Materials Forming, Machining and Tribology

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A Brief History of Mechanical Engineering

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To
Mechanical Engineering Fraternity

Preface

Mechanical engineering is concerned with reducing or eliminating physical effort of humans or domestic animals with the help of tools and/or machines. In that sense, mechanical engineering has been in existence almost since the primitive man was born on the Earth; tools in very crude form must have been used by the primitive man. Wheel was invented a few millennia before Christ, and theory of lever was proposed a few centuries before Christ. However, up to nineteenth century, the distinction between science and engineering was blurred. Different disciplines of engineering did not have separate identity. Mechanical engineering emerged as separate strong discipline of engineering in nineteenth century. The Institution of Engineers was formed in 1847 in UK. Today, mechanical engineering is flourishing along with its offspring like production engineering, industrial engineering, manufacturing engineering, mechatronics, automobile engineering, and aerospace engineering. In spite of it, most of the persons are not familiar with the history of mechanical engineering. There are a very few books on this topic, and they have been written a few decades ago. Since then, a lot of changes have taken place in mechanical engineering with the general development of technology in various fields particularly in electronics and computer science. At the same time, growing industrialization and population have put tremendous pressure on environment forcing us to think about the issue of sustainability. A book on the history of mechanical engineering narrating the development of this discipline since the times immemorial till modern age is the need of the hour. In this backdrop, three of us decided to write a brief history of mechanical engineering.

We decided to keep our treatment brief only, so that the book can be useful for professionals interested in a quick grasp of the history of mechanical engineering as well as for general public. Due to concise and simplified narration, the book can be used as a textbook for one-semester elective courses in engineering, management, or humanities. The attempt has been not only to present the development in the field of mechanical engineering chronologically but also to explain related technological concepts in a highly simplified form. This will help the general audience to understand mechanical engineering and will be a recapitulation for mechanical engineers.

There are eight chapters in this book. Chapter 1 “What is Mechanical Engineering?” provides an introduction to mechanical engineering and describes its scope and objectives along with some discussion on the educational aspects of mechanical engineering. Chapter 2 “Landmark Revolutionary Inventions in Mechanical Engineering” discusses the history of landmark inventions as well as their working principle. The readers with imaginative minds will find this chapter very exciting. The chapter describes the development of those technological products, which have become very common in day-to-day life and it is difficult to live without some of those products, and yet there was a time, when the engineers were struggling to develop them.

Chapter 3 “History of Mechanics” describes the development of mechanics since the times of Aristotle to Einstein. Biographical details of the leading pioneers are also provided. Mechanics comprises solid mechanics as well as fluid mechanics and is a part of physics and mathematics. It finds profound application in civil and mechanical engineering. Chapter 4 “History of Thermodynamics and Heat Transfer” describes the development of thermodynamics beginning from about one century before Sadi Carnot (1796–1832). Sadi Carnot is considered as the father of thermodynamics. In that sense, thermodynamics is much younger to mechanics and got impetus from the development of steam engine. Heat transfer is considered to have started since the period of Newton. Apart from mechanical engineering, thermodynamics and heat transfer are important subjects of physics, mathematics, and chemical engineering.

Chapter 5 “Manufacturing through Ages” describes the history of manufacturing. The development of steam engine provided an impetus to industrial revolution (circa 1750–1850). Various machine tools were invented in this period. Manufacturing sector took a momentum with the concept of mass production. Today, 3D printing may produce economical product even when producing a single component. In this chapter, apart from the history of technological inventions, a review of various manufacturing processes (particularly machining and metal forming) is presented. Chapter 6 “Emergence of Production and Industrial Engineering” presents a brief history of production and industrial engineering. Production and industrial engineering have emerged as separate disciplines, but they are also part of a typical mechanical engineering curriculum. The students and professionals of management may also find this chapter interesting.

Chapter 7 “History of Mechatronics” describes the developments in the field of mechatronics starting from 1970s to early 2010s. This chapter contains the history of electrical engineering, as well as electronics engineering. Developments in the area of computer science and engineering are also discussed. Finally, the importance of these developments in the mechanical engineering is discussed. Mechatronics is the synergetic combination of mechanical engineering, electronics engineering as well as other related disciplines. Chapter 8 “Future of Mechanical Engineering” concludes the book. It discusses the future trend based on the past history and present state of the art. It also provides some guidelines to mechanical engineering students and professionals.

This book will be useful for the professional and budding engineers for getting a general knowledge of the subject and familiarity with its history. It will also be helpful for school-level students planning to take up mechanical engineering as a profession. Finally, the book may be useful for anyone interested to know about mechanical engineering. The book may be adopted for a one-semester course on the history of mechanical engineering. It can also serve as a reference book for a course introducing the mechanical engineering.

While writing this book, a number of books, papers, and Web sites have been referred. The references have been listed. Any omission is inadvertent. Readers are requested to point out any correction. We shall try to incorporate it in future editions. We also request the readers to provide their valuable feedback through e-mails at uday@iitg.ac.in or pdavim@ua.pt.

We are grateful to our family members and friends for their encouragement and patience. We are thankful to Mr. Vinod Yadav, Ph.D. student of Department of Mechanical Engineering, Indian Institute of Technology Guwahati, for drawing some figures. We also thank the staff of Springer especially Dr. Mayra Castro for the kind cooperation we received.

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Contents

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Dr. J. Paulo Davim received his Ph.D. in mechanical engineering from the University of Porto in 1997, the Aggregate title from the University of Coimbra in 2005, and a DSc from London Metropolitan University in 2013. Currently, he is a professor at the Department of Mechanical Engineering of the University of Aveiro. He has about 30 years of teaching and research experience in manufacturing, materials, and mechanical engineering with special emphasis in machining and tribology.

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Chapter 1
What Is Mechanical Engineering?

Abstract Mechanical engineering is one of the oldest disciplines of engineering, although it gained separate identity in the nineteenth century. The word engineer itself means the constructor of military engines, which falls in the scope of modern day mechanical engineers. Scope of mechanical engineering is quite wide. It finds applications in many fields. Mechanical engineers perform a variety of tasks starting from design to management of machines and equipment. They also perform supportive role in other engineering disciplines. Several engineering disciplines have undergone successful marriage with mechanical engineering. A number of disciplines have emerged as offspring of mechanical engineering, e.g., production engineering, industrial engineering, manufacturing engineering, automobile engineering, aerospace engineering, and mechatronics. Mechanical engineering education has been continuously evolving with the changing level of technology.

Keywords Engineering · Mechanical engineering · Production engineering · Industrial engineering · Manufacturing engineering · Automobile engineering · Aerospace engineering · Mechatronics · Mechanical engineering education

1.1 Introduction

Engineering is as old as the human civilization, although the word 'engineer' came into existence around 1325 AD (Baofu 2009). Our life is very much dependent on engineers and everyone has a feel of engineering, but for many persons there is often a lack of clarity about engineering profession. The more difficult task is to define engineering. The word engineering seems to come from the Latin word 'ingenium' meaning cleverness or from the Latin word 'ingeniare' meaning to contrive device. It is very clear that an engineer is expected to exploit the resources of the nature in an intelligent and optimum manner. Since the time immemorial, human race has been doing this. Like animals, it did not depend only on the organs and limbs provided by the nature. It invented tools, wheel, fire, and many such devices. The process of invention is going on. However, in the beginning, humans

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used to live in small groups and one person used to possess several skills. With the gradual drift toward globalization, the need was felt for the specialization and division of labor. Thus, around fourteenth century, engineering was recognized as a profession in some countries for making weapons and structures, but before that there were many artists and scientist, who were basically engineers.

Many opine that there is no difference between engineering and applied science. Science reveals the truth of the nature. The word science comes from the Latin word ‘scientia’ meaning knowledge (Wenning and Vieyra 2015). To know the truth is inherent in human nature. The craving for truth is as essential as for the food, water, air, and shelter. We read newspapers, press reports, and analytical articles to know the truth. We carry out space exploration to find out if there is life in other planets or satellites or if it is possible to live on them. The quest for knowledge apparently may not have any motive for getting any benefit out of them. Several mathematicians do research on irrational numbers just for academic interest, deriving pleasure from developing algorithms. Some of them would never have assumed that some of their findings will be useful in cryptography, which is a method of storing and transmitting data in a particular form so that only those for whom it is intended can read and process it (Goldreich 2011). On the other hand, applied scientists aim at practical applications of science.

An engineer uses scientific knowledge for inventing, designing, building, or maintaining some object or system. However, scientific knowledge is not the only knowledge an engineer needs. An engineer also utilizes economic, social, and traditional knowledge. In fact, in several fields, engineering may be older than science. For example, the fire might have been invented accidently and humans learnt to utilize it. The chemistry of fire came to be known much later. Often the term, technology is used interchangeably with science. Several universities provide degree in Bachelor or Master of Technology from their engineering departments. Often there is no distinction in Bachelor of Technology, Bachelor of Engineering, or Bachelor of Science in engineering. That reminds a famous quote of William Shakespeare: ‘What’s in a name? That which we call a rose, By any other name would smell as sweet’ (Shakespeare 1597). However, from an academic point of view, engineering and technology are different though interrelated.

The word ‘technology’ is derived from the Greek word ‘technologia’ meaning systematic treatment (Monsma 1986). There are several and sometimes differing interpretation of the word ‘technology’ and its relation with engineering. Cambridge dictionary defines technology as (the study and knowledge of) the practical, especially industrial, use of scientific discoveries (CUP 2008). The Oxford English Dictionary (2002) defines technology as the application of scientific knowledge for practical purposes, especially in industry. It also defines technology as machinery or devices developed from scientific knowledge and as the branch of knowledge dealing with engineering or applied sciences. These definitions do not bring out clear cut difference between engineering and technology. One way to differentiate engineering with technology is as follows. Technology provides one or several techniques to accomplish a task. The techniques may be based on science or mere common sense. It is the engineer who chooses the proper technology

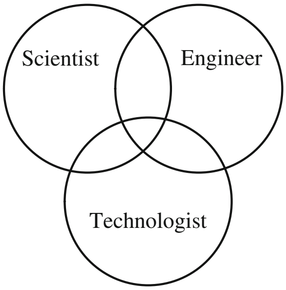

Fig. 1.1 Domains of scientists, engineers, and technologists

considering the economic, social, and environmental factors. It should not, however, be inferred that technology is a part of engineering. Just as engineering utilizes the scientific knowledge, it also utilizes the technology. Scientists, engineers, and technologists at times work together, but may work independently as shown in the form of a Venn diagram in Fig. 1.1.

Suppose there is a sophisticated machine shop. The computer numerical control (CNC) machines of the shop use computer technology, software technology, electrical and electronics technology, and mechanical technology. An engineer managing the shop is dependent on these technologies for the proper functioning of the shop, but the proper functioning also depends on optimum layout, maintenance schedule, proper lighting, and also proper working conditions for the workers including their incentive plans. Technology, for example, will not answer how much incentive should be provided, but the engineering has to deal with this aspect as well.

The following anecdote may bring out the differences between science, engineering, and technology more clearly. Once upon a time, three friends were passing through a forest. They were feeling thirsty, but their water pot was empty. Suddenly they saw a well, but there was no rope to draw the water from the well. The first man asked the second man, ‘You know a lot about plants. Can you identify the grass around here that is strong?’ The second man identified the grass, which had a good tensile strength. Then, the first man asked the third man, ‘You are very skilled. Can you join the number of grass plants by making strong knots and then tie it with the pot?’ The third man made strong knots and the pot was tied with the grass rope and water was drawn from the well. Among these, the first man was an engineer, the second a scientist, and the third a technologist.

Engineering needs inputs from various disciplines for accomplishing a task. Traditional knowledge, technology, physical sciences, economics, social science, and environmental science play a major role in engineering. This is illustrated through Fig. 1.2.

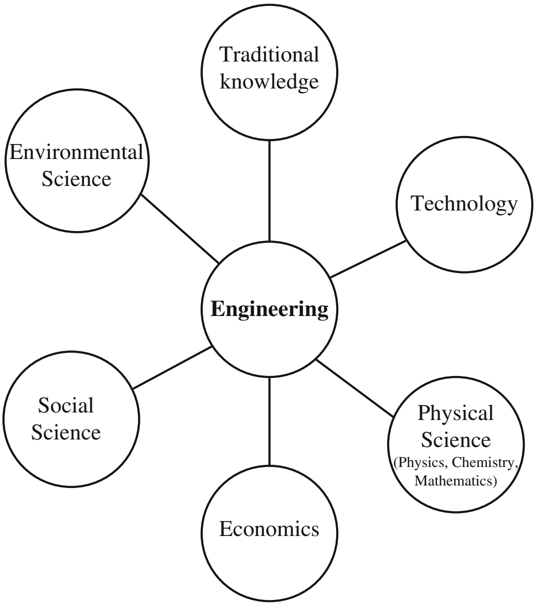

Fig. 1.2 Disciplines that interact with engineering

1.2 Definition of Mechanical Engineering

The word ‘engineer’ was in use around 1325 AD (Baofu 2009), which meant ‘constructor of military engines.’ Engines in those days meant military weapons such as catapult or military machines; steam engines were not invented by then. In the eighteenth century, the term civil engineering was coined to distinguish it from military engineering. John Smeaton (1724–1792) is often considered as the father of civil engineering (Duckham 1965). It is clear that civil engineering comprised all engineering branches in those days. Growth of industry and transportation led to provide separate identity to mechanical engineering. In 1847, Institution of Mechanical Engineers was formed in UK (IMechE 2015: http://www.imeche.org/knowledge/library/archive/institution-and-engineering-history). The mechanical engineering can be defined as the branch of engineering dealing with the design, construction, operation, and maintenance of machine. The American Heritage Dictionary of the English Language defines mechanical engineering as the branch of engineering that encompasses the generation and application of heat and mechanical power and the design, production, and use of machines and tools (American Heritage® Dictionary of the English Language 2011).

1.3 Scope of Mechanical Engineering

The scope of mechanical engineering is very wide and apart from primarily mechanical industries like automobiles and machine tools; it finds supportive role in virtually all engineering disciplines. In the ancient and medieval periods of history, a number of inventions were carried out for either reducing the human effort or totally eliminating it. For example, the lever was invented for amplifying the force, so that heavy objects can be lifted with a small amount of force. Similarly, the steam engines and hydraulic turbines totally eliminated the human effort in generating the power. Traditionally, the mechanical engineering has been applying solid mechanics, fluid mechanics, and thermodynamics to the design, fabrication, operation, and maintenance of plants and machinery. Ship designing requires the knowledge of fluid statics and solid–fluid interaction. In thermal power stations, one needs the knowledge of thermodynamics, strength of materials, material science, fluid mechanics, and heat transfer for designing a boiler. Design of hydraulic turbines also requires the knowledge of fluid mechanics for understanding the process of conversion of hydraulic energy into mechanical energy and solid mechanics for mitigating the problems related to stress and vibration of the turbine blades and other rotating parts. Nowadays, in designing and fabricating a device, various disciplines interact, in which the mechanical engineering often plays a major role. A new field called mechatronics is emerging. In fact, mechatronics is often defined as the application of methodology, techniques, and understanding of one or more disciplines to another discipline (Dixit 2012).

Mechanical engineering finds applications in transportation sectors like railways, automotive industries, aeronautical industries, and shipping industries. In the power generation units, the mechanical and electrical engineering have very important roles. In the military field, mechanical engineering finds application in design, manufacture, operation, and maintenance of weapons such as guns, missiles, and tanks. Nowadays, mechanical engineering is having a lot of scope in biomedical field particularly in designing and manufacturing various devices such as pacemakers, dialysis machines, implants, and artificial limbs. In the field of robotics, mechanical, computer, and electronics engineers contribute together. In chemical industries also, the mechanical engineering contribute to the design, maintenance, and operation of plant and machinery. Thermodynamics, heat transfer, and fluid mechanics find a lot of application in chemical industries, which are major subjects of mechanical engineering. The scope of mechanical engineering is expanding to newer fields like nanotechnology and synthetic biology.

1.4 Mechanical Engineering Profession

A young graduate engineer has various options to start a career. A large percentage of mechanical engineers are employed in various industries. In the olden days, the mechanical engineer was responsible for almost all activities related to mechanical engineering. Nowadays, barring very small industries, there are a number of specialized fields in mechanical engineering. Some mechanical engineers become designer, who has the primary task to design plants and machinery or tools, jigs, and fixtures for production purpose. Some mechanical engineers manage the production shops. Some mechanical engineers work in maintenance department, where the main task is to carry out preventive and breakdown maintenance. Of late, condition monitoring-based maintenance is gaining popularity, in which the health of machine is monitored by observing signals such as vibration, and appropriate action is chosen by inferring the signals.

Mechanical engineers working in quality control or assurance department are responsible for in-process and final inspection. They also design various strategies for enhancing the product quality. In the field of marketing, mechanical engineers participate in sales and servicing of the products. Other departments in which mechanical engineers are employed are process planning, stores, purchase and safety.

Opportunities also exist in banking and insurance sector, where mechanical engineers assess the worth of a project, machinery, and plant. They get jobs in software sector as well. There are a number of software jobs, which directly utilize their mechanical engineering skills. For example, mechanical engineers contribute to the development of computer-aided design (CAD) and computer-aided manufacturing (CAM) packages. Other types of software industries use the skills of mechanical engineers in an indirect manner. These industries do not develop mechanical engineering-related software, but prefer to employ the mechanical engineers for their analytical and practical skills. Apart from this, some mechanical engineers take up various managerial and administrative positions.

1.5 Mechanical Engineering Education

A number of universities and colleges run diploma, degree, and postgraduation programs in mechanical engineering. The duration of programs varies from country to country; however, in most of the places, a diploma program is of 3 years duration, a degree program is of 4 years duration and a postgraduation program is of 1 or 2 years duration. A Ph.D. program does not have a fixed duration, although the minimum (say 2 years) and maximum (say 7 years) duration may be prescribed.

Mechanical engineering education comprises courses on basic sciences, humanities and social sciences, mathematics and computer programming, mechanical engineering, and allied engineering. A mechanical engineering student has to study a wide range of theoretical and laboratory courses. On one hand, a student studies the analytical courses like mathematics and computer programming; on the other hand, the student also has to study many applied courses like workshop and machine drawing. The workshop and machine drawing are the important practical courses. In the workshop, student learns basic skills of a craftsman and the operation of machines. In the machine drawing, the student learns to represent physical objects by means of drawings. The important physics-oriented courses are solid mechanics, fluid mechanics, thermodynamics, and heat transfer. The important production-oriented courses are manufacturing technology and industrial engineering. The student also has to study the courses on electrical and electronics engineering. Three broad streams of mechanical engineering are as follows: (1) machine design or solid mechanics, (2) fluid mechanics and thermal engineering, and (3) manufacturing or production.

The world's first institution of technology, the Berg-Schola, which is called University of Miskolc now was founded in Hungary in 1735 (http://www.uni-miskolc.hu/). The oldest German institute of technology called Braunschweig University of Technology (https://www.braunschweig.de/english/business_science_education/tu_bs_eng.html) was founded in 1745 as Collegium Carolinum. Ecole Polytechnique (http://www.polytechnique.edu/) was established in 1794 in France.

In 1818, the first British Professional Society of Civil Engineers was formed in UK (https://www.ice.org.uk/), Institution of Mechanical Engineers, UK was formed in 1847 (http://www.imeche.org/knowledge/library/archive/institution-and-engineering- history). In USA, Civil Engineering Society (http://www.asce.org/) was formed in 1852 and Mining and Metallurgical Engineering Society was formed in 1871 (http://www.aimehq.org/). The American Society of Mechanical Engineering (ASME) was formed in 1880 (http://www.asme.org/) followed by American Society of Electrical Engineering (www.asee.org/) in 1884.

The early schools in the USA to offer engineering education were United States Military Academy (established in 1817), an institution now known as Norwich University (established in 1819) and Rensselaer Polytechnic Institute (established in 1825) (http://www.futuresinengineering.com/what.php?id=1). The first engineering college in Asia was established at Roorkee, India in 1847 (http://www.iitr.ac.in/). It is now known as Indian Institute of Technology Roorkee. However, the first technical institution is School of Survey Guindy established in 1794 (https://www.annauniv.edu/). It started mechanical engineering program in 1894. College of Engineering, Pune (www.coep.org.in/) is the second oldest engineering college in India.

1.6 Offshoots of Mechanical Engineering

As discussed earlier, the term civil engineering was used to refer to non-military applications. Further specialization led to the emergence of mechanical engineering. Four years after the establishment of American Society of Mechanical Engineers, Electrical Engineering Society was formed in 1884. American Society of Chemical Engineers was formed in 1908. Mining and Metallurgical Engineering society was formed in 1871. Although a number of courses of mechanical engineering are taught to students of chemical engineering, mining engineering, and metallurgical engineering, these disciplines evolved more from applied science than from engineering. However, a number of disciplines that exist today can be called as the offshoots of mechanical engineering. In this section, introduction to some important disciplines is provided. The students of these disciplines study several subjects of mechanical engineering.

1.6.1 Production Engineering

As discussed earlier, manufacturing technology is an important part of mechanical engineering, as virtually all manufacturing activities of today take the assistance of machines. In order to achieve high production, proper technology as well as its management is required. Production engineering is a combination of manufacturing technology and management. In America, H.R. Towne (1844–1924) was one of the pioneers in the field of production engineering (Armytage 1961). Production engineering courses became more popular after World War II. In India, the first department of production engineering was established in 1959 at Veermata Jijabai Technological Institute (VJTI), Mumbai, initially as Department of Industrial Engineering.

1.6.2 Industrial Engineering

Frederick Winslow Taylor (1856–1915) is often credited as the father of industrial engineering (Copley 1923). By profession, he was a mechanical engineer and he introduced a lot of techniques for improving the efficiency of the production system. In USA, Henry R. Towne (1844–1924), an ASME member, was one of the pioneers in developing industrial engineering field (http://www.stamfordhistory.org/towne1905.htm). In 1948, a society called American Institute of Industrial Engineers was founded (http://www.iienet2.org/). The word American was dropped in 1981.

From a practical point of view, there is not much difference in the course structure of production engineering and industrial engineering. Both of these disciplines pay more emphasis to manufacturing technology and management-related courses at the cost of in-depth study of basic courses like thermodynamics, heat transfer, fluid mechanics, and solid mechanics. In essence, a production and industrial engineer is provided exposure to almost all courses of mechanical engineering, but the focus is on the courses on manufacturing, quality control, optimization, and decision making.

Many define industrial engineering as a branch of engineering that deals with the optimization of complex processes and systems (Kahraman 2012). From an academic point of view, a production engineer is equally expert in manufacturing technology and its management, while an industrial engineer is more adept in utilizing the technology than in developing the technologies. Thus, industrial engineering is very close to technology management. In practice, the distinction between a production engineer and an industrial engineer is blurred.

1.6.3 Manufacturing Engineering

Whereas industrial engineering and production engineering comprise manufacturing technology and its management, manufacturing engineering is more biased toward technology part at least from a theoretical point of view. Manufacturing engineering is a discipline of engineering dealing with different manufacturing practices and includes the research, design and development of systems, processes, machines, tools, and equipment. A student of manufacturing engineering gets exposure of almost all mechanical engineering, production engineering, and industrial engineering courses, but theoretically the emphasis should be more toward technology. In practice, manufacturing is very close to production engineering and industrial engineering and appears as a branch of mechanical engineering. The Society of Manufacturing Engineers was founded in 1932 (http://www.sme.org/). It was originally named the Society of Tool Engineers. A year later, it was renamed the American Society of Tool Engineers (ASTE). From 1960–1969, it was known as the American Society of Tool and Manufacturing Engineers (ASTME). It became the Society of Manufacturing Engineers (SME) in 1970. In 2013, the use of its full legal name, the Society of Manufacturing Engineers, was discontinued and the organization became known as SME.

The knowledge about materials is as important in manufacturing as the knowledge of fluid properties in fluid mechanics. A manufacturing engineer should be familiar with material science and strength of materials for understanding the mechanics of machining and metal forming. Metal casting requires the melting, flow, and solidification of materials. Many advanced manufacturing processes are based on thermal effects. Therefore, a familiarity with fluid mechanics, heat transfer, and thermodynamics is also essential for a manufacturing engineer. Some process uses the principles of electricity, magnetism, chemistry, and electrochemistry, including relevant topics of physics and chemistry in the curriculum of manufacturing engineering. Moreover, the importance of electrical/electronics, computer science, and manufacturing technology has increased tremendously since last 3–4 decades.

1.6.4 Automobile Engineering

The term automobile is used for a vehicle with engine and wheels that runs on the road. It includes cars, trucks, buses, scooters, motorcycles, and farm tractors. Automobiles are one of the landmark inventions of mechanical engineering. The first car powered by an internal combustion engine was developed in 1807 by Francois Isaac de Rivaz of Switzerland (http://inventors.about.com/od/cstartinventions/a/Car_History.htm). It used a mixture of hydrogen and oxygen for fuel. It was not a very good design, and continuous effort to design the cars resulted in developing comfortable cars as we see them today. Initially, mechanical engineering degree was considered sufficient for working in an automobile industry. With the growth of automobile sector and technology, the discipline of automobile engineering emerged. Today, automobiles utilize mechanical as well as electrical–electronics and computer technology. Hence, the curriculum of automobile engineering comprises the courses on mechanical, electrical, electronics, and computer engineering. Nevertheless, a large portion is from mechanical engineering.

