

ARMOUR

Materials, Theory,
and Design



Paul J. Hazell

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*Dedicated to all the brave men and women of the military services
who risk their lives in the defence of their nation.*

One who puts on his armour should not boast like one who takes it off.

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Preface

Over the years, I have had the privilege of engaging with the brave men and women of the armed services from the United Kingdom and Australia, both at the UK Defence Academy at Shrivenham and at the Australian Defence Force Academy in Canberra. Many of my students have been serving military officers pursuing a technical career path where they are required to exercise strength in leadership, decision making and technical know-how. Many of my students had finished their undergraduate studies several years ago and were in the process of embarking on a master's programme. Some had never earned an undergraduate degree. Consequently, as they were not career scientists per se, many students would struggle with some of the more 'taken-for-granted' scientific principles. And this became all the more clear to me when I taught classes on impact dynamics, terminal ballistics, armour systems design and firepower and protection technologies. These are not traditional university courses! As such, there are relatively few texts that are available that can cover some of the more important theoretical elements of these courses as well as introduce in detail some of the materials that are used in constructing protective structures. This is what I have attempted to do in this book. Of course, there are some excellent texts that I regularly use for teaching purposes, each with their own strengths, and you will find references to some of these texts scattered in this book.

I suppose my overall aim in this text is to provide the student or engineer with an insight and the know-how for informing, choosing, buying and making protective structures that will be used in dangerous military environments. Hopefully, our troops will be safer as a result.

I would like to close this section by thanking some notable people who have helped me along the way with this manuscript. These include the staff at Taylor & Francis for their patience and encouragement during this project (particularly when using multiple equation editors). I particularly acknowledge Mr Jonathan Plant for his friendly counsel. I also thank my proofreaders and checkers: Dr. G. Appleby-Thomas, Dr. J. P. Escobedo, Maj (Retd) H. Pratt, Mr Hongxu Wang and Prof Stephen Yeomans.

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Prof. Hazell graduated from the University of Leeds in 1992 with a BEng (Hons) degree in mechanical engineering, and after a couple of years in the automotive industry, he pursued his doctoral studies at the Shrivenham campus of Cranfield University (at the Royal Military College of Science). He was subsequently taken onto the faculty to teach terminal ballistics – to a student cohort that mostly consisted of British Army Officers.

1

Introduction

The concept of armour is as old as the hills. The need to defend, protect, save, shield and guard from harm is engrained within the human consciousness. It is natural, so too is the propensity to progress. Advancements in armour technology have occurred so that we are no longer resorting to ever-greater thickness of material to provide resistance to penetration. Instead, we have relied on new advances in materials technology. This book will summarise some of the more recent advancements.

If we were to plot a graph showing the variation of armour performance with time, we would be left in no doubt that, in recent years at least, huge strides have been made in armour technology. The metric that would be used for armour performance is rather arbitrary – it could be described as ‘some performance criteria based on areal density (i.e. mass per unit area)’. That is to say, lighter-weight armour that provides sufficient protection is a good thing. Again, this is a concept that is as old as the hills. It is a notion that the shepherd boy David knew when he fought Goliath – spurning the heavy and clumsy armour of King Saul in favour of speed and agility (and a very good shot with a sling).

Of course, heavy armour, if you can wear it, or drive it, does provide a notable degree of reassurance. Perhaps this was the reasoning behind the German King Tiger tanks of World War II (WWII) that weighed in the region of 70 tonnes. As a fighting machine, they were an awesome sight and regularly struck fear into the Allied forces. These tanks were heavily armoured with their front hull armour being 150 mm thick. However, they were regularly prone to mechanical failure that was caused, in part, by their enormous weight. And, in the end, only 489 vehicles of this type were manufactured (Ogorkiewicz 1991).

With the introduction of advanced processing techniques, explosive-reactive armours, composite materials and ceramic materials around 30–40 years ago, the performance of armour systems improved dramatically. These developments were key to the drive for reduced armour weight. Further enhancements in performance were made by studying the penetration mechanisms of projectiles in armour materials using high-speed diagnostic equipment such as flash x-ray and high-speed photography. System design was enhanced by the development of analytical and computational codes, with the latter being used to study penetration mechanisms. These codes have since enabled engineers to test different armour designs and conduct optimisation studies without even leaving the office.

Much of this development in armour performance went hand in hand with weapon development but meant that lightweight vehicles could offer the same, if not better, protection than their heavier predecessors. Nevertheless, the basic structure of vehicle armour has not changed much in the past 100 years with most armoured vehicles being made from metal. Much of the existing armour development that has occurred has relied on using materials and systems applied to existing metallic hulls, where the hulls have provided the last line of defence and are an integral part of the complete armour solution.

1.1 Survivability and Onions

There has been much written about the concept of the 'survivability onion'. This is a notion that is frequently used to talk about a layered concept of survivability. So, to maximise individual survivability, there needs to be multiple layers of protection – with each layer exercising a particular purpose (see Figure 1.1).

The first layer of defence should always be camouflage. Today's military no longer simply rely on the shading and colouring on their clothing and equipment. There are much more advanced ways to hide from the enemy – mainly because the enemy has more advanced ways of detecting his/her foe. Armoured vehicles particularly will use signature management techniques to limit the thermal, audio, electromagnetic and radar cross section of the vehicle. However, if we are seen (or detected), then the next layer of defence is important: do not be acquired. By that, we mean that a gun, missile or a person who is a very good shot with a bow and arrow has got you in his/her sights and it is only a matter of time before he/she pulls the trigger, pushes

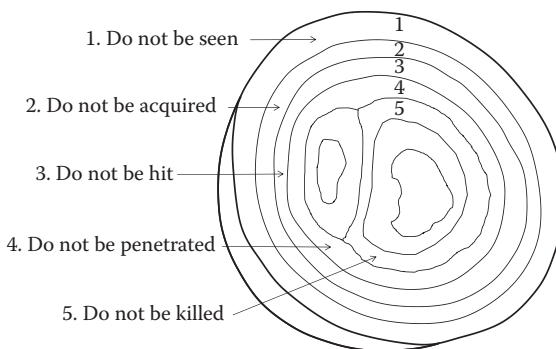


FIGURE 1.1
Onion approach to survivability.

the button or releases his/her arrow to hit you. Not being 'acquired' can be achieved by speed, mobility and agility. It can also be achieved by more technological options such as the use of obscurants such as smoke or electronic countermeasures to jam the enemies' targeting system or simply by unnerving the enemy by firing your weapon at them. So, if we are acquired, the next step is to ensure that we are not hit. This may be achieved by using some form of kinetic countermeasure (some of these will be discussed in Chapter 9). Then, if we are hit, we do not want to be penetrated. Well, technically, we do not want to be perforated. This is where this book comes in. Here, the fourth layer of the survivability onion will be discussed in that we will be looking at how armour works. This includes active armour and passive armour. The final layer is, of course, equally important. If we are penetrated/perforated, we should not be killed. This is achieved by using good spall liners, fire suppression systems and good exit strategies.

1.2 Some Basic Concepts

Fundamentally, there are two types of armour that are available to the armour designer: passive and reactive. Passive systems work by stopping the projectile by the material properties of the armour components alone. In contrast, reactive systems generally work by the projectile incurring a kinetic response in the armour material, the nature of which intends to reduce the lethality of the projectile by disruption or deflection. An example of the latter is explosive-reactive armour; this will be discussed in Chapter 9.

Ideally, the armour system should be as effective and as lightweight as possible and not too bulky. Therefore, a desirable system would employ materials of low density and high resistance to penetration. The choice of materials used in passive armour depends on what the engineer wishes to achieve. Armour materials can be divided into two different categories that depend on their material properties and the way in which they deal with the energy of the projectile. Armour materials tend to be either energy 'disruptive' in nature or energy 'absorbing'. Disruptors (or 'disturbers') tend to be made from high-strength materials such as high-strength steels or ceramic materials. The purpose of these high-strength materials is to blunt the incoming projectile or rapidly erode it. If the projectile is fragmented, a hard material will tend to radially disperse the fragments, and therefore, the kinetic energy of the projectile is deflected and dispersed in the fragments. An absorber, on the other hand, works to absorb the kinetic energy of the projectile or fragments through large amounts of plastic deformation, thereby converting it to a lower form of energy such as heat. The disruptive component of an armour system is either a hard material such as ceramic or high-hardness steel; it can also be a moving material such as an explosive-reactive armour plate – if

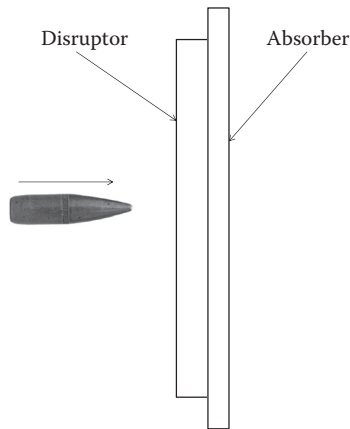


FIGURE 1.2

Disruptor-absorber concept. Most ceramic armours work best in this way.

disruption of a shaped charge jet is the objective. The absorbing components of armour systems are generally materials that can undergo large amounts of plastic deformation before they fail. This is also important when ways of protecting against blast are examined. Usually, it is found that the disruptor plate is attached to an absorber plate – especially in the case of brittle disruptors such as ceramic (see Figure 1.2).

Some hard-facing disruptor materials such as ceramics or glasses are susceptible to brittle fracture, and therefore, it is frequently necessary to contain the material so that the fragments are retained in place after the tile has been perforated. In doing so, it is possible to provide some level of multi-hit protection, although performance against subsequent hits would be compromised. Other disrupting materials such as certain high-hardness steels and hard aluminium alloy plates can be susceptible to gross cracking if penetrated, which means that the plate would need to be replaced. However in these cases, a good multi-hit capability would still be retained despite the fracture.

1.3 The Disposition of Armour

Frequently, it is found that even with modern armour systems, providing all-round protection for a person or a vehicle is practically impossible. All-round protection often means that the system is too bulky or too heavy. Therefore, choices have to be made so that the location of the armour is most likely to provide the maximum amount of protection available whilst maintaining the required amount of comfort (for personnel protection) and

mobility (for vehicle protection). For example, to maximise the life-saving ability of a bullet-resistant vest, ceramic inserts are provided to protect the vital organs such as the heart and lungs whilst providing minimal protection for the shoulders and arms. Furthermore, it is found that most protection offered by the vest is located at the front because in the majority of cases, it is the frontal area that is attacked.

For vehicle armour, similar choices have to be made. These 'choices' have led to the development of 'directional probability variations (dpv's)'.

The term directional probability variation was first introduced as a means to assess the chance that an armoured fighting vehicle (AFV) is attacked from a particular direction. There have been several dpv's proposed for tank hulls, but that due to Lt Col J. M. Whittaker, published in 1943 (Gye 1948), is the best known and is based on a theoretical model.

The basic assumption of Whittaker's model is that a tank is travelling towards a line of anti-tank guns with a constant velocity. The line of travel of the tank is straight and is perpendicular to that of the anti-tank guns, and the total number of shots that can be fired at a certain aspect of a tank is directly proportional to the time that the tank presents that aspect to the gun. Additional assumptions are made about the range of the guns and their ability to fire in any direction. Whittaker's model predicted that it was more probable that a tank will be struck in a frontal segment of the vehicle.

Despite a rather simple model of a tank approaching a line of anti-tank guns at constant velocity, analysis of tank casualties in Northwest Europe during WWII showed that Whittaker's theory fitted the battle data reasonably well. After the war, an important lesson was drawn that the weight of armour should be more concentrated at the front of the AFV.

How well the lessons learnt from this model fit with today's AFV design is questionable. This is mainly due to the variety of mechanisms that are now available to deliver anti-tank shaped-charge warheads to the target. Other factors such as the nature of the conflict and the speed and technological superiority of the attacking force will affect the chance of a hit in a particular segment. For example, subsequent battle data from the 1991 Gulf War have suggested that the number of hits on an Iraqi AFV was more evenly spread around the azimuth (Held 2000); 70% of the hits that were assessed by this work were from shaped charge-type warheads with only 20% of the hits being from a kinetic-energy (KE) type round. Furthermore, 77% of the hits were on the turret, although it is noted that the most likely reason for this is because the majority of Iraqi main battle tanks (MBTs) were located in defensive trenches so that the hulls were not exposed to direct hits. The evidence suggests that we can no longer rely on Whittaker's initial concept for AFV design but rather on a more evenly distributed system of protection to defeat the large variety of munitions, and their delivery method, is required. Thus, it is desirable to use the lightest and most ballistically efficient armour systems and materials as possible.

1.4 Early Applications

1.4.1 Personal Protection

Most armour has evolved to meet threats as they appeared. And, in recent conflicts, the nature of the threats that have been faced by the West has shifted from conventional projectiles fired from big guns to improvised explosive devices and mines. For the individual soldier, the threat will come from blast, high-velocity small-arms bullets and fragments. Therefore, wearable personal protection is important, although it is worth noting that in recent conflicts, fragments, not bullets, are still the major cause of military casualties.

Wearable protective equipment dates back millennia, although modern war-fighting equipment is considerably more lightweight, versatile and comfortable than its ancient predecessors that were made from bronze, steel or even gold.

An infamous early user of ballistic body armour was the Australian bushranger Ned Kelly. He was a notorious criminal who used body armour at the siege at Glenrowan in 1880 to defend himself from the bullets of the police Martini–Henry rifles. To do this, Kelly and his gang forged the now iconic-looking armour out of mould boards stolen from local ploughs (see Figure 1.3). The use of the armour was so unusual to the police at the time that they could not understand what it was that was taunting them.



FIGURE 1.3

The armour of the bushranger Ned Kelly on display at the Melbourne State Library.

The Argus (29 June 1880) captures the scene nicely as the scene unfolded at daybreak on Monday, 28 June 1880:

He [Kelly] however, walked coolly from tree to tree, and received the fire of the police with the utmost indifference, returning a shot from his revolver when a good opportunity presented itself. Three men went for him, viz., Sergeant Steele of Wangaratta, Senior-constable Kelly, and a railway guard named Dowsett. The latter, however, was only armed with a revolver. They fired at him persistently, but to their surprise with no effect. He seemed bullet-proof. It then occurred to Sergeant Steele that the fellow was encased in mail, and he then aimed at the outlaw's legs.

Several years later, Kelly's exploits even led to the debate in the press as to whether it was sensible to wear body armour in conflict (Dean 1915). In fact, Kelly's armour was arguably the inspiration behind the US Brewster Body* Shield that was tried in the early twentieth century.

Now, of course, it is generally a standard issue for troops who are going into conflict, and the modern vests use materials such as ceramic and Kevlar™. Body armour was revolutionised with the invention of Kevlar in 1962 and ceramic armour plates in 1963. More on this will be discussed later.

1.4.2 Vehicle Armour

Of course, military vehicles are a large user of armour. Much of the history here can be traced back to the original tank from WWI. These behemoths of the battlefield were slow lumbering beasts that could barely break 4 mph. Nevertheless, they provided a useful means of protecting advancing troops. This was achieved by constructing these vehicles from 6 to 8 mm of high-hardness steel. And this thickness of high-strength steel is still used today – albeit with a tougher formulation.

Of course, steel was the armour of choice, and there were some good advances in steel processing that served the production of warships from 1845 onwards. However, there was only so much steel you can put into an AFV – a lesson that Adolf Hitler had not learned when he approved the development of a super-heavy tank – the Maus (mouse). Weighing in at 188 tonnes and with armour up to 240 mm thick, it was impossible to cross most bridges. Its mass also meant that no engine was available to give it reasonable speed. Only two were built with one incomplete before the invading Soviet forces overtook the testing grounds.

After WWII, an attempt to maximise the protection and survivability of tanks was achieved by lowering the overall height of the vehicle. This had two effects: Firstly, the silhouette of the tank was reduced (although notably, it was still a behemoth), and secondly, the weight that was saved from the height reduction could be put into the frontal armour. This was achieved by adopting a prone position for the driver.

* The Brewster Body Shield was a wearable 18-kg steel shield resembling Kelly's armour.

However, there is a limit to the thickness of steel that can be employed. As the thickness of steel was increased, it was found that achieving consistency through thickness became more difficult, and working with the large thicknesses of steel became near-impossible. Therefore, new approaches to armour were required.

1.4.3 Aircraft Armour

Ordinarily, it is difficult to armour an aircraft mainly due to the restrictions in adding weight to the structure. Nevertheless, towards the end of WWI, Germany introduced armoured aeroplanes: the single-engine two-seater ground attack Allgemeine Elektrizitäts-Gesellschaft JI/II and a twin-engine three-seater bomber G.IVk. The armour on the single-engine machine was 5.1 mm thick – too thin to provide protection against the British armour-piercing bullets fired from the ground at a lower height than 500 ft. (152 m). It was parasitic too, adding a whopping 860 lb. (390 kg) to the mass of the aeroplane (Fox 2006).

It seemed sensible to adopt a lower-density armour material than steel for aircraft armour applications, and some efforts were given over to this in WWII with the examination of whether magnesium alloys would make suitable ballistic armour plates (Sullivan 1943). At that time, it appeared that the best solution was to armour the individual rather than the structure, and so the term ‘flak jacket’ was born due to the vests that the bomber crews used to protect them from anti-aircraft ‘flak’. These were made from a manganese steel encased in a canvas support structure (later nylon) and weighed in at 7.9 kg for front and back protection (Tobin and Iremonger 2006). This was also the approach that was used by the crew of helicopters during the Vietnam conflict that had the benefit of the newly invented ceramic-based body armour vests. These vests, however, very often ended up on the floor of the aircraft to protect against small arms fired from the ground.

1.4.4 Ship Armour

Arguably, much of the theoretical understanding of armour penetration stems from the early work carried out on battleship armour. And much of the armour that was historically used on ships was made of iron and steel. The importance of naval armour is probably best summarised by the battle of the Denmark Strait where the German battleship *Bismarck* sank *HMS Hood* resulting in the death of all but 3 of the 1418 crew. It is generally thought that the weak deck armour contributed to the *Hood's* sinking as it was penetrated by a 15-in. (380-mm) armour-piercing shell from the *Bismarck* resulting in the explosion of the *Hood's* 4-in. magazine*. Nowadays, advances in long-range

* Although it should be noted that other theories on the demise of the *Hood* exist – particularly on the location of the fatal shell's strike location, e.g. Santarini (2013).

anti-ship missile systems and torpedo technologies have led to the demise of large-calibre naval guns typified by the Bismarck's *Panzersprenggranate L/4.4* 380-mm calibre shells*. Consequently, modern warships no longer rely on a belt of armour for protection but rather a complex array of sensors and defensive aid suites that can detect, track and engage the incoming threat.

It was in 1805 that a proposal was made to clad wooden ships with iron to provide ballistic protection. Some early examples of ship armour employed wrought iron of many inches thick (typically 4.5 in. or 114 mm) backed by up to 36 in. (0.9 m) of teak or oak to combat the large-calibre naval shells. The French ship *Gloire* was the first armour-clad ship to sail, and this was completed in 1859 (Johnson 1988). It was a wooden frigate employing a 4.75-in. (121-mm) belt of wrought iron armour. Two years later, the British ship *HMS Warrior* was completed and was the first ship to be completely made from iron. The hull was 4.5 in. (114 mm) thick and made from wrought iron plate.

The changes in battleship armour from 1845 to 1945 are nicely captured by W. Johnson (1988); some notable changes are summarised in Table 1.1.

By c. 1900, there was a tendency to reduce the thickness of the armour on the ship. The practice in the United States at that time was to protect the whole length of the waterline with approximately 8 ft. (2.44 m) of armour extending 4.5 ft. (1.37 m) above it and 3.5 ft. (1.07 m) below it. A schematic of the battleship *Connecticut*, commissioned in September 1906, is shown in Figure 1.4 (Lissak 1907). The thickest sections of armour were reserved for the front turret (12 in. or 305 mm) and barbette (an armoured structure that protected the mechanisms of ammunition supply and turret operation), whilst various thicknesses of armour protected the waterline (4–11 in.).

It soon became clear that it was sensible to design ship armour such that it comprised a hard outer face and a tougher rear face. First attempts to do this were by developing compound armour that was composed of a hard steel impact face (with perhaps 0.5%–0.6% C) joined to a softer but tougher wrought iron plate. The ballistic performance of the compound armour was judged to be down to the combination of the hardness of the steel face plate and the quality of the weld between the two plates. Best results were achieved with a thickness of one-third steel to two-thirds iron (Johnson 1988).

Compound armour was soon replaced by the invention of nickel-steel armour where the addition of nickel led to an increase in strength and toughness of the steel. Where successfully treated, a 10-in. (254-mm) nickel-steel armour could be as effective as 13 in. (330 mm) of wrought iron plate. Other developments included carburising the face of steel armour plate by holding in contact with bone, finely divided charcoal or other carbonaceous compounds at elevated temperature (this is a super-carburising or 'cementing' process). This had the effect of increasing the carbon content close to the

* These shells had a mass of 800 kg and contained a small mass of explosives (~19 kg); the maximum range with a naval gun installation was 36 km.

TABLE 1.1

Changes in Warship Armour from 1859 to 1901

Date	Ship	Type of Armour	Thickness (in.)	Thickness (mm)
1859	<i>Gloire</i>	Wrought iron (wooden frigate protected by a belt of armour)	4.75	121
1860	<i>HMS Warrior</i>	Wrought iron (first armour-clad ship to be built entirely from iron)	4.5	114
1876	<i>HMS Inflexible</i>	Sandwich (two plates of iron)	2 × 12 = 24	610
1882	<i>HMS Collingwood</i>	Compound armour	18	457
1895	<i>HMS Majestic</i>	Nickel–steel armour	9	229
1901	<i>HMS Duncan</i>	Krupp armour	7	178

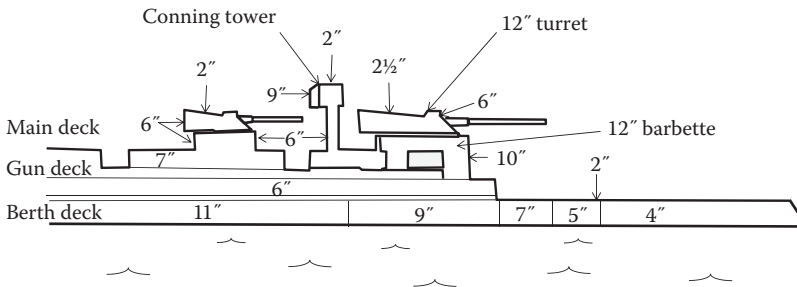


FIGURE 1.4

Distribution of armour on the United States Connecticut. (From Lissak, O. M., *Ordinance and Gunnery: A Text Book*, 1st edition. 1907. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.)

surface of the steel, and therefore, a product comprising a hard face and a tough body was produced.

Krupp was able to deepen the hardening process (cemented plates only had a carbon infusion to approximately 1 in. or 25.4 mm) by embedding nickel-chrome steel cemented plates in clay whilst leaving the cemented side exposed to air. Then, the exposed face was subjected to a process of rapidly heating and rapidly cooling the steel with water spray. This process of decemental face hardening produced a very hard face of between 30% and 40% of the plate's thickness with the remainder retaining the original properties of the plate.

1.4.5 Fortifications

Fortifications have had a very long history, and there has been little change in the principles of protection throughout the centuries. Today, we use very similar (and in some cases, identical) materials to what was used over 2000 years ago. Take a well-known and well-used protection solution in HESCO



FIGURE 1.5
Thornycroft Bison.

Bastion. It uses the benefit of naturally occurring materials to provide cover and protection. In fact, it is found that rock, brick and concrete are pretty effective at stopping modern weapons as they were at stopping ancient projectiles. The reason for this lies in their hardness and the fact that there is rarely any limit on the amount of material that can be applied as protection, that is, given that there is sufficient space available. Therein lies the golden rule of protection: 'given enough space and not being limited by weight, all kinetic-energy-based weapons can be defeated'. The challenge, as will be seen in this book, is that rarely do we have the luxury of providing limitless space and accommodating large masses.

Concrete has long been known to provide an effective and cheap means of providing protection to fortifications. The Thornycroft Bison was developed in 1940 as a mobile pillbox with the intention that it would be deployed on and around airfields. Arguably, the Bison is a concrete AFV; an example located at the Bovington Tank Museum (United Kingdom) is shown in Figure 1.5.

Nowadays, the damage tolerance of concrete structures is enhanced by adding reinforcing fibres made from steel or polymer materials – such as polyvinyl alcohol or polyethylene. These fibres have been shown to enhance the blast resistance of concrete structures.

1.5 Early Empirical Models of Penetration

Much of the early work on attempting to predict the thickness of armour required to stop projectiles was carried out with the intention of providing

better protection for ships. Much of this work was carried out from the late 1880s with semi-analytical equations proposed for predicting the thickness of plate that could be penetrated. These were based on two different hypotheses of penetration (Bruff 1896):

1. The projectile acted like a punch by shearing the metal along the circumference of a disk.
2. The projectile acted like a wedge forcing the particles of the metal apart.

And so from here on in, we must turn mathematical. For penetration into wrought iron, the formulas deduced under the first hypothesis were

$$\text{(Fairbairn)} \quad h^2 = \frac{E}{k d} \quad (1.1)$$

$$\text{(English Admiralty)} \quad h^{2.035} = \frac{E}{0.86 k d} \quad (1.2)$$

$$\text{(Muggiano)} \quad h^{1.868} = \frac{E}{k d} \quad (1.3)$$

For the case of the second hypothesis, the derived equations were

$$\text{(de Marre)} \quad h^{1.3} = \frac{E}{5.8169 d^{1.5}} \quad (1.4)$$

$$\text{(Maitland)} \quad h = \frac{v_0}{608.3} \sqrt{\frac{w}{d}} - 0.14 d \quad (1.5)$$

$$\text{(Krupp)} \quad h^{1.33} = \frac{E}{4.156 d^{1.67}} \quad (1.6)$$

$$\text{(Gâvre)} \quad h^{1.4} = \frac{w v_0^2}{2265464 d} \quad (1.7)$$

Here, we resort to imperial units: where h is the thickness of wrought iron, in inches, that the projectile would penetrate; E is the kinetic energy of the projectile (in foot-tons); d is its diameter (in inches); w is its weight in pounds; v_0 is the projectile's striking velocity (in feet/seconds); and k is a constant.

As a rule of thumb, Captain Orde Browne was able to deduce a guide on how a projectile would penetrate the enemy's armour: 'The penetration of a projectile in wrought iron armour is one calibre for every thousand feet striking velocity' (Bruff 1896, p. 327). So for example, a 10-in. projectile striking with a velocity of 1000 ft./s will penetrate 1 calibre or 10 in.

Historically, for steel armour, engineers would calculate the penetration for wrought iron plate and add a percentage (varying from 10% to 30%) to accommodate the increased levels of strength and toughness. However, this was deduced unsatisfactorily due to the variability in steel armour properties from one type of steel to the next. Therefore, equations for different steels were deduced based on the *de Marre* formula as follows.

For soft plates of Creusot steel (generally used for heavy armour), backed by wood,

$$h^{0.7} = 0.0009787 \frac{w^{0.5} v_0}{d^{0.75}} \quad (1.8)$$

For perforation of the wooden backing only (Metcalf 1891),

$$h^{1.2} = \frac{E}{0.1823d^{1.8}} \quad (1.9)$$

where E is the kinetic energy of the projectile in foot-tons given by

$$E = \frac{wv_0^2}{2g2240} \quad (1.10)$$

where g is the acceleration due to gravity (32.2 ft./s²) and noting that a ton is defined as 2240 lb., giving

$$h^{0.6} = 0.006169 \frac{w^{0.5} v_0}{d^{0.9}} \quad (1.11)$$

For thin hard steel plates used as protection against rapid-fire guns (unbacked),

$$h^{0.7} = 0.000734 \frac{w^{0.5} v_0}{d^{0.75}} \quad (1.12)$$

These equations are provided purely for historical context, and some analytical and empirical equations for penetration will be revisited later.

1.6 Summary

In this book, the intention is to provide an overview of the science and technology that is used to provide protection against blasts and ballistic attacks. The theory and applications will be mostly concerned with vehicles, ships and personnel with some reference to fortifications.

We will start by examining the theory of material behaviour and the typical threats that are out there. Next, we will look at the materials technologies that have been used in protection ranging from the common garden steel to ceramic- and composite-based systems. We will also discuss some of the system effects of adding blast-wave shaping to vehicles, and finally, we will close this book examining the effect on the human body and blast and ballistic testing techniques.

2

An Introduction to Materials

2.1 Introduction

Armour materials are subjected to large forces in very short timescales. In fact, they are doing their job very well if they are able to accommodate these forces. Therefore, to understand the behaviour of an armour material that has been impacted by a bullet or fragment from an exploding shell, or subjected to an explosive blast wave, we must take a look at its properties.

2.2 A Quick Introduction to the Structure of Materials

The types of materials that are used in armour construction are quite extensive and range from low-density and low-stiffness materials such as polymers to high-density and high-hardness materials such as tungsten carbide. Naturally, the structure of these materials differs too. Most armour materials tend to be polycrystalline. That is to say that they are made up of multiple crystals 'stuck' together – each with a different orientation. Each crystal will be separated by a grain boundary. Materials in this category include most metals and ceramics. Additional structures include

- Mono-crystalline materials (such as sapphire) – where there is complete atomic order.
- Glassy materials – where there is limited order (i.e. glass).
- Amorphous structures – where there is no order. Many polymers fit into this category.

The way that a crystal is built is dependent on the atoms that make up the unit cell. The unit cell is the smallest repetitive unit that defines the relative locations of the atoms and forms the basic building block of the crystal. Multiple unit cells are stacked together to produce the crystal. And, in fact,

TABLE 2.1

Crystal Structures for 12 Metals

Metal	Crystal Structure	Metal	Crystal Structure	Metal	Crystal Structure
Aluminium	FCC	Lead	FCC	Tantalum	BCC
Copper	FCC	Magnesium	HCP	Titanium (α)	HCP
Gold	FCC	Platinum	FCC	Tungsten	BCC
Iron (α)	BCC	Silver	FCC	Zinc	HCP

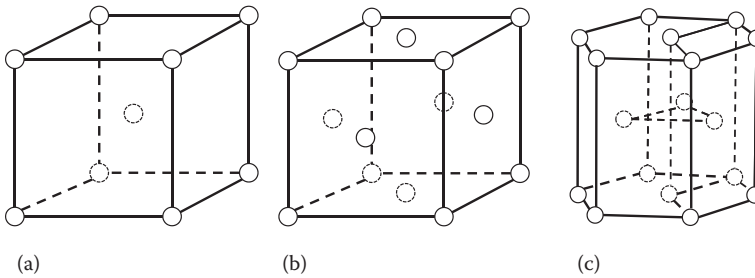


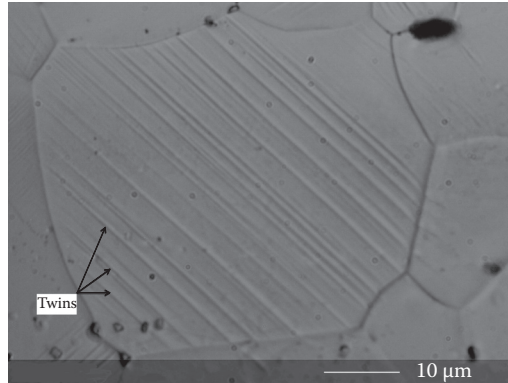
FIGURE 2.1

(a) BCC, (b) FCC and (c) HCP crystal structures.

there are a limited number of crystal shapes (seven is the current number). The three most common unit cell shapes in metals are body-centred cubic (BCC), face-centred cubic (FCC) and hexagonal close-packed (HCP). These crystal shapes define how the atoms are arranged, and the type of the crystal shape will affect the way in which plastic deformation is accommodated. A summary of crystal structures for 12 important metals used in defence applications is provided in Table 2.1. The corresponding structures representing BCC, FCC and HCP are shown in Figure 2.1.

2.2.1 Mechanisms of Plastic Deformation

Both hardness and tensile (strength) tests result in plastic deformation of the sample. The mechanisms of plasticity are quite complex, and a readable explanation is provided by Callister (2007). The theory is largely based on the fact that crystals possess defects, and it is these defects that can move through a process called slip. These defects are known as *dislocations*. In an arrangement of atoms for a particular crystal, a dislocation is a defect about which there is a misalignment of atoms. Slip occurs because the stress that is applied in the tensile, compression or hardness tests (or indeed any stress for that matter) is transferred to the individual crystals in that material. This stress causes the movement of dislocations resulting in distortion of the crystal. The crystallographic plane along which this occurs is called the slip plane. This is the

**FIGURE 2.2**

Examples of twinning in a magnesium material that has been shocked to 1.3 GPa.

preferred plane for dislocation movement. For a particular crystal structure, the slip plane is the plane with the densest packing of atoms.

In addition to slip, plastic deformation can also occur by the formation of *mechanical twins* or *twinning*. Twinning occurs in metals that have a BCC and HCP structure at low temperatures and at high rates of loading – such as you would expect when a bullet penetrates an armour material. Twinning is a process whereby a shear force results in atomic displacement. An important characteristic of twinning is that atomic displacement results in a perfectly symmetrical atomic arrangement about the twin plane. Figure 2.2 shows examples of twinning that has occurred in a shocked HCP magnesium material. The parallel lines that traverse the individual grain are due to the distortion that occurs due to twinning.

2.3 Stress and Strain

Let us start with the basics. We will be referring to different types of stress during the course of this book. Stress is simply a measure of the applied force divided by the area over which that force acts and has the SI-derived unit of N/m^2 or pascals (Pa).

In simple tension, the stress, σ , can be written as

$$\sigma = \frac{F}{A} \quad (2.1)$$

where F is the applied force, and A is the area over which the force acts. A schematic of a simple tension case is shown in Figure 2.3a. Suppose that we

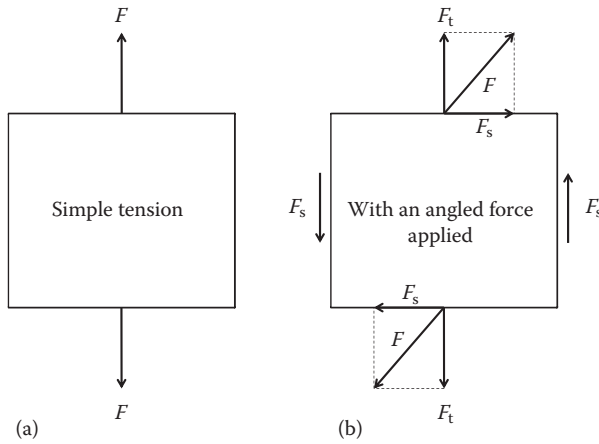


FIGURE 2.3

Schematic of (a) an element subjected to simple tension and (b) where the element is subjected to a force at an angle from the parallel surface.

have a case where the force no longer acts normal to the surface but at some angle to it. The force can now be resolved into two components: one component of force acting perpendicular to the surface, F_t , and one component of force acting parallel to the surface, F_s . The force acting parallel to the surface loads the element in shear. So, a shear stress, τ , that is acting on the element can now be defined, and this is given as

$$\tau = \frac{F_s}{A} \quad (2.2)$$

Note too that in Figure 2.3b the forces acting on the vertical surfaces of the element due to the presence of shear have to be drawn. This is simply to satisfy equilibrium – otherwise, the element would spin clockwise.

There are three states of pure stress that will be discussed from time to time in this book. They are defined as *simple tension or compression* (the tensile case is shown in Figure 2.3a), *pure shear* (as defined in Equation 2.2) and *hydrostatic stress or pressure*. This occurs when a solid is subjected to equal compression on all sides. Pressure will be discussed in detail when the role of shock waves in penetration and blast is examined.

A material will accommodate stress by deforming or *straining*. Referring to a simple tensile case, then the amount of strain can be defined by measuring the amount of deformation and dividing that by the original length of the sample. So, strain, in simple tension, where a load is applied to a sample of length x_0 can be defined as

$$\epsilon_n = \frac{x - x_0}{x_0} \quad (2.3)$$

where x is the new length due to the application of the load. This is the definition of *engineering or nominal strain* where the initial and final states of the sample are measured during an experiment. However, there is an additional important definition of strain that is frequently used in computational codes, or in the analysis of wave propagation, that the reader should be aware of, and that is *true strain or natural strain*. For a continually straining object, it is the precise measure of strain at one particular point in time. Therefore, an increment of true strain can be defined according to

$$d\varepsilon = \frac{dx}{x} \quad (2.4)$$

Integrating between x_0 and x , we have

$$\varepsilon = \int_{x_0}^x \frac{dx}{x} = \ln\left(\frac{x}{x_0}\right) \quad (2.5)$$

From Equation 2.3, it is seen that

$$x = x_0(1 + \varepsilon_n) \quad (2.6)$$

Therefore, the equation for true strain can be rewritten as:

$$\varepsilon = \ln\left(\frac{x_0(1 + \varepsilon_n)}{x_0}\right) \quad (2.7)$$

and so, true strain is defined as

$$\varepsilon = \ln(1 + \varepsilon_n). \quad (2.8)$$

This nicely gives us the relationship between true strain and engineering strain.

In simple tension, the length of the sample will increase, but the thickness, or diameter for a cylindrical specimen, will decrease. To describe this effect, the Poisson's ratio is defined. This has the symbol of ν and relates the longitudinal strain to the transverse strain, ε_t ; thus,

$$\nu = -\frac{\varepsilon_t}{\varepsilon_n} \quad (2.9)$$

If the transverse dimension of the specimen is defined as d , then the transverse strain is defined as $\varepsilon_t = -\Delta d/d$.

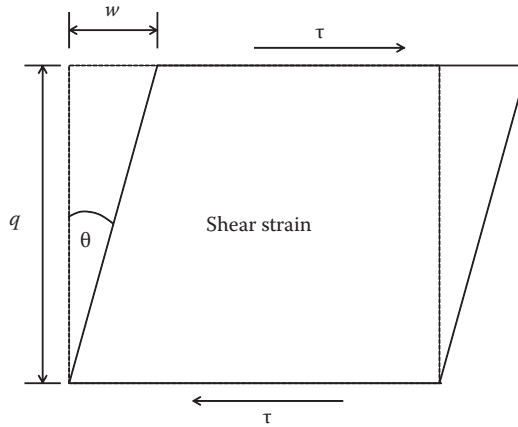


FIGURE 2.4
An element subjected to pure shear.

Engineering shear strain is given to us with reference to Figure 2.4. This is defined as follows:

$$\gamma = \frac{w}{q} = \tan \theta. \quad (2.10)$$

where $\gamma \approx \theta$ for small angles.

In a similar fashion, volumetric strain can be defined in the change in volume divided by the original volume (V_0). So the engineering definition of volumetric strain is given to us as

$$\epsilon_{v-n} = \frac{V - V_0}{V_0} \quad (2.11)$$

and the true volumetric strain is defined by

$$\epsilon_v = \ln \left(\frac{V_0}{V} \right). \quad (2.12)$$

Note that here, the strain (and pressure) is positive in compression, and therefore, Equation 2.12 is in a slightly different form to Equation 2.5.

Example 2.1

A steel test specimen is loaded by 10 kN as shown in Figure 2.5. Calculate the stress in each section. The diameters of each section are (1) 40 mm, (2) 20 mm and (3) 30 mm.

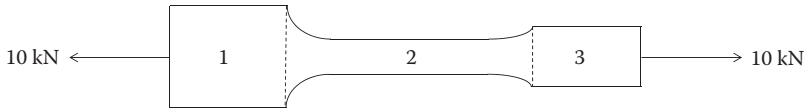


FIGURE 2.5
A steel test specimen with three cross-sectional areas.

TABLE 2.2

Answers to Example 2.1

Section	Diameter (mm)	Area (mm ²)	Load (N)	Stress (MPa)
1	40	1257	10,000	8.0
2	20	314	10,000	31.8
3	30	707	10,000	14.1

This can be solved very simply with reference to Equation 2.1. The important point to learn here is that stress is a function of the cross-sectional area through which a force acts, and therefore, it is variable. Even though there is a single force acting through the specimen, the stress will vary throughout its length. In this case, it is remembered that $1 \text{ N/mm}^2 = 1 \text{ MPa}$ and that the equation for the area of a circle is given by

$$A = \frac{d^2}{4} \quad (2.13)$$

Therefore, the answers can now be tabulated in Table 2.2.

2.4 Elasticity

When a load is applied to a material, initially, it will deform elastically. In fact, all materials will deform elastically when subjected to small strains. Up to a predetermined stress limit, the amount of deformation is reversible as the material has incurred no permanent deformation. In this region, the stress is directly proportional to the strain; thus,

$$\sigma = E\varepsilon \quad (2.14)$$

where E is defined as the modulus of elasticity or the Young's modulus of the material. This relationship was originally discovered by Robert Hooke in 1678 and is sometimes referred to as *Hooke's law*. At an atomic level, ε is a measure of the increase in atomic spacing due to the applied stress. As

the load is increased, the inter-atomic spacing increases, and when the load is removed, the atoms return to their equilibrium position. The greater the attraction between atoms – that is, the stronger the bonding – the greater the stress required to increase the inter-atomic spacing. Certain ceramic armour materials are good examples of materials with high values of E due to their strong atomic bonding. Materials with relatively weak ionic bonding tend to possess relatively low values of E .

A common way for measuring the elastic properties of a material uses ultrasonic methods. An ultrasonic transducer is used to send a longitudinal elastic wave into the material. Knowing the sample's thickness and the time it takes for the ultrasonic wave to transit the thickness of the sample, we can work out how fast the wave travels through the sample. By knowing the material's density and the longitudinal and shear wave speed of the material, it is possible to calculate the Young's modulus, Poisson's ratio and other important elastic properties including the shear modulus (G) and bulk modulus (K) according to the following equations:

$$\nu = \frac{1 - 2\left(\frac{c_s}{c_l}\right)^2}{2 - 2\left(\frac{c_s}{c_l}\right)^2}, \quad E = \frac{c_l^2 \rho + (1 + \nu)(1 - 2\nu)}{(1 - \nu)}, \quad G = c_s^2 \rho \quad (2.15)$$

where c_l and c_s are the longitudinal and shear wave velocities, respectively.

An example of a typical waveform from an ultrasonic transducer in contact with a silicon carbide tile is shown in Figure 2.6. The transducer is a longitudinal type (Olympus V109-RB) connected to an Olympus 5077PR square wave pulser/receiver. A digital storage oscilloscope captures the waveform. It can be seen that the pulse reflects back and forth from the surface of the sample, and as it does so, the magnitude drops. The time between each pulse is the time for the wave to transit twice the thickness of the sample.

In our example, it is known that

- The sample thickness, $h = 9.82$ mm
- The time between two pulses, $\Delta t = 1.64$ μ s

Therefore, to calculate the longitudinal wave velocity in a sample of thickness 9.82 mm, we have

$$c_l = \frac{2h}{\Delta t} = \frac{19.64}{1.64} = 11.976 \text{ mm/s} \quad (2.16)$$

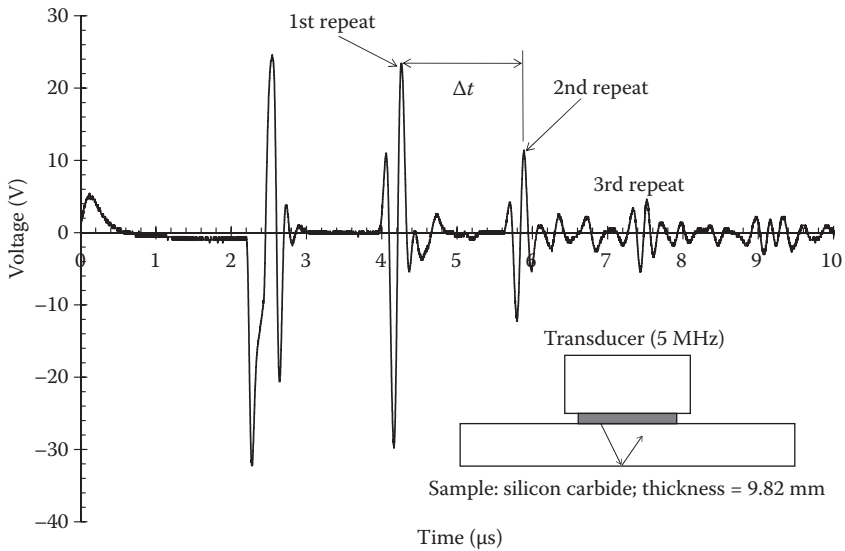


FIGURE 2.6

Longitudinal wave transmission through a silicon carbide target. Here, the transducer is used in 'pulse-echo' mode, which means that the transducer detects the reflection of the wave from the free surface of the target.

This is the longitudinal wave velocity for the silicon carbide.

In practice, it is common to use as many 'repeats' as possible where the identical feature is discernible in both pulses from which the measurements are taken. This is to minimise the error in timing acquisition. Furthermore, it is common that a contact medium is applied between the transducer and the sample to facilitate wave transmission. For longitudinal transducers, something like a low-viscosity washing-up liquid is usually sufficient, whereas for shear-wave transducers, something like higher-viscosity honey or treacle is usually required.

A list of the elastic properties of a range of materials is presented in Table 2.3.

Materials of the same type generally have very similar elastic properties irrespective of their strength. For example, it is well known that rolled homogeneous armour (RHA) is a much stronger steel than mild steel, yet their stiffness values are similar ($\pm 3\%$). The reason for this is that strength properties are dominated at the microstructural level, which is affected by processing, whereas the stiffness is very much affected by changes at the atomic scale.

TABLE 2.3

Elastic Properties of a Range of Materials

Material	Density (kg/m ³)	c ₁ (m/s)	c _s (m/s)	c _b (m/s)	E (GPa)	G (GPa)	K (GPa)	ν
Epoxy resin (cured)	1141	2699.0	1283.5	2255.7	5.1	1.9	5.8	0.354
Perspex	1190	2768.0	1389.5	2255.6	6.1	2.3	6.1	0.332
Borosilicate glass	2200	5584.4	3411.8	3958.0	61.6	25.6	34.5	0.202
Float glass	2440	5797.9	3461.9	4199.5	71.5	29.2	43.0	0.223
Aluminium 5083-0	2660	6359.7	3187.7	5186.3	72.0	27.0	71.5	0.332
Aluminium 6082-T651	2703	6412.5	3188.3	5250.4	73.4	27.5	74.5	0.336
Aluminium 1318B	2780	6268.9	3112.0	5136.8	72.0	26.9	73.4	0.336
Silicon carbide (PS-5000)	3140	12,071.4	7629.8	8252.3	426.8	182.8	213.8	0.167
Alumina (Sintox™FA)	3694	10,088.3	5933.0	7405.4	321.3	130.0	202.6	0.236
Alumina (AD-995)	3900	10,650.3	6260.3	7821.4	377.9	152.8	238.6	0.236
Steel (mild)	7800	5926.8	3241.3	4595.4	210.9	81.9	164.7	0.287
Steel (UK-RHA)	7838	5919.3	3300.8	4528.9	217.7	85.4	160.8	0.274
Stainless steel (304L)	7890	5739.5	3155.0	4435.0	201.6	78.5	155.2	0.283
Tungsten carbide	14,740	6829.0	4085.0	4938.2	600.9	246.0	359.4	0.221

2.5 Strength

The theoretical strength that can be achieved by a material is defined by the elastic modulus, the inter-atomic spacing and the energy required to create a fracture surface – that is, the fracture surface energy. The theoretical strength can be defined by the following equation:

$$\sigma_{\text{th}} = \left(\frac{E\gamma}{a_0} \right)^{\frac{1}{2}} \quad (2.17)$$

where E is the elastic modulus, γ is the fracture surface energy and a_0 is the inter-atomic spacing. Sadly, many hard and brittle materials such as glass and ceramic never even come close to obtaining their theoretical strength as their structure contains small flaws or pores that provide a source for crack propagation when the materials are placed under load. For example, fracture strengths for polycrystalline ceramics are typically of the order of 1% that of σ_{th} .

Griffith (1921), a British engineer, was the first to offer an explanation of the very low fracture strength of brittle materials compared to their theoretical strength. He deduced that it was due to the presence of small cracks or flaws in the material. He developed the foundation for the theory that led to the

equation that defines the fracture strength of a brittle material in terms of the flaw size and fracture toughness:

$$\sigma_f = \frac{K_c}{\sqrt{\pi a}} \quad (2.18)$$

where a is half the defect size, and K_c is the critical stress intensity factor – a measure of the fracture toughness of the material. K_c , like E , is a material property and as such can be measured. The important thing to realise from this equation is that the fracture strength is dependent on the largest flaw size in the material. The larger the flaw, the lower the fracture strength.

The measurement of the strength of metal materials is generally carried out in tension by what is called a 'simple tensile test'. Loading a ductile material such as mild steel in a simple tension results in a stress–strain profile shown in Figure 2.7. Inset is a typical 'dumbbell'-shaped specimen that may be used with metals showing a reduced section where the strain is measured. The curves for both true stress and engineering stress are shown. Consider the engineering stress behaviour: At point 'A', the yield strength (Y) of the material is reached. At this point, the material is no longer linear elastic and starts to deform plastically. This continues until at point 'B', the maximum engineering stress is reached, which is known as the ultimate tensile stress (UTS). At this point, the onset of necking occurs, and the stress is relaxed until fracture occurs at point 'C'.

The engineering (or nominal) stress curve sits lower than the true stress curve. This is because the calculation of engineering stress takes into

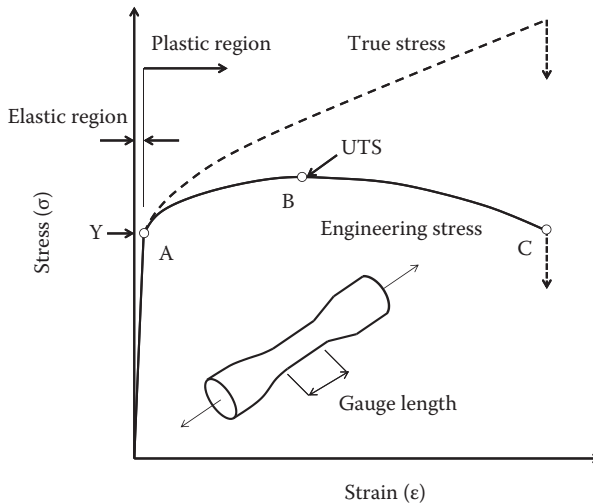


FIGURE 2.7

A schematic of a typical stress–strain curve for steel.

account the original cross-sectional area before the sample is deformed. As the sample is stretched, it will narrow, and the true stress takes into account the reduced cross-sectional area, i.e. the instantaneous cross-sectional area.

The true stress and engineering stress are related by the following relationship:

$$\sigma = \sigma_n(1 + \epsilon_n) \quad (2.19)$$

where σ_n is the engineering stress, and ϵ_n is the engineering strain.

The application of tensile load produces strains in the test specimen. The effect of these strains is to raise the energy levels in the bar itself. The increase in energy within the bar is called the *strain energy* and is equal to the work done on the bar provided that no energy is added or subtracted in the form of heat. The strain energy, U , can be calculated from

$$U = \int F \cdot dx \quad (2.20)$$

where F is the load applied to the bar, and x is the distance through which the bar is stretched. The above equation including the cross-sectional area A and the original length L of the bar can be rewritten as follows:

$$U = A \cdot L \int \frac{F}{A} \cdot \frac{dx}{L} \quad (2.21)$$

and therefore,

$$\frac{U}{V} = \int \sigma \cdot d\epsilon \quad (2.22)$$

Therefore, the area under the curve is a measure of the strain energy absorbed per unit volume, V , and is a measure of the material's toughness. For an armour designer, toughness is a desirable property as a tough material requires more energy to induce fracture. However, that is not the whole story as will be seen later. Ceramics are very brittle and cannot accommodate much plastic deformation. Yet, they are used extensively in armour.

For elastic collisions, the term *resilience* is often used to describe the behaviour of the material. Essentially, this is the capacity of the material to absorb energy when it is deformed elastically. So, assuming that the material has a linear-elastic region, then the elastic strain energy absorbed is given to us by the area under the linear portion of the stress-strain curve. Therefore,

$$U_r = \frac{1}{2} Y \epsilon_y \quad (2.23)$$

where Y is the yield strength, and ϵ_y is the strain at the yield point. Therefore, incorporating Equation 2.13, it is seen that

$$U_r = \frac{Y^2}{2E} \quad (2.24)$$

U_r has the units of J/m^3 , and so it is the energy absorbed per unit volume of material. As this is strictly for the case of elastic deformation, this energy can also be released. Noting the above equation, it is therefore desirable to use a material with a high yield strength and low elastic modulus when faced with low-velocity collisions.

Example 2.2

A 10-mm diameter bar of 1040 carbon steel is subjected to a tensile load of 60 kN taking it beyond its yield limit ($Y = 580 \text{ MPa}$). Calculate the elastic recovery that would occur on removal of the load given that $E = 200 \text{ GPa}$.

Elastic recovery is assumed to occur in a linear fashion as the stress is released from down an elastic path parallel to the elastic loading (see Figure 2.8).

First, the area needs to be calculated; this is given by

$$\begin{aligned} A &= \frac{d^2}{4} = \frac{10^2}{4} \\ &= 78.5 \text{ mm}^2 \end{aligned}$$

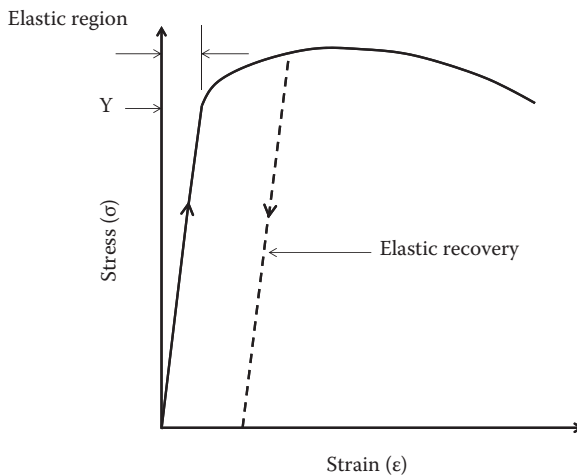


FIGURE 2.8

Elastic recovery from a plastic stress value.

Using Equation 2.1, the stress can be calculated:

$$\begin{aligned}\sigma &= \frac{F}{A} = \frac{60,000}{78.5} \\ &= 764.3 \text{ MPa}\end{aligned}$$

The elastic recovery can be calculated from Hooke's law and therefore is given by

$$\begin{aligned}\varepsilon &= \frac{\sigma}{E} = \frac{764.3 \times 10^6}{200 \times 10^9} \\ &= 3.82 \times 10^{-3}\end{aligned}$$

Note that the elastic recovery here is calculated as a value of strain and therefore is dimensionless.

Example 2.3

You are designing a new type of crash box for low-velocity collisions, and you are given the option of four materials. These are summarised in Table 2.4. During the collision, you expected that the structure would remain elastic at all times. Which material would you choose and why?

During a low-velocity elastic collision, we would want the structure to absorb as much kinetic energy as possible. Therefore, choosing a material that has high elastic resilience is sensible. From Equation 2.23, it is a relatively trivial task to work out the elastic resilience of our choices. Remember to write the equation so that the values are in base SI units. The answers are summarised in Table 2.5.

It can be seen from Table 2.5 that Ti-6Al-4V is the clear winner by virtue of its high yield strength, whereas AA 2024-T6 performs reasonably well and is ranked second by virtue of its low elastic modulus. Budgetary factors may well impact your choice, and given the cost of titanium alloys, the aluminium alloy option may turn out to be the better one (titanium alloys are very expensive).

The strength of brittle materials is generally characterised by using a *bend test*, as illustrated in Figure 2.9. There are two types that are principally used: the three-point bend test and the four-point bend test. In both cases, a

TABLE 2.4

Properties of Selected Materials

Material	E (GPa)	Y (MPa)
AA 2024-T6	72	350
AISI 304 stainless steel	193	205
AISI 1040 cold drawn steel	200	450
Ti-6Al-4V	110	825

TABLE 2.5
Elastic Resilience of Selected Materials

Material	U_r (J/m ³)	Rank
AA 2024-T6	8.51×10^5	2
AISI 304 stainless steel	1.09×10^5	4
AISI 1040 cold drawn steel	5.06×10^5	3
Ti-6Al-4V	3.09×10^6	1

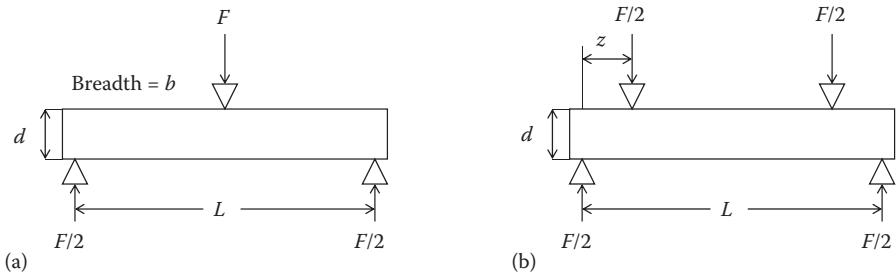


FIGURE 2.9
(a) Three-point bend test and (b) four-point bend test.

rectangular beam of breadth b and depth d is loaded by a universal testing machine, as shown in Figure 2.9.

The bend strength of a rectangular specimen can be evaluated using the general bending equation; thus,

$$\sigma_b = \frac{My}{I} \tag{2.25}$$

where M is the applied moment calculated from the applied load that causes fracture, y is the distance from the neutral axis to the top surface of the beam (in this case, where the beam is perfectly symmetrical, the neutral axis sits in the central axis; therefore, $y = d/2$) and I is the second moment of area and for a rectangular beam can be calculated from

$$I = \frac{bd^3}{12} \tag{2.26}$$

The bend strength is often referred to as the modulus of rupture (MOR) and can be calculated from the following equations:

$$\text{Three-point bend test} \quad MOR = \frac{3}{2} \frac{FL}{bd^2} \tag{2.27}$$

$$\text{Four-point bend test } MOR = \frac{3Fz}{bd^2} \quad (2.28)$$

However, there is a severe limitation in using the *MOR* for evaluating the fracture strength of brittle materials such as ceramics as the result will depend on the size of the sample and the test method used. For example, the three-point test method will tend to give higher results of the fracture strength of the sample when compared to the four-point test method. This has simply to do with the way in which the stress acts along the length of the specimen due to the applied moment.

The four-point test method produces a more uniform stress distribution when compared to the three-point test method, and therefore, more of the sample is loaded at an elevated stress level. For ceramics, the failure is determined by the presence of a critical flaw, and so, the sample is more likely to fail under the action of a smaller applied load. Therefore, the measured fracture strength will be lower.

Brittle materials such as ceramics do not possess high toughness values, and the strain to failure under tensile loading conditions is very low (<0.001%); therefore, deformation is difficult to measure. The toughness of a ceramic can be measured using a similar method shown in Figure 2.9. However, this time, a crack of known length is artificially machined into the sample on the tensile side of the specimen (in this case, the bottom), the load increased until the crack propagates and the sample fails catastrophically. The fracture toughness of the sample can then be calculated from the load at fracture, the initial crack geometry and the geometrical aspects of the sample. Fracture toughness can also be measured by applying an indenter (usually a Vickers) under load to the sample as we do when measuring the hardness of the material (see Section 2.6). When the load is removed, the sizes of the cracks that emanate from the sides of the indentation are measured, and the toughness can be calculated from their length and the hardness of the ceramic. Fracture toughness has the units of MPa m^{1/2} and for a ceramic can be as little as 2 MPa m^{1/2}; for metals, the values will range from around 20 to 200 MPa m^{1/2}.

2.6 Hardness

For the disruption of a projectile, an important material property is hardness. The hardness of a material is a measure of the material's resistance to indentation, abrasion and wear; there are a number of ways that this can be measured.

The Vickers hardness number (VHN), or Vickers pyramid number, is one of the most widely used measures of hardness, and it is evaluated by using a diamond indenter with an apex angle of 68° . A load is applied to the indenter such that it embeds itself within the sample material; the size of the indentation is a direct measure of the sample's hardness. The VHN is then calculated by

$$\text{VHN} = 1.854 \cdot \frac{F}{d^2} \tag{2.29}$$

where F is the load applied to the indenter, and d is the average distance between the opposite apexes of the diamond indentation (see Figure 2.10a).

The Knoop hardness number (KHN) is measured using an elongated pyramid indenter, and it can be calculated from

$$\text{KHN} = 14.2 \cdot \frac{F}{l^2} \tag{2.30}$$

where l is the length of the indentation along its axis (see Figure 2.10b).

The Knoop hardness test is generally carried out on very hard ceramics. Other hardness measurement methods include the Brinell test where a hardened steel ball is used as the indenter. The Brinell hardness number (BHN) is the applied force F divided by the surface area of the indentation. Therefore,

$$\text{BHN} = \frac{2F}{\pi D \left(D - \sqrt{D^2 - d_0^2} \right)} \tag{2.31}$$

where D is the diameter of the ball (see Figure 2.10c), and d_0 is the diameter of the indentation. This hardness measurement is commonly used for metals and is not appropriate for most ceramics due to the hardness of the ceramic overmatching the steel ball indenter. This is a commonly used hardness metric that is quoted for armour-grade steels. Sometimes, it is convenient to use

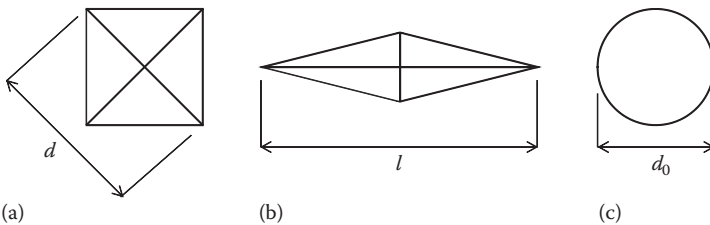


FIGURE 2.10 Top-view geometries of hardness indentations: (a) Vickers, (b) Knoop and (c) Brinell.

TABLE 2.6

VHN Hardness and UTS Values of Some Typical Armour Materials

Material	VHN	UTS (MPa)
Aluminium alloy 7039 (armour plate)	130–150	450–480
RHA steel	270–350	900–1200
High-hardness armour (HHA) steel	500–550	1600–1900
Alumina (ceramic)	1300–1800	–
Silicon carbide (ceramic)	1900–2800	–

the *Meyer hardness* measurement instead of Brinell; this is simply calculated from the applied load divided by the projected surface area of the indenter.

Measuring the hardness of hard brittle materials such as engineering ceramics is problematic at best. If too small a load is applied to the indenter, then a very small indentation is left that can be difficult to measure accurately. If too large a load is applied, then the edges can spall, leading to problems in measuring the size of the indentation. Ideally, the sample should be polished, flat and parallel, and the indenter should be applied perfectly perpendicular to the sample to ensure a symmetrical indentation. Recording the applied load is also critical, as the measured hardness value will be affected by it. Typical VHN values of some armour materials are presented in Table 2.6 along with the UTS for each material.

For metals, the hardness of a material can be related to a material's UTS with a linear relationship. Table 2.6 shows why materials such as alumina and silicon carbide make very good disruptors. However, these materials are relatively brittle and therefore are susceptible to fragmentation.

2.7 Dynamic Behaviour of Materials

When a bullet, penetrator or shaped charge jet impacts and penetrates a material, the rate of deformation the projectile encounters is much higher than is observed when compared to conventional quasi-static material tests discussed in Section 2.5. The behaviour of the metal (projectile) and the armour target is different at high rates of loading than at relatively low loading rates. Frequently, it is necessary to understand how the armour material behaves under dynamic loading, and there are various tests that can be used to assess behaviour and measure properties. Figure 2.11 summarises the range of strain rates that are of interest to material scientists and engineers. Note that the units of strain rate are s^{-1} . As the strain rates are increased, it is necessary to use different techniques to probe the response of the material and to measure the state of stress under dynamic loading.

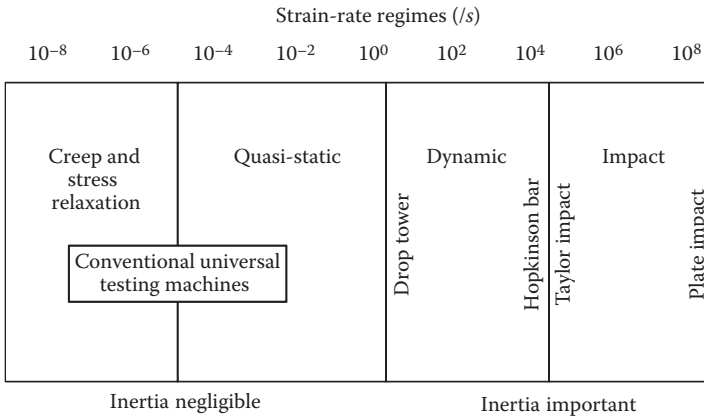


FIGURE 2.11

Strain-rate regimes. (Reprinted from *International Journal of Impact Engineering*, 30 (7), Field, J. E., S. M. Walley, W. G. Proud, H. T. Goldrein, and C. R. Siviour, 725–775, Copyright 2004, with permission from Elsevier.)

For materials that are subjected to relatively high strain rates (when compared to quasi-static values), their strengths can change and, for most materials, increase markedly. Generally speaking, metals will get stronger but less ductile at elevated strain rates, but unlike some non-metals, their stiffness is relatively unaffected by increased deformation rates.

The reason for the increased strength with strain rate is due to complex micro-structural behaviour that is dependent on the nature of the material. For example, with most metals, the mechanism can be explained by dislocation movements being impeded during plastic deformation. For long-chain polymers, the strain-rate sensitivity is due to molecules becoming entangled at high rates of loading, and therefore, their relative movement is impeded. A good demonstration of this effect can be shown with ‘silly putty’. Rolling a sample of silly putty into a sausage and pulling it apart (just using your hands) at different rates produces very different results. At low strain rates, the silly putty behaves much in the same way as a viscous fluid and is able to flow. Very little resistance to flow is offered by the material. At higher rates of loading, the user will experience a resistance to flow as the long-chain molecules bind up. Brittle failure usually ensues.

For most metals, it is generally recognised that the dynamic yield strength of a material (or flow stress) can be defined by the following proportionality:

$$\sigma \propto \ln \dot{\epsilon} \tag{2.32}$$

where $\dot{\epsilon}$ is the strain rate; it has the unit of s^{-1} . The flow stress in this case is the stress taken at any point along the plastic stress–strain curve. During inelastic deformation, a considerable amount of work is converted to heat.

This can lead to thermal softening of the metal where the flow strength of the material is reduced with increasing temperature. For high strain-rate applications, the process is adiabatic as there is little time for heat to be dissipated in the surrounding material. This gives rise to localised thermal softening. The effect of thermal softening on the yield strength of a metal can be described by the following equation:

$$\sigma = Y \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (2.33)$$

where T_m is the melting temperature, and T_r is some reference temperature (such as the room temperature), T is the measured temperature and Y is the yield strength of the material. The exponent m is called the thermal softening exponent and is constant for a known material.

Johnson and Cook (1983) brought these equations together along with a strain hardening term to describe the tensile flow stress of a number of metals. It has now become one of the most widely used equations to describe the flow stress of a material subjected to large strains, strain rates and temperature and is regularly used within computational codes called hydrocodes that can simulate dynamic phenomena such as impact and penetration (mainly because of its elegant simplicity). The Johnson–Cook equation is given by

$$\sigma = \left(A + B\varepsilon_p^n \right) (1 + C \ln \dot{\varepsilon}) \left(1 - \left(\frac{T - 298}{T_m - 298} \right)^m \right) \quad (2.34)$$

where

A is the yield strength of the material.

B is strain hardening constant.

ε_p is the amount of plastic strain.

n is the strain (or work) hardening exponent.

C is a strain-rate constant.

m is the thermal softening exponent.

T_m is the melting temperature. The temperatures are measured in degrees Kelvin.

Some Johnson–Cook parameters for aluminium alloys and some steels are shown in Table 2.7.

Notably, there are other constitutive models that describe the dynamic behaviour of materials, and the reader is directed to seminal works by Steinberg et al. (1980), Zerilli and Armstrong (1987) and Follansbee and Kocks (1988) as examples. A good overview of these and other constitutive models is provided by Meyers (1994).

TABLE 2.7

Properties for the Johnson–Cook Equation

Material	Ref.	<i>A</i> (MPa)	<i>B</i> (MPa)	<i>n</i>	<i>C</i>	<i>m</i>	<i>T_m</i> (K)
Al 5083 ^a	(Gray III et al. 1994)	270	470	0.600	0.0105	1.200	933
Al 7039	(Johnson and Cook 1983)	337	343	0.410	0.0100	1.000	877
Al 7039 ^a	(Gray III et al. 1994)	220	500	0.220	0.0160	0.905	933
Ti–6Al–4V (low cost)	(Meyer, Jr. and Kleponis 2001)	896	656	0.500	0.0128	0.800	1930
1006 steel	(Johnson and Cook 1983)	350	275	0.360	0.0220	1.000	1811
4340 steel	(Johnson and Cook 1983)	792	510	0.260	0.0140	1.030	1793
RHA	(Gray III et al. 1994)	1225	1575	0.768	0.0049	1.090	1783
HHA	(Johnson and Holmquist 1989; Gray III et al. 1994)	1504	569	0.220	0.0030	0.900	1783

^a The plate was obtained directly from the manufacturing line for the Bradley infantry fighting vehicle.

For ceramic materials, it is generally accepted that their strength is relatively insensitive to strain rate until around $10^2/s$ – $10^3/s$ is reached. At this point, the strength of the ceramic becomes highly strain-rate sensitive. The reason for this is unclear, although some researchers have suggested that crack inertia plays a part (Lankford 1981; Walley 2010) (i.e. the crack growth rate determines the strain rate–sensitive nature of these materials). However, ultimately, there are a multitude of problems with testing the high strain-rate response of ceramics due mostly to their highly brittle nature and high compressive strength (Walley 2010).

There is a school of thought that suggests that the strain-rate response of ceramic materials in particular is less important than their pressure-dependent behaviour. Further, it is possible that during bullet penetration, the resistance offered by highly fractured material is affected by the local pressure. It is known that as a projectile penetrates a ceramic target, the material at the impact site changes very quickly from an intact state to a highly broken or comminuted state. The challenge is measuring the strength of this material during a penetration event. Various attempts have been made to assess the properties of comminuted ceramic materials, and the evidence suggests that there is a considerable stiffness reduction, and there is possibly a cap on the maximum strength that such material can withstand. However, what is surprising is that broken ceramic still has use in resisting penetration.

There are various tests that can be used to investigate the high strain rate of materials, and a brief review is given here. Notably, more extensive reviews can be found in references (Meyers 1994; Field et al. 2004). Each test

TABLE 2.8

Summary of Common Material Testing Techniques

Test	Velocity of Impactor (m/s)	Stress/Strain Condition	Strain Rate (/s)	Result of Test
Quasi-static tensile/compression test	Not measured	Uniaxial stress	10^{-4} – 10^{-2}	Stress–strain curve
Charpy impact test	Not measured	Combined stress	10^2 – 10^3	Impact energy required to break notched coupon
Instrumented drop tower	1–25	Variable	10 – 10^2	Force–time curve
Split-Hopkinson pressure bar (SHPB) test	5–40	Uniaxial stress	10^2 – 10^3	Dynamic stress–strain curve
Taylor test	100–500	Combined stress	10^2 – 10^4	Dynamic strength; validation of computational models
Flyer plate test	100–4000+	Uniaxial strain	10^5 – 10^7	Hugoniot curves; Hugoniot elastic limit (HEL) measurements; spall strengths

that will apply stress to the material is a slightly different fashion to another test. Table 2.8 summarises these tests.

2.7.1 Charpy Impact Test

This test was developed to examine the amount of energy that was expended during an impact. It is sometimes referred to as the Charpy V-notch test, and the Charpy V-notch test is an American Standards of Testing Materials (ASTM) standard.

A Charpy impact test consists of releasing a pendulum of a fix mass and length such that it impacts a V-notched sample. Despite the fact that the velocity of impact is low (~ 5 m/s), the strain rate accessed in a Charpy test can be quite high due to the small dimension over which plastic deformation occurs (Meyers and Chawla 1999). The sample is square in cross section and has a V-notch machined into one surface. Once fracture occurs in the sample, the amount of energy that is transferred to the sample can be estimated by measuring the initial and final heights of the pendulum. This provides a measure of the energy to fracture the sample. Both the size of the notch and the size of the sample affect the result, and therefore, this test is only used to compare the impact toughness for identical geometries of samples. Hence, the results are more qualitative in nature and are generally of little use for design purposes – except in the sense of when comparing like materials.

A variation on the theme of the test is the Izod test with the principal difference being the way in which the specimen is supported.

2.7.2 Instrumented Drop Tower Test

Instrumented drop towers are not usually used to measure the dynamic properties of materials, although they can be configured to do so. A single drop tower can be configured for both compression and tensile tests, and the main data collection is usually achieved through a piezo-elastic transducer located in the impactor (or 'tup'). Equally, strain data are acquired through the use of a strain gauge applied to the sample or by visual means using a high-speed camera. Velocities of impact are quite modest ($\sim 1\text{--}25$ m/s), and the main purpose of the machine is to simulate an impact from a dropped mass at height by either dropping the tup mounted on a carriage from the actual height or from a 'simulated' height through the use of spring acceleration or a bungee cord attached to the carriage and base.

2.7.3 Split-Hopkinson Pressure Bar Test

The split-Hopkinson pressure bar apparatus was developed in the 1940s by Herbert Kolsky (it is sometimes referred to as the Kolsky bar). It is principally used to derive a dynamic stress-strain curve for a material at varying temperatures, and therefore, it ideally lends itself for furnishing constitutive models, such as the Johnson-Cook strength model discussed in Section 2.7.

Essentially, a projectile (or striker bar) strikes an incident bar so that the pulse that is measured within it is large with respect to the size of the specimen. The incident bar must remain elastic, and therefore, the wave that is travelling along it is elastic in nature; typically, this means that the incident bar is made from a material with high (or relatively high) yield strength such as maraging steel. Other materials (including aluminium and magnesium alloys) are used when the specimen in question is of low impedance. The elastic wave traverses the incident bar and reaches the specimen that is sandwiched between it and the transmitted bar. Again, the transmitted bar remains elastic. Strain gauges are attached to both the incident and transmitted bars to measure the strain. Measurements are made of the incident pulse, the reflected pulse (reflected from the sample) and the transmitted pulse. From these three pulses, a stress-strain relationship can be established for the sample; strain rates of $10^2\text{--}10^4/s$ are usually accessible by this technique.

It is important to note that the state of stress is not directly measured from the sample but rather calculated from the incident, reflected and transmitted pulses. The sample is plastically deformed during the process, and this is achieved either by using a sample of lower impedance and/or yield strength or cross-sectional area change that 'amplifies' the stress in the sample according to

$$\sigma(t) = E \frac{A_0}{A_s} \varepsilon_T(t) \quad (2.35)$$

where σ is the stress in the specimen, E is the Young's modulus of the bars, A_0 is the cross-sectional area of the bar, A_s is the cross-sectional area of the specimen and ε_T is the transmitted strain measured in the transmitter bar.

The strain rate $\dot{\varepsilon}(t)$ and strain $\varepsilon(t)$ in the specimen are then given by the following equations:

$$\dot{\varepsilon}(t) = -\frac{2c}{l_s} \varepsilon_R \quad (2.36)$$

$$\varepsilon(t) = -\frac{2c}{l_s} \int_0^t \varepsilon_R \cdot dt \quad (2.37)$$

where l_s is the current length (or thickness) of the specimen, ε_R is the reflected strain magnitude and c is the elastic wave speed in the bar and can be calculated using

$$c = \sqrt{\frac{E}{\rho}} \quad (2.38)$$

Two important assumptions are made in the derivation of these equations: (i) The forces on the two ends of the specimen are identical, and (ii) the specimen plastically deforms at constant volume. The full theoretical derivation of the theory is provided in Gray III (2000).

Different materials can be tested with this technique, and typically, specimens are quite small in diameter. However, given that a large number of grains (crystals) are required to ensure that the specimen behaves as a bulk material, large-grained materials (or material with large aggregate present such as concrete) require larger apparatus (e.g. 200 × 200 mm; see Albertini et al. 1999).

2.7.4 Taylor Test

The Taylor test was developed by G. I. Taylor (1946, 1948) to examine the high-rate response of ductile materials and is achieved by simply firing a rod onto a rigid anvil. Modern high-speed photographic techniques have provided a route to study the real-time deformation of the rod from which pertinent high strain-rate data can be derived. During the experiment, the rod is fired at the anvil and recovered, and the deformation is measured.

The mechanics of how the Taylor rod deforms can be described as follows. On impact, an elastic wave traverses along the length of the rod at the elastic wave speed. This is followed by the slower-moving plastic compression wave. When the elastic compression wave reflects off the rear surface of the rod, it travels back towards the impact face as a release wave. At some point, the elastic release wave and the plastic compression front collide, and the plastic deformation ceases due to the stress being released to zero. Thus, the recovered sample will have a plastically deformed section of a given length that can be measured.

2.7.4.1 Introductory Concepts

The theoretical treatment of how a rod plastically deforms when striking an anvil will now be considered as this is relevant to the deformation of bullets during the impact of a target. It can be considered that the rod can plastically deform such that h is the temporal thickness of the plastically deformed section, x is the length of material that has not been plastically compressed and u is the velocity of the material that has not been compressed (i.e. including the end of the rod); U is the rod's impact velocity and is initially equal to u (the velocity of the rear boundary) until the arrival of the elastic wave. The following equations describe the small changes in u , h and x during one passage of the elastic wave from the plastic boundary and back to it.

The time taken for the passage of the elastic wave to traverse from the elastic boundary and back to it (see Figure 2.12) is

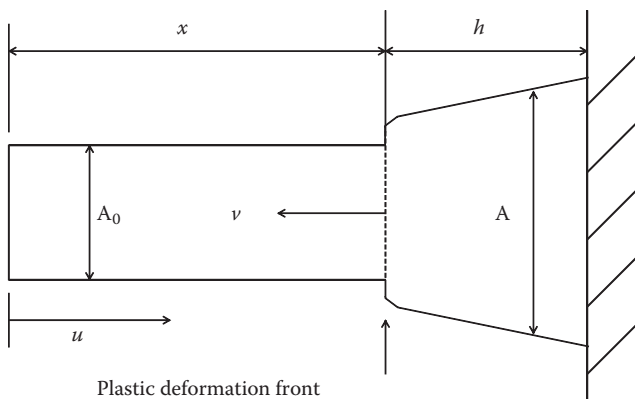


FIGURE 2.12

Taylor impact test showing the plastic deformation front and associated dimensions.

$$dt = \frac{2x}{c} \quad (2.39)$$

where c is the elastic wave velocity.

The extension to the plastic portion in the rod during this time (i.e. $2x/c$) is

$$dh = v \frac{2x}{c} \quad (2.40)$$

where v is the velocity of the plastic wave front.

The reduction in length of the elastic portion during this time (i.e. $2x/c$) is

$$dx = -(u + v) \frac{2x}{c} \quad (2.41)$$

Remember that $dx \neq dh$ due to the elastic portion continuing towards the anvil at velocity u .

2.7.4.2 Approximate Formula for Estimating the Yield Point

To establish an approximate formula for estimating the yield strength from the measurements of slugs after impact, Taylor (1948) presented the following analysis assuming that the plastic-elastic boundary moves outwards from the impact face at a uniform velocity to its final position. It should be noted that in the following analysis, the plastic wave front velocity v is a constant.

It is already known (from Equation 2.39) that

$$dt = \frac{2x}{c} \quad (2.42)$$

But the velocity of the plastic wave front is given to us by

$$v = \frac{dh}{dt} \quad (2.43)$$

Therefore,

$$dh = v \cdot dt = v \frac{2x}{c} \quad (2.44)$$

And

$$\frac{dx}{dt} = -(u + v) \quad (2.45)$$

It is also known that the change in the velocity of the back portion of the velocity is given to us by

$$du = -\frac{2Y}{\rho_0 c} \quad (2.46)$$

It will be seen in Chapter 5 how this formula is derived; essentially, this is the formula for the particle velocity in the material at the free surface (Meyers 1994). Here, it is assumed that the material is elastic–perfectly plastic, and therefore, the plastic stress is constant irrespective of strain.

As

$$dx = -(u + v) \frac{2x}{c} \quad (2.47)$$

$$\frac{du}{dx} = \frac{Y}{(u + v)\rho_0 x} \quad (2.48)$$

Integrating

$$\int (u + v) du = \frac{Y}{\rho_0} \int \frac{dx}{x} \quad (2.49)$$

$$\frac{(u + v)^2}{2} = \frac{Y}{\rho_0} \ln x + C \quad (2.50)$$

Initially, it is known that $u = U$ and $x = L$ (the initial length of the rod). So now, C can be solved, and this gives

$$\frac{(u + v)^2}{2} - \frac{(U + v)^2}{2} = \frac{Y}{\rho_0} \ln \left(\frac{x}{L} \right) \quad (2.51)$$

$$\frac{u^2}{2} + vu - \frac{U^2}{2} - vU = \frac{Y}{\rho_0} \ln \left(\frac{x}{L} \right) \quad (2.52)$$

However, in the final state, when $u = 0$, $x = X$; therefore,

$$-\frac{U^2}{2} - vU = \frac{Y}{\rho_0} \ln\left(\frac{X}{L}\right) \quad (2.53)$$

Now, to eliminate v , it is assumed that the time taken to decelerate the rod to zero could be given by

$$T = \frac{L_1 - X}{v} = \frac{2(L - L_1)}{U} \quad (2.54)$$

Therefore,

$$\frac{v}{U} = \frac{(L_1 - X)}{2(L - L_1)} \quad (2.55)$$

which, when substituted into Equation 2.53, becomes

$$Y = \frac{\rho_0 U^2 (L - X)}{2(L - L_1) \ln\left(\frac{L}{X}\right)} \quad (2.56)$$

Measurements are taken according to Figure 2.13. Taylor pointed out that this equation is only an approximation as a uniform deceleration ($v = \text{const}$) has been assumed. In reality, deceleration is non-uniform. However, as a first-order approximation, it gives reasonable values when compared to Whiffin's (1948) experimental results.

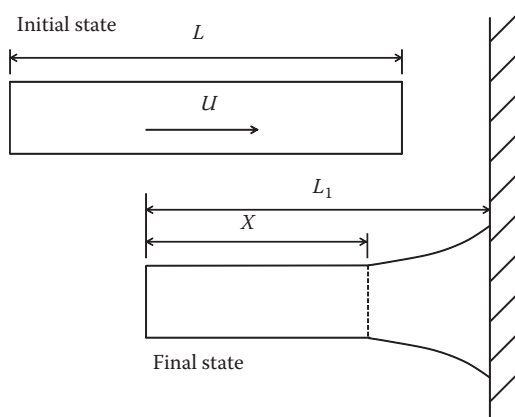


FIGURE 2.13

Taylor test showing before and after states.

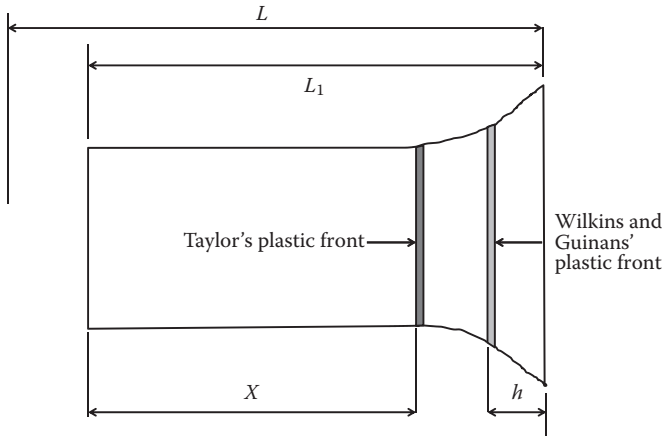


FIGURE 2.14 Deformation of the rod showing the positions of the deformation front as assumed by Taylor (1948) and Wilkins and Guinan (1973). (From Taylor, G., *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 194 (1038):289–299, 1948; Wilkins, M. L., and M. W. Guinan, *Journal of Applied Physics*, 44 (3):1200–1206, 1973.)

Wilkins and Guinan (1973) built up Taylor’s analysis and developed a similar model for establishing the yield point of a material from recovered specimens based on Newton’s second law ($F = ma$). They showed that

$$\frac{L_1}{L} = \exp\left(-\frac{\rho_0 U^2}{2Y}\right) \tag{2.57}$$

Again, similar to Taylor, this implied that the only parameters that affected a cylinder’s geometry after impact were the density and the yield strength of the material. Using computer simulations, they also showed that the profile of the projectile gives an erroneous location of the plastic front that decelerates the elastic portion, and it actually stays closer to the rigid boundary than originally thought (see Figure 2.14). To account for this, they showed that

$$\frac{L_1}{L} = \left(1 - \frac{h}{L}\right) \exp\left(-\frac{\rho_0 U^2}{2Y}\right) + \frac{h}{L} \tag{2.58}$$

where h is the distance from the anvil to the plastic wave front that contributes to the deceleration.

In this analysis, they noted that the position to which the plastic wave moved was independent of velocity but proportional to the original length of the specimen (i.e. $h/L = \text{const.}$).

Example 2.4

A mild steel-cored bullet strikes a rigid steel armour plate at 200 m/s. The original length of the bullet was 25 mm. If computer simulations show that the plastic wave front ceased at $h = 5$ mm from the rigid surface, and the final length of the bullet was 15 mm, calculate the yield strength, Y , of the bullet.

Firstly, let us look at Taylor's (1948) approach. We are going to assume that in this case, the position of the plastic boundary, h , is the same position of the plastic boundary as assumed by Taylor.

