 carbine, .30-30 rifle or more energetic projectiles. The term 'bulletproof' has been discarded by both armor testers and armor producers in favor of the more descriptive term 'ballistic resistant' shortly after a rational testing scheme for these materials was adapted.

The grim reality of the race between protection and lethality is that no matter how assiduously the designer attempts to protect a user from death and injury, there is always something that can deliver a fatal or disabling wound through any given armor. Until humans so radically changes their nature that they cease their desire to murder or maim their fellow creatures, this will remain true.

Categories of military armor

Ballistic resistant materials for military purposes presently fall into three general categories:

1. garments, such as vests.
2. helmets.
3. vehicle and structural reinforcement.

Ballistic resistant vests, jackets, and similar garments are often mainly for protection against shrapnel and bomb fragments. Protection from military caliber small arms is quite challenging in most cases because of the high velocities, low aspect ratios and hard surfaces of the projectiles. Although such high level protection is vital, it is cumbersome for long-term use in field situations.

Law enforcement armor needs

Police protective equipment is usually designed for handgun threats and sharp instrument threats such as one would encounter from ordinary criminals. Higher level protection is available for protection from more organized criminal threats, terrorism and riots, but it is not normally issued for daily use. Police equipment is ideally designed for constant use for the most commonly expected threat.

Police departments usually have to rely on city budget managers, city councils and mayors to receive whatever protective products they can get, and most such people are not sufficiently educated about ballistic protection to decide these life and death issues. The real dangers of daily situations in the life of a law enforcement officer are poorly understood by buyers, the press and the public. Even the end users are often ill-informed about what protective materials can and cannot do.

It seems appropriate, therefore, to discuss what levels of protections are provided by various products and categories, and how the products are defined for specific end-uses.

9.2 Protective materials, devices and end-use requirements

All ballistic resistant materials have certain common characteristics. The use of polymer materials has made the protection to weight ratio very favorable for their use over metals or ceramics. Lower weight also permits greater mobility and better capability for police or military personnel to perform their assignments with reduced threats from attackers.

In addition to the desired characteristic of low weight, there are also important demands for flexibility and thermal transport. Stiff, inflexible ballistic garments inhibit performance even at low weight. Garments or materials that trap body heat and moisture are unpleasant for intended wearers and are cited as one of the main reasons such garments are not worn in the line of duty.

9.2.1 Conventional approaches

Regardless of any individual fiber capabilities, all fibers must be formed into a structure to be useful as armor. Conventional devices for protecting police and military personnel from ballistic threats are now at least peripherally known in both the professional and the civilian community, albeit within previously discussed boundaries of understanding. It is still not uncommon for both the users of these products and the news media to refer to such products as 'bulletproof vests' or even 'Kevlar vests'. Most of those who lightly use these phrases do not know the material is not universally 'bulletproof', nor do they realize that not all such materials are made of Kevlar, a fiber produced only by DuPont.

If an expert were to tell the lay person that flexible body and structural armor products are actually textiles, they would often be met with astonishment and even disbelief. Yet all but a few such products are made of fiber, and anything produced from or with fiber is a textile. Most of the products designed to protect the wearer from ballistic threats are now made of woven filament materials produced by technologies that originated in far ancient times. Other, newer, types of products are also appearing both on the market and in research labs that bypass the ancient techniques of weaving, are faster to produce and offer unique capabilities that woven materials do not have.

Of the significant technologies available for consideration – weaving, knitting, non-wovens and resin fortified, filament lay-up composites – only knitting seems to be inappropriate for use in the ballistic resistant materials area at present.

Weaving is by definition the interlacing of at least two sets of yarns with each other and conventionally at approximately right angles to each other. For the weaving process to occur, the set of warp yarns must be parted in some desired order for a pattern, weft must be inserted through the opening, the warp yarns must exchange positions, trapping the weft between them, and the weft must be pushed into place in the cloth. Once these operations have been performed, there is a fabric which has been manufactured on the loom. This fabric must be taken away from the loom and more unwoven yarn moved forward to make more fabric as a result.

The style specifications describe a desired look or function of a fabric. What they mean is how the fabric should be made.

'End' is the common mill expression for a warp yarn in a woven fabric. In the USA, textile specifications are still given in avoirdupois units (inches, pounds, etc.). Ends per inch (EPI for short) refers to the warp yarns per inch in the fabric off the loom. 'Pick' is yet another term for weft or filling, but it applies to weft yarns in the fabric after it has been woven. Picks per inch are normally abbreviated PPI.

All weaving processes have certain characteristics in common and all require certain processing steps. Yarn is the basic building component of woven fabric structure. Yarns must be prepared for presentation to the weaving machine at least in so far as requiring an assembly of some useful length and organization of the yarns are concerned. All weaving processes require at least two different sets of yarns for the process to be accomplished, and all present weaving processes need to have one set of yarns presented simultaneously to the weaving machine.

9.2.2 Fiber components

Almost all ballistic resistant structures require the use of yarns rather than fibers as their primary components. Yarn is the correct textile term for unitary or conglomerate assemblies of fiber materials which are used to make fabrics by weaving. It is not sufficient simply to state that yarns are the basic product materials which compose woven or knitted goods. Modern textile manufacturing has offered the weaver a choice among types of yarns which could be applied to the production of a fabric simply by virtue of several distinct yarn production methods. These methods are not free from consideration of the fiber material to be applied, but the production methods themselves do determine subsequent processing steps which are required.

Yarns in a fabric can be described in several ways most of which depend on the type of fibers which compose the yarns. All methods used for yarn size descriptions use ratios of mass (or weight) and length.

There are many forms of yarn counts which exist in textile science. These include direct yarn counts (mass/unit length) and indirect (length/unit weight or mass). In the synthetic yarns industry such as is encountered in ballistic resistant armor, direct yarn counts are preferred. The most common direct yarn counts are:

- Denier, the number of grams of mass in a yarn per 9000 meters, is the measure used by man-made fiber producers to describe their products.
- Tex, the number of grams of mass in a yarn per 1000 meters, is a measure employed by the scientific community in textiles.

9.2.3 Unconventional non-wovens approaches

Needle-punching is a simpler operation than weaving by which a variety of properties can be obtained in the fabric by varying the process components. Continuous ballistic fibers are chopped into smaller fibers, carded and (usually) randomly oriented by cross-lapping to form an isotropic mat or sheet. This sheet is subsequently consolidated by a set of barbed needles. The needles push a limited amount of fibers at 90° through the sheet of randomly oriented fiber felt. The felt material engages fragments much better than traditional woven fabrics.

A 1966 US Department of Defense study found that a needle-punched structure containing ballistic resistant nylon could be produced at one third the weight of a woven duck fabric while retaining 80% of its ballistic resistance.[5] The process is still being used with success today in special applications.

9.3 Proper selections of fibers

Nylon became the ballistic resistant fiber of choice (i.e. 'ballistic nylon') for many years because it had a high strength-to-weight ratio and could be fashioned in sufficient layers to capture shrapnel fragments from some explosive projectiles and devices.

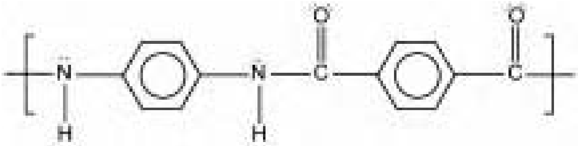
According to one source,[4]

> Reports received by the Office of the Surgeon General of the Army on the combat testing of the new Army nylon vest showed that the armor deflected approximately 65 per cent of all types of missiles, 75 per cent of all fragments, and 25 per cent of all small-arms fire. The reports also stated that the armor reduced torso wounds by 60 to 70 per cent, while those inflicted in spite of the armor's protection were reduced in severity by 25 to 35 per cent.

As polymer science progressed, fibers such as high tenacity polyamides, aramids, and linear, high density polyethylene (HPPE) were developed for ballistic resistant applications. The protection offered per unit weight of the material increased greatly. Such structures provide higher comfort, and less conspicuous means of providing protection against a ballistic threat. Ballistic nylons are no longer used because modern fibers offer superior performance.

9.3.1 Aramid types

Aramid fibers are condensation polymers belonging to the polyamide family of fibers, but their amide links are formed at aromatic ring structures (Fig. 9.4). This chemistry allows the fiber to form very rigid, long chain structures with high modulus, high tensile strength and high temperature resistance. Unlike nylons, aramid fibers are not thermoplastic and must be solution spun into sulfuric acid or similar oxidative solvents for formation.



9.4 Chemical structure of para-aramid fibers (Stouffer, J., http://web.umr.edu/~wlf/Synthesis/kevlar.html).

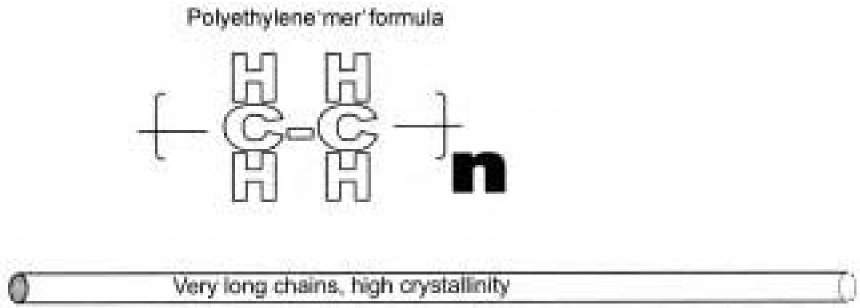
Two typical aramids used in ballistic resistant fabrics are DuPont Kevlar® and Teijin Twaron®. DuPont introduced Kevlar® 29 aramid in the early 1970s for vests and helmets. This fiber's name has become synonymous with ballistic resistant material in the popular media. Kevlar® 129 was introduced in the late 1980s and was offered in smaller denier per filament for increased flexibility and comfort. It was designed to defeat rounds such as the 9 mm full metal jacket (FMJ) handgun projectile.

The most current Kevlar® fiber for military use in both fragment and bullet defeat roles is KM2. This venerable contender in the military armor role is the preferred type for use in the US military's 'Interceptor' body armor.

Teijin-Twaron produces several types of Twaron® for ballistic resistant garments. The first generation, Twaron® Standard, was introduced in 1986. The latest generation of Twaron® is CT Microfilament. This product contains up to 50% more individual filaments than other equivalent weight aramid yarns. The 930 dtex Twaron® CT Microfilament yarn has a 1000 filament content. The result of this new technology is a weight reduction of 41% from Twaron® standard with equivalent performance.

9.3.2 Linear polyethylene types

A totally different technology from aramid fibers is used to produce the extremely lightweight polyethylene ballistic resistant fibers. Polyethylene is an additive polymer, which requires a special withdrawal procedure called gel spinning for its formation as a ballistic resistant material (Fig. 9.5). The fibers have extremely linear molecular chains, resulting in very high parallel orientation and crystallinity. This fiber type has very low specific gravity and tensile strength 15 times greater than steel. This family of fibers includes the Dyneema® products from DSM and the Spectra® products from Honeywell. They are variously known as high performance polyethylenes (HPPE), extended chain polyethylenes (ECPE) or ultra high molecular weight polyethylenes (UHMWPE).

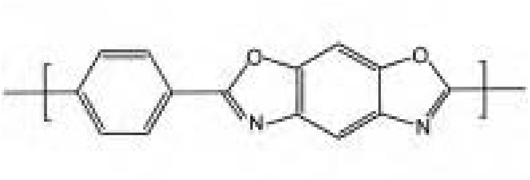


9.5 Chemical structure of HPPE/ECPE/UHMWPE fibers.

One important concern in the use of polyethylene fiber in high temperature environments is its sensitive thermoplastic nature. Tests by both Honeywell and DSM have shown little influence on the fiber performance in room temperature conditions after they were stored at elevated temperatures.

9.3.3 PBO types

One of the more newsworthy candidates in the ballistic resistant fibers market is PBO. This fiber is marketed by Toyobo of Japan under the trade name 'Zylon'. PBO is the abbreviation for Poly(p-phenylene-2,6-benzobisoxazole), a rigid-rod, isotropic, crystal polymer (Fig. 9.6).



9.6 Poly(p-phenylene-2,6-benzobisoxazole), or PBO structure (Toyobo Company, Ltd., http://www.toyobo.co.jp/e/seihin/kc/pbo).

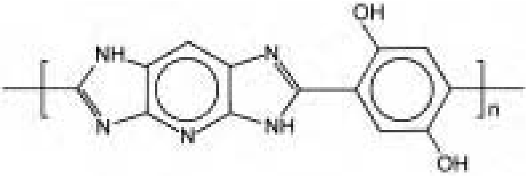
Data from Toyobo indicates that the tensile modulus of PBO is greater than carbon, HPPE or aramid fiber types. The fiber is chemically more similar to aramid than to HPPE and therefore has great resistance to heat. Its specific gravity is higher than HPPE, however, so the sonic modulus of the fiber is lower than the linear polyethylenes.

9.3.4 Liquid crystal polymers

Vectran is a high-performance thermoplastic multifilament yarn spun from Vectran® liquid crystal polymer (LCP). Vectran® is the only commercially available melt spun LCP fiber in the world. It is not yet a player in the ballistic resistant fibers market, but modifications to this fiber may permit it to become a contender in the future.

9.3.5 M5 fiber

PIPD or poly{2,6-diimidazo[4,5-b4′,5′-e]pyridinylene-1,4(2,5-dihydroxy)-phenylene} is a much anticipated and apparent likely contender in the ballistic protection market (Fig. 9.7). The fiber is being developed and marketed by Magellan Systems International, but it is not yet commercially available. Tests by the US Army at the Natick Soldier Center labs have indicated a very promising likelihood of success with this new high strength polymer.



9.7 Chemical structure of M5, PIPD fiber (Magellan Systems International, LLC, http://www.m5fiber.com/magellan/m5fiber.htm).

9.4 Variations of fiber forms

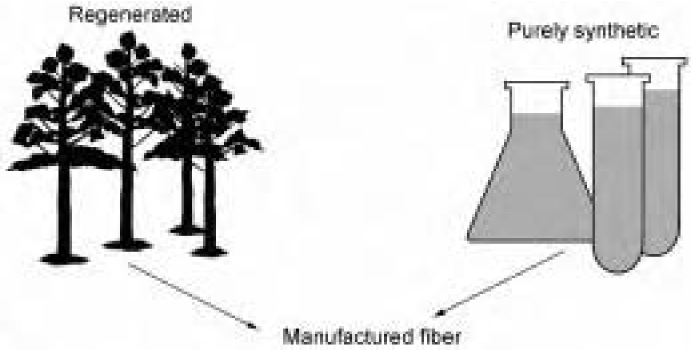
The characteristics of any fabric or fiber-based material structure are most dependent at the outset on whether yarns are continuous filament or staple fiber types (Figs 9.8 and 9.9). The two varieties are easily distinguished by the length of fibers which make up the yarns. In continuous filament yarns, each individual fiber has a length equal to that of the entire yarn being processed. With the exception of silk, all yarns of this type are man-made. Interestingly, silk is the only natural fiber that has been successfully used in forms of ballistic resistant armor.

The man-made yarns may be further distinguished between regenerated types such as rayon, acetate, glass, etc., or purely synthetic types including polyesters, polyamides, polyolefins, etc. (Fig. 9.10). In all cases, the continuous filament yarns are delivered wound in very great lengths onto a surface such as a tube or a spool.

Staple fiber yarns have measurable, discrete lengths and are easily recognizable as shorter than filaments. They are the common types of fibers

9.8 Aramid fiber in staple form (photo by the author).

9.9 Continuous filament form (Toyobo Company, Ltd., http://www.toyobo.co.jp/e/seihin/kc/pbo).



9.10 Manufactured (man-made or artificial) fiber sources.

we have been accustomed to seeing from our youth such as cotton, wool and pillow or quilt battings of synthetic fibers. Although the synthetics and regenerated fibers are produced in continuous filament form as either yarns or tow, they can be cut into determinate discrete lengths as required by a manufacturer of fiber-based goods.

9.4.1 Methods of creating non-wovens

Although numerous methods have existed for decades to produce fiber-based material structures within the broad category known as 'non-wovens', not all of these are of practical use for ballistic resistant structures. Indeed the definition of a non-woven is in itself a difficulty, since there is disagreement among professionals about what constitutes a member of this category of fabric.

Certainly wovens are not non-wovens, but are non-woven felts needled into woven fabrics both or neither? Certainly knits are not wovens, yet they are not non-wovens. And if a knit incorporates non-woven into it, does it become a non-woven? While such questions are comical, they are also the subject of serious debate because large corporate investments in marketing and customer outreach depend on what at first appears to be a trivial and fun semantic.

INDA, the Association of the Nonwoven Fabrics Industry, should perhaps wield some considerable authority in this arena to help define what a non-woven is. According to INDA's *The Nonwovens Handbook*,[6] 'Nonwoven fabrics are flat, porous sheets that are made directly form separate fibers or from molten plastic or from plastic film. They are not made by weaving or knitting and do not require converting of fibers to yarn.' Even with this definition, some experts disagree with the restrictions inherent in the wording.

For the sake of convenience, a ballistic resistant non-woven structure is defined herein as one that is fiber based, not exclusively woven, not exclusively knitted and not exclusively a fiber-matrix composite in construction. But some will disagree.

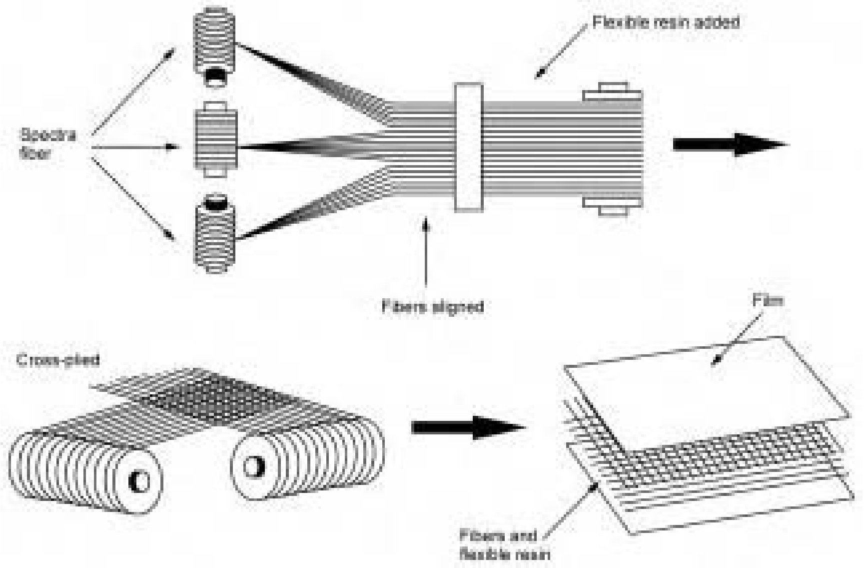
9.4.2 Filament

In conventional ballistic resistant structures, filament yarns are used to absorb projectile impact force. The logic behind the use of filaments is to present a network of high modulus, high strength fiber structure components that individually extend the entire breadth or length of the structure into which a ballistic impact is directed. Such filament structures do not depend on frictional forces among themselves to hold themselves into a physical continuum and thereby avoid inherent weak places within themselves to resist penetrative impacts.

Parallel filament lay-up with resin reinforcement

A very significant type of ballistic resistant structure is encompassed by those that may be described as filament lay-up composites. Although these structures are neither woven nor knitted, and they are sometimes marketed as non-wovens, they also fit the definition of a fiber-matrix composite.

In the filament lay-up structure, all of the fibers are lined parallel to each other as in the beaming operation for woven fabric. A binder is then applied to form the structure into a continuous resin-fixed web of aligned fibers. The resin holds the fibers' spacing for further processing. A web of similarly constructed filaments is aligned at 90° to form a continuous roll. The 0-degree and 90-degree webs are further consolidated to form a cross-plied unidirectional roll product (Fig. 9.11).



9.11 Spectra Shield^{TM} manufacturing process.

The roll product developed by this technology is a patented process; commonly this material is referred to as ‘shield’. The shield technology is applicable to all types of continuous ballistic fibers including HPPE/ECPE fibers, aramid and PBO fibers.[7]

Stitchbonding

The stitchbonding process is best described as a warp knitting process that is modified to use far fewer filaments, often of a much coarser type than is typical of warp knitting, and often also involving the use of felts or loose fiber mats. Although this process in not presently used for any commercial ballistic resistant products, there is clearly reason to believe that it could offer some significant advantages by combining the lateral and transverse stability of a warp knit type structure while utilizing the isotropic impact absorbing power of a fiber mat or needled non-woven.

Stitchbonding machines were initially introduced in eastern European countries during the Cold War era, and they managed to make incursions into Western textile production facilities despite the politics of the time. Krčma[8] distinguishes between what he calls a ‘true’ stitchbonding system and a knitting through system for thread systems only. The former system would mimic closely a triaxial weaving system with the corresponding advantages of an additional two translational energy vectors available to divert impact forces. At the same time the disadvantages of warp knit loop overshot and undershot geometries would create numerous opportunities for high impact forces to stress brittle high modulus ballistic resistant fibers beyond their breaking strain limits. Thus, the advantages of such a 'knit through' structure may likely be cancelled out before they come into play.

True stitchbonded structures include those formed by machines such as the Maliwatt and Arachne types.[9] Although these types of fabrics are conventionally used for insulations, there is considerable promise for their application in the market niches for needled non-wovens as well.

9.4.3 Staple fiber

Staple fibers have not traditionally been used in ballistic resistant non-woven structures because they have the exact limitation of discrete, discontinuous character that the use of filaments seeks to overcome. On the other hand, if formed together correctly, these tiny, particulate materials can offer potential advantages of structural isotropy that filaments specifically cannot offer. They can also be consolidated and compressed so that the fiber population is density in such structures is greater than that which can be achieved with woven or composite structures.

The disadvantage to the use of staple fibers is that they are presented to the manufacturing process in a random, unconsolidated, and non-uniform mass. Most commonly staple fibers are packed in 'bale' form. They must be mechanically processed through several stages before they can be made ready for use.

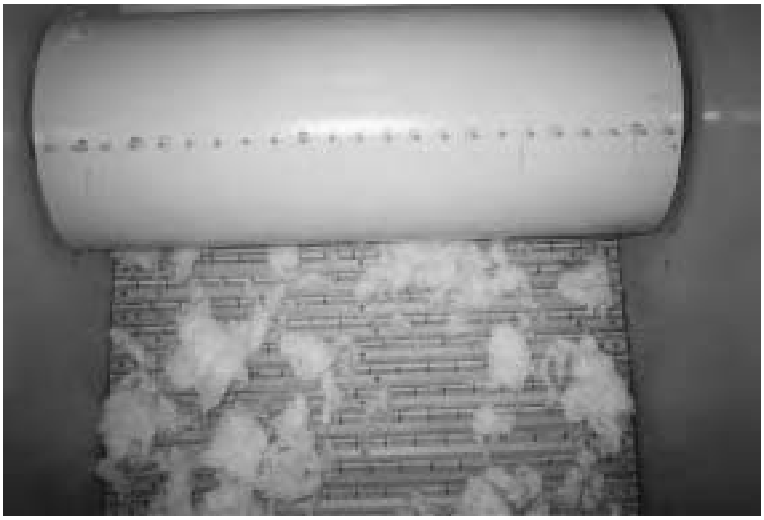
Opening and blending

In one classical definition of the opening process, 'The term opening originates with compact baled fibers being separated into small loose pieces or tufts'.[10] Because of the immense pressures required to compress a loosely arranged mass of fibers into a tight, dense bale of roughly 225 kilograms, fiber-to-fiber interfaces are increased and thus large groupings of fibers will form themselves into tufts.

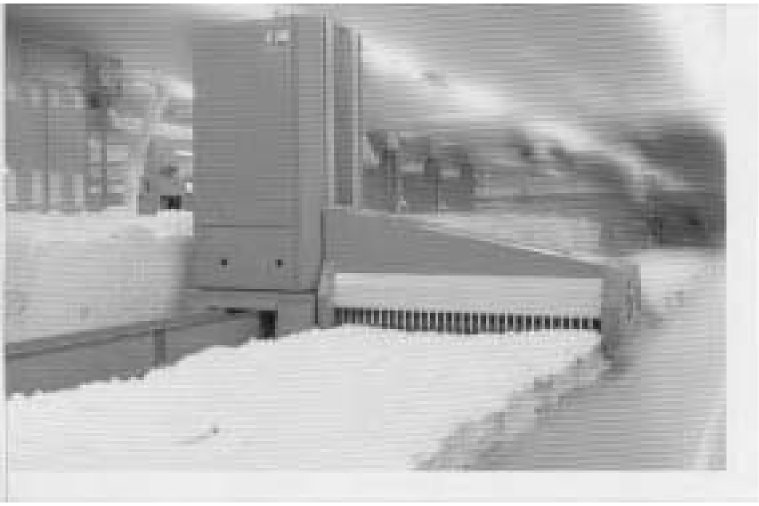
Blending is included in preparing staple fiber for use because it is the most logical place for this step to occur. Even in the case of modern, high modulus ballistic resistant fibers, there are slight variations in the physical characteristics of the fibers from one lot to another. These variations are reduced with blending of various lots of fibers. The most advanced method of preparing staple fibers for conversion into ballistic resistant non-wovens is blending of two or more fiber types together at this step. The manufacturer must determine whether the customer needs the blend to be expressed as a ratio of percentages of fiber types present by weight ratios or by actual fiber populations. The most common terminology refers to weight ratios.

Opening machines today fall into two major categories:

1. Those using a spiked apron conveyor feed with rotating beaters positioned at the ends of the conveyors (Fig. 9.12).
2. Those designed accurately and delicately to remove small layers of fibers from bale surfaces in a series of feeder bales known as a ‘lay down’ (Fig. 9.13).



9.12 Spiked ‘apron’ feed lifts partially separated fiber tufts to a rotary beater (photo by the author).



9.13 Metered layer removal by modern bale opener (Marzoli spa, Marzoli Spinning Solutions Blowroom Machines, 2001).

Both of these methods may be used in modern facilities, but the extremely high strength of ballistic resistant fibers and the range of useful fiber lengths for such a specification make the spiked conveyor and beater arrangement the more flexible alternative for non-wovens plants.

Mat formation methods

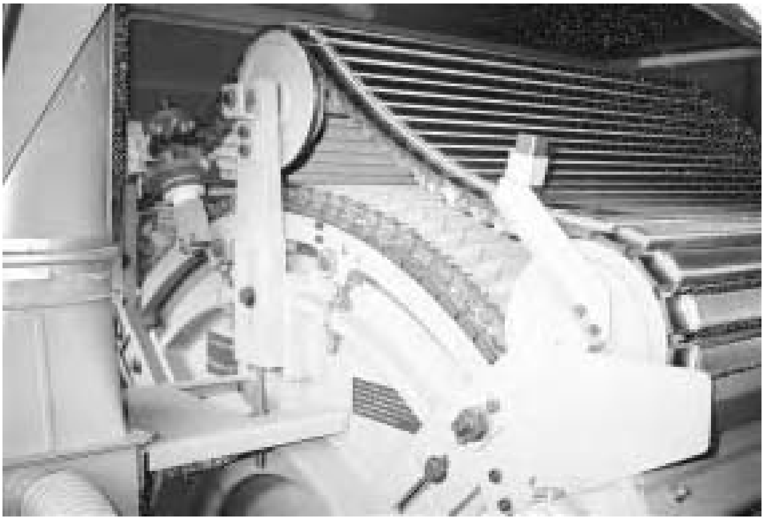
Once the staple fibers have been opened and blended together, they must be metered out into a form that approaches the final desired density or volume (Fig. 9.14).

The fibers must also be arranged in a desired orientation, or machine limitations that restrict the orientation of the fibers to a single direction or small range of directions must be recognized so that other manufacturing methods may be applied to achieve the desired result.

The earliest, and still most prevalent, method of forming staple fibers into a mat is the card. The card was originally designed to create a thick strand of paralleled fibers from cleaned, blended, opened fibers in preparation for converting those fibers into yarns. To accomplish this task, it is constructed of at least three large rotating cylinders, each of which is covered with a fine, angled and chisel-pointed wire 'clothing' (Fig. 9.15).

The modern card is actually not ideally suited to the formation of non-woven webs for ballistic resistant fabrics because it is designed to produce a stream of nearly perfectly paralleled fibers to eventually form into a staple fiber yarn. A ballistic resistant material must be able to engage an incoming projectile – bullet, shrapnel fragment or energetically propelled rubble from an explosion –

9.14 Opened, blended staple fibers being fed in mat form into a card (photo by the author).



9.15 A standard 'flat top' card, showing wire clothing on flats (photo by author).

from any angle, under any spins or tumble condition and in any geometry. Yet, this basic, long pedigreed piece of traditional textile equipment was the first to be applied to the formation of useful mats for non-woven fabrics. It is, in fact, one of the most commonly applied technologies for the manufacture of non-woven ballistic resistant materials.

One step in this manufacturing process was still lacking. Converting a thin, paralleled mat of fibers into a useful, ballistic resistant structure requires a technology that was unknown to textiles before the successful advent of non-woven fabrics. That technology is known as cross-lapping.

Cross-lapping (cross-plying)

Webs delivered from a card are only two to four fibers thick. Such a fine, gossamer-like structure may be useful for adhesive bonded non-wovens like dryer sheets with fabric softeners, but they certainly have far too little ballistic resistance to be useful. In order to create a structure with sufficient fiber population and varied orientation to engage various projectile shapes, a new way of combining fiber layers was required.

The functions of the cross-lapper are:

1. To fold a desired number of multiple layers of carded webs together to form a final web or fiber mat of desired weight per unit area
2. While layering the carded webs together, lay them onto each other at varying angles that are different from the original carding machine delivery direction.

9.16 A modern type of cross-lapper (http://www.nonwovens.net/photo26.htm).

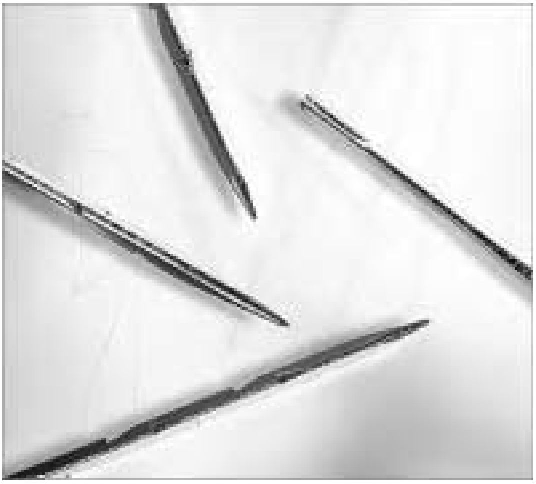
The cross-lapper can perform this function by picking up the carded web on a moving conveyor, laying it onto a conveyor that is moving perpendicular to that conveyor and at a slower speed from the first conveyor. This scheme of delivery allows the webs to be stacked on each other in various thicknesses and average angles of fiber orientation, depending on conveyor speed differences (Fig. 9.16).

Further control of the final web thicknesses, orientations and uniformity can come from total frictional contact and pressure between conveyors and individual speed controls of the driving rolls. This latter scheme is becoming the most favored and common among needlepunchers.

Needlepunching

Needlepunching is a simpler operation than weaving by which a variety of properties can be obtained in the fabric by varying the process components. Continuous ballistic fibers are chopped into smaller fibers, carded and (usually) randomly oriented by cross-lapping to form an isotropic mat or sheet. This sheet is subsequently consolidated by a set of barbed needles. The needles push a limited amount of fibers at 90° through the sheet of randomly oriented fiber felt. The felt material engages fragments much better than traditional woven fabrics. Needlepunching is a rather simple operation, but a variety of properties can be realized in a needled web structure by varying different parameters of the process.

One of the most important parameters that can be controlled in the process is the shape of the individual needles used to consolidate the felted structure. Needles are designed for a variety of purposes, including relief structuring, creating density gradients in the fabric and for simple, uniform consolidation (Fig. 9.17). For ballistic resistant structures, the most common needle type is the simple barbed, triangular or four-pointed star-shaped cross-section types.



9.17 Examples of various types of felting needles (Groz-Beckert, http://gbu.groz-beckert.com/website/gbu/en/fn_innovations.html).

Needle barbs may be varied in shape, number and orientation along the axis of the needle. Additional control of fiber entanglement angles, depth, extent and frictional contact lengths are provided by the barb throat depth and barb angle ('kick-up').

The next considerations are those of needle population in the fixing structure, known as the needle board, the rate of feed of the fiber mat and the punch frequency. The foregoing factors combine to create the critical defining characteristic of a needled non-woven fabric known as punches per square inch.

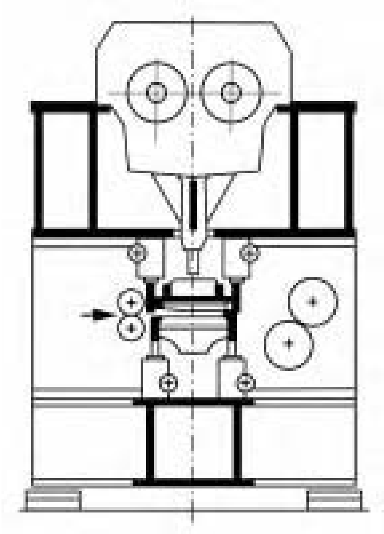
Finally, needlepunch machines, or needle looms, as some companies call them, may have their needleboards arranged to punch from the top down, from the bottom up, or in both directions simultaneously (Fig. 9.18).

While some ballistic resistant and ballistic assisting non-wovens may be formed directly on one pass through a needlepunch machine, most require a lighter needling step known as pre-needling.

The final fabric product from the above process is actually only a network of randomly arranged fibers, held together only by frictional contact among its constituent fibers.

9.5 Filament lay-up composites

The filament lay-up composite, or those structures made by parallel lay and resin reinforcement as described in the section 'Parallel filament lay-up with resin reinforcement', on page 254, occupy an increasingly important and, ironically, traditional sector of the ballistic resistant materials spectrum. These unique structures are designed to engage an incoming projectile with a much larger



9.18 Schematic of a 'top punch' needlepunch machine or 'needle loom' (Fehrer AG, http://www.fehrerag.com/Fehrer/frame.htm).

population of high strength fibers than can be brought against such a threat with a woven or knitted fabric. The presence of a reinforcing resin also assists in the energy dissipation and the composite structure together quickly acts to strip a bullet of its casing and flatten it upon impact. Two major products in the present market that use this same principle are Honeywell Spectra Shield and DSM Dyneema UD armors. Both products depend on the same ballistic resistance principles to defeat incoming threats.

Energy absorption and dissipation energy is the secret to ballistic resistance. A ballistic resistant fiber's strength must be utilized in the most effective manner for such a fabric or structure to be effective. The principle has been expressed in the following manner[11]:

> A woven fabric dissipates energy at yarn interlacings. When a projectile strikes the surface of a fabric, energy is distributed along the yarn axis to each interlacing point. Most woven fabrics exhibit yarn strength translational efficiencies between 60 and 80%. Only about one-third of the strength loss can be attributed to degradation during weaving. The remaining strength reduction is caused by mechanical interaction between warp and filling yarns during tensile loading. High warp crimp in a woven structure is accompanied by low strength translation efficiency. A compromise must be reached in fabric construction between weave density and fabric strength where neither is at an optimum level.
>
> Spectra Shield fabric forces the projectile to engage many more fibers upon initial impact than a woven fabric because of the wide dispersion of filaments in the untwisted yarn. Resin prevents the projectile shock wave

from pushing the fibers out of the projectile's path; the fiber strength has higher translation efficiency in the structure.

Ideally a structure should dissipate impact energy rather than obstructing it. Fiber friction is one property which may assist in absorbing energy while utilizing the strain wave velocity of a fibrous system. This theory is of interest when considering a nonwoven structure, because large numbers of fibers are present in a nonwoven, oriented in many different directions.

Strain wave velocity is the speed at which a fiber or structure can absorb and disperse strain energy. It can be expressed as

$$v = \sqrt{F/\mu}$$

where
v = strain wave velocity
F = force applied to the fiber (from projectile)
μ = linear density expressed as kg/m
At the same time, one can also express v as

$$v = \sqrt{E/\rho}$$

where
E = material Young's modulus
ρ = specific gravity of material
By combining the equations, an expression for optimum dissipation of impact energy can be found.

$$F = E\mu/\rho$$

The more impact energy a structure disperses, the more efficient the energy absorption mechanism is. Three reactions occur in a needlepunched structure when a projectile strikes it. These reactions are fiber elongation, fiber slippage, and fiber breakage. Designers want to create a structure which optimizes each of these properties to yield the best ballistic properties.

9.5.1 Flexible ('soft') armor uses of filament composites

The most traditional way of applying filament lay-up composites to armor is in the arena of 'soft' body armor that encompasses the US NIJ threat levels I through IIIA. The present range of products made by this method include the previously mentioned Spectra Shield and Dyneema UD families, containing only extended chain, high performance polyethylenes and the Goldflex products (Honeywell) that contain aramid fibers fixed in resin. Both of these product types retain a thinner profile than woven fabrics, and they are usually not fixed by stitching.

Resin fixed PBO fiber structures have also been produced and marketed that exhibit very high ballistic performance. To date there have been no documented uses of PIPD fibers in filament lay-up composites, but this is a certain logical evolution of that fiber.