1.6.5 Aerospace Engineering

On December 17, 1903, Wilbur Wright and Orville Wright became the first persons to fly a controllable and self-propelled aircraft made of wood and muslin cloth. The first commercial flight took place between St. Petersburg and Tampa in 1914 (Kalam and Singh 2015). Today, aerospace engineering has emerged as a distinct discipline for engineering related to aircraft and rockets. It is broadly divided into two parts—aeronautical engineering and astronautical engineering. The aeronautical engineering deals with the various aspects of aircraft design, manufacture, maintenance, and operation. The astronautical engineering deals with the outer space. Often it is called rocket science.

1.6.6 Mechatronics

The term mechatronics was coined by a Japanese engineer, Tetsuro Mori, of Yaskawa Electric Corporation (https://www.asme.org/engineering-topics/articles/mechatronics/mechatronics-and-the-role-of-engineers). The trademark right for the word 'mechatronics' was granted to Yaskawa in 1971 and latter abandoned its right on the word in 1982. Mechatronics is defined as the synergetic integration of mechanical engineering, with electrical engineering and/or electronics and possibility with other disciplines for the purposes of design, manufacture, operation, and maintenance of a product (Dixit 2012). Mechatronics education gained popularity since 1991.

Robotics requires the application of mechanical, electrical, electronics, and computer science. It can be called a mechatronics product. Similarly, the automation of machines and processes is gaining importance, which can be the part of mechatronics. Many mechanical engineers are deeply involved in control area, which is a popular subject of electrical/electronics engineering. At many academic institutions, control theory is a compulsory course in mechanical engineering as well.

1.7 Relation of Mechanical Engineering with Other Engineering Disciplines

Mechanical Engineering is closely related with a number of other engineering disciplines. There are many similarities with civil engineering. Both disciplines require a solid foundation in solid mechanics. Civil engineers also have to deal with machines for material testing and constructions. Mechanical engineers have to depend on civil engineering for construction of factory buildings and foundations. Chemical engineers also study courses on fluid mechanics, thermodynamics, heat transfer, and strength of materials. It will not be wrong to assume that chemical engineering largely comprises applied chemistry and mechanical engineering. Pulp and paper technology applies chemical engineering for the manufacture of pulp and papers. Invariably, there is a lot of mechanical engineering involved in it. Mining and metallurgical engineering also has a lot of subjects common with the mechanical engineering. A metallurgist uses a lot of machines and has to be conversant with thermodynamics, heat and mass transfer, and fluid mechanics. Similarly, textile engineering also has to rely on the basic skills of mechanical engineering, particularly in the design of textile machinery.

Electrical engineering plays a vital role in most of the primarily mechanical engineering products. Same is the case of electronics and computer science. These disciplines interact a lot with mechanical engineering. They also require the help of mechanical engineering. Other industry-oriented engineering disciplines that use the mechanical engineering concepts heavily are sugar technology and leather engineering. The engineers working in these fields must be familiar with the basic concept of machines and other equipment such as boiler. Agricultural engineering also includes the elements of mechanical engineering, particularly for the design, maintenance, and operation of agricultural machinery.

Nowadays, there is increasing emphasis on green engineering and sustainability. According to the US Environmental Protection Agency, green engineering is the design, commercialization, and use of processes and products, which are feasible and economical while minimizing (a) generation of pollution at the source and (b) risk to human health and environment (http://www.epa.gov/oppt/greenengineering/pubs/whats_ge.html). The sustainability is the ability to maintain the desired living conditions for all times to go (Dixit et al. 2012). Mechanical engineering finds a vital role in green and sustainable engineering. Some institutions have started a program on environmental engineering within the mechanical engineering department (http://maeweb.ucsd.edu/enviroeng). Mechanical engineers are focusing on improving the efficiency of machines and devices, thereby reducing the pollution. For example, fluidized bed combustion is increasingly used in boilers instead of the traditional burning of coal. At the same time, alternate renewable energy sources, like wind energy and solar energy, are being explored. There is also a drive to minimize cutting fluids and lubricants in machining because of the harm they cause to human health (Dixit et al. 2012). Concept of life cycle thinking is gaining importance. For example, some metallic components in an automobile may be replaced by a fiber reinforced polymer matrix composites. However, one must consider the issue of disposal once the lives of components are over. It is easier to recycle a metallic component than a polymer matrix composite. Environmental engineering includes the drainage system, green building, and weather monitoring. Mechanical engineering subjects like fluid mechanics, heat transfer, and thermodynamics are finding increasing application in environmental engineering.

Another emerging field is the biomedical engineering. It is the application of engineering principles and design concepts to medicine and biology for healthcare purposes (Bronzino 2000). It is the combination of medical science and engineering. Many medical devices, like pacemaker, need the expertise of mechanical and electronics engineering for their design. A subject biomechanics has emerged. It is the study of the structure and function of biological systems such as humans, animals, plants, organs, and cells by means of the methods of mechanics (Hall 2011). Biomechanics is useful in designing implants. Apart from mechanics, material science plays an important role in identifying a suitable biocompatible material. In sports, biomechanics helps in reducing sport injuries by training the sport person for proper movement of the body and proper design of sports implements. Biofluid mechanics studies the behavior of body fluid movement such as blood. Such type of study is helpful in the treatment of many diseases such as heart disease. Microfluidics is also finding application in the diagnostics. Using the principle of microfluidics, one can find the level of blood sugar. Thus, mechanical engineering is finding its presence across the gamut of life.

1.8 Changes in Mechanical Engineering Education Through Ages

In the beginning, craftsmen-based courses were dominant in mechanical engineering curriculum. Machine drawing and workshop were the two important courses. Graphical methods of analysis were employed. After the World War II, there was a drastic change in engineering curricula. The importance of basic science courses was recognized. Gradually, electronics was applied to mechanical engineering products. The first numerical control (NC) milling machine was developed at MIT in 1952 (http://www.mfg.mtu.edu/cyberman/machtool/auto/nc/intro.html).

In the 1960s, mechanical engineering curriculum included computer programming. The mainframe machines were used for computing. In 1980s, PCs gained popularity. A significant portion of the mechanical engineering curriculum got filled with computational courses. In 1990s, the more emphasis has been on using the software rather than developing the codes. Modern trend is toward micro- and nano-engineering, green engineering, and synthetic biology. The subjects like quantum mechanics are expected to gain importance.

Developments in the field of computer science and information have greatly influenced the education of mechanical engineering. Ray Tomlinson invented e-mail in 1971, which helped in the exchange of information between two remotely located institutions. Internet came into existence in around 1973. However, it could not become much popular until the advent of the World Wide Web (WWW) (Isaacson 2014). It was announced by Tim Berners-Lee in 1991. Web is a convenient way of accessing and transmitting information through Internet. Nowadays, a lot of teaching materials including videos are available on Internet, which contributes a lot to mechanical engineering education.

1.9 Conclusion

In this chapter, an introduction to mechanical engineering has been provided. One has to understand the mechanical engineering from a professional as well as educational point of view. Although mechanical engineering has been in existence since the time immemorial, it took a formal shape in nineteenth century in the form of profession and education. The seeds of formal form of mechanical engineering were planted during industrial revolution. As the technology is progressing, the form of mechanical engineering is changing. Today, computer, electronics and electrical engineering are intermingled with the mechanical engineering. Primarily mechanical processes are getting replaced by chemical and biological processes. In that sense, importance of interdisciplinary research is increasing. However, the basic nature of mechanical engineering remains the same. It deals with the development and deployment of machines for human comfort.

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Chapter 2
Landmark Revolutionary Inventions in Mechanical Engineering

Abstract In this chapter, important inventions in mechanical engineering since the advent of human civilization are discussed. The emphasis is on those inventions, which had long-lasting effect on the human civilization. Notable among them are wheel, cutting tool, internal combustion engine, railway, aircraft, refrigeration, and air-conditioning. These revolutionary inventions are still in use and have been undergoing through evolutionary changes. Inventions such as steam engine and Wootz steel are no longer used in the original form. Nevertheless, these inventions have paved the way for future inventions. The underlying principles of these inventions are also briefly described.

Keywords Mechanical engineering · Inventions · Wheel · Cutting tools · Ship · Aircraft · Windmill · Archimedes' screw · Steam engine · Railways · CNC machines · Wootz steel · 3D printing · Refrigeration and air-conditioning

2.1 Introduction

New inventions and their application to enhance the quality of human life is a continuous process since eternity. Mechanical engineering, being one of the oldest branches of engineering, pioneered many inventions that revolutionized the lifestyle of mankind. The roots of many latest gadgets and technologies can be dated back to thousands of years. A number of epoch-making inventions have taken place in mechanical engineering through the centuries. Continuous evolution and application of those inventions in various fields have resulted in industrialization, modern civilization, and better lifestyle. In this chapter, important revolutionary inventions and their impact on the civilization are discussed.

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2.2 Invention of Wheel

Invention of the wheel is indeed a landmark in the history of human civilization. It is one of the most ancient mechanical inventions of the world. The invention of wheel is considered such an important event that 'reinventing the wheel' has become a popular idiom for duplicating certain invention or finding. Wheel finds such as an important role in mechanical engineering, as fire in chemistry and money in economics. There are many evidences of existence of wheels in the early ages of civilization. However, the exact point of time of invention of wheel is yet unknown. It appears that the potters were the first ones to use wheels in 3500 BC for making earthen pots. The first ever wheel that was found in an archaeological excavation in Mesopotamia is believed to be a potter's wheel. Some ancient paintings of wheeled carts and toys found in caves and potteries led to the belief that wheels were developed simultaneously in different places of the world. For example, wheels were used in Sumerian civilization, northern Caucasus, Central Europe, and Eurasian Steppes in the later part of the fourth millennium at around 3500–3350 BC (http://www.localhistories.org/techhist.html).

Although wheels were used for irrigation, milling grains, and pottery making for a long time, it was used for transportation around 300 years later after its invention (Anthony 2007). The earliest wheels were made from wood, a natural choice from the abundant trees in the forests. It is believed that initially wooden logs were used as rollers for moving heavy loads. With passage of time and continuous effort for modification, wheels were evolved from these rollers and used for transportation. The first use of wheel for transportation in chariots is dated back to 3200 BC in Mesopotamia. The idea of wheels with spokes led to the construction of lighter wheels. Spokes are the radial rods joining the wheel center to the outer wheel ring. In 2000 BC, the first wheel with spokes was invented in Egypt and used in chariots. From the ancient paintings and cave arts, it can be assumed that spoked wheels were used in toy carts and vehicles in Caucasus region, Central Europe, China, Indus Valley, and northwestern India around 2000 BC. Iron rims around a wheel were first introduced by the Celtics in 1000 BC (http://www.autoevolution.com/news/history-of-the-wheel-7334.html). A rim is the outer circular ring wound around a wheel attached to the outer ends of the spokes. Simple wooden spoked wheels were in use for a long time without major modification until 1802, when wire spokes with tension were invented. The rims of wire wheels are connected to the wheel center by the stiff wires in tension, e.g., bicycles' wheels. G.F. Bauer took the first patent for it in 1802. In the nineteenth century, continuous improvement of the wheel has made it an indispensable part of modern technology and industrialization. With the onset of the Industrial Revolution, wheels were used in different mechanisms, starting with spinning wheel, water wheel, and propellers to more advanced forms in turbines, engines, flywheels, automobiles, jet engines, ships, clocks, toys, and computers.

2.2.1 Mechanics of Wheel Motion

A wheel rolls along a surface in contrast to sliding/dragging motion of flat objects along a surface. If the rolling takes place without slipping (and which is desirable most of the cases), it is called pure rolling. In pure rolling, the velocity of the contact point between roll and the ground surface is zero. The magnitude of velocity of a point on the wheel is proportional to distance of the point from the contact point measured in the vertical plane. It is easier to roll an object across a surface than slide, as rolling experiences less resistance from the surface than sliding. Rolling of a wheel reduces the frictional resistance to motion to a great extent. A perfectly rigid roll can undergo pure rolling motion on a perfectly rigid flat horizontal surface forever. The resistance to rolling will be zero in that case, and there need not be any friction between the roll and the horizontal surface. In practice, to eliminate slipping at the point of contact between the wheel and the surface, some amount of friction is required. However, in pure rolling, no energy is dissipated due to sliding friction as there is no relative motion between the roll and the surface on which it moves at the point of contact. Thus, theoretically, there is no upper limit on the sliding friction.

It is our experience that to sustain the rolling motion of a wheel, a moment is to be applied to the wheel by the application of a force or torque. This is due to deformable nature of wheel as well as the surface on which it moves. Existence of a contact point is an idealization. It is not possible to have the contact of wheel and the surface just at a point, as it will lead to infinite stress at the contact point. No matter how small, there is a contact area. Figure 2.1 shows a simple wheel of weight W that rolls along a surface (without slipping) due to the pulling force F. The deformation of the contact surface is exaggerated. The resultant force applied by the ground on to the wheel is N, which is inclined at an angle ϕ from the surface, but passes through the center of wheel for maintaining the equilibrium. It is

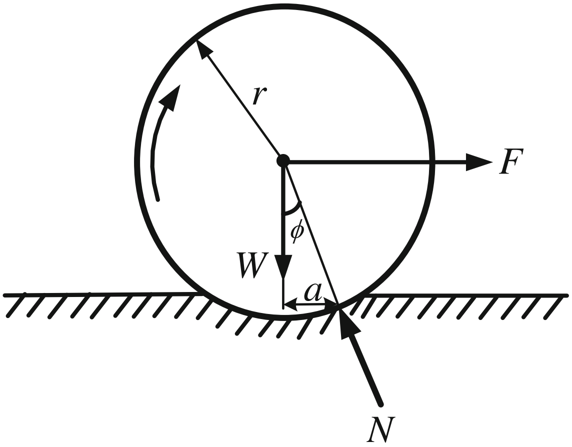


Fig. 2.1 A rolling wheel

to be noted that the resultant force due to the ground has line of action toward the leading side of the moving wheel. It is clear that the horizontal component of N will be equal to F if the wheel is moving without any horizontal component of the acceleration of its center of mass. The force F must be less than the limiting sliding frictional force. If the force F is more than the liming sliding frictional force, the wheel will skid. The force balance provides

$$F = N \sin \phi, \quad W = N \cos \phi. \tag{2.1}$$

Hence,

$$\tan \phi = \frac{F}{W} = \mu_r \approx \frac{a}{r}, \tag{2.2}$$

where r is the radius of the wheel and a is the horizontal distance between the point of the contact and the point through which the resultant of the ground forces passes. The variable μ_r in Eq. (2.2) is called the non-dimensional coefficient of rolling resistance (Shames 1997). The variable a is called the coefficient of rolling resistance. Compared to sliding friction, the rolling resistance is much lower. It depends on the nature of the surface, material of the wheel, material of the ground, the contact force, and the applied force/torque.

2.2.2 *Uses of Wheel in Mechanical Engineering*

Some important adaptations of a wheel used in mechanical engineering are gear, pulley, flywheel, turbine, grinding wheel, and automobile wheel. For transportation purpose, wheels are used in combination with axles. An axle is a cylindrical component on which either the wheel can be fixed or is free to rotate about the central axis of axle. If the wheel is fixed on the axle, the axle is supported on bearings and is free to rotate. In the wheels of railway car and some vehicles, the axle is fixed to the wheels and both wheel and the axle rotate in unison. In some vehicles, the axle is fixed on the vehicle and the wheels rotate around the axle. In order to reduce the friction at the wheel–axle interface, rolling-element bearings may be used.

Gears are the toothed wheels that are used for changing the speed and/or for amplifying the torque. Pulleys are used in conjunction with belts and perform the same function as gears. They can transmit power to a far distance. Nowadays, belt-pulley drives do not find much application as small motors can be easily fitted where required, avoiding the need of somewhat less efficient belt-pulley drives. Flywheels store energy in a part of cycle and release it in another part. The purpose is to avoid fluctuation in speed during a cycle. For example, in a mechanical punching press, a large amount of energy is required during punching operation, but there is very less energy requirement in another part of the cycle. A flywheel is fitted on the machine, which stores the energy in most part of the cycle in the form of rotational kinetic energy and releases it during punching operation. Thus, the punching can be accomplished with relatively smaller size of motor. A turbine converts hydraulic and thermal energy into rotational kinetic energy. The rotational kinetic energy of the turbine is transformed into electrical energy with the help of a generator. A grinding wheel is used to sharpen and shape various products. Here, the rotational kinetic energy of the grinding wheel is used to remove unwanted material from the workpiece.

2.3 Invention of Tools

In the modern times, tools in various forms have become necessities for mankind. A tool is used to either augment the human effort or replace it if powered by other source. It may not be possible to fix a nail by the blow of hand; a hammer is needed. A plow fitted on tractor can cut the earth of a form. Without proper tools, it would not have been possible to produce gadgets such as television, mobile phone, and computers, which have become a necessity for our day-to-day life. However, it is impossible to pinpoint exactly when the first tool was invented in the history of mankind. It is assumed that stones were used as tools by the early human during Stone Age. Broken sharp-edged rocks/stones were used for hunting and self-defense from the wild animals. Undoubtedly, stone tool and fire are the most ancient inventions in the history of human civilization. Tools played a vital role in the evolution of mankind.

2.3.1 Tools of Early Age

From the archaeological study of the Stone Age tools excavated from different parts all over the world, it is assumed that these tools date back to 5–2.6 million years before present. There are archaeological evidences of using wooden spears made from trees by early human about 5 million years ago. Perhaps the early human beings were in search of harder material as wood decayed soon and started using stone as it was easily available on the earth in caves, forests, and riverbanks. Around 2.8 million years ago, spears with stone blade and wooden handle were used. The very first stone tools found in Gona in Ethiopia were made from flint (Semaw et al. 2003). Flint (a form of quartz) was used as tool as it is hard and can be split to form sharp edges. Other types of stones were also used for making tools. The stone tool industry in its earliest form was called the Oldowan. The term Oldowan is taken from the name of a site in Tanzania. Oldowan tools were used about 2.6 million years back. Mostly hammering action was performed with these handheld stones. Other commonly used stone tools were hand axe, knife, scraper, chopper, anvil, wedge, etc. Primary objective of using these tools was for hunting animals for food, skinning them, and chopping their meat. Possibly, the tools were also used for felling the trees and cutting the fruits. At a later point of time, early human used the stone tools to sharpen the bones of the hunted animals and make pointed needles and fishhooks to catch fish and other water animals for food. In India, animal horns are used as musical instrument by certain sects of mendicants or saints. Evidences of using bone sickles for agriculture and bow drills for boring, drilling, and fire generation are found from the remains of early civilizations in different parts of the world. However, gathering knowledge about using stone as a tool, sharpening it by breaking, and splitting, making sharp points for arrows, drills, and spears required a very long period of time. Evolution of these tools was an extremely slow process spanning over millions of years.

The use of an advanced tool such as bow drill was an achievement in the prehistoric period. Stone tools were the only option up to 1.5 million years ago for human race. As civilization progressed, gradually improved techniques and materials were used for tool making. Innovation of the technique of smelting metal ore has ended the Stone Age and ushered in the Copper Age. The early human learnt to use copper ores by burning them for tool making. It is assumed that discovery and use of copper ore for making tools dated around 8000 BC. However, copper being a soft metal was not ideal for tools and weapons. In quest for improvement, blending of copper with tin gave birth to a much harder metal, bronze. Thus with the progression of metalworking, alloys such as bronze and brass (a mixture of copper and zinc) were discovered. Bronze became very useful for making tools, jewelry, and utensils. An entire period of early civilization starting around 3000 BC and spanning up to around 1000 BC is named as the Bronze Age. The discovery of metals and the use of metal smelting and casting technologies have given tool making a new height. The Bronze Age was succeeded by the Iron Age around 1500 BC. With the advancement of metalworking, iron with high melting point could be processed at elevated temperature and iron and its alloys were used for tool making. There were profound improvements in the design and quality of the tools. The use of copper, bronze, and iron has gradually replaced the stone, wood, and bone tools. With progress of Industrial Revolution, better technology, machines and materials have contributed to producing better tools. From the inception of the first stone tool, there is tremendous development in tool making, and now, different types of tools have innumerable applications in different fields.

2.3.2 Types of Tools

Tools in general have numerous types and applications. Stone and wooden tools are still in use for household purposes, e.g., stone milling wheel for grinding grains and wooden plow. Classification of tools is not an easy task as there are wide varieties of tools which may be manual and automatic. Some simple handheld cutting tools are knife, axe, sickle, saw, scissor, nail cutter, and razor blade, where there is a sharp cutting edge and the cutting is accomplished by shearing action. Some typical tools used in a mechanical engineering workshop are shown in Fig. 2.2. These include measuring tools, viz. try square, ruler, and vernier calliper. Lever can also be considered as a tool having mechanical advantage. It was also used in prehistoric times for digging, moving/lifting heavy loads, weighing, and irrigation. Pliers and wrenches are used to fit nuts and bolts by applying torque. Screwdrivers, drill bits, and milling cutters use both rotational as well as translational motion to achieve cutting action. A hammer is used to apply concentrated force, e.g., fixing a nail in the wall. Rulers, set squares, callipers, and different types of gauges are used for linear and angular measurements. Microscope and magnifying glasses are used for magnified view of an object. In a broader sense, household gadgets, mobile phones, computers, clocks, printers, sensors, etc., can also be considered as tools.

Applications of rotary as well as linear motion have given birth to many mechanical engineering tools, for example, different types of machine tools, cutting tools, and jigs and fixtures. The idea of partial rotary motion by the hand for digging or boring probably led to the inception of drilling tools. Bow drill was an important and essential tool used by early man for drilling and boring which was the basis for the modern drilling tools. Primitive lathe was developed from the idea of bow drill in the Eastern Mediterranean in around 1500 BC during Egyptian period (Burstall 1963). This can be considered as the first machine tool and was used for turning wood. During Greek and Roman periods, the primitive lathe was continuously modified and used for making furniture, spoked wheels, and ornaments. Modified forms of lathe were strap lathe, bow lathe, and pole and treadle (foot-operated) lathe. Greeks and Romans used to and fro motion of a stone plate over another for milling grains. Rotary hand mills with a wooden handle were used by the Romans

Fig. 2.2 Some tools of a mechanical workshop

for milling grains, where a stone wheel rotated on top of another with grains in between. With time and continuous improvement, the primitive machine tools were evolved into the sophisticated automated machine tools.

2.4 Ship

From time immemorial, mankind had been using waterways, which is the oldest means of transport on earth. Roadways, railways, and airways were developed much later. It is a long history of evolution of modern ships since the days when tree trunks and logs were used as boats. Although there are many subtle differences between a boat and a ship, the main difference is related to its size. The popular saying is that a boat cannot carry a ship, but a ship can carry a boat. Some terms related to boats and ships are explained in Sect. 2.4.1 followed by a brief history of their use and development in Sect. 2.4.2.

2.4.1 A Brief Introduction to Boats and Ships

Since ancient times, boats and ships have been used to transport passengers and cargo through waterways. They are also called naval vessels. The most primitive boat is the raft. It is flat in structure and thus highly stable, but may experience a lot of drag (resistance to forward motion). They cannot move at a very high speed. A dugout is a boat made from a hollowed tree trunk. A canoe is a lightweight narrow boat, typically pointed at both ends and open on the top. Dinghies are similar to canoe but are much wider.

For long-distance travel, sailboats and sailing ships were used. Sailboats and sailing ships are powered by means of sail that makes use of wind power. The sail is usually made of woven fabric and is supported by a mast. There can be more than one sail in a boat. Figure 2.3 shows the schematic of a typical sailboat. The important parts are labeled. The forward part of the boat is called the bow, and the back or aft-most part is called the stern. The rudder is used to steer the boat. The mainsail is the principal sail on a sailboat and is set on the aft-side of the main mast. The foot of the mainsail is supported by a spar called the boom. The mainsail creates the lift for the windward motion. The jib is also called foresail or headsail and helps to get lift in upwind direction. The hull is primarily the structural watertight body of a vessel. The line where the hull meets the water surface is called waterline. A horizontal structure called the deck forms the roof of the hull. The structure above the hull is called the superstructure. The rooms for the cargo and passenger can be below the deck. An extension of the hull that goes deeper into the water is called keel. It provides stability to the ship. A well-designed keel can provide the lift. A pulpit is a raised platform in the bow of certain boats.

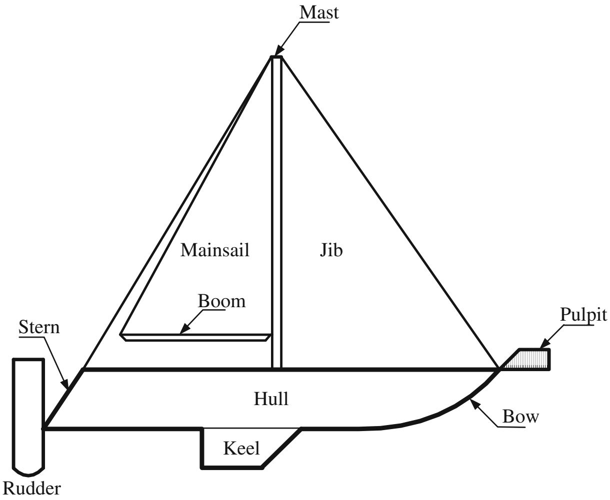


Fig. 2.3 A schematic of a typical sailboat

The boats can be driven by human power by means of oars. In past, in certain civilizations, slaves were employed to row the boats. Sometimes, the same boat had the provision for rowing and sailing. With the advent of steam engines, the dependency on wind and human power diminished in favor of boats and ships powered by thermal engines.