So,

$$\begin{aligned} X &= L_1 - h = 15 \times 10^{-3} - 5 \times 10^{-3} \\ &= 10 \text{ mm} \end{aligned}$$

From Equation 2.56, it is seen that

$$\begin{aligned} Y &= \frac{\rho_0 U^2 (L - X)}{2(L - L_1) \ln\left(\frac{L}{X}\right)} = \frac{7800 \times 200^2 (25 \times 10^{-3} - 10 \times 10^{-3})}{2(25 \times 10^{-3} - 15 \times 10^{-3}) \ln\left(\frac{25 \times 10^{-3}}{10 \times 10^{-3}}\right)} \\ &= 255 \text{ MPa} \end{aligned}$$

This problem will now be analysed using the work of Wilkins and Guinan (1973), but first, Equation 2.58 needs to be rearranged to find Y . This is given by

$$Y = \frac{-\rho_0 U^2}{2[\ln(L_1 - h) - \ln(L - h)]} \quad (2.59)$$

and therefore

$$\begin{aligned} Y &= \frac{-7800 \times 200^2}{2[\ln(15 \times 10^{-3} - 5 \times 10^{-3}) - \ln(25 \times 10^{-3} - 5 \times 10^{-3})]} \\ &= 225 \text{ MPa} \end{aligned}$$

So, both types of analysis provide similar results for the yield strength of the bullet core with the Wilkins and Guinan method providing a more conservative result. Note that larger differences are observed when there

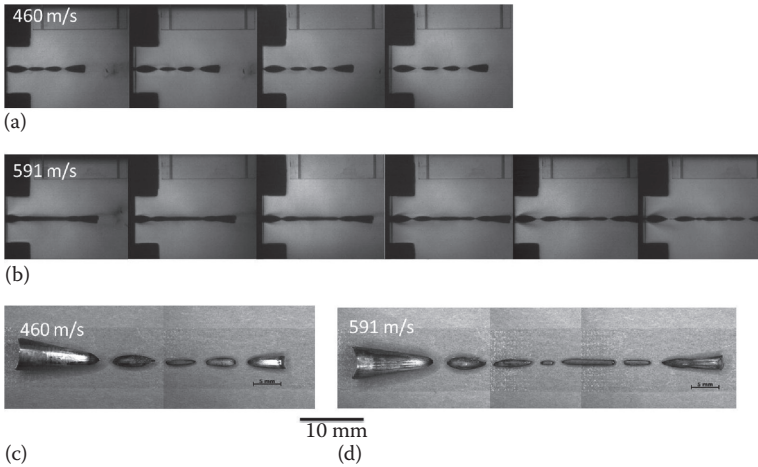


FIGURE 2.15

High-speed photography showing how zirconium samples exited a die after extrusion (a and b). Stereographic images of reassembled Z_r specimens (c and d). (Reprinted from Escobedo, J. P. et al., *Acta Materialia*, 60 (11), 4379–4392, Copyright 2012, with permission from Elsevier.)

are small deformations (i.e. $L_1 \rightarrow L$). This analysis assumes that the final plastic wave front position is the same.

2.7.5 Dynamic Extrusion Test

A modification to the Taylor test is the dynamic extrusion test where, instead of a rod being fired at a flat anvil, a sphere or bullet-shaped projectile is fired into a conical die. The purpose of this is to look at the main deformation modes and examine how the material fails as it is being stretched during the dynamic extrusion process. This technique was first proposed by Gray et al. (2006) for copper and has subsequently been used to investigate other materials. Figure 2.15 shows some results of dynamically extruded zirconium (Escobedo et al. 2012). Here, the necking and failure are captured using high-speed photography. The material is subsequently decelerated in a low-density medium to soft-capture the fragments for microstructural analysis. The high-speed photography data are particularly useful for the validation of constitutive models and provide a route for tweaking material property data in the model.

2.7.6 Flyer-Plate Test

Flyer-plate tests were developed to examine shock wave propagation in materials, and these experiments take the material to extremely high strain rates.

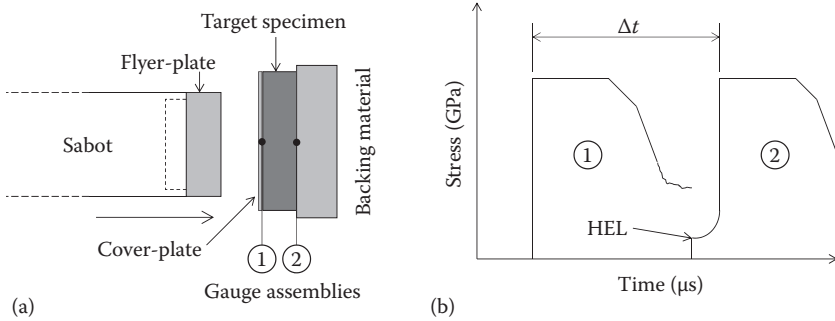


FIGURE 2.16

(a) A schematic of the flyer-plate technique where gauges are employed and (b) the expected gauge response when the backing material has the same shock impedance as the target material.

A typical experimental set-up is shown in Figure 2.16. Here, a flyer plate is accelerated towards the target and arrives so that all points on the projectile's surface make contact with the target simultaneously. Consequently, both the flyer plate (projectile) and the target need to be lapped to very high tolerances (typically $<\pm 5 \mu\text{m}$). Projectile alignment before impact is also important. The impact of a flyer plate generates a planar shock wave in the target. In this situation, all strain is accommodated along the impact axis, whilst the orthogonal components of strain are zero due to inertial confinement. Consequently, the orthogonal components of stress are non-zero. Therefore, in summary, the conditions of stress and strain are written in the target as

$$\varepsilon_x \neq \varepsilon_y = \varepsilon_z = 0 \quad \text{and} \quad \sigma_x \neq \sigma_y = \sigma_z \neq 0, \quad (2.60)$$

where the subscript x denotes the condition along the impact axis, and the subscripts y and z denote the conditions orthogonal to the impact axis.

The set-up shown in Figure 2.16 denotes a gun-launched flyer plate mounted on a sabot, although it is also possible to explosively accelerate a flyer plate. In this experimental set-up, two spatially separated gauges are shown to measure the shock wave velocity in the material (attached to a suitable digital storage oscilloscope) and stress within the sample. A cover plate is necessary to protect the first gauge and would be made from the same material as the flyer plate. The first gauge records a rapid rise in stress due to the arrival of the shock wave followed by a plateau stress (referred to as the Hugoniot stress) and an elastic-plastic release. The second gauge records a precursor wave that has separated out from the main shock front, and this is apparent when the shock wave velocity is slower than the elastic wave speed in the material. The magnitude of the precursor is known as the Hugoniot elastic limit (HEL) and is analogous to the yield strength of the material. The HEL has been linked to the ballistic performance of certain materials such

as ceramics. This is followed by post-yield flow and the 'plastic' shock front. The shock velocity is then established by measuring Δt , and with knowledge of the sample thickness, it is possible to calculate the shock wave velocity.

These types of experiments are fundamental to the establishment of an equation of state for the material by providing a reference curve called a Hugoniot. Once a Hugoniot is established, the parameters for the equation of state can be calculated that can be input into hydrocodes (such as ANSYS AUTODYNTM or LS-DYNA), which are commonly used to simulate the ballistic response of materials. It is important to realise that the Hugoniot is not a plot of the history of pressure increase as a shock is formed but rather that it is a locus of all the possible shock states achievable. This will be discussed in more detail in Chapter 5 where stress waves and shock are examined.

2.8 Summary

Material science plays a large role in armour designs, and having a good understanding of how materials behave under load is crucial for good designs. In particular, bullets, bombs and blast push materials to their extreme limits of strength, and therefore, it is good to know how materials fail. Materials have a theoretical strength – that is, the maximum strength that can be achieved for a perfectly uniform structure that is defect-free. However, all materials possess defects that compromise their ability to withstand load. We have seen in this chapter that crystals have natural defects called dislocations, and these play a role in how a material will deform plastically.

We have seen that the behaviour of materials at elevated deformation rates is generally different than at lower deformation rates. Therefore, the behaviour of a bullet striking a target cannot be predicted just from knowing the quasi-static values of strength and ductility (although they do serve as a good approximation in the first instance). A complete picture of the work hardening, strain-rate sensitivity and thermal-softening characteristics of the jacket, core and target will help us understand how the bullet penetrates.

There are a number of techniques that can be employed to investigate the high strain-rate response of a material, and these have been quickly reviewed here. These techniques subject the material to different loading rates and subject the sample to different stress states. The results from these tests can then be used to input into computer codes to simulate complex loading problems.

3

Bullets, Blast, Jets and Fragments

3.1 Introduction

Before we look at the technologies that help in saving lives, we need to assess what has historically been designed to take life away. It is only with a full understanding of these technologies that we can begin to assess how to protect. The mechanisms of damage can be quite varied, and therefore, an introduction to bullets, blast, jets and fragments is given here.

3.2 Small-Arms Ammunition

The word ‘ammunition’ is the term given to describe a bullet and its associated components that give it velocity. So, in the case of small arms, the ammunition is composed of (see Figure 3.1)

- a. The primer
- b. The cartridge
- c. The propellant
- d. Any ancillary piece (such as propellant packing)
- e. The projectile (bullet)

Small-arms ammunition is typically characterised by the fact that the projectiles (or ‘bullets’) are small (relatively speaking), and the weapon system can be carried in an individual’s ‘arms’. The bullet generally consists of a penetrating mass (i.e. the bit that does all the work during penetration) surrounded by a gilding jacket that acts as a barrier, protecting the core of the bullet from the rifling of the barrel. Other types of bullets include incendiary and tracer rounds – these will not be covered here. The bullet itself comes in all sorts of shapes and sizes. Most bullets possess an ogival nose simply for aerodynamic stability and to reduce drag during flight. Similarly, some

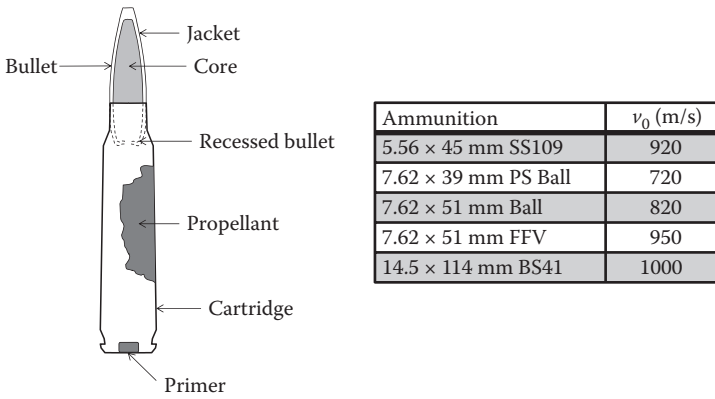


FIGURE 3.1 Small-arms ammunition. Inset: a table of typical muzzle velocities (v_0) for different bullets.

bullets may have a ‘boat tail’ (that is, a slightly reduced diameter at the base) to reduce drag at the rear of the bullet.

3.2.1 Bullet Notation

Ammunition is usually described in terms of the bullet’s calibre and cartridge length. So, the ammunition that is described as 7.62 × 51 mm refers to a bullet of calibre of 7.62 mm and a cartridge length of 51 mm. Usually, the actual diameter of the bullet will be slightly larger than the stated calibre (by ~0.2 mm), and this is so that the bullet’s jacket can engage in the grooves of the rifling with the calibre being measured to the ‘lands’ of the rifling in the gun barrel. A schematic showing the barrel and how the calibre is measured is given in Figure 3.2.

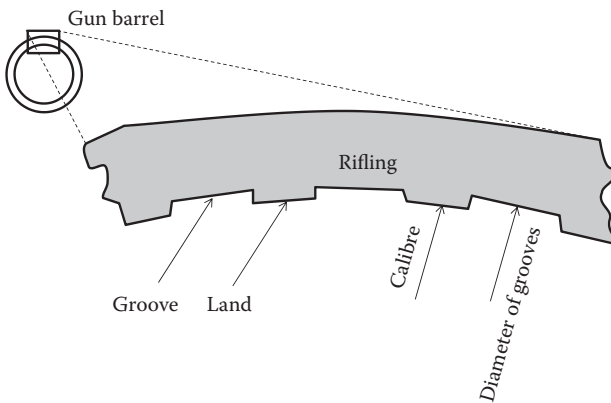


FIGURE 3.2 Definitions of rifling.

The purpose of the rifling is so that stability can be imparted to the projectile by causing it to spin during flight. As the projectile is fired, the rifle lands are driven into the jacket material. The rifling in the gun barrel is designed with a specific twist such that as the bullet moves up the gun barrel, it is forced to turn – thereby inducing its spin.

3.2.2 Penetrability

The effect of the bullet depends largely on its weight, velocity, shape, calibre, stability and the strength (hardness) of the core. For a bullet with a relatively high penetrative ability into armour, a fast, high-strength non-deforming core is important (such as tungsten carbide or hard steel). Such bullets are unsurprisingly called ‘armour-piercing’ (AP) bullets. For a bullet with relatively high stopping power in a human target, a heavy soft-deforming core is important (such as lead or ‘soft’ steel). Such bullets are normally called ‘ball’ rounds, presumably named after the first spherical lead shots.

An example of a ball round is shown in Figure 3.3. The core is made from a relatively soft steel (VHN = 280), which enables it to deform when penetrating the target, and is enveloped by a lead filler and a steel jacket*. These types of bullets are relatively easy to stop with hard materials, and this projectile can be stopped (when fired from 10 m) by as little as 12 mm of mild steel (and less if the steel is an armour-grade). However, the other type of small-arms ammunition (the AP type) is more difficult to stop – mainly because of the relatively high kinetic energy (KE) densities and hardness values of the cores. KE density is a term that is frequently used to describe how penetrative an armour piercing projectile is. It is given by the formula

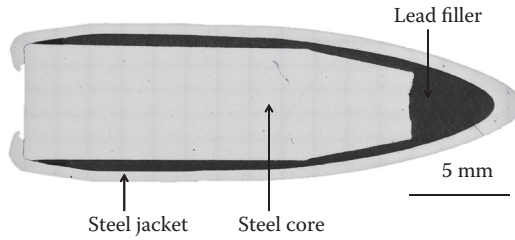
$$KE_d = \frac{mv_0^2}{2A} \quad (3.1)$$

where KE_d is the kinetic energy density, m is the mass of the projectile, v_0 is its velocity, and A is the cross-sectional area offered by the bullet.

For AP bullets, it is common to refer to the KE of the bullet’s core – as it is this that does all the work in penetrating armour. The KE densities of various AP cores are presented in Table 3.1.

Figure 3.4 shows three different AP cores: (1) the Soviet 14.5 × 114-mm API BS41 core with a WC-Co core ($v_0 = \sim 1000$ m/s, $\rho = 14.9$ g/cc, VHN = 1400), (2) the Soviet 7.62 × 54-mm R API B32 steel core ($v_0 = \sim 830$ m/s, $\rho = 7.8$ g/cc, VHN = 920) and (3) the 7.62 × 51-mm FFV core with a WC-Co core ($v_0 = \sim 950$ m/s, $\rho = 14.9$ g/cc, VHN = 1550). Tungsten carbide is a hard and dense material, and therefore, the masses of these types of cores are high compared

* There are a large number of variants of this type of bullet, and the design depends largely on the country of origin.

**FIGURE 3.3**

A polished section of a 7.62 × 39-mm Kalashnikov ball bullet showing the steel core, lead filler and jacket. (Courtesy of J. P. Escobedo.)

TABLE 3.1

KE Densities of a Selection of AP Cores

Designation	Core Material	Core Dia. (mm)	Mass of Core (g)	KE _d (MJ/m ²) ^a
14.5-mm API BS41	Tungsten carbide	10.75	38.3	211
7.62-mm AP FFV	Tungsten carbide	5.60	5.9	108
7.62-mm API B32	Steel	6.09	5.4	63

^a At muzzle velocity.

**FIGURE 3.4**

From left to right: 14.5 × 114-mm BS41 Armour-Piercing Incendiary (API) core, 7.62 × 54-mm R B32 API core and 7.62 × 51-mm Förenade Fabriksverken (FFV) core.

to similar steel-cored rounds (of similar volumes). The muzzle velocities of these WC-Co cored bullets are relatively high too (for small-arms ammunition). Both of these factors lead to an increased KE density.

It is clear that reducing the diameter of the penetrator is important for increasing the level of penetration. Indeed, this is partly the reason why sub-calibre

projectiles were invented in World War II. It was soon discovered that reducing the diameter of the round and housing it within a lightweight sabot, whilst maintaining a relatively large calibre of gun, improved penetrability dramatically.

3.2.3 The Effect of the Bullet's Jacket during Penetration

With tungsten–carbide-cored bullets such as the 7.62-mm M993, the jacket metal is made from soft steel that envelopes a tungsten carbide core with an acute front tip. The jacket serves three main purposes: (1) to protect the barrel from the core, (2) to engage with the rifling of the barrel and (3) to provide a projectile shape optimised for free flight.

The bullet's jacket can affect penetration too – particularly into ceramic-faced armours. It has been known since 1878 that chilled cast iron projectiles would not penetrate a compound armour plate where the impact surface was hard, but when fired at the softer rear surface of the same plate, perforation occurred. This resulted in a Captain English proposing that a projectile with a 'cap' of relatively soft wrought iron would stop the projectile from shattering to secure perforation against a hard face (Johnson 1988). However, it was not until WWII that this technique was extensively applied with the British 6-lb. armour-piercing cap (APC) projectile and armour-piercing cap, ballistic-cap (APCBC) projectile (see Figure 3.5). This is composed of the penetrator fitted with a ductile cap on the nose of the projectile. The purpose of the nose was to inhibit shattering when the projectile impacted a hard target (Goad and Halsey 1982). With modern jacketed projectiles, the impact situation becomes slightly more complex in that hard-cored AP projectiles are

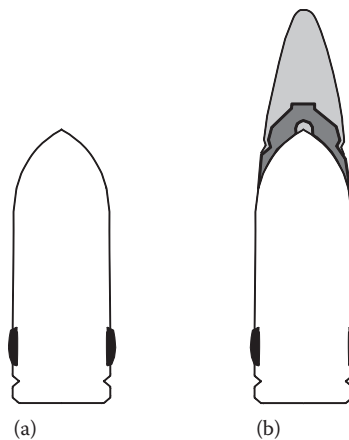


FIGURE 3.5

British 6-lb. AP shot showing (a) an uncapped AP projectile and (b) an APCBC shot. This shell was fired from a 2.24-in. (57-mm) calibre gun and had a mass of ~6 lb. (2.72 kg).

designed to attack hard ceramic-based armour systems where both the core of the projectile and the ceramic plates are intrinsically brittle. Rosenberg et al. (1990) observed that removing the tip of the jacket from a 14.5-mm AP core resulted in poor performance against a ceramic (AD-85) tile, whereas covering the ceramic with 3-mm copper plates appeared to result in the projectile performing better. They concluded that when the hard core impacted the ceramic tile, the lateral confinement of the cover plate prevented radial expansion of the core, and therefore, it could penetrate deeper into the target. Further results have been presented by Hazell et al. (2013) that showed that the jacket appeared to be pre-damaging the ceramic tile before the core arrives – further adding to the complexity.

3.3 Higher-Calibre KE Rounds

Generally, there are two types of higher-calibre KE ammunition that are commonly fielded: the armour-piercing discarding sabot (APDS) round and the armour-piercing fin-stabilised discarding sabot (APFSDS) round (see Figure 3.6).

The APDS round normally consists of a dense core (usually tungsten carbide) with a length-to-diameter ratio (L/d) of between 6 and 7. These have been used in anti-tank guns since the latter part of WWII and have largely been superseded by the APFSDS round. An APFSDS round is usually made from tungsten-heavy alloy (WHA) or depleted uranium (DU) alloy, although



FIGURE 3.6

A tungsten alloy APFSDS round complete with sabot, slipping driving bands and fin protector.

some early Soviet APFSDS rounds were made from maraging steel. These projectiles have L/d ratios of between 15 and 25 and muzzle velocities in the range of 1400–1900 m/s.

DU possesses superior penetrative ability (when penetrating steel) than WHA for two reasons: Firstly, DU is relatively dense. This higher density is particularly important for maximising penetration at elevated impact velocities. Secondly, DU has the ability to self-sharpen during penetration. This is due to a phenomenon called adiabatic shear and is principally caused by the rate of thermal softening exceeding the rate of work hardening during penetration. The disadvantage of DU when compared to WHA is the stiffness – with DU possessing a Young's modulus of 170 GPa as opposed to 300 GPa for a WHA. This means that a DU rod will give a higher deflection for the same stress as it passes through oblique targets. Furthermore, the long-term health consequences of this type of material in ingestible particulate form are, as yet, uncertain. However, due to DU being only weakly radioactive, it is possible to handle these penetrators for a long period of time without any adverse health effect.

The design shown in Figure 3.6 is typical for a large-calibre APFSDS round with a penetrator made from a heavy metal. The rod itself will be sub-calibre, that is, it will have a smaller diameter than the bore of the gun tube from which it is fired. For a 120-mm APFSDS round, rod diameters in the range of 25–35 mm are not uncommon. The rod itself will be carried up the gun tube by a sabot system, and in this case, there are three sabot segments that will become detached from the rod and separate out after the round has left the gun tube. The white plastic rings are the *slipping driving bands* that enable this particular round to be fired from a rifled gun tube – the United Kingdom's L30 120-mm gun from the Challenger 2. These rings engage with the rifling and reduce the amount of spin imparted to the sub-projectile (rod) – which is drag stabilised by six aluminium alloy fins. However, a small amount of spin is still desirable to maintain a stable trajectory as it cancels out any asymmetry in the rod due to manufacturing errors.

Penetration of these types of rods into semi-infinite rolled homogeneous armour (RHA) target stack usually results in a penetration depth roughly equal to the length of the penetrator, which corresponds to a penetration depth of between 400 and 600 mm for 105–120-mm calibre APFSDS rounds.

The typical expected penetration depths from a range of ammunition are summarised in Table 3.2.

3.4 Explosive Materials

Explosives are extensively used in the propulsion of high-velocity fragments or to damage structures by a blast wave, and it is worth mentioning these

TABLE 3.2

Armour-Piercing Capabilities of Machine Gun and Cannon Ammunition:
Thickness of Homogeneous Steel Armour Penetrated at Normal Impact

Calibre	Type	Range (m)	Thickness (mm)
7.62 × 51 mm	Ball	0	8
7.62 × 51 mm	AP	0	15
7.62 × 51 mm	AP (WC)	0	24
12.7 × 99 mm	AP	200	24
12.7 × 99 mm	AP (WC)	200	41
12.7 × 99 mm	SLAP	200	30
14.5 × 114 mm	AP	500	28
14.5 × 114 mm	AP (WC)	500	35
20 × 139 mm	AP	500	30
20 × 139 mm	AP (WC)	500	38
25 × 137 mm	APDS	1000	50
25 × 137 mm	APFSDS	1000	80
30 × 165 mm	AP	1000	36
30 × 165 mm	APDS	1000	54
30 × 173 mm	APDS	1000	61
30 × 173 mm	APFSDS	1000	110
35 × 228 mm	APDS	1000	90
35 × 228 mm	APFSDS	1000	120
40 × 225 mm	APFSDS (CTA)	1500	150
40 × 365 mm	APFSDS	1500	135
50 × 330 mm	APFSDS	1500	135
60 × 411 mm	APFSDS	2000	240

Source: Ogorkiewicz, R. M. *AFV Armour and Armour Systems*. Course notes on: Survivability of Armoured Vehicles, Cranfield University, Shrivenham, Swindon, UK, 18–20 March 2002.

materials here. Notably, the rate of energy release in a detonation is incredibly quick and occurs within the microsecond timescale. Further, the detonation products are gases that are highly compressed, and their expansion produces shock waves in air.

Pure explosives are very difficult to handle, and so these are blended with other explosives or inert materials to change the mechanical behaviour or sensitivity of the material. Typical forms of products include the following: castings, slurries and gels, putties, machined polymer-bonded forms and rubberised materials.

Explosives are separated into two types:

- Primary explosives – sensitive to flame/heat, percussion or friction
- Secondary explosives – less sensitive to external stimuli but reliable in detonation

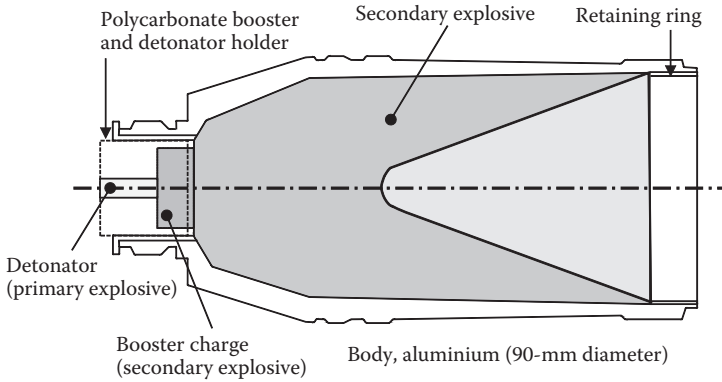


FIGURE 3.7

Shaped-charge warhead showing the presence of the detonator (primary explosive), a booster charge (secondary explosive) and main explosive charge (secondary explosive).

An example of the typical use of explosives in a warhead is shown in Figure 3.7. The detonator is used to initiate the secondary (booster) charge that provides an even detonation front for the main charge. The main purpose of separating out primary and secondary explosives is so that the risk of a massive explosion due to an accident whilst the warhead is in storage is minimised. Thus, the detonators are usually mechanically (or completely) separated from the booster charge until the time comes to arm the warhead.

Once the detonator is initiated, the rapid pressure imparted to the secondary charge initiates the detonation. This process involves the formation of a chemically supported shock wave that traverses the length of the booster charge. This shock wave moves at the detonation velocity, U_D . As it does so, the unreacted material is converted to detonation products over the width of a reaction zone. The interface at which all the material has been converted to the gaseous explosion products is known as the Chapman–Jouguet (C–J) interface. The C–J (or detonation) pressure within the explosive can be estimated from the following equation:

$$P_{CJ} = \frac{\rho U_D^2}{\gamma + 1} \quad (3.2)$$

where ρ is the density of the unreacted explosive, and γ is the polytropic gas constant and for most explosives varies between 1.3 and 3.0.

3.4.1 Blast

In the past decade, this threat has been responsible for a large number of deaths and serious injuries within warzones of both civilians and troops, and therefore, a good understanding of the physics of blast is warranted.

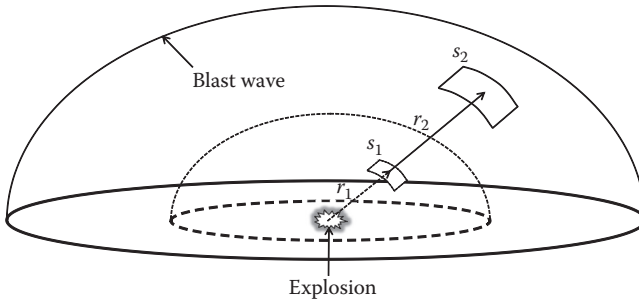


FIGURE 3.8
Expansion of a blast wave.

There have been numerous overviews provided that give a good insight to the physics of blast and the effect on structures, and the student is directed to works by Baker (1973), Baker et al. (1983) and Smith and Hetherington (1994).

When an explosive material is detonated, a chemical reaction occurs in the explosive that results in the expulsion of a gas at such a high rate that a shock wave is formed in air. It is this shock wave that can tear flesh, propel fragments and lift vehicles. Surprisingly, quite a small volume of gas is generated during the detonation. Roughly speaking, a 1-kg mass of trinitrotoluene (TNT) will produce 1000 L of gas as a result of the explosion.

The physics of blast waves is actually quite complicated; however, there is one golden rule for maximising protection against explosive devices: maximise your distance from the explosion. The reason for this is that the blast resultants (pressure and impulse values) decrease very rapidly as the distance from the explosive and the structure that you wish to protect increases. This can be explained by the following qualitative analysis. Figure 3.8 shows a simplified schematic of what can be expected to happen when a mass of explosive is detonated on a flat and horizontal surface. Ignoring 'ground effects' such as the excavation of the surface, it can be seen that as the radius of the blast increases from r_1 to $r_1 + r_2$, the surface area of the blast also increases (from s_1 to s_2). Thus, the energy density that is released by the detonation decreases as the radius increases. The energy density (energy per unit volume) within the blast wave front decreases according to $1/r^3$. Therefore, doubling your distance from a charge leads to a 7/8 reduction in energy density. This is why vehicles that have been designed to withstand mine blast generally have the main cabin high off the ground. So, if you need to provide protection from a blast wave, then putting as much distance between the potential location of the bomb and you is going to help.

3.4.2 Blast Wave Parameters

The pressure time history of a typical blast wave can be described by exponential functions such as the one given by the Friedlander equation (Baker 1973):

$$P(t) = P_0 + P_s \left(1 - \frac{t}{T_s} \right) \exp \left[- \frac{bt}{T_s} \right] \tag{3.3}$$

where b is the waveform parameter, which is a function of the peak overpressure, P_s . Other parameters are defined in Figure 3.9. It should be pointed out that this equation is strictly empirical (i.e. it provides a good fit to observed experimental data) rather than theoretical. Other simpler and more complicated empirical equations exist (see Baker 1973 for a review).

A typical structure of an ideal blast wave is shown in Figure 3.9. Prior to the arrival of the blast wave, the pressure is at ambient (atmospheric) pressure, P_0 . On arrival of the shock front (at time = t_a), the pressure jumps in a discontinuous fashion. The quantity, P_s , is termed the peak side-on overpressure or simply the peak overpressure. The portion of the wave above P_0 is called the positive phase, whereas the portion below P_0 is called the negative phase or the ‘suction phase’.

Other significant parameters include

- T_s = the duration of the positive phase
- i_s = the impulse of the positive phase (calculated by taking the area under the curve in the positive phase). So, this is defined as

$$i_s = \int_{t_a}^{t_a+T_s} P(t).dt \tag{3.4}$$

The shock front is moving at U_s .

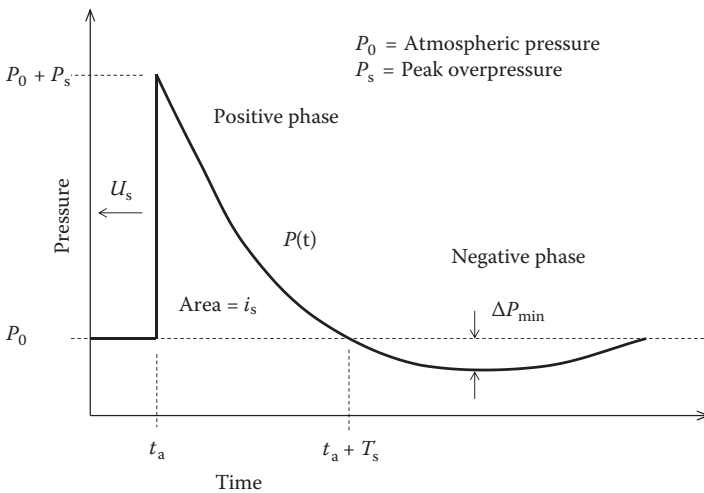


FIGURE 3.9
Ideal blast wave structure due to the detonation of an explosive.

3.4.3 Blast Scaling Laws

It is often convenient to scale the properties of blast waves so that it is possible to predict the properties of blast waves from large-scale explosions based on the measurements from small-scale explosions. The scaling law that is most frequently used is the Hopkinson–Cranz scaling law, which was independently developed by Hopkinson (1915) and Cranz (1926) and is sometimes referred to as the cube-root scaling law. The basis of the scaling law is as follows (Baker et al. 1983): Self-similar blast waves are produced at identical scaled distances when two explosive charges of identical geometry and type but of different sizes are detonated in the same atmosphere.

So, from Smith and Hetherington (1994), consider two charge masses of W_1 and W_2 with diameters of d_1 and d_2 . Note that here, we are breaking from the convention of listing mass by the letter ‘ W ’ instead of the letter ‘ m ’.

It is known that

$$W_1 \propto d_1^3$$

$$W_2 \propto d_2^3$$

and therefore

$$\frac{W_1}{W_2} = \left(\frac{d_1}{d_2} \right)^3 \quad (3.5)$$

and therefore

$$\frac{d_1}{d_2} = \left(\frac{W_1}{W_2} \right)^{\frac{1}{3}} \quad (3.6)$$

Therefore, if the two charge diameters (CDs) are in the ratio $d_1/d_2 = \lambda$, then for identical overpressures to be seen by an observer, the ratio of the ranges from the explosive to the observer will be given by

$$\frac{R_1}{R_2} = \lambda \quad (3.7)$$

where R_1 and R_2 are the ranges for the explosives of masses W_1 and W_2 , respectively. Similarly, the same applies to the positive-phase duration:

$$\frac{T_{s1}}{T_{s2}} = \lambda \quad (3.8)$$

and the impulse of the positive phase:

$$\frac{i_{s1}}{i_{s2}} = \lambda \quad (3.9)$$

Thus, it follows that ranges at which a given overpressure will be produced by explosions from different masses of explosives can be calculated from

$$\frac{R_1}{R_2} = \left(\frac{W_1}{W_2} \right)^{\frac{1}{3}} \quad (3.10)$$

where R_1 is the range at which an overpressure is produced by an explosive with mass W_1 , and R_2 is the range at which an identical overpressure is produced with a charge of mass W_2 . So, an observer located a distance R_2 from the centre of an explosive with a characteristic dimension of d_2 will be subjected to a blast wave of magnitude P_s with a duration of T_{s2} and impulse i_{s2} . So the Hopkinson–Cranz scaling law states that another observer who is located at a distance of λR_2 from an explosive with size λd_2 will be subjected to a blast wave with magnitude P_s with a duration of λT_{s2} and impulse λi_{s2} . The blast wave overpressure, P_s , does not change (neither does its velocity nor temperature), whereas the duration and the impulse of the wave do. The Hopkinson–Cranz scaling law has been thoroughly verified over the years by many experiments conducted over a large range of explosive energies (Baker et al. 1983).

The Hopkinson–Cranz approach leads to the specification of a parameter known as the scaled distance, Z , which is a constant of proportionality. This is used to present normalised blast data in a general way so that from a single curve, it is possible to work out a blast wave parameter for variable ranges and masses. It is defined as

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (3.11)$$

where Z is the scaled distance, R is the range and W is the charge mass.

The charge mass is often expressed in kilograms of TNT, which is used as a reference explosive. To calculate the parameters from explosives other than TNT, it is convenient to convert the mass of the charge into a TNT 'equivalent mass'. To do this, a conversion factor is used based on the ratio of the specific internal energies of the explosive to TNT. A selection of properties and conversion factors for several explosives taken from Baker et al. (1983) are shown in Table 3.3.

So, a 100-kg charge of PETN converts to 128.2 kg of TNT since the ratio of the specific energies is $5800:4520 = 1.282$.

TABLE 3.3

Conversion Factors (TNT Equivalence) for Some High Explosives

Explosive	Density (kg/m ³)	Mass-Specific Energy Q _x (kJ/kg)	TNT Equivalence (Q _x /Q _{TNT})
Amatol 80/20 (80% ammonium nitrate, 20% TNT)	1600	2650	0.586
Comp B (60% RDX, 40% TNT)	1690	5190	1.148
RDX (cyclonite)	1650	5360	1.185
HMX	1900	5680	1.256
Lead azide	3800	1540	0.340
Lead styphnate	2900	1910	0.423
Nitroglycerin (liquid)	1590	6700	1.481
Octol 70/30 (70% HMX, 30% TNT)	1800	4500	0.994
Pentaerythritol tetranitrate (PETN)	1770	5800	1.282
Pentolite 50/50 (50% PETN, 50% TNT)	1660	5110	1.129
Tetryl	1730	4520	1.000
TNT	1600	4520	1.000
C-4 (91% RDX, 9% plasticiser)	1580	4870	1.078
PBX 9404 (94% HMX, 3% nitrocellulose, 3% plasticiser)	1844	5770	1.277

3.4.4 Predicting Blast Loading on Structures

There are several computational codes available for predicting the blast loading on structures for highly complex structures including ANSYS® AUTODYN and Cranfield University's Propagation of Shocks in Air (ProSAir). However, it is possible to carry out a desktop analysis of the types of loading on structure based on a series of empirical data fits that have been published in the open literature. A good collection of data based on the scaled distance ($Z = R/W^{1/3}$) of a TNT charge is provided by Baker et al. (1983), a sample of which is presented in Figure 3.10.

Much of these data are for free air bursts, that is, away from any reflecting surface such as the ground. Where an explosion occurs close to the ground, it is necessary to adjust the charge mass or yield before using the graph presented in Figure 3.10. Good correlation for surface blasts of high explosives with free-air burst data results if an enhancement factor of 1.8 is assumed (Smith and Hetherington 1994). Where the ground is assumed to be perfect reflector (i.e. no wave energy is absorbed by the ground), then an enhancement factor of 2.0 can be assumed.

Example 3.1

An improvised explosive device (IED) is detonated at 2 m from an armoured fighting vehicle (AFV). The IED is manufactured from 7.6 kg

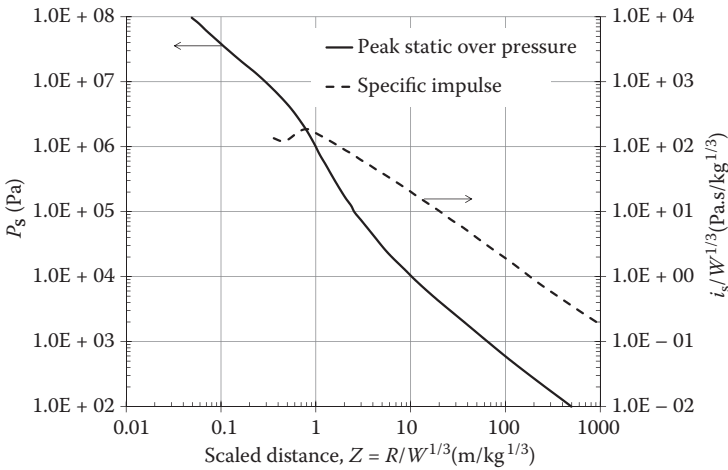


FIGURE 3.10

Side-on blast parameters for a spherical charge of TNT. (Adapted from Baker, W. E. et al., *Explosion Hazards and Evaluation, Vol. 5, Fundamental Studies in Engineering*, Copyright 1983, with permission from Elsevier.)

of amatol. Calculate the peak static overpressure and the specific impulse that is seen by the AFV. A schematic of the problem is shown in Figure 3.11.

First, it is known that the explosive is amatol, and therefore, the mass of the explosive needs to be converted into a TNT equivalent mass. Therefore, from Table 3.3,

$$7.6 \text{ kg} \times 0.586 = 4.5 \text{ kg (equivalent mass of TNT)}$$

It is also known that the IED is located on the ground, and therefore, the blast is equivalent to

$$1.8 \times 4.5 \text{ kg} = 8.0 \text{ kg (due to a surface burst)}$$

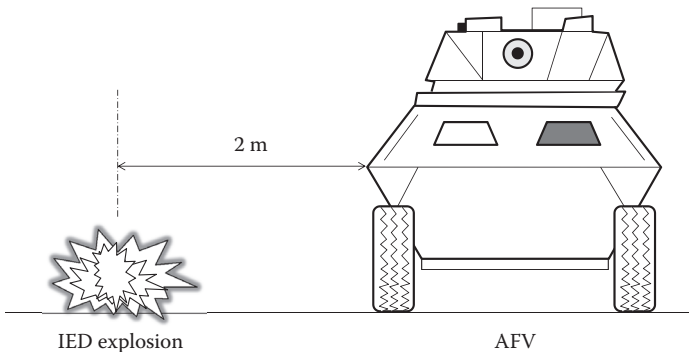


FIGURE 3.11

Attack of an AFV: calculating the pressure and impulse due to the detonation of an IED.

The scaled distance, Z , can now be calculated. From Equation 3.11, it is known that $Z = R/W^{1/3} = 2/8^{1/3} = 1.0 \text{ m/kg}^{1/3}$. Therefore, reading off Figure 3.11, it is seen that

$$P_s = 1 \times 10^6 \text{ Pa} = 1 \text{ MPa}$$

$$i_s/W^3 = 170 \text{ Pa}\cdot\text{s}/\text{kg}^3$$

$$\therefore i_s = 170 \times 8^3 = 340 \text{ Pa}\cdot\text{s}$$

3.4.5 Underwater Blasts

Underwater blasts have similar characteristics to air blasts except that the medium through which the shock wave is transmitted has a density of $\sim 1000 \text{ kg/m}^3$ as opposed to $\sim 1.2 \text{ kg/m}^3$. During an underwater explosion, the solid explosive material is converted into high-pressure gaseous products in a timescale of the order of microseconds. The expansion of the solid material to gas through the detonation process highly compresses the surrounding water leading to the formation of a supersonic shock wave that expands out radially.

The shape of the shock wave and its decay characteristics (with time and distance) are given by Swisdak, Jr. (1978). The shape of the shock pulse in water follows a similar shape to Figure 3.9 and is shown in Figure 3.12.

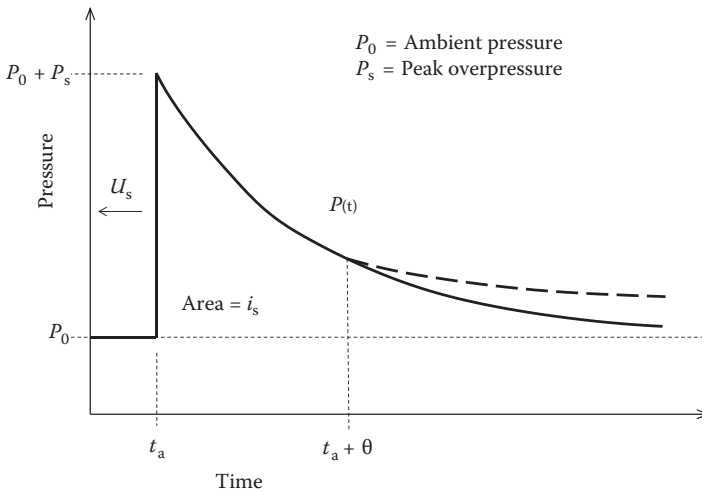


FIGURE 3.12 Ideal pressure pulse structure from an underwater explosion. (Adapted from Swisdak, Jr., M. M., *Explosion Effects and Properties: Part II – Explosion Effects in Water*, White Oak, Silver Spring, Maryland, Naval Surface Weapons Center, 1978.)

It is generally assumed that the shock pressure decays from its peak exponentially for a period of one time constant (θ) after which the pressure decays more slowly with time (see the dashed line in Figure 3.12).

Assuming a full exponential decay, the shape of this pressure pulse is given by

$$P(t) = P_s \exp\left(-\frac{t}{\theta}\right) \tag{3.12}$$

Swisdak, Jr. provides a summary of empirically derived constants and coefficients for various explosives and for TNT, the peak pressure, P_s , impulse, i_s , and time constant, θ . In terms of the mass (W) and the range (R), we have

$$P_s = 52.4 \left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} \tag{3.13}$$

$$i_s = 5.75 \times W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R}\right)^{0.89} \tag{3.14}$$

and

$$\theta = 0.084 \times W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R}\right)^{-0.23} \tag{3.15}$$

Example 3.2

A 10-kg TNT blast mine is detonated underwater. Plot how the pressure and impulse decays with range (R) from the blast up to 10 m. Plot the shape of the expected pressure pulse at 10 m.

Equations 3.13 and 3.14 provide the solution. In this case, it is known that $W = 10$ kg, and therefore, substituting into the equations provides a solution shown in Figure 3.13.

Figure 3.13 shows that the pressure and impulse values drop off very rapidly with range – similar to an air blast. Note that two vertical axes have been plotted here: one to represent the peak pressure (right-hand axis) and one to represent the impulse.

The next step is to work out the profile of the wave at 10 m. To do this, we need the time constant θ .

Using Equation 3.15, it is seen that the time constant is given by

$$\theta = 0.084 \times 10^{\frac{1}{3}} \left(\frac{10^{\frac{1}{3}}}{10}\right)^{-0.23} = 0.257598 \text{ ms}$$

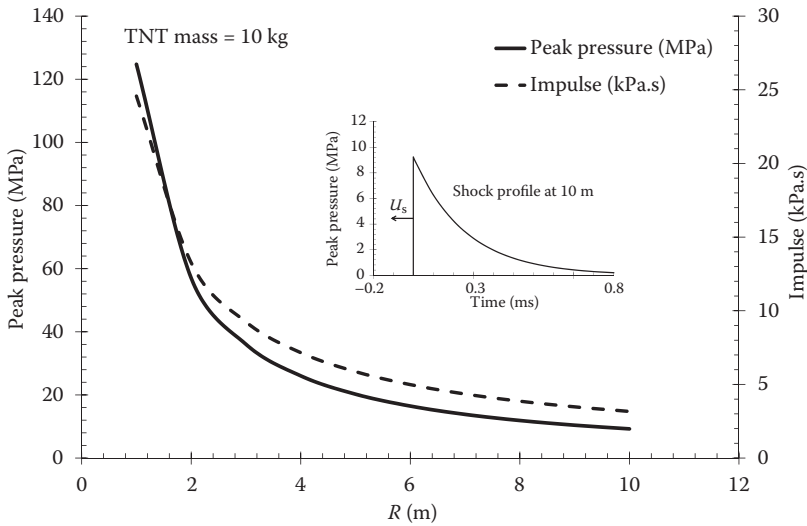


FIGURE 3.13

Peak pressure and impulse value of a spherically expanding shock wave in water. Inset: the shock profile at $R = 10$ m calculated by the means outlined in the text.

From Equation 3.13,

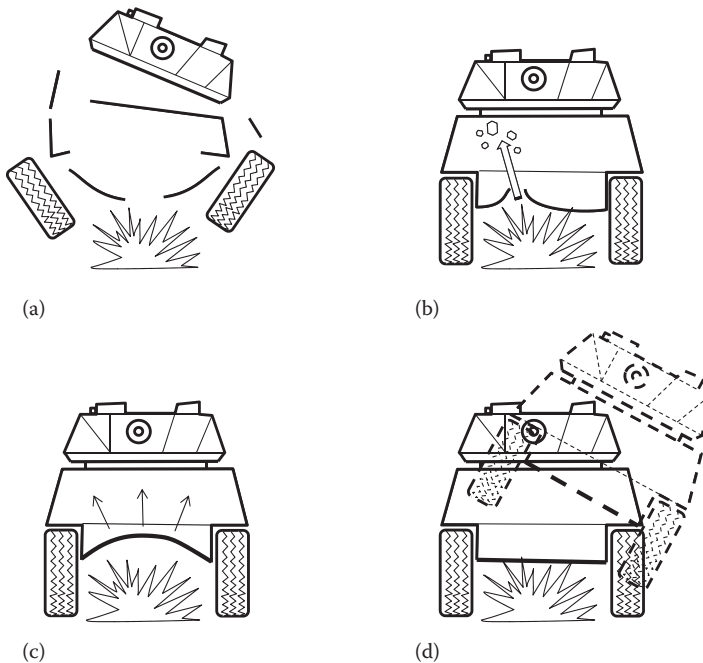
$$P_s = 52.4 \left(\frac{10^3}{10} \right)^{1.13} = 9.25 \text{ MPa}$$

Therefore, using Equation 3.12, the pressure profile for various arbitrary time values (e.g. ranging from 0 to 1 ms) can now be plotted. This is shown in the inset in Figure 3.13.

3.4.6 Buried Mines and IEDs

Up until the end of the Cold War, 80% of mines that were likely to be encountered were blast mines (mainly because of their relative simplicity). It was also apparent that 95% of these mines that were encountered contained not more than 9–10 kg of explosive. This was probably due to the fact that 9–10 kg is about the mass limit that someone can easily handle whilst deploying multiple mines. Because of these factors, most battle tanks and APCs were designed to withstand 9 kg of TNT (or equivalent) exploding under their wheels or tracks.

However, since the end of the Cold War, AFVs have been subjected to an ever-increasing threat from buried weapon systems that include IEDs. IEDs are particularly insidious in that they are, as the name implies, 'improvised', and this means that it is often difficult to predict the mass of the explosive, the type of explosive used and the nature of the fragmentation that it will produce. The

**FIGURE 3.14**

The effect of an IED or mine on an armoured vehicle detonated under the vehicle. (a) Loss of structural integrity, (b) perforation, (c) floor plate deformation and (d) lift.

effect that these weapons may have on a vehicle is, as most readers would be aware from the news reports, devastating. In Figure 3.14, there are four examples of what can happen to an AFV when an explosive device is detonated under the centre of the vehicle. Failure will occur according to one of these examples or even a combination of events. They are summarised as follows:

1. *Loss of structural integrity*: The explosive load is powerful enough to bend the steel structure beyond its strain-to-failure limits, the weld lines fail and parts of the structure are propelled radially outward.
2. *Floor plate perforation*: The bottom plate is perforated by either a fragment, explosively formed projectile (EFP) or a piece of debris that is explosively accelerated from the ground into the AFV. The floor plate fails as it is unable to resist the penetration and ultimately perforation of the fragment.
3. *Floor plate deformation*: The impulse delivered by the explosion causes the bottom of the vehicle to deform. The floor plate is accelerated up into the cabin of the AFV; anybody who is in direct contact with the floor is likely to suffer serious injury due to the fast acceleration of the plate.

4. *Lift*: It is caused when the expanding blast wave is unable to be diverted away from the underside of the vehicle, and consequently, the vehicle is accelerated upward. Again, the acceleration loads are going to be huge; injury is most likely. Anybody who is not strapped in will almost certainly suffer serious injury or death as they are thrown around the inside of the cabin. Any loose object will turn into a lethal projectile.

Thankfully, considerable progress has been made in recent years in providing defence against improvised devices. More about this will be discussed in Chapter 10.

It should be noted that the use of IEDs is not a modern phenomenon, and modern concepts can be traced back to medieval examples such as the 'Fougasse'. These were first used in Italy in c. 1530 and simply composed of a hole in the ground into which black powder and various projectiles (rock/iron) were filled. The black powder was lit by a fuze resulting in an explosion that propelled the numerous rocks and other projectile materials towards the enemy.

3.5 Shaped-Charge

A shaped-charge warhead consists of a mass of explosive surrounding a conically shaped metal, usually copper, and some form of detonator to initiate the explosive. The most infamous weapon system that employs a shaped-charge warhead is the rocket-propelled grenade (RPG-7). Although it is called a grenade, and it does have some fragmentation effects, it is in fact a shaped-charge system. This is its primary means of attack. The formation of a shaped-charge jet is schematically shown in Figure 3.15.

A shaped-charge jet is formed by the collapse of a liner of material (usually copper) due to a high-compressive detonation wave evolving in an explosive charge. The resulting jet possesses a tip velocity in the range of 5–11 km/s and is determined by several factors including the apex angle of the conical liner, the detonation wave velocity and the material from which the liner is made. The smaller the apex angle (α), the faster the jet. In fact, it can be shown from a trigonometric point of view that as $\alpha \rightarrow 0$ (i.e. as the apex angle is reduced to zero), the maximum velocity that can be achieved is

$$v_{\max} = 2U_D \quad (3.16)$$

where U_D is the detonation wave velocity of the explosive.

So, the velocity of the shaped-charge jet can never exceed twice the detonation wave velocity in the explosive. In reality, α needs to be a finite value to get a good length of jet (which is also very important for penetration).

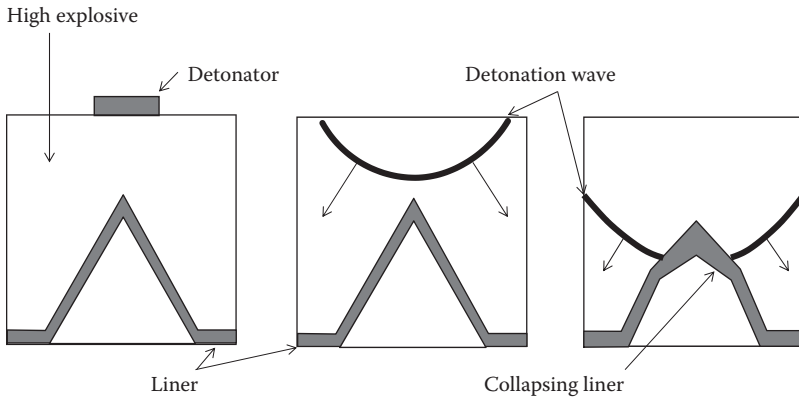


FIGURE 3.15
Initial stages of shaped-charge jet formation.

3.5.1 Penetration Prediction

The penetration of a shaped-charge jet into a target material is assumed to be hydrodynamic due to the high pressures formed on contact. There are excellent reviews on shaped-charge technology that are covered in Chou and Flis (1986) and Walters and Zukas (1989).

An equation to predict jet penetration is

$$p = l_j \sqrt{\frac{\lambda \rho_j}{\rho_t}} \tag{3.17}$$

where

l_j is the length of the jet (which, on first approximation, can be taken to be the standoff).

ρ_j is the density of the jet.

ρ_t is the density of the target.

λ is a constant (for cohesive jets = 1; for particulating jets = 2).

The derivation of this type of equation will be discussed in Chapter 4. A slight modification to this penetration mode was provided by Pack and Evans (1951), which took into account both the strength of the target and the velocity of the jet. The Pack and Evans equation is

$$p = l_j \sqrt{\frac{\rho_j}{\rho_t} \left(1 - \frac{\alpha_1 \gamma}{\rho_j v^2} \right)} \tag{3.18}$$

where

v is the velocity of the jet.

Y is the yield strength of the target.

α_1 is a function of the densities of the jet and target.

They showed that for armour with a very high yield stress, the correction term $\alpha_1 Y / \rho_j v^2$ can be as high as 0.3 (i.e. the penetration can be reduced by as much as 30% for a high-strength target).

Alternative penetration equations are provided by DiPersio and Simon (1964) for three cases: (a) penetration before the jet break-up, (b) the jet breaks up during penetration and (c) the jet breaks up before reaching the target.

For case a, where a cohesive jet is expected during penetration,

$$p = s \left[\left(\frac{v}{v_{\min}} \right)^{\frac{1}{\gamma}} - 1 \right] \quad (3.19)$$

where

$$\gamma = \sqrt{\frac{\rho_t}{\rho_j}} \quad (3.20)$$

s = the effective standoff, which is calculated from the virtual origin of the shaped charge to the target, and v_{\min} = minimum jet velocity that contributes to material penetration.

For case b, where particulation occurs during penetration, it is found that

$$p = \frac{(1 + \gamma)(vt_b)^{[1/(1+\gamma)]} s^{[\gamma/(1+\gamma)]} - v_{\min} t_b}{\gamma} - s \quad (3.21)$$

Finally, for the third case c, it is found that

$$p = \frac{(v - v_{\min})t_b}{\gamma} \quad (3.22)$$

where t_b = the time of jet break-up.

For a shaped-charge jet with a constant liner thickness, the stretching of the jet occurs in a linear fashion. Therefore, there is a linear velocity distribution from the fast-moving tip all the way to the slow-moving slug at the rear. Counter-intuitively, it also can be assumed that each particle in the jet has a constant velocity. This is because it can be assumed that each portion of the jet is accelerated nearly instantaneously by the high explosive.

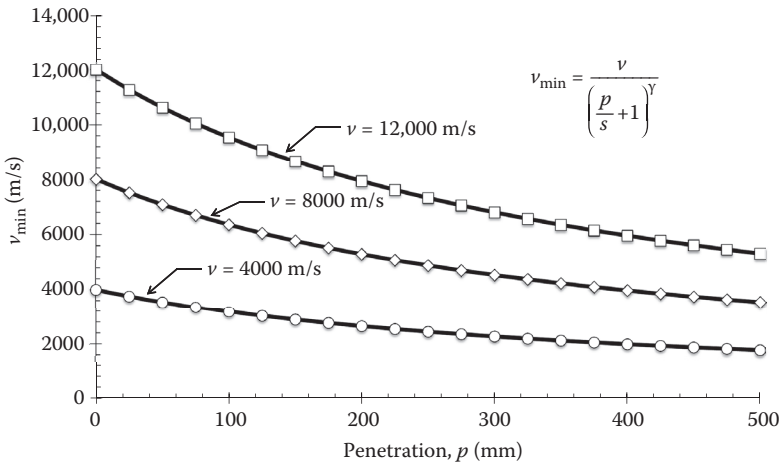


FIGURE 3.16

Variation of v_{\min} with penetration depths for different values of initial jet velocities, v . The jet is made from copper ($\rho_j = 8900 \text{ kg/m}^3$), and the target is made from steel ($\rho_t = 7800 \text{ kg/m}^3$); $s = 360 \text{ mm}$ for each case.

It should be noted that v_{\min} is not a constant and varies as the penetration ensues. Rearranging Equation 3.19 gives a relationship of how v_{\min} varies as it penetrates a target. So,

$$v_{\min} = \frac{v}{\left(\frac{p}{s} + 1\right)^\gamma} \tag{3.23}$$

This relationship is plotted graphically in Figure 3.16 for a copper jet penetrating a steel target at different initial values of v .

Note that Equation 3.23 also provides the exit velocity of the jet after penetrating a target of finite thickness, P . In other words, the exit velocity (v_{out}) of the jet after it has penetrated through a finite thickness of plate is given by

$$v_{\text{out}} = \frac{v}{\left(\frac{p}{s} + 1\right)^\gamma} \tag{3.24}$$

3.5.2 Jet Formation

The first real analysis of how shaped-charge jets were formed occurred just after WWII when Birkhoff et al. (1948) published an analysis of shaped-charge formation. They recognised that the detonation pressure is much larger than the strength of the liner and therefore treated the liner material

as if it behaved like a non-viscous fluid (hence the word 'jet'). Later, the development of Birkhoff et al.'s work was carried out by Pugh et al. (1952) who built on the hydrodynamic concepts postulated by Birkhoff et al. and provided a theory for liner collapse and subsequent jet stretching. They theorised that the velocity of liner collapse changed continuously from the apex of the cone to its base, and this led to the stretching phenomena seen with shaped-charge jets. Good reviews of the history of shaped-charge jets are provided in Kennedy (1990) and Walters (1990).

A schematic of shaped-charge formation is shown in Figure 3.17. The explosive charge is detonated and forms a high-pressure detonation wave that expands hemispherically within the cylinder of high explosive. Eventually, the detonation front engulfs the liner and locally deforms the liner material to very high strains over a very short period of time. After the formation of the jet ($>40 \mu\text{s}$), a residual slug follows the jet at a much-reduced velocity (1–2 km/s).

The cone is usually made from copper, but jets can also be made from brittle materials such as glass and ceramic. Copper has a face-centred cubic (FCC) crystalline structure, which lends itself to achieving good ductility. However, molybdenum (a body-centred cubic [BCC] metal, which is inherently less ductile) has also been used in shaped-charge weapon design. BCC metals (such as Fe, Mo and Ta) tend to produce chunky jets, whereas FCC metals produce long thin ductile jets. Hexagonal close-packed materials such as magnesium and titanium tend to produce powdery jets; this is due to the limited modes available to accommodate plastic deformation in these structures.

Of course, a shaped-charge liner can be formed into all sorts of shapes and sizes as can be seen in Figure 3.18. Each shape can bestow a different velocity gradient and therefore different jet length and jet shape. Liners with steeper gradients will result in a jet with high velocity. Variable gradient liners will produce jets with a large velocity gradient. For example, a trumpet liner (see Figure 3.18) will produce a longer and more penetrating jet, whereas a Norman helmet shape will produce a shorter but larger-diameter jet.

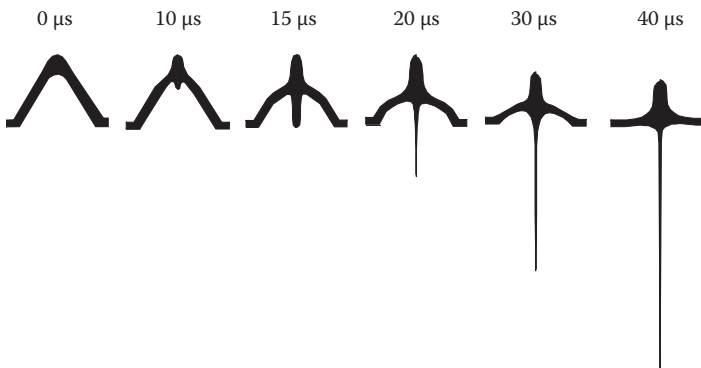


FIGURE 3.17

Formation of a copper shaped-charge jet.

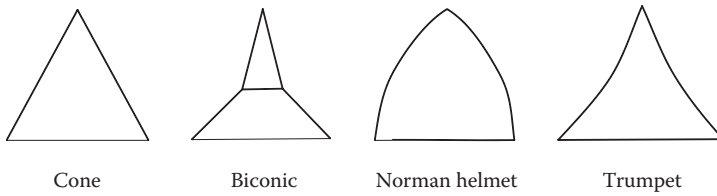


FIGURE 3.18
Examples of liner shapes.

Shaped-charge liners can also be very large as exemplified by the Mistel (mistletoe) warhead developed by the Germans in WWII. A fighter aircraft was mounted piggyback on the top of a large unmanned bomber aircraft that carried the Mistel warhead. Amazingly, the warhead consisted of a 2-m-diameter conical-shaped charge with an explosive mass of 1720 kg. It is thought that the liner had a 120° apex angle and was about 30 mm thick (and made from aluminium or steel). The fighter pilot flew the warhead to the target who, after aiming it, released it before returning to base (Walters 2008).

Due to the nature of the formation of the jet, a stand-off distance from the armour is required to achieve optimum penetration. If the stand-off distance is too large, the jet will begin to particulate, and its penetration depth will be compromised. If the stand-off is too low, the jet will not have the space to form, and therefore, again, the penetration depth into the armour will be reduced. Typically, a stand-off distance of 4–5 CDs is used as the optimum stand-off distance; however, a much reduced stand-off is usually employed by using a spigot protruding from the front of the ammunition casing. The reason for this is a combination of practicalities and external rather than terminal ballistic reasons as an excessively long spigot causes manual handling and flight-stability problems.

The relationship between stand-off and penetration for two jet materials is shown in Figure 3.19. Not only does the stand-off affect penetration, but also the length and density of the jet play a role. The higher the density of the jet, the greater the penetration depth, and that is why copper ($\rho = 8900 \text{ kg/m}^3$) provides a higher penetration than aluminium ($\rho = 2800 \text{ kg/m}^3$). Both are FCC metals.

Shaped-charge jets are not jets of fluid as their name implies, but rather, they are thought to be super-plastic solids. Temperature measurements taken from copper jets formed from 81.3-mm-diameter liners have resulted in a mean temperature of 432°C (with a standard deviation of 76°C ; Von Holle and Trimble 1976). Although the authors acknowledged that these measurements were preliminary, it is worth noting that this temperature is less than half the melting temperature of copper (1085°C).

An advanced PG-7 shaped-charge grenade that can be launched from these weapons can penetrate up close to 1 m of RHA. Penetration depths are dependent on the geometry and material of the liner, the explosives used

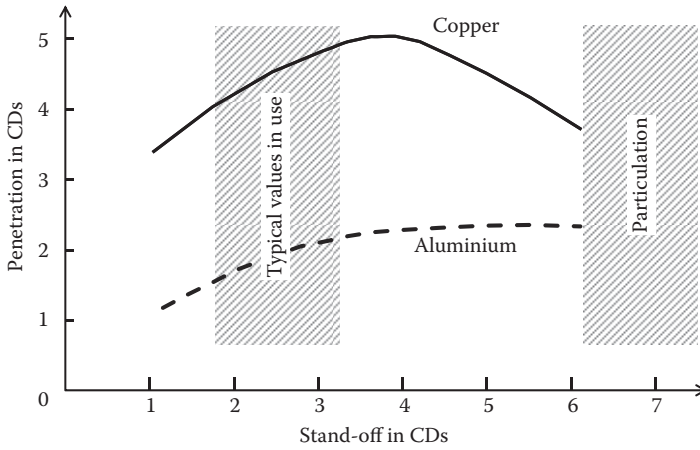


FIGURE 3.19 Effect of weapon stand-off on the penetration of a shaped-charge jet formed from different liner materials.

TABLE 3.4

Armour Penetration Data for Some Grenades Launched from the RPG – 7 Knut 40-mm Portable Rocket Launcher

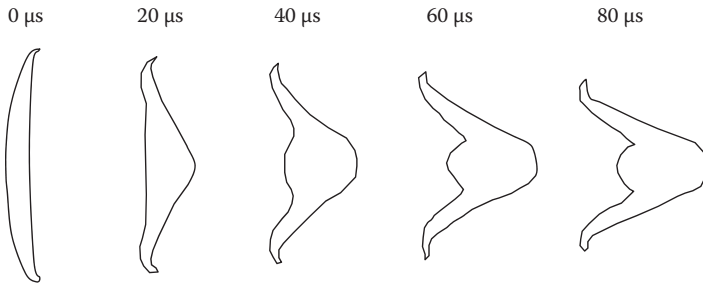
Grenade	Charge Diameter (mm)	Armour Penetration (mm)
PG – 7VM	70	300
PG – 7N	–	400
PG – 7L	93	600
PG – 7LT ^a	93	700
PG – 7M 110	110	600–700

^a Tandem warhead.

and the manufacturing tolerances that are applied (see Table 3.4). Typically, a 40-mm high-precision shaped charge will penetrate ~200 mm of RHA; a 50-mm high-precision shaped charge will penetrate ~300 mm of RHA.

3.6 Explosively Formed Projectiles

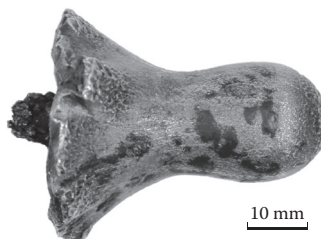
The use of an EFP or self-forging fragment remains one of the most versatile methods of attacking armour. The projectile is formed by the dynamic deformation of a metallic dish due to the detonation of an explosive charge located behind it. The formation of the EFP is illustrated in Figure 3.20, and a soft-captured EFP (captured by using large thicknesses of ever-increasing

**FIGURE 3.20**

Result from a numerical simulation showing the formation of an EFP.

densities of layered materials) is shown in Figure 3.21. The mechanism of dish deformation is very similar to that of a shaped-charge warhead (see Section 3.5), and indeed, this warhead is sometimes described as a shaped-charge warhead. The fundamental difference is that instead of a conical liner being deformed into a jet, a relatively shallow dish is formed into a slug or projectile. The nature and size of the projectile can be optimised for a particular application by the use of different explosives, CDs, various ‘wave-shaping’ techniques, case and dish materials. The dish is often made of a relatively soft material to ensure that it deforms into an appropriate projectile-like shape. Relatively dense metals such as steel ($\rho = 7850 \text{ kg/m}^3$), iron ($\rho = 7870 \text{ kg/m}^3$), copper ($\rho = 8930 \text{ kg/m}^3$) and, more recently, tantalum ($\rho = 16,690 \text{ kg/m}^3$) are used to ensure effective penetrative performance, especially in the lower part of the hydrodynamic regime (2–3 km/s).

Unlike shaped-charge warheads, an explosively formed projectile is insensitive to stand-off distance (the distance between the warhead at initial slug formation and the target). Hence, it can be used in a wide variety of applications such as mines (for example, the M70 Remote Anti-Armour Mine and the Yugoslav TMRP-6 anti-tank mine). It is also used in top-attack submunitions such as those available in the M898 Sense and Destroy Armour (SADARM) projectile and guided weapons.

**FIGURE 3.21**

A well-designed soft-captured EFP.

Relatively little research has been published in the open literature providing specific details on protecting against this threat. Instead, researchers have been preoccupied in disseminating information regarding protection against KE ammunition (long-rod penetrators [LRPs]) and shaped-charge jets. EFPs have a lower length-to-diameter ratio than LRPs, travel faster, are traditionally made of less-dense materials and are softer in construction. Conversely, the shaped-charge jet is almost universally formed from a copper liner and extends at a velocity far in excess of the flight velocity of an EFP. These factors alone would lead us to conclude that the penetration mechanics of an EFP are likely to be different from that of a shaped-charge jet or a LRP.

3.7 High-Explosive Squash Head

The use of high-explosive squash head (HESH) rounds is gradually diminishing due to the interest in fitting smoothbore guns into main battle tank (MBT). HESH has been mainly used to attack bunkers and occasionally thin-skinned vehicles where the use of an APFSDS round would completely overmatch the armour and therefore not transfer sufficient energy to the target. A HESH round consists of a base-fuze explosive shell that is spin stabilised. On contact with the target, the thin shell nose rapidly deforms and spreads a layer of polymer-bonded explosive over the target (a typical 120-mm round will contain approximately 4 kg of explosive). The fuze is embedded in the explosive and then detonates the explosive leading to a compressive stress wave propagating into the target. An inert filling is normally placed in the nose to lessen the shock directly imparted to the explosive on impact with the target. If the shock is sufficiently high, then premature detonation will occur, and the detonation wave will propagate away from the target. A schematic of a typical HESH round is shown in Figure 3.22.

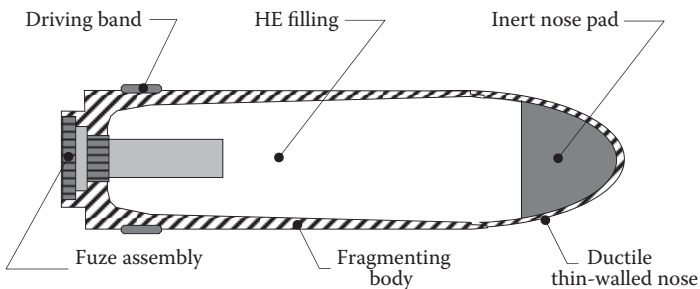
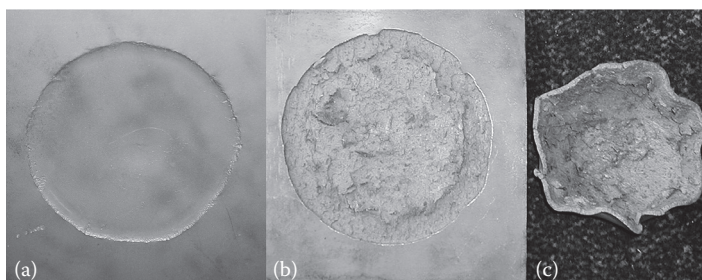


FIGURE 3.22

A typical HESH shell.

**FIGURE 3.23**

A steel target that has been subjected to attack from a HESH round, showing (a) the impact surface, (b) the scabbed surface and (c) the scab.

If the compressive wave front that is moving into the target encounters a free surface, then the wave is reflected back as a tensile wave. During reflection, the leading edge of the tensile wave overlaps the trailing edge of the compressive wave. Therefore, the resultant stress in the target can be calculated by summing the compressive stress at a specific point with the tensile stress. The magnitude of the tensile stress increases as it moves towards the point of impact, and eventually, the entire compressive wave is reflected.

Because most materials are weaker in tension than they are under compression, tensile failure normally follows and occurs when the net tensile stress exceeds the tensile strength of the material. This process is called spalling and can lead to the formation of a lump of material (sometimes referred to as a 'scab') that becomes separated from the target material (Figure 3.23). A steel scab can travel at velocities of around one-third the speed of sound.

HESH is effective against thick concrete structures and has reasonable fragmentation effects that can threaten thin-skinned vehicles.

3.8 Fragments

The final consideration in this chapter is that of fragments that are propelled by a blast wave produced from an exploding shell, pipe bomb or IED, etc. These shells produce fragments of varying velocities and shapes. A modern 155-mm shell can propel up to 10,000 fragments on detonation that are lethal up to approximately 50 m. Because these fragments have a somewhat irregular shape, and tend to be unstable in flight, they lose velocity fairly quickly with distance travelled with lighter-weight fragments exhibiting a faster drop-off than heavier fragments. Their penetration characteristics are similar to high-velocity rifle bullets in that they are of a similar average mass

to, say, 14.5-mm bullets, and although they may be travelling at a relatively high velocity when compared to a bullet, their shapes are not ideal for maximising penetration.

There are various ways in which fragmentation occurs in a shell casing. This can be achieved by making grooves in the case that act as stress concentration points for the shock wave. Alternatively, notched wire has sometimes been used where the wire has been brazed together. Adding grooves in an explosive is sometimes employed where the grooves in an explosive provide a mini shaped-charge focusing effect. Similarly, a metal liner can be added in between the explosive and shell casing to modify the shape of the shock wave interacting with the case metal to focus the stress on the metal casing. Such a liner is often called a 'Buxton liner'.

The first real consideration to fragmentation was published by Mott (1947) just after WWII. Mott's fragmentation theory provided the foundation to what we understand of the mechanism of natural fragmentation today (Figure 3.24), that is to say, fragmentation that occurs due to the material's microstructure as opposed to pre-notched bombs. Mott realised that if a uniform cylinder was subjected to an internal blast pressure, then in an ideal material, it would expand continually until fragmentation occurs simultaneously, and an infinite number of fragments are formed. Of course, this does not happen. Instead, as a crack begins to propagate, the presence of the free surface generated by the crack leads to a release in stress in the surrounding material. Consequently, a 'release wave' propagates away from the position of the crack, and this releases the stress in the surrounding material, thereby inhibiting crack growth. Thus, the number and size of fragments that are formed are determined by the balance between the rate of increasing hoop strain and velocity of the release wave.

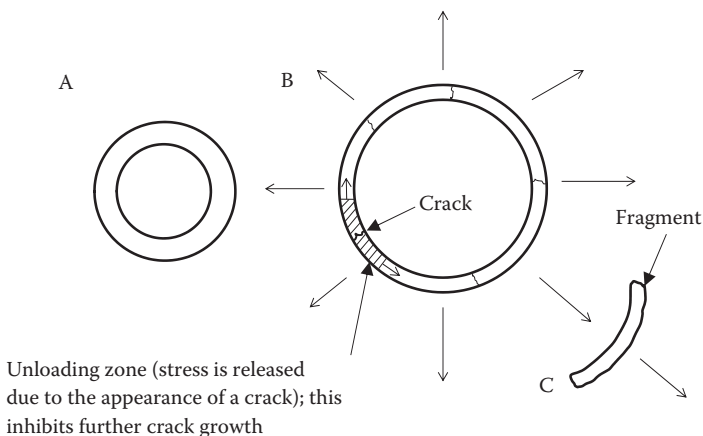


FIGURE 3.24

Mott's fragmentation theory: A – the cylinder is at rest, B – the cylinder expands due to an explosion and C – a fragment is formed.

Mott showed that the average fragment length is proportional to a number of properties according to

$$l_f \propto \sigma_{\text{UTS}} \sqrt{\frac{1 + \varepsilon_f}{\rho_0 n}} \quad (3.25)$$

where

σ_{UTS} is the true ultimate tensile strength (UTS) of the shell casing.

ε_f is the failure strain.

ρ_0 is the density of the shell casing.

n is the strain hardening characteristic of the shell casing assuming that the stress–strain (σ – ε) response of the material (for large strains) can be written as

$$\sigma = Y + n \log(1 + \varepsilon) \quad (3.26)$$

Thus, a shell casing material that has a high UTS at fracture gives large fragments, and a high ductility also results in large fragments. Increasing the density of the material and the strain hardening parameter, n , results in smaller fragments.

3.8.1 Gurney Analysis to Predict Fragment Velocity

Around a similar time to Mott, Gurney (1943) provided an analysis of the estimation of fragment velocity. Gurney realised that the important parameters for estimating the velocity of a fragment were the internal energy per unit mass of the explosive material (E) and the ratio of the mass of the metal to the mass of the charge (M/C). Assuming that all the internal energy of the explosive was translated over to KE of the metal fragments (i.e. ignoring heat, light and the KE of the air that is exposed to the blast gases), Gurney arrived at a series of equations to predict the velocities of fragments for different initial geometries. The theory for a cylindrical pipe bomb is provided here.

Assume that there is a cylindrical pipe bomb such that the ends are closed off, and there is no leakage (see Figure 3.25). When the explosive detonates, there is little resistance to fragmentation, and the material in the cylinder expands uniformly at velocity v_0 . It is assumed that the velocity of the gases that result from the detonation varies linearly from the centre of the core to the interface with the metal. At the interface, the velocity of the metal cylinder is equal to the velocity of the detonation gases, whereas at the centre of the cylinder, the velocity is equal to zero. Detonation is assumed to be instantaneous. For a cylinder of internal radius, a , the velocity of the gas, v , at radius, r , is given by

$$v = v_0 \left(\frac{r}{a} \right) \quad (3.27)$$

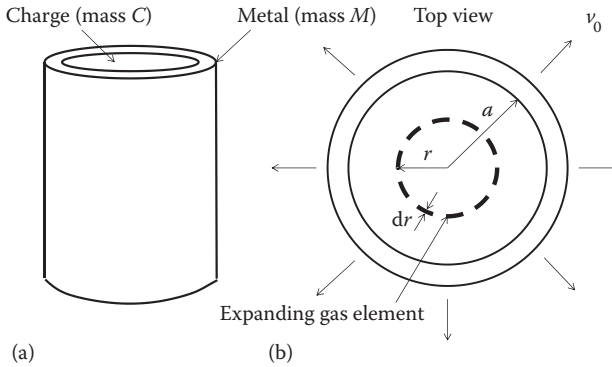


FIGURE 3.25

(a) A cylindrical charge and (b) the top view showing the gas element expanding at velocity v with the metal tube expanding at velocity v_0 .

The KE of the gas is given by

$$KE_g = \frac{1}{2} \int v^2 \cdot dm_g \quad (3.28)$$

and

$$dm_g = \rho 2\pi r \cdot dr \quad (3.29)$$

Therefore,

$$KE_g = \frac{1}{2} \int_0^a v_0^2 \frac{r^2}{a^2} \rho 2\pi r \cdot dr \quad (3.30)$$

leading to the solution of

$$KE = \frac{1}{4} v_0^2 \pi a^2 \rho \quad (3.31)$$

However, it is known that

$$C = \pi a^2 \rho \quad (3.32)$$

Therefore, the KE of the gases is given by

$$KE_g = \frac{1}{4} C v_0^2 \quad (3.33)$$

Remembering that $KE = EC$, the total KE is given by

$$KE = \frac{1}{2} Mv_0^2 + \frac{1}{4} Cv_0^2 \quad (3.34)$$

$$EC = \frac{1}{2} Mv_0^2 + \frac{1}{4} Cv_0^2 \quad (3.35)$$

and rearranging

$$v_0^2 = \frac{2EC}{\left[M + \frac{1}{2}C \right]} \quad (3.36)$$

and again

$$v_0 = \sqrt{2E} \left[\frac{M}{C} + \frac{1}{2} \right]^{-\frac{1}{2}} \quad (3.37)$$

The equation above provides a first-order approximation of the velocities that would be expected from a cylindrical bomb. And, actually, it works quite well – particularly where the shell material is ductile enough to expand up to diameters where the force acting by the detonation gases is small. For brittle materials, the actual velocity of the fragments will be lower than that predicted by this theory – mainly due to the fact that fracture occurs allowing for gas blow-by, although work with explosively accelerated ceramic tiles (very brittle materials) has shown pretty good correlation (Hazell et al. 2012). The equation for the velocities will vary slightly depending on the initial geometry of the set-up; good overviews of the various calculations for the different geometries are presented here (Meyers 1994; Cooper 1996). It should be noted that in all the derivations for the various geometries, there is one variable that keeps cropping up, namely $\sqrt{2E}$. This is known as the Gurney constant, and it has the units of velocity. It is possible to measure the Gurney constant for explosives by measuring the terminal velocities of explosively driven metals (Kennedy 1970); a selection of constants are presented in Table 3.5 (Meyers 1994).

Generally speaking, the Gurney constant is similar for similar types of explosives. Figure 3.26 shows the calculated fragment velocities for three explosives in terms of the ratio between the mass of the metal and the mass of the explosive charge (M/C). The three explosives are HMX (a powerful and relatively insensitive nitroamine high explosive), Comp B (a castable mixture of RDX and TNT) and nitromethane (a relative insensitive liquid explosive). You will notice that there is not a great deal of difference between them.

TABLE 3.5

The Gurney Constant for a Selection of Explosives

No.	Explosive	Density (g/cc)	$\sqrt{2E}$ (mm/ μ s)
1	RDX	1.77	2.93
2	Composition C-3	1.60	2.68
3	TNT	1.63	2.37
4	Tritonal	1.72	2.32
5	Comp B	1.72	2.71
6	HMX	1.89	2.97
7	PBX-9404	1.84	2.90
8	Tetryl	1.62	2.50
9	PETN (duPont sheet)	1.76	2.93
10	Nitromethane	1.14	2.41

Source: Meyers, M. A.: *Dynamic Behaviour of Materials*. 1994. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

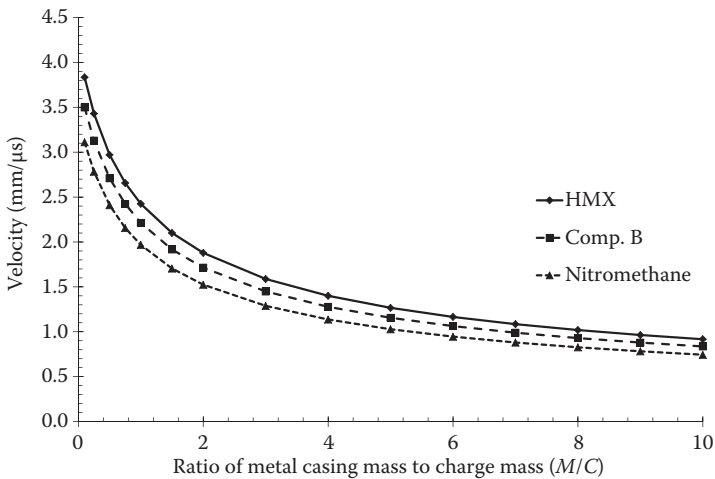


FIGURE 3.26

The effect of the M/C ratio on fragment velocities.

Of course, the Gurney analysis presented above is limited to a cylindrical example. Additional analysis is required where the geometry of the initial set-up is varied. These have been presented in a number of sources (e.g. Zukas 1990; Meyers 1994; Cooper 1996; Zukas and Walters 1998), and the velocity equations are summarised in Table 3.6.

Example 3.3

Calculate the velocity of the metal casing from a pipe bomb that is made from steel (density = 7800 kg/m³) and is 200 mm long with an external diameter of 150 mm and an internal diameter of 75 mm. Assume that the internal part of the tube is filled with an explosive (density = 1500 kg/m³) and has a Gurney constant value of 2.9 mm/μs.

First, the mass of the explosive and the mass of the metal casing need to be calculated.

The mass of the explosive (C) is given by

$$\rho_0 \pi \frac{d_i^2}{4} l = 1500 \times \pi \times \frac{(75 \times 10^{-3})^2}{4} \times 200 \times 10^{-3}$$

$$C = 1.33 \text{ Kg.}$$

The mass of the steel (M) is given by

$$\rho_0 \frac{\pi}{4} (d_0^2 - d_i^2) l = 7800 \times \frac{\pi}{4} \times \left[(150 \times 10^{-3})^2 - (75 \times 10^{-3})^2 \right] \times 200 \times 10^{-3}$$

$$M = 20.68 \text{ Kg.}$$

The velocity of the casing is given in Table 3.6 and is

$$v_0 = \sqrt{2E} \left[\frac{M}{C} + \frac{1}{2} \right]^{-\frac{1}{2}} = 2.9 \times \left[\frac{20.68}{1.33} + \frac{1}{2} \right]^{-\frac{1}{2}}$$

$$v_0 = 0.724 \text{ mm}/\mu\text{s} = 724 \text{ m/s.}$$

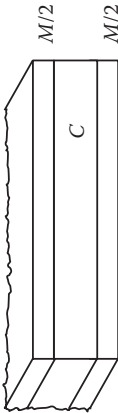


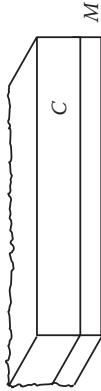

3.8.2 Drag on Fragments and Other Projectiles

Anything flying through the air will be subjected to drag forces, and that includes bullets. There are several aerodynamic forces acting on free-flying projectiles. The most important ones are forebody drag and base drag. Skin friction also exists and, of course, gravity. However, for a first-order calculation, these effects can be ignored. A useful equation to describe the effect of drag on a free-flying fragment (or bullet) is given below. This is derived from the original work carried out by Lord Rayleigh who calculated the force acting on an object moving through a fluid.

Following Newton's second law,

$$F = m \frac{dv}{dt} \tag{3.38}$$

TABLE 3.6
Gurney Equations

Type	Schematic	Equation
Symmetric flat sandwich		$v_0 = \sqrt{2E} \left[\frac{M}{C} + 3 \right]^{-\frac{1}{2}}$
Cylinder		$v_0 = \sqrt{2E} \left[\frac{M}{C} + 2 \right]^{-\frac{1}{2}}$
Spherical		$v_0 = \sqrt{2E} \left[\frac{M}{C} + 5 \right]^{-\frac{1}{2}}$
Open-faced sandwich		$v_0 = \sqrt{2E} \left[\frac{\left(1 + 2\frac{M}{C}\right)^3 + 1}{6\left(1 + \frac{M}{C}\right)} + 1 \right]^{-\frac{1}{2}}$
Asymmetric sandwich		$v_0 = \sqrt{2E} \left[\frac{1 + A^3}{3(1 + A)} + \frac{N}{C} A^2 + \frac{M}{C} \right]^{-\frac{1}{2}} \text{ where } A = \frac{1 + 2\frac{M}{C}}{1 + 2\frac{N}{C}}$

where

m is the mass of the projectile.

v is the velocity the projectile.

F is the drag force acting on the projectile.

It is assumed that the drag force acting on the object is given by

$$F = -\frac{1}{2}C_D\rho_{\text{air}}Av^2 \quad (3.39)$$

where

C_D is the coefficient of drag of the projectile and assumed to be constant.

ρ_{air} is the density of air (1.225 kg/m³).

A is the presented area of the projectile.

Newton's second law then becomes

$$m \frac{dv}{dt} + \frac{1}{2}C_D\rho_{\text{air}}Av^2 = 0 \quad (3.40)$$

Assuming that C_D is not a function of velocity (a rather simplified assumption), then all of the constants can be lumped together in terms of L :

$$L = \frac{2m}{C_D\rho_{\text{air}}A} \quad (3.41)$$

Therefore, the equation becomes

$$L \frac{dv}{dt} + v^2 = 0 \quad (3.42)$$

and

$$L \int \frac{dv}{v^2} = - \int dt \quad (3.43)$$

where the solution is (in terms of the initial velocity, v_0)

$$v = \frac{Lv_0}{(v_0t + L)} \quad (3.44)$$

Integrating this equation, knowing that

$$v = \frac{dx}{dt} \quad (3.45)$$

where x is the displacement, and eliminating t , rearranging such that

$$t = L \left(\frac{1}{v} - \frac{1}{v_0} \right) \quad (3.46)$$

and substituting gives

$$v = v_0 \exp \left(-\frac{x}{L} \right) \quad (3.47)$$

when expanded gives

$$v = v_0 \exp \left[-C_D \rho_{\text{air}} x \left(\frac{A}{2m} \right) \right] \quad (3.48)$$

where v is the velocity of the fragment after flying distance x , v_0 is the velocity at detonation, ρ_{air} is the density of the air (1.225 kg/m³ at sea level), A is the projected area of the fragment offered to the flow, m is its mass, and C_D is the coefficient of drag. C_D is a dimensionless constant and depends on the fragment's geometry and velocity. The higher the drag coefficient, the higher the drag forces acting on the projectile and consequently, the faster its velocity will drop off. The fact that C_D also changes with velocity markedly around the transonic region (Mach 0.8–Mach 1.2) also complicates things – particularly for flat-headed projectiles (see Figure 3.27). However, for a first-order calculation, it is possible to calculate the velocity decay as a consequence of drag using a constant value of C_D .