9.5.2 Level III filament lay-up armors

One of the more astounding developments of the filament lay-up composite structure has been in rifle resistant (NIJ Level III) armor. Both Spectra and Dyneema fibers have been successfully applied to this end so far. Studies from both US Army and Honeywell researchers were pursued in the early 1990s to define how best to back ceramic plates for rifle projectile defense. The studies reported,[12]

> Both woven fabric-reinforced laminates and angle-plied unidirectional fiber-reinforced laminates were found to exhibit sequential delamination, cut-out of a plug induced by through-the-thickness shear, and combined modes of shear and tensile failure of fibers as observed in the cases of glass and graphite fiber composites. At low areal density, both laminates demonstrated similar ballistic limits. However, as areal density increased, differences in ballistic limit became more apparent, with angle-plied composite laminates showing higher values. When subjected to the repeated impact of a constant striking velocity below the ballistic limit, a progressive growth of local delamination was observed until gross failure of composites occurred. The use of lower striking velocity of the projectile led to the increase in cumulative numbers of impacts for full penetration defining an impact fatigue lifetime profile. The results of impact testing indicated that Spectra fiber-reinforced composites with vinyl ester resin matrix have a higher ballistic limit and longer impact fatigue life at a given striking velocity than the polyurethane matrix composites. Less effective absorption of impact energy by flexible polyurethane matrix composites was attributed to much more restrained pattern of delamination growth. Correlated with the results of dynamic mechanical analysis, these trends indicated that the stiffness of resin matrices plays an important role in controlling the ballistic impact resistance of Spectra fiber composites.

9.6 Historical uses of non-woven ballistic resistant fibers

The first instinct of the technology student or fiber engineer is to assume that non-woven ballistic resistant armor is a relatively new idea, since the machine technology to produce it postdates that of weaving and knitting by a considerable time period. In truth, non-woven armor in the form of quilting has been used since at least the Middle Ages. Indeed, British historians have determined that Viking chain mail, reinforced and supplemented by quilted, fiber-filled underlays were likely the secret to its ability to withstand even spear attacks in battles.[13]

9.6.1 Test results from US Army Natick labs

The US Department of Defense has performed testing on ballistic resistant non-wovens at its laboratories in Natick, Massachusetts and through other research facilities. The tests were designed to examine whether non-woven fabric could be used in military ballistic applications. The Natick studies found that a needlepunched structure could be produced at one-third the weight of woven fabrics for certain ranges of protection. These Army studies were inconclusive as to the extent of practicality that the use of non-wovens would bring to ballistic applications.[14]

9.6.2 Results from British researchers

The needlepunched structure has not been as thoroughly evaluated for geometrical and physical relationships as other fabric structures such as knits and woven fabrics. John W. S. Hearle[15] has offered the most complete explanation of the fabric which he describes in a geometric model of the needlepunched structure. This model shows the vertical structure consisting of tufts of fibers pulled through the web by felting needles. The horizontal structure consists of fibers following curved paths around the tufts. When looked at in a three-dimensional plane, individual fibers pass through both the horizontal and vertical sections.

9.6.3 Test results and developments from independent and commercial entities

Few commercial needlepunched non-wovens exist in the market yet. One reason for this is their greater bulk (volume) per unit area than their woven or filament composite lay-up competition. Many law enforcement and military personnel find thickness a less desirable trait than lighter weight even when the protection afforded by the non-woven is equal or better. Despite these limitations, a few companies such as DSM (Netherlands), National Nonwovens (Massachusetts, USA) and Plainsman Armor (Alabama, USA) are offering products of this nature in the marketplace.

DSM was the first commercial entity to have success in the marketplace with a 100% needled non-woven product that is known as Fraglight or FR10. This non-woven armor is composed entirely of DSM Dyneema staple fiber, and it has been used in fragment resistant vests in European armies. DSM researchers found that the early versions of the product suffered from abrasion of fibers from the structure that deteriorated its ballistic performance over time. Further work is continuing with the Fraglight product to improve it now.

National Nonwovens has a standalone needled non-woven that has been certified for use in commercial airliners by the FAA. The Plainsman products have been successfully tested in this role as well, but are currently being developed more for modified body armor and vehicular armor use.

A hybrid armor of both needled non-woven and woven ground fabric has been jointly developed by Barrday (Canada) and TexTech Industries (USA). Further testing and marketing of this product is presently underway.

9.7 Methodologies for use of non-woven ballistic resistant fabrics

As stated in the previous section, needled non-woven armors may be applied in standalone or in supplementation configurations. Regardless of the intended final product, careful consideration of the construction methodologies for individual components must be made and from these, rational decisions about the architecture and composition follow.

9.7.1 Single fiber components

The most common and natural scheme for assembly of ballistic resistant fibers into a non-woven structure is a uniform assembly of the same fiber types. Almost all present, commercial, ballistic resistant fabrics are made of the same fiber types, thicknesses and lengths. This scheme is easiest for a manufacturing facility because the fiber inputs are uniform, predictable and minimal blending steps are required.

According to one producer of such fabrics, these structures can be produced to sufficiently rigorous standards to qualify for FAA flight deck protection against the standard test projectiles of NIJ Level III-A.[16] Such performance qualifications show that 100% needled non-wovens of uniform fiber types have great promise in a variety of ballistic resistant applications.

9.7.2 Multiple layering of various single fibers

Layering of various kinds of non-woven fabrics and/or conventional fabrics was proposed as early as 1992 by a team from Allied Signal, the original owners of Spectra Fiber technology.[17] Although the scheme has been variously tested by military organizations, research institutions and universities, it is presently only applied commercially as combinations of woven and filament lay-up composites (shield-type fabrics). The application of needled non-wovens of individual fiber types in individual layers or combinations thereof have not been commercially applied.

9.7.3 Blended fiber constructions

Tests conducted by Auburn University indicated that combinations of aramid and HPPE/ECPE fibers in non-woven blends produced higher than anticipated performance beyond those of the advantages of both fiber types. Energy absorption properties 30% greater than in unblended structures were observed in initial tests of the material (Fig. 9.19). The combination of thermoplastic and non-thermoplastic fibers in the structure allowed an energy dissipation mechanism by phase change that boosted the fabric areal weight performance.

Energy absorption in ECPE, aramid blends

◆ Radiated strain energy
— transferred by aramids and ECPE outside impact
◆ Fibrillation of aramids
◆ Phase change induced in ECPE

9.19 Results of aramid and ECPE fabric ballistic impact.

The original tests to develop a blended non-woven ballistic fabric, a 50% HPPE/ECPE and 50% aramid indicated that the new fabric thickness was significantly less than that of 100% aramid fiber blends. Fiber denier differences between the aramid and HPPE/ECPE fibers were attributed to the observed effect. The HPPE/ECPE fibers were 5.5 dpf; the aramid fibers were 1.5 dpf. As a result of their higher denier, HPPE/ECPE fibers present in the blend afforded more voids in the blended needlepunched samples compared to the 100% aramid samples.

The HPPE/ECPE fibers/aramid blend had better ballistic resistance than 100% aramid blends in the tests. Ballistic resistance was also enhanced with increases from 4 layers to 8 layers. Web layers had less effect in the HPPE/ECPE fibers/aramid blends than in the 100% aramid samples. As the number of layers was increased, the differences between the blended conditions and the 100% aramid became less, but they retained significance. Variation in density showed a similar response of V_{50} ballistic resistance with varying fabric density for the different fiber type conditions.

Further testing of the fragmentation stopping capability of blended non-woven fabrics continued between 1997 and 2001. Among findings during this development, it was clear that significant advantage exists where HPPE/ECPE fibers are 5.5 denier or finer. Disadvantage was observed when fiber blends with PBO present were tested because of the very low frictional characteristics of these fibers.[7]

9.7.4 Fragment protection

In 2002, blended, non-woven, needlepunched, ballistic resistant fabrics were tested in 2002 at both Honeywell Performance Fibers Laboratory in Petersburg, Virginia and the US Army Aberdeen Proving Grounds, against woven aramid fabrics and against woven PBO fabric to compare performances in defeating explosion fragments. In those military specifications tests, flexible armor was tested against the most common specified fragment threat (MIL-STR-662F). Results of fragment testing at Honeywell are shown in Table 9.3.

9.7.5 Tests by US Army

Evaluation of the blended non-woven was conducted in 2002 as a part of the development of a fragment resistant cover for the Army's LOSAT KEM trailer.

Table 9.3 Comparative averages of fragment (FSP) testing on flexible armor system

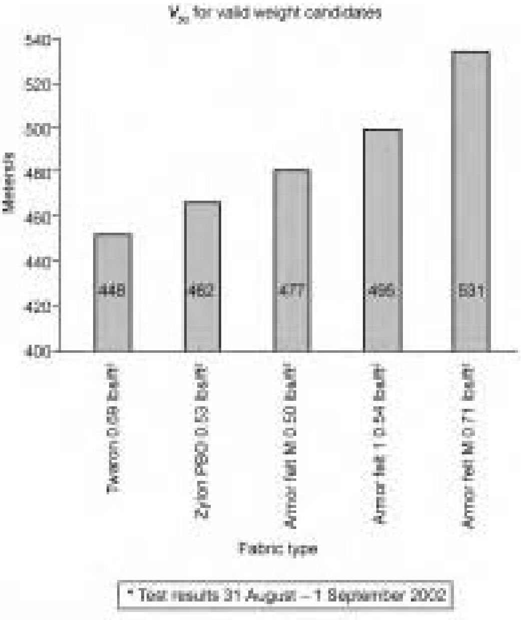
Material	Number of plies	Areal density kg/m^2 (psf)	V_{50} m/s (ft/s)
GF	25	5.81 (1.19)	586 (1924)
AF + GF	2+23	5.81 (1.19)	575 (1887)
GF + AF	23+2	5.81 (1.19)	593 (1944)
AF	15	3.61 (0.74)	573 (1880)

Key: GF = Aramid filament lay-up composite; AF = Blended non-woven

In the test, at Aberdeen Proving Grounds, the parameters as specified by the US Army were weight of 0.75 pounds/square foot or less and projectile speed of 425 meters/sec (1400 feet/second) or more. The test results determined conclusively that blended non-woven outperformed woven aramid and woven PBO by a large difference (Fig. 9.20).

Fragment armor improvements with non-woven technology

- Results from US Army Aberdeen Proving Grounds test
  - .22 cal. 1.10 gram, fragment simulating projectile, steel
- Parameters
  - Weight < 3.42 kg/m^2
  - Projectile speed > 425 m/s (1400 fps)
- Non-woven materials were superior to woven aramid and woven PBO
- Historical development of non-woven armor
  - Original Kevlar 29 = 389 m/s
  - Original (1991) blend yielded 434 m/s (HPPE, 2nd quality and Kevlar 29)



9.20 Performance of blended non-woven in fragment defeat.

9.7.6 Combinations of non-wovens and conventional materials

A significant factor which has contributed to soft armor advances is the hybrid concept of combining more than one ballistic material in a single armor system. This technique allows armor design engineers to utilize the full potential of various ballistic materials.

Combinations of conventional materials and/or shield-based products with ArmorFelt have shown significant advantages when used against rated soft body armor threats. Testing of these systems using a modified NIJ 0101.04 Level IIIA Standard, .44 Magnum is shown in Tables 9.4, 9.5 and 9.6.

Table 9.4 Level IIIA baseline test results aramid filament lay-up only

Sample	Material	Bullet type	Speed m/s (ft/s)	Penetration	Backface deformation (mm)
1	24 Aramid filament lay-up composite	.44 mag JHP	433 (1422)	Partial	47
2	5.57 kg/m^2 (1.14 psf)	.44 mag JHP	438 (1438)	Partial	42
3		.44 mag JHP	442 (1450)	Partial	41
4		.44 mag JHP	438 (1438)	Partial	42
5		.44 mag JHP	442 (1449)	Partial	47
6		.44 mag JHP	435 (1427)	Partial	49
Averages			438 (1437)		44

Table 9.5 Level IIIA test results aramid filament lay-up + 4 ply blended non-woven

Sample	Material	Bullet type	Speed m/s (ft/s)	Penetration	Backface deformation (mm)
1	19 Aramid filament lay-up	.44 mag JHP	440 (1442)	Partial	39
2	1 felt 4 ply	.44 mag JHP	441 (1446)	Partial	38
3	5.57 kg/m^2	.44 mag JHP	440 (1443)	Partial	37
4	(1.14 psf)	.44 mag JHP	441 (1448)	Partial	43
5		.44 mag JHP	443 (1452)	Partial	35
6		.44 mag JHP	445 (1461)	Partial	42
Averages			439 (1440)		38

Table 9.6 Level IIIA test results aramid filament lay-up + 3 ply blended non-woven

Sample	Material	Bullet type	Speed m/s (ft/s)	Penetration	Backface deformation (mm)
1	18 Aramid filament lay-up	.44 mag JHP	427 (1402)	Partial	40
2	1 felt 3 ply	.44 mag JHP	430 (1411)	Partial	39
3	5.42 kg/m^2	.44 mag JHP	430 (1410)	Partial	39
4	(1.11 psf)	.44 mag JHP	437 (1435)	Partial	40
5		.44 mag JHP	440 (1444)	Partial	38
6		.44 mag JHP	431 (1413)	Partial	37
Averages			433 (1419)		38

9.8 Future directions for non-woven fabric applications

The use of high strength polymer materials created advances in armor protection far above those anticipated just 35 years ago. Further improvements may be anticipated by the advent of new materials and nanoscale technologies that will permit even better armor performances against very high level ballistic threats.

Improvements that utilize the strongest characteristics of each fiber assembly method will yield the optimum ballistic protection device instead of simple reliance on standard and unitary assembly techniques.[2]

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10

Prepreg ballistic composites

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10.1 Introduction

With the advancement of ballistic materials and technologies, the ballistic prepregs are becoming an essential construction technique for getting the maximum performance out of the high performance fibers. The ballistic prepregs help to maximize the engagement between fibers and high speed projectiles penetrating the ballistic material, thus reducing the amount of ballistic material required to defeat the projectiles.

The backbone of lightweight ballistic materials is high performance ballistic fiber. However, the ballistic fibers alone cannot engage a high speed projectile because the projectile can push fibers aside without breaking a single filament in the fiber bundle. To overcome this limitation, the fibers are converted into either a woven fabric (see Chapter 8) or a non-woven material such as a cross-plied unidirectional or felt type material (see Chapter 9). These ballistic materials have fibers in at least two directions which forces the projectile to engage with the fibers. For soft armor, these ballistic materials are tailored into a flexible vest. However, for rigid armor, these prepregs are molded into the shape of the finished product by utilizing proper molds and molding conditions.

During a ballistic event the ballistic materials engage the projectile by:

- slowing the projectile;
- deforming the projectile as it is passes through the layers;
- stopping the projectile; and
- lowering the backface deformation.

The stresses created on the ballistic materials are limited to a small area near the projectile penetration area. This indicates that only a limited number of the ballistic fibers are used to engage with the projectile. Since stresses are limited to a local area, the backface deformation is usually excessive. However, adding an appropriate amount of resin, which binds the ballistic fibers, reduces some of these shortcomings. The ballistic prepregs consist of ballistic fibers, either in woven form, or in a continuous cross-ply form, or chopped and converted into felt type material with limited amount of bonding material. This is usually termed a *pre-impregnated* material, or in short, prepreg material or prepregs. The ballistic prepregs consist of high performance fibers and at least one type of resin in the form of laminating film or as coating on the ballistic material.

The resin, also called matrix or binder adhesive, is the weak link in the ballistic composites, especially because resins do not presently exist that allow utilization of the stresses that ballistic fibers are able to withstand during a projectile penetration in a ballistic event. Thus, when a ballistic composite is under load due to high speed projectile penetration, the resin may micro crack and craze, form larger cracks through macro and micro cracks, debond from the fiber surface, and generally break down at varying stages of stress generated by high speed bullet penetration. Nevertheless, the resin provides many essential functions during manufacturing and during and after a ballistic event. The resin keeps the ballistic fibers in the proper orientation and location so that the fibers can resist the penetration of high speed projectiles. The resin also helps to distribute the load due to projectile penetration evenly among the ballistic fibers, provides resistance to crack propagation due to projectile penetration, and provides durability during manufacturing and in service.

Because of the resin in a ballistic system, the stresses created by a penetrating projectile are distributed over an area. It is therefore possible to manufacture lighter and more durable ballistic vests and other such converted or molded ballistic products. The prepregs also increase the friction between the high speed projectile and the ballistic material.

Other benefits of prepreg ballistic materials are:

- reduced damage to ballistic fibers due to rubbing against each other during normal wear and tear;
- protection of ballistic fibers from moisture and moisture variation;
- protection from day-to-day chemicals (coffee, soda, ketchup, salad dressing, etc.);
- abrasive dust, sand and other airborne micro particles.

Furthermore, the resins generally determine the overall body to the ballistic material, and may also control its environmental resistance.

Using prepregs for molding ballistic components such as helmets, breastplates, vehicle armor components as compared to wet-lay-up and in-line impregnation of the ballistic fibers during the final composite fabrication process can offer significant advantages. The prepregs have very precise, controlled fiber : resin ratios, uniform resin distribution, better control of fiber orientation, and controlled resin flow during the cure or consolidation process. The prepregs allow better quality of finished components irrespective of technician skill for moldings consistent composites. The prepreg materials can be produced and stored well in advance and thus reduce the possibility of delay. Once in prepreg form, ballistic materials can be shipped to any part of the world irrespective of the local temperature and moisture conditions.

The performance of ballistic components is sensitive to the fiber:resin ratio. Ballistic prepregs are usually resin-starved systems. It is difficult to fabricate resin-starved ballistic composites using either hand-lay-up, or resin transfer molding (RTM), or on-line resin coating

During the prepregs process, the resins are usually applied to the ballistic material in a fluid form to wet the surface fibers completely. To develop good bonding between ballistic fibers and adhesive resin, the adhesive resin must be applied uniformly. One common technique is to dilute the adhesive resin to a low viscosity at the time of application. After coating the ballistic material with a resin, all the volatile solvents, or moisture from aqueous resins, are removed by applying heat. A fully dried prepreg has less than 1% volatile organic solvent (VOC) once it is out of the coating machine. This helps to increase the shelflife of the prepregs during in-house storage, during transportation to customers and during storage at the customer location before converting into the final component. This is true for all types of ballistic prepregs irrespective of the chemistry of the resin and type of the fiber.

As mentioned earlier, lightweight high-performance fiber-reinforced prepreg ballistic materials are used in two major types of application. These two applications are generally categorized as soft armor and hard armor materials. The soft, flexible armors are used in bullet resistant applications such as vests, collar, arm, leg, groin protectors, ballistic bomb blankets, and roll-on fragment protection for vehicles. Such flexible armor products are generally used for protecting police, law enforcement, peacekeeper and military personnel and in vehicles for stopping handgun bullets and fragments generated by hand grenades or blast under a ground vehicle. The hard armor materials are used for rigid molded armor such as ballistic helmets for military and police, molded breastplates and ballistic kits, shaped and molded air, sea, and ground vehicle armor.

10.2 Soft armor

Soft armor ballistic materials are usually made with high performance fibers converted into either woven fabric or non-woven materials, either with or without coating and also with or without film lamination.

The woven fabrics for soft armor applications are made with either aramid fibers or HMPE fibers. The woven fabrics are manufactured on high-speed automated looms. The technology of weaving fabric is relatively simple. Once ballistic fabric is woven, a water-repellent coating is applied on the fabric to reduce the effect of water on fabric efficiency. The coating is usually applied on prepreg type equipment with dipping bath and drying area.

However, a new class of non-woven coated and film laminated materials for soft armor has become popular due to their inherent higher performance against handgun and rifle bullets. The laminated film on coated unidirectional cross-plied materials allows ballistic layers to slip inside the vest during body movement thus reducing resistance during movements. The performance benefit includes higher energy bullet stopping power, lower backface deformation, multiple bullet hits fired from 0° and from various angles. The ballistic vests made with these new materials are not quilted and therefore inherently thinner and more flexible (see Chapter 9).

Soft, flexible armors are used for stopping handgun bullets, such as 9 mm FMJ, 357 Magnum and 44 Magnum, and low energy fragments generated by hand grenade explosion or due to artillery explosion in a battlefield. Based on the ballistic threat level a soft armor bullet resistant vest consists of several layers of ballistic materials which can limit the body movement to a certain extent. A good ergonomically designed vest flexes during human body motion and thus reduces the resistance to human body movement during sitting, walking, running or driving a vehicle.

Since the soft armor materials applications require flexibility, the choice of prepreg resin is usually limited to high elongation thermoplastic resins and laminating films. Thin high elongation laminating films are also used which maintain flexibility once laminated to the fiber-reinforced substrate either in the form of woven fabric or cross-plied materials consisting of two sets of unitapes bonded at right angles to each other.

Other characteristics for selecting prepreg resin for soft armor materials are:

- fairly low resin content;
- high elongation resins (> 200%);
- discrete coating on substrate (resin content below 20%);
- no cross-linking of coating material, if possible;
- introducing micro size voids;
- adhesion to substrate.

10.3 Hard armor

Similar to soft armor, hard armor ballistic materials are usually made with high performance fibers converted into either woven fabric or non-woven materials and coated with an adhesive or laminating resins. The coated woven fabric materials for hard armor are made with either aramid fibers or HMPE fibers. The coating is usually applied on a woven fabric using one or more than one process listed in Section 10.9.

Prepregs are converted into molded armor or a semi-rigid or rigid armor by using molds and any one of the following processes:

- autoclave;
- match-die molding;

- vacuum bag techniques;
- hand-lay-up.

These processes are described in detail in Chapter 11.

10.4 Ballistic prepregs with thermoplastics resins

The thermoplastic resins for prepregs are very different from the commercial thermoplastics that are commonly used as plastic bags, injection molding resins, and other engineering plastics. The thermoplastic resins are tougher and higher energy absorption resins. These resins usually have high strains to failure, high elongation, low to intermediate modulus, and high elongation and moderate strength. The thermoplastic resins for ballistic applications are also different than those used by structural composites. The thermoplastic resins such as polyether etherketone (PEEK), polyphenylene sulfide (PPS) and polyetherimide (PEI) are usually used for structural load-bearing composites.

Current thermoplastic resins for ballistic composites application have:

- low molecular weight;
- high elongation to failure;
- low modulus;
- low strength;
- high energy absorption;
- lower viscosity;
- lower melting and softening temperature;
- availability in solvent-based and aqueous-based system;
- relatively poor bond strength with fiber;
- do not absorb moisture;
- good chemical resistance;
- excellent shelflife at room temperature.

Thermoplastics are available in many forms for ballistic prepregs. This includes adhesive in powder form, pellet form, thick liquid form or diluted ready-to-use form.

The prepregs resins for ballistic materials contain the adhesive composition in a mixture with additives such as organic solvent or an aqueous media. These additives help to lower the viscosity of the prepreg resin sufficiently to permit coating of the ballistic materials. The organic solvents used to dilute prepreg resins may be undesirable because of a number of factors such as environmental concerns, toxicity, flammability, and other local regulations in force.

Organic solvent-based resin contains industrial solvents that require proper disposal or recovery after prepregs process. However these solvent-based resins offer many benefits that enable them to play an important role for ballistic applications. Benefits include:

- excellent wetting characteristics;
- high solid content;
- higher prepreg rates;
- lower prepreg temperature;
- high and uniform fiber coverage;
- ease of secondary processes (such as film lamination);
- long-term durability;
- excellent moisture resistance;
- long-term storage.

The aqueous-based resin offers advantages such as:

- they are environmentally friendly;
- they require no disposal or recovery;
- an unlimited volume can be used;
- cost effective to dilute;
- easy to store;
- easy to transport.

With the aqueous resin formulation, eliminating all the water from the prepreg material may require additional heat energy and equipment space during the prepreg process. Similarly, during the secondary operation such as film lamination and molding into a molded ballistic panel the additional precaution may be required of removing all the moisture from the system. And to achieve solid content above 50%, it is necessary that at least a portion of the prepreg polymer be present in agglomerates of greater than colloidal size.

Both organic solvent-based and aqueous-based resins are used for ballistic prepregs.

10.5 Hard armor prepregs

The hard armor prepregs are used for molding hard armor products. Such molded armors not only defeat projectiles but also absorb low speed impact and other mechanical and structural stresses encountered in a battlefield. Some of the typical uses of hard armor include military and police helmets, breastplates, vehicle armor, and small liner and explosion containment.

The hard armors used by police, law enforcement, peacekeeper and military personnel are designed to defeat handgun bullets. Typical handgun bullets are 9 mm FMJ, 357 Magnum and 44 Magnum. The hard armor used by the military includes low and high energy rifle bullets and numerous sizes and shapes of fragments generated by hand grenade explosion or artillery explosion in a battlefield.

Hard armor ballistic products are designed to be durable and maintain ballistic performance and the molded shape during their use. Since the hard armor materials require good ballistic performance, lower weight, good rigidity and durability, the choice of prepreg resin is critical.

Criteria for selecting thermoset prepregs resin for hard armor materials are:

1. Low resin content (<20%).
2. Low volatile organic contents (VOCs).
3. Commercial availability and long history of maintaining performance.
4. Stable at room temperature storage.
5. Relatively lower bond strength between fiber and resin.
6. Discrete coating on substrate (resin content below 20%).
7. Controlled cross-linking of prepreg resin.
8. Higher ballistic performance.
9. Good mechanical properties.
10. Maintain elevated temperature (180 ºF) performance.
11. Decent glass transition temperature (Tg).
12. Good combustibility performance.
13. Tack free for molding helmets and other curved articles.
14. Good bonding with facing materials such as metals and ceramics.
15. Ease of machining, drilling and painting.
16. Micro size voids.

Criteria for selecting thermoplastic prepreg resin for hard armor materials are:

1. Low resin content (<20%).
2. Higher elongation (+100%).
3. Controlled resin flow at high pressure.
4. Relatively low bond strength between fiber and resin.
5. Discrete coating on substrate (resin content below 20%).
6. Good ballistic performance, both for bullets and fragments.
7. Good bonding with metals and ceramics.
8. Decent combustibility.
9. Stable at room temperature storage.
10. Micro size voids.
11. Minimum substrate fiber penetration.

Both thermoplastic resins and thermoset resins can be used for hard armor applications.

The above requirements are desirable or may be referred to as a wish list of a ballistic design engineer, but commercially, it is difficult to meet all the performance requirements. A compromise is usually accepted meeting a number of critical properties. Once a compromise is accepted, other desired performances are worked around to manage the lack of these features.

Once either a thermoplastic or thermoset resin is selected, the next step in any ballistic prepreg design is selection of appropriate interface between ballistic fibers and the resin. The interface greatly influences the ballistic resistance, backface trauma, rigidity, durability, and other features of a soft and hard armor. The interface is a function of surface properties of the ballistic fiber and the chemistry of the prepreg resin.

10.6 Surface properties of ballistic materials

The surface tension of liquid resins is important in relation to wetting the coating surface of woven fabrics or unitape or felt materials. Because liquid resins are spread into a thin layer with a very large surface area, the surface of the substrate plays a major role in accepting the liquid resin. The terms ‘surface tension’ and ‘surface energy’ are sometimes used interchangeably to describe this effect. Surface tension is expressed as force per unit length, such as dyne/cm.

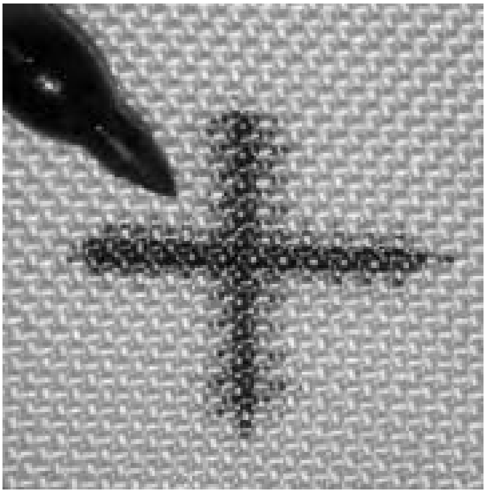
The surface treatment for either unidirectional ballistic prepregs or woven ballistic material can alter the performance of the finished ballistic product. The primary objective of a surface treatment is to remove some of the polymer atoms and replace these with a polar group or a functional chemical group on the surface of the fiber. The replacement enhances the wetting characteristic and reactivity with the resin matrix. This helps in promoting an excellent bond between fiber surface and resin. The surface treatment could be at the ballistic fiber level or to the entire fiber web made of a number of fully aligned fibers. Similarly woven ballistic materials can be treated after the weaving operation is complete.

The surface tension of a substrate can be measured by the contact angle of a drop of a solution with the substrate. A drop of liquid is placed on the surface and viewed through a microscope to measure the contact angle. However, for a fibrous surface this technique may not work as it works on a continuous surface. In such cases a series of calibrated and variable surface tension liquids are used for a qualitative test of the wettability of the surface. The drops are placed on the fibrous substrate and if they bead up, the surface tension of the substrate is poor. However, if it flows and spreads along the fiber direction its surface tension is much lower. With a series of liquids an estimate of the surface energy or tension can be obtained.

A quick test for wettability could be by touching a Sharpie on the fibrous surface. If the ink from the Sharpie starts spreading along the fiber direction, it is most likely the surface energy of fibrous material will accept laminating resin (Fig. 10.1).

10.6.1 Surface treatments of ballistic fibers and materials

A major difference between structural fiber and ballistic fiber is the level of treatment. The ballistic fibers require limited treatment for controlled delamination compared to the structural fibers that require more or less perfect bonding for load bearing and hence more surface treatment to increase the bond strength between fiber and resin.



10.1 Sharpie surface treatment test.

Each high performance ballistic fiber has a unique chemical composition. It is therefore essential to determine what will be the best, commercially viable, lowest cost and environmentally friendly surface treatment. It is not only the surface treatment but also the byproducts that are released after the fiber surface is treated and which have to be environmentally friendly before disposal or release to the atmosphere.

The following are some of the treatments used for ballistic fibers and materials before prepregging for further processing into soft or hard armor:

- scouring;
- chemical treatment;
- plasma treatment;
- corona discharge treatment;
- UV grafting.

Scouring treatment

In scouring treatment, the fibers or fabric to be treated go through a chemical solution which removes any of the undesirable residual fiber finish or weaving aid used during the web formation.

The following scouring process is used by some of the weavers in the ballistic industries:

Step 1 Wet out fabric in water at room temperature.
Step 2 Scour fabric in a solution of pH between 9.0 and 9.5 which consists of:
  I Hostapur CX 0.1 grams/liter.
  II TSP 0.5 grams/liter.

Table 10.1 Effect of scouring on ballistic performance prepregs: Spectra® Style 903/Vinylester product: PASGT shape medium helmet

Scour level	Shell weight (lbs)	V_{50} 17 gr FSP (fps)	V_{50} 2gr RCC (fps)
Control (no scour)	2.55	2277	4152
Half scour	2.59	2408	4428
Full scour	2.57	2378	4335

Step 3 Scour at 120 °F.
Step 4 Rinse at 120 °F.
Step 5 Rinse at 80 °F.
Step 6 Dry out the fabric.

After the scouring process, the residual chemicals on the ballistic fiber or fabric are analyzed again. The surface tension decreases after the scouring process. For ballistic application, this increases the projectile engagement with the coated fabric or coated cross-ply ballistic material.

The example shown above demonstrates that scouring increases the performance of ballistic helmet material against 17 grain FSP and 2 grain RCC fragments.

As demonstrated in Table 10.1, the optimum ballistic is achieved with the half scour condition, which allows improved bonding and lower lamination during the ballistic event.

Chemical treatment

Although a number of chemical treatments are known for treating high performance fibers to increase the bond strength at the interface of the fibers and resins for structural and aerospace applications, none of these treatments are currently commercially used for ballistic composites. This is partially due to the surface chemistry of both aramid fibers and HMPE fibers and partially due to other current treatments, which are less complex and easier to implement for continuous treatment of the ballistic fibers, fabrics and felt materials.

Plasma treatment

The plasma treatment process is an electric discharge into a vacuum chamber filled with either oxygen or ammonia and also carrying ballistic fiber, fabric, or felt which requires treatment. The electric discharge is by radio frequency (RF) energy which dissociates the gas into electrons, ions, free radicals and

Table 10.2 Effect of plasma treatment on HMPE fiber composites

Fiber treatment	Matrix content (% weight)	Interlaminar shear strength (Mpa)
Untreated	34.6	05.7 ± 0.3
Ammonia plasma, 1 min	37.9	11.1 ± 0.3
Ammonia plasma, 2 min	37.6	11.8 ± 0.6
Ammonia plasma, 10 min	35.4	11.8 ± 1.9
Oxygen plasma, 2 min	35.3	06.6 ± 0.6
Corona discharge	35.2	07.0 ± 0.8

Source: *J. of Surface and Interface Analysis*, Vol. 17, 143–150, 1991

metastable products. The selection of gas is fairly complicated and critical for the surface treatment. Electrons and free radicals created in the plasma collide with the fiber surface, rupturing covalent bonds and creating free radicals on the fiber surface. After a predetermined reaction time or temperature, the process gas and RF energy are turned off. Without RF energy, residual gas particles quickly recombine to extinguish the plasma. At this point the vacuum pump removes the leftover gases and other byproducts.

A number of plasma treatment units allow continuous treatment of the ballistic fibers or fabrics. Multiple fiber bobbins or a roll of ballistic fabric are kept outside the vacuum chamber and pass through transition zones to the plasma reactor which is maintained at reduced pressure for plasma treatment. The yarns or fabric then pass through another transition zone to a take-up unit kept outside the vacuum chamber (see Table 10.2).

Corona discharge treatment

The corona discharge treatment is a low-level electric discharge carried out on ballistic fibers, fabrics and felts. The corona discharge unit does not require a vacuum chamber or a chamber filled with oxygen or ammonia gas. The fibers or fabric from the fiber spools or fabric holder pass through the corona discharge and immediately after treatment it is re-spooled or rewound on a unit on the other side of the corona discharge unit. The corona discharge is usually associated with a low-level glow on the material. A pump exhausts any reactive gas produced during corona discharge treatment (see Table 10.3).

The data in Table 10.3 shows that the higher corona levels increase the bond strength between fiber and resin and therefore lower the ballistic resistance. The higher treatment level not only increases the bonding between resin and fiber but increases mechanical rigidity and durability, which lowers the delamination and backface deformation of the hard armor products. Both plasma treatment and corona discharge treatment demonstrate aging of the treatment with time. However, a good level treatment stays on the surface once treatment has

Table 10.3 Effect of corona treatment on flat ballistic molded panels prepregs: Spectra® fabric style 903/vinylester ballistic testing: 17 grain FSP, MIL-STD-662F

Treatment level	Layers	Thickness (inch)	Weight (psf)	V_{50} (fps)
A	30	0.325	1.53	1845
2 × A	30	0.323	1.53	1769
3 × A	30	0.322	1.52	1754

stabilized after a few days. The stabilizing can happen within hours or days, depending upon the treatment level and chemistry of the fiber's or fabric's surface.

UV grafting

The UV grafting is carried out on a ballistic fiber surface by passing the fibers or fabric through a heated solution of monomer, photo sensitizer and solvent. Once the surface of the fibers or fabric is soaked, they are passed through an acetone wash to remove excess presoak solvent. After the acetone wash, the fibers are passed through a dip bath at ambient temperature. This bath is immediately prior to UV irradiation and serves to surface coat the fibers with monomer and photo sensitizer dissolved in acetone. The coated fibers pass through a central quartz tube that runs the length of the UV irradiation chamber. Counter-current nitrogen is provided in this tube and serves to cool the fibers directly and partially eliminates oxygen from the system. The UV grafted fiber is washed by hot water followed by an acetone wash (see Table 10.4).

Table 10.4 Interlaminar shear strength (ILSS) of HMPE fibers

Treatment	ILSS (MPa)
Untreated fiber	10 (1.5 ksi)
Plasma treated fiber	20 (3 ksi)
UV grafted fiber	30 (4.5 ksi)

Source: *Composite Interfaces*, Vol. 1, No. 1, 55–73, 1993

10.7 Prepreg tension control

There are a number of factors that contribute to consistent uniform resin content on a substrate. Uniform tension on the substrate during the entire prepreg process is one of the factors.

Tension through a prepreg machine is the force applied to the high performance ballistic fiber web between adjacent sections. The tension force tends to stretch or elongate the prepreg material depending upon a number of factors such as the width of the web, type of web fiber, woven or unidirectional, differential tension between the prepreg material, and temperature effect on the web's fiber. It is usually recommended to keep the same tension during a repeated run of the same web base and prepreg resin. This will control the resin pick up within fairly tight limits. Most ballistic prepregs equipment tends to run best when the tension throughout the machine is kept at the same level. A good knowledge of how each prepreg runs under a known tension may allow processing the materials at higher speed without increasing the size of existing equipment.

Tension during prepregs is applied to the ballistic web between entry and exit. Before applying tension it is important to know about the ballistic web strength and prepreg machine controls. The tension controls system of the prepreg machine should apply enough tension throughout the web to make it straight without slack or too much tension.

The prepregs of ballistic materials can be run at a higher speed compared to structural composite prepregs. This is due to the low amount of resin required for ballistic prepregs and usually there is no precise 'B' stage, which is essential for structural prepregs. Current prepreg machines have microprocessor-based controls that accepts a speed-related signal from each motor and sensing device from the prepreg machines

10.8 Ballistic versus structural prepregs

Compared to the aerospace and structural composite prepregs, the ballistic prepregs are different in several respects. These differences are:

- resin in a ballistic prepregs does not surround each fiber;
- the ballistic prepregs are a resin starved system;
- resin content is in the range of 10–20% by weight;
- the prepregs are not tacky;
- ballistic prepregs are in 'A' stage, whereas aerospace prepregs are in 'B' stage;
- structural prepregs are always stored below 0 ºC;
- majorities of ballistic prepregs have fairly long shelflife at room temperature.

A brief comparison in included in Table 10.5.