2.4.2 A Historical Note on Boats and Ships

It is impossible to ascertain who exactly invented the concept of using a boat or a ship. However, historians across the globe are of the opinion that the Egyptians were the first to use boats and ships for trade, travel, and exploration. There are archaeological evidences that Egyptians used wooden planks and dugout made of tree logs with sail and rows during the Bronze Age. The boat of Khufu, excavated in 1954 near a pyramid in Giza, dating back to 2500 BC, is an example of Egyptians shipbuilding expertise (Garrison 1999). Over the centuries, Greeks started exploring and colonizing the Mediterranean navigating in sea with boats/ships. Information of Greek sailors navigating to Western Europe, Great Britain, and Indian Ocean is found in history. There are evidences in history that ships were used for trading among northeast Africa, India, Sri Lanka, Persia, Rome, Arabian Peninsula, and many other places. In ancient times, there were skilled Indian shipbuilders as found from a panel excavated in Mohenjo Daro with the painting of a sailing ship. Although shipbuilding started in Japan in fifteenth century, the credit of using iron for ship building for the first time goes to Japan. In

1492, Christopher Columbus reached America from Palos de la Frontera, a Spanish province. In 1498, Vasco da Gama, a Portuguese explorer, reached India through the Indian Ocean from the Atlantic.

Early wooden boats were dugouts, rafts, and canoes (slender, open boats, tapering to a point at both ends). Before the invention of compass, navigation at sea was done by reading the positions of stars, the Sun, and the Moon. Gradually the use of mast, sail, and oars were introduced for proper steering, navigation, and sailing. However, main motive force for sailing was wind in these primitive ships. Better models of warships and merchant ships were developed by the Greeks with the modifications in the design of hull and the addition of top sail, keel, higher length-to-width ratio, and multiple oars and rowers. The theories on buoyancy, center of gravity, and equilibrium of floating bodies put forward by the great Greek scientist Archimedes (287 BC–212 BC) had revolutionized the field of fluid dynamics. 'Syrakosia' was the first three-mast ship in the world designed by Archimedes. Although some modifications were introduced in the design of ship building throughout the centuries, there were not many improvements until nineteenth century. The Industrial Revolution, invention of steam engine, improved propulsion techniques, and the use of iron for construction of ships brought about radical changes in the ship design. Mark Brunel (1769–1849), the French engineer, was the pioneer in introducing large ships made of iron with improved hull design emphasizing on the longitudinal strength of the ship. His son Isambard Kingdom Brunel (1806–1859) was also a great ship designer. 'The Great Eastern,' the largest steamship until twentieth century, built by Isambard Kingdom Brunel was the first ship designed based on the principles of hydrodynamics. Naval architecture and engineering reached a new height after the introduction and use of the concepts of metacenter, buoyancy force, Froude number, and wave resistance in hydrodynamics. The noteworthy works of Pierre Bouguer, William Froude, Mark Brunel, and many others in the nineteenth century are considered as the greatest contributions made in ship building and design. There were in-depth studies of hydrostatics, hydrodynamics, pitch, roll, drag of a vessel in water, effect of water, and wind resistance in naval engineering. Introduction of steam turbines for ship propulsion was indeed revolutionary, and HMS Viper and HMS Cobra were the first two ships to use steam turbine as prime mover in 1900 (Burstall 1963). In twentieth century, ship building progressed fast and there were boats and ships for trade, transportation, marine fishery, firefighting, rescue, explorations, military, luxury yachts, and many other functions. Gradually, superships such as very-large cargo carrier (VLCC) and ultra-large cargo carrier (ULCC) have come up for carrying petroleum, grains, minerals, and heavy goods. 'Fastship' is another improved variant of a cargo ship which is smaller and faster and carries the cargo within the hull.

Now, ships are designed using computer modeling and its dynamic properties and performance are simulated before manufacturing. There are tremendous improvements in design, materials used, propulsion system, and performance. Ship building has come a long way from the primitive dugouts made of tree to fully automated unmanned submarines used for undersea explorations.

One of the most severe accidents of shipping industry was the sinking of RMS Titanic. It was a huge ship and constructed by taking enough safety factor. It sank in the North Atlantic Ocean on April 15, 1912, after colliding with an iceberg on its maiden voyage from Southampton, UK, to New York, USA. Out of 2600 people on board, 1500 people perished in the water.

2.5 Windmills

A windmill converts the energy of wind into rotational kinetic energy. Natural wind is used as the prime mover for producing rotary power and for doing work. It contains some sails/blades that are rotated by wind, and the output is used for doing various works such as lifting water from wells, milling grains, sawing wood, and producing electricity. According to the historians, a wind organ designed by the Greek engineer Hero of Alexandria around first century is the first machine in history to use wind power (Burstall 1963). It is believed that wind was used to rotate prayer wheels in China around fourth century AD where radial sails were mounted to a vertical pole. However, windmills were used for doing works such as milling, pumping, and sawing wood around ninth century in the Far East, e.g., in Persia, Afghanistan, Asia, India, and China. Windmills were believed to come into existence in Europe much later, in the twelfth century in France and England. The earlier windmills had long vertical shafts with rectangular blades. Post mill (1180 AD) was such a vertical windmill used in Western Europe where sails/blades moved about a horizontal axis making a millstone rotate about a vertical axis to mill grains. Gears were used for power transmission from the sails to the millstone. Tower mill was another variant of windmill developed by fourteenth century which was more rigid and sturdy compared to the post mill. Up to the middle of the eighteenth century, use of windmills was very common for sawing, grinding, milling, and even for fans used in mines for ventilation. The construction detail of windmills, e.g., use of worm gears, bearings, fantails, and inclination of the sails, was indeed remarkable at that age. With the onset of Industrial Revolution, modifications of windmills took place with the use of bevel gears and cast iron in place of wood. There were continuous efforts to improve the design of sails/blades, and some designs were patented. Windmills were used by Stephen Hales for ventilating prisons and hospitals in 1752 (Armytage 1961). John Smeaton was the pioneer to conduct scientific study on windmill and published a paper in 1759 with the results of his experiments. He established a five-sail windmill in Leeds, England. However, during the period 1750–1850, there was a gradual transition from the use of windmills as prime movers to the use of steam engines. In 1784, the first steam power-driven flour mill was introduced and the trend set in. By the end of the eighteenth century and early part of the nineteenth century, small windmills were replaced by the steam-powered mills. However, large windmills (called wind turbines) were the next phase of modified windmills used for generation of electricity. Large windmills were also used for pumping water and called wind pump/engine.

The first wind turbine built by Professor James Blyth in Scotland in 1887 was followed by the construction of a number of wind turbines during the period 1887–1908 in various places in Cleveland, Ohio, and Denmark producing power from 5 to 25 kW (Cleveland 2007). Steel blades and towers replaced the earlier wooden counterparts in nineteenth-century windmills/turbines/pumps. In the twentieth century, wind power was tapped to a greater extent. A wind turbine constructed by Prof J.B. Wilbur of MIT and Palmer C. Putnam in Vermont in 1941 produced 1250 kW power. There were a number of successors constructing wind turbines/pumps around the world and a lot of modifications took place in their design and structure. In addition to producing electricity, some were extensively used for powering saw mills, grain mills, water pumping, irrigation, and agriculture across Europe, USA, Canada, Africa, and Australia. The power produced by the modern wind turbines ranges from about 20 kW to about 7 MW. Global warming, energy crisis, and fast-depleting fossil fuels have increased the importance of wind power as it is a renewable and environmentally friendly source of energy. Effort to tap wind energy is going on around the globe at the appropriate sites, for example, coastal areas and high altitude places where wind velocity is more.

According to Global Wind Energy Council (GWEC) report of 2014, the total installed wind power capacity in the world is 369, 553 MW (http://www.gwec.net/wp-content/uploads/2015/02/GWEC_GlobalWindStats2014_FINAL_10.2.2015.pdf). It was just 7600 MW in 1997. The share of five top nations in utilizing wind energy is as follows: PR China: 31 %, USA: 17.8 %, Germany: 10.6 %, Spain: 6.2 %, and India: 6.1 %. Modern wind turbines are classified as horizontal axis wind turbines and vertical axis wind turbines. In the horizontal axis wind turbines, the axis of rotation is horizontal. The number of blades may vary in different designs. Vertical axis wind turbines are called panemones. In these turbines, the main rotor shaft runs vertically and the plane of blade rotation is parallel to the wind direction. The advantage of these turbines is that the generator and the gear box can be placed at the bottom avoiding the need of tower and deep foundation. The blades need not be pointed in the wind direction unlike in horizontal axis wind turbine. Two designs of vertical axis wind turbine are common—the Savonius rotor and the Darrieus rotor. S.J. Savonius, a Finnish Scientist, invented the vertical axis Savonius rotor in 1922 (Savonius 1931). A schematic diagram of Savonius rotor wind turbine is shown in Fig. 2.4a. In this, two buckets are attached to a vertical shaft, such that the cross section resembles the letter S. It works due to the thrust force of the wind. The troposkein (a curve that a rope anchored at its ends assumes when spun along its long axis at constant angular velocity)-shaped Darrieus rotor was originally invented and patented by G.J.M. Darrieus, a French aeronautical engineer, in the year 1931 (Darrieus 1931). A schematic diagram of Darrieus rotor is shown in Fig. 2.4b. Various variants as well as combination of Savonius and Darrieus rotors are being used and researched.

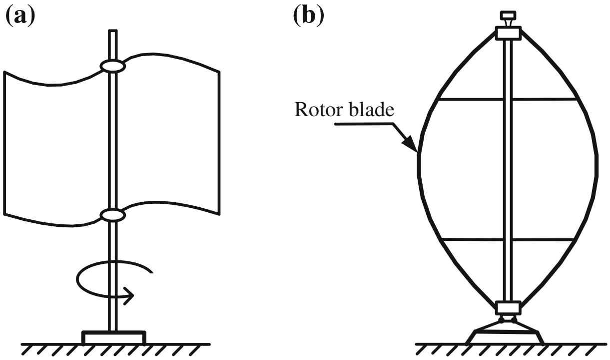


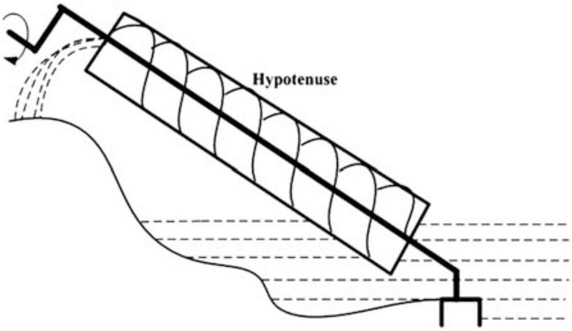
Fig. 2.4 Vertical axis wind turbine: **a** Savonius rotor and **b** Darrieus rotor

2.6 Archimedes' Screw

Screw is a mechanical element with helical spirals where both rotational and translational motion can be used to achieve the desired work. Archimedes, the great Greek scientist, first used the principle of screw to raise water in the third century BC. Therefore, the concept of screw, in particular screw as a system of raising water, is associated with Archimedes. In Archimedes' screw, water is pumped by turning a helical screw-shaped surface inside a hollow cylindrical shaft. With the rotation of the shaft and the helical surface, water gets carried up along the spiral and delivered at the end. In ancient times, Archimedes' screw was mainly used for irrigation, raising water, and draining water from mines and low lying areas. It was rotated manually or by a windmill. It is believed that Archimedes' screw was used for watering the Hanging Gardens of Babylon, one of the Seven Wonders of the World (Dalley and Oleson 2003). The geometry of an Archimedes screw is important for the volume of water to be lifted which depends on certain parameters such as the diameter, length and inclination of the outer cylinder, number of blades and their pitch and helix angle, water head, and the speed of rotation of the screw. The original Archimedes' screw had a wooden rotor with eight number of spiral blades with pitch equal to the circumference of the rotor, the length of the rotor being 16 times its diameter (Rorres 2000). An outer cylinder was constructed with wooden planks to cover the rotor blades. Depending on the height up to which water was to be lifted, the Archimedes' screw was placed inclined along the hypotenuse of a right-angled triangle with the bottom part immersed in water as shown in Fig. 2.5. With rotation of the blades, water got trapped in the helical blades and carried upward. Volume of water delivered per rotation can be increased by increasing the rotor blade diameter. Similarly, water delivered per unit time can be increased by increasing the speed of rotation.

The application of the principle of the Archimedes' screw is seen in many modern machines. For example, screw conveyors and rotary feeders are used to

Fig. 2.5 Archimedes' screw



transfer both solids and liquids from one end of the conveyor to the other in industrial applications. It is widely used to drain wastewater with debris in treatment plants, rivers, and lakes. Archimedes' screw can also be used to run like a turbine, which can be coupled with generator for producing the electricity. Modified forms of Archimedes' screw are used in forming processes such as extrusion, injection molding, and die-casting. It also has application in the field of solid waste disposal where a large conveyor screw with decreasing pitch is used to compress the waste material. Same principle is used in the rotary screw air compressor.

2.7 Steam Engine

A steam engine performs mechanical work using steam as its source of power. Use of steam as driving power for machines and engines is indeed an act of revolution. The inception of the idea of using steam as motive power dates back to first century BC when the Greek engineer Hero of Alexandria developed the famous 'aeolipile,' the first device to use steam as power (Burstall 1963). A schematic diagram of aeolipile is shown in Fig. 2.6. It contained a sphere partially filled with water, and two outlets were placed at 180° to each other. The device fitted on a frame was heated over a fire. Boiling water in the sphere produced two opposite jets of steam through the outlets that kept the sphere rotating. Although, at that time, this device was invented as a toy, it illustrated the power of the steam. Aeolipile was not an efficient device.

A number of steam-operated devices were designed, experimented, and modified since its inception. The contributions of a number of persons, viz. della Porta, de Caus, Boyle, Marriotte, Otto von Guericke, Dennis Papin, and Thomas Savery, toward the study of air and steam were invaluable for the invention of the steam engine. The first steam-operated device designed professionally for practical purpose is the 'pulsometer pump' by Thomas Savery in 1698. This was a steam-operated pump used for excavation in mines. Savery's steam pump had no moving parts. Steam was admitted to an empty chamber and condensed. The

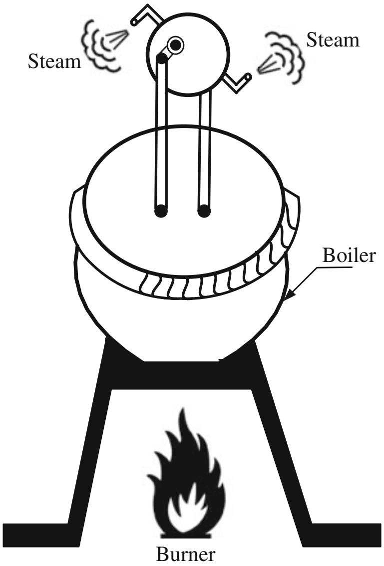


Fig. 2.6 A schematic of aeolipile

vacuum thus created drew wastewater from the bottom of the mine. However, it had disadvantages of low lift, high steam pressure, and propensity to accidents. Dennis Papin (1647-circa 1712) was a contemporary scientist who also experimented with condensed steam as a source of power. He is given the credit for using steam to move a piston within a cylinder for the first time. However, it was Thomas Newcomen (1664–1729) who first developed a practical steam engine with a piston and cylinder called Newcomen's atmospheric engine. The engine was developed in 1712 for raising the water in Dudley Castle, Staffordshire (Brown 2002). It had a piston in a cylinder which was attached by an iron chain to one end of a rocker beam that moved on a central pivot. At the other end of the rocker beam, another chain was attached to a plunger-type water pump. The rocker beam controlled the valves. Steam from the boiler entered the cylinder and condensed, thus creating the vacuum. The vacuum caused the piston to descend in the cylinder, which activated the plunger-type pump with the chain and rocker beam. Newcomen's steam engine worked at atmospheric pressure. Newcomen's invention was obviously influenced by the achievements in this field by his predecessors, viz. Savery (circa 1650–1715) and Denis Papin (1647-circa 1712) (Ainger 1829). There were considerable advancements in pumping water and air during this period. The act of using steam power to pump water was what made this engine unique. It was the first heat engine to be used as a source of mechanical power. In all the previous devices, manual and animal work, natural power from water wheels and windmills was used to get the driving force to produce mechanical work. Newcomen's steam engine opened the possibilities of freedom from dependence on nature and human being for doing mechanical work. It was a great success and widely used across Europe for pumping water, draining mines, and driving water wheels by 1750. It paved the way for all types of engines that were to follow using reciprocating piston to do work within a cylinder. It was undoubtedly the most significant invention in mechanical engineering that had accelerated the Industrial Revolution which set in from the middle of the eighteenth century. There were continuous efforts for improvements on the Newcoman's steam engine by the scientists John Smeaton and James Watt during the Industrial Revolution, which resulted in better versions in terms of thermal efficiency and horse power produced. A milestone in the history of steam engine was the modified version of the Newcomen's engine designed and patented by James Watt in 1781. It had a separate condenser and a double-acting cylinder–piston assembly that produced continued rotary motion. Moreover, it worked above atmospheric pressure. This engine was widely used to run the machines in the factories set up during Industrial Revolution (1750–1850). Watt succeeded in his efforts to provide rotary motion to his engine for driving factory machineries that enabled factories to be established away from the rivers (Rosen 2012). Earlier most of the factories were dependent on the flowing water of rivers for driving the water wheels.

Richard Trevithick (1771–1883) was the first to use a steam engine with a horizontal cylinder in 1803. This engine consisted as the basis for steam locomotives. By the end of nineteenth century, steam engine was used to drive vehicles and railway locomotives in addition to machineries in factories. Toward the end of the nineteenth century, steam turbines were introduced in the field of steam power. Steam turbines had less moving parts, could produce higher power, and were more efficient than reciprocating steam engine. Although a number of patents were provided for steam turbines during 1784–1884, Sir Charles Parsons (1854–1931) is credited for inventing the reaction turbine in 1884. During 1850–1900, many highly efficient steam engines were built, which were used in big ships, locomotives, and steam-operated road vehicles. The longest lasting steam engine used for road vehicle was the steam traction engine for carrying heavy loads. Steam engines and steam turbines were the dominant source of power until the early parts of the twentieth century. The contributions of some great scientific minds, viz. William Murdock, Arthur Woolf, George Stephenson, and Oliver Evans (in addition to those already mentioned above), are invaluable in the field of steam power. Although internal combustion engines and steam turbines have been replacing the steam engines in modern times, they can still be seen working at some places.

It is interesting to mention that the steam engine developed by Newcomen had an efficiency of 0.5 %. John Smeaton enhanced it to 1 %. Around 1885, the efficiency reached to 30 %. Theoretical thermodynamic efficiency of modern steam turbine may go up to 90 %.

2.8 Railways

The history of evolution of railways dates back to around 1600 when coal was transported in Britain by horse-driven wagons on wooden rails. They were in fact called tramways where a number of wagons were connected together and ran on wooden (and later on iron) rails. Wagons pulled by horses on tracks were used to transport people till nineteenth century. Mechanized railway was first used in England in the 1820s. After the development of steam engines, advances in railways and roadways progressed. There were continuous efforts to make steam engines smaller with higher power output so that they could be made mobile and used in vehicles. Although the father–son duo George Stephenson and Robert Stephenson are famous for inventing steam locomotive, the pioneering works of many contemporary scientists contributed toward the invention. Some early efforts were a prototype steam road locomotive by William Murdoch in Scotland in 1784 followed by a working model of a steam rail locomotive by John Fitch in the USA during the 1780s–1790s. Richard Trevithick was the first to invent and run a steam locomotive from Pendarren to South Wales in Britain in 1804 (Burstall 1963). It was in crude form and was not much reliable. However, it formed the foundation of modern locomotive engines for railways. Trevithick continued his efforts and developed a compact modified steam locomotive called ‘Catch Me Who Can’ in 1808. The locomotive had a speed of 19 km/h. Efforts continued with construction of more steam locomotives primarily for carrying coals from the collieries by Matthew Murray, Christopher Blackett, and William Hedley.

George Stephenson (1781–1848) built his first locomotive in 1813 for transporting coal in Killingworth Colliery. George Stephenson along with his son Robert Stephenson developed a number of improved steam locomotives and also concentrated on the issues relating to layout of railway track, signals, contact between wheel and track, and similar problems. The success story of practical railways started with the year 1825 when a railroad was opened from Stockton to Darlington with Stephenson’s steam locomotive called ‘Locomotion’ to carry coals. The ‘Rocket’ was another achievement by the Stephenson in 1829 which ran at about 48 km/h. The success of ‘Rocket’ was a landmark in the history of railways which opened the floodgates for construction of a number of railway lines in Britain. During 1830, a railway line was constructed by Stephenson between Liverpool and Manchester followed by a line constructed from London to Birmingham in 1838, which brought in the Railway Era in Britain. Another locomotive worth mentioning during this period is ‘The Lord of the Isles’ designed by Brunel for the Great Western Railway in 1841. In India, the first train ran between Mumbai and Thane in 1853.

Design of railway wheels were indeed challenging as they ran on rails. In the beginning of nineteenth century, rack-type tracks were developed on which a toothed wheel moved. However, it was difficult to use toothed wheels on rails. It took considerable efforts and experiments in the design of wheels for rails to realize that smooth rails in contact with the wheel rim could give sufficient friction to run the trains. Two types of wheel–rail combinations were initially used—flanged type and plated type. John Curr (circa 1756–1823) first introduced L-shaped flanged rails made with cast iron plates in 1776 (Roth and Divall 2015). Subsequently, the plate rail was introduced by Benjamin Outram and William Jessop in 1789. Initially, rails were made of a combination of wooden rails on transverse wooden sleepers. Later on, cast iron plates were laid on top of wood. These were replaced gradually by cast iron and steel rails for greater durability and safety. Around 1860, steel was used for making rails, which made it possible to carry heavy loads and run longer trains. Nowadays, steel rails with concrete or timber sleepers are common. Another challenge for expansion of railway lines was the construction of bridges on the rivers. With constructional and structural advancements in the field of civil engineering, more and more bridges were built on the rivers to meet this problem.

By the end of nineteenth century, more than 35,000 km of railway tracks were constructed in Britain and railways spread rapidly across the world in the twentieth century. It thus became the primary form of land transport all over the world for passengers and for carrying goods. Railways played a pivotal role in accelerating the Industrial Revolution. Railways continued to be used extensively in the twentieth century as it was cheap, could carry heavy goods, and convenient for long journey. Continuous efforts for improvement resulted in lightweight high-speed trains run by diesel engines and electricity. Nowadays, high-speed bullet train, sky train, and metro rails are common. Started in 2004, Shanghai Maglev (magnetic levitation) train is the fastest train with the maximum speed of around 430 km per hour (km/h). The fastest long-distance passenger train in the world is Jinghu High Speed Rail. It is a magnetic levitation train operating between Beijing and Shanghai at a speed of 300 km/h. The Chuo Shinkansen, a Japanese magnetic train, broke the world speed record for a passenger train in April 2015 (Reader’s digest 2016). During a test run, it reached a speed of 603 km/h. Its planned top speed is 505 km/h, and it will connect Tokyo, Nagoya, and Osaka. It is expect to start from 2027.

2.9 Internal Combustion Engine

In internal combustion engines, the burning of fuel takes place in a closed combustion chamber that is an integral part of the engine and the combustion process releases high-temperature and high-pressure gases. Expansion of these hot gases is directly used to do work by acting on a piston or a rotor. It differs from the external combustion engine, where combustion takes place externally, e.g., in steam engine. In steam engine, water is heated separately in a boiler to produce steam, which is used to do work by actuating piston. The steam turbine is also a type of external combustion engine, where the steam generated in boiler is used to run rotor. In internal combustion engines, volatile fuels such as diesel, petrol, gasoline, natural gas, biodiesel are used, which release high amount of energy during combustion.

Invention of internal combustion engine (IC engine) is one of the most remarkable achievements in the history of mechanical engineering. Its invention has ushered in a new era in transportation. Internal combustion engines are widely used in automobiles, two-wheelers, aircrafts, locomotives, boats, and ships in addition to portable gadgets and machinery. It took scientific rigor and decades of research by a number of scientists to design a practical and efficient internal combustion engine. A host of professional engineers and scientists experimented and patented the designs of their IC engines but were not met with success. Early IC engines did not have the compression stroke, e.g., the engine built by Robert Street in 1794, which was in use for nearly a century (Davison 1957). The cylinder of the engine was opened at the top and closed at the bottom. Combustion was carried out at the bottom of the cylinder that moved the piston upward. Samuel Brown got patent for a compression-less IC engine in 1823 followed by Samuel Morey in 1826. By this time, Sadi Carnot, the father of thermodynamics, established the need for a compression stroke in IC engines for increasing efficiency. William Barnet tried to incorporate in-cylinder compression in his engine and patented it in 1838; however, it was not properly developed. Eugenio Barsanti and Felice Matteucci also met with similar fate in 1854. A commercially successful two-stroke IC engine developed by Etienne Lenoir in 1860 was similar in construction to horizontal double-acting steam engine, where combustion of gas–air mixture was used to do work in the place of steam. Lenoir’s gas engine was capable of producing 0.5–3 hp power and was sold in hundreds in France. Nikolas Otto, the German scientist famous for inventing four stroke cycle (called Otto cycle), developed the Otto gas engine in 1876 with a compression stroke. The engine developed by Otto brought about phenomenal change in the history of IC engines. The success story of the Otto engine continued with selling of 45,000 engines in England, France, and the USA by 1885 (Burstall 1963). In 1880, Dugald Clark made some changes to Otto engine and invented the two-stroke IC engine. Dugald Clark is also credited for introducing supercharging of the working fluid. Subsequently, Atkinson cycle engine by James Atkinson was invented in 1882 with a higher efficiency than the Otto cycle. Early IC engines were used to run farm equipment, blowing blast furnaces, in pumping stations, and steel industries. Karl Benz was the first to build an IC engine based on Otto cycle to be used in automobile in 1879. Use of oil in IC engine in place of gas was also tried by many scientists. Daimler first made an IC engine to run on petrol for automobiles in 1884 where carburetor and electric spark were used for the first time. Another milestone in the history of IC engines was the invention of diesel engine by Rudolf Diesel in 1893. It had a higher thermal efficiency compared to its predecessors and successfully used for both stationary and automobile engines. Continuous efforts for improvements made IC engines more efficient, lightweight, smaller, cheaper, and most importantly reliable. Gradually, these engines were used in ships, aircraft, locomotives, automobiles, and power plants. Petrol engines were used for automobiles and aircraft and large diesel engines were used for stationary applications and ships, whereas high-speed diesel engines were used for heavy road vehicles and locomotives. The contributions of some great personalities such as Lanchester, Kettering, Daimler, Ford, Austin, and Morris are invaluable in the application of IC engines to automobile. Similarly, Wright brothers, Santos Dumont, Ellehammer, S.F. Cody, Hugo Junkers, and many others put efforts to fly aircraft with IC engines and gradually tasted success.