It can be seen from this equation that heavier fragments will decelerate less than lighter-weight fragments when they both have the same initial velocity.

Example 3.4

A 9-mm calibre bullet with a mass of 10 g is fired from a muzzle of a gun at 300 m/s. Assuming a C_D of 0.2, calculate the velocity drop-off in air at 500 m.

First, the presented area, A , must be calculated:

$$\begin{aligned} A &= \pi \frac{d^2}{4} = \pi \frac{(9 \times 10^{-3})^2}{4} \\ &= 63.62 \times 10^{-6} \text{ m}^2. \end{aligned}$$

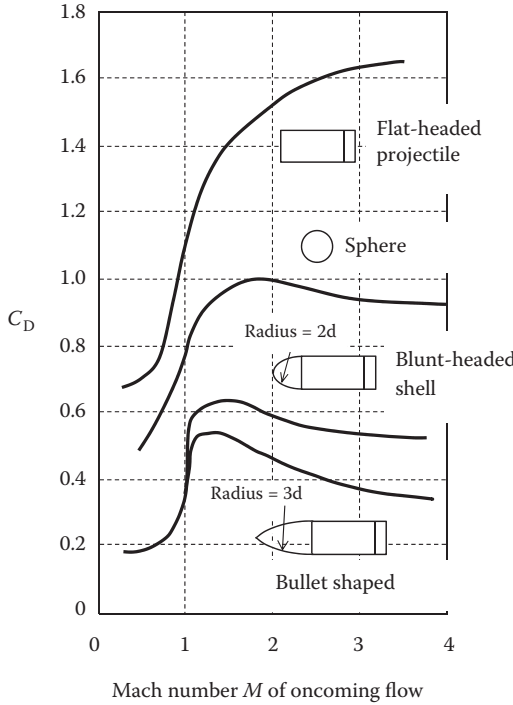


FIGURE 3.27 Variation of C_D with Mach number. (Adapted from Massey, B. S., *Mechanics of Fluids*, 6th edition, London, Van Nostrand Reinhold [International], 1989.)

From Equation 3.48, it is known that

$$v = v_0 \exp \left[-C_D \rho_{\text{air}} x \left(\frac{A}{2m} \right) \right] = 300 \exp \left[-0.2 \times 1.225 \times 500 \times \left(\frac{63.62 \times 10^{-6}}{20 \times 10^{-3}} \right) \right]$$

$v = 203.2 \text{ m/s}$. So, the velocity would have dropped by a third.

3.8.3 Fragment Penetration

A series of equations were developed in the 1960s by the Project THOR working group (Ballistic Analysis Laboratory 1961) specifically for understanding the penetration characteristics of various materials by explosively propelled fragments. The equations were derived from a large number of empirical tests. The Project THOR equation given for the ballistic limit velocity is given as follows (in SI units) after (Crull and Swisdak, Jr. 2005)

$$v_{bl} = 0.3048 \cdot 10^{C_1} (0.061024hA)^{\alpha_1} (15432.4m)^{\beta_1} (\sec \theta)^{\gamma_1} \tag{3.49}$$

where

- v_{bl} is the ballistic limit velocity in m/s.
- h is the target thickness in cm.
- A is the average impact area of the fragment in cm^2 .
- m is the mass of the original fragment in kg.
- C_1, α_1, β_1 and γ_1 are empirical constants of the material to be penetrated.

A selection of empirical constants for different materials are provided in Tables 3.7 and 3.8.

Therefore, Equation 3.49 can be rearranged to calculate the thickness required to stop a fragment of given mass, projected area and velocity, according to

$$h = \left(\frac{v_0}{0.3048 \cdot 10^{C_1} (15432.4m)^{\beta_1}} \right)^{\frac{1}{\alpha_1}} (0.061024A)^{-1} \tag{3.50}$$

where v_0 is the impact velocity in m/s. Impact is at normal incidence.

Data are also available for non-metallic materials (Ballistic Analysis Laboratory 1963) and presented in Table 3.8.

The applicability of the THOR equation is summarised by King (2010; Table 3.9).

Figure 3.28 shows the results of the THOR prediction for the thickness of metal required to defend against a specific fragment ($m = 15 \text{ g}$, $A = 4 \text{ cm}^2$) travelling at velocity. The thinnest material that is able to provide protection against this threat is hard steel. However, it will not be the lightest in weight. In fact, the lightest solution (per square metre) is a competition between the

TABLE 3.7

Empirical Constants for the Project THOR Equation (No Particular Fragment Shape Assumed); Metallic Materials

Material	Hardness (BHN)	C_1	α_1	β_1	γ_1
AA 2024-T3	120	6.185	0.903	-0.941	1.098
Cast iron	150-220	10.153	2.186	-2.204	2.156
Copper	42	14.065	3.476	-3.687	4.27
Lead	5.5	10.955	2.735	-2.753	3.59
Magnesium alloy	72	6.349	1.004	-1.076	0.966
Steel, face hardened	480-550 (front) 331-375 (rear)	7.694	1.191	-1.397	1.747
Steel, homogeneous hard	380	6.601	0.906	-0.963	1.286
Steel, homogeneous mild	150	6.523	0.906	-0.963	1.286
Titanium alloy	190	7.552	1.325	-1.314	1.643

TABLE 3.8

Empirical Constants for the Project THOR Equation (No Particular Fragment Shape Assumed); Non-Metallic Materials

Material	Hardness (Rockwell)	C_1	α_1	β_1	γ_1
Doron (glass-fibre reinforced plastic [GFRP])	R74	5.581	0.75	-0.745	0.673
Glass, bullet resistant	–	6.991	1.316	-1.351	1.289
Lexan (polycarbonate)	R70–R118	7.329	1.814	-1.652	1.948
Nylon, bonded ^a (Nylon 66)	–	7.689	1.883	-1.593	1.222
Nylon, unbonded ^a (Nylon 66)	–	5.006	0.719	-0.563	-0.852
Plexiglass, cast	R93	6.913	1.377	-1.364	1.415
Plexiglass, stretched	–	11.468	3.537	-2.871	2.274

^a Material unable to break up the projectile in the velocity range tested.

TABLE 3.9

Applicability of Project THOR Parameters

Target Material	Target Thickness Range h (mm)	Impact Velocity v (m/s)	Fragment Mass Range m (g)
AA 2024-T3	0.5–51.0	366–3353	0.32–16.0
Cast iron	4.8–14.0	335–1859	0.97–16.0
Copper	1.5–25.0	335–3475	0.97–16.0
Doron	1.3–38.0	152–3353	0.16–38.9
Glass, bullet resistant	5.0–42.0	61–3048	0.97–30.8
Lead	1.8–25.0	152–3170	0.97–16.0
Lexan	3.2–25.0	305–3505	0.32–15.6
Magnesium alloy	1.3–76.0	152–3200	0.97–16.0
Nylon, bonded	11.0–51.0	305–3658	0.32–53.5
Nylon, unbonded	0.5–76.0	91–3048	0.32–13.4
Plexiglass, as cast	5.0–28.0	61–2897	0.32–30.8
Plexiglass, stretched	1.3–25.0	152–3353	0.32–30.8
Steel, face hardened	3.6–13.0	762–2987	0.97–16.0
Steel, homogeneous	8.0–25.0	183–3658	0.32–53.0
Titanium alloy	1.0–30.0	213–3170	1.9–16.0

Source: King, K., Fragmentation, in *Handbook for Blast Resistant Design of Buildings*, edited by D. O. Dusenberry, 215–238, Hoboken, New Jersey, Wiley, 2010.

aluminium alloy and titanium alloy with the aluminium alloy performing well at the lower-impact velocities and the titanium alloy performing better at the elevated velocities.

Penetration equations will be explored further when the subject of penetration is again examined in Chapter 4.

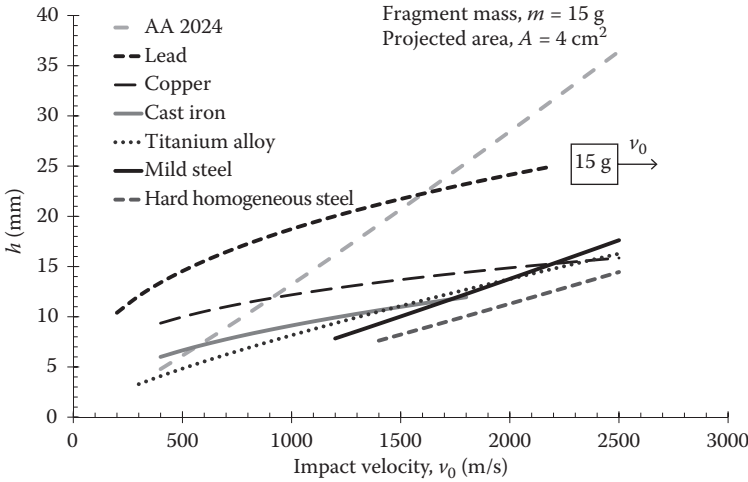


FIGURE 3.28 THOR predictions (using Equation 3.50) for the thickness of metal required to defend against a fragment of 15 g and a projected area of 4 cm².

3.9 Summary

Sadly, there are a wide variety of ingenious ways to attack a building, vehicle or person. For protection, recent attention has been turned toward providing better survivability against blast mines and IEDs. The latter is particularly insidious because often, we do not know the weapon’s construction (hence the word ‘improvised’). This redirected attention has mainly been driven by the problems encountered in peacekeeping operations after the second Gulf War and in Afghanistan. However, the science behind these threats, whether it is the way the explosive detonates or how the fragments are formed, is quite well understood and has been studied for more than 70 years. The challenge, however, is to mitigate against them.

4

Penetration Mechanics

4.1 Introduction

To try and solve how best to protect people from flying projectiles, it is useful to have an understanding of how projectiles penetrate materials and structures. Penetration processes are affected by material properties of the penetrator and the target, the impact velocity and the geometry of the incoming projectile. Furthermore, it is found that how a projectile penetrates a target is frequently divided into two fundamental processes: sub-hydrodynamic – where the strength of the material is of great importance, and hydrodynamic, where the material strength takes a lesser role. These will now be reviewed in this chapter.

4.2 Failure Mechanisms

A projectile penetrating a target subjects the material to a complex state of stress that can and will result in material failure. There are several types of failure that will occur and can be compartmentalised into five failure mechanisms:

1. Brittle failure will occur with materials of low fracture toughness – such as a ceramic or glass. Generally speaking, for brittle materials, kinetic energy (KE) from the projectile is required to create the fracture surfaces within the material during penetration; however, very little KE in the projectile is expended in doing this in brittle materials (Woodward et al. 1994). More of the KE of the projectile is often transferred to the KE of the resulting fragments. Brittleness is not always a disadvantage as it is the generation of fracture surfaces that leads to the ‘bulking’ of the material. This is very useful for defeating shaped-charge jets – as will be seen in Chapter 7.

2. Gross cracking is a failure that will occur in hard strong materials such as metals. Cracks propagate at the velocity that is close to the speed of sound in the material, and therefore, the cracking process happens very quickly. Armours that have welded joints are susceptible to this (Edwards and Mathewson 1997) as are high-carbon steels. Frequently, however, this type of failure does not impede the protective ability of the material as long as the plates are restrained from flying apart. Gross cracking can compromise the load-bearing capability of the structure, however.
3. Shear plug failure is a problem when materials are susceptible to adiabatic shear processes and are impacted by blunt compact fragments. This is particularly problematic in that the energy required to generate shear bands in metals is quite low and depends on several material properties including the material's propensity to thermally soften and low work-hardening coefficients. This is particularly important as ballistic penetration events are, by their very definition, over in a very short time. This means that the heat generated through plastic deformation processes does not have time to dissipate and therefore can lead to the separation of a shear plug in the armour material.
4. Lamination failure occurs when the material is subjected to stress wave reflections, which ultimately results in the tensile strength of the material being exceeded. If this occurs in a planar impact, then ultimately, the material will be pulled apart by inertial forces (this will be discussed again later).
5. Viscous flow results in the parting of the material due to localised melting. This is usually associated with hard-pointed projectiles.

The sixth failure mechanism is due to hydrodynamic flow. This is a special case that is reserved for very-high-velocity collisions that result in the super-plastic flow of the material due to high-confining pressure that is present. More on that will be discussed later.

4.3 Penetration Analysis

Comprehensive reviews of penetration equations are provided by Backman and Goldsmith (1978), Wright (1983), Zukas (1990a) and Corbett et al. (1996); however, a short overview is given here.

A very simple analysis can be used to predict the penetration of a rigid body into a plastically deforming target medium. However, one should exercise caution here due to a simplified approach that is used.

Consider a flat-nosed cylinder striking a plate of specific thickness, h , with a velocity less than 1000 m/s and normal to the target. The cylinder does not deform, and the penetration occurs due to the plate plastically deforming.

The cylinder (of diameter d) exerts a pressure P on the target. It is assumed that if the pressure is greater than or equal to the flow stress (σ)* of the target material, then the plate will deform. For the projectile to be arrested, the KE of the cylinder must be transferred to the work done in plastically deforming the target. The relevant equations are shown below:

$$\frac{1}{2}mv_0^2 = (\sigma A_1)h \quad (4.1)$$

where A_1 is the cross-sectional area and is given by

$$A_1 = \frac{\pi d^2}{4} \quad (4.2)$$

where m is the mass of the cylinder, and v_0 is the impact velocity.

Substituting and rearranging

$$\left[\frac{\frac{1}{2}mv_0^2}{A_1} \right] \times \frac{1}{d} = \sigma \left[\frac{h}{d} \right] \quad (4.3)$$

Notice now that, on the left-hand side, we have a measure of the KE density. It is then convenient to rearrange and simplify:

$$\frac{mv_0^2}{d^3} = \frac{\pi}{2} \sigma \left[\frac{h}{d} \right] \quad (4.4)$$

If we take into account an oblique impact, then the equation can be modified using the angle of obliquity θ ; thus,

$$\frac{mv_0^2}{d^3} = \frac{\pi}{2} \sigma \left[\frac{h}{d} \right] \left[\frac{1}{\cos \theta} \right]^k \quad (4.5)$$

where k is an empirical constant that determines a material's ability to turn the projectile during penetration. Note that $t/\cos \theta$ is the effective through-thickness offered to the projectile by a plate of thickness t set at an angle of obliquity θ .

The above model is a simplification of what occurs in real life; it is very unlikely that a target would suffer from pure plastic flow as prescribed by the

* The flow stress is a point on the plastic stress-strain curve for the material and for elastic-perfectly-plastic materials is assumed to be the yield strength (Y).

above derivation. Occasionally, shear failure also occurs, and consequently, the above derivation can be repeated assuming that pure shear failure is occurring. Assuming that the target is penetrated when the *shear strength*, as described by τ , is exceeded, a plug is formed with the cylindrical area of

$$A_2 = \pi dh \quad (4.6)$$

Following the logic outlined previously, it is found that the penetration equation can be given by

$$\left[\frac{\frac{1}{2}mv_0^2}{A_2} \right] \times \frac{1}{d} = \tau \left[\frac{h}{d} \right] \quad (4.7)$$

and finally,

$$\frac{mv_0^2}{d^3} = 2\pi\tau \left[\frac{h}{d} \right]^2 \quad (4.8)$$

A general equation for penetration is therefore given by the following:

$$\frac{mv_0^2}{d^3} = c \left[\frac{h}{d} \right]^n \quad (4.9)$$

where c and n are empirically derived constants.

Jacobson used the above analysis to describe the transition from plugging to piercing (plastic flow; see Carlucci and Jacobson 2014). If it is assumed that at some ratio of h/d , the projectile will transition from a state of plugging to a state of piercing (plastic flow), then the analysis outlines above can be used to predict the value of h/d at which that occurred. So to recap, the energy for a piercing-type flow is

$$E_{\text{piercing}} = \sigma \frac{\pi d^2}{4} h = \sigma \frac{\pi d^3}{4} \left(\frac{h}{d} \right) \quad (4.10)$$

The energy required for plugging failure is

$$E_{\text{plugging}} = \tau \pi d h^2 = \tau \pi d^3 \left(\frac{h}{d} \right)^2 \quad (4.11)$$

If it is assumed that

$$\tau \approx 0.6\sigma \quad (4.12)$$

then

$$E_{\text{plugging}} = 0.6\sigma\pi d^3 \left(\frac{h}{d}\right)^2 \tag{4.13}$$

Therefore, the transition will occur when $E_{\text{piercing}} = E_{\text{plugging}}$:

$$0.6\sigma\pi d^3 \left(\frac{h}{d}\right)^2 = \sigma \frac{\pi d^3}{4} \left(\frac{h}{d}\right) \rightarrow \left(\frac{h}{d}\right)_{\text{crit}} = 0.42 \tag{4.14}$$

This analysis implies that once the ratio of (h/d) exceeds 0.42, then piercing would be expected, whereas below this, plugging would be anticipated. This is illustrated in Figure 4.1 where the energy required to penetrate a plate is plotted for both piercing and plugging. The projectile diameter is 7.62 mm and is assumed to be rigid. The flow (yield) strength of the plate is 500 MPa, and its thickness is varied to provide a variable (h/d) value. The projectile will penetrate at the lowest possible energy, and therefore, below $h/d = 0.42$, the projectile causes plate plugging. This is a simple analysis and, as will be seen later, does not always hold true. In fact, it is known that the propensity to plug is very much determined by the material properties of the material (Walley 2007) as well as the shape of the projectile tip.

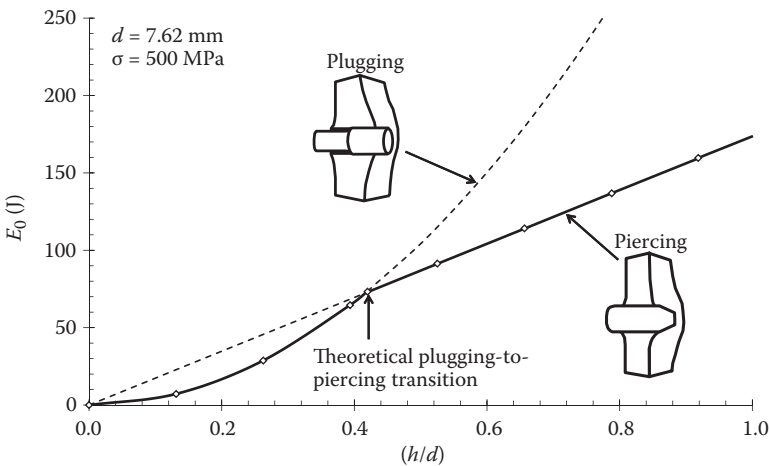


FIGURE 4.1 Transitioning from plugging to piercing during penetration (E_0 = energy required to perforate the plate, $\sigma = 500$ MPa and $d = 7.62$ mm).

This energy-based approach was originally taken by de Marre in 1886 who derived an empirical model for the energy required to achieve complete penetration in a thin hard steel plate (see Chapter 1), viz.,

$$E_0 = cd^{1.5}h^{1.4} \quad (4.15)$$

where E_0 is the KE of the projectile required to perforate the plate, and c is an empirically derived constant. The thickness of the plate penetrated is given by

$$h^{0.7} = k \frac{m^{0.5}v_0}{d^{0.75}} \quad (4.16)$$

where k is an empirically derived constant.

4.3.1 Penetration into Thick Plates

The simplest way to analyse the penetration of a material is to consider it as a semi-infinite plate. That is to say that the depth of penetration is considerably less than the depth of penetration achieved by the projectile. The resulting value of the penetration depth gives a crude approximation of the thickness that would be required to stop the projectile; however, it is usually sufficient for design purposes.

A common approach is to use the equations of motion to determine penetration (as opposed to the conservation of energy that was used above). So, for example, a resistive force applied to the projectile is determined by some parameters involving velocity, v , e.g.

$$F = a_0 + a_1v + a_3v^2 \quad (4.17)$$

where a_0 , a_1 and a_3 are constants. There are several equations in use that vary in complexity. Poncelet described the resisting force offered to the projectile as

$$F = -A_x(P_d + C_\alpha\rho v^2) \quad (4.18)$$

where A_x is the presented area of the immersed projectile, P_d is the distortion pressure in the target and C_α is an empirical dimensionless constant. Poncelet used this equation to predict the penetration into a target by incorporating into the motion equation $F = mdv/dt = mv dv/dx$. His empirically based equations was of the form (Backman and Goldsmith 1978)

$$p = c_1 \ln(1 + c_2v_0^2) \quad (4.19)$$

where c_1 and c_2 are empirically derived constants, p is the penetration and v_0 is the impact velocity.

4.3.1.1 Recht Penetration Formula

Recht (1967, 1990) described the resisting force in a more complex fashion that included mechanical strength terms and a dynamic friction coefficient:

$$F = -A_x \left[C_n \left(C_v v \sqrt{K\rho} \sin \alpha + 2\tau_s \ln(2Z_m) \right) \times \left(1 + \frac{f}{\tan \alpha} \right) \right] \quad (4.20)$$

where C_n is an empirical dimensionless constant dependent on nose shape (=0.62 for conical penetrators and for ogive projectiles where the radius of tangent ogive divided by the penetrator diameter is between 1 and 8), C_v is an empirical dimensionless constant that recognises that inertial pressure decreases with time due to wave dispersion (=0.25) and α is the half-angle of the conical nose of the projectile. For ogives described above, Recht deduced that these can be described as conical with a half-angle, α , of 23.5°. K is the bulk modulus of the target material, τ_s is the static shear strength of the target material, f is the dynamic friction coefficient (≈ 0.01 for metal on metal) and Z_m is given by

$$Z_m = \left(\frac{E}{Y} \right) \times \left(1 + 2 \frac{E}{Y} \right)^{-0.5} \quad (4.21)$$

where E is the Young's modulus of the target material, and Y is its static yield strength. The beauty of the Recht equation is that it is purely analytical, and predictions can be made simply by using a handbook of engineering properties and provide a good prediction capability for predicting the penetration depth obtained by rigid projectiles into ductile targets. Incorporating the force definition into the equation of motion provides an equation of the form

$$\int_0^x \frac{A_x}{A_p} dx = \frac{2 \left(\frac{m}{2A_p} \right)}{C_n b} \left[(v_0 - v) - \frac{a}{b} \ln \left(\frac{a + bv_0}{a + bv} \right) \right] \quad (4.22)$$

where A_x is the incremental area presented by the conical/ogival part of the penetrator, A_p is the area presented to by the projectile once it is completely immersed in the target, v_0 is the initial velocity and

$$a = 2\tau_s \ln(2Z_m) \left(1 + \frac{f}{\tan \alpha} \right) \quad (4.23)$$

$$b = C_v \sqrt{K\rho} \left(1 + \frac{f}{\tan \alpha} \right) \sin \alpha \quad (4.24)$$

If the penetrator is completely immersed in the target material, then the left-hand side of the above penetration equation is simply ' x_2 ' (the displacement into the target), and so the penetration equation becomes

$$x_2 = \frac{2 \left(\frac{m}{2A_p} \right)}{C_n b} \left[(v_{02} - v) - \frac{a}{b} \ln \left(\frac{a + bv_0}{a + bv} \right) \right] \quad (4.25)$$

where v_{02} is the velocity of the projectile as it becomes completely immersed in the target (i.e. after penetrating its length). This is a reasonable estimate for penetration depth and will give a first-order approximation that is usually suitable for design purposes when allowing for a factor of safety. Maximum penetration can be calculated by setting $v = 0$.

Knowing that

$$A_p = \frac{\pi d^2}{4} \quad (4.26)$$

and dividing both sides of the penetration equation by the diameter – d gives

$$\frac{x_2}{d} = \frac{4 \left(\frac{m}{\pi d^3} \right)}{C_n b} \left[(v_0 - v) - \frac{a}{b} \ln \left(\frac{a + bv_0}{a + bv} \right) \right] \quad (4.27)$$

This equation gives a dimensionless value of penetration (x/d) that can be used to compare predicted computations for different calibres of armour-piercing bullets.

Various material properties that are used for penetration analysis are presented in Table 4.1. The majority of the data are from Recht (1990).

Figure 4.2 shows the penetration prediction by using the Recht equation when compared to experimental penetration values into AA 6082-T651. The properties for the aluminium are presented in Table 4.1. The details of the bullet (7.62-mm FFV AP) are presented in Table 4.2, and the experimental data for the aluminium alloy were deduced from Hazell (2010). It can be seen that there is excellent agreement between the absolute penetration data and the predicted values of x_2 (the penetration depth when the penetrator is fully immersed in the target). Also included is the prediction of the penetration depth (x_2) when only the core is taken into account. With the core-only data, it is seen that Recht overpredicts the penetration depth, as the penetration through the jacket (and removing it) has not been taken into account. However, it shows nicely the differences in penetration that could be expected with and without a jacket.

TABLE 4.1
Engineering Material Properties for Some Common Metals

Material	Hardness (Brinell Hardness Number [BHN])	Density (kg/m ³)	Bulk Modulus, K (×10 ⁹ N/m ²)	Young's Modulus, E (×10 ⁹ N/m ²)	Yield Strength, Y (×10 ⁶ N/m ²)	Compressive Shear Strength, τ _s (×10 ⁶ N/m ²)
<i>Steel Alloys</i>						
Steel—soft	100	7830	158	206	172	206
Steel—mild	150	7830	158	206	309	275
Ship armour	200	7830	158	206	549	377
Ship armour	250	7830	158	206	756	470
Armour	300	7830	158	206	893	549
MIL-12560	350	7830	158	206	1030	618
<i>Aluminium Alloys</i>						
AA 7075-0	60	2765	69	71	103	151
AA 5083-0		2660	71	72	145	172
AA 5083-H113	75	2765	69	71	227	185
AA 6082-T651		2680	69	70	240	210
AA 2024-T3	120	2765	69	71	343	281
AA 7075-T6	150	2765	69	71	500	330
<i>Titanium Alloys</i>						
Ti-6Al-4V	285	4500	126	114	827	483
<i>Magnesium Alloys</i>						
Mg-13Li-6Al	55	1720	41	45	200	152

Source: Recht, R. F. 1990. High velocity impact dynamics: Analytical modeling of plate penetration dynamics. In *High Velocity Impact Dynamics*, edited by J. A. Zukas, 443–513. New York: John Wiley & Sons, Inc.

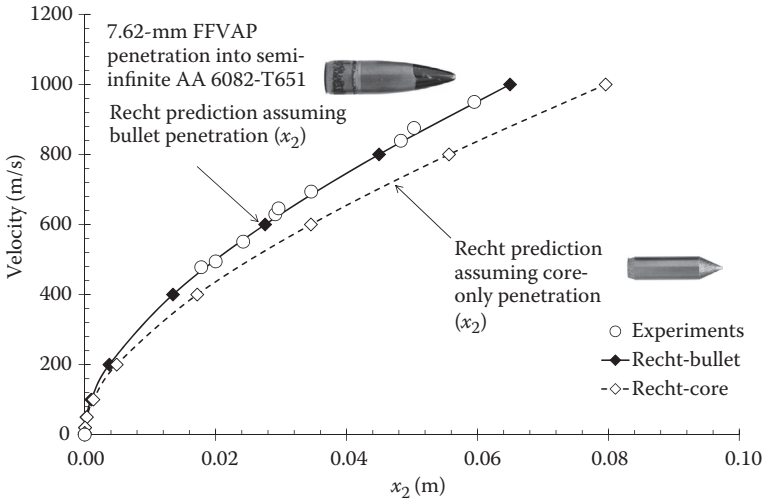


FIGURE 4.2 Penetration curves for AA 6082-T651 showing the comparison between the Recht predictions and experimental data for the 7.62-mm FFV AP bullet – with and without a jacket.

TABLE 4.2
Parameters for the 7.62-mm AP FFV Bullet Used in the Recht Model

Parameter	Symbol	Bullet	Core
Mass ($\times 10^{-3}$ kg)	m	8.23	5.90
Diameter ($\times 10^{-3}$ m)	d	7.62	5.59
Projected area ($\times 10^{-6}$ m ²)	A_p	45.60	24.50
Half-angle of cone ($^\circ$)	α	23.50	29.95

For higher-fidelity estimates, it is necessary to carry out the calculation in two steps knowing the length of the cone/ogive, l . First, for the case where $x < l$, penetration is calculated taking into account the varying change of the nose of the penetrator. To do this, the left-hand side of the penetration equation is replaced with the following:

$$\int_0^x \frac{A_x}{A_p} \cdot dx = \frac{\pi x^3}{3A_p} \tan^2 \alpha \tag{4.28}$$

Penetration (as a function of v) is computed using the equation that applies for $x < l$. When $x = l$, the computation is stopped, and the velocity at which $x = l$ is set equal to v_{02} , i.e. the velocity at which the penetrator is completely

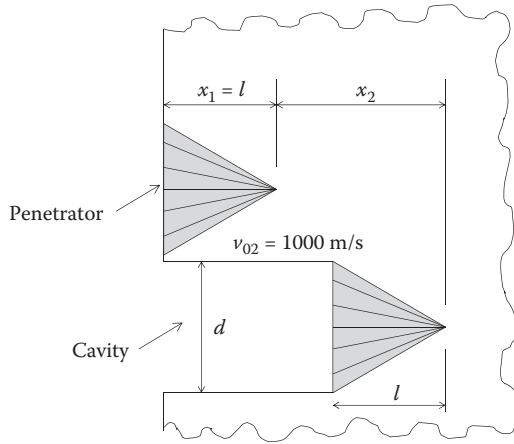


FIGURE 4.3

Penetration of a non-deforming cone-shaped projectile into ductile media. After penetrating a distance of L , the velocity = 1000 m/s (v_{02}).

immersed in the target (see Figure 4.3). The computation then continues with the calculation of x_2 .

The total depth of penetration is then given by

$$p = l + x_2 \tag{4.29}$$

where l is the length of the conical/ogival part of the penetrator and assuming that $p > l$.

This equation has been used extensively to predict penetration into various ductile target materials and is a useful tool for armour designers. Figure 4.4

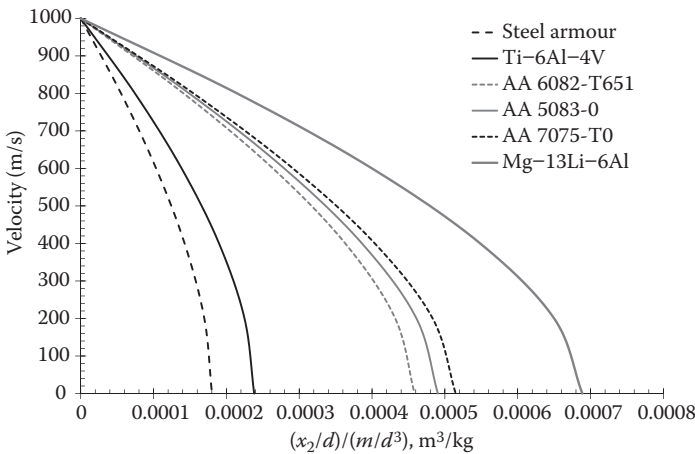


FIGURE 4.4

Penetration into ductile target media by a conical projectile.

shows some predicted penetration values of a projectile shaped as a cone with a half-angle of 23.5° into various ductile metals using the data from Table 4.1; the solid lines indicate the prediction of the projectile velocity as it penetrates deeper into the target. The x -axis is presented of the form (x_2/d) (m/d^3), which is a measure of penetration. Recht (1990) has shown that these penetration curves correlate very well with experimental data.

4.3.1.2 Forrestal Penetration Formula

Forrestal et al. (1988, 1992) examined the penetration performance of rods into aluminium alloys. In these works, they developed a formula for the axial force on an ogival nose as it penetrated an aluminium alloy target.

The projectile is shown in Figure 4.5. The shape of the nose is important, and it is commonplace to define the shape of an ogive in terms of its calibre radius head (CRH). With reference to Figure 4.5, CRH is defined by

$$\text{CRH} = \frac{s}{d} = \psi \quad (4.30)$$

The nose length, l , is given by

$$l = \frac{d}{2}(4\psi - 1)^{1/2} \quad (4.31)$$

The projectile strikes the target at velocity v_0 and penetrates at a constant velocity (as a rigid body) at velocity, v_z . The axial force acting on the ogival nose was derived as

$$F_z = 2\pi s^2 \int_{\theta_0}^{\pi/2} \left\{ \left[\sin \theta - \left(\frac{s - \frac{d}{2}}{s} \right) \right] (\cos \theta + \mu \sin \theta) \right\} \sigma_n(v_z, \theta) \cdot d\theta \quad (4.32)$$

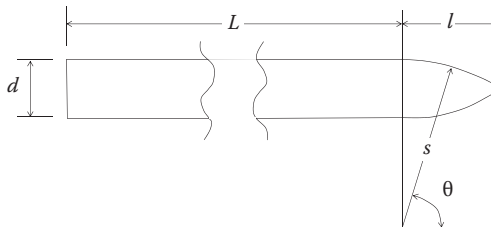


FIGURE 4.5

Ogival-nosed rod used for the Forrestal analysis. (Adapted from Forrestal, M. J. et al., *International Journal of Solids and Structures*, 29 (14–15):1729–1736, 1992.)

where

$$\theta_0 = \sin^{-1} \left(\frac{s - \frac{d}{2}}{s} \right) \quad (4.33)$$

In this equation, v_z is the instantaneous axial velocity during penetration, and s, d and θ are defined in Figure 4.5. The normal stress component $\sigma_n(v_z, 0)$ is the normal stress approximated assuming that the penetration of the rod causes a spherical cavity to grow in the material from rest to a constant velocity, v .

The derivation of the penetration formula will now be outlined according to Forrestal et al. (1992) that takes into account a cavity expansion that considers the strain hardening of the material. This is different from Forrestal et al.'s (1988) paper that only considered elastic–perfectly plastic behaviour (i.e. no strain hardening).

The coefficient of sliding friction introduced above (μ) is calculated by noting that the tangential stress is directly proportional to the normal stress according to

$$\sigma_t = \mu \sigma_n \quad (4.34)$$

For a spherically expanding cavity, a radial stress is applied to the material that results in cavity growth at a velocity v . This is defined as

$$\frac{\sigma_r}{Y} = A + B \left(\sqrt{\frac{\rho_t}{Y}} v \right)^2 \quad (4.35)$$

where A and B are dependent on the material properties of the target material. For an *incompressible* material, the following equations were derived (Luk et al. 1991):

$$A = \frac{2}{3} \left[1 + \left(\frac{2}{3} \frac{E}{Y} \right)^n I \right] \quad (4.36)$$

$$B = \frac{3}{2} \quad (4.37)$$

$$I = \int_0^{1-(3Y/2E)} \frac{(-\ln x)^n}{1-x} dx \quad (4.38)$$

where

I is evaluated numerically (Forrestal and Romero 2007).

E is the Young's modulus.

Y is the yield strength of the material.

n is the work hardening exponent used to curve-fit the stress–strain data.

For an AA 7075-T651, $I = 3.896$, and $A = 4.609$. It is important to point out that these equations are valid for incompressible material flow. That is to say that the density remains constant. For compressible behaviour, the density becomes a dependent variable. Based on previously published procedures (Luk et al. 1991), the radial stress at the cavity surface can be plotted against the cavity expansion velocity for both incompressible and compressible flow; the results for AA 7075-T651 (including the stress–strain response) are shown in Figure 4.6. It is then possible to curve-fit Equation 4.35 such that the parameters A and B are found. For a compressible AA 7075-T651, these results are $A = 4.418$ and $B = 1.068$.

Next, the particle velocity associated with the penetrating ogival-nosed projectile needs to be established. As the material is being penetrated, the material surrounding the ogival tip will be ‘pushed away’ at a velocity given by

$$u_p(v_z, 0) = v_z \cos \theta \tag{4.39}$$

The normal stress on the nose of the projectile is approximated by replacing the spherically symmetric cavity expansion velocity v with the particle velocity of the target material, u_p .

Therefore, Equation 4.35 becomes

$$\frac{\sigma_n(v_z, \theta)}{Y} = A + B \left[\left(\frac{\rho_t}{Y} \right)^{1/2} v_z \cos \theta \right]^2 \tag{4.40}$$

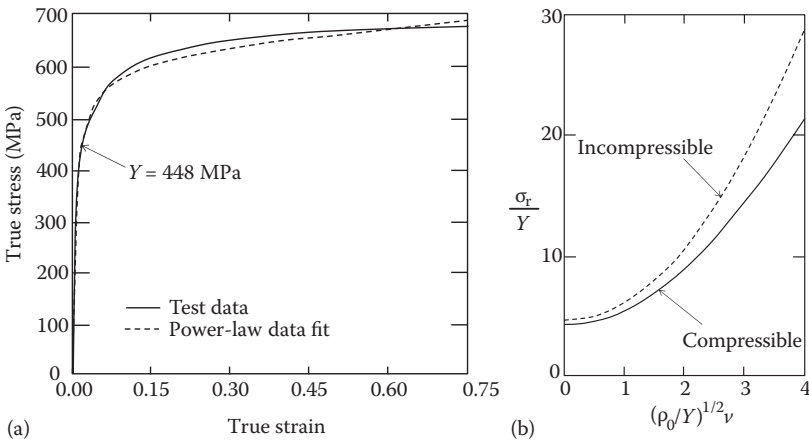


FIGURE 4.6 (a) Compression stress–strain data for 7075-T651 target material and the power law data fit and (b) radial stress at the cavity surface versus cavity expansion velocity for an elastic, strain-hardening material. (Reprinted from Forrestal, M. J. et al., *International Journal of Solids and Structures*, 29 (14–15), 1729–1736, Copyright 1992 with permission from Elsevier.)

Substituting into Equation 4.32 and integrating gives

$$F_z = \frac{\pi d^2}{4} Y \left(\alpha + \frac{\beta \rho_t v_z^2}{Y} \right) \quad (4.41)$$

$$\alpha = A \left[1 + 4\mu\psi^2 \left(\frac{\pi}{2} - \theta_0 \right) - \mu(2\psi - 1)(4\psi - 1)^{1/2} \right] \quad (4.42)$$

$$\beta = B \left[\frac{(8\psi - 1)}{24\psi^2} + \mu\psi^2 \left(\frac{\pi}{2} - \theta_0 \right) - \frac{\mu(2\psi - 1)(6\psi^2 + 4\psi - 1)(4\psi - 1)^{1/2}}{24\psi^2} \right] \quad (4.43)$$

$$\theta_0 = \sin^{-1} \left(\frac{2\psi - 1}{2\psi} \right) \quad (4.44)$$

The final penetration depth is obtained from

$$m \left(\frac{dv_z}{dt} \right) = mv_z \left(\frac{dv_z}{dz} \right) = -F_z \quad (4.45)$$

where m is the projectile mass, and z is the penetration depth.

The mass of the cylindrical portion of the rod is given by

$$m_c = \rho_p \frac{\pi d^2}{4} L \quad (4.46)$$

The mass of the ogival part of the projectile is given by

$$m_o = \rho_p \frac{\pi d^3}{8} k \quad (4.47)$$

where k is given by

$$k = \left(4\psi^2 - \frac{4\psi}{3} + \frac{1}{3} \right) (4\psi - 1)^{1/2} - 4\psi^2 (2\psi - 1) \sin^{-1} \left[\frac{(4\psi - 1)^{1/2}}{2\psi} \right] \quad (4.48)$$

Therefore, the total mass of the projectile is

$$m_p = m_c + m_o = \rho_p \frac{\pi d^2}{4} \left(L + \frac{kd}{2} \right) \quad (4.49)$$

Equations 4.41 and 4.49 can now be inserted into Equation 4.45 to give

$$-dz = \rho_p \left(L + \frac{kd}{2} \right) \frac{v_z}{\alpha Y + \beta \rho_t v_z^2} dv_z \quad (4.50)$$

This is then integrated between 0 and v_0 to give the final penetration depth (p):

$$p = \frac{1}{2\beta} \left(L + k \frac{d}{2} \right) \left(\frac{\rho_p}{\rho_t} \right) \ln \left[1 + \left(\frac{\beta}{\alpha} \right) \left(\frac{\rho_t v_0^2}{Y} \right) \right] \quad (4.51)$$

The predicted penetration results due to varying the impact velocity into AA 7075-T651 are given in Figure 4.7. It is clear that the coefficient of sliding friction plays a moderate role in reducing the penetration depth. However, measuring the coefficient of sliding friction during fast penetration is problematic. Forrestal et al. (1992) used values of between 0.0 and 0.06 that appeared to correlate well with the experimental results, which, given the extent of thermal softening that would be expected to occur, is reasonable. In fact, subsequent models assumed that $\mu = 0.0$ due to the expectation that a thin layer of melted material existed between the projectile/target material interface allowing for nearly frictionless contact (Forrestal and Warren 2008).

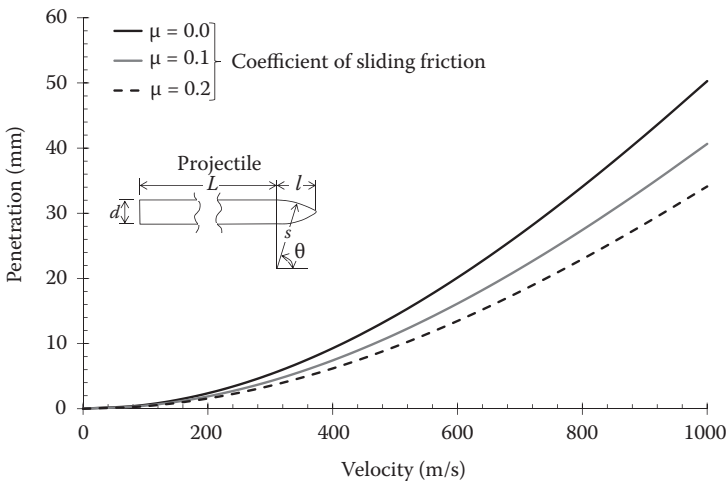


FIGURE 4.7

Calculated penetration results into an AA 7075-T651 by the projectile shown in the chart $d = 10$ mm, $L = 25$ mm and $l = 9$ mm. The coefficient of sliding friction is varied to show its effect.

Example 4.1

A conically nosed steel penetrator 25 mm long and 10 mm in diameter impacts an AA 7075-T6 target at 1000 m/s. The length of the conical portion of the projectile is 9 mm. Using the data from Table 4.1, calculate the penetration depth into the aluminium alloy using the Recht equation.

$$C_n = 0.62$$

$$C_v = 0.25$$

$$f = 0.01$$

Firstly, the half-angle of the cone needs to be calculated; this is done according to

$$\tan \alpha = \frac{d}{l} \quad (4.52)$$

The projected area is calculated from

$$A_p = \frac{\pi d^2}{4} \quad (4.53)$$

And the volume (V_{proj}) of the projectile (to calculate its mass) needs to be calculated according to

$$V_{\text{proj}} = \frac{\pi d^2}{4} \left(L + \frac{l}{3} \right) \quad (4.54)$$

where L is the length of the cylindrical section.

The penetration needs to be calculated in two steps:

Firstly, the velocity of the projectile is calculated at the point that the conical section is completely immersed in the target by setting $x = l$, and solving for the velocity, v , in the following equation using trial and error,

$$\frac{\pi x^3}{3A_p} \tan^2 \alpha = \frac{2 \left(\frac{m}{2A_p} \right)}{C_n b} \left[(v_0 - v) - \frac{a}{b} \ln \left(\frac{a + bv_0}{a + bv} \right) \right] \quad (4.55)$$

This can be solved very easily using Goal Seek in Microsoft Excel®.

So, in this first step, the volume of the projectile (V_{proj}) is needed:

$$V_{\text{proj}} = 2.2 \times 10^{-6} \text{ m}^3$$

which then gives us the mass ($\rho = m \times V$)

$$m = 17.2 \text{ g} = 1.72 \times 10^{-2} \text{ kg}$$

The half-angle of the cone is given by

$$\alpha = \tan^{-1}\left(\frac{5}{9}\right) = 29.055^\circ$$

And the left-hand side of the penetration equation gives us

$$\frac{\pi x^3}{3A_p} \tan^2 \alpha = \frac{4\pi l^3}{3\pi d^2} \frac{2^2}{l^2} = \frac{l}{3} = 9/3 = 3 \times 10^{-3} \text{ m}$$

From Table 4.1, the values for Z_m , a and b can be calculated. They are

$$Z_m = 8.41, a = 1.90 \times 10^9 \text{ N/m}^2 \text{ and } b = 1.71 \times 10^6 \text{ N s/m}^3.$$

Therefore, the penetration equation now becomes

$$3.0 \times 10^{-3} = 2.1 \times 10^{-4} \left(1000 - v - 1111 \ln \left(\frac{220}{1.9 \times 10^9 \times 1.71 \times 10^6 v} \right) \right)$$

Solving for v gives 969 m/s.

The second step is to replace v_0 with the calculated value of v from the previous step so that it is now v_{02} (=969 m/s), and use the following equation to calculate the penetration depth by the fully immersed penetrator and setting $v = 0$:

$$x_2 = \frac{2 \left(\frac{m}{2A_p} \right)}{C_n b} \left[(v_{02} - v) - \frac{a}{b} \ln \left(\frac{a + bv_0}{a + bv} \right) \right] \quad (4.56)$$

Doing this, we arrive at a value of $x_2 = 56.4 \times 10^{-3} \text{ m} = 56.4 \text{ mm}$.

Total penetration is then given by

$$p = l + x_2 \quad (4.57)$$

So, the total penetration = 9.0 + 56.4 = 65.4 mm.

Example 4.2

An ogival-nosed steel penetrator 25 mm long and 10 mm in diameter impacts an AA 7075-T6 target at 1000 m/s. The length of the ogival portion of the projectile is 9 mm. Using the Forrestal equation, calculate the penetration depth into a compressible aluminium alloy.

First, the projectile parameters shall be dealt with.

TABLE 4.3

Parameters Calculated for Example 4.2

Parameter	k (Radians)	m (kg)	θ_0 (Radians)	α (Radians)	β (Radians)	μ
Value	1.041	1.862×10^{-2}	0.556	4.420	0.296	0.00

The projectile parameter s needs to be calculated. From Equations 4.30 and 4.31,

$$s = \frac{1}{d} l^2 + \frac{d^2}{4} \quad (4.58)$$

For our projectile,

$$d = 0.010 \text{ m}$$

$$L = 0.025 \text{ m}$$

$$l = 0.009 \text{ m}$$

$$s = 0.0106 \text{ m}$$

Next, the other parameters need to be established (noting that the angles are in radians). These can be calculated simply by substituting into the equations presented previously and summarised in Table 4.3.

Here too, it is being assumed that the properties of AA 7075-T6 are identical to AA 7075-T651 (they are pretty close), and therefore, $A = 4.418$ and $B = 1.068$ are adopted for a compressible material; $Y = 448 \text{ MPa}$. Substituting into Equation 4.51, we get

$$p = \frac{1}{2 \times 0.296} \left(0.025 + 1.041 \times \frac{0.01}{2} \right) \left(\frac{7850}{2710} \right) \ln \left[1 + \left(\frac{0.296}{4.420} \right) \left(\frac{2710 \times 1000^2}{448 \times 10^6} \right) \right]$$

$$= 50.3 \times 10^{-3} \text{ m (50.3 mm)}.$$

This is somewhat lower than the Recht prediction for a conical shape (23%), and this is due to the different approaches used and the expectation of deeper penetration with a conical nose. Full penetration curves for this projectile into AA 7075-T651 are shown in Figure 4.7.

4.3.2 Penetration of Thin Plates

4.3.2.1 The Effect of Projectile Shape on Penetration

How a thin plate fails during ballistic penetration is largely driven by the shape of the projectile nose, its strength and its mass. It also depends on the target material and particularly how susceptible it is to adiabatic shear failure. Investigations of the projectile nose shape on Weldox steel have been carried out by Børvik et al. (2002) and Dey et al. (2004). It is quite clear from

these works that flat-nosed projectiles resulted in the lowest ballistic limit velocity for the plate, whereas conical, ogival and hemispherical projectiles result in similar ballistic limit velocities. The reason why flat (blunt)-nosed projectiles were able to perforate the plate at a lower velocity was because of the nature of plate failure, i.e. adiabatic shearing resulting in plug formation. Whereas with the more pointy projectiles, the higher ballistic limit result was due to ductile hole enlargement. This is an energy-expensive process.

4.3.2.2 Penetration of Thin Plates by Blunt-Nosed Projectiles

As we have discussed, penetration of thin plates is a little more complex as we have to take into account the role of petalling or plugging – particularly with regards to energy absorption. There are a number of analytical expressions that one can use to predict the v_{50} of thin plates impacted by compact blunt fragments, and these are summarised below (Recht 1971):

Modified de Marre (imperial units)

$$v_{50} = 2.34 \times 10^4 \left(\frac{h}{m^{1/3}} \right)^{3/4} \quad (4.59)$$

Thor (imperial units)

$$v_{50} = 4.05 \times 10^4 \left(\frac{h^{0.906}}{m^{0.359}} \right) \quad (4.60)$$

Recht–Ipson (imperial units)

$$v_{50} = 810 \frac{h^2}{Ld} \left\{ 1 + [(1 + L/h)(1 + d/0.098h)]^{0.5} \right\} \quad (4.61)$$

where

h is the plate thickness (in).

L is the cylindrical fragment length (in).

d is the cylindrical fragment diameter (in).

m is the fragment mass (gr).

It should be pointed out that the coefficients present in these equations have been derived using imperial units (inches, grains), and therefore, they need to be converted into SI units.

Figure 4.8 shows the data for the ballistic limit velocity (v_{50}) for compact blunt steel fragments impacting steel plates of varying hardness. These data

are plotted here in SI units (m, s, kg), although they were originally plotted in Recht (1971) using imperial units; the unit of mass used was grains rather than pounds, as at that time, most ballistic fragment studies used that unit. It can be seen that the modified de Marre equation for compact ballistic fragments fitted through the data is now given to us as

Modified de Marre (SI units)

$$v_{50} = 0.89 \times 10^4 \left(\frac{h}{m^{1/3}} \right)^{3/4} \tag{4.62}$$

There is also a lesson from Figure 4.8 on the type of steel plates that are best used to contain ballistic fragments. Mild steel plates (100–200 BHN) have low shear strengths, and therefore, they have low v_{50} values. The Hadfield manganese steel is especially tough and is a good performer in stopping the projectiles at small plate thicknesses. However, the high-hardness steel plates (400–550 BHN) do not perform so well. The reason for this is that these steels have a low coefficient of work hardening but are strong and generate high heat when deformed. This means that they are susceptible to adiabatic shear failure early on in the penetration process, and therefore, a plug shear occurs before much plate deformation occurs.

A good fit for the mild steel targets (from Figure 4.8) for low velocities is given below:

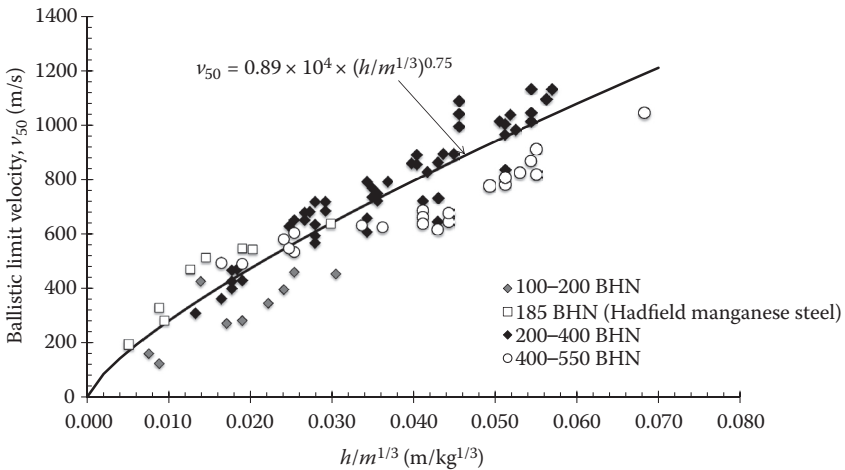


FIGURE 4.8 Ballistic limit correlations for steel plate. (Data extracted and converted from Recht, R. F., Containing ballistic fragments, in *Engineering Solids Under Pressure*, edited by H. L. D. Pugh, 50–60, London, The Institution of Mechanical Engineers, 1971.)

TABLE 4.4

Parameters for Blunt-Nosed Deformable Projectile Penetration

Parameter	Steel (300 BHN)	AA 2024-T4
C (m/s)	1297	227
K (m/s)	-164	141
J (m/s)	1544	1450
b	0.61	1.75

Modified de Marre (SI units) – mild steel

$$v_{50} = 0.89 \times 10^4 \left(\frac{h}{m^{1/3}} \right)^{0.84} \quad (4.63)$$

Further data are provided by Recht (1990). For blunt deformable penetrators impacting ductile plates, the following equations can represent the data well:

$$h/d \geq 0.1: \quad v_{50} = \frac{[C(h/d)^b + K]}{(L/d)^{1/2}} \quad (4.64)$$

$$h/d < 0.1: \quad v_{50} = \frac{J(h/d)}{(L/d)^{1/2}} \quad (4.65)$$

where

C, K, J = empirical constants (units of m/s).

b = dimensionless empirical constant.

L = length of the penetrator.

The typical values for 300-BHN steel and AA 2024-T4 are provided in Table 4.4.

4.3.2.3 Penetration of Thin Plates by Sharp-Nosed Projectiles

As one would expect, the penetration process as outlined for a blunt-nosed projectile will differ from the case where a sharp-nosed projectile penetrates the target. An example of a sharp-nosed projectile would be an armour-piercing core. Recht and Ipson (1963) developed an analytical description that appears to work well for a variety of data.

The energy balance for the case where a projectile perforates a thin plate is given by

$$\frac{1}{2}mv_0^2 = \frac{1}{2}mv_r^2 + W \quad (4.66)$$

where

m is the mass of the projectile.

v_0 is the impact velocity.

v_r is the residual velocity.

W is the work done during perforation.

If $v_r = 0$, then $v_0 = v_{bl}$.

And therefore,

$$W = \frac{1}{2}mv_{bl}^2 \quad (4.67)$$

where v_{bl} is the ballistic limit velocity – i.e. the velocity required to just completely penetrate the target (this can be approximated to v_{50}).

Therefore, combining the equations leads to

$$v_0^2 = v_r^2 + v_{bl}^2 \quad (4.68)$$

And therefore, normalising and rearranging,

$$\frac{v_r}{v_{bl}} = \left(\frac{v_0^2}{v_{bl}^2} - 1 \right)^{1/2} \quad (4.69)$$

So, knowing the impact velocity and the ballistic limit velocity, it is possible to calculate the residual velocity of the projectile (after the plate has been perforated). This equation is seen to work especially well where the impact velocities exceed the ballistic limit velocities by at least 50%.

In a more general sense, this is sometimes used for curve-fitting ballistic data such that Equation 4.69 is rearranged in terms of the residual velocity, and empirical parameters are introduced, viz.,

$$v_r = a \left(v_0^p - v_{bl}^p \right)^{1/p} \quad (4.70)$$

where a and p are the Recht–Ipson parameters and are dimensionless. Figure 4.9 shows an example of how these data are frequently presented (for a fictitious series of experiments).

Recht (1990) provides an empirical equation for the ballistic limit for the penetration of an armour-piercing projectile into a 300-BHN steel.

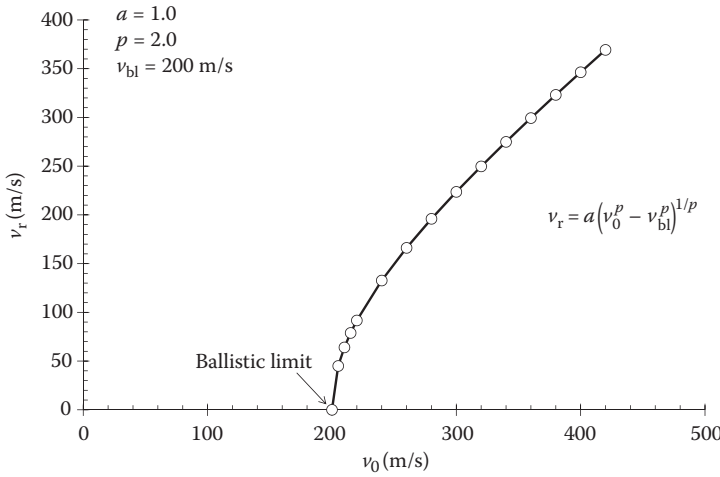


FIGURE 4.9 Recht-Ipson model where the ballistic limit velocity of the projectile = 200 m/s; $a = 1.0$ and $p = 2.0$.

For cases where $h/d \geq 0.5$, this is given by

$$v_{50} = C_s \left[\frac{\rho_0(h/d)}{m/d^3} \right]^{b_s} \tag{4.71}$$

where

- ρ_0 = density (units of kg/m^3).
- m = mass of the penetrator (kg).
- C_s = empirical constants (units of m/s).
- b_s = dimensionless empirical constant.

For a 300-BHN steel, C_s and b_s are estimated to be 781 m/s and 0.63, respectively ($h/d \geq 0.5$). Where $h/d < 0.5$, different constants would apply as petalling is a dominant failure process in the target.

4.3.3 Introducing Obliquity

Introducing obliquity to an armour plate will lead to an increase in the effective path length that will be offered to the projectile. This is clearly advantageous, although the advantage offered is often marred by the prospect of using a longer plate of armour to achieve height. The T34 is widely recognised for being the first mass-produced armoured vehicle that used angle plate deliberately to improve the ballistic performance of its armour. Since then, there have been many vehicles that have adopted similar strategies.

Take the BMP-1 for instance; the thickness of the steel armour on the front upper glacis plate of the hull was only 7 mm thick, but due to its steep angle to the vertical plane (80°), this thickness of steel offered 40 mm of effective thickness to a horizontal attack.

There are further advantages of inclining a plate of steel to an incoming projectile: namely, encouraging the projectile to turn. This can be an energy-expensive process. A projectile will usually exit a plate perpendicular to the plane of the plate and so therefore will be subjected to turning forces (see Figure 4.10). The harder the plate, the better. Harder materials encourage more ricochet compared to their softer counterparts. Certainly, for ceramics, it has been shown for small-arms ammunition that the ballistic limit velocity (v_{50}) increases with obliquity, although there is evidence that the increase in performance with obliquity does not match that of steels (Hetherington and Lemieux 1994).

A demonstration of the advantage of obliquity in steels can be shown by plotting the energy absorbed by the plate that has been shot at increasing thickness and comparing that for a single thickness inclined at an increasing angle. The relevant equations are as follows.

The percentage of energy absorbed by the plate (assuming that the mass of the projectile is not eroded during penetration, i.e. $m_i = m_r$) is given by

$$KE_a = 1 - \left(\frac{v_r}{v_0} \right)^2 \tag{4.72}$$

where KE_a is the fraction of the KE absorbed by the plate, v_r is the measured residual velocity after the plate has been perforated and v_0 is the initial velocity of the projectile before it strikes the target. Sequentially, shooting

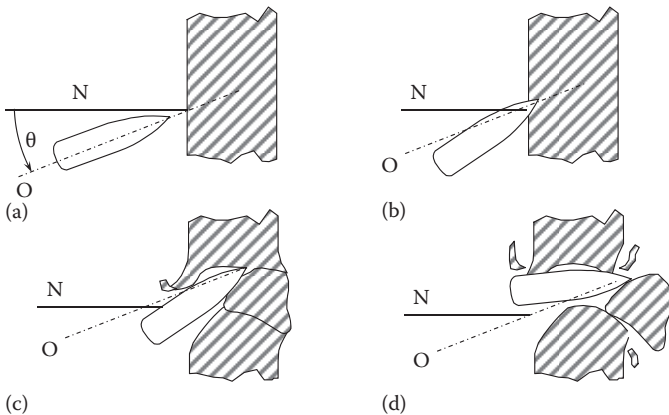


FIGURE 4.10

Bullet penetration at an oblique angle showing the sequence of events: (a) before impact, (b) the bullet embeds into the target, (c) the target fails and (d) the bullet perforates the target.

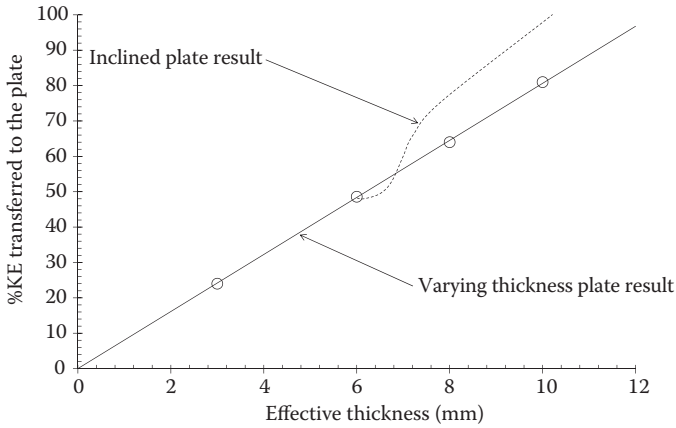


FIGURE 4.11 Calculation of the fraction of KE transferred to a mild steel plate ($\gamma = 300$ MPa) with increasing thickness compared to a 6-mm plate that is angled between 10° and 55° .

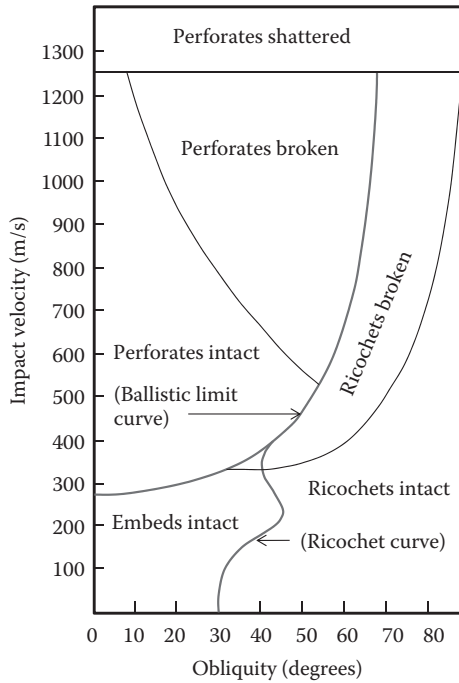


FIGURE 4.12 Phase diagram for a 6.35-mm-diameter ogival-nosed projectile impacting and penetrating a 6.35-mm-thick aluminium alloy target. (Reprinted from Backman, M. E., and W. Goldsmith, *The mechanics of penetration of projectiles into targets*, *International Journal of Engineering Science*, 16, 1, 1-99, Copyright 1978, with permission from Elsevier.)

projectiles (say, 5.56×45 -mm SS109) at a mild steel plate of thickness 3, 6, 8 and 10 mm will result in a linear correlation between the fraction of the KE absorbed by the plate and the thickness of the plate. Taking a 6-mm plate and inclining at angles ranging from 10° to 55° will result in an increase in effective path length from 6.09 to 10.46 mm (according to the equation $h_0 = h/\cos \theta$). This will result in a relationship as shown in Figure 4.11. For the normal incident example, the steel plate stops the projectile at a thickness of ~ 12 mm, whereas for the 6-mm inclined plate, this is accomplished at an angle of 55° and a resultant effective path length of 10.46 mm. As the plate is inclined, the effective path length that is offered to the projectile is also increased and appears to outperform equal thickness of steel at normal incidence. Thus, the obliquity is working positively to take energy out of the bullet.

Other studies have concentrated on mapping obliquity results with velocity and inclination. A good example of this is provided by Backman and Goldsmith (1978) (Figure 4.12).

4.4 Hydrodynamic Penetration

Armour-piercing fin-stabilised discarding sabot (APFSDS) rounds will commonly have an impact velocity in the range of 1300–1900 m/s, and therefore, penetration is approaching what we call hydrodynamic behaviour. Hydrodynamic penetration is described as a regime when the pressure below the tip of the penetrator is sufficiently high so as to cause the materials to behave like fluids (that is, with no resistance to shear). For tungsten alloy penetrators impacting steel, fully hydrodynamic penetration will not occur until an impact velocity of approximately 3000 m/s. This velocity is known as the *hydrodynamic limit*. Below this velocity, the strength of the steel target is important and provides a principle role in decelerating the rod. However, the required velocity for full hydrodynamic interaction depends on the materials and can be as high as 5000 m/s for ceramic materials, and therefore, this type of penetration regime will only be approached by very-high-velocity rod projectiles and shaped-charge jets. For a soft projectile penetrating a polymer, the hydrodynamic limit may be as low as 500 m/s.

Figure 4.13 shows an example of what happens during hydrodynamic penetration. Presented here are results from a computational simulation. Here, we have a strengthless W penetrator impacting a strong steel target at 3000 m/s. The first thing to realise is that despite the target being strong (tool steel) and the penetrator having zero strength (which is artificially set within the code), the penetrator is still able to penetrate. This is because the penetrator is still able to exert huge pressures in the target. In fact, similar results would be seen if the penetrator was given realistic strength values – although the strength of the penetrator does play a role as will be

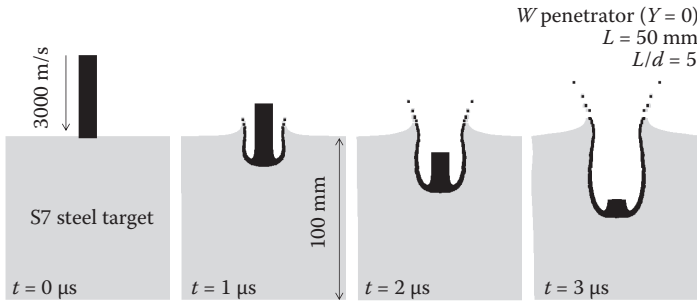


FIGURE 4.13
Hydrodynamic penetration.

seen later. Secondly, as the penetrator penetrates, it is being continually eroded by the target. Furthermore, the crater growth rate (that is to say, the velocity at which the crater moves downward in Figure 4.13) is constant. Thirdly, we see that the penetrator material is being deposited on the inside of the crater – a phenomenon that is readily observed after shaped-charge penetration.

There are four phases to hydrodynamic penetration that are summarised by the diagram in Figure 4.14 (Christman and Gehring 1966).

During the initial penetration, high transient pressures in the penetrator and the target material occur. This lasts for only a few microseconds as the material is rapidly compressed. During this time, impact flash is generated, and this can be partially attributed to the conversion of the thermal energy due to shock heating to visible light. At this point, a shock wave

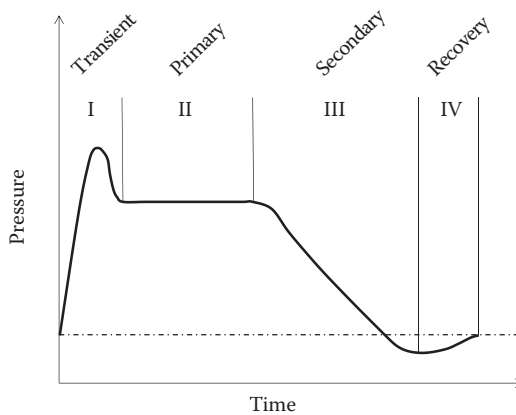


FIGURE 4.14
Four phases of penetration. (Reprinted with permission from Christman, D. R., and J. W. Gehring, Analysis of high-velocity projectile penetration mechanics, *Journal of Applied Physics*, 37 (4): 1579–1587, Copyright 1966. American Institute of Physics.)

detaches from the interface between the penetrating projectile and the target, and the crater grows. The pressure spike from the primary phase of penetration then rapidly decays to a steady state (phase II) when, for a long-rod penetrator or shaped-charge jet, the majority of the penetration occurs. This penetration is known as *primary penetration*, and at this stage, the rate of penetration is constant and can last for tens of microseconds. During the first two phases, the penetrator deforms and erodes and becomes increasingly shorter with increasing penetration depth. If the penetrator is completely eroded, as is the case when the impact velocity is sufficiently high, then phase III penetration occurs. This is *secondary penetration* when, under certain conditions, target material at the penetrator–target interface retains a proportion of inertia, and therefore, the crater continues to grow even after the penetrator has eroded or ceased penetration. During this time, the pressure decays in the target. Historically, this has sometimes been referred to as cavitation. The final phase (phase IV) is the elastic return of the target material and is normally very small and therefore ignored.

4.4.1 Fluid Jet Penetration Model

The theory to predict the primary phase of penetration was presented by Birkhoff et al. 1948. Consider a jet of material penetrating a target block hydrodynamically. The tail of the jet is travelling into the material at velocity v (this is the initial impact velocity). However, the penetration velocity is somewhat lower than v , and the tip of the jet penetrates into the target at velocity u . It is convenient to change the co-ordinate system to a Lagrangian one such that the origin or stagnation point is at the interface between the tip of the jet and the crater (Figure 4.15).

At this point, the velocity of the material is zero, and the pressure on the left-hand side of the stagnation point equals the pressure on the right-hand side. Note that for hydrodynamic penetration, it is assumed that the velocity of penetration into the target by the tip of the jet is constant – that is, the penetration is said to be in a steady state (no acceleration or deceleration). This is illustrated by the primary (phase II) penetration in Figure 4.14. From our new co-ordinate system, the tail of the jet is approaching the stagnation point at $v - u$, and the target material is approaching the stagnation point (from right to left) at a velocity u .

Consequently, the penetration can be described by a modified one-dimensional incompressible flow equation from the field of fluid mechanics:

$$\frac{1}{2}\rho_p(v - u)^2 = \frac{1}{2}\rho_t u^2 = \text{const.} \quad (4.73)$$

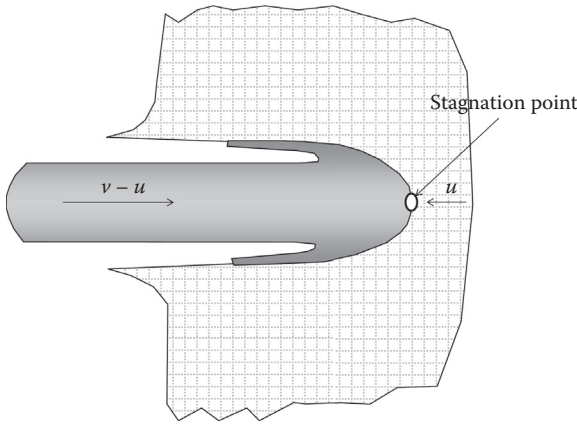


FIGURE 4.15

A jet of material penetrating a target hydrodynamically.

where ρ_p and ρ_t are the densities of the penetrator and the target, respectively, v is the impact velocity, which is also equal to the penetrator's tail velocity, and u is the penetration velocity.

This equation holds true for a projectile penetrating a target hydrodynamically with a constant penetration velocity and a constant erosion rate of $v - u$. From here, we can derive an equation that describes the total depth of penetration that is achievable through hydrodynamic penetration.

The time t taken for the total rod of length l to completely erode is given by

$$t = \frac{L}{v - u} \quad (4.74)$$

Therefore, the total penetration depth, p , is given by

$$p = u \cdot t \quad (4.75)$$

and substituting gives

$$p = \frac{L \cdot u}{v - u} \quad (4.76)$$

Furthermore, we obtain

$$\frac{u}{v - u} = \sqrt{\frac{\rho_p}{\rho_t}} \quad (4.77)$$

Therefore, substituting, we get

$$p = L \cdot \sqrt{\frac{\rho_p}{\rho_t}} \quad (4.78)$$

This equation tells us that when a jet penetrates a target hydrodynamically, the depth of penetration does not depend on the velocity of the penetrator. Instead, the depth of penetration depends on the length of the penetrator and the densities of the penetrator and the target. Therefore, it can be seen that maximum penetration can be achieved with long and dense penetrators.

We can also work out the desirable density of the material that, during fully hydrodynamic penetration, will provide the most weight-efficient means of eroding the penetrator. Multiplying both sides by ρ_t , we get

$$p \times \rho_t = L \cdot \sqrt{\rho_p \times \rho_t} \tag{4.79}$$

Therefore, for a known penetrator of length L and density ρ_p , the relationship between the areal density (A_D) of the material required to completely erode the penetrator and the bulk density of the material is

$$A_D \propto \sqrt{\rho_t} \tag{4.80}$$

Therefore, water, with its low density, offers weight-efficient protection against hydrodynamic attack. However, you will need a lot of it. The lower the density of the material, the lower the areal density required to provide protection. However, the ‘thickness’ of the material you require would be quite large. This is shown graphically in Figure 4.16 with annotations for water (H₂O), copper (Cu), mercury (Hg) and platinum (Pt).

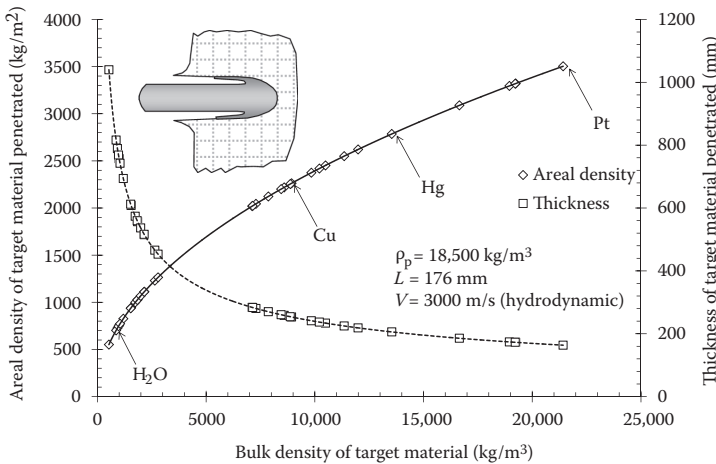


FIGURE 4.16 Effect of the bulk density of a material on the resultant areal density (the curve sloping upward from left to right) and thickness of material (the curve sloping downward from left to right) penetrated by a hydrodynamic threat.

Christman and Gehring (1966) fired a steel rod into two transparent plastics (polystyrene and polymethacrylate). Using a framing camera, they observed the shock wave as it swept through the thickness of the material. Using the Hugoniot properties of the target and the projectile, they deduced the impact pressure in the transient phase of the penetration. We will discuss how to do this in Chapter 5; however, in short, this is achieved by taking the known Hugoniot properties of the projectile and the target and using an impedance matching technique to establish the particle velocity and shock pressure.

The shock wave turned the transparent plastic opaque, and therefore, it was possible to track the shock front using a high-speed framing camera. Using the conservation of momentum across a shock front and the linear shock velocity–particle velocity relationship, Christman and Gehring were able to calculate the shock pressures (P) in the target and particle velocities (u_p) behind the shock wave. This theory will be discussed again in Chapter 5.

The appropriate equations are

$$U_s = c_0 + S \cdot u_p \quad (4.81)$$

$$P = \rho_0 U_s u_p \quad (4.82)$$

and therefore

$$P = \rho_0 (c_0 + S \cdot u_p) u_p \quad (4.83)$$

For methacrylate: $U_s = 2.68 + 1.61 \cdot u_p$, for $U_s < 6.9$ km/s

For polystyrene: $U_s = 2.48 + 1.63 \cdot u_p$, for $U_s < 6.7$ km/s

The measured shock waves in the methacrylate and polystyrene were 3.0 and 2.7 km/s, respectively, corresponding to primary-phase-penetration pressures of 0.71 and 0.38 GPa – much lower than the impact shock pressures.

Christman and Gehring also examined the penetration rate for a range of materials by taking a flash x-ray of the rod/cavity at about half the penetration depth. The results are shown in Table 4.5. They observed that the penetration rate was close to the initial calculated particle velocities (i.e. in the initial transient contact phase); however, the particle velocities exceeded the penetration velocity by between 6% and 19%. Also, assuming that the material behaved like an incompressible fluid, assuming a fluid jet penetration model provided better results for the penetration rate when compared to experimental data. The penetration rate can be calculated by rearranging Equation 4.73 to get

$$u = \frac{v}{1 + \sqrt{\frac{\rho_t}{\rho_p}}} \quad (4.84)$$

TABLE 4.5
Rod Penetration Rate Data for a C1015 Steel Rod ($L/D = 10$, $m = 0.6$ g) Impacting Various Target Materials

Target Material	Density ρ_0	Impact Velocity (km/s) v	Penetration Rate (km/s) (Measured) u_e	Initial Hugoniot Conditions					Penetration Rate (km/s) (Calculated) u
				Pressure (GPa) P	Shock Velocity (km/s) U_s	Particle Velocity (km/s) u_p	Penetration Rate (km/s) (Calculated) u		
AA 2024-T3	2770	3.84	2.2	6.20	8.76	2.53	2.40		
AA 2024-T3	2770	4.95	2.9	8.85	9.73	3.25	3.10		
AA 1100-0	2720	3.32	2.0	5.11	8.32	2.20	2.09		
AZ31B-F	1770	3.54	2.5	3.59	7.65	2.65	2.40		
Methacrylate	1190	3.66	2.5	2.56	7.23	2.98	2.63		
Polystyrene	1050	3.66	2.6	2.19	6.89	3.04	2.68		
Water	1000	3.72	2.8	2.09	6.70	3.12	2.74		
Polyethylene	940	3.63	2.8	2.06	7.25	3.04	2.70		

Source: Christman, D. R., and J. W. Gehring, *Journal of Applied Physics*, 37 (4):1579–1587, 1966.

It can also be seen that the calculated pressures were much higher than the yield strengths of these materials, and therefore, the strengths can be ignored, and the penetration can be described as hydrodynamic.

Their data are presented in Table 4.5.

4.4.2 Improvements on the Fluid Jet Penetration Model

With that said, it has been found that materials exhibit a dynamic strength capability even when the penetration is hydrodynamic. And, of course, a 1D model is being examined here. Therefore, it is prudent to add a dynamic strength coefficient that represents the resistance of the material to plastic flow. This approach was first suggested by Mott et al. 1944 in an unpublished Ministry of Supply report. It was later published in the open literature by Pack and Evans (1951) and Eichelberger (1956).

Early work to improve the fluid jet penetration model was carried out by Allen and Rogers (1961) who examined the penetration of Au, Pb, Cu, Sn, Al and Mg rods into aluminium targets using a modified Bernoulli equation:

$$\frac{1}{2} \rho_p (v - u)^2 = \frac{1}{2} \rho_t u^2 + R' \quad (4.85)$$

Allen and Rogers regarded the quantity R' as a strain rate function involving the material strength of both the rod and the target. Assuming that the yield strength of the rod = 0 (i.e. it acts purely like a fluid), then the strength of the target = R' can be written. Solving the above equation for u , we get

$$u = \frac{\rho_p v - \left[\rho_p^2 v^2 - 2(\rho_p - \rho_t)(0.5\rho_p v^2 - R') \right]^{1/2}}{(\rho_p - \rho_t)} \quad (4.86)$$

and, substituting this equation into Equation 4.75 and using Equation 4.74, we get

$$p = L \frac{-\rho_p v + \left[\rho_p^2 v^2 - 2(\rho_p - \rho_t)(0.5\rho_p v^2 - R') \right]^{1/2}}{\rho_t v - \left[\rho_p^2 v^2 - 2(\rho_p - \rho_t)(0.5\rho_p v^2 - R') \right]^{1/2}} \quad (4.87)$$

In the special case where $\rho_p = \rho_t = \rho$, then the above equations simplify to

$$u = \frac{v}{2} \left(1 - \frac{2R'}{\rho v^2} \right) \quad (4.88)$$

$$p = L \frac{1 - (2R'/\rho v^2)}{1 + (2R'/\rho v^2)} \quad (4.89)$$

At very high velocities $R' = 0$ and the equations for penetration velocity and penetration revert to

$$u = \frac{v}{1 + \sqrt{\frac{\rho_t}{\rho_p}}} \quad (4.90)$$

$$p = L \cdot \sqrt{\frac{\rho_p}{\rho_t}} \quad (4.91)$$

The beauty of this approach is that it now gives a way of predicting penetration velocities and penetration depths in the intermediate velocities as well as at the very high velocity.

From consideration of Equation 4.88, if the penetration velocity, $u = 0$, then the strength can be defined in terms of a critical velocity to allow penetration. In essence,

$$v_c = \frac{\sqrt{2R'}}{\rho_p} \quad (4.92)$$

where v_c is a critical velocity at which the rod will start to penetrate. Below this velocity, no penetration occurs ($u = 0$). From this, Allen and Rogers used an analytical model to deduce the strength of their 7075-T6 targets as being $1.87 \text{ GPa} \pm 0.12 \text{ GPa}$. The static compressive strength of 7075-T6 is 0.496 GPa . However, it had also been observed that the dynamic yield strength of a similar alloy was ~50% higher than its quasi-static yield strength. Also, it was noted that Tabor's (1951) analysis stated that plastic yielding occurred when the mean pressure applied by a penetrating punch is approximately $2.8Y$; for the case of a spherical punch, plastic flow occurs at $2.6Y$ (Allen and Rogers 1961), where Y is the quasi-static yield strength of the material. Therefore, the value of R' could be calculated from

$$R' = 0.496 \text{ GPa} \times 1.5 \times 2.6 = 1.93 \text{ GPa}$$

which is very close to the value predicted by the penetration experiments.

In fact, the best fit for R' gives a value of 2.22 GPa . This was based on the average value from the penetration experiments carried out on the rod metals that Allen and Rogers tested. The results are shown in Figure 4.17.

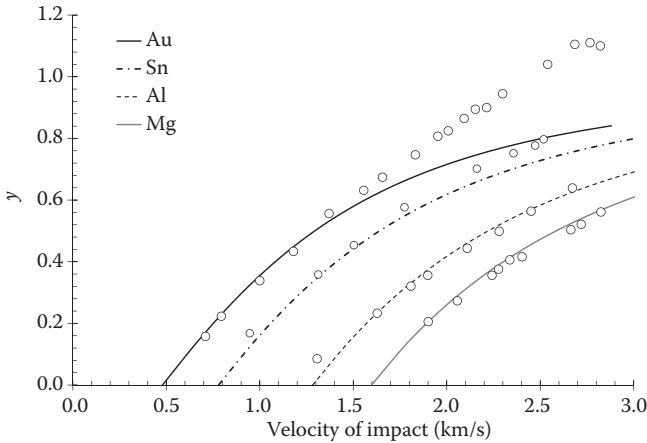


FIGURE 4.17

Comparison of theory and experiment. (Reprinted from Allen, W. A., and J. W. Rogers, Penetration of a rod into a semi-infinite target, *Journal of the Franklin Institute*, 272 (4), 275–284, Copyright 1961, with permission from Elsevier.)

Allen and Rogers also observed that the gold rods appeared to penetrate deeper into the aluminium targets than expected. They deduced that this was down to a process that they called ‘secondary’ or ‘residual penetration’ and is caused by the high relative density between the gold rods and the aluminium targets. They also noted that this effect was proportional to the jet length. This can be explained as follows: When the rod material is penetrating the aluminium, the rod material that has not been eroded has a velocity = $v - u$ (relative to the position of the crater, moving at velocity u). When the material is eroded at the crater, the material is reflected rearward with a velocity of $2u - v$. So, as the rod length is completely consumed, the eroded mass retains a velocity = $2u - v$. If $2u > v$ (which is determined by the densities of the projectile and the target), then deeper penetration can be expected.

Allen and Rogers’ model is a good approximation where it is assumed that the strength of the rod is zero. Of course, for most tank gun applications, this is not the case.

This has led the introduction of two terms by Alekseevskii (1966) and Tate (1967). The resulting equation indicating the pressure equality at the stagnation point is given by

$$\frac{1}{2}\rho_p(v-u)^2 + Y_p = \frac{1}{2}\rho_t u^2 + R_t \quad (4.93)$$

where Y_p is the projectile’s dynamic strength, and R_t is the target’s strength. The term R_t is not the shear or yield strength of the material but can be described as a measure of the overall resistance to penetration of the target. This takes into account the strength of the material and the dimensional

effects due to approximating a two-dimensional penetration phenomenon (assuming axial symmetry) with a strictly one-dimensional equation. A material with a large R_t term will perform well as an armour system when it is subjected to attack by an APFSDS projectile.

As outlined by Tate (1967), from Equation 4.93, the following equations can be derived that describes the penetration velocity:

$$u = \frac{1}{1 - \mu^2} \left[v - \mu \sqrt{v^2 + A} \right] \tag{4.94}$$

where

$$\mu = \sqrt{\frac{\rho_t}{\rho_p}} \quad \text{and} \quad A = 2 \frac{(R_t - Y_p)(1 - \mu^2)}{\rho_t} \tag{4.95}$$

Tate observed that some experiments had shown that the rod came to rest before it was all used up, and therefore, some deceleration had occurred, and therefore, the rear of the rod is slowing down.

Tate considered that the dynamic yield strength as measured from plate-impact experiments was a good indicator for the value of Y_p and R_t . This property can be calculated from the Hugoniot Elastic Limit (HEL) of the material measured under uniaxial strain shock-loading conditions and is given by

$$Y_d = \left[\frac{(1 - 2\nu)}{(1 - \nu)} \right] \sigma_{\text{HEL}} \tag{4.96}$$

where Y_d is the dynamic yield strength (under uniaxial stress conditions), ν is Poisson's ratio and σ_{HEL} is the HEL.

Now, Alekseevskii and Tate took into account the deceleration of the residual rod as the elastic waves travelled up the length of the rod and reflected from its free surface. The force per unit area retarding the rod is approximately Y_p . Therefore, knowing the momentary velocity of the back of the rod = v_b (i.e. it is not constant), we have

$$Y_p = -\rho_p l \frac{dv_b}{dt} \tag{4.97}$$

where l is the length of the rod at any point in time. Now, noting that any decrease in length in time is given to us by

$$\frac{dl}{dt} = -(v_b - u) \tag{4.98}$$

Equation 4.97 gives us the time integral, i.e. rearranging, we have

$$dt = \frac{-l\rho_p dv_b}{Y_p} \quad (4.99)$$

and substituting into Equation 4.98, we have

$$\frac{dl}{l} = \frac{\rho_p(v_b - u)dv_b}{Y_p} \quad (4.100)$$

By substituting Equation 4.94 into Equation 4.100 and integrating both sides, we arrive at an equation that describes the momentary rod length and the momentary rod velocity.

$$\frac{l}{L} = \left\{ \frac{v_b + \sqrt{v_b^2 + A}}{v + \sqrt{v^2 + A}} \right\}^{\left(\frac{R_t - Y_p}{\mu Y_p} \right)} \exp \left[\frac{\mu \rho_p}{2(1 - \mu^2) Y_p} \left([v_b \sqrt{v_b^2 + A} - \mu v_b^2] - [v \sqrt{v^2 + A} - \mu v^2] \right) \right] \quad (4.101)$$

remember that v is the initial velocity and v_b is the momentary velocity of the rear of the rod.