10.9 Prepreg techniques

10.9.1 Dip and dry

This is one of the simplest techniques to make ballistic prepregs. In this technique a continuous web of high performance fibers or fabric or felt web is

Table 10.5 Structural composite prepregs versus lightweight ballistic composites

	Structural composites	Lightweight ballistic composites
Fibers	HM graphite, S-2 glass HM aramids	HMPE, aramids, PBO S-2 glass, E glass
Fiber content	50–60% by volume	80–90% by weight
Resin	High temperature cure thermosets and thermoplastics	Relatively low temperature cure thermosets and thermoplastics
Resin content	40–60%	10–25%
Resin flow	Good	Limited to no resin flow
Fiber surface treatment	Essential	Not essential
Interface	Excellent	Limited bonding for control Delamination
Structural properties	Excellent	Relatively low
Ballistic properties	Poor	Excellent
Microcracking	Limited	Widespread
Void content	<1%	> 5%
Surface porosity	None	Micro porous surface
Water absorption	Negligible	As much as 5%
Failure mode	Brittle	Ductile
Hybrids composites	Yes	Yes

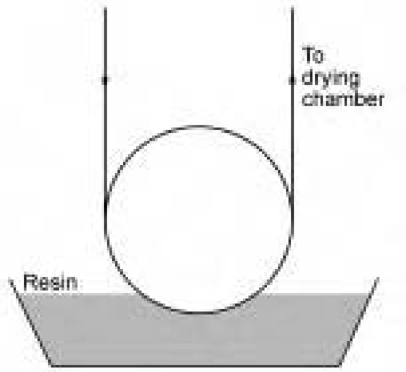
dipped into the coating resin formulation having predetermined solid and solvent content. Final solid content on the prepregs determines if there is need of scraper or other techniques to squeeze coating.

In thermoplastic coating, the main parameters that determine the final dried resin content on the prepregs are:

- consistent solid content in the coating resin formulation;
- uniform viscosity of coating during the entire prepreg duration;
- uniform tension on the ballistic base material web;
- consistent coating temperature irrespective of the seasonal temperature variation;
- controlled humidity and temperature in the coating area.

Similarly, for thermoset prepregs the main parameters that determine the final dried resin content on the prepregs are:

- consistent solid content of the resin formulation;
- uniform viscosity of resin mixture during the entire prepreg duration;
- uniform tension on the ballistic base material web;



10.2 Dip and dry coating technique.

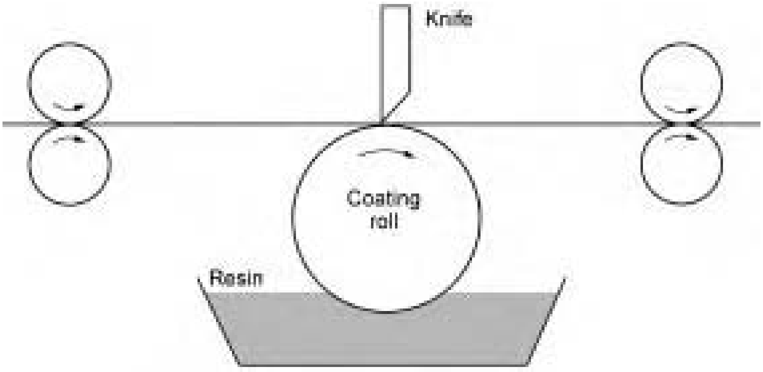
- consistent resin mix temperature irrespective of the seasonal temperature variation;
- controlled humidity and temperature in the prepreg area.

(See Fig. 10.2.)

10.9.2 Knife coating

In knife coating a rigid, stationary metal edge is used to remove the excessive resin from the prepreg ballistic material supported against a roll. The excessive coating is removed and mixed with the rest of the coating. The knife could be flat, tapered or a sharp metal rod. The gap between the knife and the ballistic material determines the final coating weight on the prepregs.

Liquid resin coating on ballistic substrate by this method is simple and needs limited skill and maintenance of the coating system. (See Fig. 10.3.)



10.3 Knife coating technique.

10.9.3 Blade coating

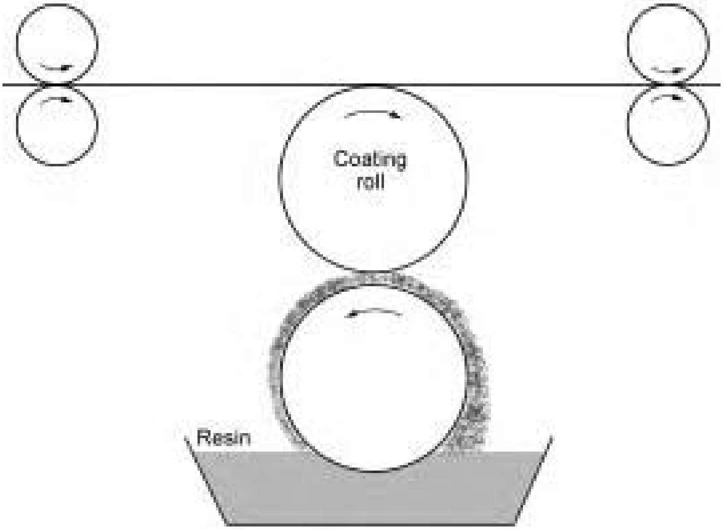
Blade coating is similar to knife coating, but a blade replaces the rigid knife which is pressed against the ballistic web to remove the excessive resin. This technique is often used for a heavily filled system such as phenolic/PVB system for aramid and fiberglass substrate. Due to the high viscosity of coating, the surface depressions at fabric intersection are filled and give a smooth surface for further processing into rigid molded hard ballistic components.

10.9.4 Forward roll coating

In forward roll coating, the applicator roll rotates in the same direction as the substrate web of ballistic material, which is supported by an impression roll support. Both the applicator roll and the web carry coating resin beyond the nip, or region of closest contact and minimum clearance in the applicator. The amount of liquid resin the web picks up depends on the amount brought to nip and the nature of film splitting beyond it. (See Fig. 10.4.)

10.9.5 Rib coating

The goal of limiting resin content on woven and felt type ballistic materials is achieved sometimes by rib coating on one side of the high performance ballistic material. Rib coating also helps to reduce the solvent content of the resin mix, thus increasing the speed of coating. Since the resin mix is high in solid content,



10.4 Forward roll coating technique.

a limited amount of solvent is evaporated from the resin mix. This reduces the amount of energy required to remove and dispose of the solvent.

Rib coating is fairly common for woven aramid prepregs used for molding helmets and hard armor panels using the phenolic/PVB system. Since coating is only on one side, bonding between layers during curing is achieved by resin flow under heat and high pressure molding.

During testing, the molded helmets and panels show improved ballistic resistance due to delamination between layers.

10.9.6 Reverse roll coating

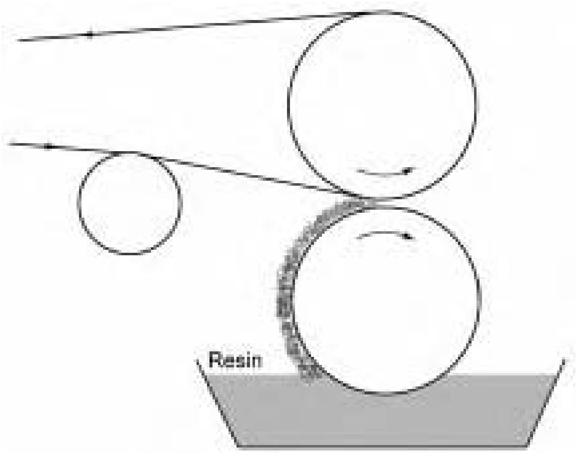
Reverse roll coating is one of the common methods for coating low viscosity resins onto ballistic materials. Due to the simplicity, precision and high speed, reverse coating has been adopted for highly diluted low solid content coating.

There are many different ways of practicing reverse roll coating, but there are a number of common features in these methods. All types of coating operations involve excess coating on the applicator roll followed by removing the excess coating between the applicator roll and the reverse roll, which wipes excessive coating from the applicator roll.

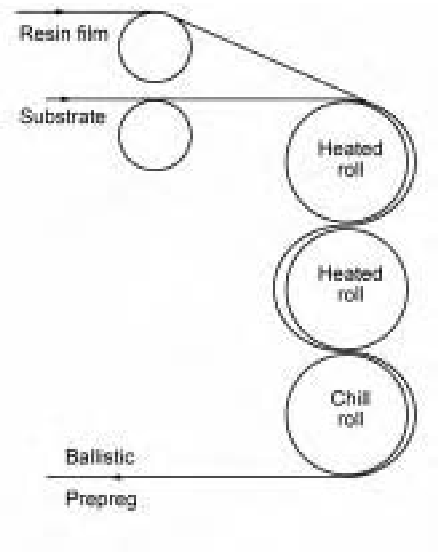
The excessive coating can be reapplied by a number of techniques. The most common method is dipping the applicator into the resin solution. The left-over thin coating is transferred to the reverse wipe ballistic material web. (See Fig. 10.5.)

10.9.7 Film prepregs

A number of commercial thin continuous films of thermoset and thermoplastic resins are available in Europe and North America. The film is laminated on the



10.5 Reverse roll coating technique.



10.6 Film lamination prepregs technique.

woven or unidirectional substrate, by heating and nip pressure. Film prepregs are gaining acceptance in the prepregs industries and provide the following benefits:

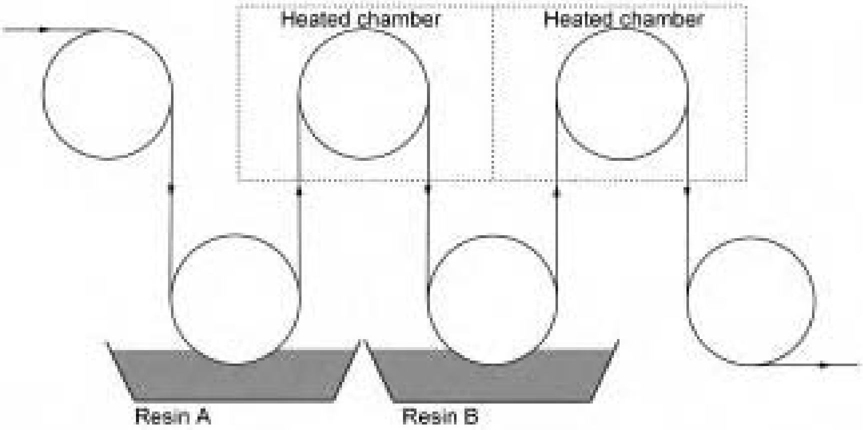
- precise resin control, < 1%;
- resin content as low as 5% by weight;
- highly uniform prepregs, resin variation less than 0.5%;
- practically no volatile organic compounds (VOCs) or moisture emitted during film lamination;
- high speed of prepregs because no drying or removing VOCs;
- extended shelflife compared to solvent or aqueous based liquid prepregs;
- controlled non-wetting or encapsulation of substrate fibers;
- superior ballistic performance.

A majority of these prepregs are used for molding military helmets and to a limited extent as backing for ceramic plates used for personal protection and vehicle protection. (See Fig. 10.6.)

10.9.8 Multiple resin coating

Multiple resin coating on substrates is needed when more than one type of function is required from the coatings. For example, the functions could be:

Coat 1: Rigid resin for structural and impact performance.
Coat 2: Flame retardant property.
Coat 3: Enhanced bonding to certain other materials.
Coat 4: Pigment.



10.7 Multiple coating prepregs technique.

In multiple coating the first coating components should not dissolve while adding the second coat components, and third coating should not dissolve other previously coated components and so on. (See Fig. 10.7.)

10.10 Thermoset resin for ballistic prepregs

10.10.1 Phenolic resin prepregs

The phenolic resins have played an important role in industrial advancement of composites for over 90 years. The term phenolics is applied to those materials formed during the condensation reaction between phenol and formaldehyde.

All phenolics chemistry revolves around two basic chemistry strategies. Although phenol is most commonly involved in phenolics, resins containing p-t-butylphenol, p-t-amylphenol, p-nonlphenol, mixed cresols, and substituted oils derived from cashew nutshell liquid are also used. Because the catalyst, mole ratio of phenol to formaldehyde, reaction conditions, additive sequence, and solvent condition can be varied, an enormous variety of products can be tailored for specific end uses.

Phenolics resins have wide use in structural and ballistic fiber-reinforced composites for their mechanical properties, impact resistance, high heat resistance under load, excellent flame retardant properties along with an attractive price. The impregnation of fiberglass, woven aramid, woven HMPE and woven PBO can be carried out using the formulation shown in Table 10.6.

For economic reasons, one-step impregnation of woven material is preferred. The phenolics resins used for ballistic prepregs are usually modified with other synthetic impact modifiers or flexibilizers. Each ballistic web made of either HMPE or aramid fibers in woven fabric or non-woven fabric form requires a unique formulation based on the projectile and its speed. One well-accepted

Table 10.6 Prepregs formulation used for ballistic helmets and armor plates

Component	Parts by weight	Percentage of total solids
Polyvinyl butyl	868 (25% solid in ethanol)	47.2
Phenol formaldehyde	100 (57% solid in ethanol)	12.4
Trimethylol phenol	267 (60% solid in ethanol)	34.8
Phthalic anhydride	25.6	5.6
Methanol	51.2	0.0

formulation is shown in Table 10.6 and is accepted for molding more than several million helmets as per the specification listed in MIL-H-44099A.

For coating ballistic material with the phenolic formulation, any one of the above-mentioned techniques can be used. Depending upon the volume and production machine availability either knife coating, rib coating or reverse roll coating techniques can be used. Drying the coated material in large heating chambers dries off all the solvents. The solid pick-up on the woven fabric is typically 15–20%, based on the dry weight of the woven fabric.

A number of woven aramid/phenolic resin prepregs are pigmented to match the military green or military desert color. This helps to hide paint chipping or wearing out by the natural wear and tear of military helmets.

For years the resin content on woven aramid fabric with the above formulation was targeted between 15 and 25% solids by weight. Since the mid-1990s lower resin content woven aramid fabrics are also accepted (between 11 and 14%) to increase the ballistic performance at the cost of increased delamination and water absorption from rain.

In Europe, woven aramid fabric prepregs for molding military helmets and other hard armor composites are also manufactured by transferring thin phenolics film to the woven aramids. The resin content by weight for such a prepreg system is about 11%. The ballistic resistance against fragments of molded helmets and hard armor components using this prepreg shows great improvement. However, the molded component is fairly porous and lacks sufficient resin to seal all the porous area. A secondary process is used for such applications to seal the outer surface so that rainwater in the field cannot penetrate the molded military helmets. If water is allowed to penetrate these helmets, the weight increase may be as high as 20% and there may be a long-term drop in the ballistic performance.

10.10.2 Vinylester resins

The vinylester resins are thermosetting resins. These resins consist of a polymer backbone with an acrylate (R=H) or methacylate (R=CH_3) termination R-[-O-C-C=C]. Although vinylester resins have sometimes been classified as polyester, they are typically di-esters that contain recurring ether linkages. The backbone component of vinylester resins can be derived from an epoxide resin, polyester resin, urethane resin and so on but those based on epoxide resins are common in the industry. Epoxide backbones of various molecular weights are used in vinylester resins. Higher molecular weights produce greater toughness and resilience, lower solvent resistance, and lower heat resistance.

Vinylester resins can be used in neat form or they can contain a reactive co-monomer such as styrene, vinyl toluene, and trimethylol propane triacylate or a non-reactive dilutant such as methyl ethyl ketone and toluene. Vinylester resins contain double bonds that react and cross-link in the presence of free radicals produced by chemical, thermal or radiation sources. Cure proceeds by a free-radical mechanism comprising initiation, propagation, and termination. Vinylester resin shows lower peak exothermal temperature and less shrinkage upon cure as compared to polyester resins. Both properties are desirable for ballistic applications.

For proof of concept, R&D purpose or low volume manufacturing, vinylester wet-lay-up process can be used. However, ballistic products perform at optimum performance when resin content is low and the cross-link density is not as high as in a typical load bearing structural application. The resin content for such an application can vary from 20–30% depending upon the reinforcing fibers and interface bonding strength. Such low content in a wet-lay-up process is difficult to achieve and maintain on a consistent basis. Wet-lay-up and resin transfer processes are therefore not widely used in the ballistic industry.

An alternative to the wet-lay-up process of manufacturing is the vinylester resins prepregs. The ballistic vinylester prepregs have precise, consistently low, resin content with a proper curing system to achieve lower peak exothermal and lower cross-link density. Such vinylester prepregs are widely used for hard armor ballistic applications such as helmets, breastplates, and armored panels for vehicle armor.

Due to a fairly large number of vinylester formulations, curing agents, additives, and other components, these prepregs are replacing phenolic prepregs in a number of applications. The vinylester prepreg system offers a wide range of elongation and tackiness required for ballistic prepregs made with aramid and HMPE for autoclave and high-pressure match die molding. The general curing temperature range for vinylester ballistic prepregs varies from 200 °F to 300 °F depending upon the curing agent.

Vinylester ballistic prepregs can be designed to achieve:

- low resin (5% by weight) content or high resin content (30% by weight);
- tackier or high tack;
- flame retardant properties;
- pigmented prepregs;
- long shelflife for extended room temperature storage.

Table 10.7 Ballistic vinylester prepregs formulation (reference US Patent 5,165,989)

Component	Parts by weight	Percentage of total solids
Vinylester resin	50.00	99.96%
PEP 308	0.01	0.01%
T-butyl-perbenzoate	0.03	0.03%
Acetone	24.98	0.00%
Isopropyl alcohol	24.98	0.00%

Controlled bond strength and shrinkage between aramid and HMPE fibers with vinylester resin make the vinylester prepregs one of the prime candidates for absorbing low and high energy associated with the armor penetrating projectiles. Vinylester formulations can be used on either woven fabric, cross-plied non-woven or felt materials consisting of continuous and chopped ballistic fibers (see Table 10.7).

The dip and dry method of coating is generally recommended for the above highly diluted vinylester resin formulation.

Steps for making ballistic vinylester prepregs

1. Prepare resin solution as described above by mixing all the components.
2. Mount the network of fibers (fabric, or non-woven) on the proper frame, which can maintain uniform tension during prepregs.
3. While maintaining the tension, let the network of fibers dip in the solution and get fully covered by the resin mix.
4. Dry the coated network of fibers under heat below 75 ºC for sufficient duration to achieve less than 1% volatile content.
5. Wrap the prepregs on a roll with a release film or paper to avoid direct contact of coated materials with each other.

10.10.3 Polyester resins

The polyester resins are a combination of reactive polymers and reactive monomers. Curing of the resin takes place by an additional reaction that involves the conversion of double bonds into single bonds. Styrene is by far the most commonly used. It combines with the reactive double bonds of the polyester chains, linking them together to form a strong polymer network.

The polyester resins are the most economic in the industry. The polyester resins are widely used in the manufacturing of a broad range of fiber-reinforced composite products such as boats, electrical components requiring low dielectric properties, automotive parts, sports equipment, and structural panels. So far, the use of polyester resins and polyester prepregs is limited to more cost effective armor with fiberglass reinforcement.

Similar to vinylester resins, the polyester resins have a fairly wide selection of formulations, curing agents, additives, and other components to provide a tremendous range of possible properties. The resulting prepreg system includes a wide range of elongation and tackiness required for ballistic prepregs made with aramid and HMPE fiber reinforcement for autoclave and high pressure match die molding.

The wide range of curing agents allows curing ballistic prepregs at a wide range of curing temperatures. Generally, the curing temperature range for ballistic prepregs varies from 200 °F to 300 °F. This allows polyester ballistic prepregs to utilize ballistic fibers with low and high melting temperatures.

The polyester prepregs can be formulated to achieve:

- low resin (5% by weight) content or high resins content (30% by weight);
- tackier, or high tack;
- flame retardant properties;
- pigmented prepregs;
- long shelflife for extended room temperature storage.

The polyester prepregs formulation (US Patent 5,165,989) is given in Table 10.7.

Steps for making ballistic polyester prepregs

The key steps for making polyester-based ballistic prepregs are as follows:

1. Prepare resin solution as described above by mixing all the components.
2. Mount the network of fibers (fabric, or non-woven) on the proper frame, which can maintain uniform tension during prepregs.
3. While maintaining the tension, let the net work of fibers dip in the solution and get fully covered in the resin mix.
4. Dry the coated network of fibers under heat below 75 °C for sufficient duration to achieve less than 1% volatile content.
5. Wrap the prepregs on a roll with a release film or paper to avoid direct contact of coated materials with each other.

10.10.4 Epoxy resins

Epoxy resins are widely used for aerospace fiber-reinforced composites due to their low weights, high load bearing structure and high temperature operating capability. Some of the important features of molded epoxy resin composites, such as excellent structural properties, excellent bond, and low shrinkage make them a relatively less attractive candidate for absorbing the impact energy associated with high-speed projectiles.

The epoxy resins are based on Bisphenol A and epichlorohydrin. Bisphenol A epoxy resins are dysfunctional, with epoxide groups on the end of the chain. As the molecular weight is increased, the resin retains its epoxide dysfunctionality while adding ‘n’ repeating groups.

Although epoxy resins are more expensive resin systems compared to other thermoset system, epoxy resin offers a wide selection of other features which may compensate for relatively lower ballistic properties. Properties, which offset ballistic deficiency, are the load bearing structural properties, chemical resistance, paintability, bonding to a number of ceramic and metal facing materials, dimensional stability and other such properties.

The selection of an appropriate curing agent for an epoxy ballistic prepreg system is as important as the selection of proper epoxy resin. The type of curing agent determines the shelflife, rate of reactivity, degree of exothermal reaction, and the heat requirement during the molding cycle. In addition to ballistic performance, structural properties, impact properties and bonding characteristics to metal, ceramic and other sub-state materials must be considered when selecting an epoxy curing system. The curing system determines the type of chemical bonds formed and degree of cross-linking which occurs during the molding of ballistic components. A high degree of chemical bond and cross-linking density usually means better structural properties, but relatively poor ballistic performance.

A proper balance between structural and ballistic performance can be achieved by designing a controlled chemical bonding between ballistic fibers and also by controlling cross-link density.

A proper selection of epoxy resin along with a suitable curing system can offer the following properties to a fully cured molded ballistic component:

- relatively high bond strength with ballistic fibers;
- low shrinkage;
- higher structural properties;
- decent ballistic performance;
- reasonable shelflife at room temperature;
- ease of molding;
- no moisture release during molding;
- ease of painting;
- easy to bond with ceramic and metal facing;
- easy to dispose of as cured solid waste.

10.11 Thermoplastic resins for ballistic prepregs

Due to excellent shelflife of thermoplastic ballistic prepregs, cost of storage and transportation is reduced compared to thermoset systems. These prepregs can potentially be remolded by application of heat and pressure. Overall thermoplastic prepregs have a lower production cost. However, repeated molding and exposure to extreme climates may affect long-term performance of certain molded ballistic components.

10.11.1 Acrylic resins

Acrylic resins are synthesized from a wide selection of acrylic and methacrylic ester monomers and low level of monomers having other functional groups. Most of the commercial processes are free-radical-type additional reactions conducted at elevated temperature in the presence of an initiator.

Acrylic resins are available in solvent-based systems and as aqueous emulsions. Viscosity in both the systems can be designed to meet the low resin content prepregs made of either fabrics or unitape fiber prepregs ballistic molding applications. Acrylic resins are known for good UV and oxidative stability. Thickeners are commonly used in acrylic emulsions. By proper choice of thickener the rheology properties can be optimized for low resin content.

Hard molded armor using thermoplastic acrylic coating on high performance ballistic materials shows good ballistic performance against fragments, but usually shows higher delamination when tested against handgun bullets. Some of these problems can be overcome by blending acrylic resin with other higher bond strength additives.

10.11.2 Polyurethane resins

The polyurethane resins are widely available in the industry for multiple uses due to their toughness, flexibility in terms of resin elongation at failure, bond strength between different substrates, high pigment loading, exceptional bonding with rubber and metals, high breaking and tearing strength when used as thin tapes loaded with magnetic oxide binder for magnetic tape, toughened and high abrasive properties, good electric wire and application ease in electrical systems.

Most polyurethane-based resin systems are applied from a solution in volatile organic solvents. Due to ecological and pollution reasons polyurethane aqueous dispersions are getting popular. The aqueous dispersions generally carry some solvents in very low concentration. The emulsion resin contains high solid content that forms a continuous film when dried at room temperature. However, if aqueous resin coating is applied to a ballistic substrate and dried out at 250 ºF to 350 ºF it improves the coating bonding strength, durability and adhesion to substrates.

Single component and two component polyurethane resins are available in a wide range of applications. However, limited commercial formulations are available with long shelflife for ballistic prepregs at room temperature. The viscosity of aqueous-based resin is generally adjusted for ballistic prepregs by adding distilled water and coating on the ballistic fiber and fabric followed by drying at elevated temperature in an oven.

10.12 Thermoset–thermoplastic hybrid prepregs

A new trend has emerged in ballistic prepregs, both for woven and non-woven (cross-plied and felt materials) where the first layer of resin coating can provide the higher level of ballistic, but relatively low bonding, and the second coating could be a thin, continuous or discrete layer of adhesive either applied as a coating or film. A pigment can also be added to the first or second coating, and also a flame retardant or other performance-enhancing additive in the second coating.

10.13 Other prepreg techniques

Some of the other prepreg techniques which are used for aerospace and structural composites such as hot melt, powder coating, extrusion and spraying are not common with the ballistic prepregs. Since the ballistic prepreg industry is relatively small as compared to structural composite applications, these techniques may develop as the ballistic market grows and new applications requiring unique structural and ballistic performance in one system become necessary.

10.14 Additives for thermoplastic and thermoset resins

Additives are frequently added to the thermoplastics and thermoset resin to enhance certain features of the prepregs which are not provided by the resin system. More than one additive could be added to provide a variety of features.

These features could be as simple as adding a pigment and as complex as adding fillers which may provide self-healing of the bullet resistant vest or a molded ballistic product once a projectile has either penetrated or stopped in the ballistic product. Other features could include toughness, flame resistance, breathability, radar transparency, electronic sensors, and nuclear–biological–chemical protection.

10.15 Quality of ballistic prepregs

The quality of ballistic prepregs can be checked throughout the manufacturing, storage, and processing of the material. The following are typical tests conducted on ballistic materials.

10.15.1 Visual inspection

Visual inspection of ballistic prepregs is simple. It is low cost, consumes minimum time and effort and can provide valuable information about the quality of the prepregs without going through expensive testing. During visual inspection, the ballistic prepregs material is unrolled and passes in front of a set of lights. Any color change, fiber missing, fluctuation in resin content or impurities are apparent to the naked eye and can be marked, recorded, and flagged. Such tests can usually be quantitative using Gardner Color Scale (ASTM D1544) and refractive index (ASTM D 542-50).

10.15.2 Total prepreg weight

Checking the per unit area weight of incoming and outgoing ballistic prepreg material against the production specification can provide useful data without going through destructive testing. A few samples of prepregs are cut from the prepreg roll and weight variation is recorded and checked against the specification. A weight variation within 2% is usually considered as good prepregs material.

10.15.3 Resin and fiber content

Washing the resin completely from the prepreg material can provide information both about resin and ballistic fiber content of the ballistic prepreg material. The washing solvents are usually industrial solvents such as acetone, MEK, toluene or other commercial solvent. The test samples, as small as 15 cm x 15 cm, are washed three to four times with fresh solvent and finally oven dried and the leftover fibers weighed to provide both resin content and fiber content.

$$\text{Resin content (\%)} = \frac{\text{Initial sample weight} - \text{Final dry fiber weight}}{\text{Initial sample weight}} \times 100$$

$$\text{Fiber content (\%)} = \frac{\text{Final dry fiber weight}}{\text{Initial sample weight}} \times 100$$

If the prepreg has partially cured or prepreg resin is a blended resin this technique may not work.

10.15.4 Volatile content

During the manufacturing of ballistic prepregs, resins are usually diluted to achieve the low resin content. To achieve this goal, solvents-based and aqueous-based resins are diluted. Although a majority of solvents are driven off during prepreg manufacturing, it is good practice to check the volatile content of prepregs.

Small samples of prepregs are cut from the prepreg roll. The samples are heated in a circulating air oven kept at 100–150 °C. After some set time the samples are taken out, cooled to room temperature and weight loss is calculated.

$$\text{Volatile content (\%)} = \frac{\text{Initial weight} - \text{Dry weight}}{\text{Initial weight}} \times 100$$

Usually, three or more samples are tested for a single test.

Other similar test are ASTM D3539-76, MIL-G-83410 (USAF) and MIL-R-7575.

10.15.5 Specific gravity

The specific gravity (or density) of ballistic prepreg materials is usually specified and may be indicative of batch quality and process control for certain prepreg materials. For molded parts and prepregs which are not soluble in certain chemicals, ASTM D792 (Specific Gravity and Density of Plastics by Displacement) and ASTM D1505 (Density of Plastics by the Density–Gradient Technique) are used to measure specific gravity of prepregs and molded parts.

10.15.6 Flow test

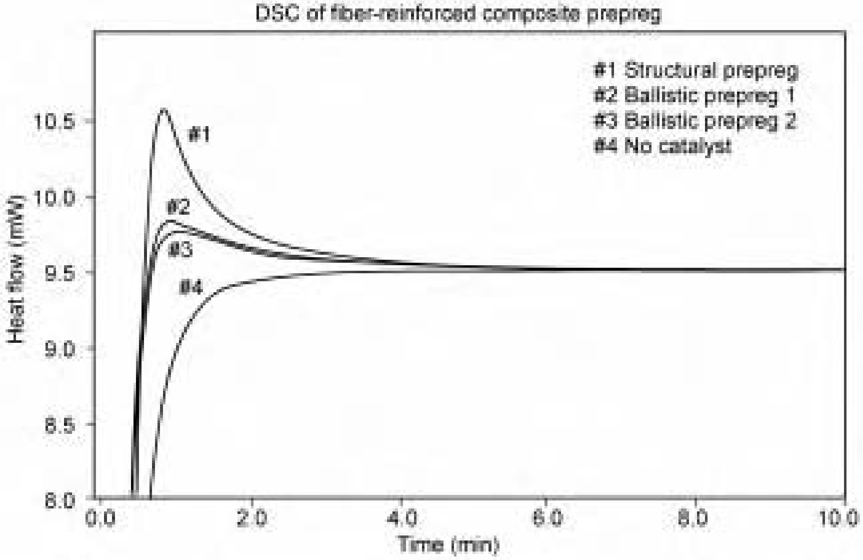
This is a common test for structural composite prepregs where resin content is fairly high and resin viscosity is not very high. However, due to low content in ballistic prepregs this test may not have sufficient resin to flow under heat and pressure. This is especially true for thermoplastic resins where the viscosity of the resin is fairly high once all the solvent is driven off during prepreg operation.

10.15.7 DSC

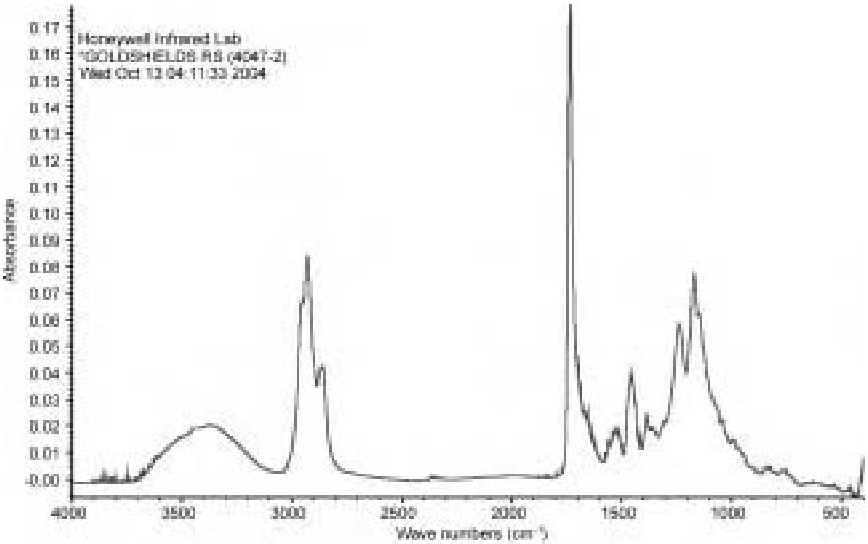
Differential Scanning Calorimeter (DSC) test is simple and requires a very small amount of ballistic prepregs to confirm the quality of the prepregs (see Fig. 10.8).

10.15.8 Infrared

Infrared (IR) or thermal techniques utilize differences in heat flow due to the presence of defects within the chemical structure of the material. The material is first heated. As the material is heated or cools, the surface temperature is observed through the use of a sensitive infrared measuring device (radiometer). Each material has a unique IR wavelength. A typical IR test is shown in Fig. 10.9.



10.8 DSC test on prepregs.



10.9 IR test on prepregs.

10.15.9 Mechanical testing

Mechanical testing for ballistic prepregs is conducted to confirm that ballistic materials in terms of fiber, fiber surface treatment resin, resin content, fiber orientation, and the molding process have the structural capability of the ballistic

Table 10.8 Flexural properties of ballistic materials (ASTM D790)

Ballistic material	Resin	Thickness (inch)	Weight (psf)	Strength (KSI)	Stiffness (KSI)
A	X	0.21	1.00	1.38	185
A	Y	0.21	1.00	0.68	49
A	Z	0.22	1.00	12.4	2060

fiber reinforced composite system. This testing is used for quality control and batch-to-batch process reliability.

Flat panels, usually 30 cm × 30 cm, are molded using the ballistic prepregs and the molding conditions recommended for the resin system. Samples are cut from the molded panel as per the recommended sample size and as per ASTM D 790 using 40 : 1 ratio. The performance of the molded ballistic panel is recorded in terms of flexural stiffness, flexural modulus and ultimate deflection (see Table 10.8). Similar tests can be conducted if the molded armor system is to be used in an application where armor will be subjected to either pure tension (ASTM D 638) or pure compression (ASTM D).

10.15.10 Scanning electron microscopy (SEM) analysis

The scanning electronic microscope analysis is conducted on ballistic prepregs to check the fiber distribution, fiber packing density, and any damage to fiber during weaving and/or prepreg process, and resin distribution within the prepregs. The analysis can also be utilized to understand any impurity in the prepregs.

Samples size is relatively small, but provides information at micro level. SEM is a variable tool for R&D purposes while designing ballistic prepregs for specific applications.

10.15.11 Ballistic testing

Depending upon the application and ballistic threat, shoot packs are prepared and tested as per the NIJ Standard 0101.04 for soft flexible vests and tested as per MIL-STD-662F for molded hard armor. For flexible vests testing is conducted on Plastilina #1 backing, calibrated as per the standard guidelines. A 45 cm × 45 cm shoot pack is prepared with the number of layers suggested by ballistic raw material for meeting a V_0 (all bullets fired at muzzle velocity) recommended by the standard. A minimum of five such shoot packs should be tested to confirm the vest design. All five such shoot packs should pass the penetration test at 0° and 30° and also stay within the deformation of 44 mm suggested by the standard.

For hard armor testing, generally 30 cm × 30 cm panels are molded as per the recommendation of a raw material supplier. The number of layers per panel is a function of the ballistic threat. For defeating armor piercing and some high-energy rifle bullets the panels have a ceramic facing.

10.16 Storage of prepregs

Prepregs with thermoset usually have an active resin with limited shelflife at room temperature. Some of the prepregs also have a low molecular weight additive. It is therefore essential to keep the prepregs in the original packing. The prepregs for extended shelflife or between the processing should be stored in a freezer below 0 °C. Once the prepreg is taken out for processing it should be kept at room temperature in its original packing for several hours to bring the entire roll to room temperature. This prevents moisture condensation from the atmosphere.

During storage inside the freezer, the rolls of prepregs should be clearly marked and stored in such a manner that the rolls do not touch each other or deform the prepreg roll shape due to the storage roll's weight. Storing rolls vertically should be avoided. The storage of prepregs with thermoplastics requires less stringent storage conditions. Most of the thermoplastic prepregs can be stored at room temperature for months without losing their processability. Both thermoset and thermoplastic prepregs should be kept away from sun, heat and other chemical environments.

10.17 Shipping of ballistic prepregs

Similar to storage, during shipment most thermoset prepregs should be stacked and shipped in a freezer truck and kept below 0 °C. Rolls of prepregs should not be stored in such a manner that the weight of other rolls distorts the shape of the prepreg rolls. During shipment prepregs should not be exposed to moisture, heat or light.

The thermoplastic prepregs are relatively easy to store. They can be shipped in normal trucks without freezing facilities. However, heat and moisture should be avoided during shipping.

10.18 Recycling of prepregs

A number of factors are forcing a number of high performance fiber manufacturers, prepreg makers, molders and final users to consider the recycling of prepreg. These factors are:

- double digit growth of ballistic materials;
- processing waste in certain cases could be as high as 20–25%;
- fiber, resin, and prepregs can be processed into other products;

- cost of raw material is fairly steep and any savings due to recycling is desirable;
- environmental awareness.

Some of the recycling involves chopping the aramid/phenolics prepregs and converting them into brake linings.

10.19 Disposal of prepregs

Similar to any active chemical, ballistic prepregs which are chemically active materials should be disposed of after curing the resin. This can be achieved by collecting all leftover pieces of thermoset prepregs and curing them in an oven kept above the curing temperature of the prepregs for a duration recommended for complete cure. After taking them out of the oven, cured prepregs should be brought to room temperature and checked for areas which might not have fully cured. All the fully cured prepregs should be disposed of as solid waste.

Similarly, when disposing thermoplastic prepregs care should be taken to avoid any possible wash-away of resin over the extended period of the prepregs being dumped in the garbage and going into the drinking water system.

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Mohr, J. G., Oleesky, S. S. and Meyer, L. S., *SPI Handbook of Technology and Engineering of Reinforced Plastics/Composites*, 2nd edn, Robert E. Krieger Publishing Company, 1981.