2.10 Aircraft, Rockets, and Satellites

From time immemorial, people dreamt of flying like birds and made innumerable attempts at it by attaching wings and flaps to their arms. In 1010, a monk named Oliver of Malmesbury became the first man to fly some distance with the aid of wings (Kalam and Singh 2015). He jumped from Malmesbury Abbey, England, and flew a short distance before crashing to the ground and causing injury to him. Realizing the impossibility of the effort, other means such as hot air balloons and hydrogen-filled balloons were tried by enthusiasts in 1783 where direction of flight was entirely controlled by the blowing wind. The basic principles of flying an aeroplane was first conceived by George Cayley (1773–1857) as early as 1799, and he made the scientific model of an aeroplane with a kite that had fixed wings and a movable tail. Inspired by Cayley's work, efforts and experiments went on by the scientists resulting in successful designs of gliders. Although control and steering posed problems, several manned flight in gliders and crude forms of planes were possible during the period 1849–1900 by some daring scientists. Some of the names worth mentioning are Octave Chanute, Otto Lilienthal, S.F. Cody, Felix du Temple, Francis Wenham, Horatio Phillips, Hiram Maxim, Santos Dumont, and many more for their invaluable contribution to the history of air travel. Based on the relentless efforts and scientific works of the predecessors, finally Wilbur Wright and Orville Wright, the two brothers of Ohio were able to achieve a successful flight on December 17, 1903, in North Carolina. It took them about four years and more than 200 models to reach this stage. Their aeroplane was made of canvas, wood, and a four cylinder IC engine of 12 HP power (Garrison 1999). Thus, Wright brothers had given wings to the age-old dream of mankind to fly in the sky.

Although Wright brothers' aeroplane was a landmark with its three-axis aerodynamic design, it was not up to the mark for commercial applications. Modifications on the existing design went on simultaneously by many scientists, and a variety of aeroplanes were constructed and tested up to 1908. Santos Dumont, Ellehammer, Hugo Junkers, Gabriel Voisin, Louis Blériot, and Henri Farman were some of the pioneers in commercialization of aircraft. The first person to fly as a passenger was Leon Delagrange, who rode with French pilot Henri Farman from a meadow outside of Paris in 1908 (http://www.avjobs.com/history/). On 25th July in 1909, Louis Blériot created history by crossing the English Channel in his aeroplane. With the advent of World War I (1914–1918) and the possibility of using aircraft in war, modifications in the design of aircraft took at an accelerated pace. Use of metals in aeroplane structure, higher speed, and height were some of the achievements. Fighter and bomber planes were extensively used during World War I. With ongoing research for improvements, gradually there were lighter, high-powered aeroplanes made of aluminum, fitted with wireless radio, gyroscope, superchargers, and cantilever wings, which were used for carrying passengers after the World War I. The aviation industry flourished with the events of flight across the Atlantic in 1919, beginning of an intercontinental flight service in 1921, and formation of several aviation companies. In 1929, the largest plane until then with 48-m-long wings made a flight with 169 passengers, which was a record that stayed intact for 20 years.

The development of jet engine was initiated in 1930 when Frank Whittle demonstrated his high-velocity propulsion jet with a gas turbine and a centrifugal compressor in 1930. The first jet aircraft called Heinkel was developed in Germany in 1939 (Garrison 1999). Helicopters were developed in Germany in 1941 during World War II. Simultaneously, design of rockets also improved with the innovation of jet propulsion and advances in fluid dynamics. The jet engines and rockets used in World War II (1939–1945) had elevated the aeronautical industry from subsonic flight level to supersonic. There was a rapid growth of commercial aviation after the World War II with a number of commercial jet airliners ushering in the Jet Age. The Boeing 747 was the largest commercial supersonic passenger jet airliner launched in 1969. Tremendous improvements took place in military aircraft with the developments of long-range bombers, supersonic interceptor aircraft, surface-to-air missiles, and ballistic missiles. The USA, Soviet Russia, and other European nations all contributed to these developments.

Fueled by the advances in science and technology, men’s imagination and the urge to know the unknown soared. Exploring the space was the next level attained in aerospace engineering in the 1950s and 1960s. Both the superpowers, the USA and Soviet Russia started space exploration programs and launched space satellites to gather information of the earth and the space hitherto considered impossible. The crowning glory of their programs included landing on the Moon, manned flight to orbit the Earth, launching space satellites, and developing space habitat. Yuri Alekseyevich Gagarin was the first human being to journey into outer space in April 1961. Neil Alden Armstrong was the first person to walk on the surface of the moon in July 1969. Twenty-first century brought in the digital era making it possible to design remote controlled automated and unmanned aircraft called unmanned aerial vehicles (UAV) to be used in wars, rescue operations, emergency, and dangerous missions. The latest feather in the cap is the flight by André Borschberg in a solar plane from Nagoya, Japan, to Honolulu, Hawaii, in 2015. Born on December 13, 1952, Borschberg is a Swiss businessman and pilot, who cofounded the Solar Impulse Project. Nowadays, several flying robots are being developed. Some of them are of the size of a fly.

2.11 CNC Machines

Automation is gaining prime importance in the modern industries to fulfill the need for improved productivity, quality, novelty, and variety in products. To address these issues, the use of computers has become necessary. Computer numerical control (CNC) can be defined as a form of programmable automation which is used for the operation of different machine tools. CNC machines are widely used by the industry where a program of instructions (codes) is stored in the memory of a computer. The computer acts as the controller for the functions to be performed by the machine as per the program of instructions. The programmer can edit, modify, and reprogram the codes as per the requirements. Before the use of computers, Numerical control (NC) machines were used where the program was fed to the machine with punch cards. NC machines were improved rapidly after the use of computers as the controlling unit and renamed as CNC machines. The CNC technology is widely used in machining processes such as turning, drilling, milling, and shaping. Once the complete program is fed and activated in the CNC controller, the machine automatically performs the machining operations to achieve the final component. The CNC controller directs the machine tool to perform various operations as per the program of instructions.

The history of NC technology dates back to the early part of the twentieth century. The first NC prototype machine was developed in 1952 in Massachusetts Institute of Technology (MIT) that used punched tap for feeding the programming instructions. The foundation of NC technique was laid by the pioneering works of John Parsons in 1940, when he tried to automatically generate a curve by providing coordinated motions to the tool path (Groover and Zimmers 1984). In 1948, Parsons developed a method of using punched cards containing the coordinate positions to control the tool path of a machine tool. He succeeded in generating the curved surface of a helicopter blade by directing the machine to move in small increments. Thus, NC technology was conceived for the first time and subsequently researched and advanced in the MIT. As the potential of NC technology for mass production and productivity was perceived, there was profound use of it among commercial machine tool manufacturers. Initially, punched tapes were used for feeding the programming instructions to the machine tools through the control unit. However, research continued as there were certain disadvantages with the conventional NC machines. When the programs were written on the punched tape, it took several passes of the tape to write a correct program, in addition to the tapes being fragile and prone to wear and tear. It was inflexible in terms of using varying speed and feed of machining operations. The machine control unit was not flexible and could not adapt to changes. With the advancements in the field of electronics, the disadvantages of the NC machines were removed over time. The new inventions of electronics, viz. miniature electronic tubes, solid-state circuits, and integrated circuits, were gradually used in NC machines making it better, smaller, and more reliable. Introduction of the computers has taken NC technology to a new height, and it came to be known as the CNC technology. The control units with punched cards in the NC machines were replaced by the computers in the CNC machines. Initial CNC machines used minicomputers in the 1960s. Computerized machine control unit led to software-based control on the machine which is very flexible. It enabled easier storing, editing, and changing of the programs, and better control and communication between the controller and the machine. Computers provided an easier programming environment and flexibility. Different programming languages such as G-codes, M-codes, and Automatically Programmed Tool (APT) were developed. The APT language is still in use in the industry, and it is also the basis of several modern programming languages. The use of CNC technology has led to higher state of automation, thus reducing the operator intervention. It can be operated automatically to produce components in large quantities, thus improving productivity. CNC technology has paved the way for computer-aided design (CAD) and computer-aided manufacturing (CAM) in the 1960s. CNC revolution accelerated in the 1970s and the 1980s with development of a number of CNC companies in the USA and Germany followed by Japan.

Manufacturing companies nowadays use CNC machines for producing better products as the competition have become very stiff. The latest CNC machines have microprocessor-based control system with feedback for higher efficiency. Adaptive control is possible in the microprocessor-based CNC machines for changing cutting environment. It incorporates feedback and optimal control through continuous monitoring and optimization of the machining parameters. Adaptive control is more accurate, precise, and advantageous for complex shapes. CNC software programs such as Enhanced Machine Controller (EMC) and Mach3 were made available as open source programs for personal use in 2003 (Groover and Zimmers 1984). Thus, CNC technology has revolutionized the manufacturing industry.

2.12 Wootz Steel

Steel, an alloy of iron and carbon, is the most widely used material in the history of metallurgy till date. The carbon in steel is in the form of iron carbide which enhances its strength and hardness. Although magnetite ore (Fe_3O_4) are abundant on the earth, melting magnetite to produce iron was a difficult task as iron has a high melting point. With the advancement of metalworking and design of better furnaces, iron could be processed at elevated temperature. It was discovered that iron mixed with carbon makes an alloy, steel, which has much higher strength compared to bronze. Soon iron and its alloys were used in all spheres of engineering and technology where strength was an important property for the working material.

Wootz steel was produced by Wootz process in India and Sri Lanka as early as first millennium (Garrison 1999). Wootz is the anglicization of ‘ukku,’ the Kannada word for steel (Srinivasan and Ranganathan 2004). There are evidences of production of crucible steel/Wootz steel in South India and Sri Lanka and exporting to Rome, Egypt, China, and Arab countries (Srinivasan 1994). The Arabs learnt this technique from India and used for making Damascus steel, another variety of high quality steel. The Damascus sword was famous for its sharpness. Recently, a wind-driven furnace was discovered along the coastline of Sri Lanka where monsoon wind of the Indian Ocean was used for natural draft to produce high carbon steel at around 1500 °C (Juleff 1996). Wootz process of making steel was developed by Indian blacksmiths where black magnetite ore was heated with bamboo charcoal in a clay crucible to produce carbon steel. Sometimes, wrought iron was first obtained by smelting the ore and then burnt with bamboo charcoal and certain plants containing carbon in a ceramic crucible up to 1200 °C. Smelting of wrought iron produced a high quality steel containing 1.5–2 % carbon. Wrought iron turned into austenite at the elevated temperature with the carbon atoms within its lattice structure which turned cementite after slow cooling. Cementite is turned into martensite by reheating and tempering, thus adding ductility and strength. In Wootz steel, a bandlike pattern is seen which is made by the precipitated iron carbides present in the martensite matrix.

As there were trade exchanges among the Asian and European countries, the technique of Wootz steel was learnt by the European traders around seventh century. British Royal Society tested and analyzed some samples of Wootz steel in 1790 with a motive of ascertaining its quality and possible production. Wootz steel played an important role in the field of metallurgy in Europe. The British Government in India prohibited the industry of Wootz steel in 1866 to reduce deforestation. Because of its high quality and novelty, efforts at reproduction of Wootz steel were tried by many metallurgists, e.g., Oleg Sherby, Jeff Wadsworth, Lawrence Livermore, J.D. Verhoeven, and Al Pendray in the twentieth century (Srinivasan 1994). The ancient technique of Wootz steel is not yet fully unveiled, and research is still going on to explore this advanced material hoping for a promising future.

2.13 Rapid Prototyping

In the present competitive market, manufacturing industry is faced with the challenges of product variety and customization combined with the requirement of enhanced product quality at lower cost. Automation is gaining prime importance in modern manufacturing industries to fulfill the above needs. The manufacturing industries have to innovate ways to reduce the time taken to design, manufacture, and market the product. There is continuous improvements and redesigning of products using CAD/CAM tools to meet the customer's demand. Recent technology such as rapid prototyping (RP) can directly fabricate a scale model of a part from 3D CAD model, thus enabling faster ways of manufacturing a part. Prototyping of a part is done prior to actual production to detect the design errors if any. In RP technique, need for prototype development is eliminated and scale models and parts are fabricated layer by layer by additive manufacturing process. Polymer powders such as polyamide, polyester, glass fiber-filled polymers, and aluminide are used in RP machines to form the layers. RP technique is also known as layered manufacturing. Although RP models are widely used for visualization and testing, it is also used for fabricating the actual parts.

Rapid Prototyping has emerged as a frontier technology in the early 1980s for its obvious benefits. It tremendously reduces the manufacturing lead time. As RP is an additive manufacturing process, need for tooling is eliminated and complex geometry can be directly manufactured from the 3D CAD model. Another contribution of RP to the conventional manufacturing industry is the rapid production of complex shaped tools which is not possible by conventional machining processes. This is called rapid tooling (RT) which is a natural extension of RP technique that enables design and fabrication of tools for casting, molding, and sheet metal-forming industries. Moreover, the product data in the 3D CAD model can be used for performance and cost analysis, engineering analysis regarding strength, structure, etc., customization of the product, and for interactive use during design and manufacturing stages. RP is preferred for customized products such as ear plugs for hearing aids, prosthetics of body parts, and cosmetic dentistry where the data from CT scan and MRI can be directly used for fabrication. It is profoundly used for artificial bone replacements in knee, jaw, and scalp in biomedical applications. RP is very important for the research and testing in the aerospace and missile industries. RP technique reduces the need to maintain a large inventory of parts. One can store the CAD model and rapidly e-manufacture the part on demand. The basic components of a RP system are 3D CAD or solid modeling software, RP machine and the related software for converting solid model data to instruction for the RP machine, and the post-processing equipment. A block diagram of the components of RP technology is shown in Fig. 2.7.

Different RP techniques available are Stereolithography Apparatus (SLA), Selective Laser Sintering (SLS®), Laminated Object Manufacturing (LOM™), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), and Inkjet printing techniques, Three-Dimensional Printing (3D Printing), and Ballistic Particle Manufacturing (BPM). The basic principle of these techniques is similar. First, the 3D solid model data is converted to.stl file format which is the input format for the RP machines. Then, the solid model is sliced into a number of 2D

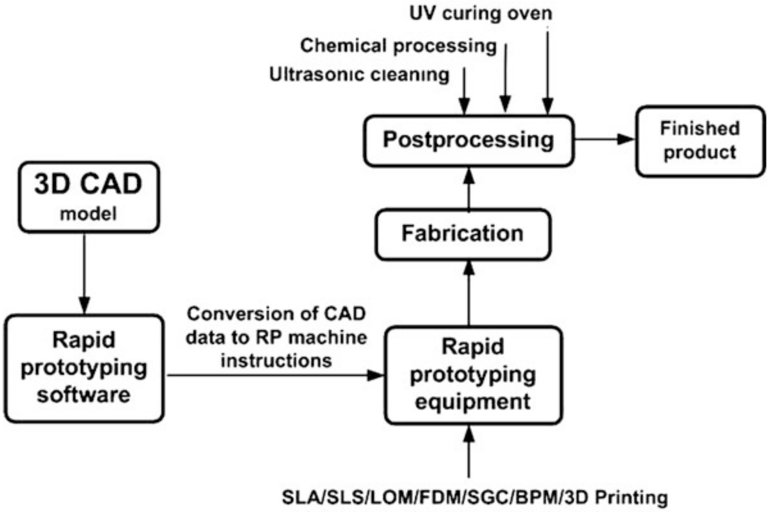


Fig. 2.7 The components of RP technology

cross-sectional layers and stacked using the bottom-up approach to fabricate the part. The part is then post-processed to rectify the defects. Initial RP machines were smaller in size and could produce small components. Large components were to be fabricated in parts and then glued. Currently, large machines are available for this purpose. RP technique has immense potential for the future and can be extended to other functions in engineering in addition to manufacturing. However, like all other techniques, RP too have its disadvantages, e.g., high cost of the machine and material, restricted part dimensions, and difficulty in accurate assembly of small sub-parts. Research is going on to bring in a new era of e-manufacturing by overcoming these difficulties (http://www.cc.utah.edu/~asn8200/rapid.html).

Nowadays, the word 3D printing is used synonymously with RP. 3D printing is a type of RP that uses a printer-type machine to make solid objects. Usually, 3D printers are easier to operate and inexpensive, but are able to produce smaller size of objects compared to a RP machine. It is envisaged that in near future, 3D printers will be as widespread and popular as the present-day computer printers. In the opinion of the authors of the present book, the term RP should be used for any technology that can develop a prototype in a short span of time; it need not be based on additive technology. On the other hand, the term 3D printing should be used for the technology that develops a product layer by layer, converting the digital image to real product.

2.14 Air-Conditioning and Refrigeration

Refrigeration is defined as the process of cooling and maintaining a temperature below that of the surroundings by the transfer of heat from one region at a lower temperature to another at a higher temperature. Refrigeration is carried out by providing external work/heat in the form of mechanical/electrical power and/or some heat. The immense importance of refrigeration is reflected by its innumerable applications. Some of them are freezer, refrigerator, and cold storage for processing, preservation, and distribution of food products, cryogenics in aerospace engineering, chemical, biomedical, and pharmaceutical industries, special applications such as cold treatment of metals, construction of artificial ice skating ring, and air-conditioning for human comfort, etc.

Air-conditioning (AC) is one of the applications of refrigeration technique to provide thermal comfort to living beings. Air-conditioning can be defined as the treatment of air by simultaneously controlling the parameters such as air temperature, humidity, air movement, odor, cleanliness, and ventilation of air to provide a more comfortable condition. It comprises cooling/heating, humidifying/dehumidifying, ventilating, and cleaning of air and circulating the same primarily to provide thermal comfort to people and to maintain a low-temperature environment for some applications such as operation theater, laboratory, pharmaceutical, and food processing industries. The conditioned air is supplied to buildings, houses, rooms, and vehicles.

The major types of refrigeration systems are as follows:

- Vapor compression refrigeration systems,
- Vapor absorption refrigeration systems,
- Gas/air cycle refrigeration systems,
- Solar energy based refrigeration systems, and
- Thermoelectric refrigeration systems.

The most widely used methods are the vapor compression refrigeration and vapor absorption refrigeration. The basic components of a vapor compression system consist of an evaporator, compressor, condenser, and an expansion valve as shown in Fig. 2.8a. The cooling effect is obtained by extracting heat by the vaporization of the refrigerant in the evaporator. The refrigerant vapor is then compressed in the compressor to a high pressure and passed through the condenser so that the vapor condenses into liquid by heat rejection to the heat sink. The high-pressure liquid refrigerant is then passed through an expansion valve to lower its pressure and temperature. The cycle repeats. The system requires input in the form of mechanical work. The vapor absorption system shown in Fig. 2.8b is similar to vapor compression system, except that the compressor is replaced by an absorber which dissolves the refrigerant in a suitable liquid. There is a liquid pump to increase the pressure of the mixture, and a vapor generator is used to extract the refrigerant vapor from the high-pressure liquid on heat addition. From vapor generator, the weakened refrigerant–absorbent solution is throttled back to absorber.

In gas/air cycle refrigeration, the working fluid is a gas/air that is compressed and expanded. Heat exchangers are used in place of condenser and evaporator. Using solar energy for refrigeration is given importance due to scarcity of fossil fuel energy sources. Solar energy-based vapor absorption refrigeration and air-conditioning are attempted using flat plate solar collectors. Recent method such as thermoelectric refrigeration is used in cryogenics and is still under research.

The history of refrigeration and air-conditioning is very long. In olden times, refrigeration and air-conditioning were achieved by the use of snow and ice and various means of natural cooling. In cold countries, ice-harvesting was done in winter and stored to be used in summer. Cooling of water by keeping in earthen pots is an age-old method where water evaporates through the pores of the pot absorbing the latent heat from the water. Evaporative cooling was used in ancient Egypt, Rome, and India by hanging straw mats in the windows that were wet with water. The evaporation of water cooled the air blowing through the window. Wind towers and flowing water ducts were some other methods used for cooling buildings.

The domestic refrigeration using natural ice in wooden insulated box was first used in 1803 and is still used by the street vendors. The era of artificial refrigeration started with the refrigerating machine (for making ice) made by the Scottish professor William Cullen in the year 1755 (Arora 2010). Invention of the first vapor compression mechanical refrigerator is credited to Jacob Perkins in 1834 (Burstall 1963). A number of patents were granted subsequently for inventing different vapor

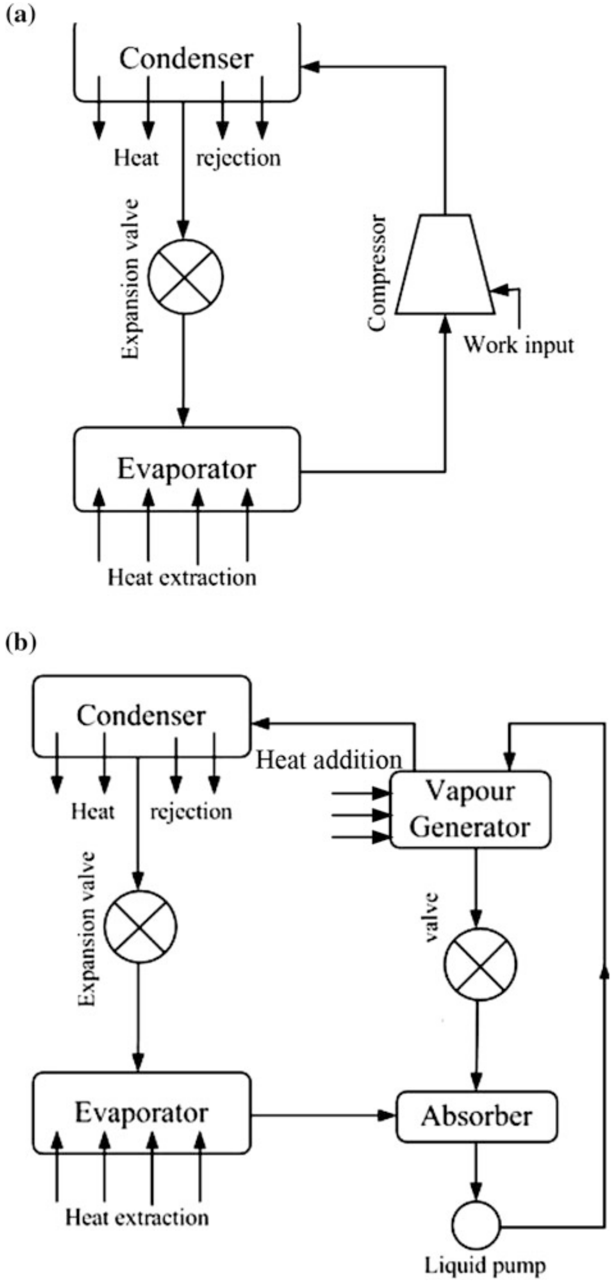


Fig. 2.8 Schematic of refrigeration system: **a** vapor compression and **b** vapor absorption

compression refrigeration machines using different refrigerants to John Gorrie (1845), James Harrison (1857), Charles Tellier (1864), David Boyle (1871), John Enright (1876), and many more (http://www.nptel.ac.in/courses/112105129/pdf/RAC%20%20Lecture%201.pdf). Refrigerated railroad cars were first used in the USA using ice to lower the temperature of the railway compartments in 1840. The early refrigerants used were mainly ether, alcohol, sulfur dioxide, methyl chloride, methylene chloride, etc. Carl Von Linde (1842–1934) first used ammonia as the refrigerant in his ice-making machine in 1876. The first vapor absorption refrigeration with ammonia was developed by Ferdinand Carré (1824–1900) in 1860 and was widely used up to the 1920s. Freon was the new refrigerant used in the early part of the twentieth century that replaced ammonia. The modern refrigerators use hydrofluorocarbon (HFC) and chlorofluorocarbon (CFC) as refrigerants. The first commercial domestic refrigerator was made by General Electric Company, USA, in 1911 and then other companies in Japan and Europe followed suit. The refrigerator based on vapor absorption principle proposed by Platen and Munters was first made by Electrolux Company in 1931. The first dual temperature refrigerator with two chambers was introduced in 1939. The development of air-conditioning is due to the pioneering work of the American scientist Willis Carrier who invented the first air conditioner in 1902. It rapidly grew based on the research of many scientists and was in wide used by 1930. Air-conditioning was in use in private homes in the USA by 1933. Modern air-conditioning is based on vapor compression or vapor absorption methods for cooling and heating of space. Air-conditioning is now widely used in residential and commercial buildings; in textiles, such as printing, manufacturing, and photographic industries; in computer rooms, such as power plants; and in mobile applications such as as railways, automobiles, and aircrafts. In modern lifestyle, refrigerator and air conditioners are the part and parcel of day-to-day life.