As before, the penetration depth is given by integrating with time the penetration rate; therefore,

$$p = \int_0^t u \cdot dt. \quad (4.102)$$

And, until the rod penetrates as a rigid body, Equation 4.102 can be rewritten as

$$p = \frac{\rho_p}{Y_p} \int_0^v ul \cdot dv_b \quad (4.103)$$

For the special case where $R_t = Y_p$, it is found that the equation for u (Equation 4.94) and l (Equation 4.101) is somewhat simplified, and the resultant penetration equation is given as

$$\frac{p}{L} = \left(\frac{1}{\rho} \right) \left[1 - \exp \left\{ -B(v^2 - v_b^2) \right\} \right] \quad (4.104)$$

where

$$B = \frac{\mu \rho_p}{2(1 + \mu) Y_p} \tag{4.105}$$

Setting $v = 0$ in Equation 4.104 gives the penetration depth in terms of L , μ , B and v . In general, Equation 4.103 needs to be integrated numerically; however, for a very specific case where $\rho_p = \rho_t = \rho$, and the ratios of the target/projectile strengths are $R_t/Y_p = 1, 3, 5$ and so on, the penetration equations can be easily written.

Establishing two dimensionless velocity parameters,

$$\bar{V}^2 = \frac{\rho v^2}{4Y_p} \quad \text{and} \quad \zeta = \frac{v_b}{v} \tag{4.106}$$

the penetration equations are given for the special case $\rho_p = \rho_t = \rho$ as follows:

$$R_t/Y_p = 1 \quad \frac{p}{L} = 1 - \exp [(\zeta^2 - 1)\bar{V}^2] \tag{4.107}$$

$$R_t/Y_p = 3 \quad \frac{p}{L} = \left(1 - \frac{2}{\bar{V}^2}\right) - \left(\zeta^2 - \frac{2}{\bar{V}^2}\right) \exp [(\zeta^2 - 1)\bar{V}^2] \tag{4.108}$$

$$R_t/Y_p = 5 \quad \frac{p}{L} = \left(1 - \frac{4}{\bar{V}^2} + \frac{4}{\bar{V}^4}\right) - \left(\zeta^4 - \frac{4\zeta^2}{\bar{V}^2} + \frac{4}{\bar{V}^4}\right) \exp [(\zeta^2 - 1)\bar{V}^2] \tag{4.109}$$

To calculate the final depth of penetration, we simply set $\zeta = 0$ in the above equations. In his original paper, Tate presented the predictions in terms of \bar{V} ; the same data are presented in the following in terms of the impact velocity (m/s) (see Figure 4.18). The strength of the steel penetrator (Y_p) was assumed to be 1.1 GPa, and the predictions and experimental data are for a steel penetrator penetrating a steel target (i.e. $\rho_p = \rho_t = 7800 \text{ kg/m}^3$).

The way that the tail of the rod decelerates can also be plotted according to theory. This is shown below for two cases: $v = 1500 \text{ m/s}$ and $v = 3000 \text{ m/s}$ ($\bar{V} = 2$ and 4 , respectively) using Equation 4.108 ($R_t/Y_p = 3$). Two important points can be seen from these data (see Figure 4.19):

1. The constant velocity of penetration is a reasonable assumption during most of the penetration process.
2. Increasing the velocity of impact results in less deceleration of the rod material over a given displacement in the primary phase of penetration.

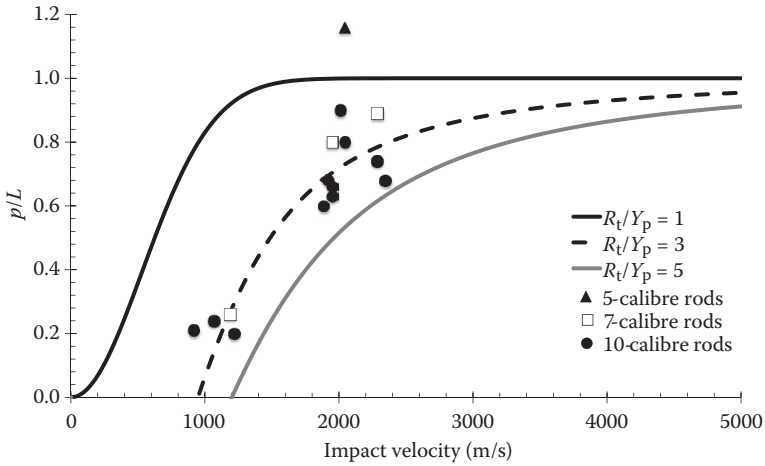


FIGURE 4.18
 Theoretical predictions for the cases where $\rho_p = \rho_t$ and $R_t/Y_p = 1, 3$ and 5 with experimental data points. (Reprinted from Tate, A., A theory for the deceleration of long rods after impact, *Journal of the Mechanics and Physics of Solids*, 15 (6), 387-399, Copyright 1967, with permission from Elsevier.)

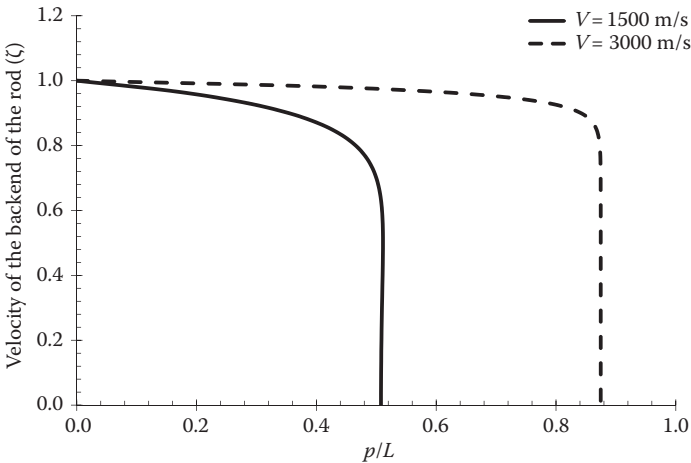


FIGURE 4.19
 Theoretical prediction of the deceleration of the rear portion of the rod assuming that $\rho_p = \rho_t$ and $R_t/Y_p = 3$; the data for impact velocities of 1500 and 3000 m/s are presented.

To evaluate the R_t term, the erosion rate of the rod needs to be assessed (assuming a constant penetration rate), and therefore, it is possible to calculate the strength difference ($R_t - Y_p$) knowing that

$$R_t - Y_p = \frac{1}{2} \rho_p v_e^2 - \frac{1}{2} \rho_t u^2 \tag{4.110}$$

where v_e is the measured erosion rate of the rod during penetration (normally taken from flash x-rays). If an estimate of Y_p can be made, then it is a relatively trivial task to calculate R_t .

Kozhushko et al. (1991) fired copper rods at ceramic targets at velocities between 5 and 8 km/s. Assuming that $Y_p \ll R_t$, they were able to estimate the value of R_t for the ceramic materials. Again, they showed that their calculated R_t correlated with the dynamic yield strength of the material.

Orphal and Franzen (1997) and Orphal et al. (1996, 1997) specify broad ranges of R_t values that are somewhat less than the values quoted by Kozhushko et al. Orphal et al. used a tungsten rod and assumed that $Y_p = 2.0$ GPa. The large discrepancy in the results from the two researchers may suggest that the magnitude of R_t is sensitive to loading conditions and velocity of impact. Certainly, with alumina, it has been suggested that R_t may in fact vary with impact velocity (Subramanian and Bless 1995). It has also been shown that R_t varies with target confinement (Anderson, Jr. and Royal-Timmons 1997).

Example 4.3

A material comprising three layers of material is subjected to attack by a shaped-charge jet with a tip velocity of 8 km/s. Assuming that the front 100-mm portion of the jet is travelling at a constant velocity (i.e. there is no velocity gradient in this portion of the rod), calculate the penetration velocities into the structure given that the layers are AA 1100-0, water and methacrylate.

Using Equation 4.84 will give us the penetration velocities:

So, for the AA 1100-0
$$u = \frac{8000}{1 + \sqrt{\frac{2720}{8930}}} = 5155 \text{ m/s}$$

For water,
$$u = \frac{8000}{1 + \sqrt{\frac{1000}{8930}}} = 5994 \text{ m/s}$$

For methacrylate,
$$u = \frac{8000}{1 + \sqrt{\frac{1190}{8930}}} = 5861 \text{ m/s}$$

There are two things to note: Firstly, the velocity that is used in each case is 8000 m/s. This is because the value ' v ' is the velocity of the rod material, from the tail to the crater (ignoring wave effects). Secondly, it is seen that the penetration rate changes as the material changes. This is to be expected as the penetration rate is governed by the densities of the materials.

Example 4.4

A solid, strengthless copper penetrator of length 200 mm impacts a target that comprises 20-mm W, 10-mm polycarbonate (PC) and 10-mm Cu. The projectile is travelling at 5 km/s. Assuming that one-dimensional penetration and all materials are strengthless, calculate the velocity of the penetrator in each layer assuming that each plate behaves like a semi-infinite plate. What is the length of the rod that exits the target?

The densities of materials are as follows:

W: 19,250 kg/m³

PC: 1210 kg/m³

Cu: 8960 kg/m³

From Equation 4.84, we have

$$u = \frac{v}{1 + \sqrt{\frac{\rho_t}{\rho_p}}} \quad (4.111)$$

Therefore, the velocities of penetration are

W: $u = 2028$ m/s

PC: $u = 3656$ m/s

Cu: $u = 2500$ m/s

To calculate the length of the rod that exits the target, we need to calculate how much of the rod is consumed during penetration of each plate. This can be done very simply by knowing that

$$dL = h \sqrt{\frac{\rho_t}{\rho_p}} \quad (4.112)$$

where dL is the length of rod consumed in each thickness (h) of plate. Therefore, the lengths consumed are

W: $dL = 29.3$ mm

PC: $dL = 3.7$ mm

Cu: $dL = 10.0$ mm

Therefore, the length of the remainder of the rod after perforation is

$$200.0 - 29.3 - 3.7 - 10.0 = 157 \text{ mm}$$

4.4.3 Segmented Penetrators

It has been well known for some time that at high velocity, shorter penetrators are more efficient at penetrating deeper than their longer counterparts. Early indications of this were seen in 1956 when Eichelberger (1956) observed that 40% of the total penetration in a lead target by a shaped-charge jet was due to the relatively slow-moving particles at the jet's tail. A good (and more recent) illustration of the effect is shown by the work of Hohler and Stilp (1987). They showed that the penetration normalised by the length of the penetrator was much higher when the length was equal to the diameter ($L/d = 1$) than when it was 9 or 10 times the diameter ($L/d = 9$ or 10). Notably, the increased performance of the short penetrator occurred at modest velocities (~ 1000 m/s) (see Figure 4.20).

Also shown in Figure 4.20 is the theoretical prediction of penetration based on the hydrodynamic theory that was discussed in Section 4.4.1 ($p/L = 1.5$). It can be seen that the long rods more or less obey the theory and plateau at a p/L value of 1.5, whereas the shorter rods do not. This behaviour was first described by Pack in 1951 as secondary penetration (Pack and Evans 1951). That is to say that after the pressure has been released from the bottom of the penetration cavity due to penetrator erosion, the material continues to flow until the motion has been damped out by the material's resistance to flow. This phenomenon is independent of penetrator length and is different from the secondary penetration observed by Allen and Rogers and discussed in Section 4.4.2.

All this suggests that if a continuous rod is broken up into discrete well-aligned segments separated by some distance, then penetrator performance

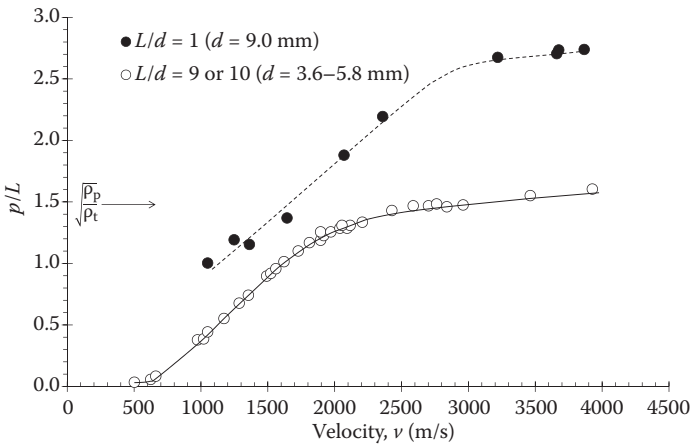
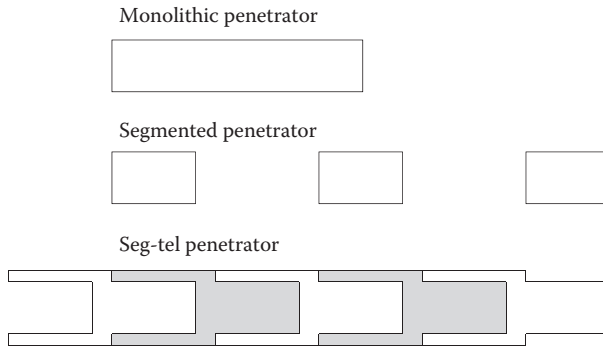


FIGURE 4.20 Penetration into a steel target (BHN = 360) by a tungsten alloy rod ($\rho = 17.6$ g/cc, BHN = 420); results are shown where the penetrator has an L/d value of 1 and 9 or 10. (Adapted from Hohler, V., and A. J. Stilp, *International Journal of Impact Engineering*, 5 (1-4):323-331, 1987.)

**FIGURE 4.21**

Monolithic, segmented and seg-tel penetrators. The seg-tel penetrator here shows the presence of low-density spacers.

can be enhanced. The trick is to ensure that the first segment is completely consumed before penetration from the second segment ensues. Engineering this is problematic, which has led to a range of solutions including the concept of segmented-telescopic (seg-tel) penetrators (Tate 1990; Brissenden 1992; Anderson, Jr. et al. 1997; see Figure 4.21).

4.5 A Brief Look at Computational Approaches

In recent years, there have been enormous advances in the use of computational approaches to understand the penetration behaviour of projectiles into targets and to simulate the blast response of structures. For the scientist and the engineer, the computational approach will complement the experiments very well – not least because the computer can provide a qualitative and quantitative account for every step in the penetration and failure processes.

More importantly, in recent years, they have become very good predictive tools, and it would be fair to say that most, if not all, government defence research labs in the world use computational methods in a predictive capacity.

4.5.1 Types

Computational approaches require constitutive models that describe the stress and deformation behaviour of the material under dynamic loading conditions. These models are commonly used within a computational code called a 'hydrocode'. This is a dynamic computational code where the

conservation of mass, momentum and (sometimes) energy equations are solved with the constitutive equations for the materials. The name 'hydrocode' arose simply because the early dynamic computations did not consider strength as the (very fast) collisions studied did not warrant it.

Initially, the problem is discretised into the appropriate geometry with a number of nodes and elements making up the complete geometry of the problem. Initial conditions such as boundary constraints and velocities are specified to the respective nodes. Then, using integration, which involves a calculated discrete time step of integration, and conservation equations, a solution for a single incremental cycle can be found. Integrating the velocities, we can calculate the displacements; having these, we can then work out the strain rates, strains, stresses, pressures, nodal forces and so on. This process is then repeated over many cycles to produce the final solution. More details on the theory of hydrocodes can be found in Anderson, Jr. (1987) and Zukas (2004).

Codes are formulated usually to use what is called the finite element method and are typically explicit as outlined above. Sometimes, codes will employ the finite difference method, and this differs from the finite element method by the way in which the mathematics is handled (Zukas 1990b, 2004).

There are two fundamental descriptions for the way the geometry is discretised and the way in which the conservation equations are described mathematically and solved numerically. An Eulerian description uses fixed nodes and cells and allows mass, momentum and energy to flow across cell boundaries. Analysis of the material that flows in and out of the cell enables us to calculate the change in mass, pressure, temperature and so on. Another approach that is often used in hydrocodes is the Lagrangian description. Here, the problem is spatially discretised with the complete geometry of the problem being defined by a mesh. As each time step progresses, cells can be stretched and compressed; the deformation of each individual cell is ultimately controlled by the nodal forces. Sadly, using a Lagrangian scheme, it is very difficult to simulate dynamic impact phenomena without experiencing highly compressed cells, and normally, there is a requirement to discard highly deformed cells from the calculation in a process called *erosion*. This can lead to inaccuracies in the solution. It is also found that shock fronts cannot be accommodated in modern-day computational codes in the same way they appear physically in nature, that is, as a finite but very thin discontinuity. Consequently, shock fronts are required to be smeared over a number of cells by the application of an *artificial viscosity* function. The use of artificial viscosity and erosion is not ideal; however, they do enable simulations of very fast events to be run.

Discrete element codes and smoothed particle hydrodynamics codes are particularly useful for modelling the failure of brittle materials as these are able to track material separation, whereas Lagrangian and Eulerian codes tend to have limited material separation characteristics.

4.6 Summary

In this chapter, some very simple approaches to understand the penetration mechanisms of a projectile into a target have been covered. It is worth noting that students can do some sensible work using some well-thought-out analytical models that are available in the literature; some of the more pertinent ones have been summarised here. In recent years, we have seen that computational codes have become extremely adept at predicting penetration into targets and modelling the structure failure response to blast. This has been due to the advances in material property measurements including measuring strain visually using digital image correlation, improvement in high-speed camera technologies and fidelity improvements in data acquisition systems. Code developments also continue to improve. Of course, it is also notable that computer technology continues to move forward in leaps and bounds, and with them the complexity of problems that can be simulated.

5

Stress Waves

5.1 Introduction

Projectile impacts and explosions result in the formation of waves of stress that can propagate deep into a target. Stress waves (and indeed shock waves) are important as they travel at very high velocities, and consequently, failure of the target linked to these waves can occur a long distance ahead of the penetrating projectile. This is very important when the spall failure of materials is considered. Understanding wave propagation mechanisms is also important when the design of armour is considered – especially in the case of brittle-based systems where small tensile waves can cause catastrophic failure. In this chapter, the physics behind stress waves and the special case where a shock wave is formed within the target material are examined.

Any contact between a moving object and stationary object will produce a wave that will emanate from the point of impact and move into the projectile and the target simultaneously. For very-low-velocity collisions in strong materials, the wave is most likely to be elastic in nature. Increasing the velocity of impact will result in an inelastic (plastic) wave being formed. Elastic wave velocities can be easily measured using ultrasonic techniques, as discussed in Chapter 2. Transducers comprised of a piezo-electric crystal that can be forced to oscillate when a voltage is applied; the oscillation results in an ultrasonic waveform with a frequency that is typically within the range of 0.02–20 MHz.

It is possible to design a multi-layered armour such that the stresses that are transmitted and reflected between each individual layer are optimised to minimise the degree of damage caused by the impacting projectile. First, the velocity of the material that is picked up by the wave and carried along with it will be established. This velocity is called the ‘particle velocity’.

5.2 Calculation of the Particle Velocity

The velocity of the particles in the elastic region is given by applying the principle of conservation of mass to an elastic wave front propagating at a velocity c (see Figure 5.1):

$$\rho_0 c = \rho(c - u_p) \quad (5.1)$$

Therefore, rearranging, it is seen that the velocity of the particles in the elastically compressed region (where the elastic wave compresses the material from ρ_0 to ρ) is given by

$$u_p = c \left(1 - \frac{\rho_0}{\rho} \right) \quad (5.2)$$

Now, for a unit mass, the specific volume is given by

$$V_0 = \frac{1}{\rho_0} \quad (5.3)$$

Assuming that the area is constant over the increment, the elastic strain in the sample is given by

$$\varepsilon = \frac{l_0 - l}{l_0} = \frac{V_0 - V}{V_0} = \frac{\rho - \rho_0}{\rho} = \left(1 - \frac{\rho_0}{\rho} \right) \quad (5.4)$$

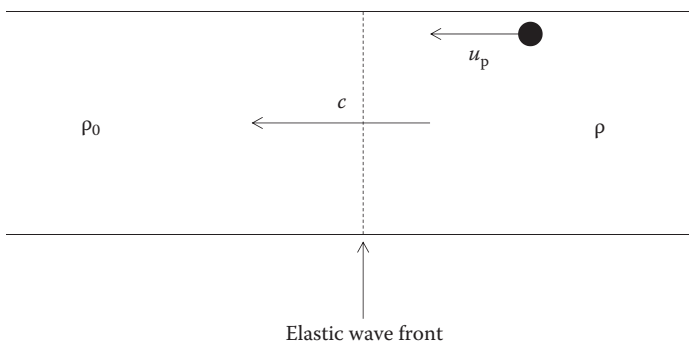


FIGURE 5.1
Elastic wave propagation.

Substituting Equation 5.4 into Equation 5.2 and assuming that the material follows Hooke's law in that $\varepsilon = \sigma/E$, we find that

$$u_p = \varepsilon c = \frac{\sigma}{E} c \quad (5.5)$$

Given that it is known that $E = \rho_0 c^2$, it therefore follows that

$$u_p = \frac{\sigma}{\rho_0 c} = \frac{\sigma}{\sqrt{\rho_0 E}} \quad (5.6)$$

Particles at a free surface will have twice this velocity due to the reflection of the wave as a rarefaction.

This is an important equation that defines the particle velocity as will be seen in Section 5.5 when shock waves are discussed. Now, where the elastic wave separates out from the plastic wave, it can be assumed that the magnitude of the elastic wave is equal to the (dynamic) yield stress, Y , of the material. Therefore, the equation becomes

$$u_p = \frac{Y}{\rho_0 c} \quad (5.7)$$

5.3 Elastic Waves

For an elastic wave (where the stress is less than the yield strength of the material), the speed is fixed and depends on the Young's modulus (E) and density (ρ_0). For a wave travelling in a bounded medium (such as a cylindrical bar or bullet), it is given by

$$c_0 = \sqrt{\frac{E}{\rho_0}} \quad (5.8)$$

For elastic wave transmission, it is assumed that $\rho \sim \rho_0$ as compressions are small.

For an elastic wave travelling in a semi-infinite medium (such as a target), the wave speed will be slightly higher than the value calculated in Equation 5.8 and is a function of the Poisson's ratio (ν) of the material as well as the Young's modulus and density. That is,

$$c_0 = \sqrt{\frac{E(1-\nu)}{\rho_0(1+\nu)(1-2\nu)}} \quad (5.9)$$

When two different materials are joined together, a portion of the elastic wave that arrives at the interface will be transmitted into the secondary layer, whilst a portion will be reflected. The relative elastic impedances of each material govern the proportion that is transmitted and reflected. The elastic impedance can be calculated from

$$Z = \sqrt{E\rho} = \rho_0 \cdot c_0 \quad (5.10)$$

It has the unit of $\text{kg}/\text{m}^2 \text{ s}$.

There are different forms of elastic waves, and in Sections 5.3 through 5.5, we are only going to concern ourselves with longitudinal waves, that is to say, where the particle motion is parallel to the wave propagation. Other types of waves include shear waves (we briefly looked at these in Chapter 2). These are evident where the particles are moving perpendicular to the direction in which the wave is propagating. For a description of other types of waves such as Rayleigh (surface) waves and waves that are particularly important in seismology (such as Love waves), consult Meyers (1994).

5.3.1 Elastic Wave Transmission and Reflection at an Interface

Elastic wave transmission and reflection across an interface will now be considered. Consider a laminate consisting of two materials (A and B), where an elastic wave of intensity σ_I travels through material A and comes into play with the interface. It will be assumed that a compressive stress wave of intensity σ_T is transmitted into material B, and a wave of intensity σ_R is reflected (see Figure 5.2). The subscripts I, T and R represent incident, transmitted and reflected, respectively.

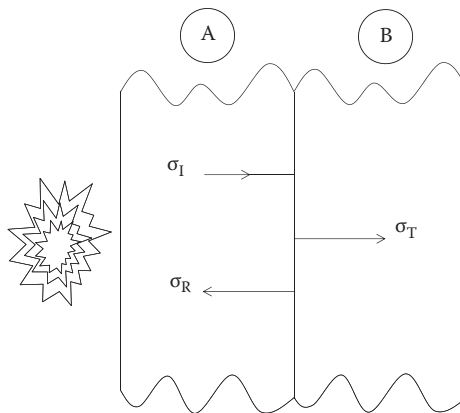


FIGURE 5.2

Transmission and reflection of an elastic wave at an interface.

The interface will be in equilibrium at the interface. Therefore,

$$\sigma_I + \sigma_R = \sigma_T \quad (5.11)$$

For continuity at the interfaces (no gaps can be created, and matter cannot superimpose itself),

$$u_{pI} + u_{pR} = u_{pT} \quad (5.12)$$

where u_p represents the particle velocity, and the subscript letters I, R and T represent incident, reflected and transmitted, respectively. In a continuum sense, the particle velocity can be assumed to be the velocity of the material behind the wave front. This is much less than the velocity at which the wave front propagates.

Now, considering two materials A and B, the incident stress wave front (σ_A) makes contact with the interface between the two materials, and some of the energy is transmitted into material B, whilst the remainder of the energy is reflected back into material A (see Figure 5.2). The particle velocities of these waves are therefore (see Equation 5.6)

$$u_{pI} = \frac{\sigma_I}{\sqrt{E_A \rho_A}}, \quad u_{pT} = \frac{\sigma_T}{\sqrt{E_B \rho_B}}, \quad u_{pR} = \frac{-\sigma_R}{\sqrt{E_A \rho_A}} \quad (5.13)$$

Assuming continuity,

$$\frac{\sigma_I}{\sqrt{\rho_A E_A}} - \frac{\sigma_R}{\sqrt{\rho_A E_A}} = \frac{\sigma_T}{\sqrt{\rho_B E_B}} \quad (5.14)$$

And solving Equations 5.11 and 5.14 simultaneously gives

$$\frac{\sigma_T}{\sigma_I} = 2 \left(\frac{\sqrt{E_B \rho_B}}{\sqrt{E_A \rho_A} + \sqrt{E_B \rho_B}} \right) \quad (5.15)$$

$$\frac{\sigma_R}{\sigma_I} = \left(\frac{\sqrt{E_B \rho_B} - \sqrt{E_A \rho_A}}{\sqrt{E_A \rho_A} + \sqrt{E_B \rho_B}} \right) \quad (5.16)$$

From Equations 5.15 and 5.16, the level of stress that is transmitted and reflected depends on the impedances of the individual materials. It is therefore possible to list the relative transmission and reflection values assuming that material A is steel. These are shown in Table 5.1.

TABLE 5.1

Ratios of the Transmitted and Reflected Stress from a Wave Transiting an Interface between Steel and a Secondary Material (B)

Material A	Material B	ρ_B (kg/m ³)	E_B (GPa)	$Z_B \times 10^6$ (kg/m ² s)	σ_T/σ_I	σ_R/σ_I
Steel	Air	1.225	0	0	0.00	-1.00
Steel	Epoxy	1140	5	2.41	0.11	-0.89
Steel	PMMA	1190	6	2.69	0.12	-0.88
Steel	Magnesium (AZ31B)	1780	41	8.55	0.35	-0.65
Steel	Aluminium (6082-T6)	2703	73	14.09	0.52	-0.48
Steel	Ti-6Al-4V	4400	114	22.40	0.71	-0.29
Steel	Copper	8900	122	33.01	0.90	-0.10
Steel	Steel	7840	210	40.58	1.00	0.00
Steel	Tungsten	19,250	411	88.95	1.37	0.37
Steel	WC	14,740	601	94.11	1.40	0.40

Note: The impedance of steel, $Z_A = 40.58 \times 10^6$ kg/m² s.

It can be seen from Table 5.1 that depending on the properties of the material that adjoins the face plate, the magnitude of the reflected stress can either be positive or negative. That is to say that the stresses are either compressive or tensile. The stress transmitted into material B is always positive (compressive). So, consider a steel face plate with an epoxy rear layer. It will be seen that 89% of the wave is reflected back into the steel as a tensile wave. If the steel is not backed by anything (i.e. material B is air), then the stress wave is completely reflected back. This can be damaging to the steel and is the reason why high-explosive squash head (HESH) causes such significant spall damage in metals.

However, it can also be seen that when material B has a higher impedance than material A, then the reflected wave is compressive. This can have implications for armour design – particularly where the face plate is brittle.

Example 5.1

A stress wave with a magnitude 100 MPa propagates into an RHA face layer of a two-component armour. The rear face is made from the aluminium alloy AA 7017. Calculate the magnitude of the stress wave in the aluminium, and sketch the wave interaction at the interface assuming an infinitely long stress pulse. Repeat the process for a case where the second material is W (as opposed to AA 7017). The properties of all materials are summarised in Table 5.2.

First, the impedance values are calculated for each of the materials:

$$\text{RHA: } Z = \sqrt{E\rho_0} = \sqrt{218 \times 10^9 \times 7838} = 41.34 \times 10^6 \text{ kg/m}^2 \text{ s}$$

$$\text{AA 7017: } Z = \sqrt{E\rho_0} = \sqrt{72 \times 10^9 \times 2780} = 14.15 \times 10^6 \text{ kg/m}^2 \text{ s}$$

TABLE 5.2
Properties of RHA and AA 7017

Material	ρ_0 (kg/m ³)	E (GPa)
RHA	7838	218
AA 7017	2780	72
W	19,200	410

So substituting into Equation 5.16,

$$\sigma_T = 2 \left(\frac{14.15 \times 10^6}{41.34 \times 10^6 + 14.15 \times 10^6} \right) \times 100 \times 10^6 = 51 \times 10^6 \text{ Pa} = +51 \text{ MPa}$$

To sketch the wave interaction, the reflected stress at the interface that travels back into the steel needs to be calculated. This can be easily done by knowing that equilibrium at the interface dictates:

$$\sigma_I + \sigma_R = \sigma_T \tag{5.17}$$

Therefore,

$$\sigma_R = 51 \times 10^6 - 100 \times 10^6 = -49 \times 10^6 \text{ Pa} = -49 \text{ MPa}$$

Therefore, tensile stress (indicated by the ‘-’ sign) is reflected back into the steel. This is shown in Figure 5.3. The tensile stress that has been reflected back into the steel will be deducted from the compressive wave in the steel.

The above calculations can now be repeated but this time using W as the second material as opposed to AA 7017. So, the impedance of the W is given by

$$W: Z = \sqrt{E\rho_0} = \sqrt{411 \times 10^9 \times 19,250} = 88.95 \times 10^6 \text{ kg/m}^2 \text{ s}$$

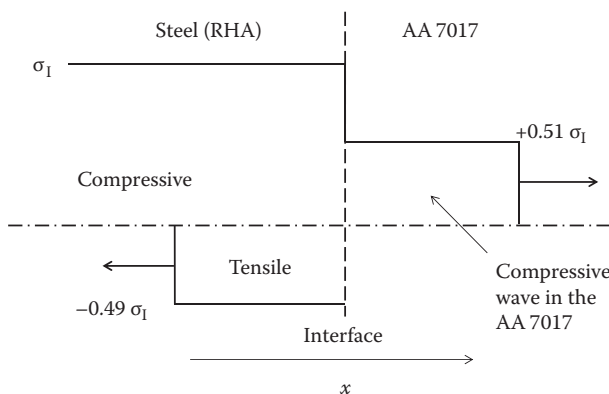


FIGURE 5.3

Stress wave transmission at the interface between steel (RHA) and an aluminium alloy (7017).

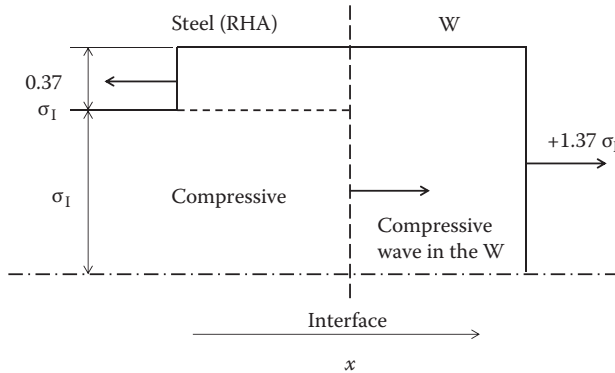


FIGURE 5.4

Stress wave transmission at the interface between steel (RHA) and tungsten (W).

And the stress transmitted into the W will be given by

$$\sigma_T = 2 \left(\frac{88.95 \times 10^6}{41.34 \times 10^6 + 88.95 \times 10^6} \right) \times 100 \times 10^6 = 137 \times 10^6 \text{ Pa} = +137 \text{ MPa}$$

It can now be seen that the stress transmitted into the W is higher than the stress that was seen in the RHA, i.e. the stress is amplified. To calculate the reflected stress back into the steel, we again can refer to the equilibrium:

$$\sigma_R = 137 \times 10^6 - 100 \times 10^6 = +37 \times 10^6 \text{ Pa} = +37 \text{ MPa}$$

Therefore, compressive stress (indicated by the '+' sign) is reflected back into the steel. This is shown in Figure 5.4. The compressive stress that has been reflected back into the steel has been added to the original compressive wave in the steel.

Example 5.2

A closed-cell aluminium foam* (see Chapter 6) is encased by two thin layers (skins) of aluminium. An impact results in a stress propagation through the front skin and is transmitted through the porous foam layer. It is estimated that the area of transmission of the foam is about one-quarter of the skin. Calculate the stress transmitted to the rear layer when a 100-MPa stress is suddenly applied to one face and maintained.

For this problem, we now need to adapt our 'equilibrium equation' to take into account the change in the area. The problem can be summarised by Figure 5.5.

The equilibrium equation now becomes

$$(\sigma_I + \sigma_R)A_1 = \sigma_T A_2 \quad (5.18)$$

* Inspired by a similar problem in Smith and Hetherington (1994).

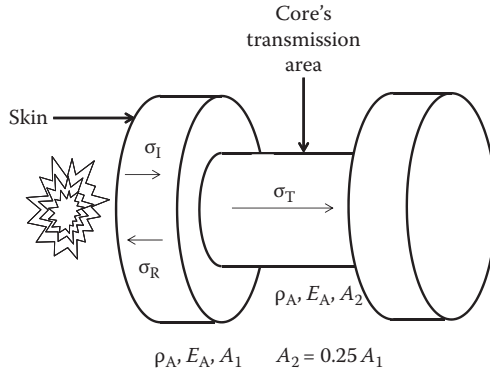


FIGURE 5.5 Stress wave transmission through a sandwich panel with a porous core – a simple approach.

or

$$(\sigma_I + \sigma_R)A_1 = \sigma_T n A_1 \tag{5.19}$$

where n is the fraction of the area, A_1 , and in this case = 0.25 if we are looking at transmission from the skin into the core.

The compatibility equation for identical materials is

$$\frac{\sigma_I}{\sqrt{\rho E}} - \frac{\sigma_R}{\sqrt{\rho E}} = \frac{\sigma_T}{\sqrt{\rho E}} \tag{5.20}$$

Therefore, solving Equations 5.19 and 5.20 simultaneously gives

$$\sigma_T = \frac{2}{n + 1} \sigma_I \tag{5.21}$$

and

$$\sigma_R = \frac{n - 1}{n + 1} \sigma_I \tag{5.22}$$

Therefore, from Equations 5.21 and 5.22, referring to our problem, it is seen that

$$\begin{aligned} \sigma_T &= \frac{2}{0.25 + 1} \times 100 \text{ MPa} \\ &= +160 \text{ MPa} \end{aligned}$$

$$\begin{aligned} \sigma_R &= \frac{0.25 - 1}{0.25 + 1} \times 100 \text{ MPa} \\ &= -60 \text{ MPa} \end{aligned}$$

The next step is to calculate the stress transmitted into the second skin. This time, the area is four times the area from which the stress arrives, and therefore, $n = 4$.

Back to Equations 5.21 and 5.22,

$$\begin{aligned}\sigma_T &= \frac{2}{4+1} \times 160 \text{ MPa} \\ &= +64 \text{ MPa}\end{aligned}$$

$$\begin{aligned}\sigma_R &= \frac{4-1}{4+1} \times 160 \text{ MPa} \\ &= +96 \text{ MPa}\end{aligned}$$

It should be pointed out that, in reality, the transmission of stress waves into foam materials is quite complex as the face plate is driven into the foam and compacts it, and therefore, the volume of the core is not a constant. Further, the waves navigate through the cell walls in a convoluted way, and the stress in the cell wall is released by virtue of their proximity to the voids. However, as an illustrative example, it is an interesting problem. Next, we will look at a problem where there is a change of both materials and area.

Example 5.3

A 50-MPa elastic wave from an aluminium bar is transmitted into a steel bar where the steel bar has half the diameter (see Figure 5.6). Calculate the stress transmitted into the steel bar and the reflected wave back into the aluminium.

If the diameter of the steel bar is half the diameter of the aluminium bar, then the area of the steel bar is one-quarter of the aluminium bar, i.e. $d_2 = 0.5 d_1$, and therefore, $A_2 = 0.25 A_1$. Therefore, $n = 0.25$ (as before) and

$$(\sigma_I + \sigma_R)A_1 = \sigma_T n A_1 \text{ (equilibrium)}$$

$$\frac{\sigma_I}{\sqrt{\rho_A E_A}} - \frac{\sigma_R}{\sqrt{\rho_A E_A}} = \frac{\sigma_T}{\sqrt{\rho_B E_B}} \text{ (compatibility)}$$

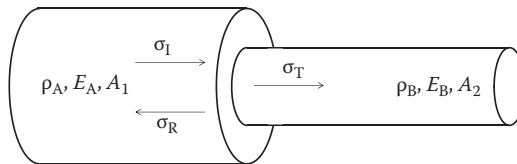


FIGURE 5.6

Wave transmission at an interface where there is a change of material and area.

Solving these equations simultaneously gives

$$\sigma_T = 2 \left(\frac{\sqrt{E_B \rho_2}}{\sqrt{E_A \rho_A} + n \sqrt{E_B \rho_B}} \right) \sigma_I \quad (5.23)$$

$$\sigma_R = \left(\frac{n \sqrt{E_B \rho_B} - \sqrt{E_A \rho_A}}{\sqrt{E_A \rho_A} + n \sqrt{E_B \rho_B}} \right) \sigma_I \quad (5.24)$$

Recalling that the impedance of the aluminium is: $Z_A = 14 \times 10^6 \text{ kg/m}^2 \text{ s}$, and the steel bar is $Z_B = 41 \times 10^6 \text{ kg/m}^2 \text{ s}$ and using Equations 5.23 and 5.24:

$$\begin{aligned} \sigma_T &= 2 \left(\frac{41 \times 10^6}{14 \times 10^6 + 0.25 \times 41 \times 10^6} \right) \sigma_I \\ &= +169.1 \text{ MPa} \end{aligned}$$

$$\begin{aligned} \sigma_R &= \left(\frac{0.25 \times 41 \times 10^6 - 14 \times 10^6}{14 \times 10^6 + 0.25 \times 41 \times 10^6} \right) \sigma_I \\ &= -7.7 \text{ MPa} \end{aligned}$$

We should now double-check that equilibrium is maintained by substituting our results into Equation 5.19, namely,

$$(50.0 - 7.7) = 169.1 \times 0.25 = 42.3 \text{ MPa}$$

5.4 Inelastic Waves

In most practical military applications where a dynamic load is applied, the magnitude of the stress wave will be much higher than the yield stress of the material. This gives rise to a two-wave structure consisting of elastic and plastic parts.

The equation for the velocity of an inelastic wave travelling in a bounded medium is similar for an elastic wave – Equation 5.8 – and is given by

$$c_i = \sqrt{\frac{S}{\rho}} \quad (5.25)$$

where S is the slope of the stress–strain curve beyond the elastic limit. This is often called the plastic modulus (as opposed to the elastic modulus). Because

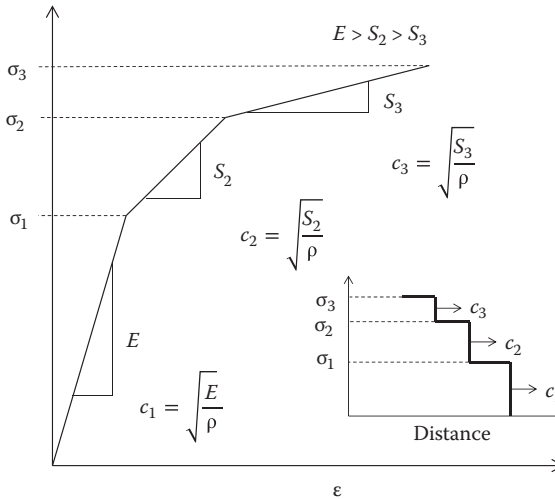


FIGURE 5.7 Stress–strain curve for a material showing three discrete gradients resulting in three different wave speeds. Inset: an idealised wave shape after the wave has travelled a certain distance.

$E > S$, the elastic wave will travel faster than the inelastic wave, and therefore, the wave fronts will become separated over time (see Figure 5.7).

If the inelastic response of the material is non-linear (as is the case with most ductile materials), then we will need to calculate the slope at each increment of stress. If the stress–strain curve for a material is considered, then the velocities at specific stress levels can be evaluated (in this case, at three locations – see Figure 5.7):

$$c_1 = \sqrt{\frac{E}{\rho}}, \quad c_2 = \sqrt{\frac{S_2}{\rho}}, \quad c_3 = \sqrt{\frac{S_3}{\rho}} \tag{5.26}$$

In the above case, it can be seen that as $E > S_2 > S_3$, then $c_1 > c_2 > c_3$ – in other words, the shape of the wave changes as the wave progresses through the material.

5.4.1 Inelastic Wave Transmission and Reflection at an Interface

In Section 5.3.1, elastic wave reflection and transmission at an interface were discussed. For inelastic waves, the same principles apply; however, the solution is a little more complicated in all but the simplest of cases. It is appropriate to separate the elastic wave calculations from the inelastic wave calculations as the following example shows.

Example 5.4

Consider a ceramic-faced armour system consisting of a ceramic front plate and an aluminium alloy back plate. The ceramic is subjected to an incident stress wave of magnitude 1500 MPa. If the yield strength (Y) of the aluminium alloy is 450 MPa and has a stress–strain curve that can be approximated in a bilinear fashion where $E = 70$ GPa and $S = 30$ GPa ($\rho = 2710$ kg/m³ – see Figure 5.8), calculate the magnitude of the elastic and inelastic stress waves that are transmitted into the aluminium alloy. The ceramic remains elastic throughout the process. For the ceramic, $\rho = 3840$ kg/m³; $E = 380$ GPa.

Firstly, the ceramic will remain elastic throughout the process; however, the aluminium will experience an elastic stress wave with a magnitude equal to the yield strength of the material and an inelastic stress wave of unknown magnitude. Therefore, the compatibility equation is modified to take this into account:

$$\frac{\sigma_I}{\sqrt{\rho_A E_A}} - \frac{\sigma_R}{\sqrt{\rho_A E_A}} = \frac{Y}{\sqrt{\rho_B E_B}} + \frac{\sigma_T^P}{\sqrt{\rho_B S_B}} \tag{5.27}$$

After calculating the impedance values, this becomes

$$\frac{1500}{38.2 \times 10^6} - \frac{\sigma_R}{38.2 \times 10^6} = \frac{450}{13.8 \times 10^6} + \frac{\sigma_T^P}{9.0 \times 10^6}$$

Considering equilibrium,

$$\sigma_I + \sigma_R = Y + \sigma_T^P \tag{5.28}$$

and solving simultaneously, $\sigma_T^P = 248.7$ MPa.

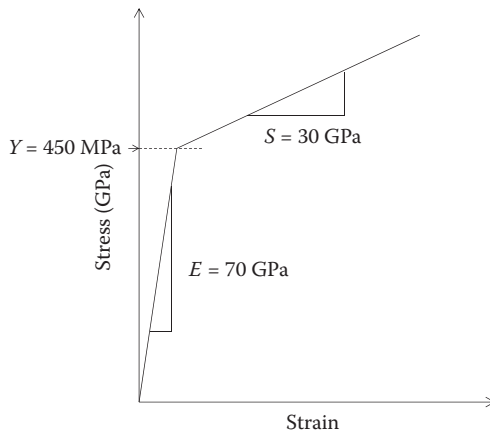


FIGURE 5.8

Strain–strain diagram for the aluminium alloy back plate in Example 5.4.

Therefore, it is seen that an elastic wave with a magnitude of 450.0 MPa and an inelastic wave with a magnitude of 248.7 MPa are transmitted into the aluminium alloy.

5.5 Shock Waves

Shock waves are normally associated as occurring in fluids or gases where the material has no shear strength. However, in the 1940s, it was realised that shock waves do occur in solid materials as well as liquids and gases. Early work deduced that if the magnitude of the stress amplitude greatly exceeds the strength of the material, then we can effectively ignore its shear strength and treat the problem hydrodynamically. That is to say, it is assumed that the medium that is shocked has no strength. Thus, much of the mathematical treatment of shock waves is done by hydrodynamic methods that are appropriate to fluids. Shock propagation in solid materials has been extensively studied, and various reviews have been presented elsewhere (Skidmore 1965; Davison and Graham 1979).

There are various analogies that explain the mechanics by which shock waves propagate through the materials. One such analogy is that of a snow plough clearing a path of freshly laid snow. As the plough moves forward, more and more snow is accumulated in front of the blade. A quick analysis will show that the 'front' of moving snow is travelling at a velocity that is faster than that of the plough. So, the front (which is synonymous with the shock front) is moving at U_s and the plough blade and the snow are travelling at u_p (i.e. the particle velocity). This is synonymous with the shock and particle velocity in a material system (see Figure 5.9).

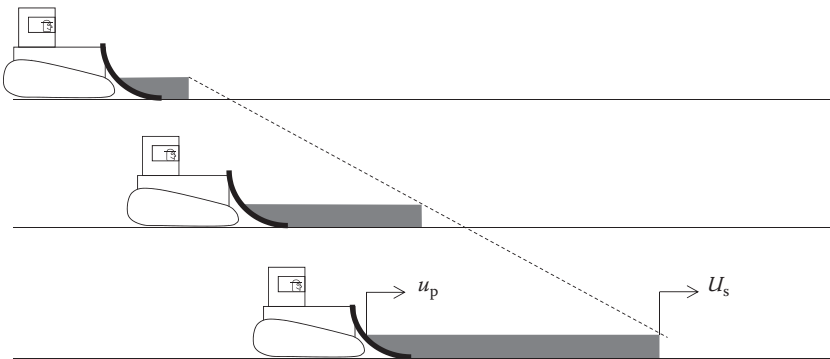


FIGURE 5.9

Analogy of a shock front propagating in a material: the snow plough model.

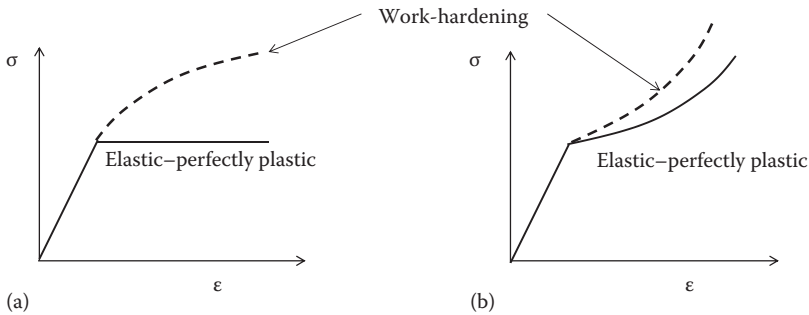


FIGURE 5.10

Strain–strain curves for conditions of (a) uniaxial stress and (b) uniaxial strain. The dashed line indicates how the material would work-harden.

Shock waves are very steep in their nature. The shock front appears infinitely steep, and the properties of the material change discontinuously from one side of the front to the other. Therefore, a shock wave can be defined as a ‘discontinuity of pressure, temperature (or internal energy) and density occurring over a very thin front’. Unlike elastic–plastic waves travelling in a cylindrical bar, shock waves ‘steepen’ with amplitude; they are also supersonic. This is because higher amplitude stresses are transmitted faster than lower amplitude stresses. Consequently, researchers have been able to shock compress materials by a factor of 2 or more, the type of densification that can only be otherwise encountered in the centre of the earth and other cosmic bodies.

In nature, it would be expected to find shock waves where the unshocked medium is being overdriven by a fast-moving material (e.g. a supersonic jet) or where the type of loading provides a unique set of uniaxial-strain conditions within the material. Previously, elastic and inelastic waves where the material was not constrained and allowed to flow in all directions have been discussed. However, if the material is constrained so that it can only flow in one direction, then it is possible to form a shock in the material. This is because that under such uniaxial-strain loading, the stress–strain curve is concave upwards (see Figure 5.10). Thus, following the rationale of Figure 5.7, instead of wavelets of stress becoming slower as the stress is increased, they speed up. This is because the gradient of the inelastic portion increases with stress (see Figure 5.10). The ultimate consequence of this is a sharp fast-moving shock front.

Eventually, it can be seen that, at some point, the gradient of the plastic part is greater than the elastic part, and at this point, the inelastic shock will overtake the elastic wave. Thus, it is no longer possible to detect the elastic wave.

5.5.1 An Ideal Shock Wave

A shock wave formed by the impact of a projectile will look something like Figure 5.11. This shows a theoretical shock profile captured in an instant of

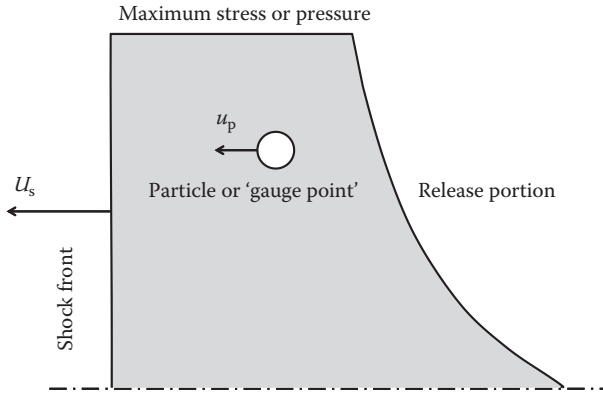


FIGURE 5.11
An ideal shock wave.

time. Actually, very often, nature is much more complicated than this, and there will be other facets present due to strength, phase changes and the type of loading. It will also change in shape with time as it propagates through the medium. However, this ideal-looking shock wave is useful for describing some key parameters. Firstly, it can be seen that the shock comprises a sudden increase in stress at the shock front. This is also accompanied by an increase in density and temperature as will be seen in Section 5.6. Theoretically, the thickness of this shock front rise will be of the order of atomic distances. So, it is very thin. At the peak stress, the stress level is constant, and the length of this plateau is the shock duration. The duration of the shock is determined by the geometry of the projectile and the properties of the projectile and target that in turn defines how quickly the stress is released. The release profile is shown at the rear of the wave.

As the shock wave sweeps through, the material is 'picked up' by the wave and travels at the particle velocity, u_p , as seen earlier. A particle is best thought of in the continuum sense as a gauge point that moves with the material.

5.5.2 Are Shock Waves Relevant in Ballistic-Attack Problems?

During penetration by a bullet, fragment, armour-piercing discarding sabot or armour-piercing fin-stabilised discarding sabot projectile, a very complex state of stress exists within the material and around the tip of the penetrating object (Figure 5.12). Just below the surface of the penetrating object, there arises a uniaxial state of strain that gives rise to the formation of shocks. However, this zone is fairly small and is most probably localised to within a calibre's depth of material. Further away from this point exists a complex state of stress that adds to the complexity to the analysis (which, incidentally, can only be sensibly done using a hydrocode). Consequently, it would be anticipated that the influence of the shocked zone would be relatively

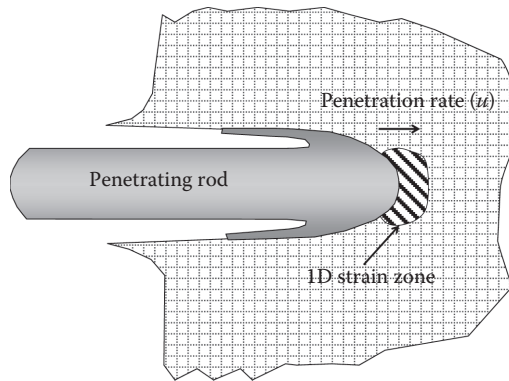


FIGURE 5.12
1D strain zone ahead of a penetrating rod.

small in most ballistic-penetration examples. Nevertheless, it is important to understand what is happening to the material in that locality.

However, it should be pointed out that shock waves are readily formed where the material is being overdriven. That is to say that the rate of penetration is faster than the speed of sound in the medium. The analogy here is of a supersonic jet exceeding the speed of sound in air (i.e. Mach 1). As the jet approaches Mach 1, pressure waves are formed that are able to dissipate away from the jet at the speed of sound. However, when the jet flies at Mach 1, the pressure waves are unable to 'get out of the way' of the jet and consequently compress together to form a shock front. This results in the characteristic sonic boom.

Therefore, when the velocity of a projectile is increased, and the subsequent penetration is higher than the speed of sound in the material in which it is penetrating, then shock waves readily propagate from the penetration interface. For example, this would occur when a shaped-charge jet penetrates a polymer such as polymethylmethacrylate (PMMA) or even some low-density metals.

Assume that a shaped-charge jet has a tip velocity of 10,000 m/s. The jet is made from copper that has a density of 8940 kg/m³ and is penetrating into PMMA with a density of 1190 kg/m³. Ignoring the fact that the jet will be stretching, the penetration rate into the PMMA can be calculated from (see Chapter 4)

$$u = \frac{v}{1 + \sqrt{\frac{\rho_t}{\rho_p}}} = \frac{10,000}{1 + \sqrt{\frac{1190}{8940}}} = 7327 \text{ m/s}$$

where

u is the penetration rate into the material.

v is the impact velocity.

ρ_t is the density of the target.

ρ_p is the density of the projectile.

Given that the speed of sound in PMMA is 2260 m/s, the material would be substantially overdriven and consequently shock-compressed ahead of the penetrating jet tip.

5.6 Rankine–Hugoniot Equations

The equations governing conservation of mass, momentum and energy across a shock front will now be derived assuming that a shock wave is moving in a strengthless fluid (i.e. hydrodynamic). It is considered that a 1D shock wave is progressing through a material, and the reference point from which all measurements are taken is at the shock front (see Figure 5.13). Further, it is assumed that the material ahead of the shock wave is at rest (i.e. unshocked). Ahead of the shock front, the pressure in the material is P_0 , the density is ρ_0 , and the internal energy (temperature) is e_0 . Behind the shock front, there has been a jump in conditions such that the pressure, density and internal energy are now P_1 , ρ_1 and e_1 , respectively. So, an observer at the shock front will be moving at a velocity U_s . In front of the observer, he/she sees a material moving towards him/her at a velocity U_s . Behind the observer, it appears

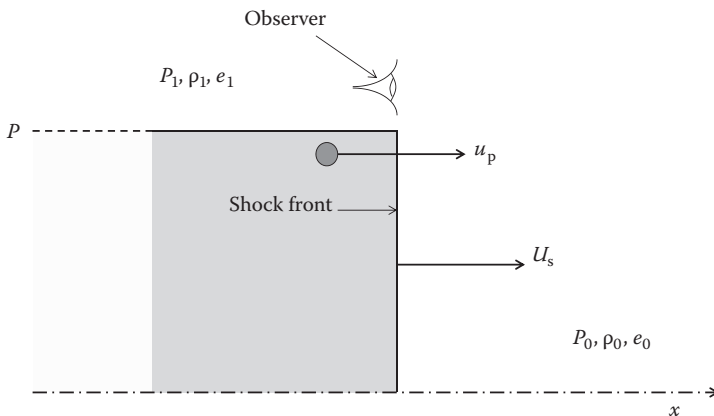


FIGURE 5.13

Schematic of a shock wave showing the position of the observer.

that the material has a velocity of $U_s - u_p$, and a specific particle (shown by the circle) is gradually moving away from him/her.

A general case where the material ahead of the shock wave is already shocked will now be considered, and the material in this zone has a particle velocity of u_0 . For most problems that students will face, this overcomplicates things a little, and for the vast number of problems that are solved with pen and paper, $u_0 = 0$. For more complicated problems, it is better to rely on a computer.

5.6.1 Conservation of Mass

Consider the mass per unit area of a material moving into the shock front. The mass of the material moving into the shock is given by

$$\text{Mass in} = \rho_0 A (U_s - u_0) dt \quad (5.29)$$

$$\text{Mass out} = \rho_1 A (U_s - u_p) dt \quad (5.30)$$

Therefore, as mass in = mass out,

$$\rho_0 A (U_s - u_0) dt = \rho_1 A (U_s - u_p) dt \quad (5.31)$$

and this simplifies to

$$\rho_0 (U_s - u_0) = \rho_1 (U_s - u_p) \quad (5.32)$$

For the case where $u_0 = 0$, this simplifies to

$$\rho_0 U_s = \rho_1 (U_s - u_p) \quad (5.33)$$

5.6.2 Conservation of Momentum

The momentum of the particles can be calculated from their mass \times velocity. The change in the momentum due to the passage of the shock must be equal to the impulse per unit area. The impulse due to the passage of the shock is given by

$$\text{Impulse} = F dt = A (P_1 - P_0) dt \quad (5.34)$$

Knowing that the material behind the shock front has a velocity of u_p , and the material ahead of the shock front has a velocity u_0 (or is at rest), we can work out the change in momentum across the shock front by

$$\begin{aligned} \text{change in momentum} &= [(\text{mass})_1 \times (\text{velocity})_1] - [(\text{mass})_0 \times (\text{velocity})_0] \\ &= [\rho_1 A (U_s - u_p) dt \times u_p] - [\rho_0 A (U_s - u_0) dt \times u_0] \end{aligned} \quad (5.35)$$

Therefore,

$$[\rho_1 A(U_s - u_p)dt \times u_p] - [\rho_0 A(U_s - u_0)dt \times u_0] = A(P_1 - P_0)dt \quad (5.36)$$

Simplifying

$$[\rho_1(U_s - u_p) \times u_p] - [\rho_0(U_s - u_0) \times u_0] = (P_1 - P_0) \quad (5.37)$$

However, it is recalled from the conservation of mass that

$$\rho_0(U_s - u_0) = \rho_1(U_s - u_p) \quad (5.38)$$

Therefore, substituting and simplifying,

$$[\rho_0(U_s - u_0) \times u_p] - [\rho_0(U_s - u_0) \times u_0] = (P_1 - P_0) \quad (5.39)$$

$$\rho_0(U_s - u_0)(u_p - u_0) = (P_1 - P_0) \quad (5.40)$$

For the case where $u_0 = 0$, this simplifies to

$$\rho_0 U_s u_p = (P_1 - P_0) \quad (5.41)$$

For most cases of interest, $P_1 \gg P_0$, and therefore, we simplify further

$$\rho_0 U_s u_p = P_1 \quad (5.42)$$

5.6.3 Conservation of Energy

We now look at the change in work due to the passage of the shock wave. The work done on a particle of a material behind the shock front is given to us by considering its force \times displacement in a small increment of time, dt . Therefore, this can be calculated from

$$W = (P_1 A)(u_p dt) \quad (5.43)$$

Therefore, the change in energy due to the passage of a shock is

$$\Delta W = (P_1 A)(u_p dt) - (P_0 A)(u_0 dt) \quad (5.44)$$

Now, the kinetic energy of a particle behind the shock front is given to us by

$$KE_1 = \frac{1}{2} [\rho_1 A(U_s - u_p)dt] u_p^2 \quad (5.45)$$

and the internal energy of a particle behind the shock front is given to us by

$$\text{internal energy behind shock front} = e_1 \rho_1 A (U_s - u_p) dt \quad (5.46)$$

Note that the internal energy per unit mass, e_1 , is multiplied by the mass to get the total energy behind the shock front. Therefore, the difference in total energy due to the passage of the shock front is given to us by

$$\begin{aligned} &= \left(\frac{1}{2} \left[\rho_1 A (U_s - u_p) dt \right] u_p^2 + e_1 \rho_1 A (U_s - u_p) dt \right) \\ &\quad - \left(\frac{1}{2} \left[\rho_0 A (U_s - u_o) dt \right] u_o^2 + e_o \rho_o A (U_s - u_o) dt \right) \end{aligned} \quad (5.47)$$

This can now be equated to ΔW ; at the same time, the equation will be simplified by assuming that $u_o = 0$:

$$(P_1 A)(u_p dt) = \left(\frac{1}{2} \left[\rho_1 A (U_s - u_p) dt \right] u_p^2 + e_1 \rho_1 A (U_s - u_p) dt \right) - (e_o \rho_o A U_s dt) \quad (5.48)$$

Simplifying

$$P_1 u_p = \frac{1}{2} \rho_1 (U_s - u_p) u_p^2 + e_1 \rho_1 (U_s - u_p) - e_o \rho_o U_s \quad (5.49)$$

However, it is known that from the conservation of mass, $\rho_0 U_s = \rho_1 (U_s - u_p)$; therefore, substituting and rearranging,

$$P_1 u_p = \frac{1}{2} \rho_0 U_s u_p^2 + e_1 \rho_0 U_s - e_o \rho_o U_s \quad (5.50)$$

$$P_1 u_p = \frac{1}{2} \rho_0 U_s u_p^2 + \rho_0 U_s (e_1 - e_o) \quad (5.51)$$

Now, this equation can be further simplified to use the more commonly used form as follows:

$$e_1 - e_o = \frac{P_1 u_p}{\rho_0 U_s} - \frac{1}{2} u_p^2 \quad (5.52)$$

From the conservation of momentum, it is known that

$$u_p = \frac{(P_1 - P_0)}{\rho_0 U_s} \quad (5.53)$$

Therefore, substituting into Equation 5.52, we get

$$e_1 - e_o = \frac{P_1(P_1 - P_0)}{\rho_0^2 U_s^2} - \frac{1}{2} \frac{(P_1 - P_0)^2}{\rho_0^2 U_s^2} \quad (5.54)$$

To simplify this equation further, an equation that describes the term $\rho_0^2 U_s^2$ in terms of pressure and specific volume is needed. To achieve this, we refer back to the conservation of momentum; thus,

$$-\rho_1 u_p = -\rho_1 \frac{(P_1 - P_0)}{\rho_0 U_s} \quad (5.55)$$

and from the conservation of mass,

$$-\rho_1 u_p = U_s(\rho_0 - \rho_1) \quad (5.56)$$

So,

$$\rho_0 U_s^2 = -\rho_1 \frac{(P - P_0)}{(\rho_0 - \rho_1)} \quad (5.57)$$

Simplifying leads to

$$\rho_0^2 U_s^2 \left(\frac{1}{\rho_1} - \frac{1}{\rho_0} \right) = -(P - P_0) \quad (5.58)$$

Knowing that $\rho = 1/V$ gives

$$\rho_0^2 U_s^2 = \frac{(P - P_0)}{(V_0 - V_1)} \quad (5.59)$$

This equation is then substituted into Equation 5.54 to give

$$e_1 - e_o = \frac{P_1(P_1 - P_0)(V_0 - V_1)}{(P_1 - P_0)} - \frac{1}{2} \frac{(P_1 - P_0)^2(V_0 - V_1)}{(P_1 - P_0)} \quad (5.60)$$

or,

$$e_1 - e_0 = \frac{1}{2}(P_1 + P_0)(V_0 - V_1) \quad (5.61)$$

Again, for most cases of interest, $P_1 \gg P_0$, and therefore, it can be simplified further to give

$$e_1 - e_0 = \frac{1}{2}P_1(V_0 - V_1) \quad (5.62)$$

In summary, for a shock wave that is travelling through an unshocked strengthless medium, the conservation of mass, momentum and energy across the shock front can be written as follows:

$$\rho_0 U_s = \rho_1(U_s - u_p) - \text{conservation of mass} \quad (5.63)$$

$$P_1 = \rho_0 U_s u_p - \text{conservation of momentum} \quad (5.64)$$

$$e_1 - e_0 = \frac{1}{2}P_1(V_0 - V) - \text{conservation of energy} \quad (5.65)$$

We now have five unknowns (e_1 , P_1 , U_s , u_p and ρ_1). By measuring one of these parameters and combining these equations with the equation of state for the material, viz.,

$$P_1 = \text{fn}(e_1, \rho_1) \quad (5.66)$$

it is possible to calculate all the other variables.

5.6.4 A Consistent Set of Units

It is worth mentioning that in the field of shock physics, base SI units are not the most commonly used form of unit. Shock velocities are very fast, and therefore, all velocities are expressed in kilometres per second or millimetres per microsecond. Therefore, times and displacements are expressed as microseconds (μs) and millimetres (mm), respectively. Pressures and stresses are generally extremely high and quoted in gigapascals (GPa). To provide a consistent set of units, density is therefore quoted in grams per cubic centimetre (g/cc) and specific volume in cubic centimetres per gram (cc/g) and so on.

5.6.5 The Hugoniot

A useful form of the equation of state is the principle Hugoniot curve (named after the French engineer Pierre-Henri Hugoniot [1851–1887]). This curve is

empirically derived and is usually described in terms of U_s and u_p , p and u_p or p and V . Typical shapes of Hugoniot curves are presented in Figure 5.14.

It is important to point out that when a material is shocked, it does not follow the path as described by the Hugoniot, but rather, it jumps from one state to the next. The linear line that links the two states is called the Rayleigh line (Figure 5.15). Consequently, the Hugoniot is a locus of attainable jump conditions. On unloading, however, the material follows the isentrope, which is a curve usually lying quite close to the Hugoniot. Due to the loading and unloading following different paths, energy is dissipated in the form of heat. So, a material that has been shocked will be hotter than it was before loading.

The gradient of the Rayleigh line can be written as

$$R = -\rho_0^2 U_s^2 \tag{5.67}$$

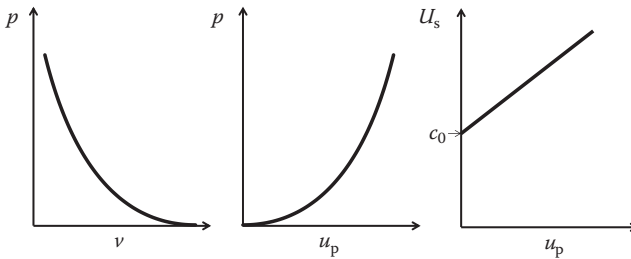


FIGURE 5.14
Hugoniot curves.

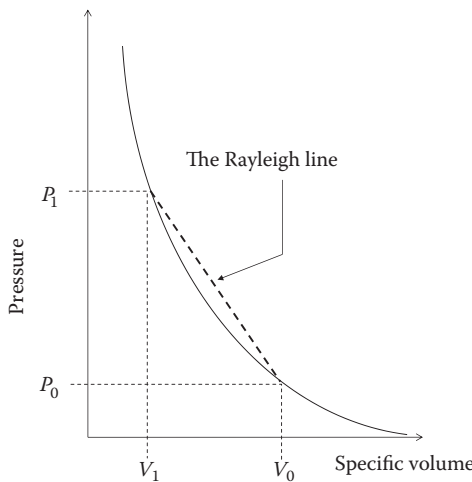


FIGURE 5.15
The Hugoniot and Rayleigh line.

where ρ_0 and U_s are the bulk (and initial) density and shock velocity, respectively. The shock impedance, Z_s , of the materials is defined as

$$Z_s = \rho_0 U_s \quad (5.68)$$

and so, the gradient of the Rayleigh line has a direct relationship with the shock impedance.

It is not too difficult to see that this equation is very similar to the equation that was cited for the elastic impedance, where the elastic impedance was written as

$$Z = \sqrt{E\rho_0} = \rho_0 c_0 \quad (5.69)$$

This is a reasonable assumption for where the elastic wave travels at the bulk sound velocity. For cases where the elastic wave is travelling at the longitudinal wave velocity (such as after a plate impact), then c_1 is used. Therefore, the equation becomes

$$Z = \rho_0 c_1 \quad (5.70)$$

It is also important to point out that despite the classical Hugoniot shapes presented in Figure 5.14, not all materials follow these shapes. Indeed, if the shock incurs a phase change within the material, then this will frequently be represented as a kink or change in gradient.

For most materials, it is generally regarded that the Hugoniot, in shock velocity–particle velocity space can be described as being linear of the form

$$U_s = c_0 + S u_p \quad (5.71)$$

where c_0 is the bulk sound speed of the material, and S is a constant.

For metals, c_0 has been correlated with the bulk sound speed of the material, whereas S has been theoretically shown to relate to the first derivative of the bulk modulus with pressure (Ruoff 1967). This is the standard form of Hugoniot description that fits for many materials and ceramics. In fact, it is highly unusual for the fit to be non-linear for a metal. For polymers, however, some are thought to behave in a non-linear fashion (Porter and Gould 2006). An example is Dyneema[®] – a commonly used armour material that crops up in lightweight armour applications – see Figure 5.16. In this case, the Hugoniot for Dyneema is described by

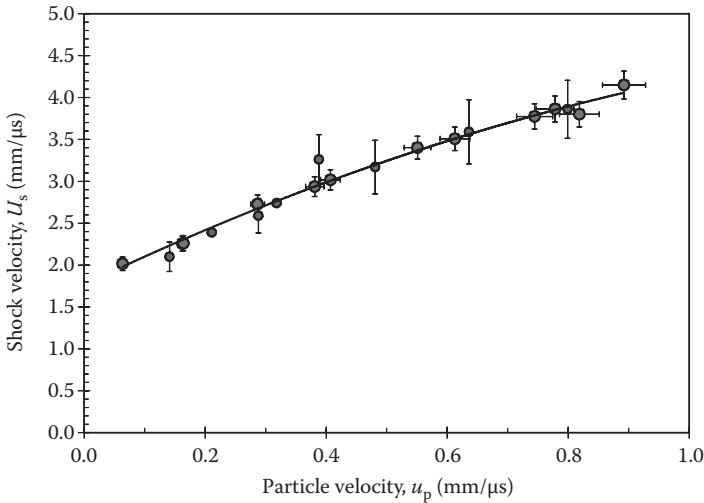
$$U_s = c_0 + a.u_p + b.u_p^2 \quad (5.72)$$

where

c_0 is the bulk sound speed (=1.77 mm/ μ s).

a is an empirically derived constant (=3.45).

b is an empirically derived constant (=–0.99 μ s/mm).

**FIGURE 5.16**

A measured Hugoniot curve for Dyneema showing a slight non-linear behaviour. (Data from Chapman, D. J. et al., *AIP Conference Proceedings*, 1195:1269–1272, 2009; Hazell, P. J. et al., *Journal of Applied Physics*, 110 (4):043504, 2011.)

TABLE 5.3

Equation-of-State Parameters for Some Materials That Could Be Used in an Armour Application

Reference	Material	Density (g/cc)	c_0 (mm/ μ s)	S	c_1^a (mm/ μ s)	c_s^a (mm/ μ s)
Marsh 1980	AA 2024	2.784	5.37	1.29	6.36	3.16
Boteler and Dandekar 2006	AA 5083-H131	2.668	5.29	1.40	6.51	3.20
	AA 5083-H32	2.668	5.14	1.27	6.51	3.20
Marsh 1980	Comp B (explosive)	1.715	3.06	2.01	3.12	1.71
	Mg (AZ31B)	1.776	4.57	1.21	5.70	3.05
	Steel, 304L	7.903	4.57	1.48	5.79	3.16
Carter and Marsh 1995	Epoxy ^b	1.192	2.69	1.51	2.641	1.177
	Polycarbonate ^c	1.196	2.33	1.57	2.187	0.886
Dandekar and Benfanti 1993	Titanium diboride	4.490	8.622	0.795	11.23	7.41

^a Ultrasonically measured data.

^b Between $U_s = 0.4$ – 2.8 mm/ μ s.

^c Between $U_s = 0.4$ – 2.6 mm/ μ s.

For a straightforward linear Hugoniot (i.e. Equation 5.71), there are various sources for the constants c_0 and S that are reported in the literature. In particular, the compendium published by Marsh gives a good list as do the works of McQueen et al. (1970), Meyers (1994) and Carter and Marsh (1995) for polymers.

A list of parameters (including elastic data) for various materials that may well be used in armour applications is provided in Table 5.3.

5.6.6 Calculating the Pressure from Two Colliding Objects

For a condition of 1D strain, it is a relatively trivial task to establish the pressure generating in two colliding bodies with knowledge of the Hugoniots of the materials and the impact velocity. Again, it is assumed that the material does not have strength. First, the Hugoniot of the target material is plotted in the $P-u_p$ space. Secondly, the Hugoniot of the projectile, reflected and re-centred, is plotted so that the curve intercepts the x -axis at the impact velocity (v_{imp}) (see Figure 5.17). Finally, the pressures and particle velocities in the both the target and the projectile are provided by reading from the intercepts between the two curves. This approach is a direct application of the impedance matching technique.

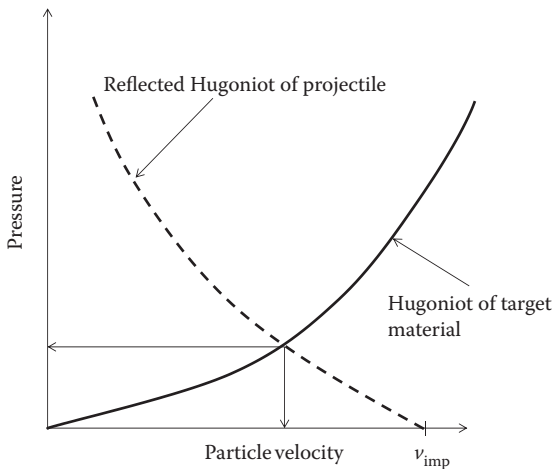


FIGURE 5.17

Calculation of the pressure and particle velocity from two colliding objects.

From this approach, it is possible to see that if the impact occurs between two identical materials, then the particle velocity resulting in both materials can be calculated by merely dividing the impact velocity by 2. Let us have a look at a couple of examples.

Example 5.5

Take a copper projectile striking a copper target at 2 mm/ μ s. The Hugoniot of copper is well known and can be described by the following polynomial equation:

$$P = \rho_0 (c_0 + Su_p)u_p \quad (5.73)$$

where $\rho_0 = 8.93$ g/cc, $c_0 = 3.94$ mm/ μ s and $S = 1.49$.

The equation for the reflected Hugoniot (for the projectile) can be written as

$$P = \rho_0(c_0 + S(v_{\text{imp}} - u_p))(v_{\text{imp}} - u_p) \quad (5.74)$$

Solving these equations simultaneously results in a pressure of 48.5 GPa and U_p value of 1 mm/ μ s. This is shown graphically in Figure 5.18.

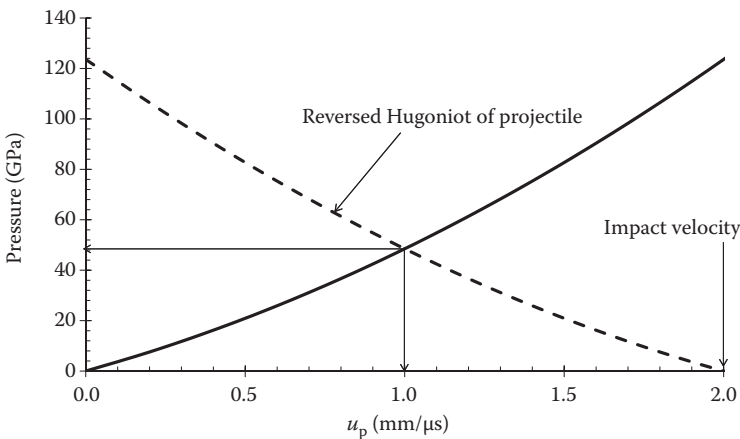


FIGURE 5.18

Calculating the impact pressure and particle velocity from an impact of a Cu projectile striking a Cu target at 2 mm/ μ s.

Example 5.6

A 50-mm-long tantalum explosively formed projectile strikes a semi-infinite RHA (steel) target at 2000 m/s such that a shock wave is produced in the steel. Calculate

- The pressure in both the tantalum and steel
- The particle velocities in the tantalum and the steel
- How long it takes the shock wave pulse to travel 50 mm into the steel
- How long it takes for the shock pulse to reach the rear free surface of the tantalum projectile

For the sake of this calculation, assume that the impact is 1D (so that it behaves as if it is a plate impact experiment). The Hugoniot properties for the materials are

$$\text{steel: } U_s = 4.61 + 1.73u_p; \rho_0 = 7.84 \text{ g/cc; } c_1 = 5.92 \text{ mm}/\mu\text{s}$$

$$\text{tantalum: } U_s = 3.41 + 1.20u_p; \rho_0 = 16.65 \text{ g/cc}$$

Parts (a) and (b): The first step is to use the impedance matching technique to establish the pressures and particle velocities. From before, it was seen that the Hugoniot for the target can be mathematically described as

$$P = \rho_0(c_0 + Su_p)u_p = 7.84(4.61 + 1.73u_p)u_p$$

and the reverse Hugoniot for the projectile (with $V = u_p$ at $P = 0$) will be given by

$$P = \rho_0(c_0 + S(v_{\text{imp}} - u_p))(v_{\text{imp}} - u_p) = 16.65(3.41 + 1.20(2000 - u_p))(2000 - u_p)$$

Solving these two equations simultaneously gives us the pressures and particle velocities in both the projectile and the target; the calculation is shown graphically in Figure 5.19.

So, the results are

$$P = 60.9 \text{ GPa; } u_p = 1.17 \text{ mm}/\mu\text{s for both the tantalum and the steel (a + b)}$$

Part (c): The next step is to calculate the shock pulse width after it has travelled 50 mm into the steel. The shock propagates into the steel at $U_s = 4.61 + 1.73 \times 1.17 = 6.63 \text{ mm}/\mu\text{s}$. Therefore, the time taken to travel 50 mm (s) is given to us as

$$t = \frac{s}{U_s} = \frac{50.00}{6.63} = 7.54 \mu\text{s}$$

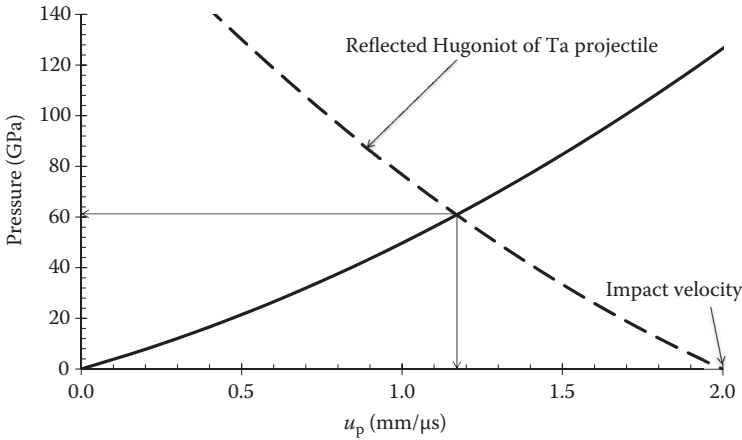


FIGURE 5.19

Calculation of the pressure and particle velocities due to the impact of a tantalum projectile onto steel at 2 km/s.

Part (d): The time taken to reach the rear free surface of the tantalum projectile is given in a similar fashion. The shock wave propagates into the Ta projectile at a speed of $U_s = 3.41 + 1.20 \times 1.17 = 4.81$ mm/ μ s. Therefore, the time taken for the shock wave to reach the rear of the projectile is

$$t = \frac{s}{U_s} = \frac{50.00}{4.81} = 10.40 \mu\text{s}$$

5.6.7 Hugoniot Elastic Limit

If a material is shocked, and the shock velocity, U_s , is less than the elastic wave speed in the material, then an elastic wave will propagate ahead of the main shock front. In plate-impact experiments, this will move at the longitudinal wave velocity for the material, c_L . The point at which the elastic wave velocity transitions to the plastic shock front is termed the Hugoniot elastic limit (HEL).

The HEL (1D strain) can be related to the dynamic yield strength (1D stress) by the following equation:

$$\gamma_d = \frac{(1-2\nu)}{(1-\nu)} \text{HEL} \quad (5.75)$$

where ν is the Poisson's ratio for the material. Thus, it is possible to measure how the shock loading has affected the yield behaviour of the material

TABLE 5.4

HELs for Various 'Armour-Type' Materials

Reference	Material	ρ (g/cc)	HEL (GPa)
Hazell et al. 2012	Elektron 675 T5 (Mg)	1.903	0.37 ± 0.04
Boteler and Dandekar 2006	AA 5083-H131	2.668	0.573 ± 0.04
	AA 5083-H32	2.668	0.40 ± 0.03
Nahme and Lach 1997	Mars 190 (armour steel)	7.840	1.2–2.0
	Mars 240 (armour steel)	7.840	1.2
	Mars 300 (armour steel)	7.840	1.6–2.2
Gust and Royce 1970	Vascomax 350 (maraging steel)	8.08	4.8 ± 2
	Alumina (AD 85)	3.420	6.1–6.5
	Alumina (AD 995)	3.810	8.3 ± 0.5
Dandekar and Bartkowski 1994	Alumina (AD 995)	3.880	6.71 ± 0.08
Gust and Royce 1970	Boron carbide, hot pressed	2.50	13.7–16.2
Yuan et al. 2001	Silicon carbide (SiC–N)	3.214	11.5 ± 0.4
Gust and Royce 1970	Titanium diboride	4.52	8.1 ± 0.4

and whether this has resulted in any strengthening (or indeed, softening) behaviour.

The HELs for various armour-type materials are shown in Table 5.4.

The effect of the HEL on the Hugoniot of the materials is shown in Section 5.6.8. Adding a HEL to a strengthless Hugoniot raises the Hugoniot. For different grades of steel, the Hugoniot will be pretty much identical (the Hugoniot is insensitive to small changes in chemistry). However, as can be seen from Table 5.4, the HEL for armour steel is quite variable.

5.6.8 Shocks in Elastic–Plastic Materials

Up to now, we have been largely concerned with strengthless materials. Of course, real armour materials have strength. Some armour materials such as ceramic are particularly strong in compression, and it is this strength that helps defeat projectiles. It is only possible to rely on hydrodynamic behaviour for the case of very strong shocks.

Figure 5.20 shows the results from a hydrocode analysis of a strengthless tungsten flyer plate striking an AA 7075-T6 target at 500 m/s. There are three types of targets considered here: (a) a strengthless target, that is, it is assumed that the material has zero strength and stiffness; (b) an elastic–perfectly plastic target with a dynamic yield strength of 0.5 GPa (this is approximately what you would expect from an AA 7075-T6 target); and (c) an elastic–perfectly plastic target with a dynamic yield strength of 1.0 GPa. This is an exaggerated strength – in reality, the alloy would never be this strong. However, in this case, exaggerating the strength enables us to clearly demonstrate the physics of what is happening. There are several things to note here:

1. Increasing the yield strength increases the magnitude of the HEL. So rearranging Equation 5.74, it can be seen that

$$\text{HEL} = \frac{(1 - \nu)}{(1 - 2\nu)} Y_d \quad (5.76)$$

Assuming that the Poisson's ratio for the material is 0.34, then for a target with a dynamic yield strength of 0.5 GPa, the HEL = 1.03 GPa. For a dynamic yield strength of 1.0 GPa, the HEL would be 2.06 GPa. This is what is seen in the shock trace.

2. When the strength of the aluminium target material is increased, the magnitude of the shock 'seen' by the target also increases. This is seen in Figure 5.20 for a $Y = 1.0$ GPa target as $\Delta\sigma_x$. The reason for this is that we need to take into account the strength of the target in our Hugoniot. So, Figure 5.17 now needs to be redrawn (see Figure 5.21). It will be seen that now, the stress has been raised in the target as the Hugoniot is shifted upwards slightly (up and to the left). This is reflected in our shock compression traces shown in Figure 5.20. It is also noted that the compression curve has been shifted up by $2/3 Y_d$. To understand why it has been shifted up by $2/3 Y_d$, the pressure in the sample needs to be considered, which is the average of the three principal stresses, i.e.

$$P = \frac{(\sigma_x + \sigma_y + \sigma_z)}{3} \quad (5.77)$$

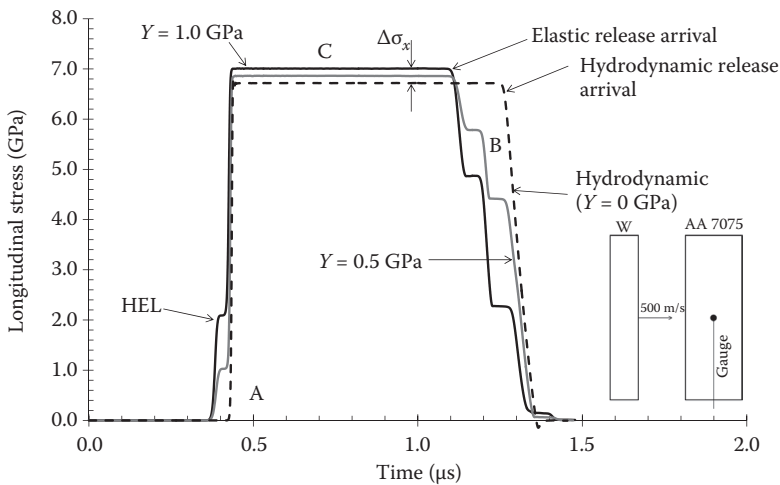


FIGURE 5.20

Shock propagation in (A) a strengthless (hydrodynamic) aluminium (AA 7075) target, (B) an aluminium target with a dynamic yield strength of 0.5 GPa and (C) an aluminium target with a dynamic yield strength of 1.0 GPa.