Skeist, I., *Handbook of Adhesives*, 3rd edn, Van Nostrand Reinhold, 1990.

10.21 Partial list of ballistic materials prepreg suppliers

1. Bedford Materials
7676 Allegheny Road
Mann Choice, PA 15550
Tel +1 814 623 9014
Fax +1 814 623 9199
www.bedfordmaterials.com

2. Lewcott Corporation
89 Providence Road
Millbury, MA 01527
Tel +1 508 865 1791
Fax +1 508 865 0302
info@Lewcott.com

3. Bryte Technologies Inc.
18410 Butterfield Blvd.
Morgan Hill, CA 95037
Tel +1 408 776 0700
Fax +1 408 776 0107
Bryte@brytetech.com

4. Cuben Fiber Corporation
4511 East Ivey Street
Mesa, Arizona 85205
Tel +1 480 641 0438
Fax +1 480 641 0439
www.cubenfiber.com

5. YLA, Inc.
   2970 Bay Vista Ct
   Benicia, California 94510
   Tel + 1 707 747-2750
   Fax +1 707 747-2754
   www.ylainc.com

6. Ten Cate Advanced Composite Group
   PO Box 360
   7440 AJ Nijverdal, Holland
   Tel +31 548 633 933
   www.tencate.com

7. SEAL
   Tel +39 0331 467 555
   www.seal.it

11

Ballistic material processing

A HANNIBAL and B WEIR, Composiflex, USA

11.1 Introduction

The objective of making ballistic armor is to reduce the speed of the projectile to zero velocity while minimizing trauma. The ability of a composite structure to do this comes from a variety of factors, typically the choice and structure of the fibrous material and the type and content of resin (binder). The interaction of these factors and their processing requirements dictate greatly the methodology of production.

A composite is any material made from more than one component; for example, concrete is a composite and so is a chocolate chip cookie. However, for our discussion, a composite consists typically of two components: fibers and resins.

11.1.1 Resin

The resin system coats or impregnates the fiber bundles and binds the composite together giving it rigidity and shape. Resins are always either thermosetting or thermoplastic in nature.

Thermosetting resins

A resin comprises two or more liquid components which when mixed together in the proper proportions cross-links or hardens, creating a new material which exhibits many advantageous physical and mechanical properties. Although many thermoset resins can cross-link at room temperature, it is usually more optimum to cure these materials in the presence of heat and pressure. Thermoset resins do not melt and the components cannot be recovered.

Thermoplastic resins

Thermoplastic resin is a single component long chain polymer that melts at elevated temperature. With the addition of pressure and/or vacuum the resin can be infiltrated into the fiber.

11.1.2 Fiber

Fibers are available in bundles or ‘tows’ wrapped on rolls of various sizes. These bundles comprise thousands of tiny fibers of very small diameter. These fiber tows are typically woven into fabrics or are processed into unidirectional prepregs.

For general applications composites are called fiber-reinforced plastics since they consist of fibers and resins (typically plastics). These composites are generally structural in nature and are not typically good ballistic materials. Composites for ballistic applications tend to differ from typical fiber-reinforced composites in the following specific ways:

- the resin content is usually much lower – in the 18 to 22% by weight range as compared to 40 to 65% by weight for structural composites;
- the resin is typically more elastomeric (rubbery) than plastic, giving the final product a soft or somewhat flexible feel;
- limited bonding is desirable between fibers and resin;
- void contents of ballistic composites are fairly high;
- the resin role is fairly limited;
- bi-directional composites in (0, 90) orientation provide the best armor material;
- unidirectional oriented ballistic composite (0, 0, 0, 0 … 0) offers poor ballistic resistance.

11.2 Materials for ballistic composites

Other than using liquid resins, like the two-part epoxy mentioned above, all composites generally incorporate the same groups of components.

11.2.1 Reinforcing fibers

Generally speaking, almost any fiber can be used to reinforce plastic; in the case of ballistically resistant composites, the most common are fiberglass, aramid or long-chain polyolefin because of their strength. Hence, we see that ballistic composites are almost always produced from long-chain polyolefin fiber – Honeywell’s Spectra® and DSM’s Dyneema®; or from Kevlar® or Twaron® aramid or polyaramid fibers.

In early attempts to make lightweight body armor, the most common fiber to use was silk – it did not gain widespread acceptance because of the price.

While silk is a very strong fiber with a tensile-strength-to-weight ratio (‘tenacity’) of a maximum of about 5 grams per denier (g/d) it is obvious why modern synthetic fibers caused a virtual revolution is lightweight armor. For example, the tenacity of the nylon that was common during the Vietnam conflict is 8 g/d. The evolution and capability of research has lead to even greater feats of resistance that led first to Kevlar® at 26 g/d and then to Spectra® at 35 g/d.

Nature is not really outdone by this – spider silk has an even greater tenacity, but it cannot be cultivated and collected economically as silkworm silk can; chemists and genetic engineers are striving to develop an economical way to synthesize and mass produce it, but the carbon nanotube may beat them to the punch.

The tensile strength of modern materials is the measure by which we can decide how well they will resist a ballistic impact, since the impact causes them to stress. If we divide the force by the cross-sectional area, we get a factor for stress:

$$\frac{F}{A} = \text{Stress} \tag{11.1}$$

Strength is the stress required to break the fiber. Usually this is expressed as N/ cm^2 – obviously the higher this number, the higher the strength.

Naturally, some fibers stretch before they break, and the amount of stretch they display is called ‘elongation’ – the elongation is the percentage of difference between the unstretched and stretched length of the fiber.

Kevlar® is a strong fiber made from polymeric aromatic amide (polyaramid, most often called ‘aramid’ today) plastic by dissolving it in a special solvent and spraying the solution through a small nozzle called a spinneret. The solvent evaporates, leaving the plastic fiber, which has a strength-to-weight ratio about five times that of steel. The possibility of making polyaramid plastic was hypothesized in 1939. It was synthesized and identified at DuPont in 1960, but polyaramid fiber could not be produced until 1965, when Stephanie Kwolek, a chemist at DuPont, discovered a practical solvent. DuPont named this product Kevlar®.

At about the same time, a team at Akzo Inc., a multinational firm headquartered in Holland, independently discovered a practical solvent and applied for a patent for the manufacture of polyaramid fiber, which it later (1984) named Twaron®.

Before Kevlar® was used for body armor, it was used as a substitute for steel in the manufacture of radial tires, including those designed for police cars.

It does not melt but does pyrolyze (decompose) at very high temperature. It loses some strength as its temperature is increased but remains strong enough to be used for applications requiring a high strength-to-weight ratio at high temperature, e.g., in the telescoping nozzles of solid-fuel rocket motors.

Spectra® is a registered trademark of Honeywell, for the high-strength synthetic fibers the company produces from high moldulus polyethylene (HMPE). Key properties of these fibers (marketed under the brand name

Note: Dyneema is a registered trademark of Dutch State Mines; Kevlar is a registered trademark of DuPont; Twaron is a registered trademark of Teijin-Twaron; Spectra is a registered trademark of Honeywell.

Spectra) include low weight and high strength, as well as resistance to impact, moisture, abrasion, chemicals, and puncture.

The first successful commercial application for Spectra® fibers, introduced in 1985, was as a substitute for steel in ropes and cordage. Other applications that followed include puncture- and cut-resistant safety gloves.

For soft body armor applications, Spectra® fibers are woven into bullet-resistant fabrics or, more commonly, used as a reinforcing fiber in a flexible, non-woven composite material called Spectra Shield®, introduced in 1988. Thicker, rigid Spectra Shield® is also made for use as hard armor in helmets, radomes (protective coverings for radar antennas), sonar, and other applications.

Spectra® fibers are made by a process called gel-spinning. Extended-chain polyethylene molecules containing 70,000 to 350,000 carbon atoms are dissolved in a solvent which is heated and forced through tiny nozzles called spinnerets.

The resulting jets of solution cool and harden into plastic fibers, which are drawn, dried, and wound onto spools for further steps in manufacturing. This fiber-producing process aligns the extended-chain polyethylene molecules so that the hydrogen atoms of each molecule bond with those of its neighbors.

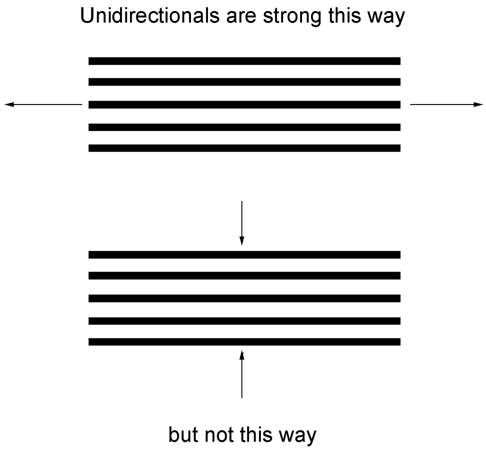
This gives Spectra® a tensile strength greater than aramid fibers. Spectra® is also less dense than other fibers; its specific gravity is only 0.97, so it floats. Pound for pound, it is ten times as strong as steel. Spectra Shield® is made by aligning Spectra® fibers side by side and bonding them with a flexible Kraton resin (produced by Shell Chemical) to make a single-ply sheet. Two plies of such sheets are crossed, so that the fibers in one are perpendicular to the fibers in the other, and bonded together.

The resulting two-ply, cross-plied sheet is coated on each side with an abrasion-resistant film to make one thin, flexible sheet of two-ply Spectra Shield® composite material for use in body armor.

Thicker, multi-ply panels for use as structural armor are made by cross-plying additional layers before coating.

Another notable characteristic of Spectra Shield® is the high velocity – 12,300 m/s – at which the stress imparted by a bullet propagates within the armor outward from the point of impact, which allows the bullet's energy to be absorbed by a large area of the armor. In the 1 to 2 milliseconds during which a low-energy bullet is decelerated by the armor and backing material, part of its energy would be distributed over and absorbed by the entire ballistic panel (Fig. 11.1).

Spectra® fabric and Spectra Shield® can be ignited but only when their temperature reaches 675 °F; they are less flammable than cotton or polyester fabrics typically used for police uniforms. Flame-retardant tactical armor has been made by enclosing Spectra Shield® in a carrier garment made of flame-retardant fabric. Spectra® melts at about 150 °C (about 300 °F), but Spectra® fabric retains 94 percent of its room-temperature ballistic resistance at a



11.1 Directional stiffness of material.

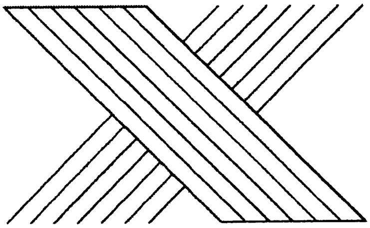
temperature of 160 °F. Armor so hot would be excruciatingly painful and would burn skin in less than a second, so ballistic resistance at so high a temperature is almost irrelevant.

11.2.2 Structure

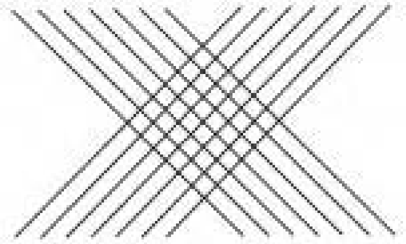
Fibers can be oriented either in a unidirectional material, or woven. The lack of strength for the oriented fiber, can be compensated for in two ways. In opposed unidirectionals, the fibers can be overlapped in a 0–90° orientation, giving strength on these two axes. Or, they can be woven, and the weaving process can pass stress at the intercise. (See Figs 11.2 and 11.3.)

11.2.3 Resins

A wide variety of resin products are used in the production of anti-ballistic composite structures; one resin typically used in US Government specifications



11.2 Cross-plied material.



11.3 Woven material.

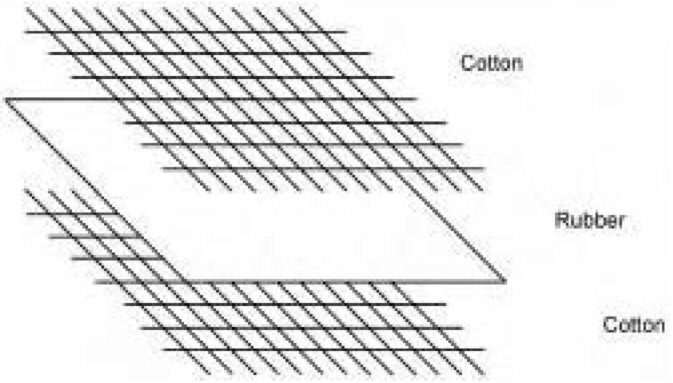
is a catalyzed system composed of 50% phenol formaldehyde and 50% polyvinyl butyral resins – the percentage of the resin is a key variable.

Using resins to produce polymer composites is a very old technology – natives in Central and South America used the elastomer polyisoprene to produce many useful things. Polyisoprene is natural rubber and its use by Charles Macintosh to produce a viable and comfortable raincoat led to one of the first real uses of a pair of polymers (since the cellulose in cotton is also a natural polymer).

The lay-up of Macintosh's composite is shown in Fig. 11.4. The rubber made it waterproof and the cotton made comfortable to wear; this is an ideal picture of how composites share characteristics to produce a better product.

To produce a ballistic composite, we need better strength than would be found using cotton fiber, the introduction illustrates how the US Army made this same discovery after the Second World War. Ballistic fibers, however, are brittle but have great tensile strength (they are strong when pulled). Mr Macintosh's rubber might do a good job for a ballistic composite, since it would give the mix better compressional strength; man-made resins, however, do the job a lot better. Rubber has shown us how to do other things.

In 1839, Charles Goodyear accidentally discovered the process of vulcanization – a process that was really cross-linking, a process of chemical



11.4 Macintosh's composite.

bridge-building that brings with it new polymer abilities that the un-cross-linked material does not have. It essentially means that a cross-linked polymer forms one big molecule. This created a thermoset – the process of thermosetting is the same as cross-linking. A non-cross-linked material is one that becomes plastic when heated. This introduced great possibilities, since the world now had what was, in essence, a thermosetting resin.

11.3 Molds

Molds play an important role during processing of high performance ballistic composites. The quality, economics, and saleability of the composite components depends upon the quality of mold on which it was produced.

Molds can be classified in three major categories:

1. Low volume low pressure molds.
2. High volume high pressure molds.
3. High volume low pressure molds.

11.3.1 Low volume molds

Low volume molds could be for fabrication of a few prototype ballistic components. These molds could be made with:

- wood;
- unreinforced plastics;
- fiberglass;
- ceramics;
- galavizing steel sheets;
- ease to machine metals.

11.3.2 High volume high pressure molds

The performance of standalone high performance ballistic composite is a function of molding pressure. In certain rifle protection applications, considerable weight saving can be achieved by high pressure molding. Similarly due to low resin content, unless high molding pressure is utilized the durability, structural and dimensional stability is limited. Molds for such applications are usually made with chrome plated die hard steel. A few typical examples include military helmets, ballistic plates and ballistic kits.

11.3.3 High volume low pressure permanent mold

Large volume low pressure molds are used for autoclave processing. These molds are usually made with relatively thin steel, high temperature cured composites, ceramics, and softer metals such as aluminum. Such molds are usually for ballistic products which have a curved shape and may be fairly expensive and heavy if made with die hard steel. A few typical examples include backing material for metals, ceramics, or other hardened faced material. Standalone low pressure molding processes are not as rigid and durable as ballistic products made with match-die high pressure molds.

Because of the specialized nature of mold making, a large number of toolmakers have established an industry for producing the molds and tools for parts and assembly fabrication. New molds are designed with computer assistance (CAD) and presented in three-dimensional form (CAM) and computers can assist with the transformation to machining (N/C) and inspection.

11.4 Heating and cooling systems for molds

Heat is essential for processing metal, plastic, composites, and a host of other materials. Heat is also applied for processing of ballistic composites. The heat could be applied from the flat heated platens attached to the hydraulic press or by circulating heated steam or oil through the mold. Steam heat is used if the fabrication plant is already using steam for processing other materials. Usually, for new plants an oil heating system is attached to the mold.

The cooling of ballistic composites is used for a number of applications. Cooling of the mold under molding pressure ensures the surface finish and ballistic performance of the molded component. Cooling is achieved either by circulating chilled water or tap water through the mold.

11.5 Mold release

Molds are treated and sometimes coated with various sealants and releases to provide the necessary surface for the quick release of a molded component. Besides assuring easy release, a properly chosen release system also eliminates mold cleaning and repeated mold repair.

Mold releases are available in solid, liquid, wax and aerosol composition containing silanes, silicans, plastic films and paste waxes. The choice of a proper release system is based upon the quality, reliability, technical service, unique quality of the release system and the cost. A release system which works every time is less expensive than one which may cost less but damages the molded part during release and also the mold.

11.6 Adhesive bonding

Adhesive bonding is the process in which an adhesive is used to attach two like or unlike ballistic materials together or ballistic composite to non-composite material. An adhesive, based on thermoplastic or thermoset resin, may be used to bond two composite laminates together, or a non-metalic to composite, or a metal to composite, or a ceramic to composite. In any case, there are a number of combinations of materials which might be joined to ballistic composites, and there are corresponding numbers of adhesives and adhesive modifications which can be used for the application.

The adhesive used for bonding ballistic composites can be grouped into the following basic categories:

1. *Solvent-based adhesives*. Solvent-based and water-based liquid adhesives are available in a wide range of viscosity and a number of bases such as epoxy, polyester, urtethane and a host of other resins. Solvent-based adhesives provide a high level of bonding. These adhesives are easy to apply. The limitations are shelflife and environmental concerns.
2. *Liquid adhesives*. Liquid adhesives could be a single component or two component material, of higher viscosity than solvent-based adhesives, and which cure fast and provide a hard or a flexible bond. Adhesive bases include epoxy, urethanes, rubber, and silicans. These adhesives do not run and can be applied *in-situ* on a vertical surface. The shelflife is limited once applied to the surface.
3. *Hot melts*. 100% solid adhesives flow when heat is applied. Hot melt solvent-free, easy to store and transport, and provide clean operation. Base material may be made with polyethylene, saturated polyester, polyamides and blended polymers and fillers.
4. *Dry resin films*. Available in several forms including hot melts, sheets, and a continuous film of adhesive. Solvent-free, extended shelflife, clean, efficient, uniform, and precision weight of adhesive are other qualities. Base materials include epoxies, phenolics, polyamides and elastomers.
5. *Contact and pressure adhesives*. Tacky adhesives are used for flexible applications. Bonds are not very strong. Generally these adhesives are applied by spray followed by light contact pressure. Base materials include rubber, and polyolefins.

11.7 Selection of bonding material

The success of any adhesive-bonded joining depends mainly on the materials to be joined, suitable adhesive and method of implementing the process. It is impossible to cover all the aspects in a chapter on processing. However, it is possible to describe some of the factors governing a great majority of applications.

- Ballistic materials to be joined.
- Surface condition of each material.
- Bond strength required for the application.
- End use of the bonded parts.

- Highest and lowest operating temperature of the component.
- Environmental conditions during the life of the component.
- Location of adhesive between the components.
- Any other factor which might limit the type of adhesive.

11.8 Material preparation for fabrication

Ballistic materials are trimmed to a general size (called blocking), or cut with a pattern. Care must be taken to note the way the material lays or drapes in the mold since folding or 'bridging' may produce an undesired effect. This effect may be partially or completely eliminated in the lay-up stage.

Cutting: like other materials used in the production of composites, anti-ballistic materials such as woven aromatic polyamides (Aramids) or extended chain polyethylene (ECPE) present some generic problems, i.e., problems that all or most woven materials may exhibit, as well as those that are unique to each individual fiber.

Generally speaking, woven materials have to be treated according to the direction of the warp, or longitudinal yarns, unless the weave is equal (e.g.: 24 × 24) and the crimp is perfectly balanced. In the event that either of these factors is irregular, then the cutting and subsequent lay-up of the materials must be carefully considered.

11.9 Mold preparation

A mold of the part to be made is created and a release film is applied to the mold's surface to allow the finished part to be removed. The mold should be free of defects and foreign objects, especially those that might deform the finished part or cause the resin to penetrate and stick.

11.9.1 Laying-up

Material is placed on or in a mold or armature through a process called laying-up. In Fig. 11.5 we can see aramid cloth being laid-up on a male helmet mold. This is one of the most critical operations since the exact positioning of pieces is vital to good performance.

Placing the material on or in the mold is called laying-up. Generally speaking, this process is the same no matter which resin system is used. The difference is that when a liquid resin is used in wet lay-up, the resin must be applied with each successive layer.

Laying-up a large part using a thermoplastic resin (in this case, a spall liner for a vehicle floor) is demonstrated in Figs 11.6–11.9. Because the resin is thermoplastic, a heat source can be used to make the resin tacky, assisting in the production of a perfect finished part.

11.5 Material laying up on mold.

11.6 The piece is positioned on the mold.

11.7 The piece is fitted to ensure that any cuts are covered by a sufficient overlap.

11.8 The angles are securely worked in to avoid bridging or bagging.

11.9 Final assembly by applying localized heating.

11.10 Effective ballistic tolerant structure

Fundamental to any effective ballistic tolerant structure are three important factors:

1. *Good design*. That is, using the best materials (fiber and resin) in the right configuration to produce the lightest weight, cost effective armor system.
2. *Processing methods*. That is, utilizing the most appropriate processing techniques. Processing methods such as vacuum bag, hydraulic press, or autoclave are all used in conjunction with the assembly methods like wet lay-up, prepreg lay-up (either thermoset or thermoplastic) or films applied to fabrics.
3. *Process control*. That is, process repeatability. Without process repeatability one can never be sure the same product is being produced with each cycle of the process method. The lack of process control can lead to potentially

deadly failures in the field. For this reason, prepregs or film are preferable to liquid resin systems.

11.11 Processing of ballistic composites

Full potential of lightweight ballistic composites is achieved when proper processing techniques and tooling are utilized. The processing methods are influenced by a number of factors. Some of the common factors are:

1. Size of ballistic component.
2. Number of units required.
3. Choice and availability of ballistic material.
4. Resin content of ballistic material.
5. Cost of raw material.
6. Labor cost.
7. Processing machines available at converters location.
8. Target performance:
    - (a) against ballistic threat;
    - (b) acceptable weight;
    - (c) structural and impact requirements;
    - (d) other requirements:
        - i operating temperature;
        - ii exposure to chemicals during the life of the product;
        - iii moisture;
        - iv exposure to lubrication, diesel, gasoline;
        - v other.

11.12 Methods of production

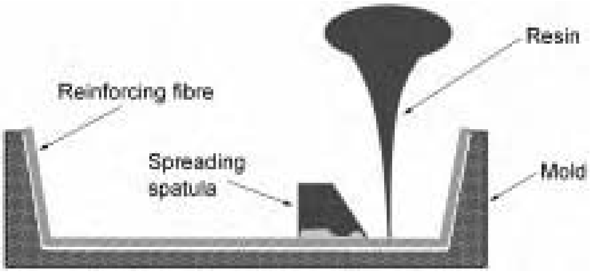
In the following sections the usual methods of production, i.e.: wet lay-up, vacuum bag, compression molding, and autoclave curing are described in detail.

11.12.1 Hand lay-up

In the production of composite materials (i.e.: fiber-reinforced plastics, or, conversely, fibers consolidated with plastic or resin) the most basic process is hand lay-up, a method which, because of the amount of handling generally associated with the process, presents a special set of realities.

Background

Hand lay-up (or wet lay-up) is a very commonly used technique for the manufacture of composite products, especially when low production volume is not a concern (Fig. 11.10). The process lends itself very well to prototyping and



11.10 Hand lay-up process.

production where complex molding or other costs might be an issue. Since this is technologically the simplest method of composite manufacture, in many ways it is most illustrative. In other words, the principles that apply to hand lay-up apply to all other techniques, but may do so to a greater or lesser degree.

Definition

This process uses molds that generally are ‘open’, i.e.: there is either a male or female mold but not both, upon which a variable number of plies of material are applied using some type of resin. The part is built up and worked by hand. The curing process is often (but not always) at ambient temperatures; the curing is dictated by the type of resin system used.

There are a number of names for this process, for example in addition to hand lay-up and wet lay-up it may be referred to as contact molding. Since the process uses only one open mold the appearance of the faces of the finished part may vary greatly.

The material (cloth, roving, chopped fiber, etc.) is manually placed into a one-sided release coated male or female mold, armature (mesh or foam is often used) or other structure. The mold or armature must be free of foreign matter (dust, dirt or other). A matrix of resin is applied onto the fiber using a spatula, brush, hand roller, etc., or is directly poured on and spread (Fig. 11.11). The fiber material, if it is dimensionally stable enough, can also be coated with resin prior to application (by placing it in a bath) and then applied in place on the mold. More layers can be added and, after drying, the composite part can be removed from the mold.

The dry part may or may not be fully cured – that depends upon the resin system in use. However, the dry part may be moved to permit the final curing, freeing the mold for another use.

The resin for ballistic components may be an epoxy, a two-part system that produces a very hard plastic when two parts are mixed. The catalytic process that makes this hard plastic is the process of curing – basically when a low-molecular-weight diepoxy is mixed with a dimine to produce a cross-linked

11.11 Spreading resin on carbon fiber.

molecule that's going to harden into a very strong adhesive to hold the composite together. The ballistic drawback to this is that the cured plastic tends to be brittle.

Some pros and cons

Wet lay-up is technologically the simplest system of making a composite and that is definitely an advantage when price and/or set-up are restrictive. However, the tendency for liquid resins to penetrate the intercise of the woven material makes their use somewhat questionable when dealing with ballistic composites using such cloth as a substrate; that is the case because the amount of resin needed to assure a good structure results in the resin penetrating the weave.

11.12.2 Bag molding

General

While the wet lay-up techniques shown above will work sufficiently well for some applications the rigors of ballistic armoring generally require better 'consolidation' (fabric/resin matrix integration) than can be had without some form of pressure exerted on the structure while curing. Bag molding isolates the structure so that contaminate properties from the atmosphere (if present) are not allowed to touch the structure during this stage (Fig. 11.12).

Composites give higher strength-to-weight ratios than many other materials, however, if the composite is too 'resin rich' the finished product will display more of the properties of the resin, if it is too 'resin poor' the structure may not

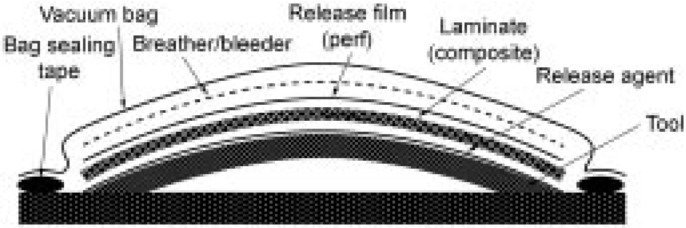
11.12 Applying bag sealing tape during bag molding.

have sufficient strength, since the fibers alone will not have the strength or performance characteristics desired. Therefore, applying even pressure, or squeezing the resin throughout the structure optimizes the resin ratio.

The ‘wetting-out’ process of a hand lay-up may use in excess of 100% of fabric weight in resin; however, higher performance composites require a much lower percentage than can be obtained by hand lay-up alone. The idea is to get the resin distributed over the textile fiber *prior* to any assembly through a process called pre-impregnation or ‘pre-pregging’. This process can help to eliminate dry or wet spots and assures an even distribution of resin, to assure that this is optimized during curing; a vacuum or pressure bag is used.

11.12.3 Vacuum bagging

The principle behind vacuum bagging (Fig. 11.13) is that of using atmospheric pressure to hold the layers of a composite structure together and tight against the mold during the curing process. This removes most of the air from the composite and the continuing vacuum will also serve to remove any off-gassing that occurs during hardening.



11.13 Vacuum bag process.

At sea level, one atmosphere weighs 14.7 psi (pounds per square inch) or 29.92 inches of mercury. In the absence of a vacuum, a surface has atmospheric pressure exerted on all sides and is equal. When a vacuum is generated on one side only, the result is an increase of pressure on the other side equal to the amount of vacuum being generated. A one square foot area receives 2,116.8 pounds of pressure with a 29.92 inches of mercury vacuum beneath it; this creates very good consolidation and also allows virtually equal pressure around a tool or mold.

Applications for vacuum bagging

Because of the relatively low cost of materials, and because of the great flexibility of the technique, vacuum bagging is usable for a wide variety of applications (Fig. 11.14). In the ballistic field, helmets can be most easily prototyped through the use of a vacuum bag since the shape of a helmet is difficult to hold otherwise.

11.14 Layers of material used during vacuum bagging.

11.12.4 Pressure bag

The pressure bag technique is very like the vacuum bag process but backwards. In the pressure bag system a tailored airtight bag is filled with air or steam and used to consolidate the resin/fiber matrix. The major difference is that the amount of pressure can be varied and controlled from a minimum of zero to a maximum of about 50 pounds per square inch, which is considerable when related to the 14.7 that can be obtained from a vacuum. Hence, if a vacuum produces the 2,116.8 pounds per square foot, then a pressure bag can create 7,200.

11.12.5 The differences of pressure

Different structures perform differently depending upon how much pressure was used to form them. In some cases, a ballistic panel will perform wonderfully when formed at 100 pounds (per square foot) pressure, but not as well when using 300 pounds. The reason for this is complex, but it is easily understood when we realize that a certain amount of movement is require to absorb the impact energy of the bullet, and that this movement would be inhibited by the presence of resin in the intercise.

11.12.6 Compression molding

Compression molding is a method of molding in which the material to be molded (fiber and uncured resin) is placed in an open mold cavity (female) or form (male) using a two-part mold system. The mold is closed and pressure is applied to force the material into contact with all mold areas, and heat and pressure are maintained until the molding material has cured.

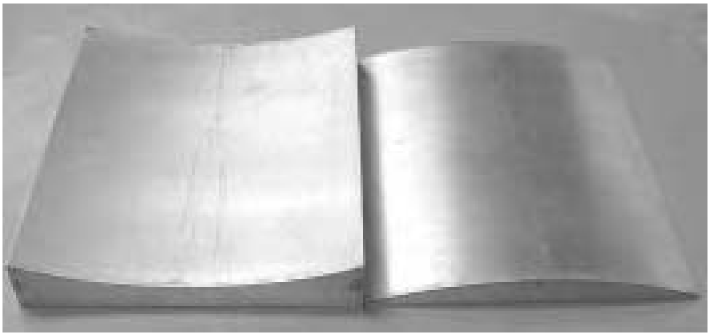
The process employs thermosetting resins in a partially cured stage, thermoplastic resins or other methods to achieve a cured matrix. With compression on one side only, the result is an increase of pressure on the other side equal to the amount of vacuum being generated. A one square foot area is receiving 2,116.8 pounds of pressure with a 29.92 inches of mercury vacuum beneath it; this creates very good consolidation and also allows virtually equal pressure around a tool or mold.

Compression molding is a high-volume, high-pressure method suitable for molding complex, high-strength composite structures.

Advanced composite thermoplastics or thermosets can also be compression molded with unidirectional tapes, woven fabrics, randomly orientated fiber mat or chopped strand. The advantage of compression molding is its ability to mold large, fairly intricate parts on a production basis.

Advantages of compression molding

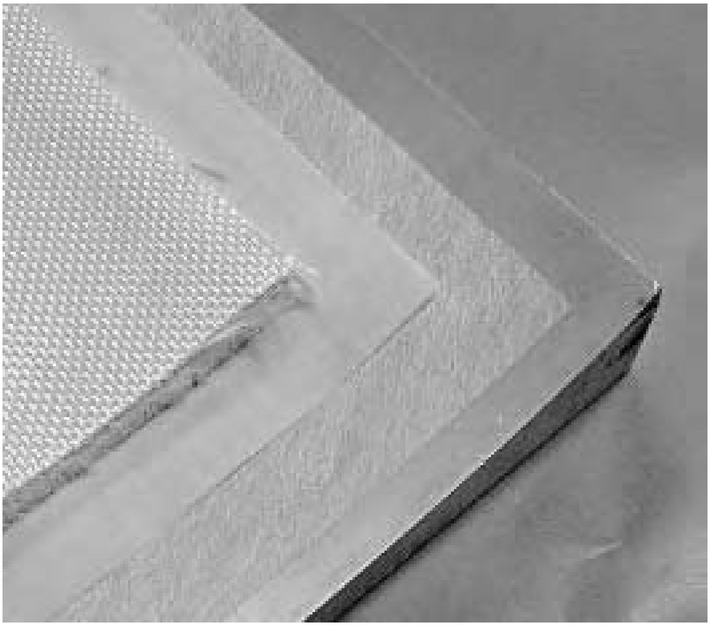
Compression molding allows exact reproduction of parts in volume production due to the precision with which all phases of the process can be controlled. In



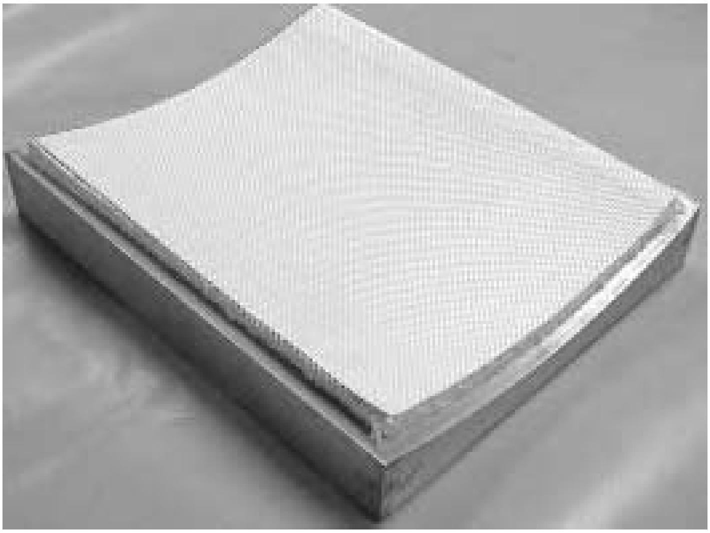
11.15 Two matching sides of a mold.

addition, the cooling process is greatly enhanced through the ability physically to cool the mold meaning that parts re-gain ambient temperature more rapidly. Parts can generally only be removed from the mold or form when they are at ambient temperature after curing.

Compression molding requires two sides of the mold; for a curved part, the mold will have a male and female side, as shown in Fig. 11.15. Figure 11.16 shows a typical lay-up for the compression molding of a small item, in this case a single curve aramid breastplate. From bottom to top we see: the female side of the metal mold, a layer of 'breather' cloth, a layer of perforated release film and the aramid part.



11.16 Laying material on female mold.



11.17 Fully assembled material on female mold.

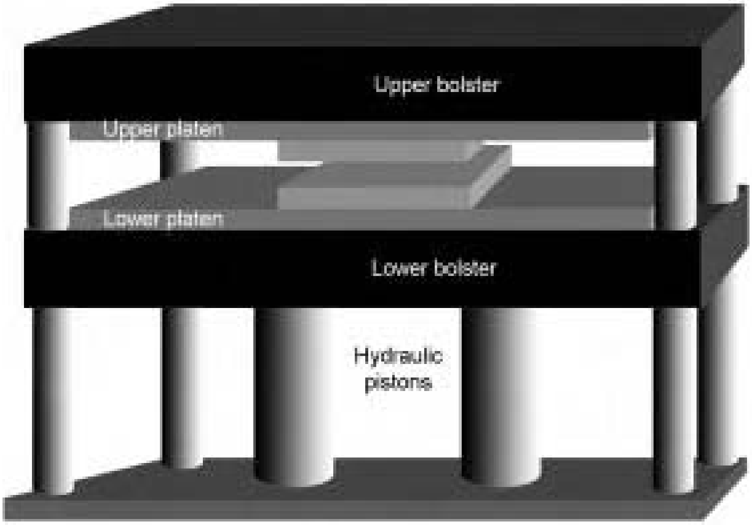
Prior to pressing, we see the shape of the material as it assumes the shape of the mold (Fig. 11.17). The top and bottom are then closed and the whole assembly is placed in a press to be consolidated in accordance with the production parameters stipulated by the particular cloth/resin package (Fig. 11.18). Close control of heat and pressure is essential to this process, since too much of either could have dire consequences for the finished product. As

11.18 Compression molding, material between male and female match mold.

mentioned in the section of this chapter pertaining to wet lay-ups: when using woven material consolidated by a resin matrix as the composite method it is almost always important to avoid filling the intercise of the weave.

11.13 The press

In order to compression-mold a part, it is necessary to use a press especially designed for the purpose. Figure 11.19 illustrates a typical press. The pressure is provided by one or more hydraulic pistons that close the press with sufficient pressure to mold the part. The upper and lower platens are heated (with oil, water or steam) causing the resin to flow – after pressing, the platens can greatly assist in cooling by passing a cooled fluid through the same tubing that caused the platen to heat.



11.19 Hydraulic press for molding ballistic composites.

11.14 Autoclave versus high pressure molding for ballistic components

Both autoclave and high pressure molding of ballistic composites are standard processes for molded ballistic composites. Both types of equipment are not expensive and available both as new and used equipment. The running and maintenance cost of this equipment is also low during the life of the equipment. The comparisons in Table 11.1 illustrate the main features of each.

Table 11.1 Processing of ballistic composites, autoclave versus high pressure press

	Autoclave (low pressure)	High pressure
Molding pressure	Low, 10–20 bars	High, 100–250 bars
Production volume	High	Decent volume
Cost/unit	Low	Higher
Surface finish	Good on mold side	Good on both sides
Structural stiffness	Good	Excellent
Tools and fixtures	Yes	No
Molds	No, for ceramic backing	Yes
Ballistic against fragments	Good	Good
Ballistic against handgun	Good	Good
Ballistic against rifle	Good	Excellent
Ceramic-faced component	Excellent	Excellent
Backface deformation	Good	Excellent

11.15 Effect of molding pressure

The ballistic performance of resin-starved composite changes with the type of fiber, type of resin and processing conditions. Usually higher specifications result in higher performance ballistic composites. An example of a molded hard panel is the Spectra Shield® Plus material shown in Table 11.2.