2.15 Mechatronic Products

Mechatronics refers to the synergistic integration of mechanical engineering with electronics, electrical engineering, and control engineering supported by computer engineering, information technology, and telecommunication engineering for better design, manufacture, and operation of products and processes. As suggested by W. Bolton, ‘a mechatronic system is not just a marriage of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them. It can be considered to be the application of computer-based digital control techniques, through electronic and electric interfaces, to mechanical engineering problems (Bolton 2006). The most important characteristic of a mechatronic system is its ability to process and communicate information in different types of signals, viz. mechanical, electrical, hydraulic, pneumatic, optical, chemical, and biological. Mechatronics can be classified into several key areas, for example, robotics, intelligent motion control, automation, actuators and sensors, modeling and design, electronics and optoelectronics, etc.

The idea of automatic control of a mechanical system originated by the end of the nineteenth century fueled by the progress in different field of engineering during the Industrial Revolution. During World War II, automatic control systems advanced with the design of various war-related gadgets such as automatic airplane pilots, gun-positioning systems, and radar. Before the 1960s, most of the industrial products and equipment were based on mechanical principles. However, the evolution of mechatronics started in the 1960s with the progress in the fields of electronics, development of microprocessors, NC technique, semiconductors, and integrated circuits. During the 1970s, there was a change in the technology of products and equipment with incorporation of electronic components with the mechanical systems. It is when the term 'mechatronics' was first coined for such products by Tetsuro Mori, an engineer in Yaskawa Electric Corporation in Japan in 1969.

During the early 1970s, mechatronic products such as automatic door opener, vending machines, dot matrix printer, and autofocus camera were developed. Gradually, the advances in control theory, computation technology, servo technology, microprocessors, and integrated circuits enabled design of products such as NC machine tools, sewing machine, digital watch, push button telephones, electronic typewriter, photocopiers, automatic washers and dryers, rice cookers, and automatic ovens. Mechatronics played a pivotal role in development in robotics in the 1970s. The 1980s saw the progress in information technology, and microprocessors were embedded into mechanical systems to improve performance, for example, antilock braking system. Digital computers were integral for control systems. Controlling and functioning of machines became much easier by the use of computer hardware and software enabling manufacturing of a product with high accuracy, for example, CNC machines. Finally, since the 1990s, there has been tremendous progress in the field of mechatronics and it is applied in robotics, flexible manufacturing systems (FMS), CAD/CAM, automated guided vehicles (AGV), data communication systems, multi-point fuel ignition, and digital engine control in automobiles, smartphones, microwave ovens, dish washers, vacuum cleaners, televisions, cameras and camcorders, video recorders, central heating controls, bar coding machines, automatic teller machines (ATM), and the list goes on. The latest addition to the list is biometrics, automatic climate control, automatic unmanned vehicles, microbots, etc. Future of mechatronics has extreme potential as the application area of mechatronics encompasses all spheres of human lifestyle.

2.16 Conclusion

In this chapter, some revolutionary mechanical engineering inventions have been discussed. Starting from wheel to mechatronic products, the technology has been continuously evolving. The mechanical engineering is a very dynamic discipline of engineering. New technologies have been replacing the old. Electronics watches have replaced the mechanical watches. The belt-pulley drive, cam follower, and even gears are phasing out in favor of sophisticated motors and control systems. However, the basic philosophy of mechanical engineering remains same. It tends to make machine, equipment, and tool for enhancing the capabilities of human being.

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Chapter 3
History of Mechanics

Abstract Mechanics is the integral part of mechanical engineering. As a field of education, it started from the time of Aristotle. Many of the concepts provided by Aristotle are proven wrong, for example, his concept that the motion continues only as long as a force is applied on it. However, he started a tradition of logic in understanding the dynamics of bodies. During the third century BC, Archimedes contributed a lot to mechanics and invented many machines. His principle of buoyancy is taught in schools nowadays. The breakthrough in mechanics came since the time of Galileo. The principles of Galileo and Newton are used by mechanical engineers profoundly. Later on, a lot of developments took place in mechanics, notably the development of methods based on energy formulation, strength of materials and plasticity. Einstein developed a theory of relativity and established that Newton's laws are not valid in all circumstances. Nevertheless, for the most of the day to day applications, Newton's laws are good enough.

Keywords Mechanics · Aristotle · Archimedes · Galileo · Newton · Hero of Alexandria · Energy methods · Einstein · Theory of relativity · Calculus of variations · Strength of materials · Plasticity

3.1 Introduction

Engineering is as old as the human civilization, although the word "engineer" came into existence around 1325 AD. Our life is very much dependent on engineers and everyone has a feel of engineering, but for many persons there is often a lack of clarity about engineering. In the beginning, engineering was considered as an art. Engineers used to invent machines and structures. Mechanics originated as the branch of physics that deals with the theory of machines. One of the oldest machines is lever. With the help of a lever, a heavy weight can be lifted by the application of small force as shown in Fig. 3.1. There is evidence of use of lever even before 2500 BC. Weighing balance also works on lever principle. Lever is one such machine that is not obsolete even today. Figure 3.2 shows a scissor that also is

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Materials Forming, Machining and Tribology,
DOI 10.1007/978-3-319-42916-8_3

Fig. 3.1 A lever for lifting a heavy load

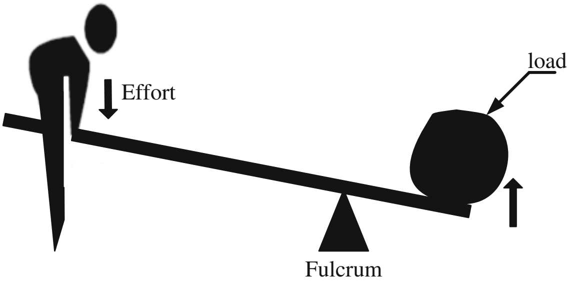
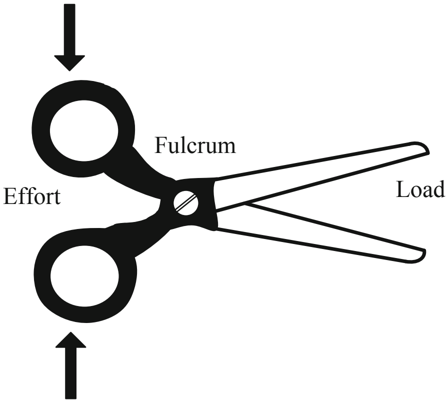


Fig. 3.2 A scissor



essentially a lever. It comprises two lever rods of type shown in Fig. 3.1. During the time of Aristotle, a law of lever was developed. This law is valid till today. Mechanics can be considered to have started during the time of Aristotle (384 BC–322 BC) mainly with the study of lever. Aristotle and some other philosophers of his time developed theories for many physical phenomena based on their intuition. Most of the theories have been proven wrong. However, those theories stimulated the logical thinking. A theory can be right or wrong; but in any case, it shows the ingenuity of human mind.

The history of science starts with the ancient Greek civilization, from the time of Socrates (469 BC–399 BC), who is credited with laying the foundation of western society. It is not that the Greek civilization was the only civilization during that time, but the modern science has its seeds mainly in the Greek civilization. From the ancient Greek civilization till today the science has been evolving like a continuous flow of water. Many other civilizations were either destroyed or could not continue the pace of development of science. India, for example, was also a very strong civilization and science was well developed as evident from the excavation carried out at Mohenjo-Daro and Harappa. It is believed that these well-developed cities were founded circa 2600 BC. The civilization called Indus Valley civilization dates back to about 6000 BC (Satyawadi 1994). In the first millennium after Christ, India was very strong in mathematics, astronomy and metallurgy. However, the continuity of scientific tradition got broken due to invasion of other civilizations and internal turmoil.

In this chapter, the history of mechanics is discussed briefly. It will be highlighted how the theoretical mechanics and experimental mechanics have influenced each other. A very brief biography of stalwarts of mechanics will also be presented. Many historical facts are debatable and any controversy is avoided here. The main focus of the present chapter is to discuss the evolution of mechanics.

3.2 Period of Aristotle

A formal study of mechanics can be traced to the period of Aristotle. Aristotle was born circa 384 BC in Stagira, Greece (Barnes 2003). At the age of 17, Aristotle joined Plato's Academy in 367 BC (Armytage' 1961). Aristotle founded his own school in Athens named Lyceum. Both Plato's Academy and Aristotle's Lyceum were important for promoting scientific thoughts. Plato was greatly influenced by the famous philosopher Socrates (Kahn 1996). It is well-known that Socrates was poisoned to death for propagating logical thinking in the Greece. Aristotle's father was Nicomachus, a court physician of the Macedonian king, Amynatas II. Nicomachus died when Aristotle was very young. Although Aristotle was a disciple of Plato, he disagreed with many philosophical treatise of Plato. His views of nature are set forth in his books Physics and Metaphysics, which mark the most serious differences between Arisotelianism and Platonism. Aristotle founded his own school in Athens in around 335 BC. He had a habit of teaching along with walking, due to which his students were nick named "peripatetic" meaning "one who travels about". Later on, an Aristotelian philosopher was called peripatetic. A famous student of Aristotle was Alexander the Great (356 BC–323 BC). Alexander became the king of Macedonia, adjacent to modern Greece, in 336 BC. Alexander expanded his kingdom. A very good relation existed between Aristotle and Alexander. After the death of Alexander, Aristotle had to leave democratic Athens due to political problems. Aristotle died of stomach problem in 322 BC in island of Euboea.

Aristotle believed that knowledge could be obtained through interacting with physical objects (Tuominen 2009). Of Aristotle's estimated 200 works, only 31 are still in circulation. He wrote on a variety of subjects like philosophy, political science, zoology, meteorology etc. He believed that there are 5 elements in nature: earth, water, air, fire and ether (space). Indian philosophers also used to believe that the world is composed of these five elements. In those days, there was a good amount of contacts between Greek and Indian Civilizations. Alexander invaded India in 326 BC. He invaded some areas of northwestern Indian subcontinent (now in Pakistan). King Porus gave a strong fight to Alexander in the battle of Jhelum that resulted in Alexander's retreat, although Porus was defeated. The first Indo-Greek kingdom was established circa 190 BC. There was a lot of cultural exchange between India and Greek in those days, although evidences of it have faded with time.

During Aristotle's times, it was believed that physical things change, while heavenly thing like the Sun and stars do not change. Aristotle classified the change in the following four categories:

(1) Change of substance (transformations, in particular of the elements earth, water, air and fire into each other). This is mainly a chemical change in the modern terms.
(2) Change of quantity (growth and shrinkage).
(3) Change of quality or alteration. For example, a hot object becomes a cold object.
(4) Change of place (locomotion).

A change can be caused because of the natural tendencies of the object or it can be a violent change. Natural things have their inner principle. For example, earth wants to join the earth. All objects composed of earth element get attracted towards the center of earth, which is also the center of universe. An object made of wood tends to fall down towards ground, because wood is an earthly material and thus has tendency to join earth. On the other hand, smoke has a tendency to move upward, because it is made of air. Aristotle also postulated that apart from the inner principle of change, natural things also follow stability. An object kept on the ground has tendency to remain stationary. For moving it, a force is needed. The object keeps on moving till the force is applied. As soon as the force is removed, the object comes to the rest. We know now, in light of Newton's laws, that Aristotle's theory on motion is wrong. An object will keep on moving in the absence of any retarding force.

On the motion of celestial bodies like the Sun and Moon, he postulated that they are composed of ether (quintessence) and hence have tendency to move in a circle, because circles are perfect. Explanation of how an arrow keeps on moving when released from bow is explained in the following manner. When an arrow moves, it creates a vacuum. As the nature abhors vacuum, the air rushes to fill up the vacuum left behind and in the process applies force on the tail of the arrow. Aristotle believed that an arrow would not be able to move in vacuum. We know today that it is wrong; in fact arrow will move more easily in vacuum, because of the absence of the drag force of the air.

About rains, Aristotle explained in the following matter. Water on earth is warmed by the Sun, changes into the air and rises up, because the air has a natural tendency to move up. Then the air cools down, changes into the water and becomes heavier, and finally falls down as the rain again. This description is weak from the point of view of modern science, but is reasonable considering the state of science during the days of Aristotle.

The pseudo-Aristotelian Mechanical Problems is considered to be the first surviving ancient Greek text on mechanics (Coxhead 2012). The prefix pseudo is used because it is not certain if the book was actually authored by Aristotle or embodies his concepts. Some say that Mechanical Problems was written by Archytas (428–347 BC) who was an ancient Greek philosopher, astronomer, statesman and strategist (Winter 2007). He belonged to the Pythagorean School. Pythagoras (circa 569 BC–circa 475 BC) is often called the first mathematician of the world. He provided the proof that in a right angle triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides. Archytas was a good friend of Plato. Whoever be the author of the book, it depicts that seeds of mechanics were sown during the ancient Greek period. In the introduction of the book, the author presents that the focus of the book is on questions of mechanical kinds, in particular questions connected with lever. There are 35 questions in the book. Some of them are as follows:

(1) Why does the exercise of little force raise great weights with the help of a lever, in spite of the added weight of the lever?
(2) Why do the men at the middle of the boat move the boat most? Is it because the oar is a lever?
(3) Why does a steering oar, small as it is, and at the end of the boat has such force that with one little handle and the force of one man, and that gentle, it moves the great bulk of ships? Is it because steering oar is a lever?
(4) Why are round things easier to move than things of other shape?
(5) Why, with larger circles, whether wheels, pulleys, or rollers, do we move more easily and quickly the things which are lifted or pulled? Is it because the farther from the center, the greater space is traveled in equal time?
(6) Why is it that the longer a board is, the weaker it gets?
(7) Why are big heavy bodies split by little wedges?
(8) Why are the so-called pebbles on the beaches round?
(9) Why do doctors pull out teeth more easily even adding weight—that of the tooth-puller—than with the bare hand? Is it because tooth-puller is two opposed levers?
(10) Why do they construct the bed so that one dimension is double the other?
(11) Why in eddying water does everything end up getting carried into the middle?

The answer to a question is in the form of a question starting with “is it because”. The questions in the Mechanical Problems have been taken from the diverse fields and the author tries to correlate many of them with the principle of lever.

Today most of the ideas of Aristotle are proven wrong. However, he cannot be blamed for it. It was just the beginning of science. In his time, quantitative physics was not well developed. Even speed was not defined quantitatively. It was described in terms of slow and fast. Similarly, temperature was also not defined in any scale like °C. People only had idea about hot and cold. Probably, they were able to appreciate that among two bodies which one is hotter, but they could not quantify it. The concept of friction was not known. Hence, it was natural for Aristotle to believe that when we remove a force from an object, it stops because it has natural tendency to stop.

3.3 Period of Archimedes

Almost all the laws of mechanics by Aristotle have been proven wrong. Thirty five years after the death of Aristotle, Archimedes was born in circa 287 BC in the city of Syracuse on the coast of Sicily (Ceccarelli 2014). This place is in Italy now. Archimedes' many laws and theorems are still valid. In that sense, Archimedes can be called as the father of mechanics. Archimedes' father, Phidias, was an astronomer, who estimated the ratio of the diameters of the Sun and the Moon. The word Archimedes in Greek means master of thought. As per his name, Archimedes has contributed a lot to mathematics and mechanical engineering. Figure 3.3 depicts a portrait of Archimedes.

Archimedes spent some time in the city of Alexandria in Egypt. In those days, the Alexandria was the center of Greek science. There were a lot of disciples of Euclid in Alexandria. Euclid was very active around 300 BC on whose name there is a branch of mathematics called Euclidean Geometry. The exact years of his birth and death are not known. Euclid had published a famous book on geometry called The Element. With the disciples of Euclid, Archimedes studied geometry. Archimedes was able to determine the area, volume and center of many important shapes (Assis 2010).

Archimedes is considered as the pioneer in statics and hydrostatics. Although he was a great mathematician, he is remembered more for applying the physics and mathematics to practical problems. The king of Sicily, Hiero II, was great admirer of Archimedes and based on his requirement, Archimedes invented many mechanical gadgets. He invented many weapons, for example catapult. Thus, he

Fig. 3.3 A portrait of Archimedes [With permission from Ceccarelli (2014), copyright Elsevier (2014)]

laid down the foundation of military engineering. There is a legend that he burnt Roman ships by concentrating the solar energy through mirrors.

One story about Archimedes is very popular. The king, Hiero II, wanted to know the purity of the gold used in making a crown. He suspected that the goldsmith might have mixed silver with it. Archimedes kept thinking about this problem. When he was taking the bath in a tub, he observed that the tub water got displaced in proportion to his submerged body. He got the idea that if the crown is submerged in a pot full of water, it will displace the water. The volume of water displaced can be easily measured, which will be the volume of the crown. The weight of the crown is known. A similar weight of any gold object should also displace the same amount of water. If the crown displaces more amount of water, then the gold in crown might have been polluted by the silver, because for the same weight, silver has more volume. He applied this method and found that indeed the goldsmith had polluted the gold. It is said that when Archimedes got this idea, he jumped from the tub and ran naked on the street of Syracuse, shouting Eureka (I have found it).

Archimedes invented a pump for lifting of water (Waters and Aggidis 2015). It is essentially a screw that rotates inside the housing filled of water. The rotation of screw imparts rotational as well as axial velocity to the water. Due to axial velocity, the water moves and can reach at a height. Some believe that this device was already being used in Egypt for irrigation purpose and Archimedes only redesigned it with the sound foundation of theory. It is also believed that king of Egypt used it to pump water from the hull of the ship. Archimedes screw is used till today. It is used for pumping water, fish or food grains from one location to another. It is used during injection molding to deliver the compound material to the mould. The low rotation rate and lack of pressure required to move the material cause little or no damage to the fibers. Presently, research is going on to use the Archimedes screw as a turbine. The first of such devise was installed in Europe during 1994 and later introduced to UK in 2005 (http://www.westernrenew.co.uk/files/case_studies/river_dart.pdf).

Archimedes also built a famous planetarium that had single hydraulic mechanism, which moved several globes simultaneously. He also invented a hydraulic organ. With the help of ropes and pulleys, he moved a heavy ship. It essentially worked on lever principle. In his book entitled "On the Equilibrium of Planes", Archimedes provided seven postulates, which in modern terms emphasize the balance of moment. A large force at one end of the lever can be balanced by small force acting at a larger distance from the fulcrum. The moment of both the forces will be equal about the fulcrum. The moment of a force about a point is the product of the force and perpendicular distance from the point. Archimedes was so confident about the law of lever that it is believed that he said, "Give me a place to stand on, and (I) will move the earth."

Today even the school children are familiar with Archimedes' principle that states that a body immersed in a fluid experiences an upward buoyancy force, which is equal to the weight of the displaced fluid. The principle applies to both floating as well as submerged bodies and to all fluids, i.e., liquids and gases. A body is able to swim if the upward buoyancy force is equal to the weight of the body.

Archimedes died in 212 BC. He was killed by a Roman soldier, when a long siege of Syracuse during the second Punic war (214–212 BC) was ended. It is said that the Roman commander, Marco Claudio Marcelo had ordered the soldiers not to kill Archimedes. When the Roman soldier approached Archimedes, he was solving a problem of mathematics and refused to accompany the Roman soldier. At this, the infuriated soldier killed him. Archimedes' tomb was constructed, where a sphere was drawn inside a cylinder as per the will of the Archimedes. In his work entitled "On the Sphere and Cylinder", he computed the volumes and areas of the sphere as well as cylinder and considered it as one of his greatest achievements.

Greek technology was at its zenith during and after some time of the period of Archimedes (300 BC–150 AD). The important innovations in this period include cranes, screws, gears, organs, odometer, wheelbarrows and roof tiles. The gears in Greek period used to have triangular teeth.

3.4 Hero of Alexandria

Hero of Alexandria, also known as Heron of Alexandria, was a Greek mathematician and engineer and was active in his native city Alexandria (http://www.britannica.com/biography/Heron-of-Alexandria). In his time, Egypt was under the control of Romans. There is a difference of opinion about the dates of his birth and death. Many believe that he was born circa 10 AD and died in circa 70 AD. He is credited for developing the first steam turbine called aeolipile (Papadopoulos 2007). It consisted of a spherical vessel from which the steam exited through two nozzles. The exiting steam provided a thrust to rotate the spherical vessel. There is no evidence that this turbine was used for any practical application.

Hero modified many inventions of his predecessors. Ctesibius (circa 285–222 BC) had invented hydraulics, which was essentially a water organ. Ctesibius is also called the father of pneumatics. Hero also developed wind powered organ and wind wheel. Marcus Vitruvius Pollio (born circa 80–70 BC, died after circa 15 BC), commonly known as Vitruvius, was a Roman author, architect, civil engineer and military engineer during the first century BC. He is known for his multi-volume work entitled *De Architectura*. Some of the inventions by Vitruvius are described in Hero's book Pneumatica. The book also describes working of a lot of toys such as singing birds, puppets and coin-operated machines. Hero was a lucid writer. The book also contains the working of siphon. Today, the working of siphon is easily explained with the help of Bernoulli's principle, which was published by Daniel Bernoulli in 1738 in his book *Hydrodynamica*. In his book *Automatopoietica*, Hero described automatic closing and opening of temple doors and statues that pour wine. This book can be called the first book on mechatronics; although there was no electronics in it, the approach was similar to mechatronics of today. He also developed a water clock. His book Dioptra describes a theodolite-like instrument used in surveying. Hero taught at Alexandria's Musaeum. Many believe that he acted as its Director and developed it as the first Polytechnic School or Technical Institute.

Hero has contributed a lot of books on geometry. The book Metric includes the derivation of Hero's formula (believed to be developed by Archimedes) for finding out the area of the triangle. The area of a triangle with sides a, b and c is given by

$$A = \sqrt{s(s-a)(s-b)(s-c)}, \tag{3.1}$$

where s is the sum of perimeter divided by 2, i.e., $s = (a + b + c)/2$. The book also contains an iterative method for approximating the square root of a number to desired accuracy. However, it is believed that this method was known to Babylonian circa 2000 BC.

Hero has contributed a lot to experimental mechanics. He recognized the value of experimental work. During the time of Aristotle, it was believed that nature abhors vacuum. Hero described an apparatus designed to show the existence of vacuum. It is a metal hollow sphere with a small hole with which a tube is attached. Hero argued that if one blows air into the sphere, then air enters in it and therefore, air must be compressible. One can also draw air out by inhaling and create a vacuum. In his book Mechanics, he described the theory of motion, statics, balance and a method for constructing three-dimensional shapes in proportion to a give shape using pantographs. He described the windlass (winch), the lever, the pulley, the wedge, the screw and the worm wheel. Hero is also credited with the construction of the first analog computer, a computing device based on gears and pins.

3.5 Period After Hero and Before Galileo

During the time of Hero, Alexandria was a great learning center. One of the greatest astronomers in Alexandria was Ptolemy (circa 100–circa 170), who developed a geo-centric model of the universe, which is called Ptolemaic system. His most popular book is Almagest (Feke 2014). He published another book "Geography" that contains the first realistic atlas of the world. Ptolemy's geocentric model makes the following assumptions:

- Heavens move spherically.
- Earth is spherical.
- Earth is at the middle of the heavens.
- Earth is immobile.

Pappus (circa 290–circa 350) lived in the fourth century. According to some historians, he studied equilibrium and motion of a body along an inclined plane. He also studied center of gravity of a body and proposed a method of finding out the center of gravity of an irregular body by suspending it using several points of suspension (Oliveira 2014). His two theorems are very popular. Pappus set forth these theorems, which were restated by the Swiss mathematician Paul Guldinus in about 1640 AD (Shames 1997). The first theorem may be stated as follows:

> The surface area A of a surface of revolution generated by rotating a plane curve C about an axis external to C and on the same plane is equal to the product of the arc length s of C and the distance d traveled by its geometric centroid.

For example, when a line of length l is given full revolution about a parallel axis at a distance of r in the same plane, it generates the surface of a right circular cylinder of length l and radius r. Here, the arc length s is equal to l and in one rotation the geometric center of the line travels a distance of $2\pi r$. As per the first theorem of Pappus, the surface area of the cylinder is the product of the arc length and the distance travelled by the centroid. Hence, the surface area comes out to be $2\pi rl$.

The second theorem of Pappus may be stated as follows:

> The volume V of a solid of revolution generated by rotating a plane figure F about an external axis is equal to the product of the area A of F and the distance d traveled by its geometric centroid.

For example, when a rectangular of sides r and l is rotated by 360° about its one side of length, a right cylinder of length l and radius r is generated. The area of the rectangular is rl and its centroid travels a distance of $2\pi(r/2)$. Hence, by the second theorem of the Pappus, the volume of the cylinder is $\pi r \times rl = \pi r^2 l$.

After the period of Pappus, the growth of the mechanics slowed down. In the meantime, there was a great expansion in the Arab world. In the period of Arabian domination, mechanics showed low progress with other fields of physics such as optics being developed instead. The situation began to change in the thirteenth century. In this period, there was a lot of growth in science and philosophy including astronomy. Arabs translated many books from the Greek.