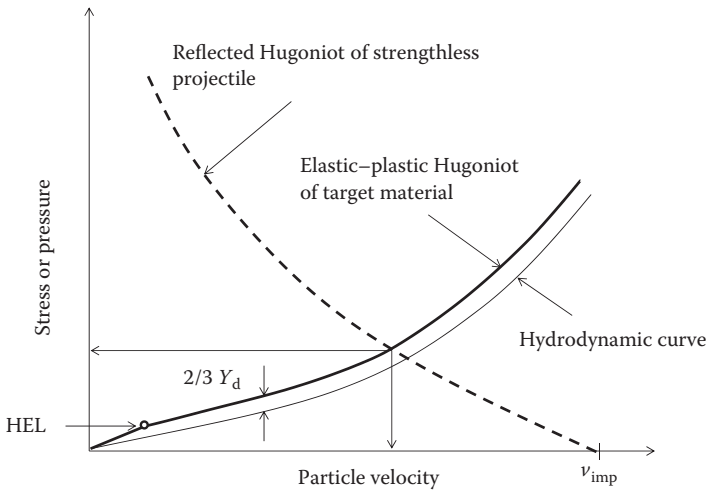


FIGURE 5.21 Calculation of the stress and particle velocity from two colliding objects using an elastic-plastic Hugoniot for the target.

In the case where the material is loaded in the uniaxial strain, $\sigma_y = \sigma_z$; therefore,

$$P = \frac{(\sigma_x + 2\sigma_y)}{3} \tag{5.78}$$

However, from Tresca, it is also noted that the yield strength is given by

$$Y = \sigma_x - \sigma_y \tag{5.79}$$

Therefore, substituting and rearranging,

$$P = \frac{(\sigma_x + 2\sigma_x - 2Y)}{3} \tag{5.80}$$

Simplifying and rearranging in terms of σ_x , we find that

$$\sigma_x = P + \frac{2}{3}Y \tag{5.81}$$

Therefore, the longitudinal stress in the material when it is shocked is given by the hydrodynamic pressure + 2/3 yield strength. As $Y = 2\tau$, according to Tresca, Equation 5.80 can also be written as

$$\sigma_x = P + \frac{4}{3}\tau \quad (5.82)$$

It should be pointed out that this assumes that the material is elastic-perfectly plastic. Some materials pressure-harden, and therefore, the Hugoniot curve will move further away from the hydrodynamic curve as the pressure increases. Some materials pressure-soften. Therefore, the Hugoniot curve moves closer to the hydrodynamic curve as the pressure increases.

3. Finally, the arrival of the release wave is observed from the rear of the projectile and into the target that results in the pulse being truncated. The target is initially released elastically followed by a plastic release. The velocity at which the wave structure is eaten away is a function of the particle velocity and the speed of sound in the material at that pressure. The hydrodynamic target appears to maintain its pulse for longer, and this is because the speed of sound is significantly reduced due to the zero stiffness.

5.6.9 Evaluating the Strength of a Material behind the Shock Wave

Frequently, it is important to evaluate how the strength of the material varies after a shock wave has passed through the material. This can be done by applying very thin in-material gauges made from such materials as manganin. The beauty of manganin is that it is a piezo-resistive material whose response is essentially insensitive to temperature. Therefore, the rise in temperature associated with a shock wave will have little effect on the response of the gauge.

The experimental technique involves splitting the material into two in a plane perpendicular to the impact direction of a flyer plate (machined flat and parallel) and inserting a suitable gauge. As the target is struck by the flyer plate, the shock that is formed sweeps the target, and although the state of strain is 1D, the state of stress is 2D. In fact, the state of stress can be written as follows:

$$\sigma_x \neq \sigma_y = \sigma_z \quad (5.83)$$

This is to say that a longitudinal stress (σ_x) state is established that is not (or unlikely to be) equal to the lateral stress, σ_y (except in fluids). With knowledge of σ_x and σ_y , it is possible to establish a value for the shear strength behind the shock front. This is given from the Tresca criteria

(which, for a 1D plate-impact experiment is identical to von Mises as $\sigma_y = \sigma_z$) as follows:

$$2\tau = \sigma_x - \sigma_y \quad (5.84)$$

This relation can then be used to establish the strength of the material behind the shock as the material is squeezed together. The strength behind the shock wave is important – particularly for providing constitutive relationships for the material.

Of course, the gauge technique to establish σ_y is naturally invasive. There have been questions on whether the gauge is measuring a true response of the material that is shocked or whether its response is a feature of the soft gauge encapsulation material (Winter and Harris 2008; Winter et al. 2008; Appleby-Thomas et al. 2010).

5.6.10 Release Waves

When a shock wave encounters a free surface, then stress will be released at the surface, and a release wave will travel back into the target in the opposite direction of the shock. Release waves will also be travelling from the free surfaces of the projectile that hit the target. When these release waves collide, the target is placed in net tension, and this causes the material to spall.

Looking again at Figure 5.11, the release portion of the wave is curved in nature as the pressure drops from the Hugoniot pressure to zero. This release portion of the wave is sometimes referred to as the rarefaction wave or expansion wave. This is because during the release process, the density of the material that is shocked is being reduced, and therefore, in real terms, the material undergoes an expansion.

As mentioned in Section 5.6.5, shock waves will follow a curve called an isentrope on pressure release. For small compressions, and for what is seen in most ballistic applications, one can assume that the isentrope is very similar to the Hugoniot curve for the material. For elastic-plastic materials (i.e. where hydrodynamic behaviour is no longer assumed), the material will initially be released elastically before following a ‘plastic’ release path. This can be seen in the simulation results in Figure 5.20.

Release waves travel faster than shock waves and eventually catch up with the wave and ‘eat away’ at it. The velocity of the rarefaction wave is given by

$$U_R = u_p + c^p \quad (5.85)$$

where u_p is the particle velocity, and c^p is the speed of sound at a given pressure. As the pressure drops in the material, so too does c^p , and this defines the shape of the release portion of the wave.

Figure 5.22 shows how this happens for a simple trapezoidal wave form. The release wave is travelling faster than the shock wave and eventually catches up with it. As it does so, the shock pressure is reduced. This process

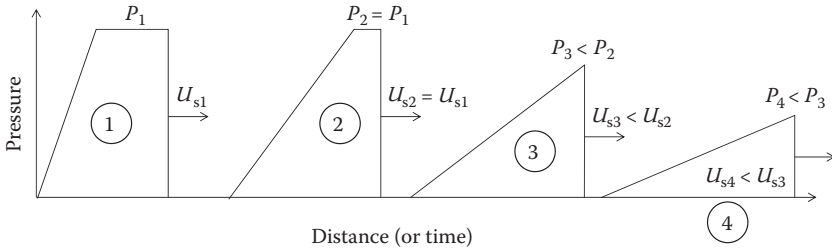


FIGURE 5.22

Change in shape and velocity of a shock wave due to the release wave attenuating the shock.

results in a slower shock wave as the shock-wave velocity is a function of pressure (see Equation 5.42). Furthermore, the trailing edge of the release wave will be moving slower than the shock front at the bulk sound speed of the material (i.e. c^P for $P = 0$). Therefore, the shock profile effectively gets shorter and broader until, eventually, it attenuates to nothing.

5.6.11 Spall in Shocked Materials

The spall behaviour of materials has been studied for decades due to the fact that it is useful to be able to predict when materials fail due to spall. Furthermore, it is found that many weapons systems are designed to create spall failures in materials, and the HESH round is one such example. Spall is, in essence, a dynamic tensile fracture, and many armour materials are susceptible to spall mainly because of their hard brittle nature.

Grady (1988) has provided a route to predict the spall strength based on readily available material properties and parameters. For brittle spall, Grady deduced that

$$P_s = (3\rho_0 c_0 K_c^2 \dot{\epsilon})^{\frac{1}{3}} \quad (5.86)$$

whereas for ductile spall,

$$P_s = (2\rho_0 c_0^2 Y \epsilon_f)^{\frac{1}{2}} \quad (5.87)$$

where ρ_0 is the density, c_0 is the bulk sound speed, K_c is the fracture toughness, Y is the yield strength, $\dot{\epsilon}$ is the strain rate, and ϵ_f is the failure strain.

For ductile spall, Rosenberg (1987) proposed an alternative predictive approach based on cavity expansion theory. By simply applying Hill's cavity expansion theory to spall from 1D plate-impact experiments, he deduced that

$$P_s = \frac{2}{3} Y \left[2 + \ln \left\{ \frac{E}{2(1-\nu)Y} \right\} \right] \quad (5.88)$$

The resisting force to cavity expansion is best reproduced by adopting the dynamic yield strength for the material calculated from the HEL. Thus, Y can be replaced by Y_d in the above equation.

In a plate-impact set-up, it is useful to initiate spall in the centre of the target. This is achieved by carrying out a symmetrical impact, as shown in Figure 5.23. At time 1, the elastic wave arrives prior to the plastic compression front, which arrives at time 2. The elastic wave is travelling at the longitudinal wave velocity (c_1). At the free surface, the shock (S) is reduced by a release wave (R) that propagates back into the target. When release waves emanating from the rear surfaces of the flyer and the target collide, a spall plane emerges. Finally, the free-surface velocity is reduced by the arrival of the release wave from the flyer plate's rear surface, reaching a minimum at time 4. The reload signal seen after time 4 contains a structure that can elucidate the failure mechanics. Generally speaking, a steep rise from the minimum is indicative of a brittle failure process, whereas a more gradual recovery rate indicates a more ductile failure (Chen et al. 2006). A good review of spall behaviour is given by Antoun et al. (2003).

For amour-grade material alloys, the interesting properties are those that lie perpendicular to the rolling direction of the plate. This is known as the short-transverse direction. The reason for this is that a projectile is likely to penetrate in the short-transverse direction due to the way the plate would be offered up as armour. And, usually, it is in the short-transverse direction that the plate is most brittle.

It is important to remember that the data for spall strengths are measured using plate-impact experiments either by directly measuring the free-surface

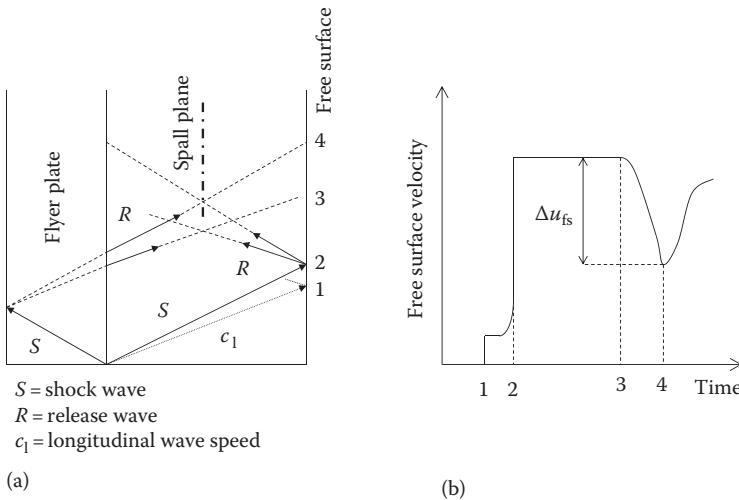


FIGURE 5.23

Schematic of spall initiation showing (a) the wave path and (b) the free-surface velocity response.

TABLE 5.5
Quasi-Static and Tensile Spall Data for Some Armour-Grade Alloys

Reference	Alloy	ρ (g/cc)	co (mm/ μ s)	ϵ_f	Y (GPa)	Measured Spall Strength (GPa)
Boteler and Dandekar 2006, 2007	AA 5083-H131	2.668	5.360	0.09	0.240	0.94
Whelchel et al. 2014	AA 5083-H321 (long)	2.668	5.31	-	-	1.06
	AA 5083-H321 (long transverse)	2.668	5.32	-	-	1.01
	AA 5083-H321 (short transverse)	2.668	5.17	-	-	1.07
Hazell et al. 2014	AA 7010-T7651 (long)	2.810	5.329	0.16	0.464	1.61
	AA 7010-T7651 (short transverse)	2.810	5.314	0.08	0.426	1.20
Millett et al. 2004 Nahme and Lach 1997	AA 7017 (peak aged)	2.740	5.211	0.05	0.402	0.63
	Mars 190	7.840	-	-	1.150	3.1-4.5
	Mars 240	7.840	-	-	1.725	3.4-5.9
	Mars 300	7.840	-	-	2.250	5.7-6.2

velocity of the rear surface or by using manganin gauges trapped between the sample and (typically) some low-density polymer (usually PMMA). The free-surface velocity method is the most common method where free-surface velocity measurements are made using a laser-based system (usually velocity interferometer system for any reflector [VISAR]), and the spall strength is calculated as follows:

$$\sigma_{\text{sp}} = \frac{1}{2} \rho_0 c_0 \Delta u_{\text{fs}} \quad (5.89)$$

where Δu_{fs} is the free-surface velocity drop in the sample (see Figure 5.23), and c_0 is the bulk sound speed in the sample.

Some evaluated spall strengths for a selection of armour-grade materials are shown in Table 5.5.

5.7 Summary

We have seen during dynamic loading that it is not just a simple case of examining the plastic deformation of the sample or the penetration of the material by the projectile. Much of these effects are governed by wave dynamics. Stress waves and shock waves are particularly important as ultimately, they can kill you. This is particularly true where spall is seen occurring in materials. This can lead to the separation of the material and fragments carried along by inertia.

This chapter started by reviewing elastic wave transmission and reflection, and there is a lot you can do in the design of an armour structure knowing the physics of wave transmission and reflection. We have seen that when a wave transmits its way through a high-impedance plate that is joined to a low-impedance plate, tensile waves emanate from the interface. This can be damaging to the armour structure if the high-impedance plate is brittle. Conversely, if a wave propagates through a low-impedance plate joined to a high-impedance plate, then it is seen that compression waves are reflected back into the front plate. This can be helpful – particularly if we are trying to suppress damage in brittle materials such as ceramics.

We have seen too that enormous pressure can be generated in the lab by virtue of loading a material in 1D strain. This allows us to interrogate materials as they are compressed to extreme pressures and thereby provides insight into the properties of the materials deep inside the earth's crust. These types of tests also reveal the behaviour of materials that are shocked because they are overdriven by a penetrating projectile such as a shaped-charge jet.

There is still much to study regarding wave dynamics, and there are numerous papers on the subject. This chapter has only skimmed the surface.

6

Metallic Armour Materials and Structures

6.1 Introduction

Metals have been used extensively in armour. Generally speaking, there are only four practical metallic contenders for armour applications: aluminium, magnesium, steel and titanium. Steel and aluminium are the most common metals in use today mainly due to the price and their ability to be worked and welded. However, magnesium and titanium, although expensive, have some desirable properties that will be discussed in Sections 6.3.3 and 6.3.4. Figure 6.1 shows a summary of how most armour is made. The vast majority of armour is wrought plate. That is to say that it is processed by rolling or pressing. Some armour is cast, although this has been mostly reserved for the turrets of tanks such as the Chieftain (see Figure 6.2).

To protect against ballistic attack, it is necessary to use a solid homogeneous plate, although there are one or two exceptions, as will be seen later. To protect against blast, this is not necessarily the case. In fact, it has been shown that hollow porous structures can aid in providing protection against blast waves.

6.2 Properties and Processing of Metallic Armour

6.2.1 Wrought Plate

Wrought plates are mechanically worked either through hot-working or cold-working the material. The typical ways that this is achieved are as follows:

- *Forging*: where the piece is subjected to successive blows or by continuous squeezing of the metal.
- *Rolling*: by far the most common method of processing wrought armour plate mainly because the desirable thicknesses and properties can be achieved through this process.

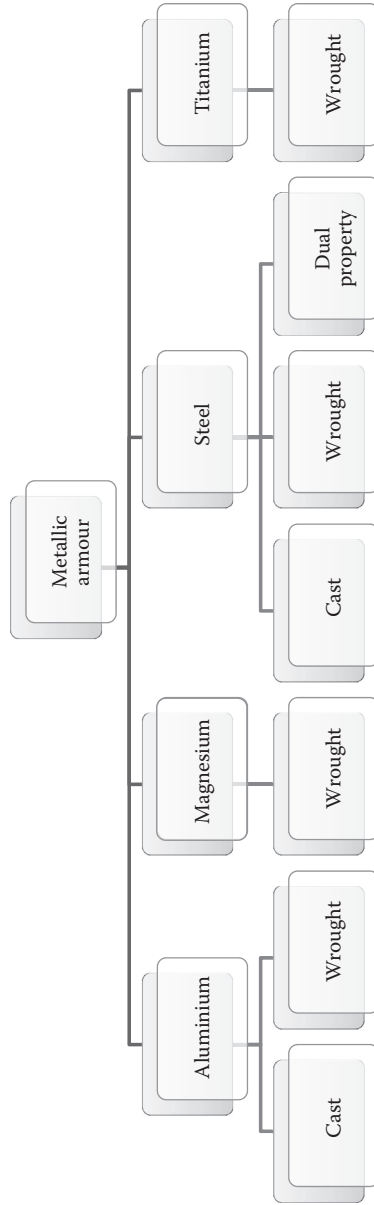


FIGURE 6.1
Classifications of materials that are used in armour applications.



FIGURE 6.2
Chieftain Main Battle Tank (MBT) employing a cast steel turret.

- *Extrusion*: where the piece is forced through a die to produce the desired shape.
- *Drawing*: where the metal is pulled through a die that has a tapered bore. Rod and wire are commonly fabricated in this way (not used for armour plate).

6.2.2 Cast Armour

Casting metal structures for armour applications, where molten metal is solidified in a mould, has become less attractive in recent years as the strength that can be offered by wrought plates is far superior. However, before and during World War II (WWII), there was a significant amount of cast armour produced. Casting metallic structures (say, for example, for turrets on tanks) can provide some geometric and cost advantages. Accordingly, the Chieftain MBT employed such a turret. However, castings are notorious for containing porosity and generally possess low toughness values.

Some improvements in casting of steels occurred in the 1970s where it was shown that cooling the metal in such a way that heat was extracted on one surface led to improvements in properties. This process resulted in columns of grains extended from the chill surface completely through the casting thereby giving the casting microstructural 'texture'. The end result was a casting that had superior ductility and ballistic performance than conventional castings (Papetti 1980).

6.2.3 Welding and Structural Failure due to Blast and Ballistic Loading

Welding is a very common way of joining metallic plates, and it is particularly important for armoured fighting vehicles (AFVs) that may be exposed to blast loading. Joins are often a source of weakness in the structures, and it is these that tend to fail first if the whole structure is subjected to a dynamic stimulus (such as a blast wave). Therefore, it is necessary to get the technique right.

During the welding process, there is diffusion of the metal so that the join is metallurgical rather than mechanical. Arc and gas welding occurs by a process of melting the work pieces and a filler material (i.e. the welding rod), whilst they are all in contact with one another. When all materials solidify, the filler material provides a join between the work pieces. Unfortunately, there will be a material that is adjacent to the weld that experiences microstructural changes due to being subjected to elevated temperatures. This will lead to change in the localised properties of the material, and this can turn out to be a source of weakness. This area of property alteration is called the 'heat-affected zone' and is sometimes abbreviated as 'HAZ'. There are several reasons why properties are changed in the HAZ, as summarised by Callister (2007):

1. If the material was previously cold-worked, the temperature increase due to the welding process may lead to grain growth or recrystallisation. This process weakens the material and can lead to a reduction of strength, hardness and toughness in this zone.
2. On cooling, the material experiences residual stresses due to different cooling rates through the thickness of the weld. These residual stresses can lead to a weakness in the joint.
3. For steels, the material may have been heated sufficiently by the welding process to form austenite. On cooling, the phases that are produced are dependent on the cooling rate and the carbon content of the steel. For plain carbon steels, normally, pearlite will form on cooling. However, for alloy steels, one possible product that is formed is martensite. This is undesirable as it is brittle. This will be discussed briefly in Section 6.3.1.1.
4. Some stainless steels may become sensitive to inter-granular corrosion in the HAZ. In essence, they begin to corrode due to the formation of a chromium-free zone adjacent to the grain boundary as chromium carbide precipitates are formed. Therefore, the grain boundaries become susceptible to corrosion.

The HAZ in the weld can be the origin of failure, as depicted in Figure 6.3, both through structural collapse and through perforation (caused by the local failure of weld material).

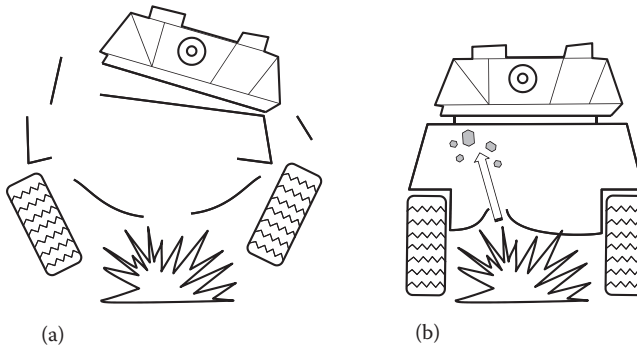


FIGURE 6.3 Failure of an armoured vehicle subjected to blast loading showing (a) structural collapse through failure of the welds and, (b) perforation of the hull bottom by explosively accelerated debris.

Care should be taken when welding armoured steel – and this is all the more important to consider when carrying out field repairs. Cracking can occur along the weld if inappropriate methods are used. Alkemade (1996) examined the weldability of high-hardness steel armour plate – specifically for the Australian light armoured vehicle (LAV) 25 that is made from welded high-hard steel plate. The purpose of his work was to examine the susceptibility to cracking after fusion welding of Bisalloy 500 armour plate (0.2% proof strength = 1580 MPa). He showed that for this armour, hydrogen-induced cracking was seen in the hardened region of the HAZ where the heat input was 0.5 kJ/mm, and the pre-heat was 75°C or less, whereas no cracking was observed at this heat input when the preheat was raised to 150°C. Additionally, when the heat input was raised to 1.2 kJ/mm, no cracking was observed even when preheat was not used.

A good weld between two armour plates can be achieved by the use of laser beam welding (LBW). LBW uses a highly focused and intense laser beam as a heat source to selectively melt the materials. Often, there is no need to supply a separate filler material, and the process can be employed in a highly automated fashion. The resulting HAZ is usually small due to the fact that the total energy input into the work pieces is small, and the welds are precise. With LBW, it is entirely possible to achieve porosity-free welds with strengths at least equal to the parent metal.

6.3 Metallic Armour Materials

Four of the more important metal alloys that are used in protection will now be reviewed: steel, aluminium, magnesium and titanium. The United States publish MIL specifications that define the minimum ballistic behaviour of

TABLE 6.1

US Military Standards for Steel, Aluminium, Magnesium and Titanium Alloys

Standard	Date	Name
MIL-DTL-12560J	24 July 2009	Homogeneous wrought armour plate
MIL-DTL-46100E	24 October 2008	Armor plate, steel, wrought, high hardness
MIL-DTL-46177C	24 October 1998	Armor, steel plate and sheet, wrought, homogeneous (1/8 to less than 1/4 in. thick)
MIL-DTL-46027K	31 July 2007	Armor plate, aluminium alloy, weldable 5083, 5456 and 5059
MIL-DTL-46063H	14 September 1998	Armor plate, aluminium alloy, 7039
MIL-DTL-32333	29 July 2009	Armor plate, magnesium alloy, AZ31B, applique
MIL-DTL-46077G	28 September 2006	Armor plate, titanium alloy, weldable

these materials against certain threats, and these are summarised in Table 6.1. A quick Google search will provide the text.

6.3.1 Steel Armour

Steel is by far the most commonly used material in armoured vehicles to date mainly because steel is a good ‘all-rounder’. Toughness, hardness, good fatigue properties, ease of fabrication and joining and its relatively low cost make steel a popular choice for armoured vehicle hulls. Steel has been used extensively over the centuries and found its first use in armoured vehicles in the tanks of World War I (WWI), and it is still used extensively today.

6.3.1.1 A Quick Word on the Metallurgy of Steel

Steels are Fe–C alloys. Introductory materials science books discuss in detail the iron–carbon phase diagrams (e.g. see Ashby and Jones 1986). This is a diagram that shows how the microstructure of the steel will develop if allowed sufficient time during cooling such that near-equilibrium conditions are maintained at all times. Unlike many non-ferrous alloys, the cooling rate plays a large part in how the microstructure (and the resultant mechanical property) is formed. Cooling a steel quickly will have a different effect than cooling it slowly – depending on the composition of carbon. For example, slowly cooling a plain carbon steel from around 850°C will result in body-centred cubic (BCC) α grains (ferrite) being formed and nodules* of pearlite. Pearlite is an alternate plate-like mixture of α and iron carbide (Fe_3C). The iron (α) phase is quite soft with a local hardness of about 90 VHN, whereas pearlite is stronger and harder with a typical hardness of 250 VHN. Slow cooling is done in air, a process known as normalising. Rapid cooling or ‘quenching’ is done in water

* Note that pearlite is a mixture of two separate phases, and therefore, it is not referred to as a ‘grain’ but rather a ‘nodule’.

or oil. Rapidly cooling the same plain carbon steel in water will result in martensite forming. Martensite is the hardest constituent obtained in a given steel, and the hardness of this phase increases with carbon content. The martensitic microstructure consists of a fine needle-like structure. These steels are hard but brittle, and therefore, they need tempering to allow for an improvement in ductility. Another constituent that can be formed on cooling in alloy steels is bainite. Through careful choice of alloying elements and tempering temperatures, it is possible to produce a super-strong bainite steel with nano-sized grain sizes. This makes the steel very strong with tensile strengths of 2 GPa quite possible. This is obviously very attractive as an armour.

There are several types of steels. These are summarised below:

1. *Low-carbon steels*: These steels generally have a low carbon content (<0.25%) and are unresponsive to heat treatment. Strengthening the material is generally achieved by cold working. They will have low yield strengths (around 150–250 MPa) and will work-harden easily. Generally, these steels are not useful for lightweight armour applications as they are too soft, and consequently, large sections are required to stop modern weapon systems. However, they exhibit excellent ductility, are easily machinable and weldable and are generally cheap. Examples of low-carbon steels are AISI 1010 and 1020 grades that have 0.1% and 0.2% carbon content, respectively, and yield strengths of 180 and 205 MPa.
2. *High-strength low-alloy steels*: These steels are stronger with yield strengths approaching 500 MPa. They also possess low carbon contents. These types of steels are useful for construction and are readily weldable. They have good toughness characteristics and provide a moderate resistance to penetration.
3. *Quenched and tempered steels*: These steels are used where high strengths are required (800–1000 MPa). They are readily weldable and provide good options for lightweight armour.
4. *High-carbon steels*: These steels have carbon contents in the range between 0.6% and 1.4%. They possess high strength and hardness due to the presence of large amounts of Fe_3C . However, unless they are combined with alloying elements, they can be brittle. They are generally used in the hardened and tempered condition. They are good for wear resistance applications.
5. *High alloy steels*: Generally expensive and used for niche applications. They possess good strength and toughness values.

6.3.1.2 Rolled Homogeneous Armour

Rolled homogeneous armour (RHA) has been used extensively as an armour material for nearly a century. It is usually used in depth-of-penetration testing

TABLE 6.2

Composition of RHA

C	Mn	Ni	Cr	Mo	S	P
0.18–0.32	0.60–1.50	0.05–0.95	0.00–0.90	0.30–0.60	0.015 (max)	0.015 (max)

as the benchmark for testing armour materials. It is also used in describing the performance of armour systems or materials in terms of RHA equivalences, that is, the thickness of RHA required to defeat a given projectile when compared to a specific armour system that is able to defeat the same projectile.

RHA is manufactured by hot-rolling ingots of steel that contain a small percentage of alloying elements followed by quench and temper processing to produce a through-hardened tempered martensitic structure. A typical chemical composition of RHA plate is shown in Table 6.2 with broad limits; the exact composition would depend on the required properties and thickness of the plate to be hardened.

Changing the alloying content and treatment of the steel will provide a range of strengths and ductility. For example, the current UK Ministry of Defence Standard for Armour Plate (MoD 2004) specifies five classes of hardened and tempered RHA within the thickness limits of 3–160 mm.

Military specifications normally provide steel suppliers latitude to satisfy the requisite armour mechanical properties and ballistic requirements within a broad range of chemistry and treatment conditions. A typical treatment process of the RHA plate is as follows.

After rolling the steel into shape, the plate would normally be hardened by reheating to between 820°C and 860°C and quenched in oil or water. The resulting product is very strong but brittle due to the formation of the hard and brittle martensite phase. This can be moderated by tempering whereby the steel is reheated in a furnace for a few hours to temperatures in the region of 400°C–650°C. The final product will be relatively ductile and tough and possess a uniform microstructure (hence the reference to homogeneous). The tempering temperature will be selected to give the wanted mechanical and ballistic properties with lower temperatures being used for the thinner harder armours and higher temperatures for the thicker, tougher armour plate.

6.3.1.3 High-Hardness Armour

High-hardness armour (HHA) is the name that is given to a class of homogeneous steel armour with hardness values in excess of 430 BHN*. Typically, the method of manufacture is similar to that of RHA involving lower tempering temperatures (~200°C as opposed to 400°C–650°C for RHA).

* In this book, I have used the scales of hardness, VHN and BHN, referring to Vickers hardness number and Brinell hardness number, respectively. Very roughly, they represent a similar level of hardness (within ~5%).

Much of the development of modern high-hard armour steel plate occurred during the Vietnam conflict where there was a requirement for thin steel plate that could provide protection against 0.30-in. ball ammunition. This was achieved using plates of hardness values of around 500 BHN. Of course, the use of hard armour in fighting vehicles is not new. In fact, the relatively thin plates of steel armour that were used in the tanks of WWI had hardness values within the range of 420–650 BHN (Ogorkiewicz 1991b). Relatively thin high-hardness plate can be used as quite an effective disruptor for most types of armour-piercing ammunition. However, with increasing hardness, the toughness is compromised, and therefore, these materials can be susceptible to gross cracking.

6.3.1.4 Variable Hardness Steel Armour

There are potential advantages in using a single steel plate with varying through-thickness properties. By surface-hardening one side of a thick low-carbon steel plate, it is possible to incorporate both hard disruptive and tough absorbing properties in a single material. The main advantage offered is that the more ductile backing layer is able to arrest crack propagation in the armour plate, whilst the hard-facing layer is able to deform or fragment the projectile.

A common approach to developing steel armour with varying through-hardness properties is by a process called face hardening. An early example of this is a process called carburising, which is described as follows. The surface of the steel is heated to a temperature around 850°C–900°C in intimate contact with a carbon-rich solid (such as wood or bone charcoal), liquid or gas. During this process, carbon atoms, being soluble in the austenite phase that is formed at elevated temperatures, migrate into the steel. Once carbon has entered the steel at the surface, it diffuses inwards at a rate that is dependent upon the composition of the steel. This produces a carbon gradient from the surface of the steel to the inside. Afterwards, the steel is heat-treated to achieve the desired material properties. The result is a plate with a thin hardened face due to the additive carbon, whilst the body of the plate remains relatively tough.

This approach to armouring was first applied to battleships in the 1890s and notably was used by Vickers–Armstrong in the production of tanks during the 1920s and 1930s (Ogorkiewicz 1991b). The armour plates from these tanks had a facing plate hardness of 600 BHN and a softer rear face of 400 BHN. Although the plate was up to 20 mm thick and was effective at defeating the contemporary armour-piercing projectiles of the time, it was virtually impossible to machine and weld and therefore had to be attached by bolts or rivets.

During WWII, the armour for the German King Tiger tanks (Figure 6.4) was produced by another surface-hardening process known as flame-hardening. This method involves heating the surface of the armour (using a gas flame) up to high temperatures and then rapidly cooling the steel (generally by water quenching) to form a very hard but brittle martensitic layer with decreasing hardness through the thickness of the steel plate (Doig 2002).



FIGURE 6.4
King Tiger tank of WWII, which used 'flame-hardened' steel armour.

An effective way of producing a plate with dual hardness values is by roll-bonding two different steels together to form a single plate (see Figure 6.5). This provides an armour plate with more discrete hardness values as opposed to a plate with a hardness gradient. This technology, which has been around before WWII in the form of Hadfield duplex armour, has become commonly known as the dual-hardness armour (DHA). This type of plate is manufactured from two separate plates of nickel-alloy steel that are roll-bonded until the two plates form a strong metallurgical bond. The face plate usually contains higher carbon content that leads to higher hardness after heat treatment.

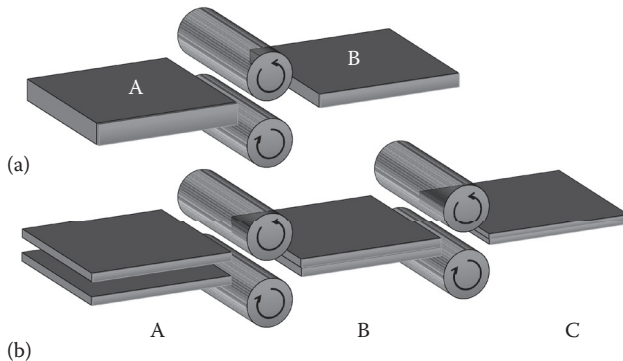


FIGURE 6.5
(a) Conventional hot rolling and (b) processing of DHA.

TABLE 6.3

Thickness, Areal Density and Mass Effectiveness Values for the Amount of Steel Required to Protect against 7.62-mm AP Bullets at Point-Blank Range and Normal Incidence

Armour Steel	Density (kg/m ³)	Thickness (mm)	Areal Density (kg/m ²)	E_m
RHA (380 BHN)	7830	14.6	114	1.00
HHA (550 BHN)	7850	12.5	98	1.16
DHA (600–440 BHN)	7850	8.1	64	1.78

Source: Data taken from Ogorkiewicz, R. M., *International Defence Review*, 4:349–352, 1991.

The performance data in Table 6.3 taken from Ogorkiewicz (1991a) demonstrate the effectiveness of DHA. As can be seen from Table 6.3, the ballistic performance of DHA is far superior to that of HHA of comparative hardness when subjected to attack from a steel-cored 7.62-mm AP bullet. However, despite the apparent advantage of using DHA, it is currently out of favour with most mainstream armour manufacturers for military applications – mainly because of the complexity and cost of manufacturing for a relatively limited number of customers.

6.3.1.5 Perforated Armour

Drilling holes in a high-hardness steel plate has been shown to be an effective means of disrupting the path of an AP projectile leading to its fragmentation or destabilisation. The complete armour system consists of a holed or perforated hard but tough steel layer spaced at some distance from the base armour of the vehicle (typically 200–300 mm). The spacing provides time for the core of the projectile to tumble or separate into discrete fragments. The base armour must be sufficient to defeat the tumbling projectiles that result after the core has been disrupted by the outer steel-perforated plate. The edges of the holes provide a point for destabilising the projectile path and, if the conditions are right, can provide a contact point that induces bending loads within the projectile core. Applying ‘dynamic’ bending loads to a projectile core will induce tensile fracture in the projectile. Optimisation of this armour is achieved by choosing appropriate properties of the plate as well as the hole diameters and spacing.

The primary use of perforated armour systems has been to up-armour armoured personnel carriers (APCs) and infantry-fighting vehicles (IFVs) to protect against armour-piercing small-arms bullets. However, some effort has been made to design a perforated system to protect against APFSDS ammunition, but the results have shown little advantage in doing so (Weber 2002). Nevertheless, if yaw can be induced into the rod, then the depth of penetration into residual armour can be significantly reduced. Even yaw angles as low as 1.5° can result in the degradation of the rod’s performance (Roecker and Grabarek 1986).

6.3.1.6 Ballistic Testing of Steel Armour

There are quite a lot of data available on the ballistic penetration capability of steel plates, and various authors have studied the behaviour of various types of projectiles against different target strengths. Probably of most interest is the behaviour of the armour-grade steels, and Børvik et al. (2009a) provide a nice summary of results for 7.62-mm ball and AP projectiles. The Recht–Ipson curve fit was used for this data (see Chapter 4) according to

$$v_r = a(v_0^p - v_{bl}^p)^{1/p} \quad (6.1)$$

where v_r is the residual velocity of the projectile, v_0 is the impact velocity, and v_{bl} is the ballistic limit velocity. The parameters a and p are the Recht–Ipson parameters (note that for all data presented here, $a = 1.0$).

The ballistic data are summarised in Tables 6.4 and 6.5.

Essentially, as would be expected, as the strength of the plate increases (as we move down Tables 6.4 and 6.5), it is seen that the ballistic limit velocity increases as well.

TABLE 6.4

Ballistic Performance Data (and Recht–Ipson Parameters) for Various Armour-Grade Steel Plates Perforated by a 7.62-mm Ball Projectile (BR6)

Steel Type	Yield Strength (MPa)	Thickness (mm)	Areal Density (kg/m ²)	Recht–Ipson Parameter, p	Ballistic Limit Velocity (m/s)
Weldox 500E	605	6.0	47.1	2.3	596
Weldox 700E	819	6.0	47.1	2.6	666
Hardox 400	1148	6.0	47.1	3.0	762
Domex 500	1592	6.0	47.1	3.4	886
Armoxx 560T	1711	6.0	47.1	3.5	918

Source: Børvik, T. et al., *International Journal of Impact Engineering*, 36 (7):948–964, 2009.

Note: $a = 1.0$.

TABLE 6.5

Ballistic Performance Data (and Recht–Ipson Parameters) for Various Armour-Grade Steel Plates Perforated by a 7.62-mm AP (APM2) Projectile (BR7)

Steel Type	Yield Strength (MPa)	Thickness (mm)	Areal Density (kg/m ²)	Recht–Ipson Parameter, p	Ballistic Limit Velocity (m/s)
Weldox 500E	605	2 × 6.0 = 12.0	94.2	2.2	624
Weldox 700E	819	2 × 6.0 = 12.0	94.2	2.4	675
Hardox 400	1148	2 × 6.0 = 12.0	94.2	2.0	741
Domex 500	1592	2 × 6.0 = 12.0	94.2	2.1	837
Armoxx 560T	1711	2 × 6.0 = 12.0	94.2	1.5	871

Source: Børvik, T. et al., *International Journal of Impact Engineering*, 36 (7):948–964, 2009.

Note: $a = 1.0$.

TABLE 6.6Ballistic Penetration of Steel (v_{50} Tests)

Alloy	t (mm)	Areal Density (kg/m ²)	Projectile	Ballistic Limit (m/s)
Bisplate HHA (530 HB)	11.9	92.8	0.30 APM2	826
Bisplate HHA (477 HB)	19.5	152.1	0.50 APM2	751
Bisplate HHA (530 HB)	11.9	92.8	0.50 FSP	835
Bisplate HHA (477 HB)	19.6	152.9	20-mm FSP	845

Source: Gooch, W. A. et al., Ballistic testing of Australian bisalloy steel for armor applications, *Proceedings of the 23rd Symposium on Ballistics*, Tarragona, Spain, 2007a.

A selection of additional steel penetration data that has been published in the open literature is presented in Table 6.6.

6.3.2 Aluminium Alloy Armour

The use of aluminium in domestic applications has increased dramatically since 1960 with the transport sector being the largest user. It was around the 1950s and 1960s that aluminium alloys were being used in the design of AFVs including the British combat vehicle reconnaissance (CVR) family of vehicles and the M113 APC. With the M113, the US Army wanted a lightly armoured, air-transportable, air-droppable amphibious vehicle. Aluminium-based armour seemed an appropriate route to take given the relatively low density of aluminium and the discovery that, ballistically, certain wrought alloys performed quite well.

For lightweight and medium-weight vehicle applications, it has been shown to be a good all-rounder, and several AFVs are made from aluminium alloys. These include the Warrior (United Kingdom), CVR family of vehicles (United Kingdom) and the Bradley AFV and as already mentioned, the M113 (United States). The reason for aluminium's choice for these vehicles is that the areal density of the material required to provide protection against 7.62-mm AP and 14.5-mm AP is lower for the wrought aluminium alloys than their steel counterparts.

6.3.2.1 Processing and Properties

The first military use of aluminium was conceived in the mid-nineteenth century in France after an impure form of aluminium was produced by H. Sainte-Claire Deville through the chemical reaction between aluminium chloride and sodium. The new metal soon gathered government support due to Napoleon the Third who thought it could be used in the manufacture of lightweight body armour (Polmear 1989). Although this form and indeed pure forms of aluminium are too soft to be realistically used in armour applications, certain wrought alloys of aluminium have been used successfully in the production of AFVs, as discussed in Section 6.3.2.

The mechanical properties of aluminium alloys are affected by a range of microstructural features including small grain sizes and control of grain shape and a dislocation substructure produced by cold working and/or a very fine distribution of sub-micron-sized precipitates and coarse inter-metallic particles produced by the age-hardening heat treatment process. For the alloys that respond well to ageing, it is finely dispersed precipitates that have a significant effect in raising the yield and tensile strengths of the alloy. For alloys that do not respond well to ageing, the increase in dislocation density through cold rolling increases the strength but does reduce the ductility of the plate. Ultimately, the strength of the alloy affects the ballistic performance of the plate.

Generally speaking, the aluminium alloys that have been used in AFV armour are wrought alloys. That is to say, they have been mechanically worked during processing. Wrought alloys are described by the International Alloy Designation System (IADS) where the first of a four-digit number designates the major alloying element. Table 6.7 summarises the designations.

Subsequent numbers are added to the H and T conditions to indicate secondary treatments used to influence mechanical properties.

Most aluminium armour is made from the 5xxx or 7xxx series of aluminium alloys with a relatively small portion manufactured from the 2xxx plate. For example, the armour on the M113 and the USMC amphibious assault vehicle consists of cold-rolled 5083 aluminium–magnesium–manganese alloy plate. The Type 5083 alloy is formed into plate by hot rolling, from ingot, at temperatures in the range of 350°C–400°C. It is then cooled at room temperature and 20% cold-rolled to the desired thickness and to provide the required strength. Consequently, the plate has been strain-hardened with 5083 – H131 being a typical example. Strain-hardening of the alloy will result in a loss of ductility, and therefore, only modest amounts of cold rolling are desirable. Also, it is known that AA 5083 exhibits a modest negative strain-rate sensitivity (Clausen et al. 2004). That is to say that as the loading rate increases, the material effectively gets softer. This is bad news for armour, although the

TABLE 6.7

IADS Aluminium Alloy and Temper Designations

Four-Digit Series	Main Alloying Element	Temper Designations (Added as a Suffix Letter)
1xxx	99% Al min.	F – as fabricated
2xxx	Cu	O – annealed wrought
3xxx	Mn	H – strain hardened
4xxx	Si	T – heat treated
5xxx	Mg	
6xxx	Mg + Si	
7xxx	Zn	
8xxx	Others	

TABLE 6.8

Material Properties of Some Aluminium Alloys Currently Used in AFVs

Armour-Grade Alloy	Proof Stress (MPa)	UTS (MPa)	Elongation (%)
AA 5083-H131	(0.2%) 285	345	10
AA 5059-H131	(0.2%) 360	405	9
AA 7017-T6	(0.2%) 385	445	11
AA 7039-T6	(0.2%) 375	435	11

Source: Aleris, Defence aluminium product data sheet, Switzerland, Aleris Switzerland GmbH, 2010.

reduction in flow strength is quite small. Typical properties of some armour-grade alloys are summarised in Table 6.8.

An alternative to 5083 is the ballistically superior Type 2024 aluminium-copper age-hardened alloy (a process whereby the aluminium alloy naturally hardens with time with a progressive reduction in ductility). However, the 2024 grade is not readily weldable, and that renders it difficult to integrate into structural armour. Certain high-strength 7xxx grades of alloy are also difficult to weld without adversely affecting their microstructure and so their mechanical properties.

6.3.2.2 Ballistic Testing of Aluminium Armour

There have been a large number of studies examining the ballistic penetration of aluminium plates. Some have examined the effect of rigid projectiles as they penetrated the plates, whilst others have examined the effect of deforming projectiles on the ballistic penetration of aluminium. Several studies have centred around the ballistic penetration of armour-grade aluminium alloys and in particular the AA 5083 grade in various treatments (Forrestal et al. 1990; Børvik et al. 2004, 2009b) by rigid penetrators. Of particular interest is the close correlation between the cavity expansion-type analytical models and the experimental results. Forrestal and co-authors have developed closed-form equations that predict the ballistic limit and residual velocities for the perforation of plates by rigid projectiles (Forrestal et al. 1987; Piekutowski et al. 1996). A typical analytical formulation is summarised in the following and applied to AA 5083-H116 plates (Børvik et al. 2009b).

For the perforation of an elastic-plastic ductile finite-thickness plate, the conservation of energy equation applies:

$$\frac{m_p}{2} (v_0^2 - v_r^2) = \pi a^2 h \sigma_r \quad (6.2)$$

where m_p is the mass of the projectile, v_r is the residual velocity, v_0 is the striking velocity, a is the radius offered by the projectile, h is the plate thickness

and σ_r is the radial compressive stress acting on the projectile's nose. Note that when the projectile comes to rest in the plate, $v_r = 0$, and therefore, $v_s = v_{bl}$ (the ballistic limit velocity). A further refinement is that the radial stress on the projectile nose is approximated to the quasi-static value of flow stress as the cavity expansion velocity approaches 0. That is to say that $\sigma_r = \sigma_s$ as $v \rightarrow 0$. For an elastic–perfectly plastic material, the 1D compressive response is $\sigma = E\varepsilon$ in the elastic reason and $\sigma = Y$ in the inelastic reason. Rearranging Equation 6.2 and noting that $\sigma_r = \sigma_s$ gives us

$$v_{bl} = \sqrt{\frac{2\pi a^2 h \sigma_s}{m_p}} \quad (6.3)$$

For the von Mises yield criterion (elastic–perfectly plastic),

$$\sigma_s = \frac{Y}{\sqrt{3}} \left(1 + \ln \left[\frac{1}{\sqrt{3}} \left(\frac{E}{Y} \right) \right] \right) \quad (6.4)$$

where Y is the yield strength, and E is the Young's modulus. Further modification of this equation is required where hardening occurs (Forrestal et al. 1990; Piekutowski et al. 1996):

$$\sigma_s = \frac{Y}{\sqrt{3}} \left(1 + \ln \left[\frac{1}{\sqrt{3}} \left(\frac{E}{Y} \right) \right] \right)^n \int_0^b \frac{[-\ln(x)]^n}{(1-x)} dx, \quad b = 1 - \frac{\sqrt{3}Y}{E} \quad (6.5)$$

where n is the work hardening exponent. Using this type of approach, Børvik et al. have shown very good correlation to the prediction of the penetration of aluminium AA 5083-H116 plates amongst other armour plates. Equally, good results for 6061-T651 have been presented by Piekutowski et al. (1996). These results are shown in Figure 6.6.

There have been numerous studies of the penetration of the finite-thickness aluminium alloy plate in the literature, and it is perhaps helpful to provide a snapshot of the results. Most studies have concentrated in establishing a ballistic limit calculation such as a v_{50} . Table 6.9 shows a summary of some results for 0.30 APM2 and 0.50 APM2 bullets.

Aluminium-alloy armour plates are applied in single thickness sections, and it has been thought that laminating the armour plates would lead to an increase in ballistic performance. This has been shown not to be so. Woodward and Cimpoeru (1998) ballistically tested 2024-T351 plates with various shaped projectiles and compared the results for single-thickness (~9.5 mm thick) plates and multiple-thickness plates. They showed that replacing a single thickness of aluminium armour with multiple plates

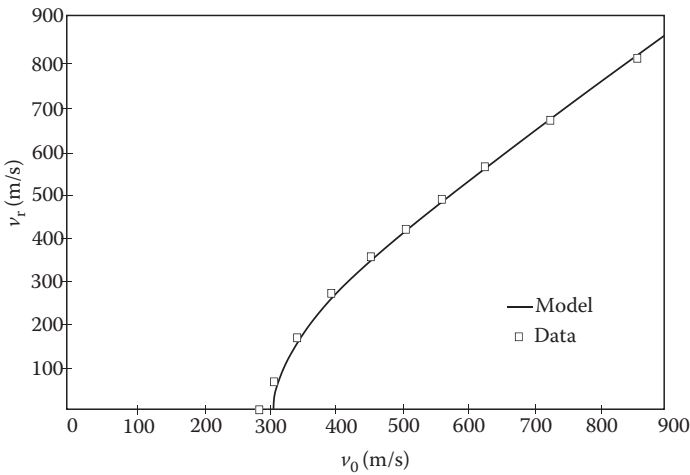


FIGURE 6.6

Relationship between residual and striking velocity showing the comparison between theoretical and experimental results for a non-deforming projectile perforating 26.3 mm of AA 6061-T651; $v_{bl} = 307$ m/s. (Reprinted from *International Journal of Impact Engineering* 18 (7–8), Piekutowski, A. J. et al., 877–887, Copyright 1996, with permission from Elsevier.)

TABLE 6.9

Penetration of Aluminium Alloys by Armour-Piercing Bullets – Ballistic Results

Ref.	Alloy	t (mm)	Areal Density (kg/m ²)	Projectile	Ballistic Limit (m/s)
Showalter et al. 2008	5059-H131	25.1	66.8	0.30 APM2	588
	5059-H131	51.2	136.2	0.30 APM2	906
	5059-H131	51.2	136.2	0.50 APM2	680
	5059-H131	77.1	205.1	0.50 APM2	830
Børvik et al. 2011	6082-T6	20.0	54.0	0.30 APM2	414 ^a
	5083-H116	20.0	53.2	0.30 APM2	492 ^a
	7075-T651	20.0	56.2	0.30 APM2	628 ^a
Gooch et al. 2007a	6061-T651	26.0	70.2	0.30 APM2	582
	6061-T651	38.8	104.8	0.30 APM2	755
	6061-T651	51.2	138.2	0.30 APM2	882

Note: This table is a snapshot of the data; more details are provided in the references.

^a Estimated from the Recht–Ipson model (Recht and Ipson 1963), i.e. $v_{bl} = \sqrt{v_0^2 - v_r^2}$.

comprising the same thickness had little change on the ballistic limit velocity. Increasing the number of layers (for a given thickness) increases the level of tensile stretching work done during perforation of the target. However, there is a reduction in other work terms, and therefore, there was little overall change in the energy absorption of the target.

6.3.2.3 Applications of Aluminium Armour

In the late 1960s, the British adopted aluminium for the Alvis Scorpion tracked reconnaissance vehicle (CVR(T)). This was the first vehicle to have a turret as well as a hull welded from the aluminium alloy plate (see Figure 6.7). Due to the strict weight limitations and the level of protection that was required, the 5083-aluminium alloy could not be used. Instead, a new alloy was developed. The result was AA 7039 – an aluminium–zinc–magnesium alloy, which derived its strength from a precipitation hardening heat treatment. This finished aluminium alloy possesses a higher strength and better ballistic properties than AA 5083.

The Type 7039 alloy performed well against AP ammunition when compared to steel armour (RHA). For 14.5-mm ammunition, the advantages of using aluminium alloy over steel are more significant than what would be required to protect against the 7.62-mm ammunition. Yet with both types of ammunition, the disadvantage of using steel narrows as the angle of obliquity increases.

A decade later, a similar aluminium alloy (AA 7017) was adopted for use as the armour plate in the Warrior IFV (Figure 6.8). In this vehicle, the use of the aluminium was limited to the hull, whereas the turret is fabricated from the RHA plate. The reason for the choice of this alloy was to reduce the risk of stress corrosion cracking. This alloy is slightly harder than the AA 7039 alloy but less tough.

Aluminium alloy plate is anisotropic, and therefore, it is convenient to describe a rolled plate's properties in three directions: longitudinal (parallel to the rolling direction), transverse (perpendicular but in plane with the rolling direction) and short transverse (through the thickness). Aluminium alloys tend to be less strong and tough when tested in the short transverse direction, and ballistically, this can lead to a difference in performance of up to 10% due to cracking; in most applications, this is never a problem as the cross section to the rolling direction is rarely exposed.

Aluminium-alloy armours provide advantages in that, due to their relatively low density, thicker sections can be used to provide optimum

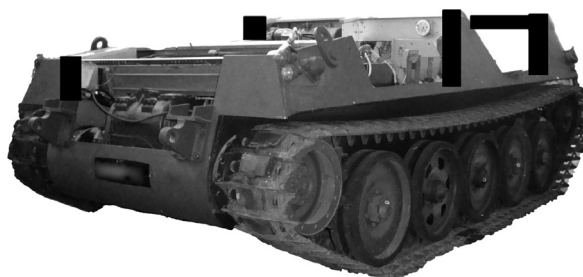


FIGURE 6.7

CVR(T) cutaway chassis with exposed hull profiles blacked out.



FIGURE 6.8
Rear of a Warrior IFV made from aluminium alloy plate.

protection. This provides the vehicle with additional structural rigidity. For example, the flexural rigidity of a plate is given by the product EI , where E is the Young's modulus, and I is the second moment of area of the rectangular cross section given by the well-known relationship

$$I = \frac{bd^3}{12} \quad (6.6)$$

where b is the breadth of the plate, and d is the depth.

However, aluminium suffers from a number of disadvantages. The most prominent disadvantage of aluminium alloys in the design of AFVs is that the harder alloys that are suitable for armour applications such as 7039 are susceptible to stress-corrosion cracking. Stress-corrosion cracking occurs when the aluminium alloy is attacked by a corrodant whilst being subjected to tensile stress. It is a particularly insidious failure because the magnitudes of stresses that are required to encourage failure are frequently lower than the yield strengths of the alloy. In fact, residual stresses induced during machining, assembling or welding can lead to failure.

Armour-grade aluminium also possesses a lower spall strength than steel and therefore is more susceptible to 'scabbing'. It is often necessary to employ internal spall shields in vehicles made of aluminium alloys. Furthermore, it possesses a relatively low melting temperature when compared with steel and therefore will soften more when the temperature is elevated (although in practical terms, this is minimal).

6.3.3 Magnesium Alloy Armour

It may come as some surprise to the reader, but magnesium-based armours are a real possibility. Although they have never been fielded on the

battlefield, their high specific strengths lend themselves to armour applications. Magnesium on its own is quite weak and brittle and consequently is never used in engineering applications unalloyed. Adding alloying elements such as aluminium, zinc or some of the rare earth metals provides a route to strengthening through precipitation-hardening heat treatments. Minimum required ballistic limit data for magnesium armour plate are provided by MIL-DTL-32333 (MR).

6.3.3.1 Processing and Properties

The crystal structure of magnesium is hexagonal close-packed (HCP). These types of crystal structures do not lend themselves to good ductility as they have few available slip systems at room temperature. Slip is an important mode of plastic deformation in metals. If a crystal lattice structure has few available slip directions, then it is difficult to plastically deform, and therefore, its ductility is curtailed. At elevated temperatures, thermally activated slip can occur, and this is why magnesium needs processing at elevated temperatures.

At higher strains or higher strain rates (including shock loading), plastic deformation in magnesium is accommodated through a process of twinning. Instead of atoms slipping past one another (as is the case in slip), there is a homogeneous deformation of the crystal structure. This leads to a reorientation across the twin plane.

Generally speaking, magnesium alloys are described by the first two letters that indicate the principal alloying elements. The letter corresponding to the greater alloying element is used first. The two letters are followed by numbers that indicate the wt% composition of each of the respective alloying elements rounded off to the nearest whole number. So for example, AZ61 indicates an alloy Mg–6Al–1Zn comprises 6% Al and 1% Zn (although the exact composition may vary). The heat-treated and work-hardened conditions are specified in the same way as aluminium alloys.

The origin of magnesium-based armour dates back to WWII where work was carried out to examine whether a magnesium alloy would make reasonable aircraft armour (Sullivan 1943). In this case, the particular grade of magnesium alloy tested (Dowmetal-grade FS) was susceptible to large amounts of spallation and therefore deemed not appropriate for this application. Recently, however, there has been renewed interest in magnesium alloys for armour applications (van de Voorde et al. 2005; Cho et al. 2009) due to improvements in processing technologies.

The attractiveness of magnesium alloys is that they have low densities (typically 1.7–1.9 g/cc), and some of the more modern alloys have strength values that compete against armour-grade aluminium alloys such as 5083-H32 (Jones et al. 2007a; Magnesium Elektron UK 2010). Table 6.10 summarises the elastic and strength properties of some magnesium alloys; an armour-grade aluminium alloy (5083-H32) is provided for comparison.

TABLE 6.10

Properties of Magnesium Alloy Materials (with a Comparison with AA 5083-H116)

Ref.	Alloy	Density (g/cc)	E (GPa)	ν	Y (MPa)
Jones et al. 2007a	AZ31B-H24	1.77	44.0	0.31	186 ^a
Polmear 1989; Millett et al. 2009	AZ61-F	1.80	43.0	0.31	180 ^a
Magnesium Elektron UK 2010; Hazell et al. 2012	Elektron 675-T5	1.90	45.9	0.31	310 ^a
–	5083-H116	2.66	71.0	0.33	228

^a 0.2% proof stress.

Although Mg ribbon burns (as we may all recall from our high school chemistry classes), larger masses of Mg will not. The reason for this lies in Mg's high thermal conductivity, which means that any localised heat is very quickly dissipated to the surrounding metal. Its melting point is comparable to aluminium too (650°C), which implies similar thermal softening properties during ballistic penetration. However, when particulated, it would be expected to burn, therefore posing a pyrophoric risk – particularly when penetrated by a shaped-charge jet.

Their low density and relatively low stiffness values mean that these materials tend to have low elastic impedance values. Following on from that, their shock impedances are very low too, and therefore, they will not impart large disruptive stress waves into the projectile. However, for small-arms bullets, where there is a general correlation between strength and ballistic performance, they will perform reasonably well.

6.3.3.2 Ballistic Testing of Magnesium Alloys

There has been relatively little ballistic work that has been done with magnesium alloys.

A selection of ballistic results is shown in Table 6.11.

Careful analysis of Tables 6.9 and 6.11 will show that magnesium alloys have the potential to perform in a comparable manner to armour-grade aluminium alloys on a weight-by-weight basis, although against fragments, the aluminium armour performs better with thicker sections. The likely reason for this is that magnesium alloys have been shown to be susceptible to adiabatic shear band formation during ballistic impact (Zhen et al. 2010; Zou et al. 2011), and therefore, they are susceptible to plugging.

6.3.4 Titanium Alloy Armour

Titanium is an attractive material for armour designers, and in its ballistic grade form (Ti-6Al-4V), it possesses a relatively low density (4.45 g/cc)

TABLE 6.11

Ballistic Results for Magnesium Alloys

Alloy	t (mm)	Areal Density (kg/m ²)	Projectile	Ballistic Limit (m/s)
AZ31B-O	31.5	55.8	0.30 APM2	511
AZ31B-H24	76.5	135.4	0.30 APM2	863
AZ31B-O	7.6	13.5	0.22 FSP	417
AZ31B-H24	7.8	13.8	0.22 FSP	421
AZ31B-O	31.5	55.8	0.50 FSP	639
AZ31B-H24	76.5	135.4	20-mm FSP	897

Source: Jones, T. L. et al., *Ballistic Evaluation of Magnesium Alloy AZ31B*. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory, 2007b.

whilst maintaining a relatively high strength and hardness (UTS = 900–1300 MPa, BHN = 300–350). In fact, its properties are not dissimilar to that of RHA of similar hardness. It is also weldable and heat-treatable. However, like magnesium, titanium possesses an HCP structure. In addition, ballistic-grade titanium alloy plate costs around 10–20 times that of steel (depending on the world metal markets).

Titanium alloy armour has been used in several armour applications including the commander's hatch and top armour protection on the M2 Bradley AFV and in some armoured components of the M1A2 Abrams MBT. It has also been used to reduce the weight of the M777 155-mm howitzer by replacing the steel that would be ordinarily used in the trails and recoil cylinders (Montgomery and Wells 2001). Titanium alloy plate has also been used in applique constructions. The Mobile Tactical Vehicle Light produced for the Canadian Army also used titanium in its protection construction to provide protection against 14.5-mm AP ammunition. Ballistic limit data requirements for testing are provided in MIL-DTL-46077G.

6.3.4.1 Processing and Properties

Titanium alloy armour can be traced back to the 1950s when the alloy (Ti–6Al–4V) was developed for ballistic applications. This alloy has since become one of the more important alloys of titanium and constitutes half of the sales of titanium alloys in both the United States and Europe (Polmear 1989). This alloy is known as an α/β alloy because it is composed of a dominant HCP α phase and a BCC β phase.

One of the drawbacks of using titanium alloy is that it is highly susceptible to adiabatic shear. This occurs when a material is subjected to a large amount of high-rate deformation leading to a temperature increase along localised bands. As the deformation of the material occurs rapidly, there is little or no time for the heat to conduct and diffuse from the plastically deforming zone, and therefore, the process is said to be adiabatic. This

localised heating can lead to thermal softening of the material and therefore further plastic flow.

The propensity of a material to fail by adiabatic shear can be assessed by the Culver criterion (Culver 1973). It can be used to calculate the critical shear strain that is required for material flow to occur and is given by

$$\gamma_i = \frac{\rho C n}{\partial \tau / \partial T} \quad (6.7)$$

where ρ is the bulk density of the material, C is the specific heat and n is the work-hardening exponent. $\partial \tau / \partial T$ is the rate of change of flow stress with temperature. $\partial \tau / \partial T$ is smaller for pure metals than it is for alloys, and therefore, they are less prone to failure by adiabatic shear. Titanium is a metal that is susceptible to adiabatic shear failure because its properties combine a relatively low n and ρ with a relatively high $\partial \tau / \partial T$. Table 6.12 summarises the instability strains for several metals.

The Culver criterion cited above is for materials that are assumed to behave with a power law-hardening dependency between strain and stress (i.e. $\tau \propto \gamma^n$). Other criteria exist (for example, with linear work-hardening laws). More details on adiabatic shearing theory are provided in Bai (1990), Bai and Dodd (1992) and Walley (2007).

Due to titanium armour's propensity to fail by adiabatic shear and the fact that it can also suffer from spalling when subjected to ballistic attack, it is normally used in combination with other materials – such as steel. However, experiments in laminating titanium armour with commercially available pure titanium plate to form a DHA have demonstrated suppressed spall failure and produced increased ballistic efficiency (Bruchey and Burkins 1998).

TABLE 6.12

Properties for the 'Culver Equation'

Material	P (kg/m ³)	n	γ_i
AA 1100-0	2707	0.32	4.5
AA 6061-T6	2707	0.075	0.43
Cu	8938	0.38	6.4
1020 Steel	7850	0.28	1.9
4130 Steel	7850	0.35	1.2
α -Ti	4533	0.17	0.32
Ti-6Al-4V	4421	0.08	0.16

Source: With kind permission from Springer Science+Business Media: Thermal instability strain in dynamic plastic deformation, in *Metallurgical Effects at High Strain Rates*, edited by R. W. Rohde et al., 1973, 519–530, Culver, R. S.

TABLE 6.13

Ballistic Data for Ti-6Al-4V

Alloy	t (mm)	Areal Density (kg/m ²)	Projectile	Ballistic Limit (m/s)
EBCHM Ti-6Al-4V	25.4	111.3	20-mm FSP	1016
EBCHM Ti-6Al-4V	38.8	172.7	20-mm FSP	1493
EBCHM Ti-6Al-4V	64.0	284.8	30-mm APDS	932

Source: Montgomery, J. S., and M. G. H. Wells, *Jom*, 53(4):29–32, 2001.

Note: EBCHM = Electron-beam cold-hearth melting.

6.3.4.2 Ballistic Testing of Titanium Alloy Armour

Gooch et al. (1995) studied the penetration of tungsten alloy and depleted uranium rods with L/D ratios of 10, 13 and 20 into Ti-6Al-4V (BHN = 302–364) and compared the results with RHA (BHN = 241–331). From these data, Gooch et al. deduced that the E_m^* values of the alloy against such penetrators ranged from 1.5 to 1.8 with approximately 10% more penetration being observed in the titanium alloy than the RHA semi-infinite targets.

Ballistic data for smaller threats are provided by Montgomery and Wells (2001), Jones (2004) and Burkins (2007). A selection of ballistic limit data is provided in Table 6.13.

6.4 Sandwich Structures

Sandwich systems that comprise either honeycombed, diamond-shaped, corrugated or pyramidal shapes have shown enhanced ability to absorb the energy from a blast wave – when compared to their monolithic counterparts (Guruprasad and Mukherjee 2000a,b; Dharmasena et al. 2008). These sandwich panels comprise thin stiff face sheets enveloping a relatively soft or collapsible porous core. The advantage offered by this construction is an increase in the second moment of the area of the structure as well as the ability to absorb energy through plastic compaction. Fleck and Deshpande (2004) presented an analytical assessment of various sandwich core topologies against blast loading. They described a model whereby the structural response of a sandwich beam occurs in three separate stages:

Stage 1: The fluid–structure interaction phase where the blast wave induces a uniform velocity in the outer face sheet.

* Here, the definition of E_m is slightly different from the one defined in this book. It is simply the ratio of the areal densities of the material penetrated of RHA to titanium alloy for the same impact velocity and in a semi-infinite target configuration.

Stage 2: The core undergoes crushing, and velocities of the core and the outer face sheet equalise as momentum is shared.

Stage 3: The sandwich beam is brought to rest through plastic bending.

Although this work centred on a two-dimensional beam, there is every reason to believe that this will equally apply to a three-dimensional plate problem. Moreover, Fleck and Deshpande noted that for the case of a water blast, an order-of-magnitude improvement in blast resistance compared to monolithic plates could be achieved. Diamond-celled cores provided the best performance. However, against a sharp air blast shock, their model indicated that sandwich structures would give a moderate gain in blast resistance when compared to a monolithic structure. This was due to the impedance mismatch between the air and the face sheet of a sandwich core being similar to that of a monolithic plate. Therefore, the energy from the blast would be reflected rather than being transferred to a compaction wave in the cellular core. Nevertheless, for deflection-limited designs (where there is a necessity to limit the deformation of a structure due to an air blast), certain sandwich structures appear to be efficient (Dharmasena et al. 2008).

6.4.1 Sandwich Core Topologies

For a given mass, cellular structures have shown to exhibit high levels of impact energy absorption. In fact, nature, as ever, has been a long way ahead of us in this. For example, a youthful bone is known to exhibit good impact resistance due to its cellular geometry as are cellular (or porous) materials such as wood and cork (Gameiro et al. 2007; Sousa-Martins et al. 2013). An extensive review of the properties and form of cellular materials is given by Gibson and Ashby (1997). In particular, cellular metallic structures such as metallic foams have shown particular promise in absorbing energy from collisions. Therefore, they offer an attractive option for mitigating blast loading – particularly from underwater blasts (see Section 6.4).

A cellular material for blast mitigation would almost certainly be incorporated into a sandwich construction comprising two outer layers (either a structural composite such as carbon fibre–reinforced polymer or a monolithic metal plate such as aluminium). A review of these are provided by Yuen et al. (2010).

6.4.1.1 Foams

There are several metals that have been used in the manufacture of metallic foams including aluminium, copper, lead, magnesium, steel, titanium and zinc. These are made through a variety of manufacturing techniques that can be summarised in four families of processes indicated by the starting material (Banhart 2001). So, to produce a porous metal, one can start from

- i. Liquid metal (e.g. 'foaming' of the material with gas bubbles)
- ii. Solid metal in powdered form (e.g. sintering of hollow spheres to produce a structure of multiple joined spheres)
- iii. Metal vapour or gaseous metallic compounds (e.g. vapour deposition of the material)
- iv. A metal ion solution (e.g. electrochemical decomposition of the material)

Of the four processes, (i) and (ii) are the most favoured for their ability to produce thick sections. The most common form of metallic foam used is aluminium foam – mainly due to the fact that it offers good specific properties and is relatively cheap.

There are two types of foam:

1. Open-cell metallic foams (where the material is composed predominantly of interconnecting cellular voids).
2. Closed-cell metallic foams (where the voids are predominately enclosed by a surrounding material). An example of this is shown in Figure 6.9.

The mechanical behaviour of a porous material is characterised by a relatively constant-plateau stress region over a large range of plastic strains. This is due to the collapse of the individual cells during compression. Eventually, the cells become completely compressed, and the measured stress increases as the material approaches full densification (see Figure 6.10). The higher and longer the plateau stress, the larger the amount of energy absorbed.

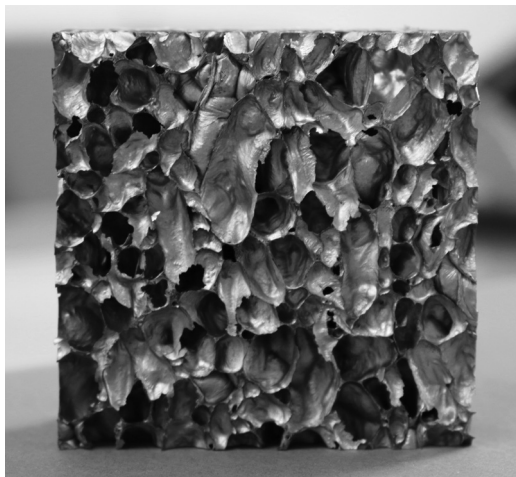
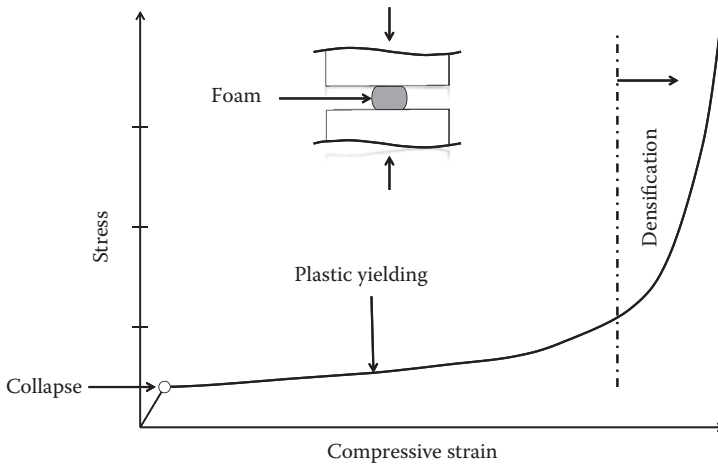


FIGURE 6.9

Closed-cell aluminium foam; the density of this foam is only 300 kg/m^3 .

**FIGURE 6.10**

Typical stress–strain response for a metallic foam in compression.

Aluminium foams show promise as stress wave attenuation layers in composite structural armour panels. Due to the porosity, it has been shown that the presence of an aluminium foam layer in a structural armour can delay and attenuate stress waves propagating to subsequent layers (Gama et al. 2001). That is, of course, before full densification. After the aluminium foam has been completely compressed, no attenuation will occur.

However, the mechanism of accommodating blast loading is complex. It has been known since 1970 that placing a cellular structure in direct contact with the structure that it is trying to protect actually leads to an amplification of the stress imparted (Monti 1970). So, it is necessary to separate the cellular plate from the protected structure. An extensive review on this phenomenon with open-celled metallic foams is provided by Seitz and Skews (2006). It has also been observed that stress waves are able to propagate through the cellular structure prior to the material achieving full densification. The nature of these waves and how they affect the cell walls are not clear.

6.4.1.2 Architected Core Topologies

As mentioned in Section 6.4, honeycombed materials have also been investigated as potential structures for blast mitigation (Dharmasena et al. 2008). The impulsive blast wave energy causes the honeycomb structure to collapse. The more inelastic strain energy that is expended by the collapse, the better.

An emerging possibility for blast mitigation may lie in the use of micro-lattice or micro-architected materials. These are most frequently made through a process of systematically selective laser melting of metallic

powders (usually SS 316L or Ti-6Al-4V) using a high-energy density laser. It is an additive manufacturing process so that the excess powders that remain after the process can be gathered up and reused (Tsopanos et al. 2010). So far, studies on the blast response of steel lattice structures have been carried out by relatively few researchers (McKown et al. 2008; Smith et al. 2011), and it is generally recognised that there is still room to optimise the performance of these materials. The structures that have been studied to date are of the BCC form (see Figures 6.11 and 6.12). Recovered specimens after both types of experiments (quasi-static and blast loading) demonstrated that similar collapse mechanisms and energy-absorption mechanisms had occurred. However, to manufacture even small samples of these structures takes a long time; therefore, they are relatively expensive compared to other cellular structures such as metallic foams, and realistically, it is unlikely that useable technologies would be made available in the next decade until the demand for these uniquely engineered structures takes off.

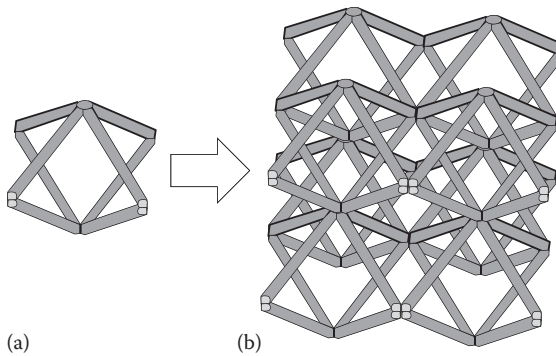


FIGURE 6.11

(a) Micro-lattice unit cell and (b) cells in a 2×2 matrix.

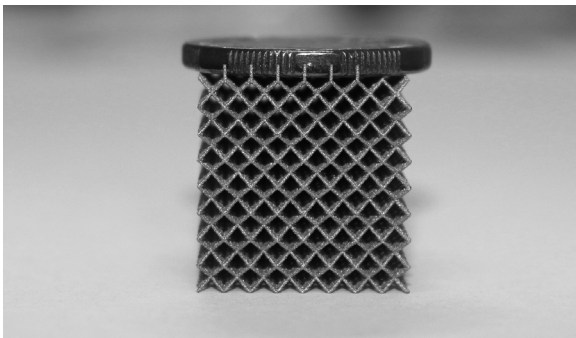


FIGURE 6.12

BCC Ti-6Al-4V micro-lattice structure supporting an Australian dollar coin (for scale).

6.5 Summary

Metallic materials have been used for millennia in armour. Steel has historically been used as it is a good all-rounder – combining reasonable hardness with good ductility and toughness. Moreover, it is relatively cheap and is a well-understood material to work with. It was not until the 1950s that aluminium alloys were used in AFV design and are more attractive than steel for protecting against large bullets such as the 14.5-mm B32 – especially at low angles of obliquity. Titanium and magnesium alloys are relatively high-performing materials, but their cost is currently prohibitive for large production volumes.

As will be seen in Chapters 7 and 8, there are many more lighter-weight non-metallic options such as high-strength fibres that have been used in personal protection, and these types of materials are largely yet to be adopted by vehicle manufacturers for structural applications. Consequently, the use of metal in armour is likely to be carried on for some time. This is all the more probable given the developments in porous or micro-architected structures that show promise in attenuating blast loads.

7

Ceramic Armour

7.1 Introduction

The term ‘ceramic’ comes from the Greek word *Keramikos*, which literally means ‘burnt things’. This tells us something of the way that the early Greeks manufactured ceramic pots, cisterns and the like. Consequently, a ceramic can be defined as an inorganic solid compound that is usually formed by the application of heat and sometimes heat and pressure. Ceramic armour materials are composed of at least one metal and non-metallic elemental solid with the raw material for ceramic production extracted from the earth and processed.

Readers will be familiar with the ceramic materials that are used in the kitchen or bathroom, and these have been termed ‘traditional ceramics’ and are largely based on clay. These tend to be quite porous and open structures with limited strength. However, around 70 years ago, progress was made in the development of what is now understood as ‘advanced ceramics’. These are materials that have unique properties and are the type of ceramic that is used in armour. Armour ceramics, in particular, are strong in compression – their microstructures are carefully controlled during manufacture, and they will possess limited porosity.

An early hint of the potential for using a hard brittle material in armour occurred when Major Neville Monroe-Hopkins found that a thin layer of enamel improved the ballistic performance of a thin steel plate (Dunstan and Volstad 1984). This work was carried out in 1918. Indeed, many early designs employed a hard ceramic face backed by a relatively ductile material, thereby employing the disruptor (or ‘disturber’)/absorber recipe that is still used in modern armour systems today. Arguably, of course, Monroe-Hopkins’s invention was not ceramic-faced armour because enamel is not polycrystalline ceramic; it is made by fusing powdered glass to a substrate at temperatures of between 750°C and 850°C. Nevertheless, one of the principles of ceramic-armour design was developed, namely, placing a hard brittle structure onto a relatively ductile backing layer to provide a disturber/absorber combination.

7.2 Structure of Armour Ceramics

The atomic bonding of ceramic materials ranges from being purely ionic to completely covalent, and many ceramics exhibit a combination of these two bonding types.

The ceramics that are used in armour applications are polycrystalline materials that comprise numerous grains (or crystallites). These grains are defined by the extent of repeatability of the ordered arrangement of atoms and are separated by a grain boundary that may include single or multiple phases of sintering-aid materials (see Figure 7.1).

In addition, the microstructure is likely to contain a certain amount of porosity left behind during manufacture. Sometimes, separate phases of a material exist within the microstructure as particles as is commonly found in reaction-bonded ceramics.

Viewed as a polished section, we cannot see the full three-dimensional nature of the grain. It is found that grains of many different polycrystalline materials have a limited range of faces – usually between 9 and 18, and each face will have around four to six edges. The tightness and packing of the structure, along with the sizes and weights of the elements in the ceramic, will determine its density. The bulk density of the ceramic will take into account the porosity, all lattice defects and the phases that are present within the material. This is the measured density, which is referred to in this book. The theoretical density of the material is the ideal density that can be calculated from the continuous defect-free lattice – taking into account the multiple phases that may exist. Elements of low atomic number and atomic weight (H, C, Si, Al, B and so on) will result in materials with a low theoretical density. Elements of high atomic number and atomic weight (W, U, Zr, Th and so on) will result

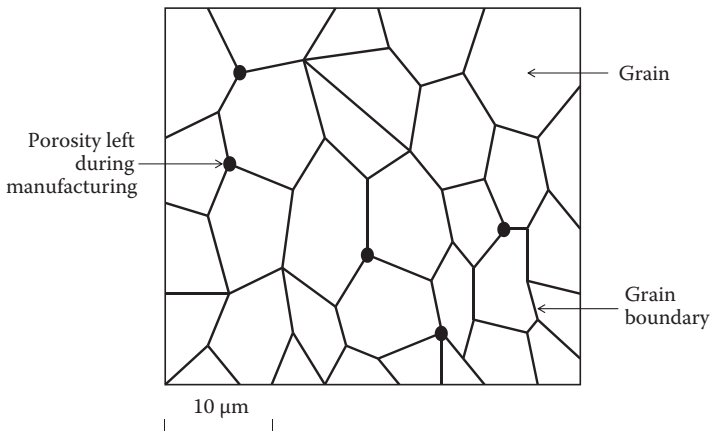


FIGURE 7.1

Schematic of a typical polycrystalline ceramic's microstructure.

in materials with a relatively high theoretical density. Therefore, tungsten carbide (WC) has a theoretical density of over six times that of boron carbide (B_4C). Armour ceramics consist of a relatively small number of self-selecting elements. These are Al, B, C, N, O, Si and Ti. These elements combine together with a good number of strong bonds that provide the desirable strength and stiffness characteristics of ceramic armour materials.

7.3 Processing of Ceramics

A base ceramic powder is fabricated into a required shape and then densified by a process called sintering. The base powder is usually very fine ($<5 \mu m$), and when it is packed together and heated to a specific temperature (hence, the term 'burnt things' was used to describe the early ceramics), the particles sinter, that is, they form very small 'joins' to one another. When the joins grow, the surface area of the particles is reduced, and the material densifies. The theoretical density is not achieved with this method due to the presence of small pores, which have a small effect on the final mechanical strength. A schematic of the sintering process is shown in Figure 7.2.

For example, aluminium oxide (Al_2O_3) occurs naturally as the mineral corundum and can be produced in large quantities from the mineral bauxite (aluminium hydroxide) by the Bayer process. This involves the selective leaching of the useful mineral by caustic soda (sodium hydroxide) and precipitation of the purified aluminium hydroxide ($Al(OH)_3$). This is then thermally converted to alumina:

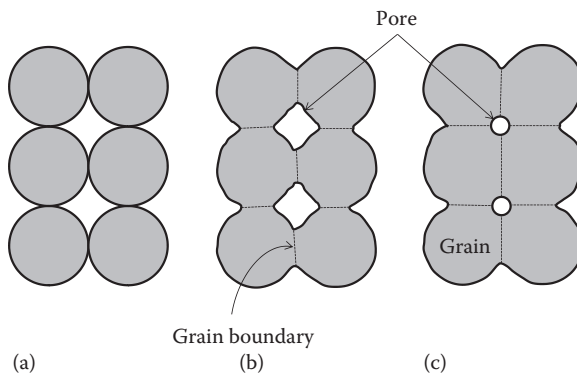


FIGURE 7.2

Sintering process showing (a) pressed powder (six particles), (b) the start of sintering and the emergence of grain boundaries and (c) the changes to pores as sintering proceeds.

The resulting material is then milled and sieved to provide a very fine powder that can be then used to manufacture a sintered or hot-pressed product. Prior to sintering, the powder can be pressed into the desired shape by cold-pressing in a uniaxial or isostatic press. Alternatively, for complex shapes, a process of slip casting can be used where ceramic particles are suspended in water and cast into porous plaster moulds. The water is sucked out through the pores in the porous mould over time, leaving a closely packed deposition of particles that are ready for densification.

During the sintering process, an agent is added to help in the bonding process and reduce the temperatures that are required during the sintering step. These sintering agents lead to a reduction in the mechanical properties of the ceramic because they form relatively soft grain boundaries with low melting temperatures. Smaller particles sinter much faster than coarse particles because the surface area is larger, and the diffusion distances are smaller. Furthermore, the rate of sintering varies with temperature.

Liquid-phase sintering (LPS) is commonly used to densify engineering ceramics. This process makes use of low-melting-point sintering aids that form a viscous liquid at the firing temperature. The liquid thoroughly wets the solid particles and increases the rate at which sintering occurs. When cooled, it forms a glassy phase in between the grain boundaries. Typical sintering-aid materials are compounds of silicon dioxide (SiO_2), magnesium oxide (MgO) and calcium oxide (CaO). Because the glassy phase will melt again at a relatively low temperature compared to the crystalline lattice, liquid-phase sintered materials have a compromised high-temperature strength.

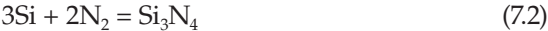
Higher densities and small grain sizes can be achieved by hot pressing. This is achieved when, simultaneously, pressure and temperature are applied to the powder. The application of pressure increases the contact stresses between particles and rearranges the particles to optimise their packing arrangement. This leads to a reduced densification time and can lead to a reduction in the temperature required to sinter – thereby reducing the amount by which the grains grow. This will lead to a final product with an increased final strength compared to a ceramic that was densified using pressureless sintering. Hot pressing can provide a near-theoretical density material with a very fine grain structure and therefore optimised strength, and therefore most suitable for armour applications. The same types of fine-grained powders suitable for pressureless sintering are usually suitable for hot-pressing applications. In most cases, a grain growth inhibitor will be added to inhibit grain growth to achieve maximum density with minimum grain size.

Hot pressing is usually conducted at temperatures of approximately half the melting temperature of the material, which is usually a lower temperature than is used with pressureless sintering, which will be approximately two-thirds of the melting temperature. But this means that careful choice of the pressing die material is made such that it can withstand the high thermal loads and thermal stresses and is sufficiently inert so that it will not react

with the ceramic powder. Graphite is a popular material for hot-pressing machinery mainly because of its high temperature capability and that it does not react with most materials. It is also suitable to heat by electrical induction. However, graphite will oxidise and therefore must be used in a vacuum or an inert atmosphere of nitrogen, helium or argon. These issues make hot-pressing machinery very expensive. A schematic of a typical hot die press is shown in Figure 7.3.

An alternative method of processing a ceramic material is by reaction bonding. Although the process has been around since the 1950s, it has only recently been used to produce armour ceramics. Two ceramics that are commonly manufactured by this method are silicon carbide and silicon nitride. With this process, densification occurs via a chemical reaction.

If pure silicon powder is heated in nitrogen gas, the following reaction occurs:



Alternatively, for reaction-bonded silicon carbide, a reaction between pure silicon and pure carbon powders can be created; thus,

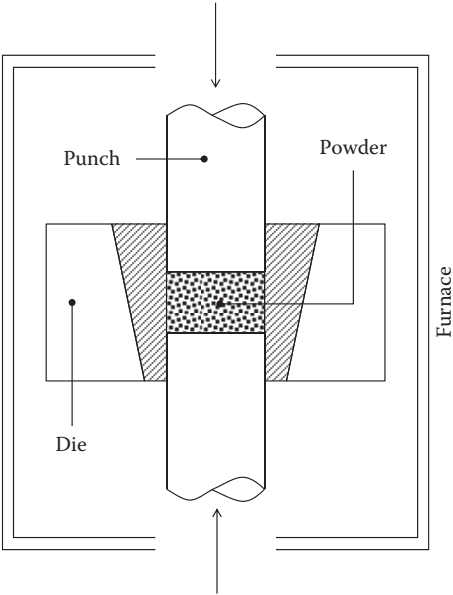


FIGURE 7.3 Schematic of hot-press system for ceramic powder densification.

Usually, reaction-bonded silicon carbide is manufactured by infiltrating a preform of silicon carbide and carbon particles with molten or vaporised silicon (Si). The silicon and the carbon react to form silicon carbide (as above), which bonds the original silicon carbide particles together. The resulting structure will be a composite of silicon and silicon carbide. The carbon is usually completely consumed.

Boron carbide can also be made from reaction bonding and has been suggested as a lightweight material for armour applications mainly because the boron carbide particles have superior properties when compared to similar-sized silicon carbide particles.

Reaction bonding has several advantages relative to other processing routes. The main advantage is that during the process, the volume change is relatively small (less than 1%), and this provides good dimensional control. Additionally, the process requires relatively low operating temperatures and no applied pressure, which reduces the operating and capital costs. The disadvantage of this approach is that, inevitably, some unreacted silicon is left behind, and therefore, the resulting ceramic is a composite of silicon and silicon carbide. Consequently, the relatively soft silicon compromises the ballistic performance. Nevertheless, there have been a number of reaction-bonded silicon carbides produced for armour applications, and ballistic penetration studies have shown that approximately 8 mm of suitably constrained reaction-bonded SiC with ~10% Si content is sufficient to defeat steel-cored armour-piercing ammunition (Hazell et al. 2005).

7.4 Properties of Ceramic

Advanced ceramics display limited plasticity at room temperature and in fact often fracture in the elastic region. Fracture toughness values for ceramics are low and much lower than predicted by theory. The reason for this is the presence of flaws within the structure that act as stress raisers, which can cause a crack to form once stress is applied. These flaws may be interior micro-cracks, internal pores or impurities. Stress raisers can even occur at the junction between neighbouring grains – which is unavoidable. In addition, boundary materials (such as the presence of a sintering aid) tend to be weaker than the grains, and therefore, they are more susceptible to failure. However, in compression, the flaws do not act as stress raisers, and therefore, much higher strengths are achievable. On average, it is found that the ceramic's strength in compression is approximately tenfold that of what it is in tension. This is good news for armour applications – as the material will be loaded in compression for at least the early stages of projectile penetration.