Table 11.2 Effect of molding pressure on ballistic performance

Molding pressure (psi)	M80 ball bullet, V_{50} (fps)
500	2230
1500	2360

11.16 Molding of ballistic products

11.16.1 Military helmet molding

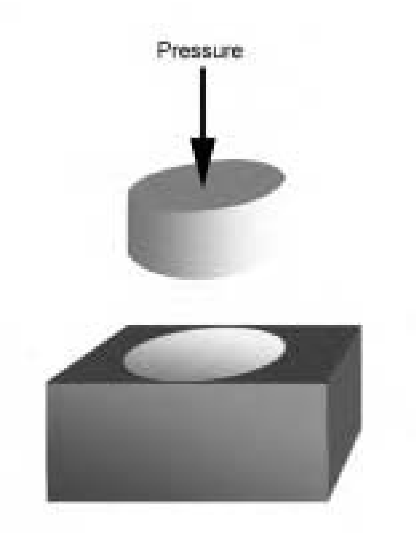
Military helmets have three-dimensional complex geometrical shapes. However, the ballistic materials are available as two-dimensional thin coated materials in roll or sheet form. Due to this mismatch in geometrical shape, pattern design plays an important role. If circular patterns are used, the pattern cutting waste will be high. However, if any other geometrical shape is used as a pattern, placing each pattern in the right location becomes critical for the helmet's uniformity of thickness and its ballistic performance. Helmet manufacturers spend a lot of time and effort to optimize the pattern.

Helmet processing

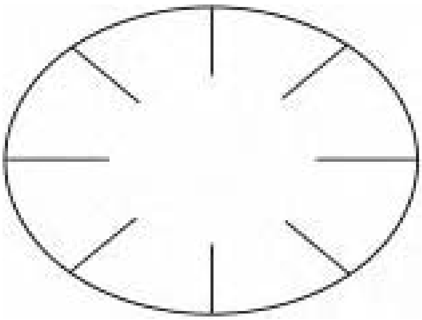
The process of making a ballistic helmet must take a somewhat difficult geometry into consideration (Fig. 11.20). While a press will exert pressure downward on the mold, a very important area of the helmet is the sidewall. In addition, since helmets are made from flat material, some method of taking a flat panel and adapting it to the shape necessary to protect the human head requires a good deal of cutting, folding and overlapping.

Hence, a shape similar to the one shown in Fig. 11.21 is cut from the ballistic material. This shape allows the necessary overlapping that offers protection to the front and side of the head. These are called pinwheels or petals.

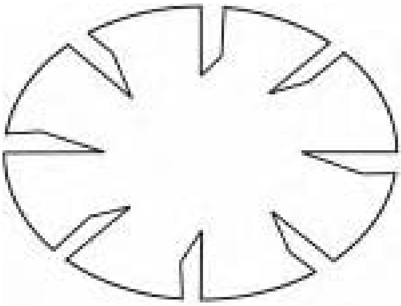
Since most ballistic protection systems require a layering of materials, and since any cuts must be overlapped, the cut shapes have to be oriented with the



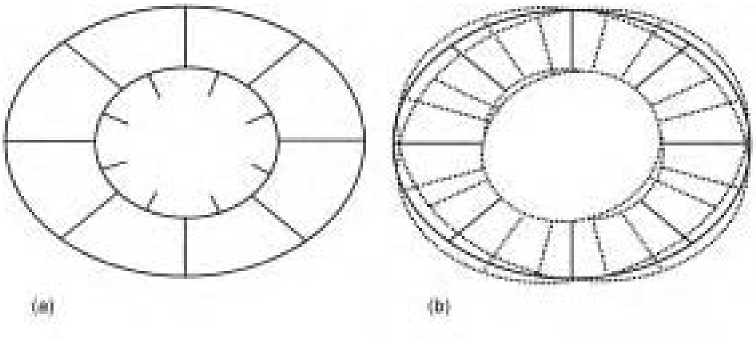
11.20 Helmet mold concept.



11.21 Pinwheel pattern.



11.22 Overlapping patterns.



11.23 (a) Helmet shell pattern; (b) augmented helmet shell pattern.

solid part being placed over the cut (three superimposed parts are shown in Fig. 11.22). This can be done repeatedly.

To avoid excess material, some of the cuts or notches can be cut-out in the manner shown in Fig. 11.23. This method reduces the weight of the finished product and can help make the overall thickness more uniform. A helmet shell using this technique is shown in Fig. 11.24. To assist even further in making the thickness uniform, the top of the helmet can be augmented through the use of extra panels that are laid-up between the pinwheeled layers.

When the parts have been laid up, they are placed in the mold, pressed, cooled and then cut to shape (Fig. 11.25).

11.17 Hand-held riot shield fabrication

Hand-held riot shield (HHRSs) are used by police to control local disturbance. The HHRSs are designed to defeat bullets fired from a handgun. A limited number of HHRSs are also designed to defeat rifle bullets. A number of types of ballistic materials are available for fabrication of HHRSs. Two common ballistics used are based on aramid and HMPE fibers. Both autoclave and high pressure molding techniques are used to fabricate HHRSs.

11.24 Molded helmet shell.

11.25 Cutting out the helmet.

11.17.1 Fabrication of HHRSs goes through following steps:

1. Select suitable woven prepreg or non-woven, cross-plied material.
2. Select optimum width based on the width of the finished size HHRS.
3. Spread the prepreg on a long table.

4. Select the number of layers of prepreg based on the ballistic threat.
5. Transfer the number of layers on the heated mold or in an autoclave.
6. Close the mold and apply molding pressure. For autoclave processing, layers are stacked on a HHRS mold kept inside an autoclave for applying vacuum and pressure.
7. Go through the cure cycle (including cooling if applicable).
8. Open the mold and release the HHRS.
9. Trim the HHRS, check for any cosmetic or permanent defect.
10. Cut-out the window in the HHRS.
11. Glue or pressure fit the trimming.
12. Install handle in the back of HHRS.
13. Paint the entire HHRS.
14. Install the rubber or metallic edging.
15. Install the ballistic resistance glass window.

11.18 Molding of ballistic inserts

The ballistic inserts, also called Small Arms Protective Insert (SAPI) plates, are an essential component for military personnel involved in armed conflict or peacekeeping missions. The SAPI plates are generally inserted into the flexible fragment or bullet protective vest carrier worn by military personnel. Depending upon the perceived threat in the conflict area and the desirable protection level, a single vest can carry as few as one SAPI plate or as many as five SAPI plates.

11.18.1 Monolithic breastplates

The monolithic breastplates and SAPI plates molded with 100% Spectra Shield® composite material and high pressure molding technology can be designed to meet the ballistic threat specified in NIJ Standard 0101.04, Level IIA, II, IIIA and III without the ceramic facing (see Table 11.3). This is one of the major advantages of using Spectra Shield® composite material. The breastplates

Table 11.3 Areal densities of molded breastplates (based on Spectra Shield® Plus material)

NIJ Standard 0101.04	Areal density (psf)
Level IIA	0.45
Level II	0.75
Level IIIA	1.10
Level III	3.80
Level IV	6.5 to 8.5 depending upon ceramic facing

without ceramic are lighter (by as much as 30%) than ceramic-faced breastplates for NIJ Level III. The process is as follows:

1. Spread the roll of Spectra Shield® material on a long table.
2. Select number of layers of Spectra Shield®.
3. Transfer the number of layers on the heated mold.
4. Close the mold and apply molding pressure.
5. Go through the cure cycle (including cooling if applicable).
6. Open the mold and release the molded ballistic threat.
7. Trim the molded plate, check for any cosmetic or permanent defect.
8. Test after 48 hours as per NIJ Standard 0101.04 to confirm the ballistic performance.

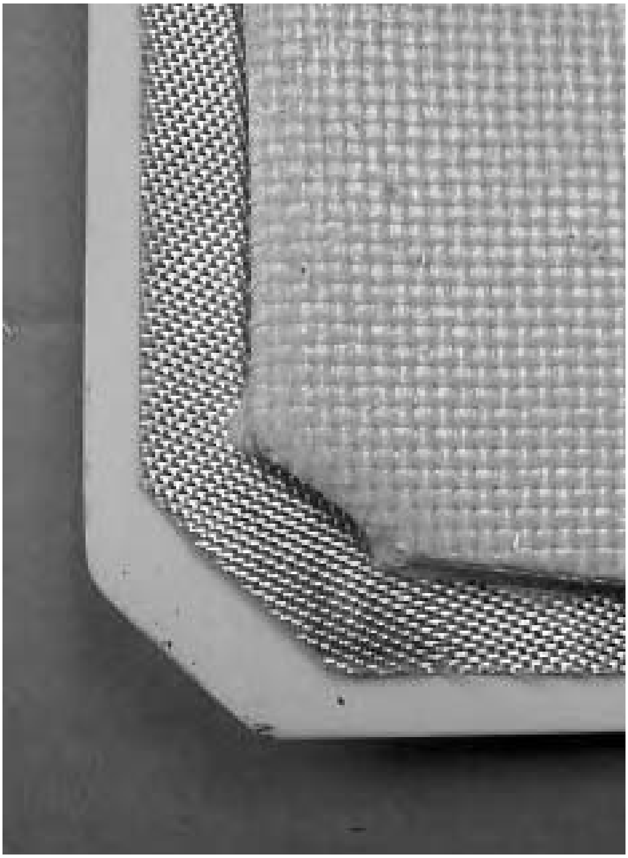
11.19 Ceramic-faced breastplates

Ceramic-faced breastplates are designed to defeat high energy bullets such as those specified in the NIJ Standard Level IV. The ceramic breaks the bullet into fragments. Then the composite backing absorbs the fragmented metals from the bullet and the shattered ceramics. Such ceramic-faced composites are used with the flexible vest to defeat high-energy rifle bullets.

11.19.1 The ceramic breastplate with composite backing

In order to produce an effective ballistic barrier, ceramic plates are generally reinforced with a composite backing (Fig. 11.26). This backing can be a hand (wet) lay-up or a more sophisticated product made from pre-impregnated resin system.

11.26 Ceramic with composite backing.



11.27 Ceramic backed with fiberglass and aramid composite.

While the methods of production can vary, best results are often gained from producing the composite plate and then marrying this to the ceramic plate.

The composite is produced on a mold, using the compression molding or autoclave process (depending upon the resin system). If the compression molding system is used, a two-piece mold is employed to form the composite part.

Figure 11.27 shows an alumina ceramic plate, a fibreglass intermediate layer and the preformed aramid composite back. These three panels can be attached using a vacuum system in an autoclave or an oven – depending upon the resin system employed.

Once the backing has been formed, it is cemented to the ceramic plate (Fig. 11.28). Because of the disparate nature of the two materials, it is sometimes necessary to use an intermediate material between the composite and ceramic layers. Some manufacturers use a further material on the strike face (impact side) of the ceramic to counteract the natural tendency of the ceramic to shatter.

11.28 Molded backing ready for assembly with ceramic facing.

11.20 Machining of ballistic composites

A number of ballistic components after processing require cutting, drilling, polishing and finishing.

11.20.1 Cutting

Because of their extremely high strength and abrasion resistance, high performance fibers and fabrics are difficult to cut by conventional methods. Dry fabrics can be cut with carbide blade shears, power shears, or rotary shears. In addition, the lower melting point fibers allow the use of hot knife and hot wire cutting techniques. For prepregs and molded laminates, water jet cutting with or without abrasives, laser cutting and techniques such as band saw and circular saw offer economical ways to cut fully cured laminates.

11.20.2 Drilling

If drilling is required in the final assembly stage, Deep-Fiber-Cut drills (a trademark product of International Carbide Corp.), or Core Drills for composite materials, are recommended for drilling fuzz-free holes. Due to lower resin content and the relatively weaker bond between fiber and resins, drilling holes requires proper jigs and fixtures for precise drilling. During drilling deep holes, the drill should be withdrawn frequently to remove the chips of materials and to prevent overheating of ballistic composites. Too slow a feed will cause increased frictional heat, rather than less heat.

Satisfactory and consistent cutting and drilling of ballistic composites is a skill that demands considerable practice. A skilled operator equipped with quality cutting and drilling tools can do the job with good results.

11.20.3 Finishing

Finishing of ballistic composites may require removal of excessive material, filling up a gap between dry fibers, and overall cleanup of the component just prior to painting.

Removal of excessive material (also called flash) from large quantities of parts can be done by a variety of standard techniques, depending upon the type of ballistic fiber, resin, resin content, type of parts and type of finish required. These techniques could include:

- die cutting;
- plain sharp knife;
- band-saw cutting;
- hot knife; and
- circular hand-held cutters.

11.20.4 Polishing

Molded ballistic composite components normally have a smooth surface, reproducing the mold surface, since such surfaces release most easily. However, if the mold surface is not chrome plated or the mold is used for an extensive period, the component may require polishing to cover the small defects. The simplest technique is to buff the component and fill up the defect with two-part epoxy resin-based filler. Once the filler has dried out, the component is polished again.

11.20.5 Painting

Coating of a ballistic composite component implies either application of a paint coat or application of a film coating on the surface. Of all the coating methods, the application of paint is the simplest and most widely used when either a large or a small portion of the surface is to be coated.

Painting provides a new color on the component and also provides additional protection from the effects of UV and weathering. Other reasons for painting might include abrasion resistance, higher chemical resistance, electrical shielding, and possibly to hide joints and molding defects.

Paint is applied after the surface of the ballistic composite component is thoroughly cleaned of all traces of mold release, dirt, oil, or other marks during processing and handling. A solvent wipe is used to prepare the surface for paint coating. The first coat of paint is dried thoroughly either in the air or by passing the article through a heated oven chamber. After the first coating has dried completely, the second coating is applied. The second coat may contain sand particles or walnut powder to provide a textured surface.

11.21 Conclusion

Composites are the most exciting modern method of dealing with the growing group of ballistics threats because of their light weight and high strength. Processing of ballistic materials plays an important role in converting these materials into life-saving components. As materials and processing technology advance so will the number of potentially great armoring solutions.

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12

New ballistic products and technologies

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12.1 Introduction

What's new today may actually be a re-invention of something demonstrated earlier and this is surely true for composites used, in part, for ballistic armors. The changes are, however, more subtle. The applications for ballistic armor have not changed greatly over the past 90 years following the First World War, although the challenge has escalated to require greater protection levels at reduced weights or lower cost. Composite materials have gradually crept into armor systems for personnel, aircraft, building structures, naval vessels, and land combat vehicles. They have displaced steel, aluminum and even titanium alloys partly due to improved ballistic efficiencies similar to the significant advancements in specific strength and stiffness made in structural materials.

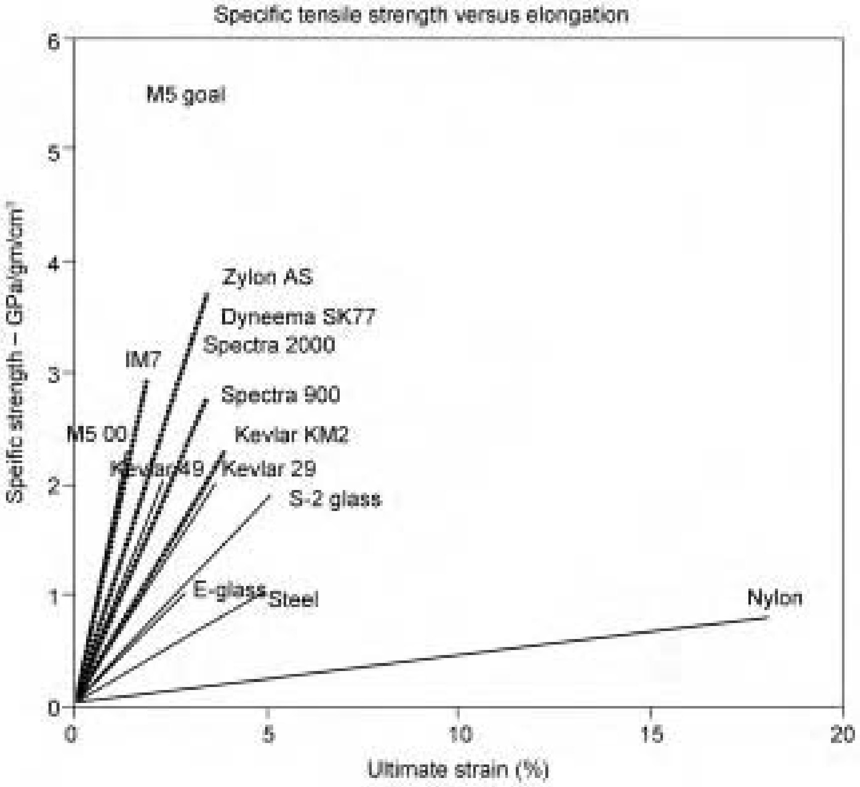
The form of the final item has changed gradually. Composite armor plates look similar to those made from steel armor of the past. Helmets, once formed from Hadfield steel are now made of fiber reinforced laminate materials with greater protection levels, lower weights or both. Vehicles and aircraft use panels of these same materials in combination with metals or ceramic tile arrays. Personnel armors include plates mounted to the front and back of the individual's torso. The historical article by Dunstan[1] describes the Chemico Body Shield, manufactured for the British Army during the First World War, constructed from multiple layers of tissue, linen scraps, cotton and silk, bonded together by some resinous substance capable of resisting a 0.45 caliber pistol projectile at 300 feet/second. What is particularly interesting is that this example of relatively modern body armor featured materials and technology used by the Assyrians some 3000 years earlier.

So, what have gradually evolved over the past century are solutions to ever increasing threats or improvements to soldiers' other needs. The technologies used in munitions and armaments have become more efficient and lethal. The desire to protect individuals and transportation platforms has continued within both military and civilian circles. New materials have been invented and commercialized, often for entirely different applications, and evaluated as potential armor materials in more or less the same designs or geometries. Steel, aluminum and titanium are still the predominant choice of armor materials used on vehicle platforms. Not so, any longer for personnel armor. High strength fiber reinforced laminates, in conjunction with optimized ceramic layers have shown the potential to arrest aggressive projectiles with less weight than required for the metallic solutions. The balance of this chapter will try to present a snapshot, as of 2005, of what and where some of these new materials are being used in lightweight armors. This presentation unfortunately reflects a bias due to this author's familiarity with those systems used by the United States military services. Along with this familiarity comes the responsibility to preclude details that could identify vulnerabilities of any armor system. In the United States, such information is excluded from open publication and one would be correct in assuming that this restriction becomes more likely as the performance of either armor or munitions increases. So, specific performance values will be avoided and details of any current armor platform will be described in only generic form.

Today's armor systems involve a combination of materials typically including a ceramic or metallic frontal layer followed by multi-layered, fiber reinforced laminates or fabric structures. We will describe more of each of these material subsets in greater detail in the following sections, but it must also be emphasized that there are other aspects which may also be important. Manufacturing processes will influence not only the final cost, but also the final performance of the system. The interface (bondline) between these two primary layers has an effect, not only on the initial projectile impact performance, but quite a pronounced influence on damage mitigation and tile retention which similarly influence the subsequent hit performance. The system architecture is important not only from a ballistic efficiency viewpoint but also for how to attach, repair and upgrade it onto the armored platform. System architecture includes such variables as thickness ratios, lateral dimensions and confinement, cover layers, reinforcement arrangement, dimensional tolerances, adhesion and surface treatments, sequencing or layering properties and others. Material availability will be important when large military procurements are needed, especially in the short term. So what is best is not always the lightest or highest protection level. What is procured is always some compromise between all of these aspects, and more.

12.2 Fiber reinforcement

Yarns of high strength and modulus are now used in laminated plates or shells for armor applications where steel and aluminum alloys once predominated. The specific tensile properties are particularly important where tensile stresses are large, like the regions of the armor adjacent to the impact footprint. Unfortunately, not all armor materials are exposed to uniquely tensile loading. While most earlier summaries[2,3] have concentrated on identifying optimal ballistic resistance from the perspective of optimal tensile strength, stiffness, or maximum strain, not all practical armors are selected from these properties alone. Nevertheless, consistent improvements in ballistic efficiencies have occurred over the past six decades with the introduction of commercially available yarns with improved tensile mechanical properties. Figure 12.1 presents a simple comparison of several fiber materials that have evolved into what we are using today. The presentation is not comprehensive but most of the current materials used will be discussed in the paragraphs below. The ordinate identifies the specific tensile strength and the abscissa reflects the ultimate elongation. Not included are cotton or other textile materials used in earlier armor systems, even though, for example, the separate inner composite liner of the M-1 steel helmet of the Second World War used cotton fabric as the reinforcement. Included in addition to the earlier polyamide (nylon), p-aramids (Kevlar, Twaron), glass (E and S), and UHMWPE (Spectra, Dyneema) are structural reinforcements (graphite or carbon fibers), and other high strength copolymers or homopolymers of even higher specific tensile strengths.



12.1 Tensile property comparison between various ballistic or potential ballistic fibers.

The trend of what works is apparent by identifying those fibers that actually made it to commercial production. While there remains disagreement in the armor design community of what correlations between mechanical and ballistic performance are most important, it is generally agreed that specific tensile strength is the most often selected optimization parameter in the armor system design. A frequent second choice is the toughness (or specific tensile strain energy capacity). Usually, fibers of high tensile strength also have high specific stiffness. Having highest strength and stiffness is not always optimum for the ballistic application. Indeed, higher toughness is often observed in those fibers with lower stiffness and higher ultimate tensile elongation. The computational model of Roylance *et al.*[4] is perhaps the first successful correlation with the empirical ballistic data that explains this ranking of performance parameters. As clearly noted in this study, the mechanical properties alone do not fully capture what is important for optimal armor designs. The reinforcement architecture along with resin distribution (in a laminate) and interface between fiber and matrix also has a significant influence on the armor behavior. The boundary conditions related to restraint of the yarns during transverse impact will influence the manner in which stresses and strain energy are distributed in individual fibers. Recognizing those fiber systems of high ballistic efficiency and viewing the figure above, the fibers with highest tenacity and a minimum elongation around 4% seem to be optimal. This observation is contrary to the fact that the volume of strained material involved is proportional to the longitudinal elastic wave speed of the particular fiber, dependent on the square root of the specific modulus. While the strain energy capacity with fixed tensile strength may increase with decreasing modulus, the area or volume of material affected may be less, resulting in interesting competitive trade-offs.

What follows is a brief description of each of the materials identified on the figure above, each within their broader material class. The discussion will not be limited to the two mechanical variables plotted, but will try to describe all those aspects which have been found to limit practical application of these fibers. As noted earlier, the tensile mechanical properties alone do not determine what is selected as an optimal armor material. When performance comparisons are made between different fiber materials, other variables often obscure the relative rankings. An example of this situation is related to architecture: the earlier ballistic laminates of nylon, glass and p-aramids were most frequently constructed from multi-ply woven structures while the newer Ultra High Molecular Weight Polyethylene (UHMWPE) reinforcements have exhibited performance improvements in non-woven, cross-plied unidirectional form. Along with the difference in reinforcement construction, these competing laminate materials will also incorporate different resin materials, fiber interface, and fineness (ply weight and count). It's rare to find comparisons in the literature between the distinct fibers in similar architectures and material combinations. Comparisons between optimum laminate systems will identify many differences only one of which is the set of fiber material properties.

12.2.1 Inorganic fibers

Glass fiber

Shortly after the commercialization of nylon in the late 1930s, fiberglass was introduced to the world in a wide range of applications. Owens–Corning Fiberglass was initially available for industrial applications as E-glass, alumino-borosilicate. This relatively inexpensive fiber is extensively used in electrical and thermal insulation and was also the reinforcement in perhaps the earliest ballistic laminate, Doron,[5] introduced in the latter part of the Second World War. First in cross-plied unidirectional form with 25% polyester matrix, it gradually was displaced by the woven roving structure in toughened polyesters and phenolics. Owens–Corning later introduced S-2 glass fiber, magnesium aluminosilicate,[6] with higher tensile strength and toughness and immediately found improved performance as an armor material by direct substitution of the E-glass in similar architectures. While S-2 fiber today is many times more expensive than E-glass, it is still one of the least expensive of all of the ballistic reinforcements available. S-2 in woven roving fabrics is manufactured in large volumes for ballistic laminates with polyester, vinyl ester, epoxy, and phenolic matrices. Resin contents between 20% to 30% by weight are typical. Due to its relatively good compressive properties it is also a good structural reinforcement, used frequently in parts required to carry structural loads as well as perform ballistically. S-2 laminates are specified as spall liners in US military combat vehicles, naval vessels and aircraft. It is also used in support plates behind high performance ceramic tiles in lightweight armor systems. Many studies have successfully demonstrated the potential to replace steel and aluminum vehicle hull structures with these S-2 laminates, but the concept of a composite hull has not found true commercial scale production, yet. The S-2 laminates, nonetheless, exhibit many desirable attributes like corrosion resistance, lighter weight, higher ballistic efficiencies, less lethal spall generated during ballistic attack, and electrical and thermal insulation and may eventually develop into larger volume vehicle structure production. Newer forms include various filament diameters, untwisted yarns with sizings ranging from epoxy compatible to semi-compatible starch-oil finishes.

Alumina fiber

Alumina fiber has been available in modest quantity for many years. With high compressive and thermal properties, it has found use in laminated form where compressive stiffness is desired or high temperature requirements dictate. Wear resistant metal matrix composites, stiffened aluminum, magnesium and lead are examples of the range of material combinations considered. These fibers have similarly been evaluated for ballistic applications, but due to relatively high density, low tensile strengths, and high cost, they have not found great success in ballistic armor.

Silicon carbide fiber

Manufactured by either chemical vapor deposition or from the pyrolysis of a precursor fiber, these expensive fibers are reserved for applications where great heat resistance is required (up to 1200 ºC in various atmospheres). The commercial Nicalon fiber has been ballistically evaluated[7] in very expensive composites known as SiC-SiC which involve the chemical vapor infiltration of beta SiC as the matrix surrounding the Nicalon SiC reinforcement. While the performance is not extraordinary, this material has found some use as an armor surrounding high temperature turbine engines on rotor aircraft. Due to its limited availability and relatively high cost, SiC fiber is not a practical candidate for large scale armor production. Its specific tensile strength is greater than E-glass, but has somewhat brittle behavior suggested by an elongation of approximately 1%. Perhaps, if it is ever made available at a significantly lower cost, it should be evaluated in a more efficient construction involving the already identified 'starved' thermoset or thermoplastic resin matrices.

Alumina boria silica fiber

A commercial product from 3M named 'Nextel' is extensively used as high temperature (>1200 ºC) insulation in fabric form. In combination with p-aramid fabrics, multi-layer blanket structures are used also in spacecraft armors[8] where hypervelocity impacts with space debris are expected. The vacuum environment of space frequently limits the use of organic matrices, so these fabrics are applied 'dry' in combination with metallic skins. The fiber is relatively expensive and has a specific tensile strength less than half that of S-2 which explains why it has not been extensively specified in conventional armor laminates. In some respects, this ceramic fiber performs the role of more standard ceramic tiles as a facing material in the standard two part armor system, but remains a flexible, damage tolerant, heat resistant layer in a very aggressive environment.

Boron

Used in specialized structural applications where compressive stiffness is necessary, this fiber is manufactured by chemical vapor deposition on a tungsten filament and is therefore quite expensive. It has specific tensile strength close to

E-glass with similar low elongation to the Nextel fiber above which suggests its limited utility in ballistic laminates. Production capacity is relatively low compared to the aramids, glasses and polyethylene, another reason for not considering it in modern armor systems.

Carbon/graphite

Depending upon its manufacturing process, carbon fibers are available in large commercial quantities for structural applications where either stiffness or strength properties dictate. Carbon fiber[9] is produced from the pyrolysis of organic precursor fibers like rayon or polyacrylonitrile (PAN) for the intermediate stiffness and highest strength variants which frequently require graphitization at temperatures in the 2000 °C range. The graphitization converts the fiber to a higher crystalline content hence the designation, graphite. An alternate process uses a mesophase pitch filament which upon pyrolysis, produces a very high stiffness fiber in both compression and tension. The pitch based carbon fibers have lower tensile strength. IM7 is plotted on Fig. 12.1 and represents the high strength, intermediate modulus variant of carbon fiber which is expected to provide the optimum of the fibers available for ballistic applications.

While the specific tensile strength is equivalent to many current ballistic fibers, its elongation of 1.8% is lower than the aramid and polyethylene competition. Most previous ballistic evaluations of this fiber have involved woven architectures in standard ballistic resins, but as noted earlier, that architecture may not be proper for this somewhat brittle fiber. It is quite possible that some of the observed lower ballistic performance is attributable to damage induced during the weaving of the more brittle yarn. Indeed, Cunniff[10] presents some interesting ballistic performance of the M5 fiber (M5 00 identified on Fig. 12.1) with similar apparent brittleness. In this study, Cunniff constructs the M5 target samples from a cross-plied unidirectional lay up. Perhaps carbon/graphite needs to be evaluated in this same cross-plied unidirectional form before it is written off as a high performance ballistic fiber.

Carbon fiber makes up for its tensile brittleness with an advantage that higher compressive properties provide. Higher compressive stiffness allows greater flexural stiffness of the final laminate which, as described in later sections, can exhibit both favorable and detrimental aspects when designing an armor system. With high elastic modulus, a laminate of carbon reinforcement will have high impedance. This property is useful in controlling the development of tensile stresses which form at interfaces and boundaries upon the reflection of compression waves. As a component beneath ceramic tiles, graphite epoxy skins have been useful for confining the damaged ceramic debris resulting from direct impact of that particular tile. The higher flexural stiffness also limits the delamination between tile and backing, thereby improving the performance of neighboring locations subject to subsequent hits. The stiffening potential of carbon reinforcement is realized due to its high properties in both compression and tension. Hybrid fiber composites will likely use this reinforcement to stiffen up the entire laminate where the ballistic portion is too compliant for practical durability. Carbon and glass fibers will likely be used, in part, for those laminates that require both structural and ballistic performance.

12.2.2 Organic fibers

Following the development of the synthetic textile yarns, rayon and nylon, in the late 1930s, polymer chemistry has continued to produce new products with ever improving strength and stiffness properties. One such advancement occurred in the 1960s with the identification of a class of polymers known as aramids.[11] Without detailing the chemistry of each of the following subsets of aramid polymer, only those particular polymers which have either been commercialized for use in armor or those which could have potential in this application will be mentioned.

Perhaps the most well known and greatest consumed ballistic fiber today is Kevlar®. Commercialized by DuPont in 1971 and immediately applied to ballistic laminates and fabric armor,[12] this high strength and modulus fiber allowed both higher protection levels at previous weights or lighter weight items with equivalent ballistic resistance. Originally called Fiber B and PRD 49, with deniers of 200 and 400; production a year later converted to heavier deniers, 1000 and 1500 and were re-named Kevlar 29 and Kevlar 49.

This author estimates well over 40 million pounds of Kevlar have been used in ballistic armors ranging from the PASGT helmet, flak jackets, spall liners, ceramic backing plates, fragmentation blankets and many other related variations over the past 34 years. In most applications, improvements in mechanical properties of the Kevlar fiber and more optimum constructions including fabric structure, fiber interface and resin formulations have provided lighter body armor and higher protection levels to ever increasing threat munitions.

Kevlar fiber is known as PPD-T or poly(p-phenylene terephthalamide). A condensation polymerization of p-phenylene diamine and terephthaloyl chloride in an amide solvent is then dissolved into sulfuric acid to form anisotropic liquid crystal solutions that are then ‘spun’ into filaments using an extraordinary dry-jet wet spinning technique. Processing conditions are adjusted in order to affect the final mechanical properties of the fiber. Over the past decades, these properties were adjusted for improving specific applications. For the ballistic application, the US Army has pushed the requirements towards more efficient extraction of energy from impacting fragments or projectiles. The government’s Casualty Reduction Analysis method suggested that the ‘toughness’ of the fiber be increased. DuPont responded with the development of Kevlar KM2® fiber, simultaneously increasing the tenacity along with the elongation. Similarly, the yarns were offered in lighter deniers (originally 850, now 600 and 400) that allowed for more efficient architectures. More details will be described in later sections on all the changes made to the final laminate constructions, but the net result was that increases in ballistic efficiency on the order of 15% were achieved over the original military specified Kevlar 29 laminate system. Part of this performance improvement is the direct result of increased toughness of the Kevlar KM2 fiber.

Twaron® is a competitive product to Kevlar now manufactured by Teijin in the Netherlands. Originally developed by Akzo Nobel, this fiber is now offered around the world in similar form as Kevlar. One new offering[13] of Twaron is identified by the CT designation. This product uses a finer individual filament with linear density of 0.84 dtex, compared to Kevlar at 1.5 denier per filament. It is claimed that this modified yarn construction allows even higher ballistic efficiency. Like that described earlier, the final laminate construction will influence the performance of the armor, even though the fiber mechanical properties are similar. Here, the finer filaments will certainly influence the amount of surface area provided for a given yarn weight, and may allow for finer fabric ply thicknesses if the fabric design is modified as well.

Technora® aramid fiber is manufactured by Teijin Limited of Japan. As reported by Yang,[2] this aromatic copolyamide is currently used as reinforcement in automotive rubber applications, amongst others. Unlike PPD-T, it is spun from an isotropic solution and drawn at elevated temperature in order to gain its high level of crystallinity and orientation. It exhibits similar specific tensile strength to Kevlar, but higher elongation (4.3%), makes it a candidate for improved performance, even over KM2. This author recalls ballistic evaluations of this fiber where the expected performance improvement was not evident. Indeed, lower ballistic efficiency was observed. Others must have concluded similarly since it is not found in significant volumes for the ballistic application. Perhaps this evaluation should be repeated with careful attention to which architectures are selected.

Russian aramids (Armos, SVM, Rusar, AuTxHt) have been appearing in small quantities in Western countries for the past several years. Little has been published in the English literature with some information obtained through simple surfing of the internet. Without much evaluation possible due to limited sampling, properties quoted should be interpreted with care. Differences in testing protocol; filament verses yarn, twist multipliers, gage length issues can influence the value reported. Polymers with densities between 1.43 and 1.47 gm/cc are claimed, similar to the aramid class with significant variations as co-polymers or slightly different homopolymers. Rusar is quoted as having a tensile strength of 3.3 GPa with an ultimate strain of 3.0%, slightly lower toughness than Kevlar KM2®. The AuTxHTDE has a quoted tensile strength of 4.2 GPa with ultimate strain of 2.3%, which may suggest a potential improvement in ballistic performance. Only ballistic testing can confirm. Care must be exercised here as well to insure that other aspects of the target constructions are similar in order to compare only the fiber property effect.

Many things have changed for the Russian manufacturing industry over the past decade. What was guessed at around four million pounds annual capacity while part of the Soviet Union, is likely lower today without the emphasis on military production. Facility consolidations are anticipated. The transition from government run manufacturing plants to those competing in the free world market must surely be a challenge for the remaining plants, especially with the current financial stability and ingredient supply infrastructure status in Russia today. A period of commercialization shake-out would be expected.

Yang[2] summarizes many of the aromatic fibers discovered, several of which have reached commercial scale production. He notes that it is interesting that not all of the commercial fibers available today have the highest tenacity. In particular, MePPD-TA, polyazomethine has a tenacity of 38 gpd, PPD/DMeBPS-T copolyamide has a tenacity of 31 gpd, and Ekonol (aromatic polyester), once commercially available, at 31 gpd all have superior specific tensile strength than Kevlar KM2. Obviously, if they are not commercially available today, ballistic evaluations are going to be difficult. Further research into what total properties these fibers exhibited in laboratory scale production may suggest the direction currently commercial fibers should move towards. Or it may be appropriate to consider resurrecting these fibers for the purpose of evaluating their potential for the ballistic application.

PBO, PBT, PBI and AB PBO are aromatic heterocyclic polymers that have exhibited high tensile strength and stiffness. Yang[2] once again describes how the different fibers have moved towards commercial availability. While PBI has found commercial use in fire resistant garments, its tenacity is less than many others and may not be attractive for the ballistic market. The other three were originally developed by SRI Research International for the Air Force Ordered Polymer Program. PBO was taken to pilot scale production by Dow Chemical during the mid-1990s, but later dropped from domestic availability. Dow's Japanese joint venture partner, Toyobo acquired the license for PBO and now is offering it as Zylon, available in limited quantities (400 ton annual capacity). It is sold in two grades, Zylon-AS and Zylon-HM with the former possessing one of the highest specific strengths observed to date. PBO has been evaluated in ballistic applications by Cunniff[14] and shown potential in both fabric and laminate forms. Limited capacity and recently observed[10] property losses related to elevated temperature moisture exposures have cast serious concern whether this fiber will continue to be considered for armor applications.

M5 (a rigid rod polymer, PIPD)[15] is a relatively new fiber originally developed by Akzo Nobel and later sold to Magellan International Limited. Due to its three-dimensional, hydrogen bonded network, lateral to the primary chain direction, this fiber exhibits good compressive strength along with the necessary high specific tensile strength. Goal properties are identified as 'M5 goal' on Fig. 12.1. The hope of 9.5 GPa may not be conservative and the anticipated ultimate strain limit of less than 2% could relegate this new fiber to ballistic performance ranges similar to the high strength graphites. M5 may exhibit brittleness during ballistic loading rates, but once again, the architecture of the laminate and the use of compliant matrices may resolve this potential limitation. Even if the tensile strength remains at the aramid level, with its superior compressive properties, the M5 fiber will allow laminates to satisfy a combination of structural and ballistic requirements using a unitary reinforcement (limit the need for hybridization). Preliminary tests have shown that M5 has less degradation than PBO from exposures to ultraviolet radiation and elevated temperature moisture.[10]

Compressive capacity, as determined through flexural testing, suggests the potential as a structural reinforcement to compete with carbon and graphite. Initial laboratory samples were configured into a cross-plied laminate and tested ballistically.[10] Despite the relatively low mechanical properties, the laminate performed quite well. Scale-up of a pilot plant manufacturing facility in Richmond Virginia is expected to be completed in early 2005. Improvements in the mechanical properties are already reported,[10] so it is very likely that improvements in ballistic performance will progress once more fiber is made available to the market.