Jean Buridan (circa 1293–circa 1363) was a French priest who developed the concept of impetus (King 1955). The concept of impetus is closely related to the concept of momentum, which is the product of mass and velocity. Buridan studied and later taught at the University of Paris. Nicole Oresme (circa 1320–1382) was a French philosopher who also contributed to mechanics (http://www.britannica.com/biography/Nicholas-Oresme, accessed on October 18, 2015). William Heytesbury (http://plato.stanford.edu/entries/heytesbury/, accessed on October 18, 2015) was chancellor of Oxford University around 1371. His greatest contribution was the concept of acceleration, an unknown concept to Buridan and Oresme at the Paris School. At the beginning of the fourteenth century, an important social and cultural change took place in Italy, which is known as Italian Renaissance (Lee et al. 2010). In the fifteenth century, the Italian school of mechanics emerged (Pisano and Capecchi 2016). Notable personalities are Blasius da Parma (1327–1416), Nicholas of Cues (1401–1464) and Leonardo da Vinci (1452–1519). Blasius wrote a treatise on weights. He was also responsible for introducing statics and kinematics to Italian schools. He was professor of mathematics at the University of Padua, where he taught from 1382 to 1388. Nicholas of Cusa held, before the time of Copernicus and Newton, that the nearly spherical earth revolves on its axis about the Sun and that the stars are other worlds. Leonardo da Vinci lived in the period immediately before Scientific Revolution (circa 1550–1700). He was an engineer, artist, scientist and inventor. He studied the following problems related to mechanics:

- Concept of a moment of a force
- Rigid body motion in an inclined plane
- Solution of a system of force
- Energy of a body in motion
- Study of Earth's shape
- Theory of Center of Gravity
- The falling bodies
- Hydrostatics and hydrodynamics

Leonardo da Vinci (1452–1519) stated the two basic laws of friction (http://www.phy.davidson.edu/fachome/dmb/PY430/Friction/history.html):

(1) If the load of an object is doubled, its friction doubles.
(2) The areas in contact have no effect on friction.

He also stated that every frictional body has a resistance equal to one quarter of its weight. In other words, he suggested a Coulomb coefficient of friction of 0.25 for the bodies. This value is high considering most of the sliding bodies today; however, in Leonardo da Vinci's time, the tribological characteristics of the bodies were definitely inferior in comparison to present age. Leonardo da Vinci did not publish his theories on friction and he never got credit for it.

Leonardo da Vinci also studied strength of materials. He hanged a basket containing sand with an iron wire (Osakada 2010). The strength of the wire could be determined by measuring the weight of the sand when the wire broke. Unfortunately, this result was also not published in the form of a book and went unnoticed for a long time.

Nicolaus Copernicus (1473–1543) born in the Kingdom of Poland formulated a model of universe that placed Sun rather than earth at the center of universe. This was against the belief of the church. Copernicus was reluctant to publish his book because of the fear of church. Finally, the book was published when Copernicus was in his death bed. Later on, Galileo further developed the model of Copernicus with his telescopic observations.

3.6 Period of Galileo

Galileo (1564–1642) is called the father of modern science. Albert Einstein called Galileo "the father of modern physics—indeed of modern science altogether." Stephen Hawking has stated, "Galileo, perhaps more than any other single person, was responsible for the birth of modern science." Here, a brief biography and scientific contributions of Galileo are presented based on several references (Hofstadter 2009; Sharratt 1994; Næss 2005; Drake 1978; Grego and Mannion 2010). Vincenzio Galilei, the father of Galileo was born at Florence in 1520. He was a musician. In 1563, Vinczio married Giulia Ammanmati of Pescia and settled in the countryside near Pisa. Galileo was born on February 15, 1564 near Pisa. Galileo was first tutored by Jacopo Borghini after which he was sent to the Camaldolese monastery at Vallombroso to study grammar, logic and rhetoric. Galileo's father, Vincenzio wanted that Galileo should become a physician. He made arrangement with his friend Tedaldi for Galileo to live in Pisa, where he was enrolled at the University as a medical student in the autumn of 1581.

The medical curriculum at the University of Pisa was based on the works of Galen and Aristotle's book on natural science. Galileo noted that some laws of Aristotle are contrary to day to day observation. For example, according to Aristotelian theorem, the speed of a falling body is proportional to its weight. Aristotle had argued if the two bodies are dropped from a height, the heavier body will reach the ground faster. Galileo coined a paradox to refute this claim. The paradox is as follows. If a light and a heavy body are tied together, they will reach ground at the same time. Suppose an independent heavy body of mass m_h reaches the ground in time t_h and an independent light body of mass m_l reaches the ground in time t_l. When the two bodies are tied together, the composite body will reach in a time lying between t_h and t_l, because the heavy body will tend to drag the light body and the light body will tend to drag the heavy body. As a result, an intermediate speed will be attained by both the bodies. Now, if we look from a different angle, the mass of the combined body is $(m_h + m_l)$, which is more than m_h. Hence, as per the Aristotle's law, the combined body should reach in lesser time than t_h. Thus, there is a contradiction and it can be resolved only by assuming that speed of a falling body is independent of the mass.

Ostilio Ricci was a famous mathematician and military engineer during that period. In 1583, Galileo met Ricci and was fascinated by his lectures on mathematics. Ricci told Vincenzio that his son preferred mathematics to medicine and sought permission to instruct him. When Galileo returned to Pisa in the autumn of 1583, he devoted his time to mathematics and philosophy and absented himself frequently from required lectures. During Galileo's time, the teaching of mathematics at the University was poor. It had low status compared to general natural philosophy. Ricci introduced algebra and geometry to Galileo. He also made Galileo familiar with the work of Tartaglia, who was Ricci's own teacher and was recognized as the greatest mathematician of the sixteenth century. Tartaglia was first to find a general method for solving a cubic equation (Darke 1978; Næss 2005).

After leaving the University of Pisa without a degree in the spring of 1585, Galileo taught mathematics privately at Florence and Siena. He held some public teaching position at Siena during the academic year 1585–86. His first scientific treatise came out in 1586 and it was entitled La Bilancetta in Italian, whose English translation is the Little Balance. It described the construction and use of a device similar to Westphal balance. Westphal's balance is used to measure the specific gravity (or density) of liquids. Galileo did not claim its invention. In the little balance, Galileo proposes that Archimedes might have found the purity of the crown by measuring its specific gravity.

Later in 1586, Galileo began to compose a Latin Dialogue on certain problems of motion. In those days, the dialogue style was very popular in scientific writing. This book discussed the motion on an inclined plane. Galileo experimented with the motion of balls on an inclined plane. He observed that the velocity of the balls is not dependent on the size of the ball and is only dependent on the angle of inclination. After reaching the foot of the inclined surface, the balls keep moving on a straight path and finally come to rest because of friction. He proposed the law of inertia, which states that a body will preserve its velocity and direction so long as no force in the direction of its motion acts on it. Later on Newton presented it as the first law of motion in 1687, which states that everybody remains at rest or moves with constant velocity in a straight line, unless it is compelled to change that state by force acting upon it. In his book Dialogue, Galileo refutes the claim of Aristotelian scientists that earth does not move. In Italy, which is a peninsula, ships were very common. He provided the example of a ship's hull, where you cannot know if the ship is moving or not. Same is the case of the motion of earth. The law of Galilean relativity states that there is no physical way to differentiate between a body moving at a constant speed and a body at rest.

Galileo began his lectures as Professor of Mathematics at the University of Pisa in November 1589. During his time at Pisa, Galileo revised and completed his treatise De Motu (On Motion). There is story that Galileo dropped balls from the leaning tower of Pisa to demonstrate that all the bodies freely dropped from a height will reach the ground at the same time. Many people doubt the authenticity of this story.

At Pisa, on observing the motion of hanging lamps of the church, Galileo concluded that the time period of a pendulum is not dependent on the mass and amplitude of the pendulum. When initial amplitude is provided to pendulum, the pendulum starts oscillating. The amplitude keeps on reducing gradually because of friction, but the time period remains same. Galileo designed a pendulum clock on this principle. However, it could not be fabricated in his life time.

Galileo invented a basic type of thermometer in 1592–1593. It consisted of a sealed glass cylinder filled with clear liquid. In this liquid, a number of objects of different densities floated. Increasing temperature caused progressively less dense objects to sink at the bottom and engraving on the objects could be read to gauge temperature. The principle is very simple. With the increase in the temperature of the liquid, its density decreases. All the objects having densities more than the liquid will sink at that particular temperature. Some authors believe that Galileo did not invent this thermometer but only mentioned in his book.

In 1592, Galileo joined University of Padua. He gave the inaugural lecture on 7th December 1592. Galileo wrote a book on mechanics, which was composed for a course. Galileo developed a calculating instrument. He also developed a military compass. Galileo invented Pulsilogium in 1603. He constructed a pendulum, the length of which could be adjusted so that it swings in time with the patient's pulse. Now, the doctor could read a diagnosis directly from the length of the pendulum.

Galileo realized that the movement of a pendulum is also a kind of fall—a natural motion, not dictated by any outside force. From a modern perspective, it is not true because the pendulum is affected by the force of gravity. However, Galileo knew nothing of this. Galileo did experiments up to 9 m long pendulum. Time was measured by weighing the amount of water that had run into a container. He used the unit of time as 'tempo'. He observed that the time period is proportional to square root of the length of the pendulum. Today we know that the time period is given by

$$T = 2\pi\sqrt{\frac{l}{g}}, \tag{3.2}$$

where l is the length of the pendulum and g is the acceleration due to gravity. In the time of Galileo, the acceleration due to gravity was unknown. Galileo also observed that time of fall for a free-falling body from rest is proportional to the square root of the height it falls.

During the summer of 1607, Galileo turned his attention towards hydrostatics and strength of materials. Strength of Material formed the part of his book entitled Two New Sciences (Darke 1978). Galileo understood the parabolic nature of the paths of projectile. From 1609, he turned his attention towards astronomy with the help of his telescope.

Credit for the invention of the telescope is attributed to the Dutch-German lens maker Hans Lippershey (1570–1619) of Middleburg, Zeeland in the Netherlands. Initially, it was having a magnification of 3X. News of this marvelous invention quickly spread around Europe and first reached the ear of Galileo in May 1609. Without any special knowledge of Lippershey's invention, Galileo figured out what kinds of lenses were required and built his first refracting telescope (Grego and Mannion 2010).

Galileo's first telescope only magnified about three times. Galileo wrote that his telescope consisted of a tube made of lead, two lenses both plane on one side but one spherically convex on the other side and the other concave. Galileo's second telescope constructed a few weeks later was of the same configuration but had a magnification of 10X. By November 1609, he had constructed a telescope with a magnification of 20X, grinding the lenses himself to his own specification in order to produce an instrument with higher magnification. It consisted of a 37 mm plano-convex objective lens with a focal length of 980 mm. The tube was of a wooden barrel-type construction made of long strips of wood glued together and consisted of two parts—the main tube to which the objective lens was attached and a small draw tube nesting inside it which housed eye lens.

In March 1610, Galileo published his amazing observations in Sidereus Nuncius (The Starry Messenger). It was a little book that made big impact. In addition to revelation about the Solar system, the Moon's cratered face and the moons of

Jupiter, the book included the observations of the milky-way, stars in Orion constellation, the bright Pleiades and beehive cluster.

Galileo's observations clearly showed that Earth was not located at the center of the Universe. Planet Venus showed phases just as the moon shows. Four star-like points were orbiting around Jupiter. They were named Galilean moons. None of these facts could be explained using the old geocentric Ptolemaic system. In terms of observing and recording astronomical phenomena, the period 1609–1612 was remarkable. Galileo's famous struggle with church began around 1612 (Grego and Mannion 2010). Those days, church used to carry out Inquisition if it suspected that anyone's activities were against the doctrine of church. In 1600, dissident thinker Giordano Bruno was convicted of heresy by the holy office and burned at stake. In 1612, Galileo offered his theory that the Sun revolves around its own axis. On February 26, 1616, cardinal Bellarmine warned Galileo not to hold, teach or defend Copernican theory. According to an unsigned transcript found in the Inquisition file in 1633, Galileo was also enjoined (prohibited) from discussing this theory either orally or in writing.

Galileo also invented a compound microscope. In his 1623 book, the Assayer, Galileo discusses a telescope modified to see objects very close. Originally called an Occhialino (small eye glass), the word 'microscope' was bestowed on this device by Galileo's fellow academician Johannes Faber. A telescope has a convex objective lens and concave eyepiece. In microscope, the eyepiece is convex and the objective lens is concave. Later on, a field lens was added at an intermediate position.

Galileo's battle with church culminated with a trial in April 1633, in which he was forced to abjure, curse and detest the heresy that he supported and taught, including the Copernician view that the Earth moved around a motionless Sun. He was placed under house arrest and forced to recite penitential psalms every day for 3 years. He was not even allowed out to walk in his garden.

During his final years, Galileo worked on his greatest book: Discourses on Two New Sciences. In this book, published in the Netherlands in 1638, he compiled all the observations and theories he had worked on over the previous 40 years. He developed kinematics and mechanics, describing the motion of bodies free from frictional forces. He was able to extrapolate from experiments that without the frictional forces, a body would keep on moving forever. The book also contains the topics on strength of material. By 1637, the eyesight of Galileo was failing. First he lost sight in his right eye. In December 1637, he was left blind. In his later years, Galileo was helped by Vincenzo Viviani, a 16 year old acolyte (assistant) who came to live with him in his home in Arcetri and who acted as his assistant and wrote his first biography (Grego and Mannion 2010). Galileo died of heart problem in 1642.

The other great scientist, during the period of Galileo was R. Descartes (1590–1650). He was a French philosopher, mathematician and scientist, who spent about 20 years of his life in Dutch republic. He is called the father of modern philosophy. He developed Cartesian coordinate system, which connected Euclidean geometry with algebra.

Johannes Kepler (1571–1630) provided three laws of planetary motion based on the data of Tycho Brahe (1546–1601). The laws of Kepler are as follows:

1. All planets move in elliptical orbits, with the Sun at one focus.
2. A line that connects a planet to the Sun sweeps out equal areas in equal times.
3. The square of the period of any planet is proportional to the cube of the semi-major axis of its orbit.

Brahe made all the observations with naked eye. Kepler worked for sometime as an assistant of Brahe. After Brahe's death he got access to the huge data left by Brahe.

Another great researcher of that period was Stevinus (1548–1620). He provided the law of parallelogram for forces that is expressed in the following form:

> The two forces acting on a particle may be replaced by a single force, called their resultant, obtained by drawing the diagonal of the parallelogram, which has sides equal to the given forces.

He also provided a principle of hydrostatics that the pressure of the fluids is proportionate to their depths.

3.7 Period of Newton

The year in which Galileo died, Newton was born. He was born into a forming family of Woodthorpe Manor on 25th December 1642 and named after his father—Isaac Newton. His mother's name was Hannah. When Newton was only three year old, his mother married a prosperous minister from a nearby village. Newton remained with his grandmother, Margery, at Woodthorpe. Newton entered Trinity College of Cambridge University. He got a degree from Trinity College in 1665. Royal Society of London was formed in 1662. Newton became its member in 1672 at the age of 30 and served as its president between 1703 and his death in 1727 (Grego and Mannion 2010).

Newton came across the Robert Hooke's famous book Micrographia that was published around 1964. Robert Hooke is famous for providing the law of elasticity in 1660. It states that for relatively small deformations of an object, the displacement or size of the deformation is directly proportional to the deforming force or load. It is said that Hooke got this idea while working with Robert Boyle (1627–1691) on whose name is a law that states that for a fixed amount of an ideal gas kept at a fixed temperature, pressure and volume are inversely proportional. In 1678, Hooke described the inverse square law to describe planetary motion. Later on Newton provided a universal law of gravitation that is stated as follows:

> Every object in the Universe attracts every other object with a force directed along the line of centers of the two objects. This force is proportional to the product of their masses and inversely proportional to the square of the distance between the centers of mass of two objects.

Mathematically, the gravitational force F_g is given by

$$F_g = G\frac{m_1 m_2}{r^2}, \tag{3.3}$$

where m_1, m_2 are the masses of the objects, r is the distance between the centers of masses and G is the universal gravitation constant. The value of G is 6.673×10^{-11} $\mathrm{m^3/kg\ s^2}$. If the two masses of 100 metric ton mass are having their mass centers separated by a distance of 10 m, they will attract each other with a force of about 6.67 mN, a small value. Hence, in machine design, this force is neglected between two elements of the machine.

In 1666, Newton invented calculus. In 1687, Newton published his famous book “Principia Mathematica Philosophia Naturalis”, which is famous by the name of Principia. It contains three laws of motion (Kumar 2003):

Law 1: Each and every body perseveres in its state of rest or of uniform motion in a right line unless it is compelled to change that state by forces impressed there on.

Law 2: The alteration (acceleration) of motion is ever proportional to the motive force impressed and is made in the direction of right line in which the force is impressed.

Law 3: To every action, there is always opposed an equal reaction or the mutual actions of two bodies upon each other are always equal and directed to contrary parts.

The first law is essentially Galileo’s law of inertia and it defines the term force. The second law relates force to mass and acceleration. If the concept of force is taken from elsewhere, then the first law can be derived from the second law. For a rigid body, the third law can be derived from the second law but not for the deformable bodies. Hence, the third law is an independent law, in general.

In 1704, Newton published his book Opticks. It included inflexion of light (diffraction). Using a glass prism, Newton investigated the refraction of light and performed elaborate experiments that enabled him to discover measurable patterns in light. He investigated 7 colors in the spectrum of light—red, orange, yellow, green, blue, indigo and violet. Newton proposed a theory that light is made of particle. On the other hand, Dutch physicist and astronomer Christian Huygens (1629–1695) proposed the wave nature of light. Albert Einstein (1879–1955) showed the particle nature of light in his 1905 paper of photoelectrical effect. Today light is considered to have a dual nature. In 1717, Newton observed a phenomenon in which an interference pattern is created by the reflection of light between two surfaces—a spherical surface and an adjacent flat surface. Due to it, circular dark and white bands are created. These are now called Newton’s ring. They are produced based on the principle of interference and form the basis of many measuring instruments.

The famous mathematician Leonhard Euler (1707–1783) provided the laws of motion for a rigid body. Euler’s as well as Newton’s laws are valid in an inertial frame of reference. A frame of reference which is at absolute rest is an inertial reference frame. A reference frame that is moving with respect to this frame of reference at a uniform linear velocity is also an inertial reference frame. An accelerating frame is a non-inertial frame of reference. In an inertial frame of reference, following are the Euler's two laws:

First law: The rate of change of linear momentum (mass of the body multiplied by the velocity of center of mass) is equal to the net impressed force on the body.

Second law: Given O is a fixed point on the inertial reference frame, the rate of change of the angular momentum of the body about O is equal to net moment of forces acting on the body about O.

Euler also provided the equations for hydrodynamics. Euler used differential calculus to express Newton's second law.

During the time of Newton, Bernoulli family contributed a lot to engineering. Jacob Bernoulli (1655–1705) along with his brother Johann Bernoulli (1667–1748) founded the calculus of variations. With the help of calculus of variations, one can find an integrand function that minimize or maximize an integral. For example, consider the following integral expression (called functional, i.e., function of functions):

$$I = \int_0^l \left\{ \frac{1}{2} EA \left(\frac{\mathrm{d}u}{\mathrm{d}x} \right)^2 - q(x)u \right\} \mathrm{d}x. \tag{3.4}$$

Suppose also that u is 0 at $x = 0$. The expression in Eq. (3.4) represents the total potential energy of a rod of cross-sectional area A and length l, whose Young's modulus of elasticity is E. The function u provides the displacement of the rod, when the load of intensity $q(x)$ is applied on the rod, i.e., the load per unit length is $q(x)$. One can substitute many possible functions u such as $\sin(x)$, x^2 or any such function that is 0 at $x = 0$. For different functions, the value of functional I will be different. Out of all possible functions, the function which minimizes the value of I represents the exact displacement field for the elastic rod. However, it is not possible to evaluate I for all possible function values. Calculus of variations provides an easy way. It finds out that the function u that minimizes I satisfies the following differential equation:

$$\frac{\mathrm{d}}{\mathrm{d}x} \left(EA \frac{\mathrm{d}u}{\mathrm{d}x} \right) + q(x) = 0; \quad \text{with } u = 0 \text{ at } x = 0. \tag{3.5}$$

Solution of Eq. (3.5) can be obtained by any standard method for solving second order ordinary differential equation. It is also possible to carry out the reverse process, i.e., given a differential equation of Eq. (3.5), the corresponding integral form of Eq. (3.4) can be obtained by using calculus of variations.

Calculus of variations seems to have started by solving brachistochrone (shortest time) problem. In 1696, Johann Bernoulli posed the following problem. "Find the shape of the curve down which a bead sliding from rest and accelerated by gravity will slip (without friction) from one point to the other in the least time." It is said that Newton solved this problem the very next day. The solution is a segment of cycloid. Later on many mathematicians solved this problem in different ways.

Another great mathematician and physicist during the time was Daniel Bernoulli (1700–1782), son of Johann Bernoulli. His excellent work titled "Hydrodynamica" was published in 1738. Bernoulli's principle for incompressible, inviscid, steady and laminar flow is the basis for the design of a number of measuring instruments and machines. The principle states that the total mechanical energy associated with flowing fluid comprising the energy associated with the fluid pressure, the gravitational potential energy of elevation and the kinetic energy of fluid motion remains constant. It is based on the principle of energy conservation.

3.8 Classical Mechanics After Newton

Nine years after the death of Newton, Charles-Augustin de Coulomb (1736–1806) was born in France. He has contributed a lot to electricity and magnetism. Coulomb was a military engineer who turned to physics later on. In mechanics, he is known for his following laws on friction:

1. The maximum force of friction is independent of the magnitude of area in contact between the surfaces.
2. The maximum force of friction is proportional to the normal force on the area of contact.
3. The maximum force of friction is less and practically constant at low velocities of sliding than that at the state of impending motion.

In the paper submitted to French Academy of Science in 1784, Coulomb showed the results of torsion test of iron wire.

Jean-Baptiste le Rond d'Alembert (1717–1783) published a book entitled Treatise of Dynamics in 1743. It contains d'Alembert's principle. Using d'Alembert's principle one can convert a dynamics problem into a statics problem. It introduces a concept of inertia force. The inertia force of a particle is the negative mass times acceleration. Thus, Newton's law states that force on a particle is mass times the acceleration, whilst d'Alembert's principle states that the particle is balanced under the action of applied force plus inertia force. Thus, $\boldsymbol{F} = m\boldsymbol{a}$ expression for Newton's second law becomes $\boldsymbol{F} + (-m\boldsymbol{a}) = 0$ as d'Alembert's expression. Although it is just algebraic expression, it is helpful in solving the complicated problems of dynamics. When a dynamics problem is converted into a statics problem, the well-established methods of statics can be applied.

Gaspard-Gustave de Coriolis (1792–1843), a mechanical engineer, introduced the concept of Coriolis force and acceleration. Suppose that a particle is moving on a link with velocity of magnitude v and the link itself is rotating with an angular velocity ω, then the particle will experience a Coriolis acceleration of magnitude

$2\omega v$, which is in addition to other acceleration viz., centrifugal, tangential and sliding accelerations. Coriolis effect comes in a non-inertial frame. In a proper inertial frame, the effect does not exist (Goldstein et al. 2002).

In 1768, Lavoisier demonstrated the law of conservation of mass, which can be stated as follows:

> The total mass of a closed system stays constant for any physical-chemical transformation to which it can be submitted.

The experiment consisted of boiling water over a period of 101 days, measuring the weight of whole system before and after the operation. It was observed that the total weight remained constant.

Alternative formulation to Newton's 2nd law was provided by Joseph-Louis Lagrange (1736–1813). He defined a Lagrangian L as

$$L = T - V, \tag{3.6}$$

where T is the kinetic energy and V is the potential energy. Lagrange showed that for a conservative system (in which the potential energy can be expressed as a function of position), the following equation holds good:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = 0, \qquad j = 1 \text{ to } n, \tag{3.7}$$

where q_j represents the jth independent coordinate that is used for specifying the position of the system, which has n degrees-of-freedom. For an n-degree-of-freedom system, there will be n equations. For getting an idea about this approach, consider a spring-mass system subjected to a force F. Keeping one end of the spring, a mass is attached with the other end and the mass is pulled with a force F. The position of the mass can be specified by a coordinate x. At $x = 0$, the stretch of the spring is zero. The kinetic energy T of the system is

$$T = \frac{1}{2}m\dot{x}^2 \tag{3.8}$$

and the potential energy is

$$V = \frac{1}{2}kx^2 - Fx. \tag{3.9}$$

Hence, the Lagrangian is given by

$$L = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2 + Fx. \tag{3.10}$$

Now applying Eq. (3.6):

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\frac{\partial\left(\frac{1}{2}m\dot{x}^2-\frac{1}{2}kx^2+Fx\right)}{\partial\dot{x}}\right\}-\frac{\partial}{\partial x}\left(\frac{1}{2}m\dot{x}^2-\frac{1}{2}kx^2+Fx\right)=0, \tag{3.11}$$

which provides

$$m\ddot{x}+kx=F. \tag{3.12}$$

This could have been obtained by applying Newton's second law, but in more complicated systems, Lagrange's method is convenient to apply. Lagrange was born in Turin, Italy and his book on Analytical Mechanics was published in 1788 (Oliveira 2013).

By using the calculus of variations, the integral form of Lagrange's method can be obtained. This is known as Hamilton's principle (Goldstein et al. 2002). It can be stated as follows:

"The motion of a conservative system is such that the line integral (called the action or the action integral)

$$\int_{t_1}^{t_2} L\ \mathrm{d}t, \tag{3.13}$$

where $L = T - V$, has a stationary value for the actual path of the motion."