Compared to ductile materials, brittle materials such as ceramics exhibit a relatively broad range of stresses that cause failure in the material. This has

led to a probabilistic approach in defining failure of ceramics. The Swedish engineer Weibull (1951) proposed the following way of handling statistical variations of failure strengths. He defined the survival probability $P_s(V_0)$ in terms of two material constants, m and σ_0 . If we have a large number of identical samples of volume V_0 , then the survival probability $P_s(V_0)$ would be given by the fraction of samples that survived testing to a stress σ . This can be written as

$$P_s(V_0) = \exp \left\{ - \left(\frac{\sigma}{\sigma_0} \right)^m \right\} \quad (7.4)$$

When the applied stress $\sigma = 0$, then as expected, all samples survive, and $P_s(V_0) = 1$. As the applied stress is increased, more and more samples fail; as $\sigma \rightarrow \infty$, so $P_s(V_0) \rightarrow 0$. Further, if we set $\sigma = \sigma_0$, then $P_s(V_0) = 1/e = 0.37$. Therefore, σ_0 can be described as the stress at which we will expect to see 37% of our samples to survive. The constant m is described as the Weibull modulus, and this is a constant that defines how quickly the strength falls as we move from $P_s(V_0) = 0$ to 1. Figure 7.4 shows a Weibull distribution function for a selection of materials where $\sigma_0 = 250$ MPa, and m varies from 3 to 100. Firstly, it is possible to see that when the applied stress = 250 MPa, then the survival probability $P_s(V_0) = 1/e = 0.37$. Secondly, it is also possible to see that for the sample where $m = 3$, there is a much larger range of stresses that result in failure of samples, whereas when $m = 100$, failure of the samples occurs over a

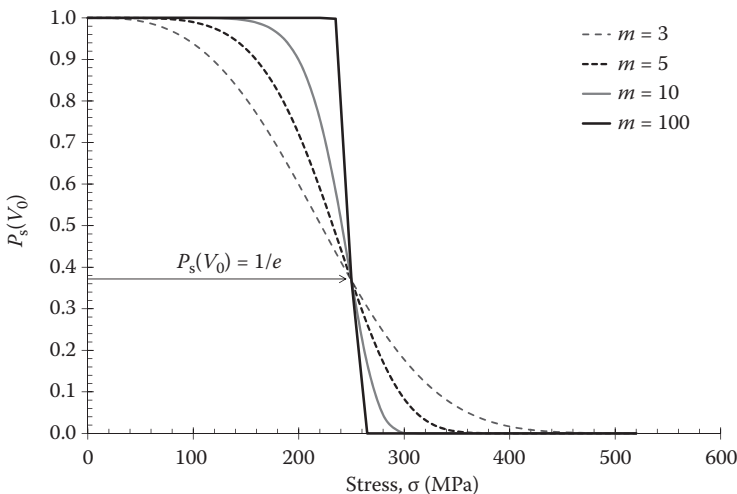


FIGURE 7.4

Weibull distribution function showing the survival probability changes due to changes in the Weibull modulus, m ; $\sigma_0 = 250$ MPa.

relatively narrow range of stresses. Advanced ceramics will have an m value in the range of 5–10, whereas metals will have an m value in the range of 90–100. Traditional ceramics such as pottery and brick will have an m value that is less than 3 (Meyers and Chawla 1999).

7.4.1 Flexural Strength of Ceramics

Ceramics are unable to be tested in a simple uniaxial tensile test like metals principally due to their incredibly low strain to failure at room temperature and their high-hardness values. Their high hardness also makes it very difficult to produce the characteristic dog bone-shaped specimen that can be produced for testing metals. A ceramic specimen is also difficult to grip without using inducing failure in the specimen. Therefore, ceramic samples are usually tested using either a three-point or four-point bend test with either cylindrical or rectangular cross sections. This method is discussed in Chapter 2. It should be noted that the three-point test configuration subjects a relatively small portion of the specimen to the maximum stress in bending. Therefore, three-point flexural strengths are likely to be much higher than four-point flexural strengths. Therefore, the four-point bending test is preferred and recommended for most characterisation purposes. A relevant standard for testing is published by the American Society for Testing and Materials International (ASTM 2013).

7.4.2 Fracture Toughness of Ceramics

The fracture toughness value for a ceramic can be calculated by the following equation:

$$K_{Ic} = Y\sigma\sqrt{\pi a} \quad (7.5)$$

This is the plane strain fracture toughness. This is for the case where the crack dimension is much smaller than the thickness of the plate. Y is a dimensionless shape factor, σ is the stress applied and a is the half-length of an internal crack. It can be seen from Equation 7.5 that for a given fracture toughness value, the larger the value of the inherent flaw, the lower the applied stress required to cause fracture.

An example of fracture toughness values for selected ceramic and glass materials is presented in Table 7.1 (after Callister 2007).

7.4.3 Fractography

There are two principle modes of cracking with polycrystalline ceramics: (1) inter-granular cracking, where the crack propagates around the grain boundaries in the weaker inter-granular material, and (2) trans-granular cracking,

TABLE 7.1

Plain Strain Fracture Toughness and Strength Values for a Selection of Glass and Ceramic Materials

Ceramic	Type	Fracture Toughness (MPa m ^{1/2})	Flexural Strength (MPa)
Aluminium oxide	99.9% pure	4.2–5.9	282–551
	96% pure	3.85–3.95	358
Glass	Borosilicate	0.77	69
	Soda–lime	0.75	69
Glass ceramic	Pyroceram	1.6–2.1	123–370
Silicon nitride	Hot pressed	4.1–6.0	700–1000
	Reaction bonded	3.6	250–350
	Sintered	5.3	414–650
Silicon carbide	Hot pressed	4.8–6.1	230–825
	Sintered	4.8	96–520

Source: Callister, W. D.: *Materials Science and Engineering: An Introduction*, 7th Edition. 2007. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

where the cracks propagate through the grains. Usually, when a ceramic fails, there will be a combination of the two failure modes, but this will depend on the packing structure and the strength of the grain boundary material.

During the initial stages of projectile penetration into a ceramic armour material, both inter-granular and trans-granular cracking are likely to occur. For resisting penetration, inter-granular cracking in the ceramic is frequently more attractive than trans-granular cracking. This is because with inter-granular cracking, the cracks have to travel along more convoluted pathways around the grains, thereby increasing the time for comminution to occur (that is, the reduction of intact ceramic to very small fragments). Furthermore, when the material is subjected to large confining pressures due to the projectile penetration, if the grains cleave in two, it is likely that the two fragments will be able to move cooperatively more readily than closely interlocked grains that have been separated by inter-granular cracking.

The maximum velocity at which cracks grow in ceramics is determined by the speed of sound of the material. After the crack tip has reached some critical terminal velocity, it will tend to divide (or bifurcate). This process will be repeated until a network of cracks has been formed in the material and the material begins to separate.

This multi-crack propagation process that results from the penetration of a projectile means that ceramics have limited multi-hit capability. However, pre-existing single cracks do not compromise the ballistic performance per se. Horsfall and Buckley (1996) showed that the ballistic limit velocity for a through-thickness pre-cracked (full width) 6-mm-thick alumina tile backed

TABLE 7.2

Ballistic Limit Data (v_{50}) for a 7.62-mm Armour-Piercing (Fabrique Nationale P80) Projectile Penetrating a Ceramic-Faced Armour (6-mm Alumina/9 mm GFRP) Showing the Results of Penetrating a Non-Cracked and Cracked Target

v_{50} Calculation	No Pre-Existing Crack in Ceramic		Pre-Existing Crack in Ceramic, Projectile Impact within 5 mm of the Crack	
	Range of Results (m/s)	v_{50} (m/s)	Range of Results (m/s)	v_{50} (m/s)
Over 6 shots	27	765	33	741
Over 8 shots	33	763	51	742

Source: Horsfall, I., and D. Buckley, *International Journal of Impact Engineering*, 18 (3):309–318, 1996.

by a 9-mm-thick glass fibre–reinforced polymer panel (17 ply, plain weave) only dropped by ~3% when penetrated by a 7.62-mm AP projectile when compared to non-cracked targets. Their ceramic tiles had a limited impact-face constraint in the form of a single layer of woven fibreglass bonded to the front surface using polyester resin. However, they noted that the effect of pre-crack was simply to increase the variability in ballistic limit data, which in turn produced a small reduction in the measured ballistic limit velocity. Their ballistic limit data (v_{50} – see Chapter 11) results are summarised in Table 7.2.

7.4.4 Hardness

For polycrystalline ceramics, as with metals, plastic deformation occurs by the motion of dislocations. One of the reasons why ceramic materials tend to be hard and brittle is the difficulty of these materials to accommodate slip (or dislocation motion). This is true for both ionic and highly covalently bonded ceramics. Consequently, it is often difficult to measure plastic deformation in ceramics at room temperature before fracture. However, it is possible to use a Vickers or a Knoop indenter (Chapter 2) to incur local plastic deformation in the sample. These methods can be used to establish the hardness of ceramic materials. Typical Knoop hardness values of ceramics are provided in Table 7.3.

7.4.5 Effect of Porosity on the Properties of Ceramics

Due to the fact that during fabrication, the precursor material is in the form of a powder, this inevitably results in porosity in the sample. The effect of porosity on the flexural strength and stiffness of a ceramic sample has been well known since the 1950s (Coble and Kingery 1956). For example, it has been shown that the porosity of certain ceramics follows the following relationship (Callister 2007):

$$E = E_0(1 - 1.9p + 0.9p^2) \quad (7.6)$$

TABLE 7.3

Approximate Knoop Hardness (100-g Load) for Several Ceramic Materials

Material	Approximate Knoop Hardness
Diamond	7000
Boron carbide (B ₄ C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminium oxide (Al ₂ O ₃)	2100
Quartz	800
Glass	550

Source: Callister, W. D.: *Materials Science and Engineering: An Introduction*, 7th Edition. 2007. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

where E is the Young's modulus, E_0 is the Young's modulus for the non-porous material and p is the volume fraction of porosity. When measuring the flexural strength of the sample, porosity also affects the strength of the ceramic. This is for two principle reasons:

1. The pores themselves reduce the cross-sectional area of the material carrying the load.
2. They act as a stress raiser to the extent that for an isolated spherical pore, the applied tensile stress is effectively doubled.

Experimentally, it has been shown that the flexural strength decreases exponentially with porosity (p) according to (Callister 2007)

$$\sigma_{fs} = \sigma_0 \exp(-np) \quad (7.7)$$

where σ_0 is the non-porous strength, and n is an experimental constant. In Figure 7.5, the effect of porosity on the transverse strength of an alumina sample is clearly seen from the data presented by Coble and Kingery. Here, the best fit to the experimental data in SI units is given by $\sigma_0 = 195.6$ MPa and $n = 3.6$. They tested alumina samples of 5%–50% porosity with comparable grain sizes and showed that the strength and stiffness reduced markedly as the volume fraction of porosity was increased.

Ultimately, this has implications for ceramic armour in that increased porosity will lead to increased probability of fracture in compression (as the bullet penetrates into the samples and collapses the pores) and failure in tension as stress waves are reflected off the free surface of the ceramic to produce tensile waves. Therefore, ceramic armour materials tend to be processed so as to minimise the extent of porosity.

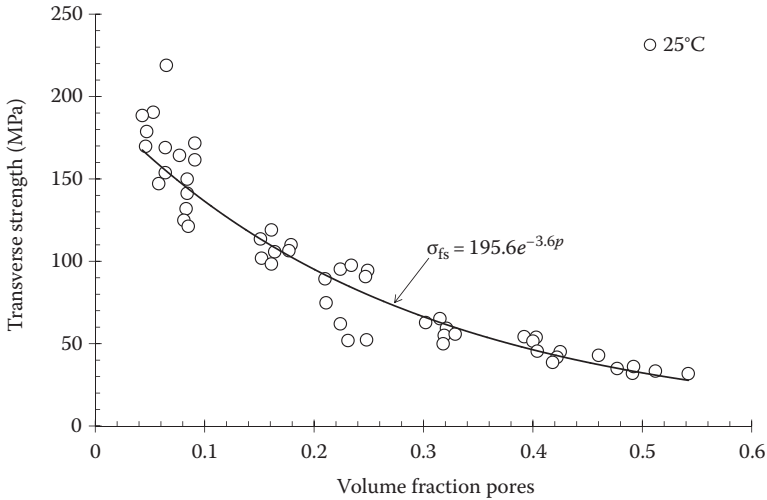


FIGURE 7.5

Effect of porosity on transverse strength on alumina samples at 25°C. (Adapted from Coble, R. L., and W. D. Kingery, *Journal of the American Ceramic Society*, 39 (11):377–385, 1956.)

7.5 Early Studies on Ceramic Armour

Patents for a ceramic-based armour were filed by the Goodyear Aerospace Company, with the first filed in 1963 and granted in 1970 (Cook 1970; Cook et al. 1979). The initial patent application detailed a ceramic-faced armour composed of an alumina facing attached to a woven substrate (see Figure 7.6). Subsequent research into the mechanics of ceramic-armour penetration was carried out by Wilkins (1967, 1968), Wilkins et al. (1967), Florence and Ahrens (1967) and Florence (1969).

Wilkins recognised that in order to optimise a two-component ceramic armour system, it is necessary to understand the interaction between the target and the projectile. Using high-speed photography, flash x-ray and numerical modelling techniques, they were able to evaluate the ballistic failure processes.

From their numerical simulations of a sharp steel projectile impacting an 8.64-mm alumina tile backed by 6.35 mm of aluminium at 853 m/s, they deduced the following:

- During the initial stages of penetration (0–9 μ s), the projectile tip is being destroyed, and the back plate yields at the ceramic interface. A crack is initiated at the rear surface of the ceramic as it tends to follow the motion of the backplate. This grows in magnitude in the

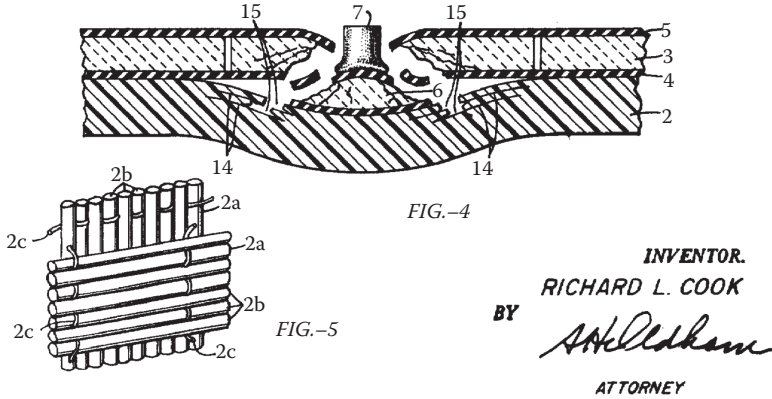


FIGURE 7.6
R. L. Cook's ceramic-faced armour from 1963. (From Cook, R. L., *Hard-Faced Ceramic and Plastic Armor*, Delaware, Goodyear Aerospace Corporation, 1970.)

direction of the impact face. Furthermore, a fracture conoid grows from the interface between the projectile and the target and grows in the direction of the projectile travel.

- Between 9 and 15 μ s, the projectile is eroded, and the ceramic has become rubble by multiple cracks intersecting and coalescing. The projectile erodes by a process of yielding and plastic flow in a direction perpendicular to the projectile travel. Erosion takes place because the stress level in the projectile is greater than the material strength of the projectile. Approximately 40% of the projectile mass and initial energy are carried off by eroded projectile material.
- After 15 μ s, the erosion of the projectile ceases, and the remainder of the energy in the target-projectile system is absorbed by the backplate.

An energy balance analysis of ballistic penetration, referring to the above events, is shown in Figure 7.7.

7.6 Cone Formation

One of the notable and helpful factors in offering resistance during ceramic armour penetration is the cone of damage that is produced ahead of the penetrator. An example is captured by Cook's early patent and shown in Figure 7.6. Sometimes, a cone is formed that remains intact, and these have been seen to evolve in real time in glass (Chaudhri and Walley 1978). Cone formation

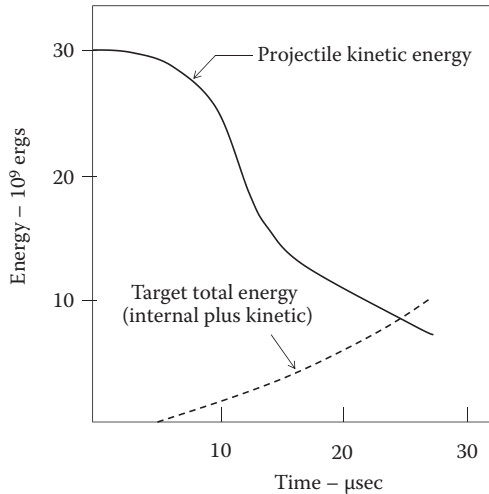


FIGURE 7.7

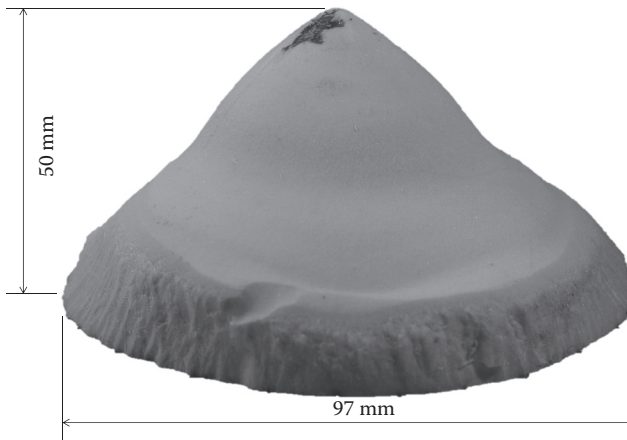
Energy versus time for an impact at 2800 ft./s (853 m/s) of a sharp steel projectile with an AD85-faced aluminium target; 1 erg = 10^{-7} J. (Adapted from Cline, C. F., and M. L. Wilkins, The importance of material properties in ceramic armor, *Proceedings of the Ceramic Armour Technology Symposium*, Columbus, OH, 29–30 January, 1969.)

is also a characteristic of quasi-static indentation. They follow paths of maximum tensile stress in the material that were first plotted by Hertz (1882, 1896a,b). An example of such a cone is provided in Figure 7.8. Here, a steel bullet was fired at a thick tile of alumina (50 mm thick). The cone is seen to broaden at its base, and this is due to the stress wave interactions from the free-surface reflections. Note too that, in this case, the diameter of the base of the cone is approximately twice the thickness of the tile.

The advantage for the ceramic armour is that the formation of the cone spreads the load of the projectile over a wider surface area. Therefore, essentially, the kinetic energy density of the projectile is reduced. A much tougher and ductile layer is then placed at the rear of the ceramic to ‘catch’ the cone and the projectile fragments.

7.7 High-Velocity Impact Studies

The high-velocity impact of ceramic materials has gained considerable interest in recent years in the drive to provide better protection against tank rounds and shaped-charge jets. The experiments designed for rods have usually involved the use of the reverse-ballistic technique (essentially, where the ‘target’ is launched toward the ‘projectile’ – see Chapter 11). For tungsten

**FIGURE 7.8**

Ceramic cone produced from an impact from a bullet into a thick block (50 mm) of alumina.

alloy penetrators impacting steel, fully hydrodynamic penetration will not occur until an impact velocity of ~ 3 km/s. The penetration that is achieved at this velocity is known as the 'hydrodynamic limit'. Up to this velocity, the strength of the target is important and therefore acts to decelerate the rod. However, the required velocity for full hydrodynamic interaction (where the target and the projectile interaction is assumed to behave in a fluid-like fashion) depends on the materials and for ceramic can be many kilometres per second (Kozhushko et al. 1991), and therefore, this type of penetration regime will only be approached by very-high velocity rod projectiles and shaped-charge jets. At 5 km/s, the penetration is still substantially less than that which is predicted by hydrodynamic theory as the results, as presented by Franzen et al. (1997), show (see Figure 7.9).

Shockey et al. (1990) investigated the long-rod penetration of a variety of ceramic materials by firing tungsten–nickel–iron penetrators at confined ceramic targets. The velocities of the projectiles ranged from 0.8 to 1.4 km/s and therefore far below the hydrodynamic threshold discussed previously in this section. Nevertheless, Shockey's results inform how ceramic armour would respond when subjected to impact from a tank-fired armour-piercing rod. Post-mortem analysis of the ceramics revealed that tensile fracture occurs soon after impact, close to the rod periphery. They built up a picture of the penetration process, which is summarised as follows. The stress fields are initially elastic, and the largest tensile stresses are in the radial direction. Therefore, the cracks that form are ring cracks concentric about the impact site. These cracks initially grow to approximately 1 mm below the surface. From these ring cracks, several large Hertzian cone cracks extend throughout the block, assuming trajectories 25° – 75° from the initial normal-to-the-surface direction. As the rod continues to advance, the compressive strength is exceeded in the

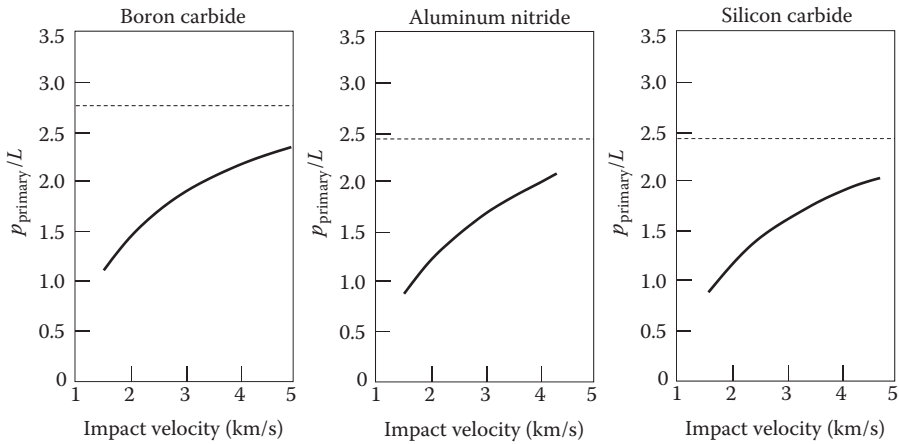


FIGURE 7.9

Primary penetration depth normalised by penetrator length for three different ceramics (dashed lines from hydrodynamic theory). (Reprinted from *International Journal of Impact Engineering*, 19 (8), Franzen, R.R. et al., 727–737, Copyright 1997, with permission from Elsevier.)

material directly below the penetrator. Microcracking occurs in a shallow zone near the penetrator tip, and the stress field changes in character. The principal tensile stresses are now hoop stresses that invoke 6–12 large radial cracks propagating outward from the impact centre like spokes in a bicycle wheel. A fourth type of crack finally develops beneath the impact surface and runs parallel to it. These intersect cone and radial cracks to form the residual crater and to produce fragmentation with a large proportion of the projectile's kinetic energy being converted to the kinetic energy of the fragments.

7.8 Studies on the Subject of Dwell

There appeared to be little interest in ceramic armour during the 1970s after the work of Wilkins; however, Cold War pressures meant that there was to be a resurgence in interest in ceramic armour during the early 1980s. One of the more notable discoveries during that period was that under certain ballistic loading conditions, the projectiles could be seen to 'dwell' on the surface of the ceramic (Hauer et al. 1992). These targets were mostly highly confined, thick targets to reduce the propensity of tensile (release) waves propagating into the penetration zone, thereby exacerbating failure. Studies in dwell are of great interest as they may provide a route to enhancing the performance of ceramic armours. Ceramic 'dwell' occurs when a high-velocity projectile impacts a ceramic target and flows out radially with little significant penetration. When the projectile is completely eroded at the ceramic's surface,

this is called ‘interface defeat’. Notably, Wilkins had previously observed similar behaviour with small-arms bullets with very thick (75 mm) alumina targets (Holmquist et al. 2010).

An example of dwell in small-arms bullets has been demonstrated by Wilkins using flash x-ray. A sequence of flash x-ray radiographs of the penetration sequence for a surrogate 7.62-mm APM2 bullet is shown in Figure 7.10. It can be seen from the sequence that penetration does not occur for the first 20 μs . Instead, the tip of the projectile is progressively blunted. After 15.8 μs , a certain degree of penetration occurs; however, the radial flow of the penetrator is extensive. Eventually, it is possible to see some evidence of conoid formation (at 25.2 μs), which appears to have a relatively large included angle. This is most likely due to the large contact area between the projectile and the ceramic due to the presence of the radially extended projectile material. Ultimately, the extended elements break off, and the projectile continues to penetrate (35.5 μs).

Dwell has also been observed with transparent armour systems. Straßburger (2009) showed that using a thin (4 mm) layer of sub-micrometre grain-sized

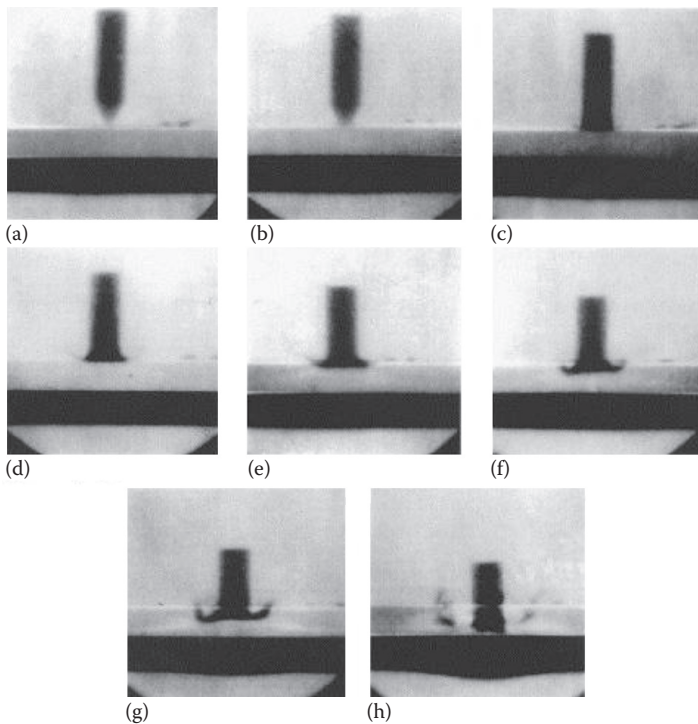


FIGURE 7.10

Flash x-ray shadowgraphs of AP surrogate projectile impacting 7.24-mm B4C/6.35-mm 6061-T6 at 701 m/s. Penetration after (a) 1.8 μs , (b) 3.8 μs , (c) 8.9 μs , (d) 11.8 μs , (e) 15.8 μs , (f) 19.8 μs , (g) 25.2 μs and (h) 35.5 μs . (Reprinted from *International Journal of Impact Engineering*, 31 (9), Anderson, Jr., C. E., and J. D. Walker, 1119–1132, Copyright 2005, with permission from Elsevier.)

alumina added to a transparent armour (3×9 mm of borosilicate glass with a 3-mm polycarbonate backing) resulted in a dwell phase that lasted approximately $10 \mu\text{s}$. In this case, the projectile was a 7.62×51 mm armour-piercing (steel-cored) projectile; the impact velocity was 850 m/s. It has also been seen in strong bullet cores made from tungsten carbide. In this case, the projectiles were penetrating silicon carbide (Hazell et al. 2013). Figure 7.11 shows the stages of penetration. By $19.2 \mu\text{s}$ after impact (Figure 7.11b), the strong tungsten carbide core is seen to flow out radially from the central penetration axis in a fashion previously seen by Wilkins with a steel-cored projectile. There is also evidence of conical fracture due to the way in which the projectile is flowing in the target. Ultimately, by $28.2 \mu\text{s}$ (Figure 7.11c), the core has been completely destroyed.

With high-velocity rods, the majority of the work has been carried out with small-scale projectiles using the reverse-ballistic techniques mentioned in Section 7.7 (with the exception of G. E. Hauver's initial findings, e.g. Hauver et al. [1992]). These studies have mostly focused on borosilicate glass (Anderson, Jr. et al. 2010), boron carbide (Lundberg et al. 1998), silicon carbide (Lundberg et al. 2000, 2001; Lundberg and Lundberg 2005), alumina (Espinosa et al. 2000) and titanium diboride (Espinosa et al. 2000; Lundberg et al. 2000).

It has been shown that below a certain threshold velocity, the strength of the ceramic during the ballistic event appears relatively high. As a result, the material of the penetrator flows outwards in a radial fashion without significant penetration of the ceramic material. Also, above a threshold velocity, the ceramic behaves as if its strength is reduced, and normal penetration ensues. That is to say that sufficient damage is accumulated at the tip of the penetrator allowing for penetration. This interface-defeat-to-penetration transition behaviour is observed over a fairly narrow range of ordnance velocities (Lundberg et al. 2000). Interface defeat is also more likely when the ceramic is confined with the confinement being of a good acoustic impedance match to the ceramic (Hauver et al. 1992) and offering sufficient rear-face support to prevent the flexure of the ceramic during ballistic loading. The extent of penetrator dwell is also determined by the geometry of the target – with

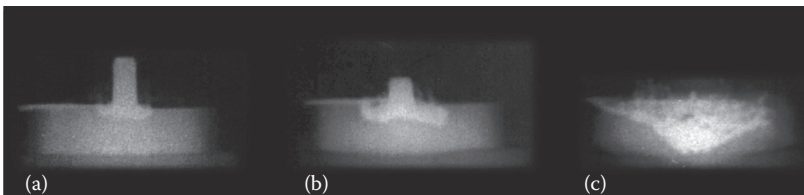


FIGURE 7.11

Series of radiographs of an FFV (tungsten carbide) core completely penetrating a ceramic-faced projectile. Timings (from core contact) were as follows: (a) $10.2 \mu\text{s}$, (b) $19.2 \mu\text{s}$ and (c) $28.2 \mu\text{s}$. (Reprinted from *International Journal of Impact Engineering*, 54, Hazell, P. J. et al., 11–18, Copyright 2013, with permission from Elsevier.)

semi-infinite targets exhibiting more dwell than thin targets. This is due to the return of tensile release waves from the rear surfaces occurring over a shorter time period in the thin targets than with relatively thick semi-infinite targets.

Work has also focused on the use of buffer plates to elucidate the mechanisms of dwell (Holmquist et al. 2010). Although it is known that specially designed cover plates extend the dwell time for SiC targets (Lundberg et al. 2001), it has been shown that using Cu buffer plates can lead to an increase in the impact velocity that requires the dwell-to-penetration transition to occur. The reason for this is that the buffer plate attenuates the shock from the projectile thereby leading to a (relatively) gradual loading profile on the surface of the ceramic (Holmquist et al. 2005). Similar results have also been seen by encapsulating the projectile in polycarbonate (Malaise et al. 2000).

The exact microstructural mechanisms of penetrator dwell are not well understood, although the effect has been successfully modelled using macroscopic pressure-hardening and strain-dependent damage laws (Holmquist and Johnson 2002a) suggesting that some kind of pressure hardening of the intact (or indeed, failed) material is occurring. It is also thought that when confined pressures are applied, certain ceramics exhibit ductility. Therefore, if sufficient confining pressure is realised during the penetration event, the ceramic can accommodate relatively high strains.

7.9 Shock Studies in Ceramic Materials

The shock response of ceramic materials has also been of interest in recent years, although it is debatable whether the target is shocked during a ballistic impact. There is, however, a small 1D zone that exists at the penetrator/target interface that can lead to the formation of shocks. Nevertheless, these would be quite short-lived. Despite all of this, carrying out 1D strain-type experiments can inform the researcher on the mechanics of ceramic yield and failure at high rates of strain. In particular, the transition from elastic behaviour to plastic flow has captured some interest in recent years.

Probably the three most important properties that can be gleaned from plate-impact test are the following: the dynamic shear strength, the Hugoniot elastic limit (HEL) and the spall strength. The HEL (which represents the yield strength under 1D strain conditions, in metals at least) is the transition from elastic to inelastic behaviour as a compression wave propagates through the material. However, in ceramics, it was widely accepted that this is the point that microcracking began. This viewpoint has been challenged by some researchers who have found evidence of damage within the elastic region (Rosenberg and Yeshurun 1985; Louro and Meyers 1989).

The HEL, which is a measure of strength in 1D strain conditions, is important for ballistic applications in that it can be used to calculate the dynamic yield strength (Y_d) in 1D stress conditions and compared to yield strengths from universal testing machine results. This is achieved knowing the Poisson's ration, ν ; thus,

$$Y_d = \frac{(1-2\nu)}{(1-\nu)} \sigma_{\text{HEL}} \quad (7.8)$$

where σ_{HEL} is the HEL of the material that would have been measured under uniaxial strain conditions.

This in turn has been historically linked to performance of a selection of ceramic tiles by Rozenberg and Yeshurun (1988) by correlating ballistic performance with average yield strength, which is an average of the quasi-static (Y) and dynamic values, viz.,

$$\bar{Y} = \frac{Y + Y_d}{2} \quad (7.9)$$

7.10 Modelling Ceramic Impact

7.10.1 Computational Modelling

Computational modelling affords the opportunity to enhance our understanding of the physics of projectile and target interaction. In brief, generally speaking, these codes solve the conservation laws of mass and momentum based on initial boundary conditions. The user is prompted for an equation of state that describes the pressure in terms of the internal energy and volume and a constitutive relationship that calculates the flow stress in terms of a number of material-dependent parameters including strain, strain rate and temperature. Failure models can be introduced to describe the failure. This latter contribution is often the tricky part for ceramic-based models.

There are several different types of constitutive models and approaches that are used to simulate the dynamic behaviour and failure of ceramic materials. One of the more widely used models that has been developed and used for understanding the physics of projectile/ceramic interaction was developed by Johnson and Holmquist, and therefore, a brief review is provided here. This model is one of the more elegant of the approaches available and is easily applied in continuum codes such as ANSYS® AUTODYN. The model has evolved somewhat since the original 1992 formulation; a summary of the models is found in Table 7.4.

TABLE 7.4

The Johnson–Holmquist Models

Year	Model	Description	Ref.
1992	JH-1	Instantaneous drop in strength only when material is deemed to be fully damaged through the accumulation of plastic strain; piecewise description of the strength	Johnson and Holmquist 1992
1994	JH-2	Gradual softening from intact to damaged strength curves as damage accumulates; analytical description of the strength	Johnson and Holmquist 1994
2003	JHB	Similar strength behaviour to JH-1; accommodation of a phase change	Johnson et al. 2003

A brief description of the JH-1 model is given as follows: The schematic illustration of the JH-1 model from Johnson and Holmquist (1992) and Holmquist and Johnson (2002b) is shown in Figure 7.12. The intact material strength is described as the linear segmented curve where the equivalent stress is a function of pressure. Any increase in the strain rate under a given pressure increases the equivalent stress and therefore makes the material stronger. This is done according to

$$\sigma = \sigma_0(1.0 + C \ln \dot{\epsilon}) \tag{7.10}$$

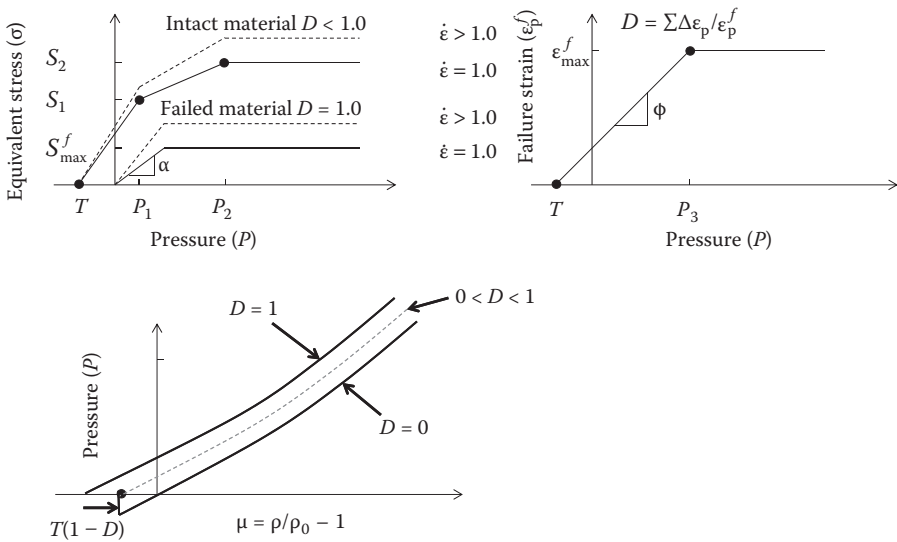


FIGURE 7.12

JH-1 formulation typically used for silicon carbide. (Reprinted with permission from Holmquist, T. J., and G. R. Johnson, *Journal of Applied Physics*, 91 (9):5858–5866, 2002b. Copyright 2002, American Institute of Physics.)

where $\dot{\epsilon}$ is the strain rate, σ is the equivalent flow strength, σ_0 is the available strength at $\dot{\epsilon} = 1.0$ and C is the strain rate constant. When damage to the ceramic occurs, the equivalent stress for a given pressure reduces, and consequently, the material becomes weaker. Damage (D) is defined as the ratio of the total accumulated increment of plastic strain and the equivalent failure strain. The material fails when either pressure reaches the tensile limit T , or damage D is equal to 1.0. After the material has failed, it cannot withstand any tensile loading but can still withstand a limited compressive loading. Further, an additional pressure contribution can be added to the equation of state to simulate the bulking of the material due to the formation of fracture surfaces.

There have been several papers dealing with the subject of ceramic armour penetration; however, it should be pointed out that of the 14 constants that are required for the Johnson–Holmquist formulation, 2 have to be established through calibration with ballistic trials data. These two constants (for the strength of the failed material and the damage parameter, ϕ) also have a dramatic effect on the ceramic's propensity to dwell, and consequently, caution should be exercised in interpreting the data.

Other approaches to modelling the dynamic response of the continuum sense have included using simplified linear elastic fracture mechanics (Hazell and Iremonger 1997, 2000), which provide a moderate degree of correlation with experimental results. These models allow damage to grow through the propagation of cracks into neighbouring computational cells through the accumulation of a scalar damage parameter.

7.10.2 Modelling Comminution

Comminution is the break-up of the ceramic into very small fragments, and these fragments can interact with one another during the ballistic penetration process. The importance of this process in understanding the ballistic penetration processes of ceramic materials was underlined by Curran et al. (1993) who developed a micromechanical model for comminution and granular flow of brittle materials. From their model, they inferred that the most important ceramic properties that govern the depth of penetration into thick ceramic targets were the friction between comminuted granules, the unconfined compressive strength of the intact material and the compaction strength of the comminuted material. In addition, it has been noted from the experiments of Shockey et al. (1990) that properties such as the dynamic compressive failure energy and the friction, flow and abrasive properties of the comminuted material govern the penetration resistance of thick confined ceramics. Indeed, it was observed during high-velocity rod penetration experiments into thick ceramic sections that the comminuted material produced at the leading edge of the rod flowed around and behind the rod, closing the hole made by the rod. Hardness and scratch tests indicated strengths of the compacted powder comparable to that of the unimpacted material.

So how can such behaviour be simulated? Well, a good start is to try and assess the shear strength of powder compacts at various pressures and use these as an analogue for the comminuted material. However, one must be cautious here as comminuted ceramic starts off as highly interlocked fragments, whereas purchasing ceramic powder off the shelf and compacting it will result in a material with lots of voids and broken edges (see Figure 7.13). This material is more representative of the material that flows away from the rod during penetration. Nevertheless, it is a good start.

There have been several studies examining the properties of damaged ceramic material under both dynamic and quasi-static loading conditions in an attempt to understand the behaviour of the comminuted material. Horsfall et al. (2010) have examined the impact behaviour of explosively shattered alumina and compressed ceramic powder using an instrumented drop-weight tower and ballistic experiments. They showed that the elastic stiffness of the highly fractured alumina tile was reduced to ~ 130 GPa by the explosive loading process as compared to the intact tile's modulus of 330 GPa. Further, they noted that the ballistic efficiency of the fractured material was approximately 70% of the monolithic tile.

Another way of deriving a constitutive model for the comminuted material is by performing experiments, modelling those experiments assuming a type of constitutive model and changing the parameters of the model until the computational results fit with the experiments. Anderson, Jr. et al. (2008) presented the experimental results of the penetration of an Au rod

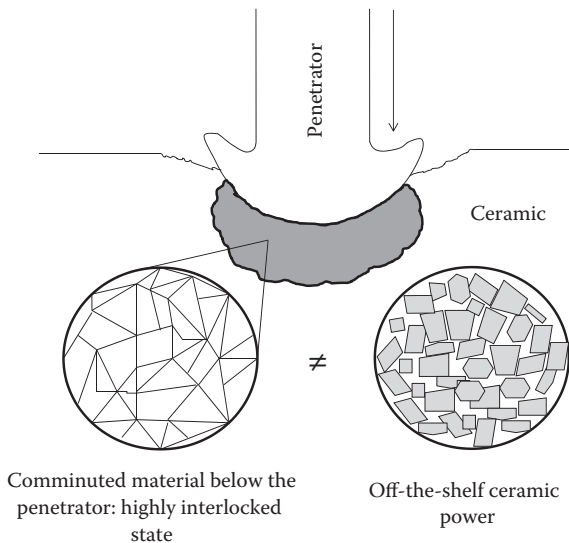


FIGURE 7.13

Penetration of a ceramic: comparison between the highly interlocked state and example of a material that one can buy off the shelf. They are not equivalent.

into both pre-damaged SiC and compacted powder. For the pre-damaged ceramic targets, they compared the experimental results with computational simulations to develop a Drucker–Prager relationship for the material. The Drucker–Prager relationship was originally developed for studying the behaviour of soils under pressure (Drucker and Prager 1952) but has been used to describe the behaviour of a range of granular materials. In terms of the equivalent stress (or von Mises stress, σ_{eq}), the Drucker–Prager equation can be written as

$$\sigma_{eq} = a + b \cdot P \quad (7.11)$$

where a and b are material constants, and P is the pressure. Some materials exhibit a cap in their strength as the pressure is increased, and therefore, in this specific case, Equation 7.11 holds true until the cap (Y_{max}) is reached and then $\sigma_{eq} = Y_{max}$ until the pressure is released.

Based on the Drucker–Prager relationship, there have been several parameters established either by experimentation or by matching computations with experimental results. Examples of these are summarised in Table 7.5 along with the way they were found.

Further work has been presented in Anderson et al. (2009) that suggests that the Drucker–Prager formulation is not adequate to describe the in situ comminuted ceramic material. Chocron et al. (2005) also developed a similar constitutive model for damaged silicon carbide. By using mechanical testing in conjunction with elasticity theory, they reported a Drucker–Prager relationship for the pre-damaged silicon carbide and a linear (pressure-dependent) model for silicon carbide powder. Their results are presented in Table 7.5.

Other works that have sought to elucidate a constitutive relationship for comminuted ceramic material have involved the use of triaxial tests on damaged materials and powder compacts. Good examples are presented by Wilkins et al. (1969), Meyer and Faber (1997), Zeuch et al. (2001) and Anderson, Jr. et al. (2012).

TABLE 7.5

Drucker–Prager Relationships for Broken Ceramic and Powdered Materials

Reference	Material Type	a (GPa)	b	Y_{max} (GPa)	How It Is Derived
Anderson, Jr. et al. 2008	In situ comminuted ceramic ^a	0.0455	2.7	2.56	Ballistic penetration experiments
	In situ comminuted ceramic ^a	1.0	0.5	–	Ballistic penetration experiments
Chocron et al. 2005	Fractured SiC	0.028	2.5	–	Mechanical testing and elasticity theory
	SiC powder	–	1.1	–	Mechanical testing and elasticity theory

^a Thermally shocked and cyclically loaded to induce damage in a ceramic.

7.10.3 Analytical Formulations

Florence (1969) derived an analytical model that provided a reasonable estimate for the ballistic limit velocity that could be achieved by using a two-component ceramic-faced armour. His approach was as follows:

- The projectile is assumed to be a non-deforming rigid body.
- The backing layer is assumed to behave as an elastic membrane of uniform mass that is fixed at the periphery of the base of the cone that is formed in the ceramic.
- The base of the (Hertzian) cone that is formed on impact is roughly equal to half the calibre of the projectile plus two times the thickness of the ceramic tile. (This was based on experimental observations – although it should be pointed out that conoid dimensions are largely dependent on the relative properties of the impactor and the target. Nevertheless, Figure 7.8 suggests that this is not far off the mark.)
- The kinetic energy of the projectile is equated to the work done in stretching a membrane until it reaches the breaking point.

Using this approach, the following expression is derived that describes the ballistic limit velocity for the system:

$$v_{50} = \left(\frac{S \cdot \varepsilon}{0.91 \cdot m \cdot f(z)} \right)^{\frac{1}{2}} \quad (7.12)$$

where $S = \sigma \times t_2$, σ is the breaking stress of the back plate, t_1 and t_2 are the thickness of the front and back plates, respectively, m is the projectile mass and ε is the breaking strain of the back plate. Furthermore,

$$f(z) = \frac{m}{(m + (t_1 \cdot \rho_1 + t_2 \cdot \rho_2)\pi \cdot z^2)\pi \cdot z^2} \quad (7.13)$$

where $z = r + 2t_1$, r is the radius of the projectile, which is cylindrical in shape, and ρ_1 and ρ_2 are the densities of the front plate and backplate, respectively.

This model has been used by Hetherington (1992) to predict the optimum ratio of front tile to backing plate tile thickness for an alumina-faced aluminium-alloy composite-armour system. It was around 2.5. Further, validation was carried out using a non-deforming armour-piercing projectile (7.62 × 51-mm FFV) that was fired at a target comprising various thicknesses of Sintox™FA (alumina) ceramic backed by a 5083 aluminium plate. For each validation shot, the areal density was kept the same (approximately 50 kg/m²). Good correlation was noted between the experimental and analytical results (see Figure 7.14).

Of course, it should be noted that the above model does not take into account the relative hardness values of the projectile and the target, and therefore, it

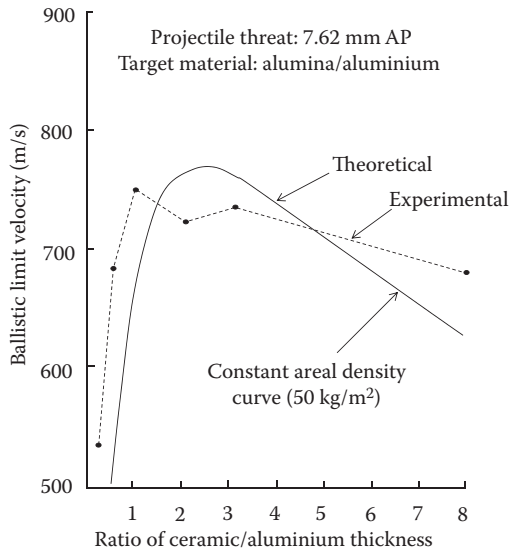


FIGURE 7.14

Dependence of v_{50} on ceramic/aluminium thickness for constant areal density – comparison of theoretical and experimental results. (Reprinted from *International Journal of Impact Engineering*, 12 (3), Hetherington, J. G., 409–414, Copyright 1992, with permission from Elsevier.)

cannot discriminate between ceramics and projectiles of different mechanical strengths. However, it can provide a very helpful approximation of the velocity required to perforate a two-component ceramic-faced armour.

7.11 Current Application and Challenges

7.11.1 Ceramic Material Choices

In many cases, the choice of the ceramic material that is purchased is determined by cost as well as performance. It is very difficult to put an absolute price on ceramic materials because it will vary depending on the quantity and the size and shape of the tiles that are required. However, if a 98% liquid phase-sintered alumina is taken as a baseline material, then Table 7.6 gives some indication of the relative costs of these materials for armour applications.

Alumina (Al_2O_3) has been the benchmark ceramic for a number of years and in its sintered state is a relatively cheap ceramic to manufacture compared to its non-oxide hot-pressed rivals. However, it possesses a relatively low hardness and high density compared with the silicon carbides and boron carbides. High-purity alumina (~99.5%) is the hardest and provides the most weight-efficient protection against hard-cored AP rounds.

TABLE 7.6

Relative Cost of Ceramic Materials for Armour Applications

Ceramic	Bulk Density (kg/m ³)	Hardness (HV)	K _{1c} (MPa m ^{1/2})	Relative Cost
98% Al ₂ O ₃	3800	1600	4.5	1.0
RB SiC	3100	1200/2200	~4.5	2.5
Sintered SiC	3150	2700	3.2	4.5
HP SiC	3220	2200	5.0	9.0
HP B ₄ C	2520	3200	2.8	16.0

Source: Roberson, C., Ceramic materials for lightweight armour applications, *Proceedings of the Combat Vehicle Survivability Symposium*, RMCS, Shrivenham, UK, 8–10 December, 2004.

Silicon carbide (SiC) is becoming more common in the design of armour systems because of its superior mechanical properties to those of alumina. Silicon carbide powders are commercially produced by the reaction of a mixture of SiO₂ (sand) and coke. The resulting compound possesses a very strong covalent bond that makes sintering difficult, and therefore, special processes have to be applied to manufacture high-density silicon carbide. Silicon carbide for armour applications can be made via three routes: pressureless sintering, hot pressing and reaction bonding. Pressureless sintering is a common yet relatively difficult process to undertake as it requires firing temperatures in excess of 2000°C. Hot pressing provides a very-high-performing ceramic for armour applications, but the cost is high (as discussed previously). Conversely, reaction bonding is a relatively cheap method of manufacture, but the ballistics performance of these ceramics is relatively poor.

Boron carbide (B₄C) was one of the original ceramic materials that were used in armour applications. It is similar to silicon carbide in that the most useful form of this material is produced via the hot-pressing route, although some boron carbide samples have been made for armour applications by reaction bonding. It has been shown that despite its promise of a very high hardness and relatively low density compared to other ceramics (2.5 g/cc), boron carbide does not perform well when subjected to very high shock stresses due to rapid brittle failure and hence strength degradation. In fact, at sufficient shock stress levels, its performance is not much better than a sintered alumina.

Titanium diboride (TiB₂) is a relatively dense ceramic (4.5 g/cc) that is normally hot-pressed mainly because it is difficult to sinter. TiB₂ is a very-high-performing ceramic but is relatively expensive – some three to four times that of hot-pressed silicon carbide. This material is electrically conductive, which has the benefit of being able to be machined using electro-discharge methods, which is very handy because it is notoriously difficult to grind in its hot-pressed form.

Tungsten carbide (WC) has also shown some promise as an armour material because of its relatively high hardness (Gooch et al. 2000). However, in

many cases, it is an unusual choice of ceramic for armour applications mainly because of its relatively high density. Nevertheless, against tungsten-alloy rods in a semi-infinite DOP-type target arrangement, it has demonstrated a performance that is better than RHA on a weight-by-weight basis and thickness. Most tungsten carbides that are produced today are in fact cermets – that is, an alloy of a ceramic and metal binder such as cobalt or nickel. These cermets are frequently used in ammunition design and are frequently manufactured by LPS. However, for the fully dense WC ceramic (15.7 g/cc), Cercom Inc. have developed a hot-pressing route that produces a 99.6% pure ceramic. This material is electrically conductive (like TiB_2) and can therefore be machined using electro-discharge methods.

Aluminium nitride (AlN) is an interesting material that is becoming widely used in the electronics and semiconductor processing industries. This material can be made using the pressureless sintering route; however, the best quality materials are hot pressed. It is believed that this material undergoes a brittle-to-ductile transition at elevated strain rates.

Silicon nitride (Si_3N_4), like silicon carbide, can be formed through the reaction-bonding process where shaped silicon powder is fired in a nitrogen-rich environment. However, the porosity of the product manufactured in this way is relatively high and therefore renders the material inappropriate for ballistic applications. Nevertheless, silicon nitride can be sintered or hot pressed and has found some niche applications in defeating small arms. However, against hard-cored AP projectiles, its performance is similar to a high-quality alumina.

7.11.2 Ceramic Armour Applications

It should be no surprise to the reader that ceramic-based armours have been extensively used in protective structures such as helicopter seats, helicopter floor plates, engineering vehicles, armoured fighting vehicles, body armour and so on.

The first battle use of ceramic armour technology was in US helicopters during the Vietnam conflict where low-level sorties made the helicopter and crew vulnerable to small-arms fire. Therefore, in 1965, the first ceramic-based aircrew body armour vest was manufactured as this was the most weight-efficient means of providing protection (Rolston et al. 1968). Also, in 1965, the UH-1 'Huey' was fitted with a 'hard-faced composite' armour kit used in the armoured seats for the pilot and co-pilot. The seats provided protection against 7.62-mm AP ammunition on the seat bottom, sides and back using a boron-carbide-faced fibreglass. Similar systems were installed on AH-1 Cobra helicopter gunships. In 1966, the first monolithic ceramic body armour vest was issued to the helicopter crews along with other protection improvements including the use of airframe-mounted armour panels. It has been estimated that, between 1968 and 1970, these improvements in aircrew armour reduced the number of non-fatal wounds by 27% and fatalities by 53% (Dunstan and Volstad 1984).

In the 1980s, the majority of the ceramic-based armour systems that were used in battlefield applications used alumina. Alumina is relatively inexpensive to manufacture, and even quite thin sections can stop high-velocity small-arms bullets. Whereas, when silicon carbide and boron carbide systems are used, the added ballistic performance (against small-arms projectiles) is small for considerable additional cost. Although the curve has changed somewhat since the 1980s, the lesson is still the same. There is a high cost trade-off for a relatively small improvement in ballistic performance. Nevertheless, the advantage of added ballistic protection (albeit small) can be attractive if minimal weight is required – such as in aircraft or body armour systems.

Boron carbide is a high-performing material. Nevertheless, apart from the incredible hardness that this material possesses and its low density, it does have one potential drawback. In recent years, there has been some evidence to suggest that this hard and strong material has been shown to not perform as well as expected when penetrated by high-velocity dense-cored bullets. This is thought to be due to physical changes that occur to the material when subjected to a high shock stress that is induced by these rounds (Chen et al. 2003). In fact, when tested with a semi-infinite aluminium backing material, there is some evidence to suggest that against specific tungsten–carbide-based projectiles, certain grades of boron carbide perform just as well as alumina targets (Roberson et al. 2005). This is despite boron carbide's superior hardness. It has also been found that when boron carbide is bonded to a high-performance fibre-reinforced laminate, a 'shatter gap' phenomenon occurs (Moynihan et al. 2002), that is, where two v_{50} velocities are found (see Chapter 11). The discovery of two v_{50} velocities has traditionally been attributed to a transition from intact projectile perforation of the target to shattered projectile defeat of the target at higher velocities. However, Moynihan et al. has showed that the upper v_{50} velocity of a boron carbide-faced composite occurs with a change in fragmentation behaviour of the ceramic. Nevertheless, the upshot from these results means that the thickness of the boron carbide plate is required to be higher than originally anticipated to defend against these dense high-velocity projectile cores. Against steel armour-piercing projectiles, there is plenty of evidence to show that boron carbide is a very good ceramic to use.

Among the new possibilities for ceramic materials is their application in the use of explosive-reactive armour packages. Against shaped-charge jets, ceramic materials perform well, and recent results suggest that they could also be used as part of an explosive reactive armour configuration (Koch and Bianchi 2010; Hazell et al. 2012). The advantage of using ceramic materials as opposed to steel as the flyer plates is that the ceramic very rapidly breaks down into small fragments, thereby minimising any collateral damage (see Figure 7.15). This is particularly useful for lightweight armoured vehicles that may be operating in urban areas. And ceramics perform just as well as steels (and potentially better) (Hazell et al. 2012).

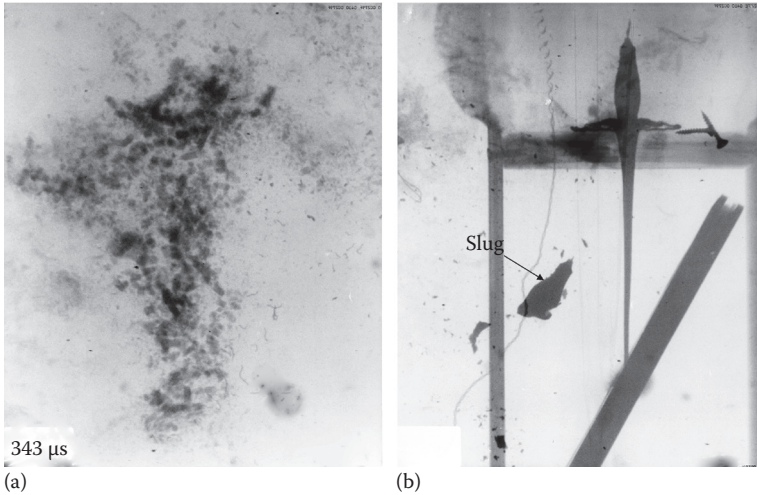


FIGURE 7.15

Flash x-ray of a ceramic plate showing two exposures: (a) the cloud of ceramic debris 343 μs later (with the slug from the disturbed jet) and (b) contact between the shaped-charge jet and the ERA at $t = 0 \mu\text{s}$. (After Hazell, P. J. et al., *International Journal of Applied Ceramic Technology*, 9 (2):382–392, 2012.)

7.12 Comparing with Other Materials

Ceramic armour systems clearly have some advantages over other materials or structures that would be used for protection; however, there are some disadvantages too. Table 7.7 provides a comparison with metal systems when applying to an armoured fighting vehicle.

7.13 Improving Performance

Improving performance can be done through two routes: either through engineering solutions, where the structure of the ceramic is designed as part of a wider system, or through material science, where understanding how the projectile interacts with the ceramic material informs the design of novel ceramic microstructures. In recent years, a large amount of effort has been put into engineering solutions for the battlefield, including adding confinement, carefully controlling the geometry of the tile or by segmenting the ceramic inserts with polymer interlayers. Even small modifications (such as using hexagonal tiles to maximise the distance from interfaces for a given area) can often help.

TABLE 7.7

Advantages and Disadvantages of Ceramic-Based Systems Compared to Metallic Systems when Applied to an Armoured Vehicle

No.	Advantage over a Metal Armour	Disadvantage over a Metal Armour
1	Good level of ballistic resistance for a given thickness	Not good at multi-hit impacts.
2	Lightweight solution for a given threat	Parasitic and therefore cannot be used as part of the vehicle's integral load-bearing structures.
3	Hard material	Low fracture toughness and therefore susceptible to damage in transit or use.
4	Relatively cheap logistic load to transport in large quantities (for a given volume)	Relatively expensive to manufacture high-performing materials.
5	–	Compared with armour-grade metals, high-performing armour ceramics are not readily available due to complex manufacturing processes.

Notably, confinement plays a large role in restricting the movement of the comminuted materials and enhancing the erosion of the penetrator. This was achieved in the 1970s by Aeronautical Research Associates of Princeton and ABEX/Norton Ceramics (Gooch, Jr. 2011) by using precision metal castings to house ceramic tiles. A further enhancement of this approach is to hot isostatically press (HIP) metal structures onto ceramic tiles; this has shown an improvement in enhancing dwell characteristics and a doubling of ceramic tile ballistic efficiencies. Further enhancements are thought possible if the ceramic is subjected to a compressive pre-stress (Holmquist and Johnson 2005) and minimising the effect of the lateral interfaces. Equally, it has been shown that fielding a 'pelletised' ceramic armour increases the multi-hit capability of the system. Such armours include Light Improved Ballistic Armour (LIBA™) manufactured by Mofet Etzion Ltd., Israel, and Super Multi-Hit Armor Technology (SMART™) manufactured by Plasan Sasa, Israel. These offer advantages in that the damage is limited to one 'cell' of the armour, and thereby, the scale of the damage is limited. All of these modifications, however, are achieved through engineering the structure. An early example of this was presented by R. L. Cook in the 1970s (Cook et al. 1979).

The challenge is to seek paths through which the improvement of the performance of the ceramic armour can be achieved through material science. Some notable examples of this have been (or could be) the following: (a) engineering a ceramic's structure to fail preferentially during ballistic impact and penetration so that the comminuted material's resistance is enhanced (Nanda et al. 2011); (b) increasing the strength of the ceramic by reducing the grain size of the ceramic to sub-micron values, e.g. Strassburger et al. (1999);

and (c) reinforcing ceramic structures with carbon nanotubes or through the design of functionally graded armour materials. This later example was originally suggested in the late 1960s by Wilkins et al. (1969). This can be achieved by using functionally graded materials (FGMs) that attempt to provide a single material construction that maximises the benefits of ceramic (hardness and compressive strength) and metals (ductility and toughness). Such materials would normally consist of a ceramic or cermet front face with subsequent sintered layers with greater metallic content. One published example of this technique was presented by Gooch et al. (1998). Here, the titanium monoboride is densified as a cermet and consisted of seven layers each with higher contents of titanium as the sample is examined from the front (impact surface) to the rear. The rear surface consisted of pure titanium. Against the 14.5-mm B32 projectile, an FGM-faced aluminium-alloyed armour provided an E_m^* value of 2.02 when compared to RHA. However, in this case, the authors report that this target system was not optimised for ballistic protection, and further improvements are thought possible. In this case, the multi-hit capability was not tested.

There has also been some recent interest in high-density ceramics such as tungsten carbide (Gooch et al. 2000). The advantage of these materials is that their high density and stiffness ($\rho = 15.6 \text{ g/cc}$; $E = 696 \text{ GPa}$) impart a large stress into the shank of the projectile on impact. Further, the high density and high hardness lead to good space effectiveness factors, meaning that the armour can be relatively thin compared to other means of protection. This is important where space, rather than weight, can be a driving factor such as on heavily armoured fighting vehicles.

7.14 Transparent Armour Materials

Providing protection whilst maintaining a transparency is a particular challenge as often the materials that are naturally transparent (i.e. glass) are particularly brittle. This means that projectile impacts or blast waves will form very small shards of glass materials, which in themselves can become lethal projectiles, that is, if the glass material is not contained.

7.14.1 Bullet-Resistant Glass

To date, almost all bullet-resistant glass comprises float or tempered glass with rubbery interlayers (such as polyurethane or polyvinyl butyral) and a backing layer of polymer, usually polycarbonate. The backing layer is optimised to contain all of the comminuted glass particles during penetration

* This metric is based on a depth-of-penetration test that will be discussed in Chapter 11.

and prevent scabbing of the rear surface layer. A glass face is used as the disruptor, the hardness of which will be in the region of 400–500 HV. This will fragment or deform the penetrator and therefore redirect its kinetic energy. As with ceramic armour, only a very small amount of the kinetic energy of the penetrator is absorbed as the glass cracks and comminutes.

Commonly, soda-lime glass or the slightly stronger and tougher borosilicate glass is used. Soda-lime glass contains a high percentage of soda ash to help with the manufacturing process; borosilicate glass contains a certain percentage of boron oxide, which provides better strength and thermal characteristics. The interlayers provide a flexible separation between layers of glass to account for thermal expansion and serve to contain any fractured glass. Depending on the threat level, different combinations of these layers form an array to prevent perforation by the projectile and provide a multi-hit capability.

However, silica-based glass plates tend to have relatively low hardness values when compared to the cores of armour-piercing ammunition. They also possess low toughness values ($K_{Ic} = 0.6\text{--}0.8 \text{ MPa m}^{1/2}$). Therefore, to provide satisfactory multi-hit protection against heavy or hard threats usually requires quite thick and hence heavy constructions. For example, to stop a 7.62-mm AP bullet, the thickness of glass armour required would be in the region of 60–100 mm depending on the nature of the round and the construction of the laminate. As the thickness increases, transparency reduces, and eventually, the weight can become prohibitive for lighter-weight vehicles. Historically, to get around this problem, smaller vision blocks have been used in vehicles, but these can compromise the situational awareness of the occupants let alone the ability to drive the vehicle. If a system can be manufactured that uses a relatively hard disrupting face, then the thicknesses (and hence the areal densities) of these armours will reduce. This will allow vehicle designers to use larger areas of transparent armour.

7.14.2 Ceramic Options

One possibility for enhancing glass-based transparent armour is by using transparent crystalline ceramic. There are currently three transparent crystalline ceramics of interest to the armour community: aluminium oxynitride or 'ALON', magnesium aluminate spinel or 'spinel' and a single crystal aluminium oxide (sapphire). The key to producing a transparent crystalline ceramic is first to use a material that is intrinsically transparent, that is, the electrons present within the atoms do not absorb the photon energy. Cubic crystal structures, unlike others, are advantageous as they have refractive index values that are independent of direction. Secondly, we can either do away with grain boundaries altogether (as we do with sapphire) or, with polycrystalline materials, minimise porosity and impurities that will refract, reflect, diffract or perturb the photons of light. It is also possible to make transparent ceramics if the grains are reduced to a size below the wavelength of visible light (0.40–0.72 μm) whilst eradicating porosity and impurities.

However, this is currently very difficult to do without resorting to very expensive processing techniques.

Sapphire (Al_2O_3) is a single crystal and therefore has no grain boundaries to diffract light and, when grown and polished, can provide a very hard replacement for bullet-resistant glass systems. Sapphire possesses a hardness value within the range of 2500–3000 HV. The main problem with sapphire is that to achieve a sample of suitable size for armoured window applications that is sufficiently free from flaws is quite time-intensive and therefore expensive. Usually, to achieve any significant size of window requires joining two or more tiles together with an appropriate bonding agent.

Aluminium oxynitride ($\text{Al}_{23}\text{O}_{27}\text{N}_5$) can be produced as a transparent polycrystalline ceramic via processing routes that are used for conventional opaque engineering ceramics. Usually, AlON will be manufactured from a pre-synthesised powder that can then be shaped (via pressing or slip casting) and then sintered in a nitrogen atmosphere.

Spinel (MgAl_2O_4) can be densified from commercially available powder either by hot pressing or by pressureless sintering. Usually, there is a requirement to HIP the samples to increase further the mechanical properties and improve transparency. Hot isostatically pressing is a process of simultaneously applying a uniform gas pressure with heat to the sample. Its main advantage over uniaxial hot pressing is that the pressure is applied equally in all directions rather than just in one direction. This results in greater material uniformity and microstructures without preferred orientations, resulting in higher strengths, Weibull modulus and transparency – the latter being very important for this type of ceramic. Both Spinel and AlON have cubic crystal structures and consequently benefit from isotropic optical properties.

All of these ceramics are still relatively immature technologies compared to opaque ceramic materials and currently are used in niche applications such as radomes. They are therefore currently very expensive materials – despite being very attractive materials to use as optical lenses. However, if the properties that they have to offer are considered, it can be seen why they may prove to be exciting alternatives to silica–glass materials in the future. Both spinel and AlON have hardness values in the range of 1200–1400 HV depending on the processing method used and have approximately 2.5 times the fracture toughness of float glass.

7.15 Summary

Since the work of Cook, Wilkins and Florence, our understanding of the behaviour of ceramic materials under impact loading conditions has been enhanced by models coupled with laboratory testing techniques that probe the high strain-rate response. However, despite the numerous studies on the

impact response of these materials, we still have a lot to learn, and there are still rich avenues of study to pursue, ranging from their quasi-static behaviour to the shock response of these materials where strain rates of 10^5 – 10^6s^{-1} are common. Current themes of research include the following: attempts to understand the flow characteristics of the comminuted material, methods for enhancing interface defeat, strength behaviour under shock loading and particularly the processing techniques to enhance their performance. The key to all of this is to understand the mechanisms by which a projectile penetrates (or 'interacts') with the ceramic and thereby deduce the important properties that maximise performance. This may appear a trivial task, but the time durations during which a penetrator is in contact with a ceramic are typically short, and this often makes analysis difficult. Furthermore, ceramic materials are required to cope with diverse threats from bullets to shaped-charge jets where the mechanism of interaction is quite different. Consequently, the properties that are useful in defeating shaped-charge jets (such as the fragmentation and subsequent flow characteristics of the material) differ from those that are best for defeating high-velocity bullets such as hardness and acoustic impedance, and particularly how the armour system is engineered. Even if one particular threat is considered, it has been known for some time that it is not one isolated material property that defines the behaviour of a ceramic during penetration, which is why it is important to study these materials using a range of different techniques.

8

Woven Fabrics and Composite Laminates for Armour Applications

8.1 Introduction

In this chapter, we review the composite materials and woven fabrics that are commonly used in the manufacture of armour materials and examine why they are used. In particular, we will focus on the structure of composite materials and why the structure and fibre choice leads to a good level of protection.

8.2 Basics

A composite is a material that is made up of two or more discrete materials that are combined together in such a way to achieve desirable properties. There are several types of composite materials including natural and engineered composites. Commonly, the composite will consist of a matrix material and some kind of reinforcement. Composite materials are now used in an increasing number of applications ranging from sporting gear to telegraph poles. Rigid composite materials have also found their way into protective structures such as in armoured vehicles.

Woven fabrics, on the other hand, do not necessarily employ matrix materials but rather make use of the high tensile strength of the fibres ($\sim 2\text{--}3$ GPa) and their low densities ($\sim 1000\text{--}1500$ kg/m³). Fibres that are used in ballistic applications generally have reasonable strains to failure ($\sim 3\%\text{--}6\%$), and that means that they have excellent energy-absorbing abilities (denoted by the area under the stress-strain curve). Of course, composite laminates can also be woven with high-strength fibres before being embedded in the matrix. A summary of some of the mechanical properties of fibres that are used in military applications is presented by Edwards (2002) and is summarised in Table 8.1.

It can be seen from Table 8.1 that the specific strength and stiffness of these fibres are high (specific strength and stiffness are calculated by dividing the

TABLE 8.1

Mechanical Properties of Some Fibres That are Found in the Military Environment

Fibre	Density (kg/m ³)	Tensile Strength (MPa)	Specific Strength (m ² /s ²)	Elastic Modulus (GPa)	Specific Stiffness (m ² /s ²)	Failure Strain (%)
Aramid (low modulus)	1440	2900	2.01×10^6	60	4.17×10^7	3.6
Aramid (high modulus)	1450	2900	2.00×10^6	120	8.28×10^7	1.9
Polyethylene (low modulus)	970	2700	2.78×10^6	89	9.18×10^7	3.5
Polyethylene (high modulus)	970	3200	3.30×10^6	99	1.02×10^8	3.7
E-glass	2600	3500	1.35×10^6	72	2.77×10^7	4.8
S-glass	2500	4600	1.84×10^6	86	3.44×10^7	5.2
Carbon (high strength)	1780	3400	1.91×10^6	240	1.35×10^8	1.4
Carbon (high modulus)	1850	2300	1.24×10^6	390	2.11×10^8	0.5

Source: Edwards, M. R., *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 216 (2):77–88, 2002.

relevant term by the density). All of these fibres (apart from carbon) can be used in blast or ballistic protection applications. Carbon fibres are too brittle for these types of applications, and as a result, they have poor translaminar strengths. However, if there is a requirement to inhibit bending in a structural component that is subjected to blast (for example), then carbon-based composites can provide an excellent solution for this by positioning the CFRP behind the face plate. Graphene may be a useful protection material too, and although there have been examples of woven structures of graphene, these are still at the very small scale, and it is unclear as to whether it will perform with exceptional ballistic performance when technology allows for macro-sized experiments. Certainly, against miniaturised bullets at the nanoscale, this material appears to offer good ballistic performance compared to steel (on a weight basis; see Lee et al. 2014).

8.2.1 Terminology and Notation

Before we proceed, here are several definitions that you might find useful along the way:

Lamina (or ply) – a layer of unidirectional (UD) fibres or woven fabric in a matrix

Laminate – two or more laminae stacked together at various orientations with a material present that acts as a bonding agent (the matrix material)

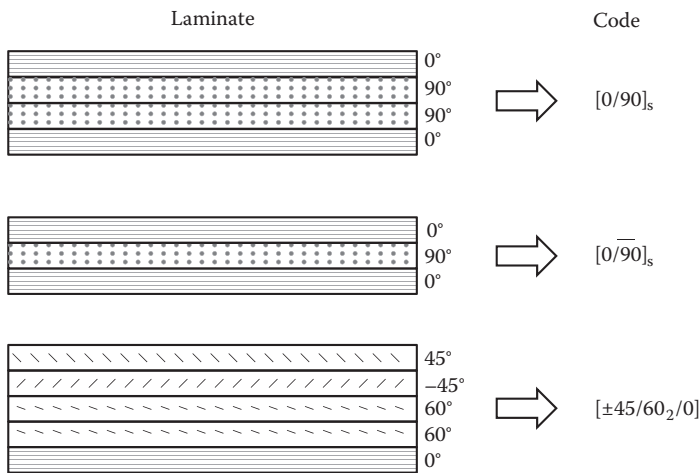


FIGURE 8.1
Examples of laminate orientation codes.

Matrix material – usually consists of a polymer-based ‘in-fill’ for the fibres

Reinforcement – usually referring to the fibres

Laminates are manufactured by stacking individual layers of plies with the fibres positioned along varying directions. Consequently, a code has been developed that describes these directions. Essentially, each lamina is defined by the angle between the fibre direction and an axis (in this case, across the paper). Furthermore, individual adjacent laminae are separated by a slash if their angles are different. Where laminates are symmetrical about a mid-plane, only half the stacking sequence is recorded with the symmetry denoted by the subscript ‘s’. Where there are an odd number of laminae, the overscore indicates that half of that laminate lies on either side of the plane of symmetry. A repeat of a particular lamina can be summarised by a subscript of the number of laminae in sequence, e.g. ‘2’ for two laminates in sequence. See Figure 8.1 for a few examples of these.

8.3 Manufacturing Processes of Composite Laminates

There is a wide variety of ways of manufacturing composite materials, and a book of this type cannot do this subject justice. Therefore, we will restrict

our attention to methods that are used to manufacture plate-like composite panels as these are the ones that are most typically used in rigid armour applications.

8.3.1 Compression Moulding

Compression moulding is a process whereby pre-impregnated composite plies are compressed together in a mould that is heated. The pre-impregnated composite plies (or pre-pregs) can be bought off the shelf and provide a very simple way of constructing a plate. The principle advantage of pre-pregs is that the resin that coats the reinforcement is mixed by the suppliers and is generally of high quality; the disadvantage is that they are expensive compared to dry reinforcement and have a finite life.

Pre-pregs can be shaped within one side of the mould to form a more complex shape. As the pressure is applied, the plies are heated, and this allows the resin to flow around the reinforcement to produce the final part.

Compression moulding is best suited to high-volume manufacturing.

8.3.2 Autoclave Moulding

Autoclave moulding is very similar to compression moulding, except that this time, a vacuum is applied to a bagged workpiece. Essentially, an autoclave is a pressure vessel with pipework to allow for a vacuum to be established in the sample. This allows for greater levels of consolidation of the resin and reinforcement. Using an autoclave is generally a slow process, and the capital cost of the equipment is high; however, the quality of the finished product – particularly where change of sections occur and where there are tight radii – is high.

8.3.3 Resin Transfer Moulding

The resin transfer moulding (RTM) process is suitable for high-volume manufacturing. This method starts with the skeleton of the fibres or a woven fibre mat, or multiple mats, that is placed into a mould of the final desired shape. The mould is then clamped together, and resin is pumped into the mould expelling the air from the edges until the mould has been filled. The heating of the mould cures the resin, and usually, relatively low temperatures (~40°C) are required. Once cured, the mould parts are separated to reveal the finished product. The advantages of this process are that good dimensional tolerances are achieved, and it is possible to produce complex shapes such as corner sections. A wide variety of reinforcements can be used too. The key is in the choice of the resin. This needs to sufficiently permeate the reinforcement and wet the fibre bundles and then undergo the curing process to produce a rigid matrix. This manufacturing process has been widely adopted by the automotive and aerospace sectors.

8.4 Fibrous Materials for Armour Applications

The majority of composite materials that are used for ballistic protection today are fibrous in nature. That is to say that they consist of multiple plies (or layers) of fibres. These tend to be used in body armour systems with the most famous of the fibres being used being Kevlar[®], which is mostly used in a woven fabric construction.

Of course, it should be of little surprise that fibrous composites are used in protection systems given the very early use of leather as armour. Leather is fibrous in nature with the outer layer (the grain) consisting of the epidermis of the animal, whereas the corium underneath provides a loose fibrous structure. The structure is tough, and consequently, it has been used for hundreds of years dating back to before the Qin dynasty of ancient China (ca. 221 BC). Arguably, wood (another fibrous composite) has been known for millennia for its protective properties and, in particular, its ability to absorb the energy of a low-velocity impact.

8.4.1 General Factors That Affect Performance

There have been several reviews on what factors affect the ballistic performance of composite materials. These have been nicely summarised by Cheeseman and Bogetti (2003), Tabiei and Nilakantan (2008) and various publications by Abrate (1991, 1994).

The ballistic penetration resistance offered by fabric and rigid composites involves a number of different parameters, and therefore, it is not possible to single out a variable that will provide enhanced protection. For example, one might think that increasing fibre toughness is an important factor in providing enhanced ballistic protection. However, if toughness was a single parameter that improved ballistic performance, then nylon fibres would be expected to perform better than Kevlar fibres – which we know is not the case (Prosser et al. 2000).

However, a metric that is often used to compare fibres for blast and ballistic protection application involves both the specific energy absorption capability of the fibre and the sonic or elastic wave speed in the fibre.

You will recall from Chapter 2 that the energy absorbed per unit volume can be calculated from the area under a tensile test, and for a high-performance fibre, this can be approximated by

$$U_r = \frac{1}{2} \sigma_t \varepsilon_t \quad (8.1)$$

where

σ_t is the tensile stress at rupture.

ε_t is the tensile strain at rupture.

This assumes a linear stress–strain response until rupture under tension and therefore for some fibres is a crude approximation; ultra-high-molecular-weight polyethylene (UHMWPE) fibres in particular show a distinct inelastic curve as the strain approaches rupture.

The specific energy absorption (per unit volume) can be calculated by

$$U_{\text{sp}} = \frac{1}{2} \frac{\sigma_t \varepsilon_t}{\rho_0} \quad (8.2)$$

The elastic velocity follows the well-known relationship

$$c = \sqrt{\frac{E}{\rho_0}} \quad (8.3)$$

The multiplication of c and U_{sp} provides an indication of the ballistic effectiveness of an individual fibre in a composite and can be used as a metric to compare fibres. It is therefore given as (Cunniff 1999)

$$U^* = \frac{1}{2} \frac{\sigma_t \varepsilon_t}{\rho_0} \sqrt{\frac{E}{\rho_0}} \quad (8.4)$$

A high elastic wave velocity is important as this allows for the rapid delocalisation of the stresses from the point of impact. The specific energy absorption (or specific toughness) of the fibre is a measure of how much of a projectile's kinetic energy (KE) can be absorbed on impact.

A further evolution of this equation has been undertaken by Cunniff to compare a dimensionless v_{50} velocity by dividing the v_{50} velocity of a fabric by the cube root of Equation 8.4. This was then compared to a dimensionless system parameter comprising the projectile's presented area, the system's areal density and the projectile's mass (Cunniff 1999). Some fibre parameters are shown in Table 8.2 with some of the parameters from Cunniff (1999).

TABLE 8.2

Specific Energy-Absorption Ability and Speed of Sound Comparisons between Fibres

Fibre	ρ_0 (kg/m ³)	E (GPa)	σ_t (GPa)	ε_t (%)	c (m/s)	$U^{*1/3}$ (m/s)
PBO	1560	169	5.20	3.10	10,408	813
Spectra® 1000	970	120	2.57	3.50	11,123	802
SK60 (Dyneema®)	970	87	2.70	3.50	9471	773
600-denier Kevlar KM2	1440	83	3.40	3.55	7592	683

8.4.2 Aramid-Based Fibres for Armour Applications

Kevlar was first developed by DuPont in the 1960s from aromatic polyamides. This and similar fibres such as Twaron, manufactured by Teijin Aramid, are known as aramids and are derived from polymer molecules containing benzene rings. These molecules readily align parallel to each other to form highly ordered structures and consequently demonstrate excellent properties along the direction of the fibres. The fibres, however, are highly anisotropic due to the weak inter-chain bonding between each of the molecules and therefore are susceptible to splitting. This is illustrated by the experiments of Cheng et al. (2004, 2005) who measured the longitudinal and transverse properties of a single Kevlar KM2 fibre. The longitudinal modulus is significantly higher. See Table 8.3.

Aramid fibres tend to fail in a ductile manner, and although the strain to failure of the fibres is small, necking occurs in the fibres followed by localised drawing of the material forming fibrils (microfibrils). This is an energy-expensive process and is an attractive mode of failure – particularly for when we need the material to stop a bullet.

Kevlar has been used extensively in the design of body armour, and many police officers and soldiers owe their life to this material (and its inventor – Stephanie Kwolek). The best types of woven systems will consist of multiple fabric layers of tightly woven material. These will be arranged in either a plain or basket weave. Loosely woven materials lead to an inferior ballistic performance (Cheeseman and Bogetti 2003). The properties of three common brands of Kevlar fibres are presented in Table 8.4.

TABLE 8.3

Transverse and Longitudinal Measurements of a Kevlar KM2 Fibre

Fibre	E_1 (Transverse Modulus)	E_3 (Longitudinal Modulus)
Kevlar KM2	1.34 ± 0.35 GPa	84.62 ± 4.18 GPa

Source: Cheng, M. et al., *Journal of Engineering Materials and Technology, Transactions of the ASME*, 127 (2):197–203, 2005.

TABLE 8.4

Properties of Kevlar Fibres

Fibre	Density (kg/m ³)	Tenacity (GPa)	Young's Modulus (GPa)	Elongation to Break (%)	Decomposition Temp (°C)
Kevlar 29	1440	2.92	70.50	3.6	427–482
Kevlar 49	1440	3.00	112.40	2.4	427–482
Kevlar KM2	1440	3.88 ± 0.40	84.62 ± 4.18	4.52 ± 0.37	–

Source: DuPont. 2001. *KEVLAR Aramid Fibre – Technical Guide*. Richmond, VA: DuPont; Cheng, M. et al., *Journal of Engineering Materials and Technology, Transactions of the ASME*, 127 (2):197–203, 2005.

8.4.2.1 Kevlar Fibres and Shear-Thickening Fluids

Improvements to the performance of fibres can be achieved via a couple of routes. In particular, it has been shown that the addition of shear-thickening fluids (STFs) to Kevlar fibres results in an enhancement to ballistic protection (Lee et al. 2003). Shear thickening is a non-Newtonian process characterised by a significant increase in viscosity with shear stress. Non-Newtonian ‘thickening’ behaviour tends to occur in colloidal suspensions where small (nanometre-sized) particles are deposited in a matrix fluid. As the rate of shear is increased, the suspended particles cluster together to provide a resistance to flow in a process called ‘hydroclustering’. Figure 8.2a and b shows how a Newtonian fluid responds to applied shear and a non-Newtonian fluid (shear thickening) responds to shear, respectively. It can be seen that for the STF, the viscosity of the fluid increases as the rate of shear is increased. This means that the fluid gets thicker (the term ‘thickness’ here is not referring to a geometrical thickness but rather a viscosity effect). The opposite of this is a shear-thinning fluid where the viscosity decreases with the increase in the rate of shear. This is particularly useful in the application of paint where applying a paint-loaded brush to a wall will result in the paint flowing smoothly (due to a reduced viscosity). However, remove the brush and the viscosity of the paint increases, thereby limiting the amount of drips that are formed. Colloidal suspensions can undergo shear thinning at low shear rates and shear thickening at high shear rates.

So, why does adding an STF to Kevlar fibres increases their ballistic performance? Lee et al. (2003) fired fragment-simulating projectiles (FSPs) into composite materials woven with Kevlar fibres impregnated with colloidal STF (silica particles dispersed in ethylene glycol). The Kevlar targets were backed with clay, and the depth of penetration into the clay was recorded.

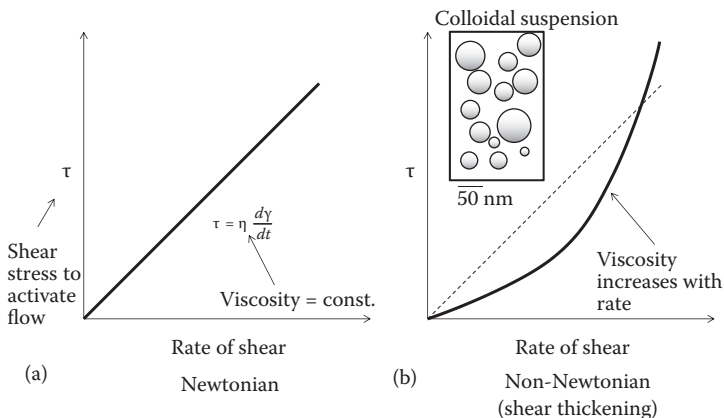


FIGURE 8.2

(a) Newtonian response and (b) a non-Newtonian response where the viscosity increases with the rate of shear; inset – an example of a colloidal suspension.

They showed an enhancement in the energy absorption of the Kevlar fabric where the STF materials were applied. In addition, they found that the shear-thickening effects were proportional to the volume of the STF applied to the fabric. It was thought that the performance enhancement was due to an increase in yarn pullout force on transition of the STF to a rigid state (Lee et al. 2003). Similar improvements in performance have been found in stab-resistant STF-treated Kevlar and nylon fabrics (Decker et al. 2007).

8.4.3 Glass Fibres for Armour Applications

Glass fibre-based materials have been used in all types of military environments ranging from mine countermeasure vessels such as HMS Wilton (Mouritz et al. 2001) to armoured fighting vehicles (Fecko 2006). To date, several technology demonstrators of armoured fighting vehicles have been used in an attempt to develop what became known in the popular media as the 'plastic tank'. In fact, for the most part, that is exactly the aim, i.e. to produce an armoured vehicle where 30%–40% of the vehicle's structure is an epoxy resin (plastic).

Glass fibre-reinforced plastics (GFRPs) have been used in developmental trial vehicles such as the Advanced Composite Armoured Vehicle Programme in the United Kingdom (see Figure 8.7) and the various Composite Armoured Vehicle programmes running in the United States. However, to date, only weight savings of approximately 10%–15% have been achieved when compared to metallic systems with similar protection levels. It is thought that further weight savings can be achieved by moving from an E-glass fibre to an S-glass fibre system if cost allows.

It is important to note that composite materials on their own will not provide sufficient protection against large ballistic threats or hard-cored AP rounds, and therefore, a ceramic or high-hardness armour plate would be attached to provide a disruptor face (Ogorkiewicz 1976; Hetherington and Rajagopalan 1991). However, glass fibre-reinforced polymers do provide useful protection against spall fragments, and therefore, spall shields are often constructed from these types of materials.