Ultra High Molecular Weight Polyethylene (UHMWPE) or Extended Chain Polyethylene (ECPE) is a rather recent (mid-1980s) development of the Dutch School of Mines (DSM) using a new gel spinning process. Commercialization of very high strength fibers branded Dyneema (Europe by DSM)[16] and Spectra (USA by Allied, now Honeywell)[17] has allowed the selective replacement of aramids in many ballistic armor applications. Increased tensile properties are certainly part of the reason for this. Dyneema SK77 claims tensile strength of 4.0 GPa, tensile modulus of 1400 GPa and ultimate strain of 3.7%. Honeywell's Spectra 2000 claims similar properties of 3.7 GPa tensile strength, 1320 GPa and ultimate strain of 2.9%. With both having density of 0.97 gm/cc, specific properties are at the top of the list of commercial fibers.

Fiber properties alone do not determine optimum ballistic performance. As stated earlier in this chapter, they, along with adjustments in the laminate architecture ultimately determine how well the armor performs. Subtle details related to filament geometry, yarn construction, surface characteristics, spin finish, lamina fineness, stacking sequence, resin type, amount and distribution, weave parameters (crimp, cover factor, yarn damage) and processing conditions can and do influence the final laminate performance. Perhaps the most obvious trend apparent from current ballistic production volume is that the aramids are used most frequently in woven fabric reinforcement architectures. The UHMWPE materials are predominantly used in cross-plied unidirectional forms. Other differences in resin types, lamina fineness, and surface adhesion will be discussed in greater detail in subsequent sections. It is not clear as to how much of the differences in ballistic performances are attributable to differences in fiber properties or all the other factors combined.

12.3 Woven versus non-woven

Reinforcement architecture in modern armor laminates generally falls into one of two major categories. Both have been found in armor materials since the Second World War[1,3] constructed from those high performance fibers available at the time. Textile fabrics, stacked upon one another with thermoset resin matrices or orthogonally oriented unidirectional tapes in the same resins were used in helmets and chest plates by air crewmen and Marines. Nylon was found in fabrics for blanket like structures or saturated with polyesters for plates or with phenolics for helmet liners. Glass fiber was initially used in cross-plied unidirectional architecture[5] with polyester resin as torso protection. Glass fiber woven into heavy basket weave fabrics gradually replaced the unidirectional Doron as backings behind ceramics in the 1960s and 1970s.[18–20]

When Kevlar® was commercially introduced in 1971,[12] the form of woven fabrics was selected for ballistic armor. The specific fabric design was similar to that developed previously for nylon. Improvements in ballistic performance were observed after considerable optimization of denier, fabric style, end density, crimp, and yarn finish Miner,[21] Bottger[13] or Schut and Tejani.[25] Ballistic efficiency was found to improve with lower denier, lighter fabric basis weight, and other non-architecture related parameters. These trends are not universal, indeed, considerable differences are noted between relatively non-deformable steel fragments and typical lead cored handgun bullets. Similarly, what is optimal for non resinous fabric systems may not be so for the same fiber used as reinforcement in a laminate of similar areal density.

Theories of how fabric architecture affects ballistic performance can be found in Roylance,[4] Laible,[3] Cunniff[22] and Lyons.[23] It is conjectured that yarns at cross-overs exhibit partial reflections of the various strain waves that propagate away from the point of impact. The cross-over density must therefore influence the strain distribution along those yarns involved in arresting the projectile. Following this hypothesis, it would be expected that as the cross-over density is reduced, the basis weight of the fabric would similarly be reduced and ply count increased for constant laminate areal density. With the lower cross-over density, the strain nearest the impact point may be lower, hence inducing greater duration of stretch prior to local rupture. Cover factor is a textile parameter which relates the percentage of presented area which is entirely covered by fibrous material. It also suggests for arbitrary impact locations that a 100% cover factor would insure that a minimum amount of fiber (filament or yarn) interacts with the projectile. High cover factor fabrics (whether woven or uni-directional) will present the greatest amount of available strain energy capacity directly underneath the projectile footprint. High cover factor fabrics will also limit the easy lateral displacement of yarns away from the direct footprint. Both of these observations have resulted in optimal armor constructions which use many layers of low weight plies of high cover factor. One final comment related to woven architectures is that the retained strength of the reinforcement is dependent upon the manner of weaving. Extracted yarn tenacity is often measured from fabrics during development trials before any particular style is commercialized. Twist, interlace, and spin finish can similarly be adjusted at the fiber producer so that the weaving process can minimize any detrimental damage to the individual yarns.

Allied reintroduced the unidirectional configuration[23] with the UHMWPE fiber, Spectra in the mid-1980s. The 'Spectrashield' materials involved cross-plied layers of very finely spread yarns in a matrix of Shell's Kraton® elastomer. Very low linear density of the impregnated tapes requires many plies to achieve laminate weights sufficient to arrest ballistic projectiles. The combination of high tenacity fiber, in a fine unidirectional architecture with an elastomeric matrix resulted in a highly efficient armor material, especially against higher speed rifle bullets. In addition to Honeywell, other companies such as DSM,[16] Park Technologies and FMS now offer similar materials for armor constructions. Claims of the order of 30%[16] in either weight reduction or ballistic performance improvement have been realized in vests and composite plates.

Along with the improvement in ballistic performance come some compromises. The cost associated with handling the greater number of layers must be greater than with the relatively heavy woven architectures. As will be discussed in following sections, the architecture, along with resin stiffness and extent of adhesion, will ultimately influence the structural properties as well. Unlike woven fabrics with finite 'crimp', the unidirectional plies do not exhibit the initial non-linear flat in the stress–strain response, characteristic of fabrics, until the crimp is removed and fiber is aligned. The unidirectional fibers will react quicker with laminate stiffness coupled to fiber stiffness. The woven structure is more compliant, at least initially, which could prolong the duration of fiber stretching prior to localized rupture. Upon projectile arrest, the armor material is partially damaged. The crimp compliant fabric often exhibits more local dishing beneath the impact location. The unidirectional systems often are more efficient in spreading the damage to a more global extent. This global involvement can involve global delamination which will affect the static structural behavior. The extent of lateral displacement of the backside of armor plate material will frequently reach limits imposed by human trauma concerns. So depending upon projectile characteristics and impact velocity, one construction may be more efficient than the other within limited ranges of these parameters. As might also be expected, processing conditions will also influence how well any laminate material may perform. More will be discussed on this subject in later sections as well.

A notable exception to the class of non-woven architectures described above has found limited use in body armor. Needle felts (needle punched non-wovens) were initially evaluated with nylon and later Kevlar®; the results discussed in Laible.[3] A more recent study is reported by Thomas[26] with combinations of the many commercial fibers available today. Thomas identifies the benefit to body armor by incorporating layers of these felts between the principal ballistic layers and the body to limit the extent of deflection into the body, thereby reducing the likely trauma to the individual wearing it. Weight is still the primary parameter that determines which body armor material is selected. Felts, by themselves, are some of the lightest materials for arresting relatively slow fragments. Unfortunately, the current trend of threat escalation is for smaller fragments at higher velocities and the felts alone are not optimal. Another practical limitation of the felt construction was noted by Laible[3] as the tendency to absorb and retain moisture. This difficulty could be reduced if the felt was sealed into a moisture impermeable bag or the individual filaments were to be coated with a water repellent finish. Both of these 'fixes' could influence comfort or ballistic performance which suggests why the felts have yet to be extensively procured by the military community.

It has been observed that lightweight felts can arrest low speed fragments by having some of the reinforcing fibers pre-aligned along the projectile trajectory, which results in efficient use of the fiber. The deflections of these felts are significantly different from those from either woven or unidirectional structures of continuous yarns. A narrower and deeper cavity is formed than the continuous systems. This may not be desirable in body armor applications where trauma may be related to the depth of the cavity.

12.4 Ballistic matrices, resins and prepregs

Laminates of high strength fibers in any architecture include the use of polymer matrices to bond filaments, yarns or plies into solid geometries. Much like their structural counterparts, ballistic composites include a range of different polymer resins, fiber interfaces, reinforcement architectures and processing methods. The two classes of laminate structures are often differentiated by their structural properties. Scott[27] presents a relatively well recognized correlation between ballistic performance and laminate rigidity. The highest ballistic performances are obtained with the laminates of relatively low flexural stiffness. Several things contribute to the flexural rigidity of the laminate, including the elastic modulus of the neat resin, the axial stiffness of the reinforcement, the amount of interlaminar surface area (ply count and ply texture), resin distribution and bond strength between fiber and resin. The use of interply reinforcement (Z pinning or stitching) is less well understood as it influences the lateral rigidity. The use of either of these techniques certainly increases the magnitude of interlaminar tensile and shear strength beyond what the neat resin is capable of, but probably does not increase the flexural stiffness under constant fiber content constraint.

The hypothesis relating ballistic performance to the ease with which the fibers can be stretched has been known for quite some time. The earliest ballistic laminates were made with phenolic or polyester resins at mass ratios less than 25%. Blends with elastomers result in tougher resin systems which were specified in many military applications. Applications as armors included helmet liners, chest plates, spall liners and support plates behind ceramics. The resin content was determined through experimental evaluations which identified the optimal range. Flexural stiffness of these laminates is lower than most optimized structural laminates. Lower resin content contributes to lower stiffness, perhaps through lower bond strength. The lower resin content also requires higher fiber content, which translates to higher ballistic performance since the fiber is known to predominate the ballistic event.

Miner[21] reviews the experimental observations for Kevlar® fabrics coated or impregnated with a range of resin materials. The epoxy matrices have highest elastic moduli but typically exhibit the lowest ballistic performances with most other parameters held constant. Along with the neat resin modulus, resin content, interface wet-out and fiber stiffness are seen to influence both the ballistic and structural properties. The particular armor application will have unique combinations of requirements, including structural. In many instances, an optimum material combination will have to compromise its ballistic performance in order for it to meet the restrictions often required to limit lateral deflection or provide a stiff support beneath ceramic tiles, especially for multiple impact performance. Examples of the use of elastomer matrices, where structural attributes are largely neglected are described in the literature.[28–30]

What are relatively new today are resin systems which have pushed the ballistic performance level without strong regard to the structural requirements. With the woven aramid systems, the original military specification for rubber (polyvinyl butyral) toughened phenolic is still frequently used, but the amount now has been reduced to the range of 10–12% (ACH helmet) in contrast to the original 15–20% (PASGT helmet). The method of prepregging has expanded from transfer roller application of the resin in solution to include film transfer from a carrier film of an already partially cured film. Allied[31] has developed a modified vinylester resin system that required lower curing temperatures more suitable for molding ballistic helmets with woven Spectra® fabrics. So, higher ballistic performing prepregs are now available for woven fabric systems with the older thermoset resins.

In addition to modifying or controlling the application of the resin, the surface of the fiber reinforcement has been modified. Riewald *et al.*[32] describes the material development leading up to the new Kevlar® prepreg now used in the higher performance Advanced Combat Vehicle Crewman's (ACVC) helmet and possibly in the current Advanced Combat Helmet (ACH). In addition to the use of higher toughness Kevlar KM2® fiber at lower denier (850 denier) in a fabric of 31 × 31 ends per inch plain weave, a major departure from the past included the use of a topically applied fluoropolymer to the woven fabric surfaces. This 'adhesion modification interface' was claimed to promote enhanced delamination during ballistic impact. It may also limit the wet-out of solvent-based prepregs during the classical transfer roller, dip tank or liquid spray application methods. The latter effect will have a more pronounced benefit with fabrics of lower basis weights.

The latest trend in prelam materials is to use the high performance fibers in conjunction with more compliant thermoplastic resin matrices. Matrices of rubber, silicone elastomer[28–30] and low modulus thermoplastics like low density polyethylene were considered in the early 1980s coated on fabrics and pressed into laminated plates. These 'compliant' laminates produced higher ballistic performance than similar reinforcement systems in the classic toughened thermoset resins. Later in the same decade, Allied Chemical combined Kraton® thermoplastic elastomer with Spectra fiber in unidirectional tape form and offered commercial 'Spectrashield'[24] of cross-plied layers of this material for both soft body armor and laminate armor applications. On a weight basis, the low modulus resin systems are more efficient due mainly to the laminates' ability to quickly deflect during ballistic impact. Partly due to the high composite flexural compliance, but also due to the greater tendency towards delamination, the compliant ballistic materials exhibit considerable lateral deflection prior to localized rupture. As mentioned earlier, this may be detrimental to system effectiveness where trauma to the body or multi-hit support of ceramic arrays is of concern. Low temperature thermoplastic resins may not be appropriate in applications where the armor may be exposed to elevated temperatures, even for short durations. Thermal stability, flammability and creep under relatively low loads may limit the use of this class of armor material, depending of course on the particular resin used.

Considerable optimization of the prelam materials has occurred over the past decade with 'shield' products now available from DSM, Honeywell and Park Technology (PTI) and thermoplastic coated fabrics available from a wide range of suppliers including weavers, yarn producers, film manufacturers and converters. Depending upon restrictions imposed by the many patents active today, it is possible to combine the many films, resins and textile reinforcements and tailor the armor recipe to meet the combination of requirements for many applications. Availability of some of these ingredients may force substitution with other less optimized forms, but the reduction of performance may be acceptable in many instances. Unfortunately, even in this day of computational capabilities, we are unable to predict, analytically, the effect of these substitutions, so the standard procedure of building prototype targets, then performing standardized ballistic tests is still necessary before the armor system should be manufactured in commercial quantity.

12.5 Ceramics and other facing materials

With the exception of personnel armor, the material of greatest use as armor is metal. Steels and later aluminum alloys have been the choice for tracked combat vehicles and naval vessels where the weight associated with the armor could be tolerated. As reviewed in the previous section on fibers, this situation began to change during the Second World War when synthetic fibers (nylon and E-glass) became available. Over the following decades, stronger fibers were commercialized and eventually found use in armors that were lighter than the metals for specific threat projectiles. As armor developed, so did the projectile threat. As fragments from explosive devices got faster and the cores of armor piercing rounds got harder, composite armor, by itself, was no longer adequate. It was apparent that the armor materials had to possess a similar hardness as the projectiles they were intended to arrest. The hardness of low carbon steels and commercial aluminum alloys were continuously increased. As early as 1918, it was reported[33] that a 1/16 inch thick hard enamel coating on top of standard steel armor improved the resistance against bullets. This application was observed on captured German tanks following the Second World War. During the war, the US Army evaluated glass materials[34] for the defeat of shaped charge warheads and later in the 1950s,[35] tried to replace some of the heavier steel with the more efficient glass materials. Standard window plate glass was evaluated as a hard facing material attached to Doron and tested with 0.30 caliber rifle projectiles by Commander A.P. Webster, a Marine Surgeon in 1945.[18] Prior to this, steel, aluminum and titanium alloys were selected as facing layers on top of leather, silk or nylon fabrics to boost the protection level against higher speed fragments or rifle bullets. The glass/composite combination provided similar protection as the metals at lower weights. For this reason, ceramics have received continuous interest for body armor or applications where weight was of concern.

Cook[36] was awarded a patent for the combination of aluminum oxide in front of the Doron laminate material. Following this publication in 1963, much research in the US[18–20] was directed towards understanding the mechanics of projectile arrest and further optimizing the combination of materials for further weight reduction or higher protection levels. Wilkins[37] combined experimental studies with the application of Lagrangian finite difference models to better understand how to design lightweight armor. Finite thickness armors are observed to initially stall the penetration of the projectile and eventually after damage accumulation; the residual penetrator perforates the rubble. Alumina ceramic tiles were bonded to both aluminum and E-glass fabric reinforced laminate backings. Mass ratios of ceramic to backing plates are reported and a wide range of ceramic materials are identified with various densities, hardness, Young's modulus and toughness. Correlations between the mechanical properties and ballistic efficiency were never clearly identified, although a general trend of higher compressive strength or hardness and lower density generally suggests high ballistic efficiency. In addition to identifying the many ceramic candidates, Wilkins ranks these with both mechanical properties and ballistic limit velocities. Hot pressed boron carbide, silicon carbide and beryllium oxides are ranked highly, followed by sintered forms of the same materials. Stiglich[38] presents similar rankings of potential armor materials but without the ballistic results. Commercial availability is identified as another important selection criterion. Stiglich also suggests ceramic materials with gradients of properties and non-planar geometry as means for improving ballistic efficiency.

More contemporary surveys of ballistic ceramics are presented in many symposia dedicated to this area.[39–41] Cost and availability have risen to greater importance as vehicle applications have demanded higher protection levels with lower system weights, over greater surface areas. Even the smaller geometries in chest plates have stressed the manufacturing base due to their demanding procurement requirements (30,000 sets/month for Interceptor alone). Gooch[42] presents a recent survey of ballistic ceramic manufacturers and the many combat vehicle applications in which their products are used. Due to the greater volume of ceramic material needed, lower cost sintered or reaction bonded materials are often selected over the higher efficiency hot pressed ceramics. Metal matrix ceramic and ceramic matrix ceramic composites have been evaluated to a lesser extent, but have the potential for lower cost production or better toughness which could eventually result in their preference over the more expensive hot pressed B_4C, SiC or TiB_2 standards. A rather recent trend in armor system manufacturing involves the encapsulation of discrete ceramic tiles in a ballistic efficient matrix. Metals can be forged or cast around the tiles. Metal matrix and ceramic matrix composite materials have also been evaluated for this encapsulation role. The boundary conditions between ceramic and backing layers, tile lateral dimension and edge restraint, and cover plate properties all influence the armor system performance. The final armor design must address these factors along with the reality of manufacturability, integration or attachment and potential cost position.

The combination of the ceramic front layer with the rear structural support is required for ballistic evaluation. A synergy between these drastically different materials results in an optimum armor design. In some instances, ball projectiles in particular, less ceramic thickness and more compliant backing structures are favored. Against the hard cored 'AP' class of projectiles, a harder, thicker ceramic layer is better along with a stiffer support plate. Requirements to sustain multiple impacts with either projectile can alter the system design towards more compliant bondlines and stiffer complete structures. Since the ceramic layer is unsuitable as a structural member, the backing layer must provide this role. Attachment, mounting and normal vehicle road dynamics requirements influence the design of the backing layer. These requirements may result in less than optimal ballistic performance. This is typical for ceramic armor applications.

12.6 Manufacturing processes

The methods of manufacture of ballistic armors are as old as the technology itself. Laminates have classically been constructed from woven reinforcements in thermoset resins like phenolics or polyester. Helmets, ceramic chest plate backings, spall liners and panel armors were pressed at temperature from prepregs (partially cured polymeric coated fabrics). Matched steel tools were most frequently kept at fixed temperatures until parts were fully cured and the pressure relaxed. Molding pressures were typically in the range of 300–3000 psi. Flat plates generally were pressed at the lower range of pressures and helmets usually at least 2000 psi. Attempts to mold helmets with low pressure processes, like vacuum bagging or autoclave, resulted in ballistic structures of lower ballistic performance. More contemporary composite making processes, like resin transfer molding (RTM) or vacuum assisted resin transfer molding (VARTM), are not candidates for the ballistic laminates due to the desire for resin content below 20%. These processes are quite efficient for making structural laminates with resin contents greater than 50% by weight. Studies of the effect of varying the molding pressures with resin starved, thermoset ballistic prepregs have concluded that molding pressure has weak influence upon ballistic performance. Much of the need for higher pressures was driven by the relatively low resin content and engineered poor wet-out attributes of typical ballistic systems. The higher pressures are necessary to remove wrinkles and reduce porosity in materials with poor flow characteristics by design.

Alesi[43] evaluates helmet material candidates in flat plate and helmet shapes with both thermoset and thermoplastic resin systems. Molding conditions are explored over a range of temperatures between 300 °F and 360 °F and pressures between autoclave (75 psi) and matched steel compression tools (2500 psi). Their observations were that the higher pressures resulted in lower peel strengths with flat samples. Recent manufacturing experience[44] with Spectrashield and Dyneema UD products suggests that enhanced ballistic performance can be achieved with relatively high molding pressures (2500 psi). Careful control of molding conditions must be maintained in order to avoid the damaging of the reinforcement fiber. One potential theory for the improved performance can be extended from the observations above, even though the class of matrix materials is different. Lower peel strengths suggest greater compliance during inelastic projectile arrest. High flexural compliance has been correlated to higher ballistic efficiency.

Alesi[43] also describes efforts to make helmets from many different reinforcement systems, including one different class: thermoplastic. The ‘XP’ product available through the mid-1980s was a unitape product made by the stretching of polypropylene film. Upon cross-plying, multiple layers were stacked and then thermoformed by pressing at temperature, followed by cool-down to room temperature while maintaining pressure. The finished product had good ballistic performance, but was very compliant. In order for it to meet practical durability requirements, structural skins of either glass/phenolic or Kevlar/phenolic were co-processed onto the XP core. Ultimately, the Kevlar/PVB toughened phenolic system in monolithic construction was selected.

More recent activity with thermoplastic resins has allowed for much lighter ballistic structures, although reductions in structural properties are usually coincident with the improved ballistic efficiencies. As described earlier, the 'Spectrashield' products developed recently have incorporated thermoplastic elastomers as matrices, along with the thermoplastic polyolefin fiber itself. The helmet application has seen materials constructed from cross-plied uni-directional layers with thermoplastic matrices as well as more modest variations of the past where only the resin was changed, keeping the same aramid fabric reinforcement architecture.

Thermoplastic resin systems require different manufacturing processes than their earlier thermoset cousins. Many of the candidate resin materials and their specific manufacturing processes are reviewed in an article by Chang and Lees.[45] The consolidation of a solid part is not limited by cure kinetics, but by simple thermal transport mechanisms. Thermoplastic parts can be re-worked or repaired. Since cure kinetics do not limit the cycle time, it is theoretically possible to mold parts at high rates of production. For example, a normal molding cycle for the Kevlar PVB phenolic PASGT helmet is approximately 20 minutes. The thermoforming process used by Cato Ringstad A/S Norway with a preform material of Kevlar fabric with nylon matrix (TEPEX[46]) is believed to take less than 5 minutes, including pre-forming. The Norwegian military helmet currently in production uses this technology.

A major advantage to the thermoplastic-based systems is the potential for conforming initially flat prelam materials to complex shapes, without the need for cutting and overlapping. The conformability of high strength fiber reinforcements has been partially addressed with the modification of fabric architecture to allow for a greater extent of in-plane shear distortion or by the preconditioning of the fiber prior to the weaving into a fabric. The latter option was developed in the 1990s and commercially available[47] as LDF (long, dis-continuous, highly aligned fibers in thermoplastic matrices) with a range of fibers to include glass, graphite and aramid. Many manufacturing processes including vacuum pressure, low pressure molding techniques were possible with this class of material. Unfortunately, the ballistic performance of the LDF reinforced laminates was always less than equivalent weight structures using continuous fibers. This system could satisfy applications where a compromise between weight, protection level and part complexity is appropriate.

12.7 New ballistic products

Laminate armors had originated in the Second World War but have proliferated into many applications where protection has to be provided at weights less than that possible with RHA steel. Gooch[42] provides a comprehensive review of ceramic armor applications of military interest within the past decade. Composite backing plates are found along with the ceramic materials.

12.7.1 Vehicle applications

The applications range from land combat vehicles to aircraft to personnel armor. Naval applications are similarly represented. The majority of these involve glass, aramid, graphite or UHMWPE fiber reinforced plates or shells used in combination with metals. Steel and aluminum still predominate amongst the materials used on vehicles, but these advanced lightweight systems are gradually finding increased use. Spall liners are fabric reinforced composites using fire resistant thermoset resin matrices. They are mounted on the inside of most aluminum hulled combat vehicles where the survivability of the crew inside is improved in the event of an overmatching threat perforation. Composite parts can be part of the primary armor, especially effective against fragmentation, originating from grenades, mortars, artillery and most recently Improvised Explosive Devices (IED). The Bradley Fighting Vehicle (BFV) uses laminates of either S-2 or Kevlar fabric. Spall liners are also mounted on the M113, Paladin, M9 ACE, and other variants. The Stryker (updated LAV) has external armor kits which include glass fiber reinforced support plates. Outside the US, there are similar applications of composite materials to combat vehicles. This author is less familiar with these and must apologize for inadvertently not including them in the list above. It should also be mentioned that considerable activity in the research and development community for future vehicles has considered composite laminates for replacement of metals in both structural and armor roles. Programs like AGS, CAV, AFV, CRUSADER, and FCS all explored this class of materials in an attempt to reduce the weight of the incumbent vehicles they were intended to replace.

In Iraq today, most of our lightly or unarmored wheeled vehicles have had armor kits applied. These kits can range from steel, aluminum or titanium plates to composite backed ceramic arrays. A likely trend will be to add composite materials to the inside surfaces of some of these ‘kit’ plates, as the threat munitions increase in severity. Already armored vehicles can similarly be upgraded with the mounting of ceramic arrays to the outboard surfaces (ex. Stryker).

Rotor and fixed wing aircraft require similar protection from fragmentation and small arms where the weight implication is much more important. High hardness, hot pressed B_4C is frequently combined with backing plates much like the chest plates used in personnel armor. The armor can be mounted onto floors, bulkheads or pilot seat backs. In some transport aircraft, hook and loop systems are utilized to mount pre-manufactured ceramic arrays onto floors and bulkheads. The weight penalty on aircraft performance is steep; here the cost is secondary to the need for the lightest protection possible. One slight advantage for the aircraft application is that the 'tightness' of the multi-hit pattern, dictated by the likelihood of automatic weapon hit probability is less severe given the relative motion of the aircraft to the threat source. It is simply less likely to get a tight hit pattern on a moving object, which frequently allows for lighter designs than typically applied.

Up to this point, the composites used on vehicles have generally involved thermoset resins with intermediate structural stiffness qualities. Lighter weight armors are possible, for some threats like fragmentation or slower deformable projectiles, if the laminate is allowed to flex to a greater extent. Higher ballistic efficiencies are possible for fabrics without any resin at all. Fragmentation vests and blast/fragmentation blankets have found use in both vehicle and personnel platforms. 'Frag blankets' have been mounted on aircraft bulkheads as well as floors and seat backs of land vehicles. The ability to add/remove and store these systems is very desirable. Due to the vibratory environment in which they are used, fatigue and exposure are of practical concern. Nylon and Kevlar fabrics have been fielded, but consideration for waterproofing must be designed into the final blanket to insure protective performance is not compromised. Glass fabrics have not been found to survive the fatigue loading and UHMWPE is not normally considered due to the relatively low oxygen index (flammability potential) of the polyolefin polymer. It is just a conservative practice to reduce the flammability potential whenever possible.

12.7.2 Personnel systems

Flexible systems are preferred for personnel armor. Long-term wear in oppressive conditions requires that comfort be considered in the design. Estimates of perhaps four million PASGT helmets[48] and two million PASGT fragmentation vests manufactured from Kevlar fabrics have saved the lives of numerous US troops since the introduction of this fiber in the early 1970s. The original vest design has evolved over the past three decades to provide enhanced protection against submachinegun and handgun threats, while providing equivalent ballistic protection against the primary fragmentation threats. These protection levels were maintained while the weights and concurrently, comfort levels improved. This performance improvement was achieved with the introduction of higher strength and toughness Kevlar KM2 yarns, more optimized fabric styles and novel vest system designs. The Ranger Body Armor (RBA) vest used 850 denier Kevlar KM2 fabrics and the current Interceptor[49] outer tactical vest (OTV) uses either 600 denier or 400 denier fabrics of the same Kevlar KM2 fiber.

Other materials like Twaron aramid, Spectrashield and Dyneema UHMWPE and Zylon (PBO) have also been evaluated as part of the OTV system. In conjunction with the OTV, ceramic plates are now being procured to provide limited protection against rifle projectiles. These small arms protective inserts

(SAPI) are positioned in pockets sewn into the front and back of the OTV to shield critical body organs against these more aggressive threats. There are reportedly 24 combinations of ceramic and composite backings that meet the various performance specifications. Ceramics include hot pressed B_4C and SiC, sintered SiC and Al_2O_3, and reaction bonded B_4C and SiC. In contrast to the past plate designs, the new SAPI plates have replaced 2″ × 2″ tile arrays with a single ceramic piece with double curvature. This eliminates the vulnerability associated with the seams between tiles and reduces the complexity of assembling the many smaller pieces. The composite backings typically are constructed from Spectrashield or Dyneema products, manufactured by several companies from several manufacturing processes (vacuum bag adhesive bonding, autoclave molding, matched metal compression molding, etc.). Indeed, it is believed that these improved protective systems have been so effective that wounds are now most prevalent outside of the OTV coverage. These ‘extremity wounds’ are now receiving attention with add-on parts being manufactured from the same materials used in the OTV, simply covering the next most vulnerable areas of the body.

No discussion of current armor technology is complete until combat helmets are described. Perhaps the largest application of ballistic composite materials has been the PASGT. Over four million have been built in the US alone, with international production assumed to be of a similar level. With the finished helmet weighing approximately 3.5 lbs, the initial desire was to reduce its weight and maintain the soldiers’ survivability. The selection of Kevlar over nylon, glass fiber and fiber XP followed the study[43] of ballistic and structural performance of a new geometry to replace the M1 steel shell with a nylon inner shell. With this fiber reinforced laminate, the total weight was kept equal to the M1, but greater surface area and higher ballistic resistance on the covered area was obtained. Higher protection level with equivalent weight has been replaced by the goal of maintaining equal protection levels but now at reduced weight. With an aramid laminate, if the surface area is held constant, the only means for weight reduction is with reduction of wall thickness.

A lightweight version of the PASGT was developed in 1989 with a reduction of 15% in wall thickness. The ballistic protection level was actually increased while reducing the amount of fiber in the shell. There were several reasons for the improvement in ballistic efficiency: increased tensile strength and toughness with the introduction of KM2 fiber, reduced interface adhesion between plies of prepreg and finer fabric with greater ply count. This material combination is now utilized in the Combat Vehicle Crewman’s (CVC) helmet worn by crewmen of the M1 main battle tank and the Bradley Advanced Fighting Vehicle (BFV). Late in the 1990s, the US Marine Corps evaluated even lighter versions of the earlier PASGT. The goal was at least 25% weight reduction with equal protection level. Spectrashield and Kevlar/thermoplastic materials had demonstrated that the ballistic performance could be met. Unfortunately, neither were selected due to limited structural and durability capability. The lightweight Marine Corps helmet has, however, recently entered production with intermediate weight using a higher strength Twaron reinforced phenolic architecture. The US Army is similarly considering the next generation combat helmet (Advanced Combat Helmet (ACH[50]). The use of a performance specification allows for any material that meets its long list of requirements, but the systems procured up to this point have utilized either high strength Kevlar KM2 or K129 in a lower resin content (higher fiber content) thermoset formulation. Other combat helmet programs are active within the US military with the same goal of reducing the weight burden on the soldier while maintaining his or her likelihood of surviving the next battle. Future Force Warrior (FFW) is one such program that is exploring, among other options, the use of higher performance thermoplastic resin fiber reinforced laminates. Along with greater ballistic efficiency, the need for extended surface area of coverage is considered over the face, frontal neck and lower neck regions. It is to be determined, what the next combat helmet will ultimately look like.

12.7.3 Architectural applications

Following the terrorist acts of September 2001, considerable activity towards hardening of buildings (and aircraft systems) has occurred in both research and procurement communities. Laminates have been designed into commercial aircraft bulkhead doors and luggage containers (hardened unit load devices (HULD)). Due to the weight implications discussed earlier, these two applications have utilized lightweight materials with high ballistic efficiency. Buildings do not have the same limitations around the weight penalty as personnel equipment or aircraft parts. Cost, availability, environmental durability and the complexity of integrating any hardening modifications will influence the choice of materials more than ballistic efficiency.

The design philosophy has centered upon either making large structures more tolerant of explosive blast loading or limiting access of terrorists by hardening doors, windows, or walls against everything from torches and axes to assault rifles. For the explosion/blast resistant applications, relatively heavy fabrics of glass, aramid and graphite have been considered for wet hand lay-ups over existing wall panels. Composite beam and column wraps or skins can increase the load carrying capacity of critical building structures. High strength materials can strengthen connections of these same structural elements. Glass fibers in forms ranging from woven fabrics to non-woven mats to random fiber lay-downs from 'chopper guns' are being evaluated. Resins include polyesters, epoxies and even cement slurries for direct concrete retrofits.

When resistance against assault rifles is desired, those systems designed for personnel and vehicles could be considered, except for the much larger volumes required. Steel reinforced concrete can be designed to accommodate any small arms threat, but if the building already exists, it is often necessary to mount more efficient panels of materials which are lighter or can be easily delivered, especially to upper floors. Instead of high performance, hot pressed ceramics, already available construction materials like floor tiles, countertops or metals could be combined with low cost E-glass laminates or steel plate backings to replace sheet rock or gypsum panels. It is certainly desirable to avoid the need to modify the building structure to carry the additional weight associated with these armor upgrades: weight efficiency cannot be entirely neglected. The ability to cut, drill and mount these ballistic enhancements with conventional tools is another desirable attribute for any candidate material system. If access or space is limited, the ability to roll or fold lightweight materials and hand carry to the hardening location must be considered. With all of these different requirements, it is likely that many different options will become commercially available.

12.8 Future of the composite armor market

Current demand for personnel and vehicle armor in Iraq has stressed the world capacity for aramid, UHMWPE, PBO and even S-2 glass fibers along with conventional steel armor plate and the exotic ballistic ceramics (B_4C and SiC). DuPont (Kevlar), Tejin (Twaron), DSM (Dyneema), Honeywell (Spectra), and Toyobo (Zylon) have all announced their intent to increase the capacity of these ballistic fibers. As in past military engagements, this demand may be cyclic. One significant difference from the past is that the threat seems to change at a more frequent rate. It is no longer adequate to upgrade following a particular terrorist event. It seems as if the terrorists are watching the evening news along with us and quickly adjust their devices according to how well our hardening retrofits seem to perform. There may never be a time in the future that some unique armor design is not immediately needed.

For the more conventional military conflict, future mobilization would benefit from lighter weight combat vehicles where air transport is required to deliver armored support of ground operations. Short of any new threats appearing, the objective of armor research is clearly directed to replace current armors with lighter systems of equal or greater protection levels. A practical challenge will include designing the new armor with those materials that will be available in sufficient quantity to meet the demand. Long-term research should include evaluation of new materials or existing materials in new or novel combinations.

The market potential for hardening our building infrastructure is quite uncertain. The shear quantity and volume requirements would preclude universal retrofit. Selective buildings could receive upgrades as risk demands. The focus for this application may have to be directed towards the use of the lowest cost materials in novel, low cost application processes.

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13

Military and law enforcement applications of lightweight ballistic materials

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13.1 Introduction

For a number of years the military, police and other law enforcement agencies have used protective products made with lightweight fiber-reinforced ballistic materials for their protection against bullets and fragments. Ballistic vests and helmets made with these fibers have saved thousands of lives. The vests made with lightweight ballistic materials are flexible, lighter and concealable. The helmets made with high performance fiber composites are lighter and have much higher ballistic performance compared with the steel helmets used during the First and Second World Wars.

The first non-metallic armor application was in the form of a flak jacket used by the military during the Second World War. However, the most visible lightweight ballistic product was a 100% composite helmet designed by the US Army R&D. More recent applications are the military helmets and vests with breastplates worn by the US, British and other troops in Afghanistan and Iraq.

The number of new products, new applications and number of human lives saved are the criteria for the success of a new material and technology. The lightweight ballistic materials have:

- increased the protection level for law enforcement and military personnel;
- lowered the weight of armor;
- increased the flexibility of vest armor;
- increased multiple bullet protection.

In the area of vehicle armor, they have provided the following benefits:

- reduced the weight of a vehicle;
- increased mobility;
- decreased number of components required to armor;
- increased the fuel efficiency;
- increased the life of the vehicle.

This chapter will focus on the commercial application of the lightweight ballistic materials used in numerous products by military, police, law enforcement agencies and UN peacekeepers around the world.

13.2 US military

13.2.1 Military helmets

PASGT helmet

Head protection is of prime importance during a military conflict and certain law enforcement and peace keeping situations. Head protection in such a situation is desirable at the lowest weight, with maximum protection against a wide variety of bullets and fragments.

In the early 1970s the US military launched a program to develop a 100% fiber-reinforced lightweight military helmet. Some of the main features of the program resulted in higher ballistic protection, more space within the helmet for better ventilation, communication devices, expanded head coverage area, lower center of gravity and overall good aesthetics. In the early 1980s the US army started procuring such helmets (see Fig. 13.1). During the Cold War, the US army was procuring as many as a quarter of a million helmets per year.

The first time these 100% fiber-reinforced military helmets were used by the US military was during the Grenada liberation.

13.1 Military helmet, courtesy AHI.

Main features of the US military helmets

- Shape of the helmet: PASGT shape.
- Material of the helmet shell:
  - woven aramid-reinforced phenolics/PVA system;
  - resin: 50% phenol formaldehyde and 50% polyvinyl butyral resin.
- Size of the helmets: four sizes.
- Weight of finished helmet:

– Size	X-small	Small	Medium	Large
– Maximum weight (g)	1418	1447	1504	1617

- Color of helmet: the finished helmet has Olive Drab 34087 of FED-STD- 595 color. The helmets have a texturing aggregate incorporated in the second coat for the exterior of the helmet shell. The texturing aggregate could be silica sand or walnut shell floor.
- Suspension assembly, chinstrap and headband. Each component is listed in the MIL-H- 44099 specification.
- Ballistic performance: the V_{50} ballistic limit for each helmet no less than 610 mps, when tested against 17 grain FSP in accordance with MIL-STD-662, and fragment conforming to MIL-P-46593.