In the late eighteenth century and early Nineteenth century, a lot of work was done in the area of strengths of materials. S.D. Poisson (1781–1840) worked in many areas of mathematics. One material property is named after him as Poisson's ratio. It is the ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched. It can be shown that for isotropic materials, the upper bound on the Poisson's ratio is 0.5 and the lower bound is −1. Suppose a 1 m long steel rod of square cross-section of 10 mm side is stretched by 1 mm and its Poisson's ratio is 0.3, then its sides will be shortened by 0.003 mm. Claude Louis Marie Henri Navier (1785–1836) was an engineer and has designed several bridges including suspension bridge. However, the suspension bridge was a failure. He has contributed a lot in solid and fluid mechanics. He is well-known because of Navier-Stokes equations which are the momentum balance equations for a viscous fluid. George Gabriel Stokes (1819–1903) has contributed a lot to hydrodynamics. A. Cauchy (1789–1857) started 3 by 3 matrix notations of the stress components. Cauchy stress tensor refers to force per unit of deformed area. G. Lame (1795–1870) also contributed to strength of materials and is well-known for Lame's constant for an elastic material. Thomas Young (1773–1829) has studied the elastic behavior of the material and provided a constant E in 1807 that is known as Young's modulus of elasticity. It is the ratio of change is stress to change in strain during the elastic range. It is said that Giordano

Riccati has used it in 1782 and Leonhard Euler published it in 1727. In mechanics, George Green (1793–1841) is well-known for providing a measure of strain in his name.

The work on plasticity also started during this period. F.J. Gerstner (1756–1832) applied the load to a piano wire of 0.63 mm diameter and 1.47 mm in length with a series of weights till plastic deformation and drew stress-strain curve (Osakada 2010). As early as 1856, Maxwell (1831–1879) studied the occurrence of the yield. Maxwell showed that the total strain energy per unit volume could be resolved into two parts—the strain energy of uniform tension or compression and strain energy of distortion. He apprehended that the distortion energy part was responsible for the plastic deformation. Henri E. Tresca (1814–1885) carried out the experiments on metal forming processes such as punching, extrusion and compression starting from 1864. Tresca graduated from Ecole Polytechnique at the age of 19, but started publishing academic papers quite late (at the age of 50). The Tresca yield criterion is well-known in the plasticity. The Tresca criterion states that whenever the maximum shear stress at a point reaches the critical value, the yielding starts at that point. This also implies that hydrostatic stress (mean stress) does not affect the yielding.

In 1871, French mathematician and engineer Barre de Saint-Venant (1797–1886) wrote a paper on elasto-plastic analysis of partly plastic problems, such as the twisting of rods, bending of rectangular beams and pressurizing of hollow cylinders. Sain-Venant considered the following assumptions:

(1) The volume of material does not change during plastic deformation.
(2) The directions of principal strains coincide with those of the principal stresses.
(3) The maximum shear stress at each point is equal to a specific constant in the plastic region.

Saint-Venant is famous for his principle in the strength of material that states that except in the immediate vicinity of the points of application of the load, the stress distribution may be assumed independent of the actual mode of application of the load as long as loadings are statically equivalent. This principle is conveniently used to find out the stresses far away from the load. In the immediate vicinity of the load, the stresses can be determined using advanced theoretical or experimental methods (Beer et al. 2004). Von Karman carried out compression test on marble under high pressure and results were published in 1911.

Johann Bauchinger (1833–1893) found that the yield stress in compression after plastic deformation was significantly lower than the initial yield stress in tension. Bauchinger conducted a lot of uniaxial loading experiments with his own designed extensometer. The lowering of the yield stress in reversed loading is caused by the residual stresses (at the microscopic scale) left in the material after unloading. In many metals, this effect is small.

A criterion alternative to Tresca criterion is von Mises criterion. In terms of principal stresses, this criterion states that at the onset of yield,

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_Y^2. \tag{3.14}$$

This criterion was first proposed by M.T. Huber (1872–1950) in 1904; however it was unnoticed for about 20 years as it was written in Polish language. Huber has developed this criterion based on a number of experiments. In 1913, Richard von Mises (1883–1953) developed this criterion on the basis of mathematics. R. von Mises was born in Lemberg (now in Ukraine) and graduated in mathematics from Vienna University of Technology. Hencky (1924) introduced the paper of Huber and derived the yield criterion on the basis of distortion energy. In 1925, Lode conducted experiments on thin tubes subjected to internal pressure as well as axial force. The materials chosen were iron, copper and nickel. The effect of intermediate principal stress on the yielding was studied. It was observed that the yielding behavior of metals is closer to von Mises criterion, whilst Tresca criterion is more conservative. In 1933, G.L. Taylor and H. Quinney also conducted experiments on thin tubes subjected to axial load. However, they applied twisting moment instead of internal pressure. The materials chosen were steel, copper and aluminum. They also confirmed that material behavior in yielding is more closely represented by von Mises criterion. In 1937, Arpad L. Nadai (1883–1963) showed that this criterion could be stated as follows: The yielding occurs when the shear stress on the octahedral plane in the space of principal stresses reaches a critical value. An octahedral plane is equally inclined to all the principal planes. Nadai was born in Hungary and graduated from Budapest University of Technology.

Tresca and R. von Mises criteria are for isotropic materials. In 1948, Rodney Hill provided a quadratic yield criterion for anisotropic materials. A special case of this criterion is von Mises criterion. In 1979, Hill proposed a non-quadratic yield criterion. Later on several other criteria were proposed including Hill's 1993 criterion. Rodney Hill (1921–2011) was born in Yorkshire, England and has tremendous contribution in the theory of plasticity.

Apart from yield criterion, one is interested in the constitutive relations. In the elastic constitutive relation, the stress is related to strain; however in the plastic constitutive relation stress can be related to strain-rate or strain-increment. In 1872, M. Levy used an incremental constitutive equation, which was later proposed by von Mises. Levy's paper was not known outside France. Levy-Mises relation considers that the increments of plastic strain increments are in proportion to deviatoric components, i.e.,

$$\frac{\mathrm{d}\varepsilon_1^p}{S_1} = \frac{\mathrm{d}\varepsilon_2^p}{S_2} = \frac{\mathrm{d}\varepsilon_3^p}{S_3}, \tag{3.15}$$

where S_i are the principal deviatoric stress components. Prandtl (1924) developed the relations including elastic part for plane strain case and Reuss (1930) did it for the general case. It is assumed that total increment in strain is the sum of increments in elastic and plastic strain. Thus,

$$d\varepsilon_i = d\varepsilon_i^p + d\varepsilon_i^e. \tag{3.16}$$

Inversion of Prandtle-Reuss equations was carried out by Hill in around 1950.

Apart from macroscopic observations, attempts were being made to understand microscopic behavior of plasticity. In 1923, Percy Williams Bridgman (1882–1961) invented a method to make a single crystal of metal by pulling it out of molten metal. He extensively studied the behavior of metals under high hydrostatic pressure. In 1946, he received the noble prize in physics for his work on high pressure physics. Taylor (1934), Polanyi (1934) and Orowan (1934) independently proposed the sliding mechanism by crystal defects, i.e., dislocations. The existence of dislocation was proved in 1950, after electron microscopy was invented. First person to recognize it experimentally was K. Yamaguchi. M. Polanyi (1891–1976) made contribution to crystallography. In 1938, he formed the Society for the Freedom of Science.

3.9 Relativistic and Quantum Mechanics

Relativistic and quantum mechanics do not find much application in conventional mechanical engineering. Here, they will be discussed very briefly. Albert Einstein (1879–1955) showed that Newtonian mechanics has its limitation. He observed that speed of light is same for all inertial observers regardless of their velocity or the velocity of the source of light. The implication of this is that events that occur simultaneously for one observer can occur at different times for other observers. Prior to Einstein, it was agreed that distance between the places of events depends on the observer, but not the time. Einstein discovered that there is no absolute time. It also depends on the state of motion. In Newtonian mechanics, space and time are totally unrelated concepts. In relativistic mechanics, they are related. Some interesting consequences of relativistic mechanics are as follows. An object cannot exceed the velocity of light in vacuum, which is 3×10^8 m/s. As the velocity of an object increases, it appears shorter. Its mass increases and hence it becomes difficult to accelerate such an object. Time clock also moves slower in an inertial frame moving with high velocity. These effects will be experienced only when an object approaches the velocity of light. For most of the practical situation, Newtonian mechanics is good enough.

For very tiny objects, such as electron, quantum mechanics is needed. Max Planck (1858–1947) is considered as the father of quantum mechanics. Salient point of quantum mechanics is that all matters and energy exhibit both wave-like and particle-like properties. If the size of the object is large, its wavelength will be too small to be observed. Also, there is a famous uncertainty principle that states that as one makes more precise measurement of the position of an object, the uncertainty in its momentum increases.

3.10 Conclusion

It is observed that in the beginning studies in the mechanics were concerned with rigid body dynamics. Aristotle pioneered to develop the theoretical foundation of dynamics. However, most of his theories are proven wrong now. Archimedes contributed to statics including fluid-statics and his many findings are still valid. Aristotelian mechanics was uprooted by Galileo. However, the proper laws of mechanics were put forth by Newton. After Newton, rigid body mechanics reached almost saturation and focus shifted to strength of materials including plasticity theory. In the beginning of twentieth century Newtonian mechanics was challenged by relativistic mechanics and quantum mechanics, but these could not overthrow Newtonian mechanics. For practical range of sizes and velocities, Newtonian mechanics is good enough.

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Chapter 4
History of Thermodynamics and Heat Transfer

Abstract Thermodynamics and heat transfer became important for mechanical engineers since the advent of steam engines. Sadi Carnot is considered as the father of thermodynamics. However, seeds of thermodynamics were sown before, particularly during the time of Boyle. There are four important laws in thermodynamics. Thermodynamics finds applications in many fields of mechanical engineering, e.g., automobiles, power plants, and refrigeration and air-conditioning. Heat transfer started much earlier. Newton provided a law of cooling. Heat can be transferred via three modes—conduction, convection, and radiation. Earlier only physicists and mathematicians were working in the area of heat transfer. Nowadays, heat transfer is a very important subject of mechanical engineering.

Keywords Thermodynamics · Heat · Work · Energy · Entropy · Enthalpy · Joule · Engine · Carnot · Heat transfer

4.1 Introduction

Thermodynamics is the science that studies the relationship between heat, work, and energy. It is basically the physics behind energy conversion through heat and work. Thermodynamics, being one of the oldest and most important subjects in science, has a long history of evolution to have reached its present stage. Development of thermodynamics had to deal with many misconceptions arising due to human ignorance of the nature of heat and its different manifestations. The basic laws and principles of thermodynamics were established by a number of great scientists as a result of their relentless research work through the centuries. Based on these laws and principles, many important inventions were made in various fields of engineering and technology, e.g., steam engine and internal combustion engine that led to modern civilization and better lifestyle of mankind. In statistical thermodynamics, the attention is paid on individual molecules of a matter. Macroscopic thermodynamics is only concerned with the effects of many molecules. In mechanical

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engineering, macroscopic thermodynamics finds more application, and the word thermodynamics will connote macroscopic thermodynamics.

Heat transfer is concerned with the transfer of heat from one body to another body or surroundings. Newton is the first person to analyze the transfer of heat in 1701. In the beginning, heat transfer was the subject of physicists and mathematicians. It came to mechanical engineering much later. This chapter will discuss the brief history of thermodynamics as well as heat transfer.

4.2 Developments in Thermal Science Before the Period of Sadi Carnot

Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference. Ancient Greeks associated heat with fire. Around 500 BC, the Greek philosopher Heraclitus of Ephesus (535 BC–475 BC) became famous as the 'flux & fire' philosopher by his proverbial quote 'all things are flowing.' He argued that three principal elements were fire, earth, and water from which all the substances of the universe were made of. He claimed that heat is associated with the motion. Although kinetic theory also associates heat with motion, Heraclitus's argument is not sound from modern perspective. He argued that all living creatures are warm due to their motion, while the dead bodies are cold. Democritus gave a vague atomistic description of the soul, viz. 'Soul is built from thin, smooth and round atoms, similar to those of fire.' It is interesting to note that Sanskrit word for the soul is 'atma,' which is very similar to 'atom.'

Abu Rayham Biruni (973–1038) known as Al-Biruni born in modern day Uzebekistan was a great scholar of medieval Islamic era. He stated that the causes of heat are movement and friction. The theory that heat is a form of motion of the atoms and molecules of a substance was supported by many philosophers and scientists in the seventeenth century. Notable scientist Francis Bacon (1561–1626) also considered heat as a kind of motion. In 1620, Francis Bacon wrote in his book 'Novum Organum Scientiarum' that 'the very essence of heat, or the substantial self of heat, is motion and nothing else' (https://www.sussex.ac.uk/webteam/gateway/file.php?name=a-thermodynamicshistory.pdf&site=35). Robert Boyle and his colleague Robert Hook opined that heat is the motion of elementary particles. In 1669, J.J. Becher (1635–1682) established Phlogiston theory that was developed by G.E. Stahl (1659–1735). In Phlogiston theory, the heat is associated with an undetectable substance called phlogiston that is driven out from the material when it is burnt. This theory was refuted in 1783 by Lavoisier (1743–1794) who proposed caloric theory. In caloric theory, the heat is considered as a weightless and invisible fluid that flows from hot body to cold body. Finally, widely accepted kinetic theory replaced the caloric theory of heat in the nineteenth century.

Since the ancient period, there have been attempts to measure heat. Philo of Byzantium (280 BC–220 BC) mentioned about a heat sensing element. Hero of

Alexandria (10 AD–70 AD) observed that water level in a container rises on heating and comes down while cooling. Galileo made a thermometer/thermoscope in 1597. It works on the principle of change in the pressure of gas upon heating and was used to measure the difference between the two temperatures. Joseph Black (1728–1799), a Scottish physician and chemist, first put forward the concept of latent heat of water and initiated quantitative measurements of heat. Latent heat is the energy absorbed by the matter in constant temperature process involving change in physical state, e.g., transformation of ice to water. He was of the opinion that when a material is heated, some matter (heat) is added to it, and when cooled, that matter (heat) is removed. Thus, heat was assumed to be a matter/fluid that flew from hot to cold body. Based on Joseph Black's concept, an ice calorimeter was used by Antoine Lavoisier and Pierre Simon Laplace in 1783 to measure the heat produced from chemical reactions. Thus, the first quantitative research on heat conversion and heat transfer was initiated. The term 'caloric' (meaning heat) was coined by Guyton de Morveau and Antoine Lavoisier in 1789. Untill then, 'caloric' or heat was assumed to be a substance/fluid that would flow from a hot body to a cold body as believed by many scientists. In 1798, Benjamin Thompson and Count Rumford finally proved by their famous cannon boring experiments that heat was not a substance/fluid that flow from a hot body when heated, rather it was the result of conversion of mechanical work. The kinetic theory that heat is a form of motion of the atoms and molecules of a substance started to replace 'caloric' theory by the end of the nineteenth century.

The idea of converting heat to work dates back to first century BC when the Greek engineer Hero of Alexandria developed a spherical device 'aeolipile' which was heated over a fire to produce steam from the water within the sphere. The steam emerging from vents of the heated sphere made the sphere rotate. Although at that time this device was invented as a toy, it illustrated the basic principle of converting heat into work. Originally, the science of thermodynamics evolved with the efforts to build different types of engines, in particular steam engines by various scientists. The German scientist Otto von Guericke built a steam vacuum pump in 1650 followed by a device (a bone digester) made by Denis Papin in 1679 where steam was used to generate high pressure. Dennis Papin experimented with condensed steam as a source of power. The 'pulsometer pump' built by Thomas Savery in 1698 was a steam-operated pump used for excavation in mines. Thomas Newcoman first developed a practical steam engine with a piston and cylinder in 1712 for raising water. The modified version of the Newcoman's engine with a separate condenser was designed and patented by James Watt in 1781. Thus, several devices were designed in the seventeenth century and eighteenth century where heat was added to produce steam which in turn was used to do some work. However, the science behind the working principles of these devices were not established and understood by people. With the ongoing developments of steam engines, there were increasing research on calorimetry and the amount of heat produced from burning coals. The period of Industrial Revolution, 1750–1850, brought in tremendous advances in all spheres of science and technology including the birth and development of thermodynamics. Gradually, there were better understanding of heat transfer phenomena, concepts of latent heat, phase change of matter due to heat addition or subtraction, ideal gas laws, and calorimetry leading to establishing laws and principles of thermodynamics. The name ‘thermodynamics’ was coined by the British scientist Lord Kelvin in circa 1854.

Study of heat transfer gained importance in different fields of science as it was an all encompassing phenomenon. Ideal gas laws were formulated relating to temperature, pressure, and volume of gases by famous scientists. Robert Boyle (1627–1691) provided a law that relates the pressure and volume of a gas. It is stated as follows:

> For a confined gas held at a constant temperature, the product of pressure and volume is a constant.

Suppose a cylinder contains 1 m^3 gas with a piston at the top. If we move down the piston to make the volume of the gas as 0.5 m^3, its pressure will get doubled, provided the process is performed slowly such that the heat can escape and temperature does not rise. We know that Boyle’s law is applicable for an ideal gas only. Robert Boyle is regarded as the father of the modern chemistry.

Charles (1746–1823) law states that when the gas is heated at constant pressure, it expands and increase in the volume is proportional to the increase in temperature. This law was published by a philosopher Joseph Luis Lussac in 1802. The modern statement of Charles is as follows:

> For a fixed mass of gas at constant pressure, the volume is directly proportional to the Kelvin temperature.

It is to be mentioned again that it is the modern form of the Charles law as the Kelvin scale was invented much later. Two laws of Gay-Lussac are popular. The first is called the law of combining volume and is stated as

> The ratio between the volumes of the reactant gases and the products can be expressed in simple whole numbers, when all the volumes are measured at the same pressure and temperature.

For example, when two volumes of hydrogen and one volume of oxygen are combined, two volumes of water vapor are produced. Volume of water vapor is twice the volume of oxygen and same as the volume of hydrogen. The second law of Gay-Lussac, also called Amonton’s law, is stated in the modern form as follows:

> The pressure of a gas of fixed mass and fixed volume is directly proportional to the gas’s absolute Kelvin temperature.

Amonton’s law, Charles law, and Boyle’s law combined together amount to ideal gas law. The ideal gas law is described by the following equation:

$$pv_m = R_m T, \tag{4.1}$$

where p is the pressure of the gas, v_m is the molar specific volume in m^3/g mol, T is the temperature in Kelvin, and R_m is the universal gas constant whose value is 8.314 J/mol K. Dividing Eq. (4.1) by the molecular weight of the gas,

$$pv = RT, \tag{4.2}$$

where v is the specific volume of the gas in m^3/kg and R is the characteristic gas constant, whose value for the air is 0.287 kJ/kg K.

In seventeenth century and eighteenth century, several scientists developed thermometers as well as temperature scale. In 1665, Christiaan Huygens (1629–1695) suggested to use the melting and boiling point of water as reference temperature. In 1724, German physicist and glassblower Daniel Gabriel Fahrenheit (1686–1736) developed a thermometer that used expansion of mercury in a glass. He also developed a Fahrenheit scale in around 1724. He used 3 reference temperatures. An equilibrium temperature of ice, water, and ammonium chloride salt was assigned 0 °F. Freezing point of water was assigned 32 °F, and normal human body temperature was assigned 96 °F. Nowadays, Fahrenheit scale uses the reference of freezing point of water as 32 °F and boiling point as 212 °F. Thus, the range between the freezing point and boiling point of water is divided into 180 parts. With the new scale, the normal body temperature comes out as 98.2 °F.

Anders Celsius (1701–1744) produced a thermometer with a standard scale in 1742. In the modern Celsius scale, the freezing point of the water is taken as 0 °C and boiling point as 100 °C. The relation between Celsius and Fahrenheit scale is expressed as follow:

$$\frac{C}{5} = \frac{F - 32}{9}. \tag{4.3}$$

A rigorous scientific study on heat transfer started from the late seventeenth century. In 1686, Edmund Halley (1656–1742) identified the fact that warm air rises up. In 1701, Isaac Newton provided law of cooling. It states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature. It was pointed out after about 100 years that this law is correct for low-temperature difference only. In 1738, Daniel Bernoulli (1700–1782) published his book Hydrodynamique where he showed that the temperature changes as square of particle velocity. In 1771, Carl Wilhem Scheele (1742–1786) distinguished three types of heat transfer—conduction, convection, and radiation. Benjamin Thompson and Count Rumford (1753–1814) studied frictional heat while boring the cannon. In 1785, J. Ingen-Housz (1730–1799) observed that some materials are good conductors of electricity, while some are insulators. It was then realized that the thermal conductivity of the materials may also differ. Swiss physicist Pierre Prevost (1751–1809) showed in 1791 that all bodies radiate heat. Jean Baptiste Joseph Fourier (1768–1830) formulated law of heat conduction in 1807. It was not accepted in peer review. Finally, Fourier published it in a monograph in 1822. Fourier's law of heat conduction states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. In one-dimensional rod, the rate of heat flow can be expressed in the form of the following equation:

$$\dot{Q} = -kA\frac{\mathrm{d}T}{\mathrm{d}x}, \tag{4.4}$$

where k is the thermal conductivity of the material and A is the cross-sectional area perpendicular to the direction x.

4.3 Father of Thermodynamics: Sadi Carnot (1796–1832)

Nicolas Léonard Sadi Carnot, the French engineer and physicist, was born in Paris in 1796. His father, Lazare Nicolas Marguerite Carnot, was in the French military service. Sadi Carnot is considered as the founder of modern thermodynamics. Famous for his invaluable contributions to science and thermodynamics, Sadi Carnot was honored with the title 'Father of Thermodynamics.' Some of his noteworthy contributions to thermodynamics are the concepts of Carnot heat engine, Carnot cycle, Carnot's theorem, Carnot efficiency, and reversible cycle.

Sadi Carnot had the privilege to be educated in the highly esteemed École Polytechnique in Paris. In 1812, he was admitted to the prestigious institute and had great scientists such as Joseph Louis Gay-Lussac, Siméon Denis Poisson, and André-Marie Ampère as his teachers. After graduating from École Polytechnique, Carnot completed a 2-year course in military engineering from École du Génie at Metz. Following in his father's footsteps, Carnot joined the French Army after graduation as a military engineer. Carnot developed a keen interest in the theory of gases and tried to solve related industrial problems. By the time Carnot graduated, the steam engines were commercially available. During his visit to Magdeburg, Germany, in 1821 to meet his father, the father–son duo was engrossed with the theory, working and functioning of a newly arrived steam engine in the town. These early steam engines were crude and used high-pressure steam, the condenser was eliminated, and steam was directly exhausted to the atmosphere. But, there were reduction in weight, size, and cost and increase in power compared to the earlier models operating at atmospheric pressure. However, the problem of determining the efficiency of a steam engine was still not solved which attracted the interest of young Sadi Carnot. This interest led to several epoch-making scientific contributions by Sadi Carnot that enriched and established thermodynamics as a key branch of science.

Returning to Paris, Carnot concentrated in developing a theory for working of steam engines. His objective was to determine the amount of mechanical work obtained from burning a given amount of coal in a steam engine. His experiments and research focused on improving the efficiency of steam engines which was only about 3 % at that time. By that time, steam engines were used to transport coal and there were continuous efforts for their improvement. The improved versions with high-pressure steam gave higher mechanical work, and the high pressure of steam was thought to be the cause behind higher efficiency. Therefore, scientists basically tried to find the range of steam pressure and its effect on efficiency. Sadi Carnot concentrated on solving two aspects of steam engine: firstly, whether there was a limit to the mechanical work available from a heat source, and secondly, whether the efficiency of steam engines can be improved by using working substance other than steam. Basically, he tried to find a way to get the maximum amount of mechanical work from a given amount of heat. The first breakthrough came when Carnot published the results of his relentless research in his book 'Reflections on the Motive Power of Fire' in 1824. Although Carnot based his research on steam engines, the results were applicable to all heat engines. He showed that no heat engine can produce work without heat flowing from a hot body (the boiler) to a cold body (the condenser). The mechanical work produced by a heat engine is equal to the net heat gain by the engine. For example, if a boiler gives 10 kJ heat to the steam and heat dissipated to condenser is 4 kJ in a given time, the work done will be 6 kJ. He developed the theory behind an ideal heat engine that worked in a cycle in several stages and finally came back to the initial conditions of temperature, pressure, and volume. His ideal heat engine cycle was later called as Carnot cycle. Moreover, he introduced the concept of reversibility, i.e., the possibility of going around a cycle in a reversible manner stage by stage maintaining the equilibrium. He showed that the maximum amount of mechanical work can be obtained with the working substance taking heat from a heat reservoir and rejecting heat to another heat reservoir at a lower temperature when all the processes undergone by the working substance (e.g., expansion, compression, heat addition, and heat rejection) are reversible processes. For example, a heat engine with steam as working substance takes heat H_S from a hot reservoir (steam boiler), does work W, rejects heat H_R to a cold reservoir (condenser or atmosphere), and returns to its original condition, and the cycle can be repeated indefinitely. Now, supposing all these processes are reversible, if work W is done on the engine in each cycle, the engine will be able to run in the reverse direction extracting heat H_R from the cold reservoir and delivering heat H_S to the hot reservoir. Thus, if an engine operating between the same two reservoirs can be more efficient (*i.e.*, can produce work W from heat lower than H_S), it could be made to drive the reversible engine backward. Therefore, the combined engines in each cycle will deliver more heat to the hot reservoir than taken from it, thus enabling continuous transfer of heat from a colder to a hotter body. He concluded from his thought experiments with ideal heat engine that no engine can be more efficient than a reversible engine when they both work within the same range of temperature which was later known as Carnot's theorem. Carnot's theorem states that among all heat engines operating between a given temperature source and a given constant temperature sink, none has higher efficiency than a reversible engine. A corollary of Carnot's theorem is that the efficiency of all reversible heat engines operating between the same temperature levels is the same. The idea that heat cannot be transferred from a colder to a hotter body without any external aid was an important aspect of the conclusion that led to the formulation of the second law of thermodynamics at a later point of time.