Repairing composite material plates that have delaminated due to penetration or have been perforated by a projectile is a relatively straightforward process – if the damage is cosmetic rather than structural. It is possible to remove the damaged zone by drilling out a core of a material and replacing it with a cylinder of a new composite material by using an adhesive to glue the contacting surfaces together. Such repairs have been ballistically tested and have been shown to have the same performance as the original composite material – even with bullets fired at the joints (Edwards 2000).

GFRP materials generally demonstrate a good resistance to shock loading, and unlike carbon-based composites, they demonstrate reasonable energy absorption when subjected to ballistic attack. Consequently, for armour applications, glass-based composite materials are considered more important.

8.4.3.1 The Effect of Stitching

There have been several studies that have focused on the penetration and failure mechanisms of stitched composite materials. Mines et al. (1999) studied the penetration behaviour of woven, z-stitched ($\pm 45^\circ$ z-stitch E-glass fabrics supplied by Tech Textiles) and through-thickness z-stitched glass polyester laminates for a number of laminate thicknesses, a number of geometries and masses of projectiles. They identified three modes of energy absorption: local perforation, delamination and friction between the projectile and the panel. They also reported that the woven and the z-stitched samples behaved in a similar manner. Their evidence suggested that the local energy absorption was dominated by shear effects during penetration. Similar evidence has also been seen by Naik and Shrirao (2004), Gama et al. (2005), Naik et al. (2006) and Naik and Doshi (2008). In particular, Gama et al. partitioned the penetration mechanisms into five stages, namely: impact contact, hydrostatic compression of the composite, compression–shear, tension–shear and structural vibration. Stitching composites does have some benefit where the composite is subjected to blast loading and it provides this by limiting delamination. This was shown by Mouritz who tested GFRP coupons (270 × 70 mm) that had been stitched in the parallel or transverse direction of the coupon (see Figure 8.3a; Mouritz 1995). The stitch was a modified lock stitch as shown in Figure 8.3b. Mouritz showed that when

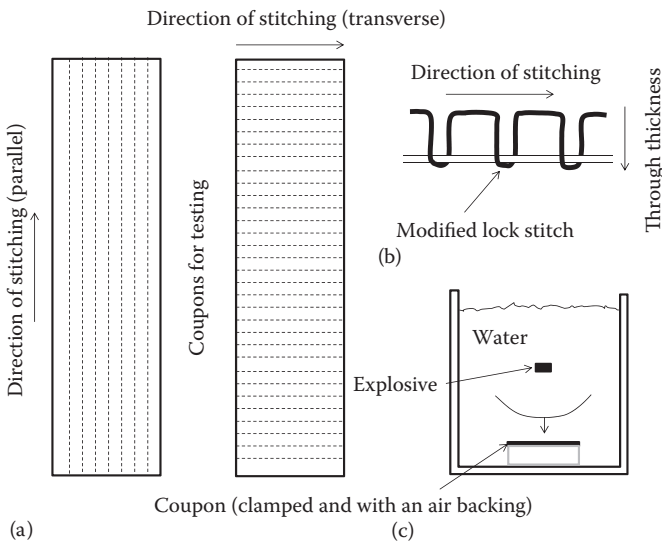


FIGURE 8.3

Experimental details showing (a) the coupons used in the testing, (b) the type of stitching employed and (c) the explosive test set-up. (From Mouritz, A. P., *Composites Science and Technology*, 55:365–374, 1995.)

subjected to underwater blast loading (see Figure 8.3c), the area of delamination damage was reduced by the stitching, with the greatest reductions occurring at a higher stitched density and when the stitches were parallel to the coupon's longest dimension. However, as the coupons bent due to the pressure exerted by the shock wave, the stitches act to produce a stress concentration, which resulted in a high amount of damage around the stitching. Significantly, bending failure is a prominent failure mechanism when coupons are subjected to bending by explosive loading (Mouritz et al. 1994; Mouritz 1996).

Stitching should also have an effect on the ballistic behaviour of the composite principally because of the improved impact damage tolerance offered by the presence of the stitching. However, Mouritz (2001) has shown that against ballistic impact, the effect of stitching is minimal on the damage reduction, whereas against blast loading, it is much more significant.

8.4.3.2 3D Woven Structures

3D woven composites offer the possibility of providing enhanced ballistic protection by virtue of the architecture providing strength and stiffness in the z-plane and enhanced damage tolerance (Mouritz et al. 1999). There have been relatively few studies that have explored the advantages of these types of materials under ballistic loading, although they have been shown to offer improvements over 2D composites in the design of ceramic-faced armour systems (Grogan et al. 2007). Under dynamic impact tests, there have been several studies that show that 3D woven composites exhibit higher energy-absorbing abilities under repeated impact when compared to 2D composites. Importantly, it has been shown that under low-velocity impact, 3D composites spread the damage from the impact over a wider area than 2D composites (Baucom et al. 2006). However, the question still remains as to whether this behaviour is translated for higher-rate ballistic impacts. Jia et al. (2011) studied the ballistic behaviour of these materials computationally and experimentally and noted that during ballistic penetration, delamination was inhibited due to the presence of the z-plane reinforcement. They concluded that the energy absorption was predominately due to shear failure on the impact surface and tensile and shear failure on the rear surface of the target ultimately leading to target failure. On the other hand, Walter et al. (2009) experimentally investigated the ballistic performance of a thick 3D-woven glass-based composite made of 27 layers of tows stacked in a cross-ply sequence and showed that under high-velocity impact, the z-plane reinforcement did not stop delamination. They also noted very different failure mechanisms due to different bullet morphologies underlining the complex failure mechanisms of these materials (Walter et al. 2009).

8.4.3.3 Thickness Effects

It has also been shown that changes in thickness have an important role in the penetration mechanisms. Gellert et al. (2000) noticed that the penetration

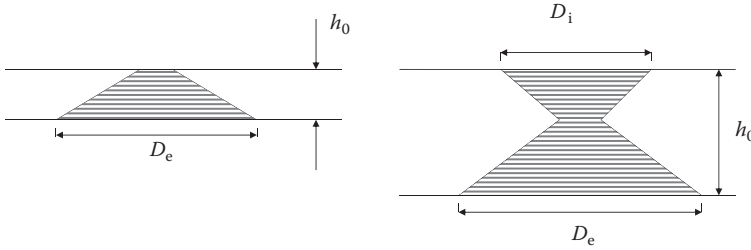


FIGURE 8.4

Differences in the type of damage for thin and thick GFRP targets. h_0 is the laminate thickness, whereas D_i and D_e represent the delamination extent on the target's incidence and exit sides, respectively. (Adapted from Gellert, E. P. et al., *International Journal of Impact Engineering*, 24 (5):445–456, 2000.)

of varying thickness of GFRP materials resulted in a bilinear relationship when the KE of the projectile at the ballistic limit was plotted against target thickness. This was also found to be the case for a broad range of reported ballistic impact data. Increasing the thickness of the GFRP target resulted in two characteristic patterns of delamination (illustrated schematically in Figure 8.4). For thin targets, the damage was in the form of a cone of delamination opening towards the target's rear surface. This cone increased in diameter and height with increasing target thickness until, with sufficiently thick targets, a cone of delamination opening towards the impact side was also added.

The reason for this was due to the way in which the target failed during ballistic penetration. A change in perforation mechanism was observed from largely dishing in thin targets to a combination of indentation and dishing for thick targets and was largely affected by projectile shape and diameter (see Figure 8.5). For thin targets, the projectile nose shape (flat-nosed or conical) did not affect the energy absorption characteristics of the target; however, for the thick targets, the conical projectiles were more effective. This is contrary to the observations in carbon/epoxy targets where conical projectiles appeared to perform less well compared to flat-ended projectiles (Ulven et al. 2003). Notably, this is due to the carbon/epoxy target failing by shear plugging at elevated velocities. Importantly, Gellert et al. (2000) concluded that the indentation phase is a significant absorber of energy in GFRP targets and indicated that it should be maximised in any bonded composite armour design.

For thin composite materials, it is anticipated that the strength and the strain to failure of the fibres are particularly important to accommodate the tensile strains that occur due to the dishing. Consequently, for these structures, using the higher-strength S-glass fibres as opposed to the E-glass fibres is desirable.

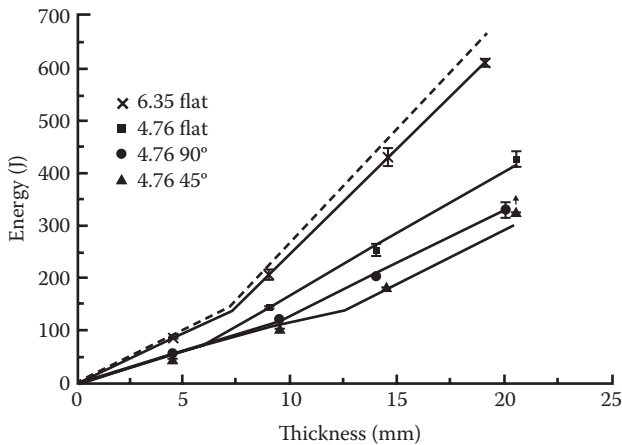


FIGURE 8.5

KE at ballistic limit versus target thickness for projectiles impacting GFRP targets. (Reprinted from *International Journal of Impact Engineering*, 24 (5), Gellert, E. P. et al., 445–456, Copyright 2000, with permission from Elsevier.)

Naik et al. (2005) have also shown how impact energy is partitioned during ballistic impact loading. Using an analytical formulation, they showed how the energy absorption can be partitioned during the ballistic penetration of 2D-woven E-glass epoxy composite ($t = 2$ mm; $\rho = 1750$ kg/m³). The result shown in Figure 8.6 is for a calculation where the composite is impacted at just below the ballistic limit (i.e. where the projectile has not completely penetrated the composite). The main energy-absorbing mechanisms were fracture of primary yarns and deformation of secondary yarns. In particular, a significant amount of the KE of the projectile was transferred to the KE of a cone of the material that was ejected from the rear surface as well as deforming the secondary yarns.

Damage from ballistic impact conditions can also be affected by the number of simultaneous impacts that the laminate experiences such as the situation where an exploding artillery munition propels multiple projectiles to the target. Using a unique gas-gun arrangement, with three barrels with an angular separation of 120°, Deka et al. (2009) showed that the progressive time-dependent damage due to sequential impacts resulted in an increased performance of an S2 glass/epoxy laminate when compared to simultaneous impacts. Specimens subjected to sequential impact exhibited an average of 10% greater energy absorption with a corresponding 18% increase in delamination damage than specimens impacted simultaneously. The energy absorption of the laminate was influenced by the stress wave interactions, particularly along the primary yarns and the amount of delamination that developed.

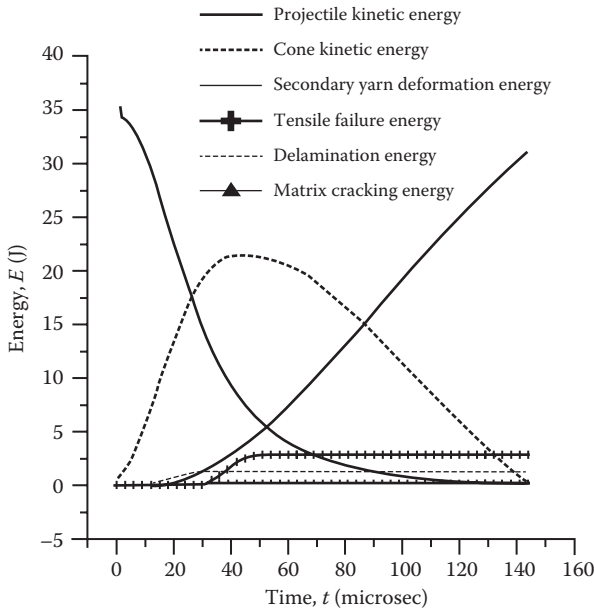


FIGURE 8.6

Energy absorbed by different mechanisms during ballistic impact event, $v = 158$ m/s, projectile mass = 2.8 g, $h = 2$ mm, $d = 5$ mm. (Reprinted from *Materials Science and Engineering A*, 412 (1–2), Naik, N. K. et al., 104–116, Copyright 2005, with permission from Elsevier.)

8.4.3.4 The Effect of Laminate Make-Up on Ballistic Performance

Various attempts have been made to analyse the penetration of composite materials, and these are generally based on energy-balance equations where the KE of the projectile is balanced with the energy required to cause shear failure of the composite, delamination, tensile failure of the yarns, KE of the resulting fragments and so on, e.g. Sun and Potti (1996) and Morye et al. (2000). Some choose to decompose the resistance offered by the composite into two stress terms – namely the static and dynamic resistive component – and derive terms for each based on the shape of the projectile penetrating the composite and the energy required to penetrate the depth, e.g. Wen (2001). Nevertheless, in the formulation of analytical models (and of course, validation of computational models), the geometry of failure is also important. Also important is the strain wave propagation along the length of the fibres/yarns, which, for soft fabric constructions at least, is one of the several mechanisms of absorbing energy (Cheeseman and Bogetti 2003). The addition of the matrices of either the thermoset or thermoplastic type clearly has an effect on the penetration mechanisms. This has been shown by Lee et al. (2001) who compared dry fabrics (i.e. without a resin in place) to a composite structure (where either a vinyl ester resin or aliphatic ester-type polyurethane was

used) on the ballistic performance of Spectra 900–reinforced composites. The effect of adding the resin reduced yarn mobility and ultimately resulted in higher energy absorption through yarn fracture. However, they noted that the resin matrix itself does not absorb much energy in itself. Nevertheless, small improvements in the ballistic performance of GFRP composites have been seen with the addition of carbon nano-tubes to the resin (Trovilleon et al. 2010).

It is perhaps no surprise that the type of reinforcement used in rigid composite construction is also critical. Wrzesien (1972) has shown that complementing the glass-fibre reinforcement with a steel wire added to the resistance to ballistic penetration. Although there is an obvious weight penalty due to the addition of the relatively dense steel (and in this case, brass coated), on a weight-by-weight basis, it has shown to be efficient at resisting penetration. Consequently, increasing the strength of the fibres should improve the ballistic performance of the composite.

On the other hand, Woodward et al. (1994) examined the ballistic performance of semi-infinite (very thick) composite materials with various reinforcements including (S2) glass, nylon and Kevlar materials (all with different tensile strength values). Unusually, they tested target structures that were at least 150 mm square and 150 mm thick, and therefore, the projectile was subjected to inertial confinement throughout the penetration phase. Using a simple energy balance, a value for the mean stress was established and found to be highest when the glass-reinforced material was tested. The mean resisting stress was calculated according to

$$\sigma_r Ad = \frac{1}{2} mv_0^2 \quad (8.5)$$

where

σ_r is the mean resisting stress.

A is the cross-sectional area of the cavity that is formed by the projectile.

d is the diameter of the projectile.

m is its mass.

v_0 is the velocity.

For GFRP, they measured a value of 1190 MPa, which was twice that measured for the Kevlar-based composite (615 MPa). It was demonstrated that for GFRP, crushing fracture of the composite occurred immediately ahead of the penetrator, and they pointed out that this was seen to be responsible for a large amount of energy absorption during the early stages of penetration in finite-thickness targets. High tensile modulus and good bonding between the fibre and the matrix were identified as important parameters for ballistic resistance. However, it should be pointed out that as this was effectively a



FIGURE 8.7

QinetiQ Advanced Composite Armoured Vehicle Programme technology demonstrator.

semi-infinite target (i.e. where the thickness exceeded the penetration depth), some of the 'break-out' mechanisms seen by others were not evident.

The post-impact structural behaviour of composites is of particular interest when consideration is given on where they would be applied. In load-bearing structures such as ships and composite armoured vehicles (such as the Advanced Composite Armoured Vehicle Platform; see Figure 8.7), it is critical to understand the degradation of strength and stiffness when the material has been subjected to blast and impact loading. And, certainly for blast-loaded structures, this has been a critical path of study.

8.4.4 Basalt Fibres for Armour Applications

Basalt fibres are derived from the igneous rock that is readily available in the earth's crust. The advantage of basalt is that, due to its abundance and the ease at which it can be mined, it is relatively cheap. It also can be readily extruded into fibres, and therefore, it is possible to manufacture ballistic protection systems that can compete against E-glass and S2-glass systems. It is also pretty good at accommodating high temperatures and therefore would not be susceptible to thermal softening at extreme temperatures (unlike UHMWPE). Basalt fibres also retain their properties at low temperatures, do not degrade in ultraviolet radiation and are inert. Given that these fibres are derived from igneous rock, they are wonderfully environmentally friendly too. To date, there is relatively little research on the viability of basalt fibres for ballistic protection. Nevertheless, some work on this product at the Army Research Laboratory at Aberdeen Proving Ground (United States) has shown that this material shows some promise. They showed that against FSP projectiles, basalt-based composites perform in a comparable fashion to S2 glass epoxy laminates (Spagnuolo et al. 2011).

8.4.5 UHMWPE Fibres for Armour Applications

UHMWPE-based composites are fairly unique in that the fibre material is accommodated in a matrix made from the same type of polymer used to manufacture the fibre. The fibres consist of a specially manufactured UHMWPE such that the carbon chain of the PE molecule is aligned along the fibre. This makes the fibres very strong. The fibre is made through a process of 'gel spinning' where the long-chain molecules of UHMWPE are dissolved in a solvent (to form a gel) and then extruded through a spinneret and cooled to form the fibre with a high degree of molecular orientation. Two principle brands exist: Dyneema (DSM) and Spectra (Honeywell). The properties of a Dyneema fibre (SK60) are provided in Table 8.5 (van Dingenen 1989).

UHMWPE fibres have two advantageous properties for goods ballistic protection for lightweight armour solutions (Jacobs and Van Dingenen 2001):

- 1. A high specific energy absorption capability
- 2. A high elastic wave velocity

This can be seen in Table 8.2.

A typical structure of the composite is shown in Figure 8.8. In this case, the composite is a ballistic-grade material (HB50) and is laid up according

TABLE 8.5
Properties of Dyneema SK60

Fibre	Density (kg/m ³)	Young's Modulus (GPa)	Tenacity (GPa)	Elongation to Break (%)
SK60	970	87	2.7	3.5

Source: van Dingenen, J. L. J., *Materials & Design*, 10 (2):101-104, 1989.

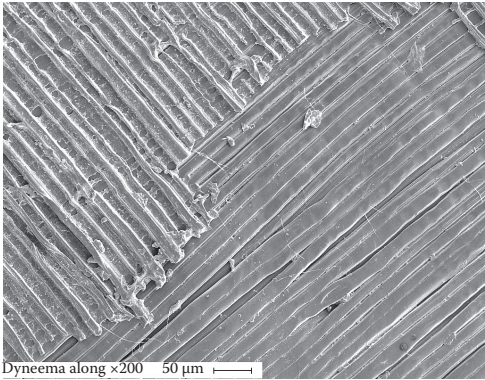


FIGURE 8.8
A micrograph of a Dyneema composite (HB50).

to a $0^\circ/90^\circ$ fashion. The PE fibres run in a UD ply and are stacked on top of one another with each fibre direction at an orthogonal angle to the previous.

Dyneema is one of the most weight-efficient composites to use for the lower threat spectrum, and for Standardization Agreement (STANAG) Level 1, which encompasses soft-cored high-velocity rifle bullets such as the 7.62×51 -mm NATO ball round, around 30 mm for this ballistic-grade composite is sufficient. Coupled with its low density ($\sim 970 \text{ kg/m}^3$), this translates to an areal density of 28.5 kg/m^2 . Of course, weight-efficient ballistic protection comes at a price, and consequently, this composite material is not cheap.

This type of composite is also used as a spall shield for armoured fighting vehicles such as the Patria XA188 in service with the Netherlands Army. However, being a PE-based composite, its decomposition temperature is relatively low compared with other composite options. The fibres melt at around 144°C – 152°C , and therefore, its performance will be considerably reduced as the temperatures approach these values.

8.4.5.1 Ballistic Penetration of Dyneema

Dyneema can be used as part of a ceramic-faced system, or it can be used as a stand-alone armour material. Figure 8.9 shows a 22-mm-thick Dyneema plate penetrated by a 5.56×45 mm SS109 (L2A2) bullet. It can be seen that the plate has stopped the bullet, but there are several important effects that have occurred during the penetration process. Firstly, it appears that on contact with the panel, the bullet has begun to compress the plies and individual fibres subjected to shear failure. Approximately a quarter of the way through the sample, the resistance offered by the panel has led to the deformation/disruption of the projectile. Delamination of the plies has also occurred. However, probably the most important resistance is offered during

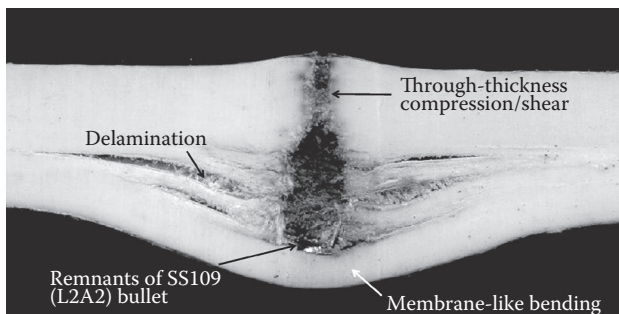


FIGURE 8.9

22-mm-thick Dyneema plate penetrated by a 5.56×45 mm SS109 (L2A2) bullet; impact velocity = 838 m/s. (From Iremonger, M. J., Polyethylene composites for protection against high velocity small arms bullets, *Proceedings of the 18th International Symposium on Ballistics*, San Antonio, Texas, 1999; Image of Dyneema courtesy of Dr. M. J. Iremonger.)

the membrane-bending action of the rear portion of the panel. Here, the high-tenacity fibres are being placed in tension, and the energy absorbed through the stretching of these fibres leads to the arrest of the projectile mass. The ballistic penetration data of Dyneema are provided by Nguyen et al. (2015) – see Table 8.6; the fractographic analysis of a projectile penetrating this material is provided by Greenhalgh et al. (2013).

Additional ballistic results are presented in Table 8.7 (Iremonger 1999).

TABLE 8.6

Ballistics Performance of HB1 Dyneema Panels against L2A2 Bullets

Target		Response of Target to Impact by an L2A2 Bullet at a Range of Impact Velocities			
Thickness (mm)	A_d (kg/m ²)	600 m/s	700 m/s	800 m/s	900 m/s
4.2	4.0	–	–	–	G
11.0	10.5	G	G	G	G
15.0	13.7	–	O	O	G
22.0	21.0	U	U	U	U
32.0	31.0	U	U	U	U

Source: Iremonger, M. J., Polyethylene composites for protection against high velocity small arms bullets, *Proceedings of the 18th International Symposium on Ballistics*, San Antonio, Texas, 1999.

Note: G = grossly overmatched by bullet; O = overmatched; U = undermatched (stopped).

TABLE 8.7

Ballistic Performance of HB26 Dyneema Panels against FSPs

Target		Standard		
Thickness (mm)	A_d (kg/m ²)	Projectile	v_{50} (m/s)	Deviation (m/s)
9.1	8.9	12.7-mm FSP	506.0	26.4
20.0	19.6	12.7-mm FSP	825.8	17.2
25.2	24.7	12.7-mm FSP	1021.4	8.5
35.1	34.4	12.7-mm FSP	1250.3	36.1
50.4	49.4	12.7-mm FSP	1656.5	16.3
10.0	9.8	20-mm FSP	393.9	43.0
20.0	19.6	20-mm FSP	620.1	19.6
36.2	35.5	20-mm FSP	901.4	9.8
75.6	74.1	20-mm FSP	1527.6	104.6
101.7	99.7	20-mm FSP	2001.8	91.8

Source: Nguyen, L. et al., *International Journal of Impact Engineering*, 75 (0):174–183, 2015.

Note: Areal densities calculated assuming $\rho = 980$ kg/m³.

8.4.5.2 Shock Loading of Dyneema

The shock properties have been studied by Chapman et al. (2009) and Hazell et al. (2011). It was shown over a limited pressure range (up to 4 GPa) that the Hugoniot followed the well-known relationship (see Chapter 5)

$$U_s = c_0 + a \cdot u_p + b \cdot u_p^2 \quad (8.6)$$

where U_s is the shock velocity, c_0 is the intercept (that we have assumed to be the bulk sound speed), a and b are the polynomial coefficients and u_p is the particle velocity. The measured values for a , b and c_0 were 3.45, -0.99 and $1.77 \text{ mm}/\mu\text{s}$, respectively (Hazell et al. 2011).

At elevated shock stresses, it was found that the Dyneema appeared to have melted. Figure 8.10 shows the micrographs of post-shocked target material recovered from the target chamber. In these cases, the shock-induced particle velocities increase from left to right according to (a) $0.16 \text{ mm}/\mu\text{s}$, (b) $0.55 \text{ mm}/\mu\text{s}$ and (c) $0.86 \text{ mm}/\mu\text{s}$. At lower particle velocities, the recovered material showed evidence of fibre definition indicating that the fibres remained intact during shock loading, whereas at the elevated values, melting of the fibres and matrix had occurred.

An assessment of the temperature rise during shock loading can be approximated by examining the temperature along the adiabat (T_a) according to the following equation:

$$T_a = T_1 \exp \left[\Gamma - \Gamma \left(\frac{V}{V_0} \right) \right] \quad (8.7)$$

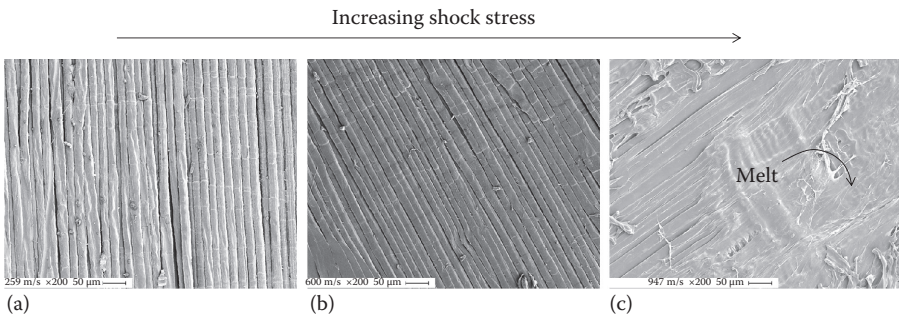


FIGURE 8.10

Recovered Dyneema target after being struck by a flyer plate; showing the fibres recovered from a shocked target up to (a) $0.16 \text{ mm}/\mu\text{s}$, (b) $0.55 \text{ mm}/\mu\text{s}$ and (c) $0.86 \text{ mm}/\mu\text{s}$.

where

Γ is Grüneisen gamma.

T_1 is the initial temperature of the sample (300 K).

V is the specific volume due to shock ($1/\rho$).

V_0 is the specific volume at ambient conditions ($1/\rho_0$).

Assuming a value of $\Gamma = 1.6$ as taken for PE, the temperature along the adiabat for a compressed Dyneema sample can be calculated, and it was shown that the melting of the samples corresponded to the calculated temperature increase due to the passage of the shock wave (Hazell et al. 2011). Localised melting has also been observed in Dyneema panels that have been subjected to air-blast loading (Fallah et al. 2014).

8.4.6 PBO Fibres

There are several other fibres that have shown promise in recent years and are currently not extensively used for blast and ballistic protection. This is due to one of two possibilities. Either it is because it is widely believed that improvement in mechanical properties is achievable but not yet sufficient to warrant extensive use, or alternatively, their mechanical properties are excellent, although their physical properties are not desirable for military applications.

One such fibre that has the strength potential and has already been used in body armour applications with controversial outcomes is poly p-phenylene-2,6-benzobisoxazole (PBO) currently manufactured under the trade name Zylon[®]. This fibre has a tensile strength of 5.2 GPa and according to Table 8.2 will perform as an excellent ballistic-grade material. However, a report from the National Institute of Justice (United States) suggested that it degrades due to environmental conditions (moisture and heat; see Walsh et al. 2006a) and this, it is thought, was a contributing factor to the failure of a vest worn by a police officer who was mortally wounded. Furthermore, the report implied that a visual inspection of a Zylon-based body armour would not indicate whether the intended ballistic performance was maintained (Hart 2005). There have been subsequent attempts to stabilise PBO fibres, but to date, these have been deemed as not being successful (Walsh et al. 2006b).

8.4.7 Carbon Fibre Composites

Carbon-based composites have enjoyed wide usage over the past several decades ranging from bicycle frames to aircraft fuselages. However, generally speaking, carbon fibre-based composites are not suitable for providing ballistic protection. In fact, the response of carbon fibre composite materials to impulsive loads is poor, and this is due to the brittleness of the epoxy resin and the low strain to failure of the carbon fibres (<1%) leading to a poor

translaminar strength. However, they are very stiff and very strong when tested in plane (along the direction of the fibres). Consequently, they are used on military platforms where lightweight structural rigidity is required. They have also been shown to provide some benefit in contributing to the strength of structural armour in aerospace applications where the presence of the CFRP layer preserves the structural integrity of the panels after ballistic impact (Horsfall et al. 2000).

They have excellent stiffness properties as well as good tensile properties, whereas their bulk densities are relatively low, typically around 1500 kg/m^3 . Carbon fibres in particular have very good stiffness and strength values with the tensile modulus reaching as high as 1000 GPa and tensile strengths reaching values of 3.8 GPa. They also possess a very low (in fact, slightly negative) coefficient of thermal expansion as well as good thermal and electrical conductivity.

There exists a large body of work examining the low-velocity impact regime of carbon composite targets. These are thoroughly summarised in review publications by Abrate (1991, 1994, 1998) and Cantwell and Morton (1991).

8.4.7.1 Failure during Ballistic Loading

Despite carbon fibre laminates finding their way into military aircraft structures as early on as the 1960s, it took an additional 15 or so years for extensive studies on these materials' high-velocity impact response to be published. Early published works of Cantwell et al. (1986), Cantwell (1988) and Cantwell and Morton (1989a,b, 1990) showed a number of facets to the high-velocity impact response of these materials. Through a series of impact experiments, they have shown that high-velocity impacts generate large areas of matrix cracking, fibre fracture and delamination within the target. With relatively low-impact energies, where the projectile was a 6-mm-diameter steel sphere, they showed that damage initiated at ply on the rear side of the target due to flexural bending. In thicker, stiffer targets, damage occurs in the uppermost plies caused by the large contact stresses around the projectile. In further studies, they showed that increasing the velocity of the projectile resulted in a localised response to the target, which is somewhat different from low-velocity impacts where the areal geometry of the target is important.

The analysis of the failure modes carried out by Cantwell and Morton on the perforated samples revealed the formation of a conical-shaped shear plug. This resulted in a shear surface extending away from the point of contact at approximately 45° . At low-velocity impacts, they suggested that three energy-absorbing mechanisms are active during low-velocity impact, namely, elastic deformation, delamination and shear out.

At higher velocities, it appears that these materials become extensively particulated, and the effect of the delamination on the projectile's KE absorption becomes negligible. The sequence of events for a high-velocity projectile striking a target at 1199 m/s is shown in Figure 8.11 and highlights how

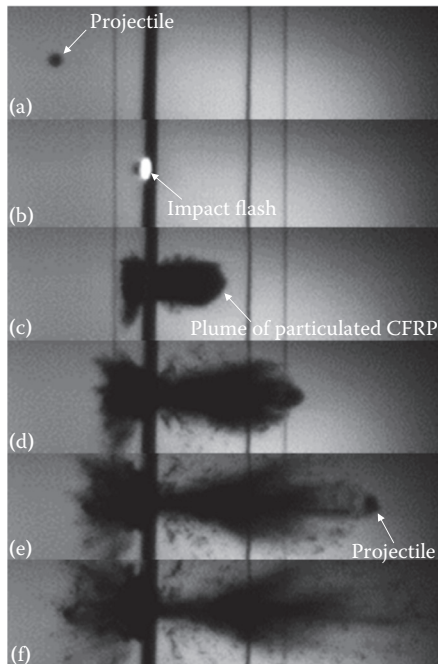


FIGURE 8.11

High-speed video images taken at 16,000 frames per second showing the perforation of a 6-mm CFRP laminate; impact energy = 5150 J (1199 m/s). (a) Time = 0 μs (reference), (b) 62.5 μs , (c) 125.0 μs , (d) 187.5 μs , (e) 250.0 μs and (f) 312.5 μs . (Reprinted from *International Journal of Impact Engineering*, 36 (9), Hazell, P. J. et al., 1136–1142, Copyright 2009, with permission from Elsevier.)

brittle these materials are. As the projectile contacts the CFRP material, light is emitted (frame B). At 125 μs , a plume of particulated CFRP material has been formed, the forward front of which precedes the projectile. Material is ejected backwards from the impact surface. At 187.5 μs , the projectile starts to emerge from the cloud of dust. The material ejected from the impact surface of the panel appears to be moving at a lower velocity than the material ejected from the rear surface. At 250 μs (frame E), the projectile is clearly defined. The large fragments formed maintain a velocity similar to the projectile (1062 m/s), whereas the large volume of lighter-weight particles is slowed. By 312.5 μs (frame F), the lighter-weight particles are moving with an average linear velocity of 200 m/s (Hazell et al. 2009).

The percentage of KE absorbed by the laminate appears to reach a plateau at elevated velocities, that is, for 5HS woven laminates at least. Figure 8.12 shows the percentage change of KE due to the perforation of a 6-mm-thick CFRP laminate. Here, the maximum impact velocity was 1875 m/s. It can be seen that above an impact energy of ~ 2000 J, the percentage KE of the

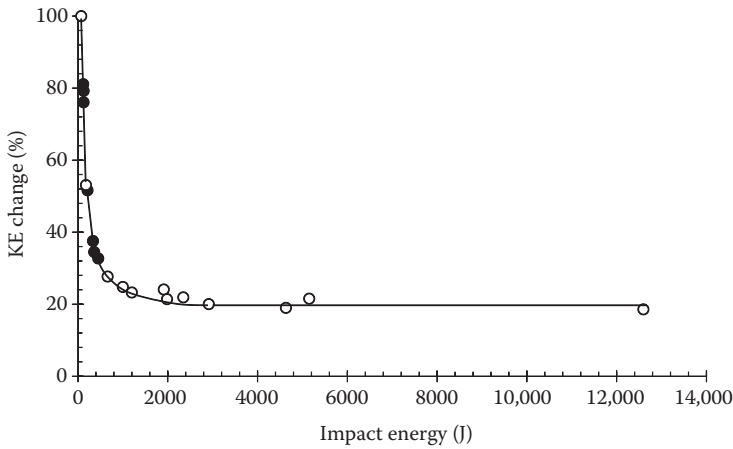


FIGURE 8.12

Percentage change in KE due to the perforation of a 5HS 6-mm-thick CFRP laminate; the different shading in data points indicates two separate experimental trials. (Reprinted from *International Journal of Impact Engineering*, 36 (9), Hazell, P. J. et al., 1136–1142, Copyright 2009, with permission from Elsevier.)

projectile that is absorbed is constant. This work also showed that the level of delamination in the sample was roughly constant, implying that at increased impact velocities, the majority of the energy that is dissipated in the CFRP laminate is from the comminution of the CFRP material and in the KE transferred to the particulated material. Given the low translaminar strength of these CFRP laminates and the weakness of the exposed fibres caused by the matrix particulation, the majority of the projectile energy would be given up to the KE of the particulates. In any case, it is clear that these materials do not respond well to ballistic impact.

8.5 Spall Shields

Most spall shields that are used in AFV design use the composite material construction that has been discussed in this chapter. The reason for this is that composite panels are

- Lightweight
- Mouldable to the internal structure of the vehicle
- Adept at ‘catching’ blunt fragments

The purpose of a spall shield is to catch any fragment that is produced when a metallic hull is perforated and limit the damage and injury that may happen inside the vehicle. This is all the more important when attack by shaped charge devices is considered. These shaped-charge jets frequently overmatch the armour and can result in the formation of high-velocity fragments. Spaced metallic plates have been shown to effectively reduce the number of fragments produced during shaped-charge attack (Horsfall 2005), and adding a 22-mm-thick plain weave E-glass polyester composite considerably improves performance (Horsfall et al. 2007) by reducing the angle of debris that is ejected. Horsfall et al. showed that more than 600 fragments were created by the penetration of a single 10-mm mild steel plate by a shaped-charge warhead. This produced a spall cone (a cone containing 95% of all fragments) with an included angle of $\sim 80^\circ$. Introducing the E-glass polyester composite panel behind this steel plate reduced the included angle of the spall cone to $<40^\circ$. This can significantly enhance survivability prospects for the crew of AFVs (see Figure 8.13).

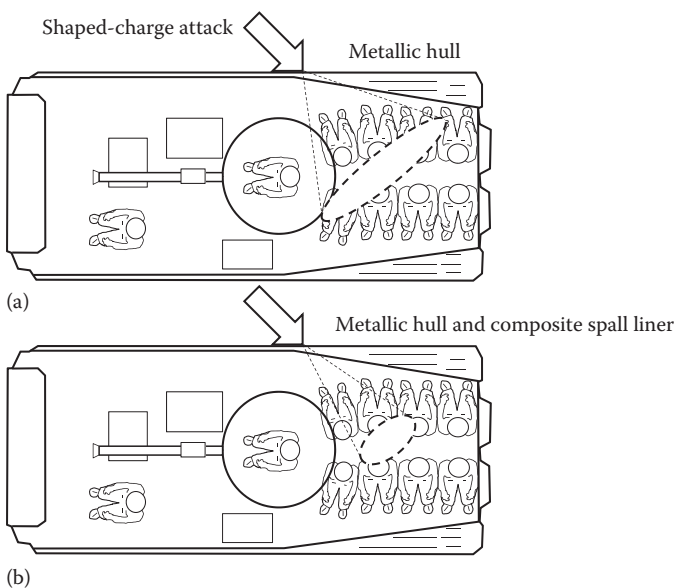


FIGURE 8.13

Spall debris formed when a shaped charge perforates the hull of an AFV with (a) no spall liner fitted and (b) with a spall liner fitted.

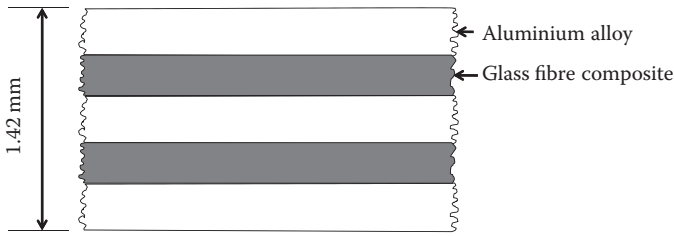


FIGURE 8.14
A schematic of GLARE.

8.6 A Word about Sandwich Constructions

We have already touched on the use of metallic sandwich constructions in Chapter 6 and seen that those with porous fillings can be useful in mitigating blast. Sandwich composite constructions are largely attractive for maintaining a high stiffness whilst ensuring good energy-absorbing abilities without excessive weight. Therefore, they are able to offer good specific strength and stiffness properties and have been attractive materials for aerospace structures.

One example of a sandwich construction that has been used in the aerospace sector is glass laminate aluminium–reinforced epoxy (GLARE). This is a fibre-metal laminate that has been used in the manufacture of the Airbus A380. It is composed of layers of aluminium alloy (usually AA 2024 T0) interspersed with layers of a glass fibre composite. The layers are bonded to each other with an epoxy resin. Several variants have been developed; a schematic of GLARE 3 is shown in Figure 8.14.

GLARE has shown improved prospects for blast mitigation when compared to a monolithic aluminium plate (Langdon et al. 2009); it has also been shown to have improved ballistic performance too when compared to plates of aluminium alloy of similar areal densities (Hoo Fatt et al. 2003).

There are multiple options for developing sandwich constructions for blast and ballistic loading, and more information on some of these structures that have been subjected to blast is given by Langdon et al. (2014).

8.7 Summary

In this chapter, some of the fibres that can be used in the construction of rigid composite panels and flexible woven materials have been reviewed. The former are commonly found in military vehicles, whereas the latter are more commonplace in personal protection applications.

The use of high-performing fibres and composite materials in the aerospace sector is well established (Soutis 2005). The reason for their use in aerospace structures is clear: they have excellent stiffness properties as well as good tensile properties, whereas their bulk densities are relatively low. They also lend themselves to vehicle design too and have good properties for blast mitigation as well as stealthy properties for reduced acoustic and thermal emissions. However, apart from a handful of demonstrators, at the time of writing, there is still a reluctance to push forward with the development of composite materials for armoured vehicle hull applications. The reason for this is probably that metallic hulls are well understood – particularly by the traditional suppliers of armoured vehicles.

The important part of the armour construction is the fibre. And it has mainly been due to the extensive research efforts dating back to the 1960s that have given us these high-strength fibres that are stronger than even the hardest steels. This, I suppose, underlines the importance of material science in the development of armour materials. If it was not for the conscientious scientists that were working away at these materials, then our ability to offer protection would have been inhibited. We can look forward to what science can produce in the coming years.

9

Reactive Armour Systems

9.1 Introduction

The shaped-charge or high-explosive anti-tank warhead has been around since before World War II. As seen in Chapter 3, the way it works is simple and elegant. High explosive, contained within a metal casing, is detonated resulting in a fast-moving shock front. This fast-moving front eventually encounters a copper liner that is essentially collapsed and turned inside out forming a stretching, fast-moving jet of material. Remarkably, contrary to popular myth, the material that forms the jet is not molten but rather a stretching plastically deforming rod. It is usually referred to as a 'jet' mainly because it is assumed that it behaves like a fluid in the models used to simulate its behaviour. However, due to the very high velocity of the tip (even velocities of over 12 km/s are possible), the jet possesses a very high energy concentrated over a very small area. This means that it is able to penetrate a large amount of steel armour such as rolled homogeneous armour (RHA). It is this fact that potentially makes armoured fighting vehicles (AFVs) vulnerable to attack from warheads such as the RPG 7* (see Figure 9.1), and consequently, it is a dangerous as well as a prolific threat. There are several approaches that are used to defeat these types of threats; these are reviewed in this chapter.

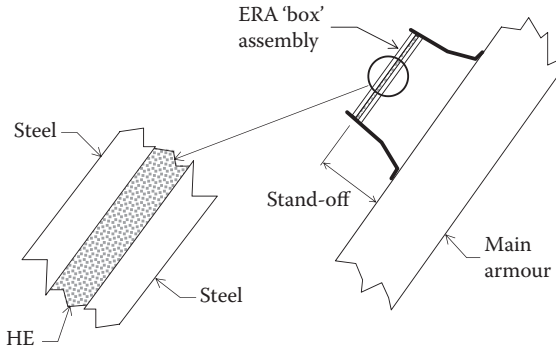
9.2 Explosive-Reactive Armour

ERA is probably one of the more widely recognised 'bolt-on' armour technologies mainly due to the fact that it stands out quite obviously on a vehicle (usually a tank). It is famous for its success in several conflicts too. Much in the same way that the formation of a shaped charge jet is simple and elegant, its defeat by ERA is also simple and elegant. Discovered by Manfred Held back in the early 1970s (Held 1970), the simplest construction of ERA consists of two steel plates sandwiching a layer of high explosive (see Figure 9.2).

* RPG = Rocket-Propelled Grenade.

**FIGURE 9.1**

A (PG 7) munition for an RPG-7 anti-tank grenade launcher.

**FIGURE 9.2**

A conventional 'tri-plate' arrangement of ERA.

These layers are usually contained in a robust mild steel housing to prevent operational and environmental damage. When the jet penetrates the outer housing and the first steel plate, it rapidly compresses the high explosive. The rapid compression of the explosive leads to detonation, propelling the steel sandwich plates apart. Frequently, the leading edge of the jet perforates through both plates before the flyer plate starts to move and therefore escapes any interaction. This portion of the jet is called the precursor, and its length is somewhat determined by the obliquity of the cassette and the velocity of the jet. It is this part, as will be seen later, that proves to be a challenge for lightweight AFVs. To maximise protection, it is necessary to accelerate the plates to a very high velocity to maximise the amount of material offered to the jet. The plate velocity depends on the mass of the plate and the type and mass of explosive – the first parameters to be varied in the pursuit of an efficient system. Finally, for optimum disruption, the ERA cassette is angled to the incoming threat. Therefore, the outer steel plate moves across the path of the jet thereby continually offering fresh steel to perforate – cutting a slot in the moving plate or plates. Disruption to the jet can also be caused at normal incidence (Brown and Finch 1989), and this is due to the impact of inverted jet material on the tail of the jet as the jet perforates the armour (Rosenberg and Dekel 1999). To have a substantial effect and be able to disrupt the jet at normal incidence, the explosive thickness should be at least twice the diameter of the jet (Brown and Finch 1989).

A typical specification of an ERA system is outlined in Table 9.1.

TABLE 9.1

Typical Specification of an ERA System Required to Protect an Armoured Vehicle

No.	Specification	Reason	How Will This Be Achieved?
1	At least two flyer plates should be used.	So that interaction with the jet will occur when impacted at the bottom of the tri-plate or the top.	By using at least one sandwich structure.
2	The flyer plate should be moving as quickly as possible.	So that the mass of material interacts with the jet as much as possible.	By using a relatively large mass of explosive as the interlayer.
3	The ERA should be able to accommodate attack from a range of incidence angles including a normal-incidence strike.	So that the performance of the armour is not compromised.	By using at least two tri-plate assemblies of different angles stacked on top of one another.
4	The ERA should be set at a distance from the main armour.	So that the rear flyer plate can travel and interact with the jet.	By using suitable fixtures.
5	The ERA should not be detonated by small-arms fire or other easily deployable weapon systems.	So that it is not easily cleared.	By using explosive materials that are not sensitive to impact.
6	Collateral damage should be minimised.	So that the risk of injury to surrounding personnel is low.	By using soft or frangible plates.
7	The ERA should be water-tight and survive extreme environmental conditions.	So that its performance is not comprised by temperature changes, wind and rain.	Coatings and coverings.
8	The ERA should be easily removable for maintenance.	So that it is easily maintained.	By using suitable fixtures.
9	The ERA should be replaceable if it is activated.	So that the vehicle can maintain good levels of protection.	By using suitable fixtures.

9.2.1 Historical Development

During 'Operation Peace for Galilee' in Lebanon in 1982, the IDF fielded its M60 main battle tanks (MBTs) with Blazer. This was the first bolt-on operational ERA package available for market. Blazer was designed and developed by the RAFAEL Armament Development Authority. Blazer can be fitted to any tank and is simply fitted by welding threaded studs to the MBT's hull. The armour is then simply bolted onto the vehicle using the threaded studs. It is claimed that, when fitted to an MBT in appropriate locations, it can completely defeat the 125-mm diameter Russian Kolomna KBM 9K11 ATGW at

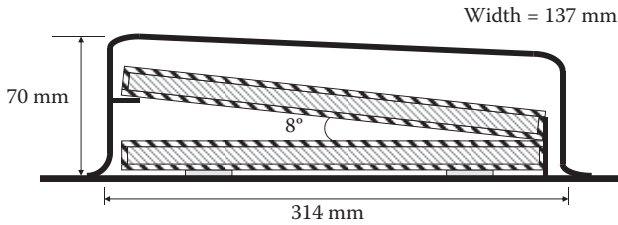


FIGURE 9.3
Early Soviet ERA twin-tri-plate assembly.

60° incidence as well as the RPG 7. The armour is, however, defeated if the missile contains more than a single warhead.

At that time, there was still considerable mystery surrounding ERA, and the raised studs observed on Centurion and M60 MBTs resulted in a number of speculative questions amongst military planners. Of course, the Soviets were not far behind in their use of ERA. The former Soviet Union has always been rather fond of applying ERA to their MBTs, and although much of the development of the armour occurred in the 1970s (soon after Held's discovery), it was not until the 1980s that they started using them on their tanks with the introduction of the 'Kontakt' series. A common form of the armour believed to have been fielded on the T 80 consisted of two explosive tri-plates within a single mild steel housing (see Figure 9.3). Two tri-plates are, of course, better than one. The additional tri-plate provides enhanced contact with the shaped charge jet. It also provides some defence to tandem warheads. If the first ERA sandwich is able to defeat the first shaped charge jet, the second ERA sandwich can be retained to defeat the main shaped charge warhead. Further, with the two tri-plates orientated at different angles, it is possible to minimise the reduced performance that would have otherwise been caused by two parallel plates colliding. It was believed that this type of ERA was capable of reducing the effectiveness of a 93-mm diameter shaped charge warhead by up to 98% when orientated at 70° obliquity. Typically, the explosive used was an RDX-based composition. An MBT would typically be fitted with between 200 and 300 boxes per vehicle.

9.2.2 Theoretical Considerations

In 1984, Mayseless et al. presented a theoretical model that showed how the flyer plates interacted with a fast-moving jet. They explained some of the characteristic patterns observed in flash x-rays of the ERA inducing a disturbance in the jet. Figure 9.4 shows a schematic of a shaped-charge jet perforating ERA. At the tip of the jet, there is an undisturbed region called the precursor. Moving back toward the warhead, there exists a region of disturbed jet material that appears to have an inherent waviness. Mayseless et al. observed that this disturbance was principally caused by the rear plate (they referred to this plate as the forward-moving plate or 'F-plate' – as it was moving in the

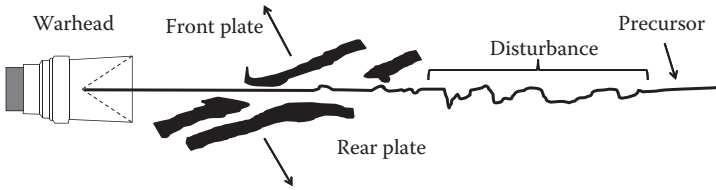


FIGURE 9.4
Perforation of ERA by a shaped charge jet.

same direction as the jet). That is, the F-plate was more effective at interacting with the jet and inducing a disturbance (i.e. see Mayselless 2011). They also proposed a model that they termed the ‘pebblestone model’ as the jet’s interaction with the plates was analogous to a pebblestone skipping on a pond.

On contact with the steel, the jet would cause the crater in the steel to grow at a velocity, v_e (Figure 9.5); this was estimated to be about half the jet velocity based on hydrodynamic penetration theory. The crater would grow until it was no longer stimulated by the jet material. Concurrently, the plate continues to move, being accelerated to the Gurney velocity by the impulse delivered to it by the explosive. Eventually, the crater wall of the flyer plate will come back into contact with the jet, and the process repeats. So, again, the crater wall is accelerated out radially in a direction parallel to the plate until it escapes the influence of the jet. The plate continues to move and so on.

If the motion of a particle (or Lagrangian gauge point) that was attached to the crater sidewall was examined such that it was not eroded by the contact with the jet, then that particle would follow a parabolic motion due to the

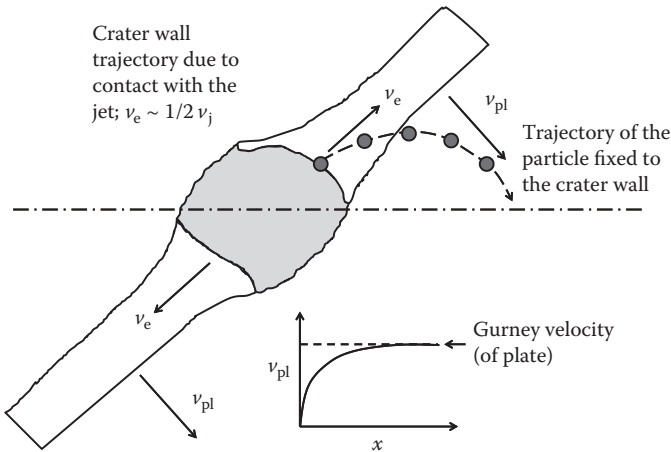


FIGURE 9.5
The ‘Pebblestone model’ to explain the jet ‘skipping’. (Adapted from Mayselless, M. et al., Interaction of shaped-charge jets with reactive armor, *Proceedings of the Eighth International Symposium on Ballistics*, Orlando, FL, 23–25 October, 1984.)

combination of crater growth and forward plate motion (see Figure 9.5). This process leads to the skipping motion that is seen in the disturbance of the jet.

Mayseless et al. deduced that the most important property in an ERA system was the mass flux (or mass flow) of material that was passed into the jet.

Held (2004) reported on a similar property to the mass flux, namely, the 'the dynamic plate thickness'. The dynamic plate thickness (Δs) is a rather arbitrary term that is a function of the plate velocity (v_{pl}), the interaction of time with the jet (Δt) and angle between the jet and the normal to the plate. It is defined by (Held 2004)

$$\Delta s = \frac{v_{pl} \Delta t}{\cos \theta} \quad (9.1)$$

The increase in plate velocity can be achieved from increasing the mass of the explosive in between the flyer plates. Held (2006) observed that increasing the mass of explosive increased the performance of 1-mm-thick flyer plates when penetrated by a shaped charge jet. Although Held did see a reduction in penetration into a mild steel witness plate (see Section 9.2.6), it was noted that increasing the thickness of explosive beyond 3 mm resulted in a diminishing return in performance. Nevertheless, the overall improvement in performance was thought to be linked to the increase in plate velocities as the explosive mass was increased.

In summary, it is probable that there are several factors that come into play during the penetration of a shaped charge jet into an ERA, and therefore, there are several parameters that can lead to the improvement in the performance of ERA systems. These can be summarised as

- The interaction between the jet and the cavity of the flyer plate (Mayseless et al. 1984)
- The interaction between the explosive products and the jet (i.e. see Mayseless et al. 1984; Brown and Finch 1989)
- The dynamic plate thickness, which takes into account the velocity of the flyer plate (Held 2004)

9.2.3 Defeating Long-Rod Penetrators

The former Soviet Union were always interested in the defeat of armour-piercing fin-stabilised discarding sabot (APFSDS) rounds too. This interest was largely driven by the large tank battles that occupied the minds of military planners during the Cold War. Such a projectile travels much slower than the tip of the shaped charge; however, they are made from heavy metallic tungsten–nickel alloys or depleted uranium alloys. The diameters of these rods are much larger too with diameters of 20–30 mm as opposed to 2–3 mm commonly seen in shaped charge jets. Consequently, they are much more

difficult to disrupt than the relatively thin jet of copper from a shaped charge warhead. Nevertheless, some early Soviet-era armours claimed to be able to do this. Mostly, APFSDS-defeating ERA consists of heavier and harder plates and larger volumes of high explosives. Probably the most famous example is Kontakt 5 that has been deployed on T80Us and T90s. Some reports suggest that it adds 300 mm of equivalent RHA protection against APFSDS rounds by the propulsion of a 15-mm-thick front flyer plate. However, thicker plates mean that you have to use thicker explosive layers.

Held (1999) presented results that showed the effectiveness of a 40/10/25 system (corresponding to 40 mm of steel, 10 mm of high explosive backed by 25 mm of steel) against long-rod penetrators. His results showed that such armour reduced the residual penetration of a modern APFSDS projectile into a backing plate of RHA from 800 to 190 mm by the addition of the ERA.

Offering the flyer plates to the incoming projectile at an oblique angle is essential. This is because the main mechanism of defeating the long-rod projectile is by the process of momentum transfer. That is, the flyer plate hits the projectile sufficiently hard so that it knocks it off course. More importantly, the rod is fragmented during the interaction, and therefore, more accurately, it is the fragments from the rod that are knocked off course. The explosive itself has relatively little effect on the rod compared to the flying metal, and therefore, nearly all of the disrupting work needs to be done by the plates themselves. There is also the risk of considerable behind armour debris too as such armour only breaks the rod into fairly large fragments. Despite the fact that these fragments of the projectile are deviated from their path with some degree of yaw, it is highly likely that a considerable mass of armour is required to 'mop up' these fragments. Consequently, this type of armour is only applicable to MBTs.

Very few manufacturers want to talk about how their armour responds to explosively formed projectiles (EFPs) that would be launched from top-attack or off-route mine weapons systems. Although many manufacturers claim very impressive non-initiation criteria, the EFP provides a particular difficult problem for ERA. This is for two reasons. First, well-formed EFPs tend to have relatively flat noses when compared to the sharp ogival form of small-arms projectiles. This can create a situation analogous to a plate-impact experiment where a high-intensity shock wave is formed on contact with the steel. They travel at relatively high velocities too and can reach impact velocities as high as 2000–3000 m/s. Both of these factors increase the propensity to cause shock initiation of the explosive in between the steel sandwich layers of the ERA. Secondly, EFPs tend to be short and fat projectiles as opposed to long and thin jets or rods. This makes it particularly difficult to disrupt the projectile by the moving steel plates unless the plates are sufficiently thick. Certainly, ERA that has been designed to defeat shaped charge jets will have very little effect on this type of projectile, whereas those that have been designed to cope with large-calibre long-rod penetrators will fare better.

9.2.4 Low Collateral Damage

So, if ERA is a very weight-efficient system, why has it taken Western countries so long to adopt the technology? In recent years, there has been a drive toward providing so-called low collateral damage reactive armour systems. This has mainly come about due to political and operational pressures. Reactive armour systems, by their very nature, can prove to be a risk to anybody that is happened to be standing around the AFV when it has been hit by RPG (although arguably, the explosive and the fragments from the warhead alone would pose considerable danger to nearby individuals). It can also prove to be a problem to any low-flying aircraft too – mainly because of the high velocity that is reached when the plates are accelerated. A calculation using the Gurney equation reveals the velocities achieved possible from a simple tri-plate assembly.

Example 9.1

An ERA trip-plate assembly consisting of a $3 \times 150 \times 100$ mm plate of steel ($\rho = 7800 \text{ kg/m}^3$) is propelled vertically into the air by 3 mm of high explosive ($\rho = 1770 \text{ kg/m}^3$). Calculate the velocity that it reaches. The plate velocity can be evaluated by using the well-known Gurney analysis (Gurney 1943), and for a symmetrical sandwich, this can be calculated by

$$v_{\text{pl}} = \sqrt{2E} \left(2 \frac{M}{C} + \frac{1}{3} \right)^{-\frac{1}{2}} \quad (9.2)$$

where v_{pl} is the velocity of the flyer plate, M is the mass of the flyer plates, C is the charge mass, and $\sqrt{2E}$ is the Gurney constant that is specific to the explosive composition used. Assume a $\sqrt{2E}$ of $2.93 \text{ mm}/\mu\text{s}$ (a value that is used for RDX (Meyers 1994).

- The mass of a single steel plate and explosive can be calculated to be 0.351 and 0.0797 kg, respectively.
- From Equation 9.2, the velocity of the flyer plates can be calculated to be 692 m/s.

From this example, it can be seen that plates can fly at very high velocities and travel very large distances; ranges of up to 80–100 m are not uncommon. A possible sensitivity to this issue by Western armed forces is exemplified by the Challenger I and Challenger II. Originally, the Challenger I was fitted with ERA modules during Operation Desert Storm and subsequently to Challenger II operations in the Balkans. These were fitted to the lower glacis plate only. Consequently, any activity from the plates would merely lead to flyer plates being driven into the ground thereby reducing the risk

to others. However, some argue that the risk to any surrounding personnel is largely unfounded because any shaped charge warhead contains enough high explosive and hard casing material to kill all individuals in close proximity to the vehicle.

Modern ERA packages also must provide sufficient protection against small-arms ammunition, and the explosive employed must be sufficiently insensitive so that it is not detonated by fragments. Protection against heat sources such as that provided by exposure to napalm is also desirable.

Protection behind the main ERA cassette is also very important for lightweight vehicles that employ ERAs. ERAs do not stop the precursor portion of the jet. An MBT has relatively thick armour behind the explosive-reactive appliqué and therefore is capable of stopping all of the jet. Lightweight vehicles, on the other hand, generally have relatively thin hull armour; therefore, the jet is more likely to perforate. This is highlighted by the common threat to lightweight armoured vehicles – the RPG-7 grenade, which is capable of penetrating 300 mm of armour steel. Whilst ERA can reduce this penetration by 90%, this still leaves the jet penetrating 30 mm of steel – a thickness greater than that offered by the hulls of lightweight vehicles.

A workaround is simply adding more steel behind the ERA cassettes. This was done when ROMOR-A, a Royal Ordnance development, was fitted to Italian Centauro vehicles for operation in Somalia in the early 1990s. However, adding sufficient steel to mop up the precursor of the jet increased the weight of the vehicles significantly. Reinforcing the vehicle's hull is also sometimes necessary when the ERA is fitted to thin-skulled vehicles such as the M113 or the FV432 (these are two similar armoured fighting vehicles). The rear plate will also have quite considerable kinetic energy and can cause considerable shock effect to the vehicle's structure. Aluminium-hulled vehicles such as the M113 are particularly vulnerable as armour-grade alloys such as the 5083 type have a tensile strength that is somewhat lower than that of armoured steel. If the rear flyer plate hits the vehicle's aluminium hull with sufficient velocity, there is a risk that serious damage could occur to the armour.

Other advances in the use of ERAs include using polyethylene flyer plates as opposed to steel plates. This approach is behind Verseidag Ballistic Protection and Dynamit Nobel Defence's Composite Lightweight Adaptable Reactive Armour (CLARA). When each module explodes, the flyer plates shatter into relatively harmless fibre shards (Ogorkiewicz 2007). Consequently, the risk to dismounted troops and civilians in the local area of the vehicle is considerably reduced. Each CLARA bolt-on module weighs 18.5 kg and is only 100 mm thick excluding the stand-off required. CLARA has also been tested on a Rheinmetall Landsysteme Marder 1A5 Infantry Fighting Vehicle using a surrogate RPG warhead. Although the surrogate warhead was capable of penetrating 320 mm of RHA without any reactive armour protection in place, the jet was almost completely destroyed by the action of CLARA with only 6 mm of penetration into the steel armour.

Kauffman and Koch (2005) used a 50-mm diameter shaped charge warhead to test a variety of candidate flyer materials. They examined a variety of materials including steel, aluminium, polycarbonate, polyethylene and a GFRP as candidate ERA flyer plates. Their work showed two important results. Firstly, the protection efficiency of the low-density materials is good compared to steel, and secondly, to reduce the collateral damage, it is advantageous to use brittle materials, producing small and lightweight fragments. These results are consistent with a sound theoretical and long-understood principle. The fact that low-density materials are in fact useful at stopping shaped charge jets is not new. Using plates that are broken into small and lightweight fragments is also attractive, and that is why others have chosen to use flyer plates constructed from brittle materials such as ceramic and glass (Koch and Bianchi 2010; Hazell et al. 2012). Smaller fragments will decelerate faster in air than heavier fragments and consequently will pose less of a risk to personnel.

9.2.5 Explosive Compositions

The use of low-sensitivity explosives in ERA is important in maximising commercial gains that can be made in the armour business. Many countries, such as the United Kingdom, are only prepared to adopt insensitive munition-compliant products in service. Explosives that are very difficult to accidentally initiate are almost universally cast polymer bonded explosive (PBX)-based materials. These materials are very difficult, if not impossible, to initiate unless a very violent stimulant such as a shaped charge jet penetrates them. Due to the very high pressure region incurred in the explosive composition by the jet, it is relatively simple to guarantee initiation when desired whilst at the same time remaining safe at all other times. There are a number of tests that are done to check this. The most stringent of tests is done according to STANAG 4496 where a steel fragment-simulating projectile is fired at the armour at around 2500 m/s to test whether the explosive is shock initiated. This is the worst-case scenario for an impact from high-velocity fragment that has been propelled from a 155-mm HE shell.

9.2.6 Testing and Performance Improvement

Testing of the ERA assemblies is not always that straightforward as warhead quality can be quite variable. The commonly used approach used to evaluate the ERA's performance is by using the standard depth-of-penetration approach (see Chapter 11). A common set-up is shown in Figure 9.6 where the performance of the armour is evaluated by measuring the depth of penetration in the steel stack. Sometimes, it is advantageous to insert a thin (~5-mm) steel plate set at some distance from the ERA cassette to 'clean' the front of the jet and to improve consistency.

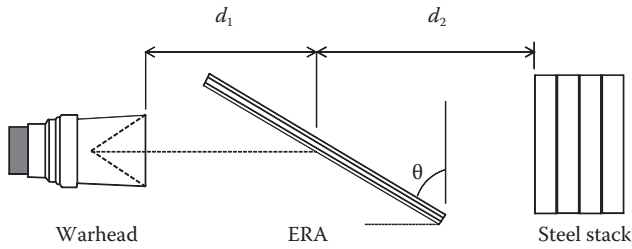


FIGURE 9.6
Standard ERA test.

9.3 Bulging Armour

The safety and lethality implications of ERA have led to the development of a reactive armour system that employs an inert rather than an explosive interlayer material. Non-ERA consists of an inert low-density interlayer material sandwiched between two parallel steel plates. This concept was first patented by Held in 1973. The plates do not separate from the armour cassette at high velocity and therefore do not pose a threat to dismounted troops and civilians. However, because the velocity of the plate separation is relatively small when compared to conventional ERA, it does not perform as well.

A generalised view of how this system works was postulated by Gov et al. (1992): A shaped charge jet that perforates the outer layer of steel deposits considerable energy into the interlayer. The interlayer is compressed by a hemispherical 'piston' that consists of the bulging front-plate material backed by the eroding jet. The filler acquires both internal energy as it compresses and kinetic energy as it moves axially and radially away from the penetrating 'piston'. The compressed interlayer presses against the rear plate of the cassette along the axis of jet penetration and accelerates it. This portion of the rear plate is also accelerated further when the jet comes into contact with it. Furthermore, a shock wave emanates from the region of local compression and propagates in a radial fashion away from the central axis accelerating the plates apart. For a cassette placed at a relatively high angle of obliquity, the plates that are accelerated apart come into contact with the shaped charge jet and disturb it thereby reducing its lethality.

The main defeat mechanism is due to the interaction between the steel plates and the shaped charge jet – it is therefore advantageous for the holes that are formed by the jet to be as small as possible. This can be achieved by using high-hardness steels to ensure that the hole growth is limited as the jet perforates the front plate. Other factors include the thickness and choice of the interlayer materials (Thoma et al. 1993), which can greatly affect the bulging velocity of the plates and hence the interaction with the jet (Rosenberg

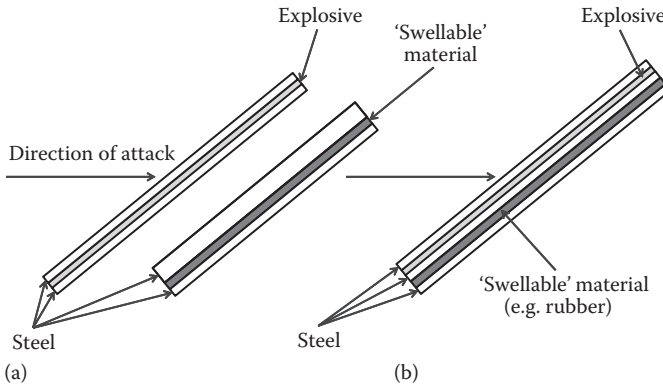


FIGURE 9.7

Two passive-reactive cassette options as suggested by Benyami et al. (1991). (From Benyami, M. et al. Combined reactive and passive armor. In *Google Patents*. Israel: The State of Israel, Ministry of Defense, Rafael Armament, 1991.)

and Dekel 1998). For example, low-density polymers such as Dyneema® have been previously used as effective interlayer materials (Held 2001).

Because of their relatively simple construction, these passive sandwich assemblies are relatively cheap and easy to apply. However, because these systems only work by minimising the residual penetration achieved by a jet after perforating the armour, they are often applied in multiple assemblies or in tandem with other effective armour systems.

9.3.1 The Passive-Reactive Cassette Concept

A notable improvement to ERA cassette design involved incorporating a bulging armour assembly with the conventional tri-plate ERA assembly (Benyami et al. 1991). This has been shown to lead to a reduction in length of the precursor element of the jet (Brand et al. 2001). The diagrams of two possible configuration options are shown in Figure 9.7.

9.4 Electric and Electromagnetic Developments

In recent years, it has been realised that it is possible to disrupt a shaped charge jet by virtue of applying a short burst of electrical energy through it. This was first proposed by Walker in 1973. The concept is shown in Figure 9.8. The system works by delivering a large electrical current ($\sim 10^2$ kA) through the jet when it makes contact with the 'hot' plate, as seen in Figure 9.8. Essentially, the jet acts like a switch – making contact with the outer ground

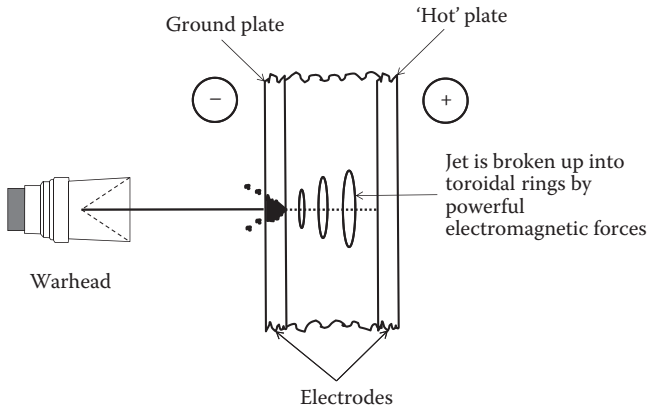


FIGURE 9.8
The electric armour concept.

plate and the inner 'hot' plate simultaneously. This results in powerful electromagnetic forces disrupting the jet causing it to split up into discrete toroidal rings through a process called magnetohydrodynamic pinch (Littlefield 1991; Shvetsov et al. 1999; Swatton et al. 2001). Experimental evidence has shown that these rings expand with a radial velocity of up to 200 m/s when a 200–250-kA current is applied to the jet (Appelgren et al. 2010). A lesser disruptive effect through lateral dispersion also occurs arising from the forces that occur due to the interaction between the current in the jet and the magnetic field generated by the plates. The dispersed/toroidal parts of the jet are then stopped by the vehicle's base armour.

Other concepts include using electromagnetic energy to propel steerable electromagnetically driven flyer plates into the direction of an incoming threat (Sterzelmeier et al. 2001). The concept is similar to ERA, except that in this case, the plates are electromagnetically driven. These are more akin to hard-kill defensive aid suites (DASs) that will be discussed in Section 9.5.

9.5 Hard-Kill Defensive Aid Suites (DASs)

A relatively modern phenomenon in the protection industry is the development of intelligent protection systems that are able to detect, track and engage an incoming projectile threat. This is not a trivial task as many of the weapon systems are travelling toward their target (i.e. you) at very high velocity. To illustrate how difficult this is to engineer, Table 9.2 lists several anti-tank weapon systems and their velocities and the time they take to travel 500 m (assuming that this is a mean engagement distance). Now,

TABLE 9.2

Typical Anti-Tank Weapon Systems, Their Velocities and the Time Taken to Travel 500 m

Threat	Typical Mean Velocity (m/s)	Time Taken to Travel 500 m (s)
M72 LAW	145	3.45
Swingfire	185	2.70
RPG-7	295	1.69
BGM-71 TOW	300	1.67
AGM-114 Hellfire	425	1.18
APFSDS	1500	0.34

clearly, there is going to be a velocity drop-off due to air drag; however, these data give a good rough order of magnitude in terms of the required response time of the target.

Notably, for APFSDS projectiles travelling at 1500 m/s (a typical muzzle velocity for these types of projectile), a system will need to respond, identify the threat and track the incoming projectile and deploy a countermeasure (or 'effector') within a very quick time.

An integral part of the active protection system is the sensor technology employed to detect and track the threat. The sensors are required to be sensitive enough to detect the threat at a suitable distance so that the active protection system has time to respond. Detection distances of up to 30–50 m are often claimed. A common way of detecting the threat is by using millimetric wave radar. The low wavelength of this type of radar enables good resolution to the extent that even the distinguishing features of a threat are observable. However, using such active radar continuously can have the adverse effect of advertising your position to the enemy. Consequently, radar is often cued into action by passive infrared sensors that look for a flash associated with a missile or gun-launched penetrator.

Ultimately, all this information needs to be processed somehow, and consequently, all systems are fitted with an onboard computer. If established technology is used, the electronic components in themselves can be relatively cheap. However, all systems need to be suitably rugged for the military environment, and it is this requirement that often pushes the price up. In particular, today's modern army places high demands on its equipment due to the variety of extreme locations and circumstances in which battles are fought.

There are two principle ways of attacking an incoming fast-moving threat. This is achieved using an 'effector' and can be done in two ways:

- a. Delivering a directed explosive blast toward the object (Lidén et al. 2013) or by
- b. Delivering a fast-moving projectile/fragment to intercept the incoming object

Delivering a directed explosive blast is more attractive for active protection applications for two reasons (Heine et al. 2013):

1. The very fast reaction times can be achieved from the detonation of the explosive to the propagation of the blast wave over several metres. This means that an impulse can be offered to the flying object in a very short period of time.
2. As the blast wave decays rapidly, there is less likely to be any collateral damage problem that would otherwise occur if the effector was a projectile.

There have been a few notable active protection systems deployed on armoured vehicles in the past. Three are now briefly discussed: Drozd, Arena and Trophy.

9.5.1 Early DAS Systems: Drozd

One of the earliest active protection systems fielded and probably the best known is the Drozd or 'Thrush'. This system was first fielded in the early 1980s by Soviet forces. The system was developed by the Konstruktorskoe Buro Priborostroeniya (KBP) Instrument Design Bureau to defeat North Atlantic Treaty Organization (NATO) missiles such as the Tow and Milan. Both missiles deploy precursor shaped charges, thereby potentially rendering ERA less effective. Therefore, having the ability to kill the missile before contact with the armour is an attractive ability. The Drozd system uses two millimetric-wave radar antennae mounted on each side of the turret to detect an incoming missile. When the radar system detects an incoming missile, an unguided 107-mm diameter rocket is launched, and at a calculated time, the rocket detonates propelling a cone of fragments toward the flight path of the incoming missile. In the vertical plane, the protection zone given by the system is $+20^\circ$ through to -6° and in the horizontal plane, $\pm 40^\circ$. The system consists of a full complement of eight missiles permitting eight separate defences; crew replenishment time is 10 min. The original Drozd system was only fitted facing forwards of the turret leaving the flanks and rear of the vehicle vulnerable to attack. A subsequent system, Drozd 2, comprises a total of 18 individual launch tubes arranged around the turret. Each of these launch tubes covers an arc of 20° and from -6° to $+20^\circ$ in the azimuth. The updated system apparently weighs no more than 800 kg making it a possible system for lightweight armoured vehicles. The system is not activated by small-arms fire and can happily deal with incoming missiles travelling at between 50 m/s and 700 m/s.

The Drozd system does highlight one of the more unfortunate aspects of active protection systems – the risk of collateral damage. Consequently, the Drozd system is fitted with an interlock system so that the unguided countermeasures cannot fire when the hatches of the tank are open. The ejection of a

cone of small fragments from a detonating munition poses a very dangerous risk to dismounted troops or civilians. Some would argue that this is largely a moot point because any personnel within the vicinity of the vehicle would be killed by the blast and fragments from the incoming warhead anyway. However, it is unclear as to the extent of the danger radius for the Drozd.

The sort of fragmenting munitions that are fired from the active protection systems can propel small fragments up to velocities of 1500 m/s, and consequently, they can be lethal to quite large distances. If explosively driven steel plates are used instead of fragments, then distances of up to 100 m can be achieved from relatively thin layers of explosive.

9.5.2 Arena

The Arena system was developed in the 1990s partly as an evolution of the Drozd system. This system can weigh up to 1300 kg depending on the vehicle that it has been applied to, and it has been exhibited on the T 80 Main Battle Tank and the BMP 3 infantry fighting vehicle. A radar mounted toward the rear of the turret detects the incoming missile at around 50 m from the vehicle. An onboard computer then decides which of 22 projectiles to launch toward the incoming threat. Like the Drozd 2 system, there is potentially 360° coverage around the vehicle; however, there is a small dead zone behind the radar making attack from behind a dangerous possibility. Moreover, the radar system is, due to its size and prominence, a vulnerable asset to the vehicle. It is supported by three legs that are most probably susceptible to damage by sustained heavy machine gun fire. Whether or not the main unit is susceptible to heavy machine gun fire is unknown.

9.5.3 Trophy

It is not just the former Soviet states that have been heavily involved in the development of active protection systems. In 2004, Israel revealed the Trophy active protection system that had been in development for approximately 10 years.

The Trophy active protection systems have been touted as defeating all types of anti-tank guided missile systems as well as rockets at a significant distance from the platform. There are two key parts to this active protection. The radar system is coupled to four-panel antennae that are located at the front sides and rear of the vehicle that is being protected. This configuration can supposedly detect top-attack munitions. The other system of importance is the hard-kill system. Relatively few details of how the active protection system works; however, it is rumoured that the hard kill part of the system works on firing a focused 'beam' of explosive energy (Ogorkiewicz 2007). That is, an explosive charge is detonated that is focused toward the incoming threat. This seems plausible as the developers have claimed that the missile can be defeated at significant distances from the vehicle with minimal

collateral damage. If a fragmenting munition is used, then collateral damage becomes a problem, as discussed in Section 9.5.1. It is also known that the system will only be activated when a direct threat to the vehicle is detected. Missiles that are predicted to miss the vehicle are deliberately ignored. The further attractive feature of Trophy is that all in it weighs less than 500 kg – considerably lighter than Drozd or Arena. And, it can be fitted to light-weight vehicles too – such as a high mobility multipurpose wheeled vehicle (HMMWV) (Foss 2011).

9.5.4 Defeating Long-Rod Penetrators

The ability of an active protection system to defeat long-rod penetrators is a particular engineering achievement. Unlike missiles and rockets, the projectile consists of a single lump of dense metal, usually depleted uranium or a tungsten alloy, the performance of which cannot usually be compromised by small fragments. One possible way of defeating a long-rod penetrator is by using the force of a shock wave to deflect the incoming projectile some distance out from its target. There are a number of technical challenges that need to be overcome to achieve this; here are a few:

1. High-fidelity detection and tracking systems are required to detect and track the incoming projectile that potentially will be travelling at between four and five times the speed of sound.
2. The countermeasure needs to be positioned very close to the penetrator at detonation as the amount of energy delivered to the projectile by the shock will rapidly diminish with distance.
3. The composition of the explosive must be such that it can withstand setback forces resulting from the acceleration to the required relatively high intercept velocities.

The main purpose is often to induce yaw into the incoming rod where the yaw is defined as the angle between the trajectory of the projectile and its axis (see Figure 9.9). Even small angles of yaw can lead to dramatic penetration ability (Hohler and Behner 1999; Anderson, Jr. et al. 2013). Hohler and Behner showed that for a rod with a length/diameter ratio of ~20, and a yaw angle (α) of 20°, the penetration into a steel target was reduced by 60% compared to a non-yawed rod – see Figure 9.9.

Other methods that have been discussed in open forums include the use explosively driven projectiles of relatively high mass. These are again designed to induce a small degree of yaw or alternatively cause the rod to fracture – thereby reducing its effective length offered to the target (see Figure 9.10). A sufficient impulse delivered to the side of a flying rod can potentially cause this effect. This method is particularly attractive if the rod is made from depleted uranium. This is because depleted uranium is less

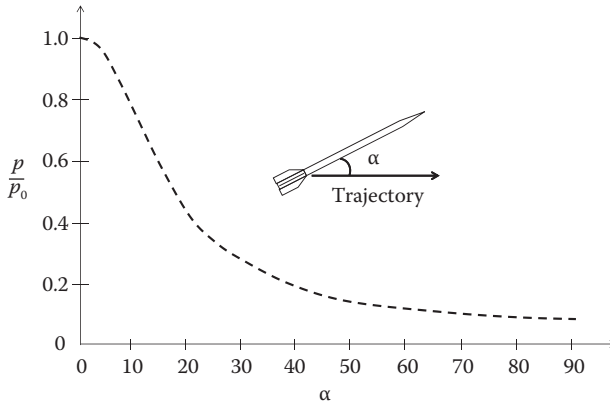


FIGURE 9.9

The drop-off in normalised penetration into steel (p/p_0) as the yaw angle of penetrator (α) is increased, where p is the penetration measured into a semi-infinite steel plate where yaw is preferentially induced before impact and p_0 is the penetration into the steel with no yaw ($\alpha = 0$). Inset: a diagram of a yawed projectile. (Adapted from Hohler, V., and Th. Behner, Influence of the yaw angle on the performance reduction of long rod projectiles, *Proceedings of the 18th International Symposium on Ballistics*, San Antonio, TX, 15–19 November, 1999.)

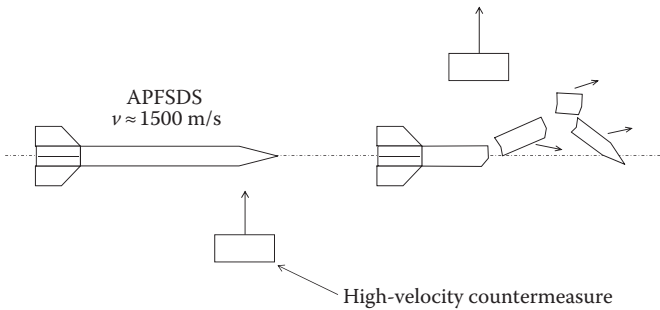


FIGURE 9.10

Inducing fragmentation in an APFSDS round by delivering an impulse.

stiff than the commonly used tungsten alloy materials and consequently will mean that it should be easier to induce failure by bending.

Once the rod has been fragmented, the effectiveness of the rod is reduced considerably. This is due to two principle reasons. Firstly, penetration depth is very much dependent on the length of the penetrator, and consequently breaking the rod up will reduce the amount of penetration in the target. Secondly and perhaps more importantly, the other advantage of fragmenting the rod is that the impulse delivered to the rod will induce yaw in the fragments. This leads to a significant reduction in penetration depth. Of course, this also highlights the importance of armour to ‘mop up’ the fragments that still could be lethal despite their effectiveness being dramatically diminished.

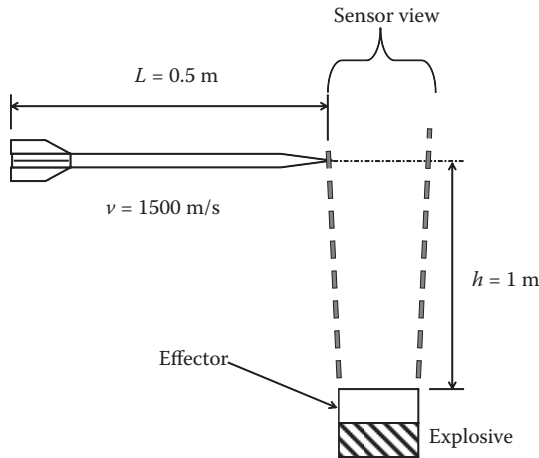


FIGURE 9.11

A hypothetical design of a hard-kill countermeasure system designed to engage an APFSDS projectile.

So, how far away do I need to be to adequately engage an APFSDS projectile? Let us consider this problem:

Consider a hypothetical case where the sensor view is restrained to just overhead of the countermeasure. The problem is described in Figure 9.11. The system is required to engage with a 0.5 m long APFSDS projectile and needs a tungsten countermeasure to contact with the projectile halfway along its length. What is the average velocity required by the countermeasure to make contact with the rod, assuming that the rod passes over at a height of 1 m at a velocity of 1500 m/s?

Firstly, the time taken for the rod to traverse 0.25 m (half its length) is given by $t = s/v$ (where s and v are displacement and velocity, respectively). Therefore, $t = 167 \times 10^{-6} \text{ s}$. So, the tungsten countermeasure needs to travel 1 m in $167 \times 10^{-6} \text{ s}$ ($167 \mu\text{s}$). Basically, it needs to be accelerated to a truly enormous velocity.

9.5.5 A Developing Trend

It is possible to use a deployed airbag to detonate an incoming RPG (Fong et al. 2007). Although using an airbag to defeat threats is not a new idea, it is an interesting development as such a system considerably reduces the collateral damage risk. Similar systems have been suggested for providing hidden yet rapidly deployable protection against small-arms bullets. These systems principally use the relative speed of the threat and the airbag to cause a disruptive effect. In the case of the RPG, this will involve detonation of the high explosive at a decent stand-off so that the shaped charge jet does not

perforate the armour. The concept that was presented by Fong et al. involved a 4-in. tactical air-bag munition that was deployed to intercept the incoming RPG. The airbag tested was from a Ford Taurus. Due to the spherical nature of the deployed airbag, the system is aerodynamically stable, which is useful when you are trying to hit a projectile travelling at high velocity.

The airbag approach is very attractive due to the reduction of the risk of collateral damage. This is particularly true if the airbag is able to disable the fuze system.

9.6 Summary: What about the Future?

So what of the future? Sadly, we are still a long way from the magical invisible shields of Star Trek fame, but there are still some exciting possibilities that are available to us from known science.

We have seen with electric armour that it is possible to use electricity to defeat shaped charge jets, but what about using electrical energy to defeat an incoming missile before it strikes the vehicle? Projectiles can, for example, be electromagnetically driven toward the incoming threat. This can be achieved by adopting a design similar to a linear motor. Linear motors are commonly used to propel trains to high speed, although the acceleration required in these applications is far less than would be desired from an active protection system. Similar systems have been proposed for weapon systems such as coil guns. With this system, electromagnetically generated forces are able to accelerate the projectile to a high velocity. The advantage of this type of system for active protection systems is that it affords the possibility of accelerating projectiles of various geometries including meshes or grids. This is unlike explosively driven projectiles that require a large surface on which the explosive products can act. Therefore, it is possible to use a lower mass projectile that reduces the risk of collateral damage whilst maximising the possibility of contact with the threat. With grids or meshes, a larger surface area is afforded for the same mass as a relatively small solid plate, and therefore, it is possible to maximise the probability of contact with the threat.

There are a number of challenging problems to overcome before we will see such a system fielded – most notably a suitably small capacitor bank that is able to deposit the large amount of electrical energy that is required to drive a projectile large enough to have a disruptive effect.

Other possibilities of using electricity to defeat incoming threats include the use of lasers. There are two notable programmes that have been developed with US funding: Tactical High-Energy Laser and the US Air Force's Airborne Laser. Both are designed to destroy missiles with the latter being mounted in the nose-cone of a Boeing 747. However, both systems are very

large and in no way could be integrated into an armoured fighting vehicle – mainly due to the high power demands of such systems.

Whatever the future holds, this author sincerely hopes that however advanced active protection systems become, the importance of passive armour is never diminished. After all, a suitably thick plate of RHA or equivalent provides occupants the guaranteed security that at least there are certain threats that will not make it through to the crew compartment.