13.2.2 Interceptor vest

Interceptor Body Armor stems from the 1994-vintage 24-pound Ranger Body Armor (RBA) designed by the US Army Soldier Systems Center (Natick, MA) at the request of the 75th Ranger Regiment. The RBA was a fairly heavy vest system and the Army was looking for a lighter vest system. The Interceptor Multi-Threat Body Armor System went into production in 1999 under a five-year contract awarded by US Army Soldier Systems Center to Point Blank Body Armor.

The Interceptor outer tactical vest consists of a very fine woven aramid fabric. Webbing on the front and back of the vest permits attaching such equipment as grenades, walkie-talkies and pistols (see Fig. 13.2). This is a flexible vest designed as a modular, multiple threat body armor system consisting of a modular carrier and removable ballistic inserts, both soft armor and rigid molded armor. The Interceptor system is designed to defeat multiple ballistic threats commonly faced by US troops in the battlefield. The vest's modular configuration allows the vest to be tailored to changing threat levels to increase or decrease weight and maximize mobility.

Ballistic protection level

The Interceptor system is designed for the following ballistic threats:

- Fragment protection.
- Multi-hit handgun, FMJ protection.

13.2 Interceptor vest, courtesy Point Blank.

Ballistic test method

- The fragment testing is conducted as per the guidelines of the Interceptor test method.
- 9 mm bullet is tested as per the guidelines of NIJ Standard 0101.03.

Other tests include:

- Fungus resistance as per MIL-STD-810E.
- Reliability.
- Service life.

Sizes of the Interceptor

Five sizes of the Interceptor are requested. These are: X-small, Small, Medium, Large, and X-large.

Material for Interceptor vest

Woven fabric consists of fine denier high tenacity aramid fibers. The Interceptor vest system comes with neck and crotch protection attachments. It works with all current and anticipated load carrying equipment. With the fasteners along the right side, the vest still protects the front of the body even when open. The vest also has a quick release feature, so if the soldier needs to drop the plates, one string pull will release them.

The average outer tactical vest weighs 3.8 kg.

13.2.3 Small Arms Protective Insert (SAPI)

The Small Arms Protective Insert (SAPI) is a breastplate. The breastplate when inserted into the Interceptor Outer Tactical Vest (OTV) fragment protective vest provides protection from certain small arms fire. The armor insert is part of a protective system, which includes a soft fragmentation and handgun tactical vest. The insert is used in conjunction with soft undergarment as a total armor (Fig. 13.3).

The SAPI program started in the late 1990s to provide protection from high-energy bullets fired against military.

Sizes and weight

SAPI is available in several sizes and weights based on compositions.

13.3 Small arms protective insert, courtesy AHI.

Thickness

The hard armor insert in finished form will have uniform thickness throughout the entire plate surface. The maximum allowable finished thickness will not exceed 0.85 ± 0.125 in.

Ballistic threat

The armor insert plate is designed to defeat a number of high powered rifle bullets when tested in conjunction with the Interceptor flexible armor vest.

- NATO 7.62 × 51 M80 Ball.
- Soviet 7.2 mm × 54 R Ball type LPS.
- US 5.56 mm M855.

Materials

The SAPI consists of the following components:

- double curvature monolithic, boron or silicon carbide ceramic;
- an adhesive layer;
- molded backing consisting of cross-plied HMPE armor material;
- wrapping the entire plate with black coated nylon fabric.

The ceramic plate may be reinforced or padded with foam or other impact resistance materials to meet the drop impact test.

Fabrication process

Autoclave molding

The autoclave is also used to fabricate the hard armor insert. Layers of HMPE cross-plied materials are stacked on the back of the ceramic facing with a layer of adhesive between the ceramic and layers of ballistic materials. The entire stack is slipped inside a vacuum bag and vacuum is applied. The entire vacuum bag with partially consolidated material is placed inside the autoclave for processing under heat and pressure. Once the insert is fully cured and consolidated a black coated water-resistant nylon layer is wrapped and molded on the entire SAPI. Finally, the sharp edges are grinned to a smooth surface and proper instructions are printed on the front and back of the SAPI.

Match-die molding

The layered backing material for ceramic facing is molded separately in a match die molding. The match die mold has the identical double curvature surface to the monolithic ceramic. Once the backing is molded, it is attached to the ceramic with an adhesive layer in between the ceramic and molded Spectra Shield PCR plates. Finally, the sharp edges are grinned to a smooth surface and proper instructions are printed on front and back of the SAPI.

Other tests

These include:

- fungus resistance as per MIL-STD-810E;
- reliability;
- service life.

The Interceptor system weighs about 7.5 kg including the insert plates. The outer tactical vest weighs 3.8 kg and each of the two inserts weighs 1.8 kg.

13.2.4 SPEAR vest and helmets

The Special Operation Forces Personal Equipment Advanced Requirement (SPEAR) is designed to take care of all of the capabilities that a special operation force wears.

The SPEAR program started in 1991 by US Army Special Operation Command (USASOC). The Army has the lead on the joint-service SPEAR effort, which also covers US Navy and Air Force Special Operation forces. Currently, US Special Operation Command (USSOCOM) is going forward to acquire large quantities of SPEAR vests and helmets.

Nine SPEAR subsystem modules include:

- Lightweight Environmental Protection (LEF).
- The Body Armor and Load-Carrying System (BALCS).
- A Modular Integrated Communications Helmet (MICH).
- Lightweight Nuclear–Biological–Chemical (NBC) protection.
- Signature reduction.
- Integrated Laser and Ballistic Optical protection.
- Modular Target Identification and Acquisition.
- Physiological Management.

Ballistic protection level

- Multiple fragment protection.
- Multi-hit handgun 9 mm, FMJ protection.

Areal density

Not to exceed 1.1 psf.

Thickness

Not to exceed 0.350″.

Ballistic test method

- The fragment testing is conducted as per the SPEAR methodology.
- 9 mm bullet resistance as per the guidelines of NIJ Standard 0101.04.

Other tests

These include:

- high and low temperature exposure;
- petroleum, oil and lubricant;
- seawater immersion;
- weatherometer resistance;
- fungus resistance as per MIL-STD-810E;
- reliability;
- service life.

Sizes of the SPEAR

Five sizes of the Interceptor are requested. These are: X-small, Small, Medium, Large, and X-large.

Material of SPEAR vest

Fine denier aramid fibers.

Molded inserts

The SPEAR molded inserts for Level IV consist of the following components:

- monolithic, boron or silicon carbide ceramic;
- an adhesive layer;
- molded backing consists of cross-plied HMPE or woven aramid prepreg armor material. The entire plate is wrapped and molded with black coated nylon fabric.

Using the current SPEAR ballistic plate, the panel shall be tested as a system in accordance with NIJ 0101.03 test protocol for Level IV.

SPEAR ballistic plate ballistic testing

The SPEAR molded test is a system in accordance with NIJ 0101.03 test protocol for Level IV with the exception that a minimum of two hits at 4 inches apart shall be used for the evaluation. Backface deformation shall not exceed 1.73 inches (44 mm) against the 9 mm projectile for the system.

SPEAR helmets

The SPEAR program adopted a new shape of helmet with a built-in communication system.

Shape

Cutout version of PASGT helmet with less head coverage area.

Ballistic requirement

- Test against multiple fragments.
- 9 mm bullet is tested as per the guidelines of NIJ Standard 0101.04.

SPEAR helmet material

840 denier woven aramid prepreg with phenolics resin.

Molding method

Match-die high-pressure molding under high pressure and temperature.

13.3 European military

13.3.1 European military helmet

In the early 1990s the French and other European militaries launched a program to replace steel helmets with a 100% lightweight fiber-reinforced military helmet. The original goal was to provide blue UN helmets to French troops going into Bosnia. The program resulted in the highest ballistic protection at the lowest weight, more space within head and helmet for better ventilation and communication devices, expanded head coverage area, lower center of gravity and overall good aesthetics (Fig. 13.4).

Main features of European military helmet

- Shape of the helmet: PASGT or similar shape.
- Material of the helmet shell: non-woven, cross-plied HMPE for France, and phenolics film laminated woven aramid prepreg for other countries.
- Size of the helmets: two sizes, medium and large.
- Color of helmet: the finished helmets are either UN blue color or military green. The helmets have a texturing aggregate incorporated in the second

13.4 UN military helmet made with HMPE cross-plied armor material, courtesy Honeywell International Inc.

paint coat for the exterior of the helmet shell. The texturing aggregate could be silica sand.

- Suspension assembly, chin strap and headband.
- Ballistic performance: the V_{50} ballistic limit for European countries helmet varies from 550 to 680 mps, when tested as per the STANAG 2920 test. Also, some countries specify 9 mm bullet test at a velocity of 430 mps, and backface deformation should be less than 30 mm.

13.3.2 European military flexible vest

Along with a 100% composite military helmet in the early 1990s, Europeans, especially the French, launched a program to increase the protection of their current vest from handgun and fragment protection to handgun, fragment and sniper bullet protection.

The vest is flexible with pockets for molded hard armor plate inserts (Fig. 13.5). The vest consists of quilted woven aramid layers and the woven fabric is made of 1100 dtex aramid fabric. The flexible vest is usually tested against fragments, and some are tested against 9 mm bullets fired at 430 m/s, maximum allowable deformation is 25 mm. Trauma pads are recommended to reduce the weight of the vest and backface deformation.

13.5 European ballistic vest and ballistic kit plates, courtesy Honeywell International Inc.

13.3.3 European ballistic vest and armor kit inserts

For protection from sniper bullets a number of materials were evaluated with and without ceramic facing. However, one material shows as much as 30% weight reduction compared to any other material system. This material was non-woven cross-plied Spectra Shield.

In 1993 the French bought 5000 ballistic kits. This design was later adopted by a number of European and Asian countries.

The outer flexible vest consists of 1100 woven aramid layers. The woven fabric is a plain weave fabric weighing 190 g/sq m. The flexible vest is tested against 9 mm bullets fired at 430 m/s, maximum allowable deformation is 30 mm. The flexible vest has pockets where ballistic kits molded plates are slipped in to provide the rifle bullet protection.

The ballistic kits consist of:

- curved front plate;
- flat back plate;
- groin area smaller plate;
- neck protection (molded collar).

Areal density

The areal density of each of the molded plates weighs between 17 and 20 ksm.

Total coverage

The total coverage is approximately 0.25 sq. meters.

Tests

The molded ballistic kits plates are tested against multiple rifle bullets and the testing is carried out on a clay block. Testing of hard armor panels is carried out with a flexible vest. The bullet should stop on the molded plate with a deformation of not more than 22 mm. The ballistic material is non-woven, cross-plied HMPE fibers and the molding method is high-pressure match-die molding.

The ballistic kit is dropped in the pocket provided for each plate in the flexible vest consisting of layers of woven aramid.

13.4 Asian military

13.4.1 South Asian helmets

Military personnel in south Asian countries are currently wearing low cost helmets either made with fiberglass/polyester or thin steel metal. The helmets have good impact resistance but fairly low ballistic resistance against bullets and fragments.

There is an accord from a number of countries from this area to either acquire or mold local high performance helmets made with either HMPE fibers or high tenacity aramids. Specifications are drafted and helmets from a number of global helmet molding companies are being evaluated at this stage.

13.4.2 South Asian military vest

For a number of south Asian countries the vest design is in early stages of evolution. However, a number of features of these vests are similar to the European vest. The vest is usually flexible with pockets for molded hard armor plate. The flexible vest consists of quilted woven aramid layers. The woven fabric is made with air-entangled aramid fabric and is tested against 9 mm bullets fired at 430 m/s, maximum allowable deformation is 25 mm. Trauma pads are recommended to reduce the weight of the vest and backface deformation.

Plates

The protection is provided with two plates, namely:

- a curved front plate;
- a flat back plate.

Ballistic material

Non-woven, cross-plied HMPE fibers.

Molding method

High-pressure match-die molding.

Ballistic threats

Multiple high energy rifle bullet hits. The testing is carried out on a clay block. Testing of hard armor panels is carried out with a flexible vest. The bullet should stop on the molded plate with a deformation of not more than 22 mm. The ballistic kit is dropped in the pocket provided for each plate in the flexible vest.

13.4.3 Asia Pacific Rim helmets

Military personnel in this region have a variety of ballistic helmets. Some countries have been using high performance helmets for a number of years and a number of countries are in the process of moving away from low performance woven nylon/phenolics helmets to high performance helmets made with either high tenacity woven or HMPE woven military helmets.

13.4.4 Asia Pacific Rim ballistic vest

A number of countries in the Asian Pacific Rim area are buying flexible vests with molded hard armor breastplate inserts. Salient features of these vests are similar to the European vest. The flexible vest consists of 1000 denier woven aramid and designed to stop 9 mm bullets at 430 mps. Trauma limit varies from country to country. Some countries such as Taiwan have adopted NIJ Standard 0101.04, and therefore the trauma limit is .44 mm on Plastilina. The flexible vest is also tested against 17 grain Fragment Simulating Projectiles. V_{50} is conducted as per MIL-STD-662F, and V_{50} should not be less than 450 mps.

Trauma pads are not accepted in these countries to reduce the trauma. The front and back molded breastplate insert plates are double curvature plates.

Ballistic threats

Ballistic threats for breastplate designs are multiple hits from high powered rifle bullets.

Armor design

The breastplate consists of monolithic double curvature silicon carbide ceramic backed with layers of cross-plied HMPE or woven aramid prepreg.

Testing

The testing is carried out on a clay block as per the NIJ Standard 0101.04. Testing of hard armor panels is carried out with the flexible vest, which is designed for a fragment V_{50} of 450 mps.

Ballistic material

Ballistic material for molded breastplates: non-woven, cross-plied HMPE fibers.

Molding method

The molding method is double curvature high-pressure match-die molding.

Other tests

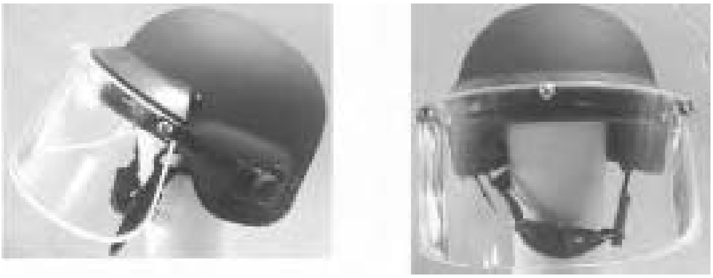
Other tests for molded breastplates include:

- flammability at 120 °C;
- drop test as per MIL-STD-810;
- durability test by dropping plate;
- temperature test at (−)50 °C and (+) 75 °C;
- temperature shock test;
- fluid test by soaking breastplate in lubrication oil and salt water;
- fungus test.

13.5 Law enforcement ballistic protection

13.5.1 Police ballistic helmets

The ballistic helmets for police are designed to stop handgun bullets. The helmets are usually painted black to differentiate from military green helmets.



13.6 Riot police ballistic helmet with face-shield, courtesy Tung Gwo.

The military helmets usually are designed to defeat fragments generated by an explosion in the battlefield (Fig. 13.6).

Other differences between military and police helmets are:

- Police helmets are designed for wearing for a short duration and hence are not designed for air flow between wearer head and helmet.
- Police helmets are padded to reduce energy transfer from bullet to skull.
- Police helmets have transparent face-shield.

The ballistic helmets for police can be tested as per National Institute of Justice (NIJ) Standard 0106.01. This Standard was revised in December 1981. Currently NIJ is working on a new draft for a test method.

As per the NIJ Standard 0106.01 ballistic helmets are classified as Type I, Type IIA, and Type II. There is no Type IIIA helmet specified by the NIJ Standard for police. One of the main reasons is the high energy associated with a .44 Magnum bullet. A number of scientists in the medical field feel that once the .44 Magnum bullet has stopped in the helmet, it will transfer the energy to human head and break the neck.

13.5.2 Law enforcement and police vests

Law enforcement and police vests (Fig. 13.7) are manufactured and sold as per the National Institute of Justice (NIJ) Standard 0101.04. This standard is classified into seven classes or types by level of ballistic performance. The ballistic threat posed by a bullet depends, among other things, on its composition, shape, caliber, mass, angle of incidence, and impact velocity. Due to the wide variety of bullets and cartridges, an armor that defeats a given bullet may not resist complete penetration by other bullets of the same caliber of different construction or configuration.

As per the NIJ Standard 0101.04, ballistic resistance body armor suitable for full-time wear throughout an entire shift of duty is available in classified Types I, IIA, II and IIIA, which provide increasing levels of protection from handgun threats:

13.7 Police vest, courtesy AHI.

- Type I body armor is the minimum level of protection.
- Type IIA body armor is for lower velocity 357 Magnum and higher velocity 9 mm ammunition.
- Type II body armor for higher velocity 357 Magnum and 9 mm bullets.
- Type IIIA provides the highest level of protection from high velocity 9 mm and 44 Magnum ammunition.

A number of high performance ballistic materials are available for these vests. These ballistic materials consist of aramid fibers, HMPE fibers and PBO fibers converted into woven and non-woven ballistic materials. Due to the availability of such a variety of ballistic materials, the majority of the vests manufactured and sold in the USA consist of at least two to three different ballistic materials. Generally such vests are hybrid vests and utilize the best performance of each material in a unique manner to increase flexibility and provide high ballistic protection and comfort.

Each police department has several choices when buying flexible vests. These choices can be summarized as:

- Economy vests, usually consisting of woven materials made with heavy denier fibers.
- Higher performance vests consisting of a combination of high tenacity woven

and non-woven cross-plied materials of either HMPE fiber or aramid fibers or PBO fibers.

- Highest performance vests consist of low denier woven materials and/or combination of more than one type of non-woven ballistic material of either HMPE fibers, or aramid fibers or PBO fibers.

13.5.3 Hand-held riot shields (HHRSs)

Hand-held riot shields are used by riot police all over the world (Fig. 13.8). The HHRS are designed to defeat bullets fired from handguns. There are HHRS that can also stop rifle bullets. The HHRS designed for stopping handgun bullets can be made with HMPE cross-plied material or made with woven prepregs of aramid and HMPE fabrics. Molding processes include hand-lay-up, autoclave and match-die molding.

Typical weight ranges of HHPE without handle, bullet resistant glass and attached spotlight are as follows:

13.8 Hand-held riot shield for police, courtesy Honeywell International Inc.

NIJ level	*Areal weight (psf)*
IIA	0.6–0.8
II	0.8–1.0
IIIIA	1.0–1.5
III	3.5–6.5
IV	6.5–7.5

In certain designs of HHRS, a thin metallic facing is bonded onto the front and back to increase the rigidity and paintability and to add flame resistance.

13.5.4 Bomb blanket

The bomb blankets are designed for skilled explosive disposal operators when confronted with a suspect bomb or improvised explosive device (IED) in a public area.

The bomb blankets are made of layers of ballistic materials enclosed into a heavy-duty, flame resistant, nylon cover with webbing as carrying handles. Some of the bomb blanket manufacturers also provide a safety circle made with layers of ballistic materials. The safety circles are designed to surround the explosive device thus eliminating any direct contact with the device and provide a safe environment for its examination and disposal. In case the IED explodes, the safety circle helps to direct the force of the explosion upwards, then the bomb blanket flexes and contains most of the explosive device fragments. Two or more safety circles can be used together to contain a larger IED.

Although the lightweight bomb blankets are made of multiple layers of ballistic materials, it can be folded up into a compact, easily carried bag. Further details are as follows:

- Ballistic materials: high tenacity woven or cross-plied aramid or HMPE fibers
- Construction technique: depends upon the type of ballistic material. For woven ballistic materials the layers are stitched using a pattern which helps to prevent drapability and foldability. For non-woven cross-plied materials stitching is limited to edges only.
- Size of bomb blankets: common sizes varies from 1.5 meters × 2.0 meters to 2.0 × 2.0 meters. Different sizes are available for covering vehicles and protection level.
- Weight: 10 kg to 15 kg.
- Protection level: V_{50} 17 grain Fragment Simulating Projectiles for a V_{50} from 400 mps to 600 mps.

Bomb blankets are also used for other applications such as in doors of police cars and other vehicles used by law enforcement and military personnel.

13.9 Pipe bomb 'Mitigator'.

13.5.5 Pipe bomb containment devices

Frequently law enforcement agencies are called to dispose of devices which are either pipe bombs or devices similar to pipe bombs. A number of containment devices (Fig. 13.9) are used to mitigate the blast from these devices and effectively arrest the fragments generated by the explosion. The devices to contain such explosions are made with lightweight composite prepregs such as cross-plied HDPE materials.

Mitigator is one such device designed for Royal Canadian Mounted Police bomb technicians. This device weighs about 70–100 lbs, is designed with HDPE ballistic material for containing fragments generated by 12-inch long by 2-inch pipe bombs containing 225 grams of black explosive powder.

The device can also be used in places, which receive pipe-bomb-type threats. The devices are robot friendly and incorporate other features such as wheels and handles.

13.6 Vehicle armor

Military operations are dependent on support from armored ground vehicles, cargo planes and helicopters. A number of vehicles take part in transporting soldiers, carrying supplies and ammunitions. Specially designed vehicles fire at the enemy along with armored battle tanks and military helicopters.

Current high performance ballistic materials used in armored ground vehicles are limited to spall liners inside the battle tanks to catch any spall generated when an enemy hits the vehicle. However, there is a major accord to develop lightweight, highly mobile, all composite load bearing armored vehicles with state-of-the-art ballistic materials. Such systems are in the early stages of design and evaluation for ground fighting vehicles, armored helicopters and other military planes.

This chapter will cover only limited armored vehicles which are currently used or in R&D stages and use limited or large quantities of high performance fiber-reinforced composites in critical performance areas.

13.7 Armored ground vehicles

13.7.1 Combat vehicle – Stryker

The Stryker (Fig. 13.10) is the first new armored combat vehicle to enter the US Army services since the introduction of Abrams main battle tank in the 1980s. The Stryker is more mobile and agile, has a great turning speed, has night visibility and improved instrumentation compared with existing US Army heavy Abrams M1-A1 and A2 battle tanks and the Bradley M2 fighting vehicle.

The Stryker deployed in Iraq, weighing 19 tons, has a range of 300 miles and a maximum speed of 60 miles per hour. A two-person crew operates which carries a commander and eight infantry troops or commandos, drops off soldiers and provides covering fire from its machineguns and grenade launchers. The vehicle is not intended for heavy combat, but it will get use in rapid-response policing missions.

Ballistic threats for Stryker

A range of high power rifle bullets and Rocket Propelled Grenades (RPG) are the main threats to the Stryker family of vehicles which are considered less vulnerable to small arms and weapons fire than the M113 family of vehicles. The crew and engine compartments of the Stryker are fully protected against armor piercing (AP) rounds. This is similar to the Bradley add-on armor that is appliquéd on top. And just like the Bradley armor, the Stryker vehicles do not drive around with it. If there is a situation that requires it, the unit deploys with it and applies it.

13.10 Stryker.

The Strykers are protected by armor sufficient to withstand heavy machinegun fire and overhead artillery fire. A strengthened undercarriage protects the personnel inside from mines.

Armor design

1. Exterior: Modular EXpandable Armor System (MEXAS) panels made with ceramic-faced woven aramid.
2. Roof interior: molded woven aramid reinforced composites.
3. Interior side: molded S2 fiberglass reinforced composites.
4. Slat armor cage to trap and defuse grenades.
5. A steel grill for stopping RPG entering the vehicle.

Testing of armor

The testing is conducted as a system, which includes the outer metal of the vehicle plus the composite armor.

13.7.2 HMMWV

The High Mobility Multi-purpose Wheeled Vehicle, better known by its 'HMMWV' acronym has been specially engineered to save the lives of passengers (Fig. 13.11). The wheeled vehicles are suitable for carrying soldiers in and out of cities without damaging street surfaces, and due to their high mobility, HMMWVs are used compared with other chain driven better armored vehicles. The Up-Armored HMMWV is recognized as one of the most advanced vehicles ever developed and delivers increased flexibility on the battlefield without compromising durability.

13.11 HMMWV armored doors, courtesy AHI.

13.12 Mounted Armored Doors on a HMMWV, courtesy AHI.

A large number of HMMWVs currently in service are not fully armored. However, ballistic kits are available for installation or removal in the field (Fig. 13.12). Utilizing the base HMMWV chassis, a number of HMMWV versions are available which can be armored for a specific military mission goal. Some of these versions are M1109, M1114, and M1116.

Ballistic threats

Multiple hits from a variety of high powered rifle bullets, plus anti-tank and ground mines are the main ballistic threats. The majority of armored HMMWVs are using hardened armor steel for armoring. Only a limited number of HMMWVs have high performance ballistic materials. However, an effort is being made by the US military to lighten the HMMWV considerably, by using high performance fiber-reinforced composites, such as fiberglass, aramid or HMPE composites.

13.7.3 Future combat system

In October 2002, United Defense Industries Inc. unveiled two ‘Future Combat System Vehicle’ prototypes at the AUSA trade show in Washington DC. Large sections of the vehicles are made with lightweight fiber-reinforced composite armored materials so that the C 130 cargo plane will be able to transport these vehicles. These vehicles will be fielded by 2008.

FCS-W

This armored vehicle uses new design material consisting of advanced hybrid structures that combine high strength aluminum, fiber-reinforced composites and ceramics for higher ballistic protection.

FCS-T

This vehicle system was originally developed jointly by UK and US. The vehicles weigh 16 tons and can be transported by C 130 cargo plane directly to the battlefield in any terrain without preparation. The hull of this vehicle is made with high strength aluminum, fiber-reinforced composites and ceramics, similar to FCS-W vehicles.

Other features

These vehicles incorporate a number of other features such as:

- ceramic-composite armor;
- increased ballistic protection;
- field-capable repair techniques;
- more than 35% weight saving over traditional metallic structure with armor.

13.7.4 Expeditionary Fighting Vehicle (EFV)

Since 1998 the Marine Corps has been working on an Expeditionary Fighting Vehicle (EFV) (Fig. 13.13). The EFV is a self-deploying, high water, fully tracked, nuclear, biological and chemical protected, armored personnel carrier.

The EFV is 336 inches long, 144 inches wide and 83 inches tall. Combat loaded, it weighs approximately 38 tons and has a cruise speed at sea of 20 knots, and 25 mph on land. The vehicle is targeted to be in service by 2006.

Armor protection objectives

- High-powered AP round.
- Heavy fragment protection from 15 meters.

13.13 EFV, courtesy Honeywell International Inc.

Armoring system

Ceramic faced lightest fiber-reinforced ballistic composites based on HMPE fibers.

13.7.5 Advanced Composite Armored Vehicle Platform (ACAVP)

The first European Armored Fighting Vehicle (AFV) represents the most revolutionary change in AFV materials since the introduction of aluminum in the early 1960s. The AFV has been developed by the Defense Evaluation and Research Agency (DERA) with its partner Vickers Defense System (Vickers). The AFV has a fiberglass reinforced epoxy hull rather than the traditional aluminum or steel hull.

The AFV composite armor was developed using epoxy resin from Ciba and fiberglass/epoxy prepreg from Hexcel. This composite armor system maintains and improves the survivability of lightweight AFV structures. Assembly was done at the Vickers plant in Leeds, UK.

The ACAVP hull has molded E-glass epoxy composite by Vosper Thornycroft. The composite hull is one of the largest and thickest moldings of its type ever produced. Up to 70 plies of fiberglass reinforcement were laid in some of the thickest sections.

Ballistic materials for ACAVP

The composite armor design not only increases ballistic protection against small arms and larger threats, but also reduces ‘behind the armor’ damage inside the vehicle leading to increased crew survivability.

Weight and speed of ACAVP

The FRP composite hull weighs about 6 tons (13,230 pounds) and the entire vehicle battle weight is around 24 tons and a maximum speed is around 75 kph.

Other benefits

Other composite materials’ benefits include:

- corrosion resistance in wet and salt water conditions;
- reduced RADAR signature;
- stealth feature possible;
- reduces thermal signature;
- lower acoustic signature;
- easy to machine;

- ease of maintenance;
- reduced noise levels, both inside and outside the vehicle.

DERA scientists are confident that future weight savings are achievable for future vehicles based on the continuing research into new materials and design methods.

13.7.6 Armored helicopters

Armor protection is required on the bottom of helicopters against ground fire from small arms. As the fuselage of helicopters needs to be light, the bottom portion is generally vulnerable to small arms fire from the ground which puts the occupants at risk. Lightweight armor for the bottoms of helicopters has been in use for a number of years. The armors are generally installed on the interior of aircraft, however, due to the lower speed of helicopters, armor can be installed on the exterior of the craft (Fig. 13.14).

Certain Russian helicopters have been constructed with armor along the interior floor. Such interior installations have the disadvantage of being difficult to install and remove in view of the structure along the floor of the helicopter as well as the helicopter seats, which have to be removed each time the armor is installed and removed.

Ballistic threat for helicopters

- 30 caliber Fragment Simulating Projectile.
- 50 caliber (12.7 mm) armor piercing M2 projectiles.

Armor design for helicopters

Depending upon the ballistic threat and weight limitation on helicopter design the armor can consist of:

13.14 Armored helicopter, courtesy Honeywell International Inc.

- High pressure-matched die-mold-shaped armor consisting of monolithic molded plates of cross-plied HMPE.
- Ceramic faced armor with following construction:
  - monolithic or small tiles of boron or silicon carbide ceramic;
  - an adhesive layer;
  - molded backing consists of cross-plied HMPE armor material or molded woven aramid prepreg.

Helicopter armors are typically constructed from a one-piece molded aramid or HMPE composite with boron carbide tiles either using an autoclave or high pressure match-die molding process. Each component is finished with a covering of durable nylon fabric that suppresses spall during ballistic impact.

Armor testing

The molded hard armor panels are tested as standalone hard armor for a V_{50} test as per MIL-STD-662F.

Other requirements

Helicopter armor is tested for the following before being installed onto a helicopter:

- durability;
- extreme temperature (−) 50 °C to (+) 65 °C;
- altitude test;
- fluid resistance;
- ozone resistance;
- weather resistance;
- vibration resistance;
- sand and dust.

13.7.7 Armored helicopter crashworthy seats

The armored seat of a helicopter is designed to protect military and civilian aviators and passengers (Fig. 13.15). A wide range of lightweight fiber-reinforced armor crashworthy helicopter seats incorporate energy attenuation systems that greatly increase the seat occupant’s chances of surviving a crash. Modern helicopter structures are designed to absorb some impact forces and prevent collapse of the cabin. However, the loads transmitted to the occupants may still exceed physiological tolerance levels.

Helicopter pilot seats can also be provided in unarmored or armored versions, the seat buckets can protect the occupant from multiple hits of rifle bullets and armor piercing projectile impacts.

13.15 Armored helicopter seat, courtesy AHI.

Construction of seat

The armored crashworthy crew seat consists of an armored seat bucket mounted on a light alloy support frame. The seat is designed to suit the crew station into which it will be installed and can be fitted with adjustable panels to provide additional side protection.

Crashworthy requirements

The armored crashworthy seat for the battlefield helicopter pilot and weapons system operator is designed to meet the requirements of crashworthy specifications FAR/JAR part 29 or MIL-S-58095 and the flammability resistance of FAR part 25.853(b).

The energy attenuation system is designed to attenuate a 50 g crash pulse to only 20 g transmitted to the seat occupant.

Ballistic threat

The armored crew seat is intended for protection against large armor piercing M2 projectiles. This lightweight armor is the standard protection specified by the majority of battlefield helicopter operators.

Ballistic materials

Ballistic materials for helicopter seats can consist of:

- High pressure-matched die mold-shaped armor consisting of monolithic molded plates of cross-plied HMPE, or
- Ceramic-faced armor with the following construction:
  - monolithic, boron or silicon carbide ceramic;
  - an adhesive layer;
  - molded backing consisting of molded woven aramid or HMPE prepreg.

Fabrication of helicopter seats

Helicopter seats are typically constructed from a one-piece molded aramid or HMPE composite with boron carbide tile using an autoclave. Seats are finished with a covering of durable nylon fabric that suppresses spall during ballistic impact.

Other requirements

The helicopter seats are required to meet other environmental requirements listed in the military standard MIL-STD-810. This includes vibration, sand and dust, shock, salt fog, humidity, hot and cold temperature and static loads.

The crew seat provides a safe and comfortable sitting platform during normal flight operations and helps protect the crewmember from impact accelerations and fire from enemy guns. The armored crew seat is easily adapted for installation in any helicopter cockpit, giving excellent all round protection.

13.7.8 Puma helicopter

In 1987, the Swiss Air Force ordered three Super Puma helicopters to increase the aerial transportation. With this, first experiences in the fields of operations and maintenance could be gathered and operational concepts were worked out. The twin engine Super Puma is equipped for instrument flight and is suitable for many military and civilian purposes (e.g. disaster relief). In case of emergency and crash landing, the Super Puma is equipped with modern safety and security features providing better protection for the two pilots who fly it for the passengers.

The 1998 Puma armaments program was created to design armored Pumas for peacekeeping and other military operations. A number of companies in Europe, the UK and the US can armor Super Puma helicopters. A removable armor is desirable for Puma helicopters. A number of techniques are used for quick and easy installation of armor panels into the helicopter without drilling holes in the helicopter flooring.

The ballistic panels of Puma helicopters are capable of protecting against multiunit bullet capability. A typical armor aerial density for stopping large caliber Fragment Simulating Projectiles and rifle bullets varies from 5.5 psf to

7.5 psf, depending upon type of ceramic, type of backing and process of manufacturing the ballistic panels.

Ballistic threats for the Puma

Multiple hits from a variety of high power rifle bullets.

Armor design for Puma helicopters

Panels are fabricated by cutting a large molded panel, assembling ceramic tiles on the panel, and then cutting with a water jet cutter to fit the shape of the panel.

The type of ceramic is silicon carbide, or boron carbide. The size of tile is usually 100 mm × 100 mm × 4 mm or 100 mm × 100 mm × 6 mm. The backing materials are cross-plied HMPE ballistic material, or woven aramid/phenolic prepreg ballistic material. Typically weight is increased due to armor and at 32 ksm areal density is as follows:

- cockpit floor: 42 kg;
- cabin floor: 155 kg.

13.7.9 C 130 Cargo gunship airplane

The C 130 Hercules, a four-engine turboprop aircraft, is the workhorse of the military (Fig. 13.16). Capable of landing and taking off from short, rough dirt runways, it is a people and cargo carrier and is used in a wide variety of other roles, such as gunship, weather watcher, tanker, firefighter and aerial ambulance. There are more than 40 versions of the Hercules, and it is widely used by more than 50 nations.

Background

Deliveries of the C 130A to the US military began in December 1956 and the first B models in April 1959. The newest is the H model. A number of C 130 cargo airplanes are armored and typical threats for C 130 are multiple hits from a variety of high power rifle bullets.

Armor and kit system for C 130

Ceramic-faced lightweight armor systems are used to armor the C 130 aircraft. A number of companies in the US and UK supply ceramic armor seats, components and panel systems for the C 130. The floors of the C 130 are equipped with ceramic armor to protect personnel from ground fire. C 130 armor kits include protection for the flight deck, crew seats, galley, radome, liquid oxygen bottle, and paratroop doors.

13.16 C 130 gunship, courtesy Honeywell International Inc.

Armor threats for C 130

The C 130 gunship panels are designed for multihit projectile capability. A typical armor areal density for stopping large caliber fragments and rifle bullet protection varies from 5.5 psf to 7.5 psf, depending upon type of ceramic, type of backing and process of manufacturing the panels.

Armor design for C 130

Large armor panels are molded in an autoclave. For the smaller components panels are fabricated by cutting a large molded panel, assembling ceramic tiles on the panel, and then cutting with a water jet cutter to fit the shape of the component.

The type of ceramic is silicon carbide, or boron carbide. The size of tiles are usually 100 mm × 100 mm × 4 mm or 100 mm × 100 mm × 6 mm. The backing materials are cross-plied HMPE ballistic material, or woven aramid/phenolics prepreg ballistic material.

The armor floor kits for C 130 gunships are removable and have modular add-on integration features for damage resistance and full environmental conditions.

13.7.10 Armored ballistic kits for aircraft

Cockpit and floor systems are commercially off-the-shelf and available for modular add-on cockpit and floor armors for aircraft such as the MH-47 Chinook, MH-60 Blackhawk and UH1H Super Huey. A number of armor molding companies offer custom armor kits tailored to specific threat and multiple hit requirements. The armor kits (Fig. 13.17) are lightweight with integration features for damage resistance and full environmental durability and

13.17 Armored parts of vehicles, courtesy AHI.

are designed for specific threats and are generally transferable from one type of airplane or helicopter to another. The joints of kits are designed in such a manner that the ballistic threat will not penetrate through the joint. This feature is designed by the overlapping of armor and by using the ballistic performance of the metal structure where the armor panel is bolted down.

The armor kit panels are designed for multi-hit projectile capability. A typical armor areal density for stopping large caliber fragments and rifle bullet protection varies from 5.5 psf to 7.5 psf, depending upon type of ceramic, type of backing and process of manufacturing the panels.

Ballistic threats

Typical ballistic threats for removable of ballistic panels are multiple hits from large caliber fragments and high energy rifle bullets.

Armor design

Large armor panels are molded in an autoclave. The smaller panels are fabricated by cutting a large molded panel, assembling ceramic tiles on the panel, and then cutting with a water jet cutter to fit the shape of the panel.

The type of ceramic is silicon carbide and/or boron carbide. The size of tiles are usually 100 mm × 100 mm × 4 mm or 100 mm × 100 mm × 6 mm. Backing materials are cross-plied HMPE ballistic material, or woven aramid/phenolics prepreg ballistic material.

13.7.11 Armored police and civilian vehicles

Increasing numbers of vehicle-related shootings have created a need to armor cars and vehicles. High profile individuals in business and government agencies need armored vehicles that can provide high mobility at maximum bullet resistance. Traditional steel armor of such vehicles provided the bare minimum protection with several fold increase in weight. The steel-armored vehicles are fairly heavy and therefore the entire engine and suspension system must be changed to accommodate the weight increase. This reduces the comfort during vehicle turning and also reduces the speed of the vehicle.

Vehicle armor weight

Table 13.1 shows the weight of armor on a vehicle for both transparent and opaque armor. State-of-the-art lightweight fiber-reinforced armor systems based on HMPE and aramid fibers are extremely light compared to steel armor and provide equivalent bullet resistance against the type of bullets which are normally encountered in a city. The weight of the vehicle after armoring with molded HMPE fiber armor system is the lowest compared to any other armor system. There is no need to change the engine or suspension system. Thus, after armoring a vehicle with HMPE the vehicle maintains its original comfort and mobility in an ambush situation (Fig. 13.18).

When using a lightweight armoring system it is easy to upgrade the vehicle for higher bullet resistance if the perceived ballistic threat is increased. Moisture, chemicals, heat, cold and a host of other environments do not affect the lightweight armor systems. The armored vehicles are designed for a number of bullets including 9 mm FMJ, 357 Magnum, 44 Magnum, AK-47, NATO ball, armor piercing bullets and a host of sniper bullets.

Table 13.1 The weight of both transparent and opaque armor on a vehicle

Material	Armor weight (kg)	
	9 mm FMJ	AK-47
Transparent armor 3.25 sq. meter	87	168
Opaque armor 4.18 sq. meter		
Steel	102	146
Woven aramid/phenolics	33	123
Spectra Shield®	20	77

13.18 Armored police and civilian vehicle, courtesy BMW.

Armoring requirements

The following requirements should be discussed with the armoring company before ordering an armored vehicle:

- area to be armored;
- threat level;
- handling characteristics;
- vehicle performance requirement;
- braking modifications;
- approval requirements;
- ergonomics considerations;
- other requirements.

Area for armoring a vehicle

Front
A post
Trunk
Fuel tank
Fuel lines
Hood
B post
Seat back
Brake lines
Header B/L
Radiator
C post
Doors
Air lockouts
Header W/S
Firewall
Roof
Floor
Electric
All transparent area
Roof rails
Door lock pillars
Door hinge pillars

13.7.12 LCAC (landing craft, air cushion) fleet

The landing craft, air cushion (LCAC – pronounced Ell-Cack) transport weapons systems involve equipment, cargo and personnel of the assault elements of the Marine Air/Ground Task Force both from ship to shore and across the beach. The landing craft, air cushion (LCAC) is a high-speed, over-the-beach fully

13.19 Landing craft, air cushion.

amphibious landing craft capable of carrying a 60–75 ton payload (Fig. 13.19).

The current armor system on the LCAC is an aramid system, weighing 13 psf. However, new armor systems based on HMPE materials with boron carbide ceramic can meet the target armor weight of 9 psf. The new armor is capable of defeating the 50 cal tungsten carbide core round.

13.7.13 Armored hovercraft

Typical weight of molded armor panels for stopping rifle bullets at NIJ Level III is 18.5 kg/sq.m, and for Level IV, it can go as high as 32 kg/sq.m, depending upon the type of ceramic and type of bullet.

13.8 Website references

Honeywell	www.spectrafiber.com
Teijin	www.twaron.com
DSM	www.dsm.com
DuPont	www.kevlar.com
Ceradyne	www.ceradyne.com
Saint-Gobin Ceramics	www.ceramicmaterials.saint-gobain.com
CoorsTek	www.coortek.com
Cercom	www.cercominc.com
Armor Holding Inc.	www.armorholdings.com
O'Gare-Hess & Eisenhardt	www.armorholdings.com/mobile/ogara.html
Point Blank	www.pointblankarmor.com
Ares Protection	www.aresprotection.com
Raibentex	www.rabintex.com
Plasan SaSa	www.plasansasa.com
ArmorWorks	www.armorworks.com
Composiflex	www.composiflex.com

14

Ceramic-faced molded armor

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14.1 Introduction

The investigation and application of ceramics against ballistic threats has a long history. Ceramic composite armor systems were first designed to defeat lead core bullets and later armor piercing (AP), kinetic energy projectiles. Over the last fifteen years the increasing use of ballistic ceramics to protect against small arms ammunitions (rifle, up to 14.5 AP) and larger calibers (from 20 mm canon) is due to their great potential for innovations. The two main reasons are the ballistic mass effectiveness and the price. Indeed ceramic materials are capable of displaying significantly better protective performance than an equivalent weight of metal armor. Besides ceramics allow the use of cheap backings like glass fiber or standard armored metals (steel, aluminum) and therefore result in relatively cheap concepts.

Ceramic materials which can be used in different shapes (tiles: squares, rectangles, hexagons, . . . and monolithic plates only for personal protection) can be bonded onto other composite backings made of high performance polyethylene, aramid fibers for instance.

During impact the penetrator fractures and breaks on the surface of the ceramic, the high compressive strength of the ceramic overmatches the loading produced by the penetrator impact, and the penetrator material flows and shatters. The backing catches the fragment and controls the blunt force trauma caused by the projectile.

However, ceramic concepts suffer from several drawbacks, chief of which is their fragility against shocks and vibrations. This fragility is being solved thanks to the evolution of the process, designs and improvement of fiber performances.

Nowadays the need for protection is a matter of increasing importance. Battlefield threat levels still increase (use of AP ammunitions and less lead core) and as a consequence directly influence the choice of ceramic protection. Ceramics, therefore, still play a significant role in the ballistic market.

This chapter shows how ceramic armors have overcome their weakest points, and the adaptability to each specific requirement in the fields of personal protection or vehicle protection. Indeed, for a similar threat level, each application has different environmental constraints which means that ceramic armor design must be flexible to adapt.

14.2 Type of ceramics

Numerous types of advanced ceramic materials are currently available and are manufactured from man-made materials rather than from naturally occurring materials. This is because the desired properties are not available in natural materials, and the complex processing requires the raw materials' properties to have very close tolerances. Consequently it is often necessary to use additives such as polymers. It is important to bear in mind that the term 'advanced' does not pertain simply to the material, but rather to the combination of material, process, product, and application.

Actually several processes exist such as high pressure, sintered, reaction bonded processes and have a significant influence on the final properties. The process must be well controlled to assure good and consistent ballistic properties. The several processes are generally divided into the lower cost sintered ceramics and the higher cost hot pressed ceramics. The higher cost ceramics are justified when the lowest areal density is the main criterion (boron carbide, silicon carbide for instance). Alumina can be used when the price and not the weight is the limiting parameter.

A basic description of properties of the most common ceramics in use for lightweight ballistic application has been realized. The aforementioned conditions indicate some differences between advanced ceramics. Thus it has been preferred to give a pragmatic description of the ceramics' final properties within the ballistic application rather than a scientific description of the intrinsic mechanical properties which vary a lot from one manufacturer to another.

14.2.1 Aluminum oxide

Up to now ceramic made of aluminum oxide (Al_2O_3) has been the most 'popular' ceramic product because of its excellent performance:cost ratio (Table 14.1).

Aluminum oxide ceramic material has good ballistic properties, it is used from small 5.56 calibers up to heavy calibers (35 mm–105 mm APFSDS). As mentioned above adjuvants can be used to upgrade ceramic mechanical properties (Zirconia).

This is the less fragile and the cheapest advanced ceramic material, which is of great importance for most applications, but has one main disadvantage, weight. It can be produced in a large number of shapes via compression molding or pelletization, mainly.

Table 14.1 Aluminum oxide properties

Average density	(g/cm^3)	3.6–3.9
Alumina content	%	90–99
Water absorption	%	0
Hardness Vickers	MPa	1200–1500
Fracture toughness	MPa m1/2	3–5
Flexural strength	MPa	330–380
Compressive strength	MPa	≥ 2000
E-modulus	GPa	270–370

Table 14.2 Silicon carbide properties

Average density	(g/cm^3)	3.1–3.3
Water absorption	%	0
Hardness Vickers	MPa	2000–2600
Fracture toughness	MPa m1/2	2–5*
Flexural strength	MPa	≥350*
Compressive strength	MPa	≥ 2500
E-modulus	GPa	≈380–450*

* Depends on the manufacturer or process

14.2.2 Silicon carbide or nitride

This type of ceramic is more and more selected for slightly lower weight applications. The average mechanical properties for such ceramics are shown in Table 14.2.

Remarks about SiC

Silicon carbide is produced in two main ways. Reaction bonded SiC is made by infiltrating compacts of relatively coarse silicon carbide powder often containing a carbon binder with molten metal in a vacuum furnace. The metal used is often silicon which reacts with the carbon forming SiC. Sintered SiC is produced from pure SiC powder with non-oxide sintering aids. Conventional ceramic forming processes are used and the material is sintered up to 2000 ºC or higher.

Remarks about SiN

Silicon nitride is produced in three main types: reaction bonded silicon nitride (RBSN), hot pressed silicon nitride (HPSN) and sintered silicon nitride (SSN). RBSN is made by direct reacting compacted silicon powder with nitrogen. HPSN and SSN materials offer better physical properties suitable for more

Table 14.3 Boron carbide properties

Average density	(g/cm^3)	2.4–2.5
B_4C content	%	98.5–99.5
Water absorption	%	0
Hardness Vickers	MPa	≈ 2800–3200
Fracture toughness	MPa m1/2	≈ 2.5–3
Flexural strength	MPa	≈ 400–420
E-modulus	GPa	≈ 450

demanding applications. As with aluminum oxide ceramic many shapes are available.

14.2.3 Boron carbide

The average mechanical properties for such ceramics are shown in Table 14.3.

Boron carbide B_4C is the third hardest material known to man after diamond and cubic boron nitride. It is a lightweight material but it suffers from a high fragility. Besides B_4C is a very expensive material.

14.3 Shape of ceramics

14.3.1 Flat tiles

Squares, rectangles, hexagons are part of flat tiles. Their sizes usually start from 20 × 20 mm up to 200 mm length or larger rectangles. Pressing flat tiles usually confers a greater homogeneity in the mechanical performance. Joints between tiles are the weakest points.

Thin and thick tiles

The size of thin tiles is reduced by the logical weakness linked to the thickness. A thin tile (3–4 mm) can be manufactured according to the size of inserts (10 × 12″) approximately, but keeping in mind its extreme fragility during storage, handling and during the lifetime of the insert, even when backed with composites.

Thick tiles can be manufactured up to 100 mm or more, even in large dimensions (300 mm side rectangles), for a heavy caliber threat. In such case the thickness makes it more difficult to obtain a homogenous mechanical behavior.

Small, large and monolithic tiles

The shape of the ceramic, but mainly the surface of each ceramic component has a predominant effect on the performance. The larger the ceramic is, the higher the absorption energy by the ceramic and the lower the backface energy absorption.

On the other hand, the larger the ceramic tile, the lower the multiple hit is. The mechanical behavior against low speed shocks is also weaker.

Small tiles of 20 mm width are of more interest when the best multiple-hit capabilities are required. Indeed ceramic is destroyed on a smaller surface and therefore it reduces the crack spread but reduces the energy absorption. As a consequence a lower weight efficiency is achieved since the backing must be heavier and must have better performance to absorb the remaining energy. One traditional solution to keep optimized weight efficiency consists of placing a spacer, the aim of which is to minimize the ammunition fragment penetration power, into the backing, between the ceramic and the backing.

On the other hand, large tiles are mainly useful for heavier calibers starting from 20 mm and up to 105 mm caliber. The largest tile is preferred in order to reach the largest energy absorption in the ceramic. The reduction of multiple hit properties is important but the precision of such weapons, and also the shooting distance, does not obviously require the armor to perform with distances under 300 mm.

The term ‘monolithic tiles’ is mainly used for personal protection. In such a case the thickness is very much reduced compared to the width and length. This directly leads to a more fragile behavior that must be balanced by using a suitable backing.

The regularity of the shape and tolerances of the ceramic is also crucial for the best bonding conditions, allowing the best ballistic performance of the ceramic.

In any case the know-how of the ceramic manufacturer is a key factor in order to insure the good dimensional and mechanical homogeneity of the ceramic.

14.3.2 Shaped ceramic

As described above several ceramic shapes exist on the market, square tiles, hexagonal tiles (flat or curved), balls, cylinders, and so on. Some have been designed for specific weight, ballistic or mechanical reasons, some for marketing reasons, without really bringing clear advantages in the final properties. Every application has specific requirements, and the use of shaped ceramic can solve several issues like the multiple-hit or complex 3D shape and high shock resistance.

Balls

Tiles and pellets absorb energy differently during impact.

For a given thickness, the sphere permits a theoretical reduction by 50% of the weight of the referenced tile. In reality, even if the use of balls helps to deviate the bullet quicker, the ball thickness must be larger by approximately 30% to compensate for the lack of ceramic in between balls. Some concepts also suggest the design of multiple layers, usually not more than two. But weight and cost efficiency of such systems has never been proven.

Cylinders

Cylinders, usually positioned vertically, but also horizontally, show similar properties to balls, because they still show a lack of ceramic between the ceramic components that cannot participate in the energy absorption. However, cylinders have a better compression strength and show, in several cases, better ballistic resistance.

Balls and cylinders belong to the pellet's shape range. As shown below they suffer from one main drawback which is the weakness in between the pellets where there is an obvious lack of ceramic.

So far improved design of the backing is the best way to solve this defect (use of advanced fibers for instance).

Multi-curvature

Monolithic multi-curved tiles can be used in small sizes (50 × 50 mm) or more conventionally in larger plates for inserts in sizes of 250 × 300 mm approximately.

The ceramic plate can be shaped under pressure or by simple gravity. The control of the internal stresses and shrinkage during the firing process is important to keep good dimensional properties and the most reliable and homogenous mechanical structure.

Multi-curved monolithic inserts are certainly the most popular ceramic armor for personal protection since the process does not require expensive machines (autoclave), and the weight efficiency is best when the bonding and backing are well designed. Nevertheless, relative mechanical fragility remains the main weak point, reducing considerably the lifetime of such a product.

Several manufacturers also produce ceramic inserts, with a thicker ceramic element in order to bond a backing of only a very few fabric plies. Thus, offering the lowest cost, but also the most fragile product, which would, theoretically, need to be replaced shortly after use. Several armies now estimate that 50% of their stock must be replaced after use, or after storage only.

14.4 Backing lightweight composite materials

As explained earlier, the backing is the second key component, which allows the ceramic to reach its optimum mechanical performance. Synthetic fibers are usually the only choice for backing lightweight structures, because of their light density, excellent mechanical properties, and because they are relatively easy to process they follow most of the required shapes. Their price range varies significantly, with fiberglass being the cheapest and HMWPE fiber the most expensive but with highest performance (approximately ten times the price of fiberglass).

However, the choice of one backing is highly dependent on the threatened penetration power. Indeed, a very lightweight 5.56 or 7.62 design based on ceramic, backed with composite fibers, does not conform to the same lightweight concept for defense against heavier threats of 20–30 mm.

14.4.1 Fiberglass

Fiberglass is the fiber with the lowest mechanical properties, but is also by far the cheapest. E-glass and S2 glass are the main two qualities. S2 glass' mechanical and ballistic properties are closer to aramid, at slightly lower cost. In most cases the choice of fiberglass is linked to a specific need for stiffness, complex curvature, in combination with high humidity constraints. When used alone, the fiberglass ballistic weight properties are close to steel, but it offers less stiffness, and a higher price.

Regarding ceramic armors, a proper ballistic steel or aluminum often exhibits better mechanical advantages to support the ceramic than fiberglass, the stiffness of which is lower. Since high rigidity behind a ceramic enhances its ballistic behavior, composites are not always the best solutions to support ceramics.

However, fiberglass still finds a place in the finishing of panels, because it can adopt complex shapes, minimizing weight and complexity compared with welded thin metallic sheets.

14.4.2 Woven aramid fabrics

One clear advantage of woven designs is their ability to stop fragments. Aramid fibers exhibit high mechanical properties. Fibers with different tenacity and count are used, from 400 dTex for the best performance, up to 3400 dTex, for the less weight-stringent applications. Axes of 0/90° have always shown best ballistic properties, in spite of all the work which has been done with multi-axial techniques, and woven aramid fibers are most probably one of the most used fabrics for ceramic backings. Indeed such fabrics combine high ballistic properties with a relatively low weight and rather good rigidity. Furthermore their good anti-trauma behavior is also one reason to chose them, compared with PE-based fabrics, which show a lighter areal density, but larger trauma.

However, it is important to point out that 100% aramid woven has difficulty stopping rifle ammunition (5.56 and 7.62 Nato Ball). When used as a ceramic backing the aramid woven fabric behaves like a fragment net, since the ceramic destroys the ammunition and the backing catches the remaining fragments. This is related to the properties of the weave and the fiber.

14.4.3 HPPE woven fabric

In the last three decades, significant progress has been made in exploiting the intrinsic properties of the macromolecular chain of polymeric fibers with regard to ultimate mechanical properties. HPPE has taken an important part in these developments. HPPE fiber has better mechanical properties than para-aramid fibers and a low areal density.

However, as surprising as it may be, 100% HPPE fabric behaves like aramid fabric. Indeed HPPE wovens have not shown any significant advantages over aramid wovens: ballistic performance remains similar for a higher cost. Furthermore, impregnated HPPE wovens are less rigid and do not support the ceramic strike face so well.

But HPPE wovens show interesting properties in specific cases where weight and humidity absorption are crucial. HPPE wovens also exhibit good performance when used as thick spall liners, without any ceramic.

14.4.4 HPPE unidirectional (shield)

Unidirectional (UD) (0/90º) is a construction in which the yarns are not woven but lie parallel to each other. HPPE fibers (Spectra®/Dyneema®) are embedded in a resin. Different resins are used: rubber-based resin (elastomer) which leads to a soft composite, or PUR-based for a rigid composite. It is important to point out that HPPE fibers are temperature sensitive (melting temperature around 140 ºC but such composites start to soften above 50–60 ºC). This is why new shields with stiffer resin systems, and which are less sensitive to temperature variations, can help to obtain the best compromise.

At present such configurations give the better weight:performance ratio against several threats (this is the only solution which can stop rifle bullets like 7.62 M80 or 7.62 AK-47 with 17 kg/m). Indeed low weight is the main quality of such unidirectional concepts (Spectra®/Dyneema®).

On the other hand, several defects should be highlighted such as the poor mechanical resistance at high temperatures. These mechanical properties are crucial when UD is used as a ceramic backing, since the ceramic support stiffness is one key to achieving good ballistic performance.

Ceramic/composite: (general – for HPPE and Aramid concept)

Ballistic protection made with ceramic and composites have the advantage of being lighter than steel (usually 2–3 times lighter). They should not lose this advantage by having properties that are too fragile and which might make them lose the main reason for their design: protection.

14.4.5 Cross-plied aramids (molded gold shield type)

Unidirectional made of aramid fibers exists too. But used as ceramic backings they have not reached the same level of performance as HPPE UD.

However, one should bear in mind that composites made of ceramic and aramid backing are too recent to draw firm conclusions. Indeed, they have been initially designed for soft armors (vests against handguns) and have only recently been associated with stiff resin systems for vehicle and ceramic backings applications.

14.5 Fabrication of ceramic-faced armor

Basically two main processes for the assembly of the ceramic and the backing exist:

- with an autoclave (under 3–20 bars); and
- with a press (under 3 to 100 bars pressure or more).

The autoclave process is suitable when bonding the backing on multi-curved ceramics, because the pressure is well spread on both faces of the composites and thus prevents the ceramic from cracking under pressure. The press is suitable for large or small flat plates and curved ones. This process requires expensive tooling like a pressing mold, whereas the autoclave process only needs simple tools.

Both these processes use a combination of pressure and temperature. Pressure can influence the backing performance, in particular for an HPPE shield, where ballistic properties are related to pressure. The temperature usually stands between 120 and 150 °C, and the cycle time lasts about one hour, depending on the thickness and the cooling–heating ramp if necessary.

The main problems to watch carefully for during the assembling process are:

- ceramic plate damage;
- ceramic displacement which creates gaps between ceramic tiles;
- good contact between the ceramic and backing which must be as consistent as possible (with the use of a suitable resin for instance).

14.5.1 Personal protection

Ceramic is widely used for personal protection because not only does it permit significantly reduced costs (compared to a 100% fiber systems using HPPE fibers) but it also has the capability of stopping armor piercing ammunitions with a relatively light weight. Indeed, ceramic can break the steel core bullet tip which a 100% fiber system will not.

However, when used for personal protection a ceramic strike face suffers from one major disadvantage which is its shock fragility and therefore its low multi impact capabilities. The manufacturers' know-how allows improvement in the ceramic shock resistance and multi-hit capability by using suitable backing and bonding processes.

Ceramic-faced hard molded armor backing

Essentially, the ceramic face consists of either a monolithic plate or multi-ceramic tiles that are assembled to form a flat, single or multi-curved shape.

It should be pointed out that the ceramic component size considerably affects the fracture behavior of both the ceramic system and the ammunition. Indeed, the larger the ceramic size, the higher the amount of energy absorbed by the ceramic and consequently the lower the amount of energy absorbed by the backing.

Besides, the more the ceramic absorbs the bullet's kinetic energy and thus damages the ammunition, the more the cracks appear over a large area. This is why over-designing the ceramic thickness permits the addition of an extremely limited number of composite fiber plies, but significantly reduces the multi-hit ability, and more importantly, turns the armor into a very brittle form of protection, which might not ensure the required performance when needed.

Therefore multi-tile configurations (small square, hexagons, tiles or pellets) usually show better multi-hit performances since the crack propagation is geometrically controlled by the size and shape of the ceramic components. However, as pointed out above, small ceramic tile-based plates absorbs less energy than larger tiles but exhibit better multi-hit properties. In addition, such small tiles can move during pressure loading which results in an improved shock protection.

Of course, tile size is linked to threat. The more powerful the ammunition is, the larger the tile. On the other hand the loss of energy absorption by the ceramic must be balanced by using a higher amount of backing content, the aim of which is to absorb the remaining energy. One should notice that the backing quality is a major parameter that must be well controlled too. Consequently the total areal density of the concept usually increases.

In other words using small ceramic tiles leads to:

- increase of shock protection;
- increase of the multi-hit capability;
- increase of backing content; and
- increase of weight.

As explained above there is no 'best armored material'. Every lightweight advanced component, ceramic or fiber, suffers from one of several disadvantages which must be balanced by using other components:

- B_4C is a very lightweight ceramic, but the most fragile, and the most expensive.

- PE is the lightest fiber, but sensitive to temperature and deformation.
- Aramid fiber shows an interesting weight versus cost compromise, but does not offer the best protection against high speed lead core ammunition.
- Monolithic ceramics offer the best absorption energy, but are fragile.
- Ceramic pellets offer the best multi-hit and shock protection, but overall a weight increase.

Ceramic-faced flexible armor backing

Over the last few years developments of flexible/bendable armors have become a matter of high interest. Several concepts exist but apparently have not been certified or are not widely available. At the moment the only commercially produced concept is named CeraFlex®. CeraFlex® armor is based on current advanced ballistic materials but with a flexible interface between the ceramic and backing that enables it to reach a better balance between weight/realistic shock protection/multi-hit/cost. It is made of multiple ceramic tiles for the strike face which are bonded onto an appropriate flexible interface support, and backed with ballistic fibers like aramid, PE or glass fibers or a metal structure (armored steel or aluminum).

This bendable/flexible technology has been tested according many standards, among others the NIJ Standard 0101.04 norm: ‘Ballistic resistance of personal body armour’. The performance improvement of fibers and ceramics should pave the way to further new developments and performance enhancement of such armors. No real interest in flexible armor for vehicles has yet been shown since not only must the kinetic energy be reduced, but also deformation in the event of blast.

Ceramic-faced helmets

Ceramic-faced helmets come to the same point. A helmet is an armor which must be designed to stop the defined threats (usually fragments), but must also be strong enough to withstand the shocks and the loads during everyday missions. Shaped monolithic tiles have been designed by some ceramic manufacturers to fit the front and the backfaces of helmets. In most cases the aramid fabric, which the helmet is made of, is the backing of the ceramic add-on. Once again, such monolithic tiles can stop the ammunition, if this fragile monolithic has not been broken before (by a shock during a previous mission, for instance).

The flexible ceramic concept made of multi-component ceramics can once again meet this gap and thus provide a good response. Nevertheless, adding ceramic to a 1 kg (2 lbs) helmet, is obviously creating additional load, more than twice the initial weight, which can only be suitable for short missions, with a high threat level.

The use of a PE shield helmet with high stiffness resin is certainly the best way to maintain acceptable weight for the helmet, while increasing the protection level up to rifle ammunition. This type of concept has already been manufactured in very limited scale.

The biomedical consequences have been studied by several doctors, but no clear statement regarding this increased protection level for the head could be made yet. It is believed that it is better to reach the highest protection level for a given weight, because this always gives a better chance for the wearer to be protected, especially with helmets, the round shape of which frequently offers an angled surface to the threat, thus significantly reducing the kinetic energy to be absorbed.

14.5.2 Vehicle armor

Most of the vehicles are already equipped with ceramic strike face armors, from lightweight 4 × 4, trucks, APC, up to IFV. The protection offered by the ceramic armor design depends highly on the projectile and its associated energy.

Ground vehicles

The multiple threats to protection are well described in the Stanag 4569. Usually 20 mm caliber up to 30 mm APFSDS represent the main threats for IFV and APC. For main battle tanks, the presence of ceramic is more confidential, and not always necessary. The mechanical behavior of kinetic energy projectiles is based on thin rods made of non-brittle tungsten alloys (1300 m/s) or similar heavy metals (uranium range) whereas shape charges (RPG7 range) consist of a high speed copper jet (4–7,000 m/s).

The ceramic-faced armors are indeed showing their best efficiency in the first case, but not against the shaped charge, which requires multi-layer material to deviate the jet, when considering passive armor only.

Large and thick ceramics, usually made of alumina Al_2O_3, between 20 mm and 90 mm thick, depending on impact angle, are the current composite response, in association with composites or metals (aluminum/titanium/steel). They compete with spaced armored metals. The weight efficiency is less than two for such applications. The greater the kinetic energy is, the lower is the weight efficiency obtained compared to add-on spaced metallic designs. The elevated kinetic energy creates a large shock wave which tends to reflect and damage a wide area of the bonding of the ceramic. The multi-hit is directly affected; therefore a specific design must confine the ceramic tiles in order to maintain their efficiency.

For such applications the very high resistance to shocks is a priority. The finish must be designed to ensure excellent protection, usually by encapsulation into rubbers or metals.

Airplanes and helicopters

For such applications, the priority is clearly that of lowest weight. For all protection against lead core ammunition, the PE shield at high pressure is clearly the best choice since it offers the lowest weight for the performance required.

For protection against 5.56 and 7.62 AP ammunitions, the lightest ceramics are used: SiC and mainly B_4C are the best compromise, in spite of the highest cost. The protection level which can be reached is up to 12.7/14.5 API threat. Due to the distance to the target, the multi-hit protection is not a key requirement. But specific resistance to vibration, and shocks (for floors) is very important to insure the compatibility of the armor with the behavior of the vehicle. The fixing of such panels is therefore very important since vibrations are transmitted via the fixing points. But the ability to load or walk on ceramic panels, without damaging their ballistic properties, is not an easy property to ensure. Stiff and thin material, based on lightweight metal or carbon fibers can play an interesting role as protective skins in a sandwich structure in order to reduce the possible deformation of the ceramic components under load.

The ability to remove the armor easily during peaceful operations can also be part of the requirement, so the fixing technique should not be overcomplicated. In addition the modification of the airplane or helicopter is limited most of the time since no hole (for screws) can be made without the consent of the vehicle manufacturer.

Boat and ship armor

For such applications, the priority is once again for the lowest weight. For all protection against lead core ammunition, the PE shield at high pressure clearly remains the best choice since it not only a lightweight material but is also water resistant (as opposed to aramid fibers which are water sensitive).

For higher threat levels (against AP threats), alumina ceramic confers affordable performance and price. The protection level can be up to 12.7/14.5 API. As for airplanes and helicopters, multiple hit protection is not an important requirement to follow. In this application, the hull of a boat may participate significantly in its ballistic structure. Usually hulls are made of fiberglass or aluminum, the stiffness of which can be useful for fixing, as well as a confinement in some cases for sandwich structures.

The balance of the boat during high speed cruising is essential, and the vibration of add-on armor is prohibited. The way to spread the armor in the boat must also be carefully studied in order not to corrupt its nautical ability. This work must be controlled by the shipbuilder. Indeed, the use of ceramics can strongly affect the balance of the boat, and, therefore, the security of the crew.

14.6 Testing of ceramic-faced armor

14.6.1 Rifle bullets

Table 14.4 presents some ammunition types from a caliber point of view. This ammunition can be divided into three groups which differ from a compositional point of view:

- Lead core-based ammunitions: they can be stopped with 100% fiber concepts (polyethylene shield, for example).
- Mild steel core ammunitions (MSC) which are more penetrating (but are not Armour Piercing): they can also be stopped with 100% fibers concepts (7.62 × 39 AK 47 Kalashnikov, for example).
- Hard core ammunitions which are high performing (called Armour Piercing (AP)): this type is more and more frequently encountered and also more penetrating because of its high hardness core.

100% fiber concepts cannot stop AP ammunition alone. Indeed, ceramic strike face solutions must be bonded to a fiber backing in order to erode the hard core and break it into fragments which are then caught by the fiber backing.

14.6.2 AP bullets

The range of AP ammunition is rather large since it starts from 5.56 rounds, up to 135 mm caliber. The main parameter is the composition of the core which is more important than the ammunition velocity. The different hard cores are made of: high hardness steel, tungsten carbide, tungsten alloy and uranium (rarely used for testing for health reasons). For instance, a 7.62 AP with tungsten carbide core has nearly the penetration power of 12.7 AP, which is approximately 10 times heavier.

For this last AP bullet type, the quality of the ceramic, in particular its hardness and toughness are very important and obliges the ceramic manufacturers to improve their current products.

Table 14.4 Type of ammunitions

Type of ammunition	Name of ammunitions
Handgun ammunitions	9 mm, 357 Magnum, 44 Magnum, . . .
Hunting ammunitions (rifles)	12 calibre, .300 Winchester, 7.64, . . .
Military ammunitions (rifles)	5.45, 5.56 (M113), 7.62 (ex: Kalashnikov), . . .
Military ammunitions (machinegun)	12.7 mm, 14.5 mm, fragments (12.7, 20 mm FSP, . . .)
Military ammunitions (canon)	Canon ball and 20 mm shell, 30 mm, . . .

14.6.3 Testing standards and method

The main ballistic standards are NIJ (USA) and PSDB (UK) for personal protection and EN 1063, and Stanag 4569 for vehicles. These four standards are, in fact, complementary and cover a large range of ammunition.

Recommendations are specified for ballistic norms, however, to avoid repetition of the standards themselves, the following are some of the main recommendations. The main criteria which must be carefully studied are:

- Exact descriptions of the ammunition which relate to the composition of the bullet, and its speed.
- Minimum shooting distance which ensures a stable flight, for the most penetrating conditions.
- Distance from the edges and between shots is very important for ceramic armors. It is usually from 25 mm up to 120 mm for rifles, from 50 mm up to 200 mm for 12.7/14.5 AP, and from 300 mm or much more for 20–30 mm calibers. This depends very much on the customer's requirements, based on applications and specific missions.
- Shots sequence. This is very important because it may affect the results. Indeed, starting the shooting from the edge leads to different results to starting from the center, even when keeping the same distance between shots.

It is admitted that the structural resistance of the different ballistic materials can hardly influence the homogeneous behavior: multiple hit protection is much better with a rigid panel than with a panel that gets softer and softer. This is the case for metals rather than ceramic armors backed with fiber-based materials which can delaminate to a greater extent.

Personal protection

The specificity of the ballistic test for personal protection is mainly linked to the presence of a large plasticine or gelatine block to support the plate and/or vest. This support is selected in order to measure backface deformation, called trauma. Such media is not a reliable simulator of the human body, but is mainly a simple tool to compare the energy absorption of each product. Great care must be taken with the composition and conditioning of this plasticine, and which is frequently used by most laboratories. Indeed, it is highly sensitive to temperature and composition, values which frequently differ from one lab to another.

It is important to note that this soft support leads to significant improvement of multiple hit performance of the ceramic plate because the backing deforms less than in empty space.

Some recent specifications incorporate standard tests near edges and with a 30° angle in order to ensure that the ceramic surface really corresponds to the protected surface, which is not obviously the case from one product to another.

This is an important step to improve the quality of ceramic armors, which can be manufactured to stop bullets mainly in the center, with no multiple hit capability.

Traditionally, the AP ammunition destroys the ceramic on a larger surface than lead core ammunitions. This is why the standard specifications usually require a minimum of 3 up to 6 shots per plate for lead core ammunition. But the evolution of the ceramic technologies can now reach up to 12 shots or more, showing that the distance between shots, and near edges has improved greatly, conferring a better protection to the wearer.

Vehicle protection

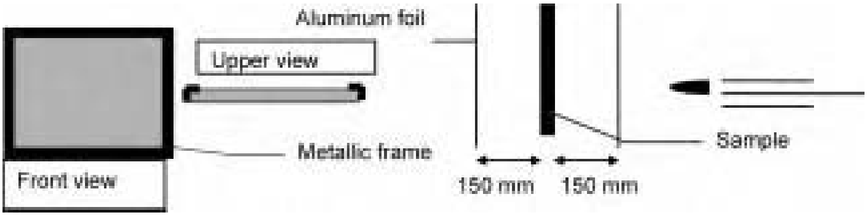
For vehicle armor testing, the plate is mounted on a frame, with empty space behind the sample, which greatly increases the area of delamination when the ceramic is backed with fibers.

Some basic testing recommendations for 5.56 and 7.62 calibers follow:

- Fixing (see Fig. 14.1):
  - mount the panel on a metallic frame (sample plate must be held by the four corners);
  - stand on the 20 mm minimum width edges of the metallic frame;
  - the plate must preferably be located between two sheets of aluminum of 5/10 mm at a distance of 150 mm from the panel in order to test the fragments in the rear and front face.
- Especially with fiber backing material, never put a stiff material behind the protection system which is to be tested. Indeed this would prevent the delaminating effect and thus reduces energy absorption.

14.6.4 Metrology

- Temperature during tests:
  - constant temperature around 20 °C ± 5 °C;
  - for extreme temperature tests: +80 °C/−40 °C.
- Shooting distance:
  - 10–20 m: rifles and shotguns;



14.1 Fixing of a plate for testing.

  - 25–100 m: cannon.
- Position of impacts:
  - 50 mm between the impacts or the edge of the frame for standardized tests (up to 25–30 mm for small calibers).
- Velocity checking:
  - Velocity calculated a few meters from the front of the sample.
- Shooting angle:
  - incidence 0° (projectile more powerful and penetrating), 30°, 45° and 60° is usually the maximum for precision reasons.
- Sequence of tests:
  - one sole type of ammunition is usually shot per target (according to the influence of impact area). But several types of ammunition may be shot if the rear deformations do not disrupt the results of the close impacts.
- Results and evaluation criteria:
  - Tests are successful when the projectile is embedded into the plate or when they do not perforate the aluminum foil situated at 150 mm.
- The ballistic test certificate must mention in order:
  1. types of ammunitions;
  2. velocity;
  3. shooting conditions: T °C, position of impacts, shooting angles;
  4. type of weapon;
  5. shooting distance;
  6. results of each shot: – perforation; – stop; – intermediate stop; – stop into the plate.

14.7 Ballistic performance of ceramic-faced material

Indications of low weight areal density which can be reached with ceramic-faced armors are shown in Table 14.5 and indications of weight and price for protection against the Russian bullet 7.62 × 54 R Dragunov LPS are shown in Table 14.6.

Table 14.5 Ballistic performance – ARES Protection 2004

Ammunitions (impact at 0° incidence)	psf
5.56*45 NATO, 7.62*51 NATO, 7.62*39 AK47, 7.62*54R Dragunov LPS	3–5.5
7.62*39 API AK 47, 5.56*45 AP, 7.62*51 AP (P80/PPI), 300 Winch, 868S, 7.62*54 API Dragunov, .3006 AP M2 (NIJ)	5.2–7.2
7.62*51 FFV Bofors (WC)	10.2–11.3
12.7 AP, 14.5 API B32	15.4
20 mm	
25 mm APDS **60° incidence** (on 40 mm aluminum structure)	22.5
25 mm APDS **45° incidence** (on 40 mm aluminum structure)	39

Table 14.6 Example of comparison against 7.62 × 54 R Dragunov LPS, published by Natick – 18th International Symposium on Ballistic, San Antonio, TX, 15–19 November 1999

System	Ceramic areal density (psf)	Composite areal density (psf)	Total areal density (psf)	System cost ($)
Rolled homogenous steel			15	100
Aluminum oxide/S2 glass	7.0	2.5	9.7	250
Silicon carbide/Kevlar 29	5.8	2.4	8.4	646
Boron carbide/Kevlar	4.3	2.0	6.5	1115

Improvements are made each year. Indeed raw material and process improvements annually lead to a drop in weight of a few percent. However, the threats also become stronger each year.

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