10

Human Vulnerability

10.1 Introduction

When providing protection, it is sensible that we develop an understanding of how the human body responds to impact and penetration by projectiles and to blast. In this chapter, some of the more pertinent discoveries will be reviewed with regard to the mechanics of wounding. We will also look at some of the techniques used in armoured vehicles to minimise injury and therefore maximise survivability.

In most conventional wars to date, fragment wounds have outnumbered bullet wounds quite considerably. With jungle warfare and the conditions associated with urban terrorism, bullets are the most common threat (Table 10.1). This is likely to be due to greater sniping activities in these environments as well as less intense artillery use. Possibly, less apparent use of artillery and more urban-based conflict are also the reasons why there was less apparent fragmentation injuries in the 2003 Gulf War compared to the 1991 conflict (Hinsley et al. 2005).

In more recent years, understanding the mechanisms of blast-related injury has become all the more important – particularly with regard to injuries sustained to vehicle occupants during an improvised explosive device (IED) attack. This will be explored in more detail later.

10.2 Human Response to Ballistic Loading

10.2.1 History

Much of the early work on wound ballistics was carried out by Emil Theodor Kocher (Fackler and Dougherty 1991). Kocher was born in Bern, Switzerland in 1841 and became professor of surgery at the University of Berne in 1872. Around that time, it was widely thought that the wounding mechanism of tissue by a bullet was caused by three factors:

TABLE 10.1

Cause of Wounds to Casualties (%) from Various Conflicts; Data Taken from Different Sample Sizes and over Different Time Durations during the Conflicts

Conflict	Bullets	Fragments	Other (e.g. Traumatic Amputation due to Blast)
World War I	39	61	–
World War II	10	85	5
Korea	7	92	1
Vietnam	52	44	4
Borneo	90	9	1
Northern Ireland	55	22	20
Israel 1982	11.6	53	35.5
Falkland Islands	31.8	55.8	12.4
Gulf War 1991	20	80	–
Gulf War 2003	37	62	1

Source: Ryan, J. M. et al., *Annals of the Royal College of Surgeons of England*, 73 (1):13–20, 1991; Spalding, T. J. W. et al., *British Journal of Surgery*, 78 (9):1102–1104, 1991; Hinsley, D. E. et al., *British Journal of Surgery*, 92 (5):637–642, 2005.

Note: The Israeli data are complicated by the inclusion of psychiatric casualties in the group 'Other'.

1. A partial melting of the bullet on impact,
2. The centrifugal force of the spinning bullet fired from a rifled barrel and
3. Hydraulic pressure (that is to say, a high pressure region emanating from the bullet and expanding out radially behind it).

Kocher fired at several targets including metals, glass bottles, pig bladders and pig intestines and human cadavers. Most pertinently, he fired a lead alloy bullet from a Vetterli rifle into a water-filled box faced with a pig bladder. The box was 1.5 m long faced with a pig's bladder (which covered a hole in the box). Kocher observed that the bullet pierced the pig's bladder and struck the rear wall of the box. Also, the box burst catastrophically at the seams due to the passage of the bullet through the water. Kocher concluded that hydraulic pressure (i.e. a high-pressure region radiating out from the bullet to form a temporary cavity) caused the box to burst and therefore was primarily responsible for tissue disruption. Consequently, Kocher concluded that partial bullet melting and centrifugal forces were of little importance to wounding.

At the time of Kocher, 'fishing' with dynamite was a commonplace pastime, and in 1898, it was shown that firing a bullet close to a fish resulted in its death without any obvious injury (*The New York Times* 1898). It was

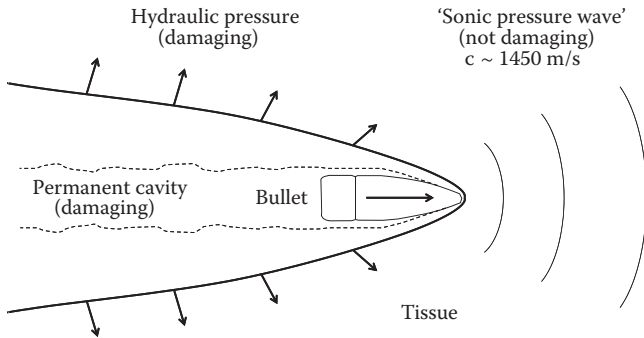


FIGURE 10.1

The effects of a projectile penetrating through tissue.

reported that an Italian officer, Major Michelini, fired an Italian (0.256-in. calibre) rifle* at water at an angle of 45° resulting in a dead fish floating to the surface. It was deduced that the death of the fish was due to the hydraulic shock caused by the bullet penetrating the water. Although this phenomenon was referred to as 'hydraulic shock', the death of the fish would have almost certainly been down to the temporary displacement of the water behind the penetrating bullet. This was the same phenomenon that caused Kocher's box to burst.

Since the work of Kocher, it is generally recognised that there are two principle modes of wounding due to projectile penetration. These are shown in Figure 10.1. A bullet will compress and shear tissue during penetration to form a permanent cavity. At the same time, tissue is propelled outward from the bullet's path and forms a temporary cavity.

A third phenomenon is also shown in Figure 10.1 – this is the sonic pressure wave. This has sometimes (quite incorrectly) been referred to as the shock wave and is different from the hydraulic pressure observed by Kocher that forms a temporary cavity behind the bullet. The sonic pressure wave travels at the speed of sound in tissue (~ 1450 m/s), and this is much faster than the impact velocity of all high-velocity rifle bullets, and there is still some debate as to whether this sonic pressure wave can cause remote injuries. More recently, it has been suggested that remote injury to the brain can be caused by sonic pressure waves due to a gunshot wound (Courtney and Courtney 2007). It has also been argued that flat-nosed projectiles could form a disruptive shock wave due to the way the tissue would be placed in uniaxial strain (much in the same way that a plate-impact experiment works). However, this effect would be severely limited in size due to the fast release of the shock front, as discussed in Chapter 5, and probably lost by the damage caused by the penetrating projectile.

* Probably a 6.5×52 -mm Mannlicher–Carcano rifle. This is the same type of rifle used in the assassination of President John F. Kennedy.

In 1947, Harvey et al. examined the effect of the sonic pressure wave on tissue by suspending frogs' hearts in a water vat and shooting a projectile near them (Harvey et al. 1947). They recorded the experiment using high-speed photography. Due to the fact that the sonic pressure wave travels ahead of the projectile, they were able to observe with the camera what exactly damaged the heart and decouple the effect of the hydraulic pressure and the sonic pressure wave. They noted that the disruption of the tissue accompanied changes in pressure due to the formation of the temporary cavity and not the sonic pressure wave. This classic work has often been used to conclude that sonic pressure waves have no wounding effect.

10.2.2 Penetration Mechanisms

How a bullet penetrates flesh depends on a number of factors. The principle factors of importance are

- The bullet's velocity
- The bullet's geometry
- The bullet's material properties

The bullet's velocity (along with its mass) determines how much kinetic energy the bullet has. However, the kinetic energy of the bullet alone does not determine the injury mechanism per se but rather the energy delivered to the tissue (Santucci and Chang 2004). So, it is possible to design a bullet that is very fast (i.e. it possesses a high kinetic energy) that simply passes through the target resulting in little-to-no energy transfer. In fact, in one notorious case, the British military introduced a new high-velocity rifle in 1890 whilst fighting in India. It was assumed that the increased muzzle energy provided by the new full-metal-jacket 0.30-in. calibre ammunition would provide an enhanced stopping power. To the dismay of the military planners, the opposite occurred as the new projectiles did not deform on impact as much as the previously used larger-calibre lead projectiles. This meant that less energy was being delivered to the target's body – particularly when the projectile passed straight through the assailant. This led to the British filing down the tips of the bullets in the Dum-Dum arsenal to increase their damage mechanism. This approach was later outlawed in the Hague Peace Conference in 1899.

The bullet's geometry is a factor and will determine how much the bullet will deform, slow down or tumble and thus determine the extent of tissue damage. The AK-47/Chinese Samozaryadnyj Karabin sistemy Simonova (SKS) military bullet (7.62 × 39 mm) is one of the most widely used bullets (see Figure 3.3). It generally does not deform in tissue and will travel 260 mm before yawing (Fackler 1996). The reason for this is due to its short stubby geometry.

The material properties of the bullet too affect the behaviour during penetration. Softer-cored projectiles will have a tendency to deform during

penetration, whereas harder-cored bullets will not. Some projectiles will fragment during penetration – particularly if they come into contact with harder tissue. Even similar types of bullet can demonstrate differences in behaviour. For example, it has been shown that with the 7.62×51 -mm NATO bullet, US-manufactured bullets have a tendency to stay intact during penetration due to the strength and thickness of the jacket, whereas non-US-manufactured bullets will fragment on impact (Santucci and Chang 2004).

10.2.3 The Wound Channel

The response of tissue to penetration by non-deforming but yawing bullet is nicely shown by the diagram presented by Fackler (1996) and reproduced here in Figure 10.2. These experiments are usually carried out in ballistic gelatin or similar tissue simulants.

The AK-47 bullet enters the tissue and travels approximately 260 mm before beginning to yaw. The penetration results in two cavities being formed: temporary and permanent. The temporary cavity is due to momentum being imparted to the tissue by the penetrating projectile. The tissue behaves in an elastic fashion and therefore mostly returns to a rested state after the passage of the projectile. The permanent cavity is caused by the inelastic compression of tissue resulting in damage. It can be seen from Figure 10.2 that the AK-47 bullet does not deform, but rather, the geometry of the permanent cavity is caused by the tumbling of the projectile.

Considerably more trauma is afforded to the patient when fragmentation of the bullet occurs such as when a hollow point projectile penetrates flesh. Again, we resort to Fackler (1996). Figure 10.3 shows the wound track that would typically result from the impact of a hollow-point projectile on a human body. The fragmentation of the bullet causes an extra dimension to patient treatment. This bullet expands to more than double its original diameter and loses about one-third of its weight in fragments, within 25 mm or so of striking tissue. These fragments cause multiple perforations of the tissue

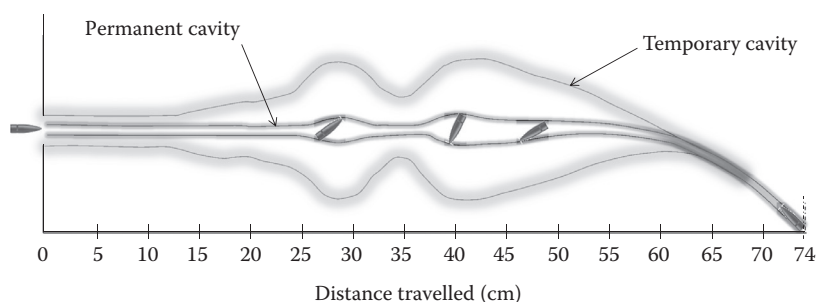


FIGURE 10.2

Wound profile produced by the Russian AK-47 (7.62×39 mm). (Reprinted from Fackler, M. L., *Annals of Emergency Medicine*, 28 (2):194–203, 1996. With permission from Elsevier.)

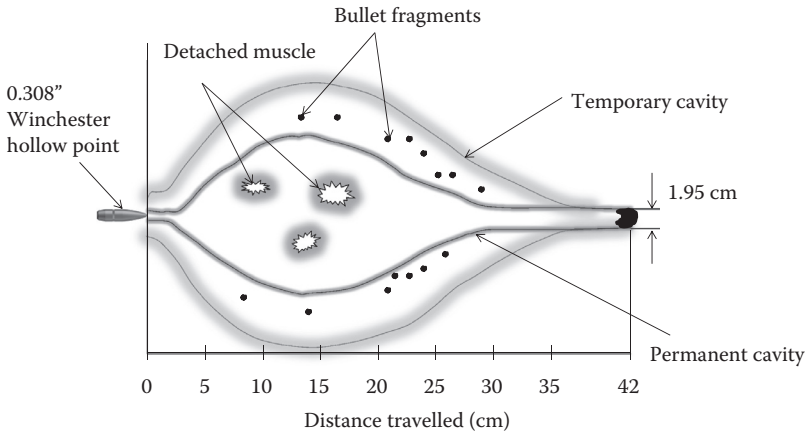


FIGURE 10.3

Wound profile produced by a hollow-point projectile. (Reprinted from Fackler, M. L., *Annals of Emergency Medicine*, 28 (2):194–203, 1996. With permission from Elsevier.)

surrounding the bullet path. The large temporary cavity then displaces this tissue, which has been weakened by multiple perforations by fragments.

10.2.4 Blunt Trauma

It is quite common for wearers of soft body armour to experience injury due to the behind-armour blunt trauma (BABT) after a bullet has been stopped. This is where excessive bruising of the flesh occurs due to a blunt impact. Unfortunately, this is the consequence of stopping a lethal bullet in a very short distance by using compliant materials that stretch and deform.

The effect of BABT is tested regularly with backing layers of Plastilina[®], ballistic soap and clays that record the temporary movement of the body armour materials into the body.

10.3 Human Response to Blast Loading

Many of the vehicles deployed in recent conflicts have faced enormous blast loads on their structures and occupants, and so there has been considerable effort of recent years to understand the way that out-of-vehicle blast loading can be managed to mitigate the injury to the occupants.

There are four classical types of injury that can occur to an individual that is subjected to a blast loading event (Zuckerman 1952). These are primary, secondary, tertiary and quarternary. The clinical effects and some of the

TABLE 10.2

Summary of Human Effects from a Blast Mine on Human Occupants

Blast Injury	Mechanism	Clinical Effects	Mitigation Requirements	Vehicle Mitigation
Primary	Blast/shock wave	Blast lung; traumatic amputation; soft tissue deformation and injury	Reduce blast transfer into the vehicle cabin	Increased stand-off; inclusion of blast-mitigation materials; V-shaping of hull
Secondary	Fragments from mine products, soil ejecta or vehicle structure	Penetrating wounds	Provide protection against fragments	Improved armour protection of the vehicle floor; improved personal protection
Tertiary	Global – vehicle acceleration; local – floor pan deformation	Significant axial loading leading to lower-limb injuries, pelvic and spinal injuries; head injuries from collision with the roof	Reduce vehicle acceleration; reduction in the trapping of the blast wave by the vehicle's structure; resistance of floor-plate deformation	Increased stand-off; V-shaping of the hull; occupants use restraints; feet lifted off the floor pan
Quaternary	Thermal effects	Burns	Protect against burns	Fire-resistant materials in vehicles; fire-retardant clothing

Source: Ramasamy, A. et al., *Journal of the Royal Army Medical Corps*, 155 (4):258–264, 2009. With permission from BMJ Publishing Group Ltd.

mitigation requirements that can be taken into account when building an armoured fighting vehicle (AFV; see Ramasamy et al. 2009) are shown in Table 10.2.

These four injury responses will now be discussed.

10.3.1 Primary Injury

Primary injury occurs simply because of the interaction between the blast wave and the human body. This is sometimes referred to as direct blast effects and is associated with the change in environmental pressure due to the passage of the blast wave. The factors that affect the level of injury due to a blast wave are summarised by Baker et al. (1983). These are

- The magnitude of the incident, reflected and dynamic overpressure
- The rate of rise to peak overpressure after the arrival of the blast wave
- The duration of the blast wave and its specific impulse

- Ambient atmospheric pressure
- The size and type of the subject animal
- The age of the animal (possibly)

Of all the organs that are most vulnerable to injury, the ones containing air are the most significant. The ear is the most sensitive and can respond to pressures as little as 2×10^{-5} Pa, and therefore, the large overpressures are generated from an explosion risk 'overloading' the ear drum.

Many of the studies that have been carried out to understand the behaviour of the ear drum to blast loading have used animals (pigs, dogs, monkeys, etc.) or human cadavers, and there is a wide variability in response. From a review of overpressure studies in a wide variety of experimental setups, circumstances and species, Hirsch (1968) concluded that the threshold pressure for damage to the middle ear structures is about 5 psi (34.5 kPa) and that at overpressures of near 15 psi (103.4 kPa), eardrum rupture will occur in about 50% of the cases.

The lungs are also prone to extensive damage due to fast compression of the chest wall. The tissue cannot respond as quickly, and the end result is shearing failure of the tissue. Much of what we know about the primary effects of air blast on human subjects was derived from experiments involving 2097 animals and compiled by Bowen et al. in 1968. They observed that species with larger lung volumes for a given mass had a higher probability of survivability.

The location of the individual is also important to assess survivability. The least survivable position is where the person is close to a reflective surface so that a reflected wave will lead to pressure enhancement. This is demonstrated in Figure 10.4 where the passage of a blast wave has been computed. The pressure reflection at the rigid surface leads to an amplification

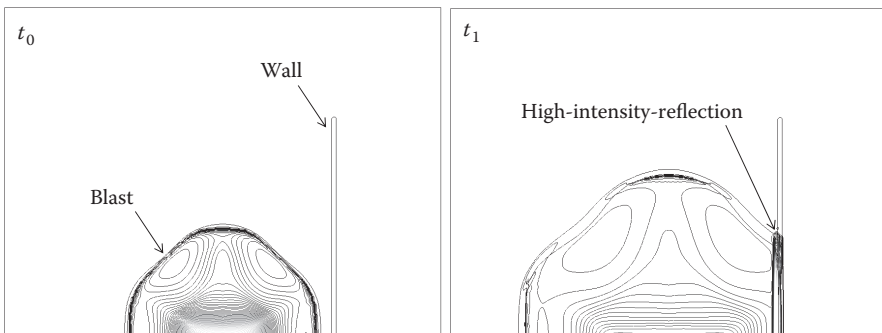


FIGURE 10.4

Computed reflection of a blast wave at a wall. The reflection results in an amplification of the pressure close to the wall.

of pressure in the locality of the wall – higher than the pressure that would have been encountered if the wall was absent. This is the most damaging of scenarios. Better survivability occurs where the individual is standing in free space with better-still survivability derived from lying down in free space where the long axis of the body is orientated in the direction of travel of the blast (see Figure 10.5).

A useful summary of the effects on an unprotected person from a primary blast overpressure of short duration is provided by and summarised in Champion et al. (2009). These are injuries that are likely to be sustained when an unprotected person is subjected to a short-duration primary blast overpressure:

- At between 30 and 40 psi (207–276 kPa), there is a slight probability of lung injury.
- At around 80 psi (552 kPa), there is a 50% probability of lung injury.
- At 100–120 psi (690–827 kPa), there is a slight probability of death.
- At 130–180 psi (896–1241 kPa), there is a 50% probability of death.
- At 200–250 psi (1379–1724 kPa), death is the most probable outcome.

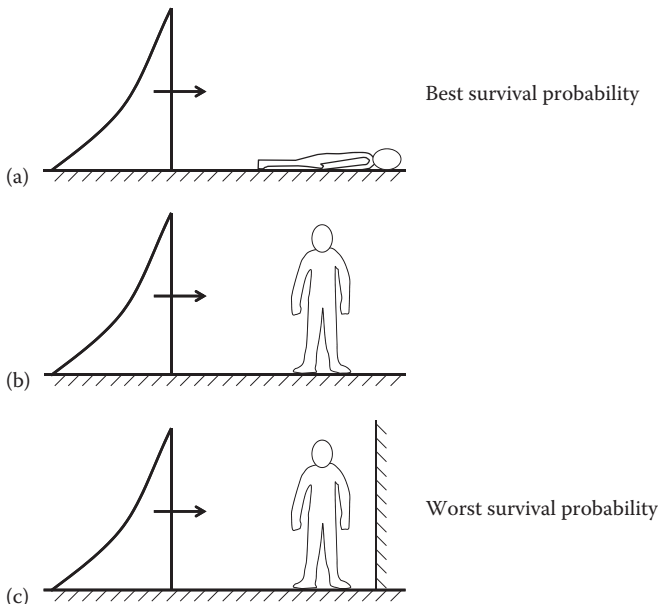


FIGURE 10.5

Human vulnerability to a blast wave: (a) lying down in a free space with the body orientated in the direction of travel of the blast (best survival probability), (b) standing up in free space and (c) standing in close proximity to a vertical wall (worst survival probability).

TABLE 10.3

Casualties Recorded from January 2006 in Iraq from the British Military Field Hospital Shaibah (Iraq)

No. of casualties injured from IEDs	53
No. of casualties displaying primary blast injuries	2 (3.8%)
No. of casualties with open wounds	53 (100%)
No. of casualties displaying fractures	28 (52.8%)
No. of casualties displaying quaternary (thermal) injuries	8 (15.1%)

Source: Ramasamy, A. et al., *Journal of Trauma and Acute Care Surgery*, 65 (4):910–914, 2008.

10.3.2 Secondary Injury

Secondary injury occurs where there is injury from fragments from an explosion. These fragments can be from a shell casing or simply from stones and soil accelerated from a buried mine. Injury due to fragment impact can be divided into two categories:

1. *Penetrating injuries*: These can cause severe lacerations resulting in loss of blood and ultimately death.
2. *Non-penetrating injuries*: These result in blunt trauma (heavy bruising) and are caused by large, non-penetrating fragments.

In recent conflicts in Iraq and Afghanistan, IEDs that propel explosively formed projectiles at high velocity (see Chapter 3) have been used. In Iraq, particularly, they have been a leading cause of death of coalition troops, and despite the close proximity of a casualty to the explosive, primary blast injury is the least common form of wounding (Ramasamy et al. 2008). From January 2006, Ramasamy et al. recorded 100 consecutive casualties at the British Military Field Hospital Shaibah* that were killed or injured in hostile action. Fifty-three casualties were subjected to IED attack, and the injury profile of these casualties is summarised in Table 10.3. Of all the 53 casualties that were subjected to IEDs, all of them displayed open wounds, whereas only two casualties displayed any evidence of being subjected to primary blast injury.

To get an idea of the ballistic resistance offered by human skin, it is necessary to carry out ballistic penetration experiments on human skin simulants. Early work on the penetration of skin from animal targets and clothing

* The British Military Field Hospital Shaibah was the military hospital supporting coalition forces in *Southeastern* Iraq. It was the location for treating both coalition troops and Iraqi civilian casualties.

showed that the v_{50} could be related to the ratio of the area of the fragment to its mass (Sperrazza and Kokinakis 1968):

$$v_{50} = K \frac{A}{m} + b \quad (10.1)$$

where

A = the area of the fragment (m^2)

m = the mass of the fragment (kg)

K, b = empirically derived constants (m/s)

Sperrazza and Kokinakis (1968) fired steel cubes, cylinders and spheres with masses up to 15 g and velocities of up to 2000 m/s into human skin and goat skin as well as into soldiers' combat clothing of the time. The skin was removed from a cadaver's thigh and was 3 mm thick; goat skin was removed from the goat's thigh with the hair removed and was also 3 mm thick. With reference to Equation 10.1, they showed that for the clothing (which is composed of six layers: sateen, oxford, frieze, ripstop, shirting and underwear), K and b were 2610.7 and 73.51 m/s, respectively, whereas for skin, K and b were 1247.1 and 22.03 m/s, respectively. Table 10.4 provides some representative ballistic limit data for steel spheres against winter uniform clothing and skin. Further data are summarised by Breeze and Clasper (2013).

10.3.3 Tertiary Injury

Tertiary injury occurs due to the acceleration (or deceleration) of the whole body due to an explosive impulse. Such examples are where a mine blast accelerates a vehicle upward or where local deformation of the floor plate is pushed up into the crew compartment. Other injury scenarios would be where the blast wave picks up an individual and throws him/her into a wall.

TABLE 10.4

Ballistic Limits for Steel Sphere against Winter Uniform Clothing and Skin

Projectile Mass (g)	Ballistic Limit, v_{50} (m/s)	
	Uniform	Skin
1	154	60
2	137	52
10	111	40

Source: Sperrazza, J., and W. Kokinakis, *Annals of the New York Academy of Sciences*, 152 (1):163–167, 1968.

With permission from John Wiley & Sons, Inc.

TABLE 10.5

Injury Criteria for Tertiary Effects Involving (Decelerative) Impact

Tolerance	Impact Velocity (m/s) ^a
<i>Skull Fracture</i>	
Mostly 'safe'	3.05
Threshold	3.96
50% fracture	5.49
Near 100% fracture	7.01
<i>Total Body Impact Tolerance</i>	
Mostly 'safe'	3.05
Lethality threshold	6.40
50% lethality	16.46
Near 100% lethality	42.06

Source: White, C. S., Nature of problems involved in estimating immediate casualties from nuclear explosions, in *Civil Effects Study*, Springfield, Virginia, Lovelace Foundation for Medical Education and Research, 1971.

^a Converted from ft./s in the original document.

Injury can occur during an accelerative phase or during decelerative impact. However, the latter tends to be more serious.

White (1968, 1971) has summarised velocity thresholds for the human body. White's most recent (and updated) summary from 1971 is presented in Table 10.5. It should be noted that these value are crude estimates as ascertaining certainty from observations and statistical history can be difficult to attain.

For personnel travelling in an armoured vehicle where they would be either seated or stood, a blast wave could lead to a vertical translation of the vehicle. Equally, there could arise a situation where the floor plate is driven upward, thereby effectively impacting on the heels, feet and legs of the occupants. White derived that if the heels, feet and legs were impacted at a velocity of between 4.0 and 4.9 m/s, then fracture of the bones would occur (White 1971).

10.3.4 Quaternary Injury

This is mostly to do with burns as a result of a fireball from the explosions or the resulting fire that would arise from an explosion. It also encompasses toxic gas inhalation (explosives can generate a reasonable amount of carbon monoxide) and injury from environmental contamination.

10.4 Limiting Blast Mine Injury to Vehicle Occupants

A large number of blast mines and IEDs are used to attack vehicles. The reason for this is that vehicles can carry lots of people and follow reasonably

predictable routes (roads). As a consequence of that, there has been a concerted effort in recent years to improve the survivability of vehicle occupants from a large mine blast.

10.4.1 Occupant Survivability

Modern test procedures now require the use of an anthropomorphic test device (ATD) or crash test dummy to evaluate the loads on the human body (NATO 2011). This is not an exact science per se as certain individuals will have a higher threshold for survivability than others. However, for the purpose of establishing a baseline survivability threshold, it is a sensible guide. Current testing guidelines (NATO 2011) specify a 50th percentile male Hybrid III ATD, which is fitted with accelerometers (to measure the accelerations) and force–moment transducers (to measure bending loads). Blast overpressure injury to the lungs is also monitored using a pressure transducer fitted to that location. Accelerations and forces are measured in the head, neck, thorax, pelvis femur and tibia. Forces and accelerations are then compared to threshold injury criteria derived from automotive car crash data to establish a pass or fail (NATO 2011). In general, the longer the duration of the acceleration phase, the less tolerance there is for the human body. Very intense head accelerations are tolerable if they are very brief. However, the head becomes much less tolerable as the pulse duration exceeds 10 or 15 ms (Versace 1971).

10.4.2 V-Shaping

To improve occupant survivability by way of reducing acceleration to the occupants, much of the effort has centred on the deflection of the blast wave away from the vehicle. And so, most modern armoured vehicles have V-shaped hulls to achieve this. Two examples are shown in Figure 10.6.

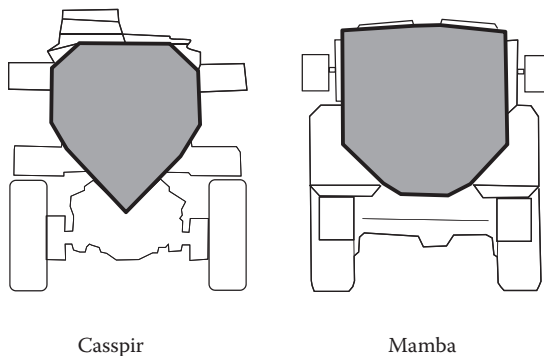


FIGURE 10.6

Two approaches to V-shaping – the Casspir and the Mamba armoured personnel carriers.

TABLE 10.6

Included Angle of the V-Shaping on Certain Rhodesian Armoured Vehicles

No.	Vehicle	V-Shape Included Angle
1	Camel	46°
2	Hyena	90°
3	Rhino	90°

Source: Hoffman, B. et al., *Lessons for Contemporary Counterinsurgencies: The Rhodesian Experience*. Santa Monica, California, RAND, 1991.

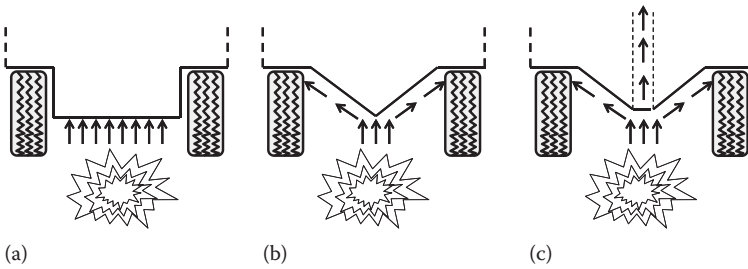
Blast deflection through V-shaping was developed in the early 1970s by the South Africans. During this time, they modified a WWII-vintage Swedish SKPF M/42 APC by integrating a special-shaped steel capsule with a 43° V-shaped bottom (Hoffman et al. 1991). Generally speaking, geometry dictates that the smaller the included angle of the V-shaping, the more the blast energy will be deflected, and therefore, a lower vertical impulse will be delivered to the vehicle. However, the height of the vehicle will also increase with the potential to make handling and stability more problematic. Table 10.6 lists some of the included angles of vehicles used by the Rhodesians. Notably, the Camel was named so due to its ‘ungainly’ appearance.

For vehicles where it is simply not possible to introduce a V-shape to the hull due to height and handling problems that may arise, it is possible to introduce a ‘double V’-shape (or essentially a ‘W’-shape). With this concept, instead of the blast being solely directed to the outside of the vehicle, a double V-shaped arrangement means that some of the blast is directed into the centre of the vehicle (Lee 2013). The blast is then spread fore and aft along the vehicle’s central axis using a suitably reinforced ‘duct’ that is concave downward. The deformation of the internal angled parts leads to a downward ‘pull’ on the central concave part thereby countering some of the upward impulse from the blast. Therefore, this provides a route to provide some meaningful blast protection in vehicles that would otherwise not be able accommodate a full ‘V’-shape.

A slight modification to this concept is the structural blast chimney method where a small (approximately laptop-sized) chimney is integrated into the centre of the vehicle (Tunis and Kendall 2013). This chimney provides a vent for the blast and therefore minimises the upward acceleration of the vehicle (see Figure 10.7).

10.4.3 General Techniques for Mine Protection

Other techniques for increasing the survivability in armoured vehicles can include using ‘breakable’ wheel axles so that the blast is not trapped by the

**FIGURE 10.7**

Different concepts for AFV hull design showing the pathways taken by a blast wave. (a) Flat bottom, (b) 'V' shaped, (c) Blast chimney concept.

wheel structure, energy-absorbing materials to accommodate the blast-wave energy and sufficient spacing from the blast to reduce the energy density of the waves in contact with the structure. The Buffel (a South African troop carrier) used some of these techniques (see Figure 10.8).

As long as the occupants are sufficiently strapped down, and there are no loose projectiles to fly around the cabin, a principal factor to consider is the acceleration to the occupant. This is why it is often expedient to 'insulate' the individual from fast-deforming structures such as floor plates. However, where the occupant is subject to acceleration (due to the upward movement of the vehicle), or where the occupant is in direct contact with an accelerating structure such as a floor plate, then serious injury can occur.

A typical schematic of protection measures that are usually employed by an AFV is shown in Figure 10.9 and Table 10.7.

In the same fashion that the V-shaping leads to an increased deflection prospect for blast-wave energy, having angled hull leads provide that advantage from a side-on blast. This can reduce the propensity of the vehicle to

**FIGURE 10.8**

A South African Buffel showing the V-shaped hull design. The Christmas decorations are not usually part of the camouflage.

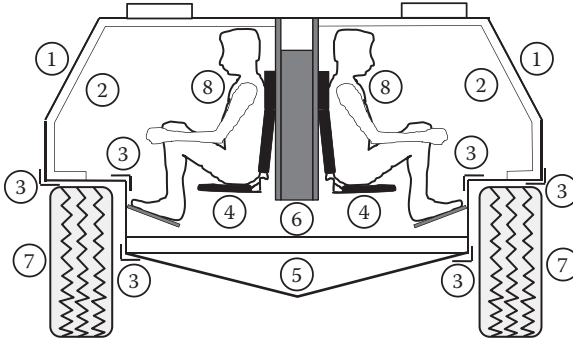


FIGURE 10.9
Protection measures employed in an AFV.

TABLE 10.7

Protection of AFVs from Mine and IED Blast

No.	Description
1	Sufficient armour to protect against fragment attack; angled for greater ballistic resistance and to deflect blast-wave energy from a side attack
2	Spall shields to protect against spalled armour and/or to limit fragment dispersion after the hull has been perforated
3	Reinforced welds
4	Suspended seats and foot rests to lift feet off the floor
5	Hull V-shaping to deflect blast-wave energy
6	Armoured floor
7	Quick-release axles to provide a release of blast-wave energy
8	Harnesses to restrain occupants

roll over (or be shunted sideways) when being subjected to a blast wave. Angled hulls are also advantageous from a ballistic point of view, as seen in Chapter 4. Having a decent amount of armour is obviously going to help survivability. The sides of hulls are particularly vulnerable to attack from IED fragments, explosively formed projectiles, shaped-charge jets and high-explosive shell fragments and, of course, bullets. It is also necessary to add a spall shield. These are generally constructed from glass fibre-reinforced plastic or ultra-high-molecular-weight polyethylene composite materials. Their advantage is that during a high-velocity attack, the diameter of the cone of fragments that is produced will be reduced. This leads to less lethality and greater survivability of a crew (see Chapter 8).

The reinforcement of the welds is also crucial to ensure that the vehicle does not suffer structural failure during blast loading. Welds are often the weak point in a structure, and therefore, good quality control needs to be maintained.

Additionally, it is beneficial to keep the occupant away from any dynamically deforming part – such as a floor plate. During a blast, the floor plate can be subjected to high accelerations that can lead to serious injury – particularly in the lower leg. Therefore, suspended seats and foot rests are used for this purpose.

10.5 Summary

In this chapter, some of the injury processes due to projectile and blast attack have been reviewed. Early work in the late nineteenth century showed that there were two principle wounding mechanisms due to projectile or fragment penetration. These are crushing or shearing of the tissue due to the physical penetration and the local propulsion of tissue to form a temporary cavity. The latter causes the tissue to stretch, and if that tissue is resistant to such forces, then relatively little wounding from this process can be expected. Examples of such ‘elastic’ tissue resides in the lung, the bowel wall and muscles (Fackler 1988). However, solid organs such as the liver are not resistant to these temporary strains.

Recent conflicts have shown that the IED is a prolific threat to coalition troops. We have also seen that there are approaches by which armoured vehicles can be designed to maximise protection from blast and IED attack. The human body is surprisingly resilient to very-short-duration accelerations; however, our tolerance diminishes very quickly as the duration increases. This is particularly problematic from the point of view of mine and IED blast protection, and there are a number of techniques that have been discussed here that can be employed for maximising protection. Many of these techniques employ ways of deflecting the blast energy, maximising the distance between the blast and the occupant and the use of energy-absorbing materials.

11

Blast and Ballistic Testing Techniques

11.1 Introduction

There are a huge variety of techniques that can be used to test the performance of an armour structure. Some testing techniques have been developed for the sole purpose of carrying our research into the performance of individual elements of armour, whereas others are well suited to understanding how well a platform responds to a given threat. Some of these will be reviewed here.

First off, it would be worth mentioning that strictly, there is no foolproof testing regime that is ever going to give you 100% confidence that the people who are protected by the armour are going to escape injury – or even death. If there was, then we would never lose soldiers on the battlefield. There are many unknowns in conflict. In fact, to quote United States Secretary of Defense Donald Rumsfeld in his speech to the United Nations in the run-up to the 2003 Gulf War – there are many known unknowns and many unknown unknowns. Frequently, it is not absolutely clear how large a threat is going to be faced by the soldier, although military intelligence is of course important.

11.2 Ballistic Testing Techniques

In the drive to understand penetration mechanisms, and to achieve a route to optimise the thickness or properties of individual elements in an armour system, several ballistic tests have been developed.

11.2.1 Depth-of-Penetration Testing

A commonly used test is carried out by attaching an armour tile to a semi-infinite ductile backing material and firing at the target, recording the resulting depth of penetration (DoP) in the backplate and comparing that value to

a value of penetration depth achieved without the armour tile in place. This DoP technique was originally developed by Rosenberg et al. (1988, 1990) as a method to suppress the tensile stresses in a ceramic tile that would otherwise be present when a thin backing was used. Over the past 20 years, there have been numerous studies that have used this technique to study the response of target materials impacted by small-arms bullets and rods. The advantage of this method is that it is relatively cheap to establish performance criteria for the armour tile in question; however, its disadvantage is that the semi-infinite backing is not representative of an armour system, and therefore, its value is in assessing comparative tile performance. These performance criteria are derived from the measured reduction in penetration and the mass of material required to reduce the penetration depth (see Figure 11.1). However, where the core of the bullet remains intact, it has been shown that the DoP test essentially measures the hardness of the ceramic tile (which is an expensive way of carrying out a hardness test; see Hazell 2010).

A number of performance factors can be calculated from the data generated by the DoP test. Three of the most common factors reported in the open literature are: (1) The mass efficiency factor; (2) The differential tile efficiency factor and (3) The critical thickness. These are now discussed below.

The mass efficiency (E_m) factor (or mass effectiveness) compares the ballistic performance of the target (e.g. a ceramic) with that of a baseline target. Rolled homogeneous armour (RHA) is frequently used for high-velocity rod-based projectiles, whereas softer and lower-density materials such as polycarbonate and aluminium are used for bullet-impact studies. E_m is defined as follows:

$$E_m = \frac{p_\infty \rho_{st}}{h_c \rho_c + p_r \rho_{st}} \quad (11.1)$$

where the subscripts 'st' and 'c' refer to steel and ceramic, respectively, h is the thickness, and ρ is the density. p_∞ is the penetration into the semi-infinite RHA (steel) baseline target without a ceramic tile. E_m represents the factor by which the areal density must be multiplied if an entire armour combination, consisting of a ceramic of thickness h_c and an RHA plate of thickness p_r , was to be replaced

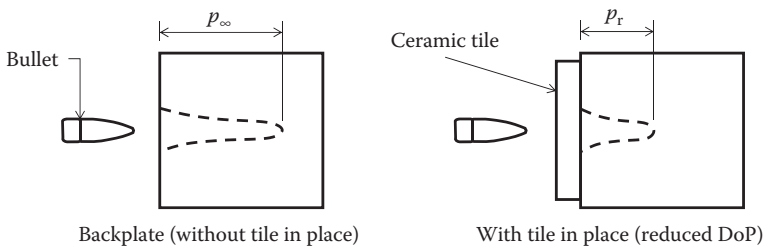


FIGURE 11.1
The DoP technique.

by RHA or equivalent to provide the same protection. But actually, when calculated from DoP measurements, the presence of the semi-infinite backing will enhance the protection offered by the backing plate, and therefore, p_∞ and p_r will be less than the thickness of plates that would be required; one rarely has the luxury of using semi-infinite backing materials in armour systems.

The differential tile efficiency (Δe_c) is the factor by which the areal density of backing plate material penetrated is reduced by the addition of a ceramic tile, normalised by the target material's areal density. It is given as

$$\Delta e_c = \frac{(p_\infty - p_r)\rho_{st}}{h_c\rho_c} \quad (11.2)$$

One further calculation can be undertaken to estimate the performance of an armour system from a single experiment and establish a critical thickness of material required to stop the round. This critical thickness (T_{cr}) is given by

$$T_{cr} = \frac{p_\infty h_c}{(p_\infty - p_r)} \quad (11.3)$$

However, where there is more than a single point of data representing a single thickness of ceramic (as is normally the case), or if you have data for multiple thicknesses, it is normally better to plot the penetration into the witness plate against the corresponding thickness of the ceramic. It is then a simple task to fit a line of regression to estimate the critical thickness that will be required to result in no penetration in the witness plate.

The choice of the back plate is important for ceramic-faced targets as it will affect the final result of the test. Rosenberg et al. (1990) have shown that increasing the strength of the back plate results in an increase in the mass efficiency (according to Equation 11.1). They showed that comparing results between three different back-plate materials (AISI 1020 steel, RHA and HHA) led to an increase in resistance. The reasoning for this behaviour is that a ceramic tile behaves better when it faces a stronger (or denser) material as it is less likely to fail by bending.

11.2.2 Non-Linear Behaviour

DoP testing is best designed to provide a snapshot of a given tile performance at a particular velocity. And, for ceramic tiles, DoP testing will tend to improve as the thickness of the tile is increased as the impact face is moved further away from the interface between the backing plate and the ceramic tile. At very high velocities (>2000 m/s), it is possible that impacting the metal backing plate alone will lead to projectile disruption and a drop in DoP at some critical impact pressure. Figure 11.2 shows the result of a 6.35-mm steel sphere impacting an aluminium alloy target (AA 6082-T6) at a range of

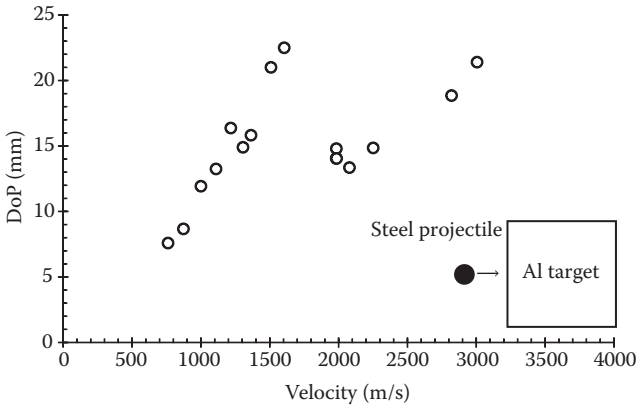


FIGURE 11.2

DoP measurements from a 6.35-mm diameter steel projectile striking an aluminium plate at high velocities. (After Hazell, P. J. et al., *International Journal of Impact Engineering*, 21 (7): 589–595, 1998.)

velocities. At approximately 1600 m/s, it can be seen that there is a drop in DoP. So measuring the ballistic efficiency over the broad range of velocities will result in a highly non-linear relationship with velocity.

11.2.3 Ballistic-Limit Testing

Another method for testing performance is by using the v_{50} approach, and this is usually reserved for actual armour systems where bending stresses would be seen on the rear surface of the ceramic. The advantage of this technique over the DoP-test technique is that the complete system is tested rather than the component of the system (i.e. the ceramic), and it will provide an indication on the performance of the armour. To carry out a ballistic-limit test, you need

- A ballistics range (obviously)
- A means of measuring the projectile velocity
- A means by which the projectile velocity can be ‘tweaked’ either by changing the mass of the propellant or by warming the propellant in the cartridge a little

The rationale behind ballistic limit testing is that for a given armour plate, there is going to be a range of mixed results across a fairly narrow velocity band. So, below the velocity that we shall call v_0 , all projectiles will be stopped by our armour (see Figure 11.3). If 10 firing shots were carried out at $v = v_0$, then all projectiles would be expected to be stopped. Equally, above a slightly higher velocity, which we shall call v_{100} , then we would expect all the

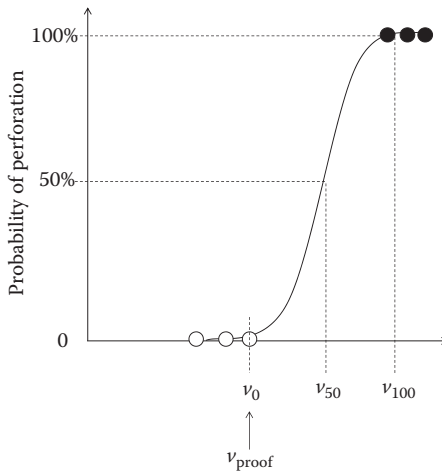


FIGURE 11.3
Ballistic limit testing.

projectiles to perforate the target. Out of 10 firings, we would expect 10 perforations when $v = v_{100}$. In between v_0 and v_{100} , we would expect to see a range of mixed results where some of the projectiles are stopped, and some are not. In fact, in this zone, it is quite possible that one projectile that is stopped by the armour has an impact velocity that is higher than a similar projectile that perforates the armour. The principle reason for this is that it is pretty much impossible to tie down every variable in a ballistic range test. Even for seemingly identical ammunition and targets, there could be small differences in

- The geometry of the bullet
- The mass of the core of the bullet
- The pitch or yaw of the bullet at the point of impact
- The strength or hardness of the armour plate at the point of impact
- The microstructure of the armour plate at the point of impact
- The thickness of the armour plate at the point of impact

Thus, it is sometimes convenient to establish a v_{50} velocity where it would be expected that 50% of our projectiles would be stopped by the plate, and 50% of the projectiles would perforate.

Of course, how is perforation or failure of the armour target defined? Early tests of gun shields followed a prescribed format as outlined by O. M. Lissak (1907, pp. 475–476) such that

The shield, firmly supported by a backing of oak timbers, is subjected to three shots from a 5-inch gun. The striking velocity of the shot is 1500 feet [per second] and the normal impact. On the first impact, near the

center of the shield, no portion of the projectile shall get through the shield, nor shall any through crack develop to an edge of the shield. The other two impacts are so located that no point of impact shall be less than three calibers of the projectile from another point of impact or from an edge of the shield. At the second or and third impacts no projectile or fragment of projectile shall go entirely through the shield.

So for Lissak's gun shields, the first projectile is not allowed to break the rear surface, whereas the other two projectiles are allowed to break the rear surface of the target but not carry on through in their entirety.

Others would be less prescriptive and dictate that perforation only occurs when an impacting projectile results in itself, a piece of the projectile or target debris passing through a witness plate located behind the target such that there is a clearly visible hole in the witness plate. This is the requirement for AEP-55 Vol. 1 (NATO-55 2011a). Further details can also be found in military standards (e.g. MIL-STD-662F [US Army Research Laboratory 1997]).

The following example outlines how to determine the v_{50} :

Example 11.1

How to calculate the v_{50} . A series of ballistic tests have been carried out on an 8-mm steel plate with a 7.62-mm NATO ball projectile. The impact velocity and the result are recorded as well as the result. CP = complete penetration (i.e. perforation), and PP = partial penetration (i.e. no perforation). The results are provided in Table 11.1. Determine the v_{50} according to MIL-STD-662F with a velocity span of 40 m/s.

Note that MIL-STD-662F allows for the v_{50} to be calculated by taking the arithmetic mean of an equal number of the highest partial and the lowest complete penetration impact velocities within an allowable velocity span as defined by the contracting officer, in this case, 40 m/s (this is the span as dictated by STANAG 2920 – a different military standard). Unfortunately, the results do not satisfy the requirements for the test as Test 6 was a PP despite it being very close to Test 4 at 749 m/s, which was a CP.

Therefore, a further test (or further tests) is required; this is given in Table 11.2.

TABLE 11.1
Ballistic Test Results

Test No.	Velocity of Impact (m/s)	Result
1	750	CP
2	720	PP
3	735	PP
4	749	CP
5	734	PP
6	748	PP

Note: CP = complete penetration; PP = partial penetration.

TABLE 11.2

Further Ballistic Test Result to Satisfy MIL-STD-662F

Test No.	Velocity of Impact (m/s)	Result
7	763	CP

Note: CP = complete penetration; PP = partial penetration.

Test 7 now satisfies our requirement as we have the three highest velocities where there was a PP (735 m/s, 734 m/s, 748 m/s) and three lowest velocities that resulted in a CP (750 m/s, 749 m/s, 763 m/s) within 40 m/s, and so, the arithmetic mean of all six firings can be taken. This is 746.5 m/s, and therefore,

$$v_{50} = 746.5 \text{ m/s}$$

It should be noted that MIL-STD-662F has strict advice on velocity increments and decrements for each subsequent firing, and these have been approximated here.

11.2.4 Shatter Gap

An interesting nuance of a ballistic-limit testing is that occasionally, it is evident that two ballistic-limit curves occur. This can occur for a couple of reasons, and it is mostly associated with ceramic-faced armour tiles. An example of the appearance of shatter gap is shown in Figure 11.4. Initially, at $v = v_0$, as before, no projectile perforates the target. Increasing the velocity of the projectile results in the possibility of perforation (1) until the velocity is increased, and the projectile begins to fragment or shatter (2). At this point, the projectile has been broken up by the target, and therefore, it is more difficult for it to perforate the target. Therefore, the probability of perforation

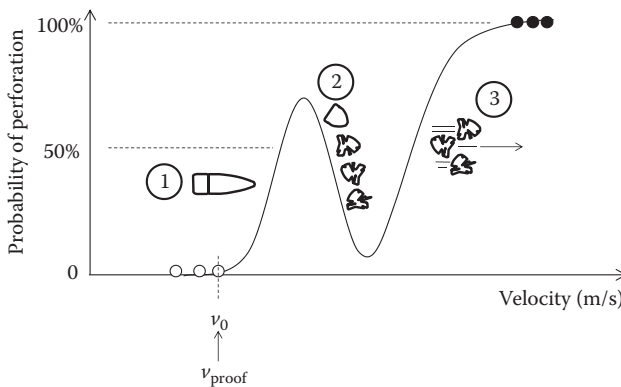


FIGURE 11.4

What happens during a series of tests that exhibit shatter gap.

reduces. That is until at (3), the velocity of the fragments that result from the shattering process as the projectile that interacts with the target is travelling fast enough to perforate the target. The end result of all of this is that it is possible to establish two v_{50} velocities, and this can (understandably) create a bit of confusion to the tester.

11.2.5 Perforation Tests

If the projectile is non-deforming, and the target does not fragment, it is possible to consider a crude energy balance for the perforation process. This was a popular lab demonstration at Cranfield University (Shrivenham campus).

Consider a projectile striking a plate at velocity v_0 with a mass of m_i that leaves the rear of the plate with a velocity v_r and with a mass of m_r . The velocities can be measured by a suitable system located before and after the target. The percentage of kinetic energy (%KE) transferred in the penetration process is given by the following:

$$\%KE = \left(\frac{\frac{1}{2} m_i v_0^2 - \frac{1}{2} m_r v_r^2}{\frac{1}{2} m_i v_0^2} \right) \times 100 \quad (11.4)$$

If the mass of the projectile remains constant throughout (i.e. $m_i = m_r$), this can be simplified to

$$\%KE = \left(\frac{v_0^2 - v_r^2}{v_0^2} \right) \times 100 = \left[1 - \left(\frac{v_r}{v_0} \right)^2 \right] \times 100 \quad (11.5)$$

In reality, there will always be mass lost by the projectile due to the jacket being stripped away or soft parts of the core (where Pb is used) being dispersed during the penetration process.

Plotting %KE against the plate thickness of several thicknesses of plate will provide the ballistic limit for the plate. This provides a fairly good approximation even for cases where the projectile is expected to deform and lose mass. Figure 11.5 shows an example of some recorded data of a bullet perforating a plate. At small plate thicknesses, the fraction of KE transferred holds to small groupings, whereas at larger plate thicknesses the dispersion of the data is as one would expect. Nevertheless, plotting an averaged trend line through the data (and through the origin) gives a reasonable prediction of what thickness of plate would result in the projectile being stopped. In this case, it is just over 12 mm, which is about right for this target plate.

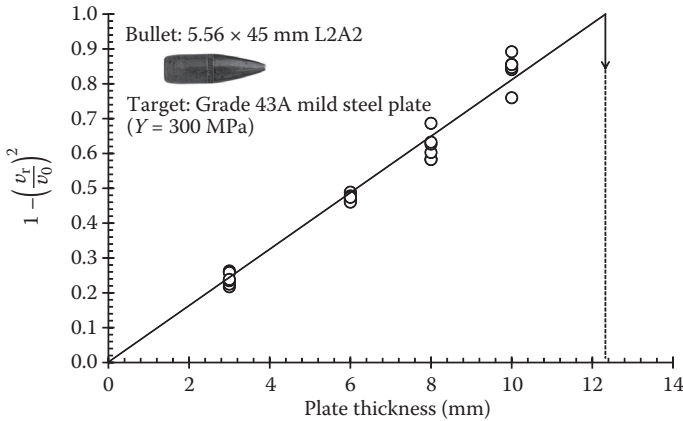


FIGURE 11.5

Fraction of KE transferred from the bullet during the perforation of a mild steel plate by a 5.56 × 45-mm L2A2 bullet. The trend line indicates the thickness at which this bullet would be stopped (at muzzle velocity ~920 m/s), which indicates a value of just over 12 mm.

11.2.6 Using a Ballistic Pendulum

A ballistic pendulum is a device that sits behind a target and measures the momentum of a bullet that has passed through a target. In its simplest form, it comprises a steel ‘catching tube’ that is suspended from the roof of the ballistics range. Before the main experiments are carried out, the pendulum is calibrated by firing various projectiles, of known mass, at varying (measured) velocities. As a bullet enters the pendulum’s catching tube, the pendulum will swing. The height of the swing is thus calibrated with the momentum of the bullet. Therefore, knowing the momentum of a bullet before impact and the momentum of the projectile after perforation, it is possible to calculate the impulse delivered to the target plate. A similar device can also be used to measure the impulse due to an explosive charge.

A problem with this approach arises when there are multiple high-velocity ejecta from the rear surface of the target. If this occurs, it is challenging to decouple the momentum of the bullet from that of the ejecta.

B. Hopkinson (1914) used a ballistic pendulum to assess the approximate shape and magnitude of a stress wave in a steel bar. Hopkinson’s experiments consisted of firing a lead-cored projectile at a steel bar. At the rear end of the bar, a rod of identical diameter was magnetically attached, which flew off into a ballistic pendulum. Thus, by measuring the momentum trapped in the flying rod (by the momentum given to the ballistic pendulum), a portion of the stress–time integral in the bar due to the impact could be established. By varying the length of the ‘flyer’ rod, a picture of the shape and magnitude

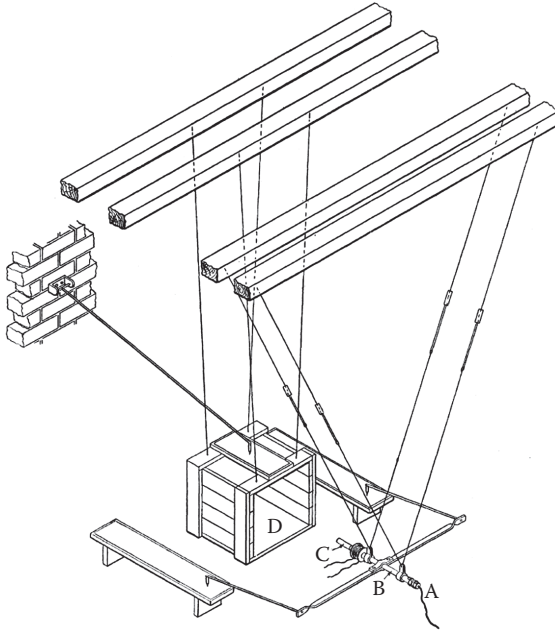


FIGURE 11.6

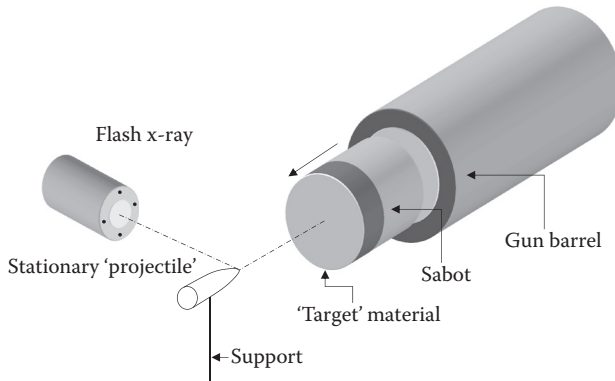
The ballistic pendulum set-up as used by B. Hopkinson. (From Hopkinson, B., *Philosophical Transactions of the Royal Society*, 213 (10):437–452, 1914.)

of the stress pulse was derived. These experiments were also repeated by detonating gun cotton at the end of the bar. A set-up of Hopkinson's famous experiment is shown in Figure 11.6.

11.2.7 The Reverse-Ballistic Test

A lot of recent work has focused on using a reverse-ballistic approach to investigate mechanisms – particularly of interface defeat and dwell and to examine the effect of bullet jackets on ballistic performance. With this technique, the 'target' is accelerated toward a stationary 'projectile'. Of course, the definition of target is switched around, and now, the projectile that would be fired in forward ballistic experiments becomes the target. There are several advantages. These are the following:

1. It is easier to set up, position and align the target at a pre-defined orientation.
2. It allows for experiments to be done in a laboratory setting using existing large-calibre gas guns.

**FIGURE 11.7**

Schematic of the reverse ballistic experimental approach showing the stationary 'projectile' and the incoming 'target'.

3. It avoids any unwanted yaw or spin that may otherwise arise due to the use of a conventional forward ballistic approach.
4. The projectile package is simple to manufacture in that it comprises the sabot made from either acetal or polycarbonate with the armour material to be tested attached to the front (similar to a plate-impact experiment projectile).

However, there are substantial disadvantages in that the lateral extent of the target is limited by the calibre of the gun. Consequently for brittle targets, confined specimens are usually required to limit the effect of the release waves emanating from free surfaces – particularly for thick samples.

A typical reverse ballistic set-up is shown in Figure 11.7 where the target is suspended on a support at the end of the muzzle of the gun. This technique has been used successfully by a variety of researchers to study the penetration of ceramic and metals. In each case, the diameter of the ceramic is very small and is surrounded by either a titanium or aluminium sleeve. Furthermore, very low diameter rods are used with rods with diameters as low as 0.762 mm being reported (Orphal et al. 1996).

11.3 Blast and Fragmentation Testing Techniques

Blast wave testing of a material, system or structure has historically been carried out on large open plan ranges that have a pre-defined limit on the mass of explosive and the degree of fragmentation hazard that can be

accommodated. Once upon a time, blast testing was a fairly crude affair where an explosive was detonated, and the only metric that was applied was to establish how 'bent the metal was'. Nowadays, range testing with explosives adopts a much more scientific approach, and this has largely been driven by the price of high-speed diagnostics and cameras becoming more affordable and the fact that there has been a significant drive to understand the effect of blast waves on vehicles and personnel since the 2003 Gulf War.

11.3.1 Fragment Simulators

One of the challenges of assessing the response of a material or structure to a fast-moving fragment propelled by an exploding shell or improvised explosive device is the problem that very often, the shape, size, velocity, angle of attack and drag characteristics of the fragment are not known. The detonation of a high-explosive shell would produce a distribution of fragments of varying mass and velocity.

Figure 11.8 shows the velocity distribution of fragments from 155- and 105-mm artillery shells (US Army Test and Evaluation Command 1983). There is a central 'main spray' region of 25° where high-velocity fragments are propelled. The maximum velocity of the fragments is around 1250 m/s. This means that it is just about achievable to simulate this velocity using a conventional barrel in a Small Arms Range.

Accordingly, STANAG 4569 levels of protection for vehicles are defined by six levels of protection where the highest level of protection must protect against a fragment simulator impacting at 1250 m/s (see Table 11.3). This

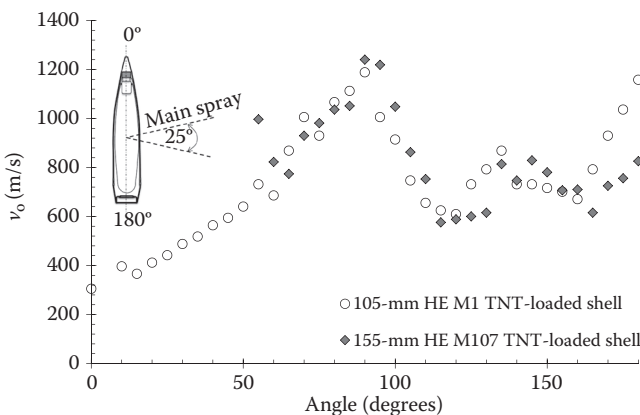


FIGURE 11.8

Initial velocity of fragments (v_0) and distribution due to the detonation of a 105-mm M1 shell and a 155-mm M107 artillery shell. (Data from US Army Test and Evaluation Command, *Fragment Penetration Tests of Armor*, Aberdeen Proving Ground, MD, 21005, US Army Aberdeen Proving Ground [STEAP-MT-M], 1983.)

TABLE 11.3

FSP Velocities for Testing against Different STANAG 4569 Protection Levels

Protection Level ^a	Range of Burst (m)	20-mm FSP Velocity (m/s)
6	10	1250
5	25	960
4	25	960
3	60	770
2	80	630
1	100	520

Source: NATO, AEP-55, *Procedures for Evaluating the Protection Level of Armoured Vehicles - Volume 1: Kinetic Energy and Artillery Threat*, Brussels, Belgium: NATO, 2011a.

^a For STANAG 4569, levels 1–3 are not required.

velocity diminishes for extended ranges (and hence protection levels). For extended ranges (Levels 1–3), the specific KE threats are more potent, and therefore, fragment simulating projectile (FSP) testing at this level is not commonplace.

A typical schematic of a 20-mm FSP and a photo of a slightly smaller (14.5-mm) FSP are shown in Figure 11.9. These will be made from cold-rolled, annealed steel (i.e. AISI 4340H) with a yield strength of ~475 MPa. The protruding flare at the tail of the FSP is larger than the 20-mm calibre. The reason for this is so that it engages in the rifling of the barrel when fired. These FSPs are pushed into conventional gun cartridges (i.e. 20 or 14.5 mm in this case), and the ammunition is then loaded in a conventional fashion. The lengths of the FSPs shown below are 24 and 20 mm for the 20- and 14.5-mm FSPs, respectively. Further details on FSP designs can also be found in NATO (2003) with some earlier designs provided by MIL-P-46593A(ORD) (US Army 1962).

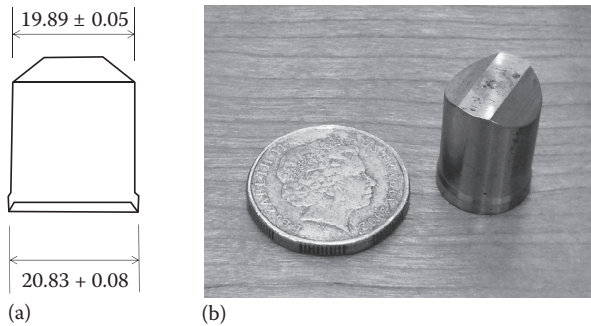


FIGURE 11.9

(a) A 20-mm FSP (From NATO, AEP-55, *Procedures for Evaluating the Protection Level of Armoured Vehicles - Volume 1: Kinetic Energy and Artillery Threat*, Brussels, Belgium: NATO, 2011a.) and (b) a photograph of a slightly smaller 14.5-mm FSP next to an Australian dollar coin; dimensions in mm.

11.3.2 Blast and Shock Simulators

It is often desirable to produce the type of impulse and reflected pressure that would be expected from an explosive blast – but without the use of an explosive. There are several reasons why this is attractive to research groups. Firstly (and probably most importantly), there is no requirement to store explosive materials. The storage of explosive materials usually requires a licence and has to be done safely and securely by appropriately trained staff. Therefore, explosive storage will carry a cost overhead. Secondly, the experiments can be done in a ‘cleaner’ laboratory environment that is usually well aligned with other activities. Thirdly, there is more control of the direction of the blast. That is to say that the ‘blast’ wave can be directed at the structure in one direction.

A very simple form of blast simulator involves the use of a shock tube. In simple terms, a shock tube consists of a cylindrical section of tube part of which contains a high-pressure region separated from an ambient-pressure region with a diaphragm. Once the diaphragm is burst by the operator, the high-pressure gas expands rapidly thereby compressing the air in the ambient pressure region. Thus, a blast wave is simulated. However, it is somewhat more complex than is outlined here, and careful attention needs to be applied to the ambient pressure tube so that reflections of surfaces do not provide a false pressure–time profile.

Similar to the shock-tube concept outlined above, it is possible to simulate an underwater shock on a material or structure by launching a projectile at a column of water to produce a wave that can be used to test shocks from underwater explosions. An example is outlined by Deshpande et al. (2006). Here, they used a tube arrangement that was 1.4 m in length with an internal diameter of 45 mm and a wall thickness of 7 mm. At one end, the test piece is placed, whilst at the other end, an aluminium piston is configured to receive a blow from a projectile (diameter = 28.5 mm). It is important that air is not trapped in the water column as this can attenuate the shock generated within the water. Consequently, a bleed valve was integrated into the aluminium piston to account for this. The pressure–time profile of the shock is measured using a piezo-electric transducer and confirmed with measurements of the hoop strain. The hoop strain, ϵ_h , is related to the thin-walled cylindrical pressure by

$$P(t) = \frac{2Ew\epsilon_h(t)}{D + w} \quad (11.6)$$

where

E is the Young’s modulus of the tube material.

w is the wall thickness of the tube.

D is the internal diameter of the tube.

The specifications of the piezo-electric transducer that Deshpande et al. used are summarised in Table 11.4. The gauge length of the strain gauge to measure the hoop strain was 1 mm to maintain a suitable frequency response.

TABLE 11.4

Piezoelectric Pressure Transducer Specifications for an Underwater Shock Simulator

Type	Model 102A03 of PCB Piezotronics Inc.
Dynamic pressure range	0–69 MPa
Rise time	<1 μ s
Resonant frequency	>500 kHz

Source: Deshpande, V. S. et al., *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 462 (2067):1021–1041, 2006.

11.3.3 Blast Mine Surrogates

Approximately 80% of the mines that are encountered by armoured vehicles are blast mines. It therefore is necessary to provide a suitable replicable method of testing how a mass of explosive interacts with a vehicle structure. Consequently, there have been several mine surrogates specified that fulfil this requirement (NATO 2011b). There are four protection levels for occupants of armoured vehicles for grenade and blast mine threats. Protection level is decided based on

- Explosive mass (10 kg for protection level 4);
- Surrogate mine location (i.e. under the wheel/track or under the vehicle's belly)

In addition, the type of soil that the mine is buried in is particularly important as the moisture content of the soil will ultimately affect the load transmitted to the vehicle. For example, in sand, it has been shown that the presence of moisture leading to a 22% increase in density resulted in a 27% increase in momentum being transferred to a flat plate located above the explosion (Anderson, Jr et al. 2011).

The main point about a surrogate is that it provides consistency in the loading to the structure, and therefore, the results are repeatable. Placing the explosive in a steel pot also increases the reproducibility of tests. Two Level 1 surrogates, as stated in NATO (2011b), are presented in Table 11.5.

TABLE 11.5

Two Level 1 Surrogate Mines; the Second is the More Severe

Level	Explosive Mass (g)	Explosive Type	Fragments	Expected Fragment Velocity (m/s)
1	>300	C4, Comp B (high explosive)	Pre-fragmented 0.4 g hard steel spheres (750 min)	1150–1200
1	550 + 20-g booster	Cast TNT	Pre-fragmented 3.9 g hard steel cylinders (350 min)	950

11.3.4 Explosive Bulge Test

The explosive bulge test is designed to test how a material deforms due to an incoming shock wave that has been generated by an underwater shock or air blast. It was originally developed by Pellini in 1952 to test welds and understand the crack propagation characteristics of a plate that had a 'synthetic' notch machined into it by means of a grinding wheel (Pellini 1952). However, it is also useful to assess how the plate bulges and whether or not the bulging will lead to failure.

Plates are positioned in either circular dies (for balanced biaxial loading) or elliptical dies (for unbalanced biaxial loading). Pellini used 381-mm (15-in.) diameter circular dies and 317.5×457.2 -mm (12.5×18 -in.) elliptical dies for the weld tests. The explosive is then set at a distance from the plate such that

- a. Uniform loading of the plate is achieved by the gas pressure of the explosive.
- b. An area of uniform strain that encompasses the area of interest (i.e. the weld) is achieved.
- c. Brisance (explosive shattering) is minimised.

The explosive blast pushes the plate into the die resulting in a bulged plate. This is then analyzed for failure.

11.4 Summary

In this chapter, some of the blast and ballistic testing techniques that are commonly used on ranges to assess the performance of materials and structures have been summarised. It is important to point out that when carrying out such experiments, acquisition of as much data as possible is desirable. This is mainly due to the destructive nature of the tests the short duration over which they occur. High-speed framing cameras or flash x-ray equipment are useful for capturing the response of the material and can serve as a good diagnostic where there is an unexpected result. Of course, we like to think that there will never be such a thing as an unexpected result.

Glossary

- Absorber:** The part of an armour system that is able to transfer the kinetic energy of the projectile or fragments to a lower form of energy, usually by a process of plastic deformation or delamination.
- Adiabatic shear:** A process where, during the penetration of a projectile in a target, the rate of thermal softening exceeds the rate of work hardening leading to the formation of shear failure bands. There is no heat transfer from (or to) the heat-affected area.
- Alloy:** A mixture of two or more elements where at least one of them is a metal.
- Ammunition:** Any munition of war whether filled with solid shot or explosive.
- Amorphous:** A non-crystalline state where the arrangement of atoms has no periodicity.
- Angle of obliquity:** The angle between the projectile trajectory and the normal to the surface of impact.
- Anisotropic:** Possessing different material properties along different axes in three-dimensional space; not isotropic.
- Anti-tank guided weapon:** A vehicle or infantry-launched warhead that is capable of being guided or guiding itself to attack a target – usually with a shaped-charge warhead.
- Areal density:** The mass of a plate divided by its cross-sectional area. It can also be calculated by multiplying the bulk density of the plate material by its thickness.
- Armoured fighting vehicle (AFV):** The generic name for a military vehicle, tracked or wheeled, that is designed to engage in warfighting.
- Armoured personnel carrier:** An armoured vehicle (tracked or wheeled) designed to carry troops into a conflict zone.
- Armour piercing:** Projectile with a hard core designed to penetrate and perforate hard targets.
- Armour-piercing discarding sabot:** A sub-calibre solid shot of relatively low length/diameter ratio (~5) that is carried up a gun barrel by a sabot that is discarded when exiting the muzzle. It is usually spin stabilised.
- Armour-piercing fin-stabilised discarding sabot:** A sub-calibre solid shot of relatively high length/diameter ratio (~15) that is carried up a gun barrel by a sabot that is discarded when exiting the muzzle. It is usually drag stabilised.
- Armour-piercing incendiary:** Projectile with an armour-piercing core and a low-explosive material encased in the tip that deflagrates when the bullet impacts armour.

- Attenuate:** To reduce in force or value. The term is frequently used to describe the weakening of a stress or shock wave.
- Austenite:** A soft crystalline structure that is formed in steels at elevated temperatures. It is occasionally present with martensite in drastically quenched steels.
- Azimuth:** A directional bearing but usually used in reference to protection in terms of a 90° arc – that is, from the zenith to the horizon.
- Ballistic limit velocity:** The velocity at which there is a specific probability that a known projectile will just perforate the target. Therefore, a v_{50} is the velocity at which 50% of the projectiles will just perforate the target.
- Ballistic pendulum:** A device for measuring the momentum of a projectile or fragment(s).
- Bauxite:** A mineral that is extracted from the earth's crust containing oxides of aluminium, silicon and iron and from which alumina powder is extracted.
- Behind armour effects:** The fragmentation, or blast and overpressure, that occurs after a projectile or shaped charge jet perforates armour.
- Blast wave:** A destructive wave produced by the detonation of an explosive.
- Blunt trauma:** Injury that occurs when a body armour vest is not perforated, but the momentum transfer of the impact causes large deformation in the backing layer. It can lead to bruising, serious injury to major organs or even death.
- Brinell indenter:** A spherical hard steel indenter that is used to measure the hardness of a material – usually metal.
- Brittle fracture:** This occurs when a projectile strikes a target with a low *fracture toughness*. Typically, the target will shatter into a large number of fragments. Examples of materials that suffer from brittle fracture are brick, ceramic and glass. Very little energy is required to form new fracture surfaces.
- Bullet:** A projectile that is fired from a gun and is usually encased in a metallic jacket that engages with the gun's rifling to enable spin stabilisation.
- Calibre:** The nominal diameter of the bore of a gun. For a rifled barrel, it is measured across the lands of the rifling.
- Carburising:** The diffusion of carbon into a material from a carbon-rich environment with the application of heat.
- Ceramic:** A solid compound that is formed by the application of heat, and sometimes heat and pressure, comprising at least one metal and non-metallic elemental solid.
- Cermet:** A composite material composed of ceramic and metallic materials. A metal is used as a binder for an oxide, boride or carbide (for example, tungsten carbide). The metallic elements normally used are nickel, molybdenum and cobalt.

- Charge:** Enclosed quantity of high explosive or propellant with its own integral means of ignition.
- Combat body armour:** A UK body armour that consists of an aramid and nylon construction to which ceramic-faced armour can be applied as an insert to protect the major organs.
- Comminution:** A collection of small fragments or rubble. A comminuted zone of material is formed when a projectile penetrates a ceramic.
- Complete penetration:** See *perforation*.
- Composite:** A structure comprising two or more materials often engineered so that the properties of the materials are complementary, and therefore, the structure is more than the sum of its parts.
- Critical thickness:** With reference to semi-infinite depth-of-penetration (DoP) experiments with a ceramic-faced witness material: the thickness of ceramic required so that there is no penetration in the witness material.
- Crystalline:** A material that possesses a structure that consists of an ordered array of atoms.
- Delamination:** With reference to a composite armour system, it is the process by which the individual layers (or laminae) become separated from one another – usually due to the penetration or perforation of a projectile.
- Detonation wave:** A chemically-supported shock wave that propagates in an explosive during detonation.
- Differential tile efficiency:** With reference to semi-infinite DoP experiments with a ceramic-faced witness material: the factor by which the areal density of the witness material penetrated is reduced by the addition of a target tile normalised by the areal density of the applied target material. It has the symbol Δe_c .
- Disruptor:** The part of the armour system that causes the projectile to fracture and fragment. Usually, these are made from materials of high hardness and/or impedance.
- Driving band:** A malleable or pre-engraved band that is pressed around the rim of the projectile, which, when engaged with the rifling of the barrel, imparts spin to the projectile.
- Ductile fracture:** The growth and coalescence of voids within a ductile medium under stress such that separation of the material is inevitable.
- Ductile hole growth:** With reference to a projectile penetrating a ductile target: this occurs when the material plastically deforms such that the material is pushed out of the way of the penetrator. It is important to realise that no localised increase in density occurs around the hole formed from the penetrator; rather, the whole plate deforms to take into account the hole that is formed – that is, the volume remains constant.

- Dwell:** Lateral flow of a penetrator's tip across the surface of a hard target due to the apparent strength of that target overmatching the strength of the penetrator.
- Elastic:** A material is said to be elastic if it returns back to its original shape after being stretched or squeezed.
- Elastic impedance:** An elastic property of a material calculated by $\sqrt{(E \cdot \rho)}$. It can also be calculated by multiplying the bulk density of the material by its elastic wave speed.
- Enhanced body armour:** A UK body armour that is designed to protect the wearer from 12.7-mm calibre bullets. It incorporates a boron-carbide insert as the disruptor.
- Equation of state:** A fundamental constitutive equation that relates a material's response to pressure in terms of density and internal energy.
- Explosively formed projectile:** A projectile that is formed from a thin geometric shape (usually a 'dish') by the action of a detonating high explosive. Also sometimes referred to as a 'self-forging fragment'.
- Explosive-reactive armour:** An armour system that works by intercepting a penetrator or shaped charge jet with explosively driven plates in order to cause disruption.
- Face hardening:** The process of hardening the surface of a material – usually by work hardening, flame hardening or carburising.
- Flame hardening:** A process of heating the surface of steel (by using a gas flame) up to very high temperatures and then rapidly cooling (quenching) to form a very hard but brittle layer with decreasing hardness through the thickness of the steel plate.
- Flexural rigidity:** The multiplication of the Young's modulus and second moment of area.
- Fracture:** The separation of material.
- Fracture toughness:** A term that defines a material's ability to resist the extension of a crack when the material is placed under load.
- Glacis plate:** The sloping plate of armour located at the front and top of an armoured fighting vehicle (AFV).
- Grain:** A single crystal of material. Polycrystalline materials exhibit multiple grains.
- Gross cracking:** If on impact by a projectile, a crack grows in a plate, that crack will propagate in a manner similar to brittle fracture (depending on the material's toughness). The crack will propagate at a high velocity and cause a large portion of the material to become separated from the bulk. High-hard armour and some hardened aluminium alloys can be susceptible to gross cracking when penetrated.
- Hardness:** A measure of resistance to indentation, abrasion and wear.
- Hot isostatic press:** A system for simultaneously applying heat and uniform (gas) pressure to a sample.
- Hot pressing:** A process used to densify ceramic by simultaneously applying heat and (usually) uniaxial pressure.

- Hugoniot:** The Hugoniot is a material property that describes the locus of states that are achievable due to the passage of a shock wave and is commonly used to derive an equation of state. A Hugoniot curve can be plotted, for example, as a relationship between pressure and density or as a relationship between shock and particle velocity.
- Hugoniot elastic limit:** Under uniaxial strain loading conditions, the point at which the material ceases to behave elastically and starts to behave inelastically.
- Hydrocode:** An explicit transient dynamic computational code where the conservation and the constitutive equations for the materials are solved simultaneously and iteratively using either finite difference or finite element techniques.
- Hydrodynamic limit:** The maximum penetration achievable according to hydrodynamic theory.
- Hydrodynamic penetration:** Penetration of a projectile or shaped charge jet into a target material where the penetrator and target behave as if they possess no strength. This tends to occur at elevated velocities of impact where the shock pressures generated are orders of magnitude higher than the strengths of materials.
- Inelastic:** Not elastic – that is, plastic.
- Interface defeat:** Resistance to penetration of a hard target due to the penetrator being completely eroded at the target's surface via dwell.
- Internal energy:** Energy that a material possesses because of the motion of its atoms and molecules.
- Isentrope:** A curve, usually plotted in terms of pressure and volume, along which there is a release of pressure (or stress) after the passage of a shock wave. It is similar to a Hugoniot curve and for small compressions can be assumed identical to it.
- Isotropic:** Possessing identical material properties in all directions in three-dimensional space.
- Kinetic energy:** Energy due to mass and velocity. It can be calculated by taking half the mass and multiplying it by the velocity squared ($1/2 mv^2$).
- Knoop indenter:** An elongated pyramidal indenter that is used to measure the hardness of a material.
- Liquid-phase sintering:** This process makes use of low-melting-point sintering aids that form a viscous liquid at the firing temperature. The liquid thoroughly wets the solid particles and, when cooled, forms a glassy phase in-between grain boundaries. Typical sintering-aid materials are compounds of silicon dioxide (SiO_2), magnesium oxide (MgO) and calcium oxide (CaO). Because the glassy phase will melt again at a relatively low temperature compared to the crystalline lattice, liquid phase-sintered materials have a compromised high-temperature strength.

- Long-rod penetrator:** A solid rod-like shot, usually sub-calibre and drag stabilised, which is used in attacking armour (see *armour-piercing fin-stabilised discarding sabot*).
- Martensite:** A fine needle-like structure that is the hardest constituent obtained in steel.
- Mass effectiveness:** The factor by which the areal density of armour will be multiplied if a specific armour system is replaced with a single witness material – usually RHA. It has the symbol E_m .
- Mass efficiency factor:** See *mass effectiveness*.
- Metal matrix composite:** Similar to a cermet. A metal matrix composite is a composite of two or more materials with one material forming the matrix and another forming the reinforcement that is embedded within the matrix. At least one of the materials must be a metal (hence metal matrix composite); the other material(s) can be metallic, ceramic or organic.
- Meyer hardness:** The hardness measured by dividing the applied load on the indenter by its projected area instead of the surface area of the indentation. Commonly calculated for the Brinell indenter but can be used with other indenters too.
- Microcrack:** A very small crack that may or may not propagate depending on the stress concentration at its tip.
- Mine:** An explosive munition that is primarily designed to remain passive until initiated by contact with the target or after a specified amount of lapsed time.
- Neutral axis:** The longitudinal axis that suffers zero direct stress when a beam is subjected to bending. For a symmetrical section of a uniform beam that is being subjected to pure bending, the neutral axis will be the same as the central axis.
- Passive armour:** Armour that works to defeat an incoming projectile or shaped charge jet by mechanical properties.
- Partial penetration:** Not *perforation*.
- Penetration:** The process of a projectile moving through a material.
- Penetrator:** A projectile that penetrates.
- Penetrator dwell:** The process of a projectile being unable to penetrate the ceramic until its strength has been diminished. The penetrator therefore appears to dwell on the surface of the target. If the strength of the ceramic does not diminish in the timescale of penetrator erosion, then interface defeat occurs.
- Perforation:** The process of the projectile moving through the material and exiting from the rear surface. Perforation is synonymous with complete penetration.
- Phase:** A distinct state of matter in a system.
- Plane strain:** A state of strain where an element or material is being subjected to a two-dimensional in-plane strain such that the strain normal to the two-dimensional plane is zero.

- Plane stress:** Similar to plane strain. A state of stress where an element or material is being subjected to a two-dimensional in-plane stress such that the stress normal to the two-dimensional plane is zero.
- Plate-impact experiment:** An experimental method used to create shock waves of a controlled magnitude and duration in solids. The experimental set-up consists of a flyer plate that is accelerated toward the target and impacts it at a predetermined velocity. The geometry of the plates is such that a one-dimensional state of strain exists within the flyer plate and target.
- Plugging:** With reference to a projectile impacting and penetrating a target: if the material is susceptible to shear failure, a plug can be detached from the armour. This forms a secondary projectile that can result in catastrophic behind-armour effects. If plugging failure does occur, the total energy that the armour absorbs will be less. This is because the failure is localised and does not allow for gross plate plastic deformation. In armour materials, plugging is usually a result of adiabatic shear.
- Polycrystalline:** With reference to a material: a structure that consists of multiple crystals (or 'grains') that are joined together.
- Proof stress:** An arbitrary yield stress calculated for materials that do not have an obvious yield point – such as aluminium. A line is drawn parallel to the linear elastic part of the stress–strain curve but is offset by some standard amount of strain (for example, 0.1%). The intersection of the offset line and the stress–strain curve is the proof stress. Sometimes referred to as the *offset yield stress*.
- Propellant:** An explosive that burns to propel a projectile or missile through the expansion of high-pressure gases.
- Quenching:** The process of hardening steel by rapidly cooling it from some elevated temperature. Water is the most commonly used medium for quenching, although oils are sometimes used.
- Radial fracture:** Cracking that resembles the pattern of spokes in a bicycle wheel.
- Rayleigh line:** The path by which a shock jumps from one state on a Hugoniot to another.
- Reaction bonding:** An exothermic chemical reaction that produces a ceramic as the end product.
- Reactive armour:** Armour that works to defeat an incoming projectile or jet by detecting the presence of the threat during penetration and responding kinetically.
- Roll bonding:** A process of rolling two metal plates (of differing mechanical properties) together at elevated temperature to form a strong metallurgical bond between the two plates.
- Rolled homogeneous armour (RHA):** Rolled steel plate for armour applications that possesses relatively high hardness and good through-thickness properties. It usually contains carbon, manganese, nickel and molybdenum.

- RHA equivalences:** The thickness of RHA required to defeat a given projectile when compared to a specific armour system that is able to defeat the same projectile. Therefore, if a ceramic-faced armour system has a RHA-e of 100 mm, then the protection offered by this armour is equivalent to 100 mm of RHA.
- Sabot:** A lightweight full-calibre casing designed to carry a sub-calibre projectile up the gun tube. It is usually discarded after the projectile leaves the muzzle.
- Secondary penetration:** Penetration that occurs in a target after a long-rod penetrator has been completely eroded by it.
- Self-forging fragment:** See *explosively formed projectile*.
- Self-propagating high-temperature synthesis:** A process whereby raw powdered starting materials are heated to a specific temperature that enables a highly exothermic chemical reaction to propagate and produce a final product.
- Shatter gap:** Occasionally, it is possible to measure two distinct v_{50} velocities when increasing the velocity over a wide range. That is, it is possible to perforate the target at relatively low velocities followed by partial penetrations at higher velocities. Perforation of the target again occurs when the velocity of the projectile is increased further. This occurs because the penetration mechanism of the projectile changes as the velocity is increased.
- Shock wave:** A propagating discontinuity of pressure, temperature (or internal energy) and density that is spread over a very thin front.
- Sintering:** Densification by the welding together of ceramic powders by the application of heat; sometimes, pressure is also used.
- Sintering aid:** A chemical used to reduce the temperature required for sintering.
- Slip casting:** A process for shaping ceramic powders into complex geometries prior to densification. Typically, ceramic particles are suspended in water and cast into porous plaster moulds. The water is sucked out though the pores in the porous mould over time leaving a close-packed deposition of particles that are ready for densification.
- Slipping driving band:** A malleable band that is able to spin around the rim of a projectile or sabot to minimise the spin imparted by the rifling of a gun barrel. It is used for launching drag-stabilised projectiles in rifled gun barrels.
- Spall:** Dynamic tensile failure due to stress wave interactions.
- Spall liner:** A sheet of material that is applied on the inside of a vehicle hull to minimise the lethal effects of a perforating projectile or jet.
- Strain:** The deformation of a material measured, in uniaxial tests, by the extension or contraction of a material divided by its original length.
- Strain hardening:** See *work hardening*.
- Strain rate:** The rate at which deformation occurs.
- Stress:** Force divided by the cross-sectional area over which the force is applied.

- Stress corrosion cracking:** This occurs when a metal is attacked by a corrodant whilst being subjected to tensile stress. It is a particularly insidious failure because the magnitudes of stresses that are required to encourage failure are frequently lower than the yield strengths of the metal. In fact, residual stresses induced during machining, assembling or welding can exacerbate this type of failure. Aluminium alloys used in some AFVs were susceptible to this type of failure.
- Tempering:** A process of heating a metal to relieve internal stresses and to produce the desired quantities of hardness and toughness.
- Ultimate tensile strength:** The maximum stress as measured from an engineering stress–strain curve.
- Uniaxial strain:** A state of strain that is acting in a material in one direction only.
- Uniaxial stress:** A state of stress that is acting in a material in one direction only.
- Vickers indenter:** A pyramidal indenter with an apex angle of 68° that is used to measure the hardness of a material.
- Wave shaper:** A material whose geometry and impedance are designed to redirect the detonation wave in a high explosive. These are usually used in shaped charge–type warheads to maximise the collapse of the liner into a slug or jet. It is sometimes referred to as an explosive lens.
- Work hardening:** Hardening of a material due to the application of work. This process is due to the presence of lattice dislocation pile-up and is sometimes referred to as *strain hardening*.
- Yield strength:** See *yield stress*.
- Yield stress:** The stress at which the material ceases to behave elastically. Also referred to as the *yield strength*.

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Chapter 2

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