Sadi Carnot established the fact that the maximum efficiency of a heat engine is governed by the difference of temperature of steam entering from the boiler and exhausted to the atmosphere. It is not dependent on the properties of steam. Therefore, focus should be in increasing steam temperature rather than steam pressure for higher efficiency. Moreover, his research proved that efficiency did not depend on the nature of the working substance (steam), rather depended on the highest and the lowest temperature of the working substance. Carnot assumed that there was no friction and heat conduction among the parts of an engine at different temperatures to attain maximum efficiency of a heat engine. The conduction of heat between bodies was an irreversible process and had to be eliminated to achieve maximum efficiency of a heat engine. He was of the opinion that the maximum amount of work could be extracted from an engine when it operated reversibly; the efficiency of such an engine is defined as the ratio of the work done to the heat supplied, and efficiency depended only on the two temperatures between which it operated (https://www.sussex.ac.uk/webteam/gateway/file.php?name=a-thermodynamicshistory.pdf&site=35). His ideal heat engine provided a standard against which the efficiency of an operating engine could be measured with the knowledge that friction, heat dissipation, and other losses would keep the actual efficiency lower than the ideal Carnot efficiency. Carnot also initiated the research on finding the mechanical equivalent of heat. He compared the work done by the flow of heat from higher to lower temperature to the work obtained from the water flowing from a waterwheel. Although he could not arrive at a mathematical expression for mechanical equivalent of heat, based on his theory, other scientists formulated it later.

Sadi Carnot's analytical research on heat engines played a pivotal role in the history of thermodynamics. His efforts toward developing a theory for steam engine established the fundamental scientific principles behind the operation of a heat engine. The concept of reversibility and the fact that mechanical work could not be obtained if there was no temperature difference were the two very important findings for thermodynamics. His analysis for engine efficiency and other findings laid the foundations for the fundamental laws of thermodynamics and many important future discoveries. It was a great loss to the scientific world that Sadi Carnot died at an early age of 36 years suffering from cholera in 1832 (http://www.thefamouspeople.com/profiles/sadi-carnot-550.php). Unfortunately, many of his scientific findings were buried with him fearing contamination.

4.4 Carnot Cycle

Sadi Carnot's most valuable contribution to thermodynamics is Carnot's ideal heat engine operating with Carnot cycle. His works on ideal heat engine provided the foundation for quantitative mathematical formulation of Carnot efficiency based on Carnot's theorem. However, Carnot's research findings were not well known until another scientist Benoit Pierre Emile Clapeyron followed in his footsteps and experimented with the change in pressure and volume of the processes of a cycle and its effect on work done. Clapeyron developed Carnot's idea of the efficiency of a reversible engine into mathematical form based on Carnot's theorem. He established that the efficiency of a reversible engine was a function of the temperatures of the two heat reservoirs—the source and the sink (http://www.thermohistory.org/historyoverview.pdf). Scientists Clausius, Lord Kelvin, Joule, and many others carried on research based on Carnot's theorem, and it was shown that the Carnot efficiency, η, of a reversible engine is given by

$$\begin{aligned}\eta &= \text{(Work done)/(Heat input)}\\ &= \text{(Heat received} - \text{Heat rejected)/(Heat received)}\\ &= \text{(Intake temperature} - \text{Exhaust temperature)/(Intake temperature).}\end{aligned} \tag{4.5}$$

It was established that no engine operating between two given temperatures (intake and exhaust temperature) can be more efficient than a Carnot engine operating between the same two temperatures. Moreover, efficiency of all the Carnot engines operating between the same two temperatures is same. It depends only on temperature and is independent of the working fluid. Carnot engine efficiency provided a standard to compare efficiencies of all other practical engine cycles, *e.g.*, Rankine cycle, Otto cycle, Diesel cycle, and Stirling cycle. Carnot cycle shows that a heat engine cannot convert all the heat into work even under ideal condition, and some heat has to be rejected. The greater is the temperature difference between the high-temperature heat source and low-temperature heat sink, the higher is the Carnot efficiency. The Carnot cycle consists of four reversible processes. The pressure–volume (P–V) diagram and temperature–entropy (T–S) diagram of these processes are shown in Fig. 4.1. The name entropy was coined by Rudolf Julius Emanuel Clausius (1822–1888). The increase in entropy of a system is equal to the ratio of heat supplied to the system in a reversible process and the

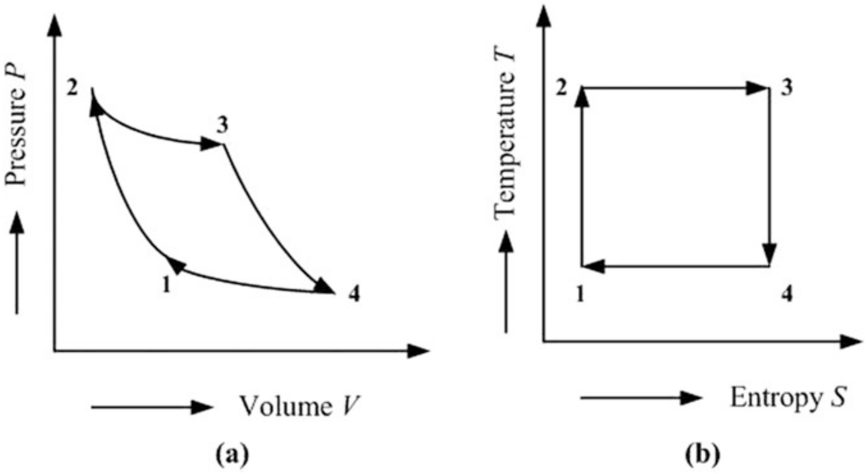


Fig. 4.1 Carnot cycle in **a** P–V and **b** T–S diagram

temperature of the system. If a system at temperature T goes from one state to the other by absorbing heat Q in a reversible manner, its entropy will increase by Q/T. The four reversible processes of a hypothetical Carnot cycle are as follows:

- Process 1–2 is reversible adiabatic (isentropic) compression of the working fluid, thus raising its pressure and temperature when the piston moves upward in a frictionless cylinder
- Process 2–3 is reversible isothermal heat addition by exposing the cylinder head to a high-temperature heat source without change in the temperature of the working fluid
- Process 3–4 is reversible adiabatic (isentropic) expansion of the working fluid when the heat source is removed and the piston moves downward
- Process 4–1 is reversible isothermal compression of the working fluid and heat rejection to a heat sink when the piston moves upward to the initial starting point 1.

From Fig. 4.1, it can be seen that maximum Carnot efficiency of a reversible engine is given by

$$\text{Carnot efficiency} = \eta_{\text{Carnot}} = \frac{T_2 - T_1}{T_2}. \tag{4.6}$$

Some amount of heat is added at constant temperature T_2 (or T_3) and some amount of heat is removed at constant temperature T_1 (or T_4). The difference gives the work done by the engine. From the T–S diagram, it is evident that if the temperature of the heat source is increased (i.e., T_2 is raised), or the temperature of the heat sink is decreased (i.e., T_1 is lowered), the area of the rectangle is increased indicating increase in work done. Therefore, Carnot deduced that thermal efficiency of an engine can be increased by increasing the temperature of heat source and/or decreasing the temperature of heat sink.

Thus, Sadi Carnot's analysis of Carnot cycle provided the theory for the formulation of the first and the second law of thermodynamics. His concept is that for a system undergoing a cycle, the net heat transfer is equal to the net work done, which led to the first law of thermodynamics. Similarly, the concept that a heat engine cannot convert all the heat absorbed from a heat source at a single temperature into work even under ideal condition led to the second law of thermodynamics. Carnot cycle efficiency gives the idea about the maximum theoretical efficiency of an engine. Sadi Carnot was rightly honored with the title 'Father of Thermodynamics' for his invaluable contribution to thermodynamics.

4.5 Salient Topics of Thermodynamics

Sadi Carnot's quest for the theory behind the working principle of steam engine paved the way for scientific research on different aspects of heat, work, and energy. Gradually, thermodynamics evolved as a core branch of science with the formulation of its laws and principles. The invaluable contributions of several great scientists such as James Prescott Joule, Benoit Pierre Emile Clapeyron, Lord Kelvin (William Thomson), Rudolf Julius Emanuel Clausius, Julius Robert Mayer, Hermann Ludwig von Helmholtz, Josiah Willard Gibbs, and James Clerk Maxwell have made thermodynamics a popular and nearly perfect engineering science. W.J.M. Rankine (1820–1872) wrote the first book on thermodynamics in 1859 entitled 'Manual of Steam Engine and other Prime Movers.' Max Planck shaped the science of thermodynamics to its modern form (http://www.mhtl.uwaterloo.ca/courses/me354/past.html). He wrote a book entitled 'Treatise on Thermodynamics' in 1897. Some of the key developments in the evolution of thermodynamics are discussed in the following subsections.

4.5.1 The Mechanical Equivalent of Heat

One of the main objectives of Sadi Carnot's research was to determine the amount of mechanical work obtained from a given amount of heat. He initiated the research on finding the mechanical equivalent of heat. In his book 'Reflections on the Motive Power of Fire' (1824), Carnot argued that the mechanical work obtained from a waterwheel and that from a steam engine are analogous. However, Carnot believed in the caloric theory of heat being a fluid that flowed from a hot body to a cold body. He compared the work done by flow of heat (a fluid as per his opinion) from higher to lower temperature to the work done by flowing water from a height from waterwheel. Although Carnot did not arrive at a concrete formula for mechanical equivalent of heat, he gave a direction for further research. James Prescott Joule (1818–1889), an English scientist, performed a series of experiments relating to mechanical and electrical systems in his own brewery to understand the relations among heat, work, temperature, and pressure (Lewis 2004). His efforts finally resulted in obtaining a reasonable value for mechanical equivalent of heat in 1843. From his famous paddle wheel experiment involving a falling weight to rotate a paddle wheel in a barrel of water, Joule deduced that the quantity of heat needed to raise the temperature of one pound of water by one degree Fahrenheit is equal to mechanical work needed for raising 838 lb to a height of one foot (Armytage 1961). In SI unit, the mechanical equivalent of heat is given as 1 kcal being equal to 4.184 kJ of work. Joule has found the value of mechanical equivalent of heat as 4.186 J/cal, which has less than 1 % error from the modern notion. Joule's experiments also laid the foundation for the first law of thermodynamics by establishing the equivalence of work and heat. Joule was considered as the founder of experimental thermodynamics, and the SI unit for work 'joule' (J) was named in honor of this great scientist.

4.5.2 The First Law of Thermodynamics

The first law of thermodynamics is essentially the law of the conservation of energy that energy cannot be created or destroyed, but can be converted from one form to another. The Carnot's theorem as proposed by Sadi Carnot, that for a system undergoing a cycle the net heat transfer is equal to the net work done, led to the first law of thermodynamics. Inspired by Carnot's findings, James Prescott Joule established the equivalence of work and heat based on a series of experiments in 1843. Julius Robert von Mayer (1814–1878), a contemporary German physician, also established the law of conservation of energy from his observations relating to human body, food consumption, physical work, and heat and published his work in 1842 (http://www.mhtl.uwaterloo.ca/courses/me354/mayer.html). By the middle of nineteenth century, it was widely accepted that heat, work, and energy are identical and only differed in their forms which led to the formulation of the first law of thermodynamics. Contributions of James Prescott Joule, Benoit Clapeyron, Lord Kelvin, and Rudolf Clausius were invaluable for the formulation of first law of thermodynamics.

The first law states that the total energy of an isolated system remains constant regardless of changes within the system. An isolated system does not interact with its surroundings. In a system where there is energy transfer, the energy transferred in various forms is equal to the change in its internal energy with the possibility of converting one form of energy into another. When there is heat transfer to a body, its internal energy is increased and it does some work. The difference in heat supplied and work done is stored as internal energy in the body. For a system undergoing a process, the change in internal energy of the system is numerically equal to the difference of net heat interaction and net work done during the process. Mathematically, first law of thermodynamics for a process is given by (Domkundwar et al. 1985; Nag 2010),

$$\int (\mathrm{d}Q - \mathrm{d}W) = \Delta E \tag{4.7}$$

where $\mathrm{d}Q$ is the heat transferred to the system, $\mathrm{d}W$ is the work done by the system, and ΔE is the internal energy of the system undergoing a process. In the above equation, $\mathrm{d}Q$ and $\mathrm{d}W$ are the path functions.

For a system undergoing a cycle, the net heat transfer is equal to the net work done. There is no change in its internal energy as the system returns to its initial state. Mathematically, first law of thermodynamics for a cycle is given by (Domkundwar et al. 1985; Nag 2010),

$$\oint (\mathrm{d}Q - \mathrm{d}W) = 0 \tag{4.8}$$

as net internal energy ΔE is 0 for a system undergoing a cycle. Here, $\mathrm{d}Q$ and $\mathrm{d}W$ have the same unit. If $\mathrm{d}W$ is in work units, Eq. 4.8 is expressed as

$$\oint \frac{\mathrm{d}W}{J} = \oint \mathrm{d}Q \tag{4.9}$$

where J is the mechanical equivalent of heat.

Thus, the first law of thermodynamics is the manifestation of the principle of conservation of energy in the form of heat and mechanical work. It states that heat transfer is equivalent to work done, but does not specify the direction of heat transfer and work done. The limitation of the first law was that it did not specifically give the direction of spontaneous natural processes. This limitation was overcome by the second law of thermodynamics.

4.5.3 The Second Law of Thermodynamics

The second law of thermodynamics was also rooted in the works of Sadi Carnot as found from his book ‘Reflections on the Motive Power of Fire’ published in 1824. His conclusions that a heat engine cannot convert all the heat absorbed from a heat source at a single temperature into work even under ideal condition and that heat cannot be transferred from a colder to a hotter body without any external aid were two important aspects that led to the formulation of the second law of thermodynamics. Clausius, Lord Kelvin, and other scientists incorporated Carnot’s ideas in the formulation of the thermodynamic laws and theories. The first formulation of the second law may be credited to both Clausius and Lord Kelvin at around middle of the nineteenth century. In 1848, Lord Kelvin defined an absolute temperature scale based on the Carnot cycle which was later named after him as Kelvin’s absolute temperature scale. In Kelvin’s scale, the zero point is 273.15 below that of the Celsius scale. In all the formulations of Carnot efficiency of an ideal heat engine, Kelvin’s absolute temperature scale is used. In 1850s, Clausius introduced the concepts of internal energy and entropy which was pivotal for the formulation and understanding of the second law of thermodynamics. In his book ‘On the Motive Power of Heat’ (1850), Clausius stated the second law from the fact that heat does not spontaneously flow from a cold body to a hot body (Garrison 1999). Clausius’s views were reconfirmed by the formulation of the second law by Lord Kelvin in 1851 (Garrison 1999). Another scientist Max Planck also stated the second law of thermodynamics in 1897 in the similar form as that put forward by Lord Kelvin.

In the discussions of the second law, Clausius introduced the quantity entropy (S) that remained unchanged over a cycle. Entropy is considered as a property that characterizes the state of a system in the same manner as pressure, volume, and temperature do. Clausius defined the change in entropy as a ratio of the heat intake or heat given out in reversible changes of a system to the absolute temperature at which the change takes place. Entropy may be defined as a property used to measure the quality of energy or irreversibility of a process. In other words, entropy indicates the amount of heat lost or turned into waste during a cycle. As efficiency of actual engine is always less than 1, $\mathrm{d}Q$ is not equal to $\mathrm{d}W$, and some wastage of heat or energy is incurred which can be explained with the idea of entropy. Change in entropy is a measure of such wastes or changes during conversion of heat to work. Clausius expressed entropy S as a function of heat and temperature as follows:

$$\mathrm{d}S = \frac{\mathrm{d}Q}{T}. \tag{4.10}$$

For a reversible cycle,

$$\oint \mathrm{d}S = 0. \tag{4.11}$$

For an irreversible cycle,

$$\oint \mathrm{d}S \geq 0. \tag{4.12}$$

As all the natural changes in the universe are irreversible, it may be concluded that the entropy of the universe is ever increasing. The concept of entropy is one of the most important concepts not only in thermodynamics but also in many fields of modern science. The second law of thermodynamics is also called the law of entropy. There is more than one statement of the second law of thermodynamics put forward by scientists as given below (Domkundwar et al. 1985; Nag 2010).

The famous Clausius statement is as follows: '*It is impossible to construct a device to work in a cyclic process whose sole effect is the transfer of heat from a body at a lower temperature to a body at a higher temperature*'. Clausius also stated the first and the second laws of thermodynamics combined together as '*The energy of the universe is constant*', and '*The entropy of the universe tends toward a maximum.*'

Kelvin–Planck statement of the second law of thermodynamics is as follows: '*It is impossible to construct an engine to work in a cyclic process whose sole effect is to convert all the heat supplied to it into an equivalent amount of work.*'

Both Clausius and Kelvin–Planck statements are related to each other, and violation of one leads to the violation of the other.

Another form of the second law of thermodynamics is as follows: '*It is impossible for heat energy to flow from a body at a lower temperature to a body at a higher temperature without the aid of external work.*'

Thus, the second law of thermodynamics overcame the limitations of the first law. The first law does not comment on the spontaneous direction of heat flow and does also not speak how much of a supplied heat can be converted into work. The second law helped to understand and formulate the theories of thermodynamics in a better way and paved the path for advanced research.

4.5.4 Third Law of Thermodynamics

The theory behind the third law of thermodynamics was initially formulated by Walther Nernst in 1906, which was known as Nernst theorem (https://www.sussex.ac.uk/webteam/gateway/file.php?name=a-thermodynamicshistory.pdf&site=35). The third law of thermodynamics was conceived from the fact that attaining absolute zero temperature is practically impossible. Lord Kelvin deduced this fact from the second law of thermodynamics with his study of heat transfer, work done, and efficiency of a number of heat engines in series. Kelvin's work was the foundation for the formulation of the third law. It can be stated as follows: '*Absolute zero temperature is not attainable in thermodynamic processes.*' Another noted scientist, Max Planck, put forward the third law of thermodynamics from his observations in 1913. It states that '*The entropy of a pure substance is zero at absolute zero temperature.*' Plank observed that only pure, perfectly crystalline structures would have zero entropy at absolute zero temperature. All other substances attain a state of minimum energy at absolute zero temperature as the molecules of the substance are arranged in their lowest possible energy state.

4.5.5 The Zeroth Law

The zeroth law originates from the concept of thermodynamic equilibrium. A system is said to be in thermodynamic equilibrium if no spontaneous change occurs in the properties of the system such as pressure and temperature even after a small disturbance. For equilibrium, there should be no chemical reaction and no velocity gradient and the pressure and temperature should be equal at all points. Such a system is in complete balance with its surroundings. If a body at a higher temperature comes into contact with another body at a lower temperature, to attain thermodynamic equilibrium, the higher temperature body will transfer heat to the lower temperature body until both attain and maintain the same temperature and stop further heat transfer to and from other bodies. The statement of the zeroth law is given as follows: '*If two systems are each in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other.*' When two bodies are in equilibrium, their temperatures will be same.

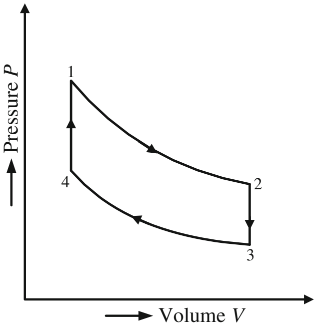
Scottish physicist and chemist Joseph Black was the first to perceive this law. James Maxwell stated the law of equal temperatures in 1871 in the following manner: ‘if when two bodies are placed in thermal communication neither of them loses or gains heat, the two bodies are said to have equal temperatures of the same temperature [and] are then said to be in thermal equilibrium.’ In 1931, Ralph Fowler stated as follows: ‘Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other’ (http://www.eoht.info/page/Zeroth+law+of+thermodynamics). The term zeroth law was first used in the book Fowler and Guggenheim (1939).

4.5.6 Various Thermodynamic Cycles

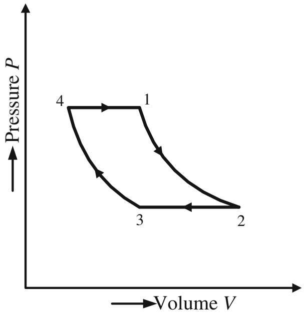
Sadi Carnot’s work on developing the theory behind the working of heat engines proved indeed revolutionary in the history of science. After quantitative formulations of his concepts were established by various scientists, new inventions based on his theory were designed and tested by famous scientists such as Nicolaus August Otto (1832–1891), Rudolf Diesel (1858–1913), Jean Joseph Lenoir (1822–1900), and William Rankine (1820–1872). There were continuous efforts to design new engines and increase engine efficiency by taking Carnot engine as the basis. The steam was replaced by air or other gases in most of these efforts. Air was mixed with some fuel, e.g., petrol, diesel oil, or gasoline, and used as working substance. The air cycle approximation used in these internal combustion engines is called the air standard cycle. Stirling cycle, Otto cycle, Diesel cycle, and Brayton cycles are some of the examples.

Robert Stirling (1790–1878) developed a hot air engine in 1845 with regeneration, and theoretically, the Stirling cycle efficiency is equal to Carnot efficiency. Jean Joseph Lenoir was a famous inventor who developed an internal combustion engine using illumination gas in 1860 and produced around 300 units producing up to 3 horse power (Garrison 1999). Internal combustion engines were patented as early as 1807, but they were commercially not successful. James Brayton developed the Brayton cycle in 1872 with gasoline as working substance. Nicolaus Otto drew idea from Lenoir’s design and developed a small four-stroke cycle internal combustion engine in 1878 which became very popular. Otto’s engine formed the basis for all modern petrol and gasoline engines. In 1881, Dugald Clerk developed a two-stroke cycle engine followed by another developed by Otto. Rudolf Diesel also used Carnot’s theories for his design of the diesel engine in 1892. His engine drew only air during suction and compressed it to a high pressure before fuel is added for combustion. In contrast, Otto cycle engine took in an air–fuel mixture during suction. As air is compressed to a high pressure and temperature of air is increased in Diesel cycle, its efficiency is more than Otto cycle efficiency. Diesel engines are widely used in vehicles and stationary applications.

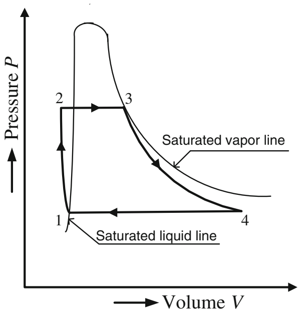
Figure 4.2 presents various thermodynamic cycles proposed in chronological order in pressure–volume diagram. Considering the ideal case, all the processes are reversible. In Stirling cycle, processes 1–2 and 3–4 are isothermal, while the other two processes are isochoric. As such the efficiency of this cycle is lesser than the



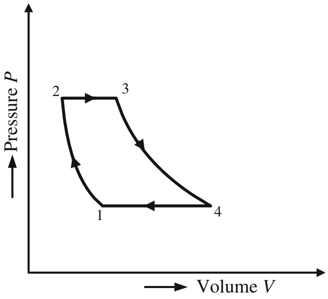
Stirling cycle (1827)



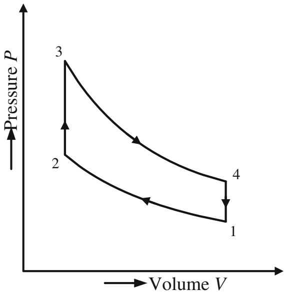
Ericsson cycle (1850)



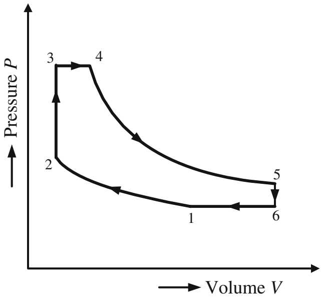
Rankine cycle (1872)



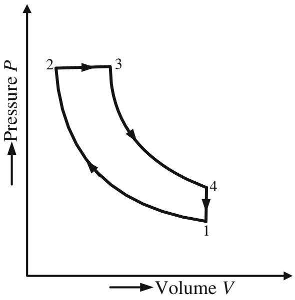
Brayton cycle (1872)



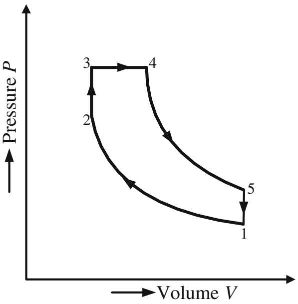
Otto cycle (1876)



Atkinson cycle (1882)



Diesel cycle (1890)



Dual cycle (circa 1906)

◄ **Fig. 4.2** Different thermodynamic cycles. Numbers in *bracket* indicates the approximate year in which they were proposed

efficiency of the Carnot cycle, but if the regeneration is employed that is the heat rejected during process 2–3 is supplied for process 4–1 and no other heat is added during this process, then the efficiency of the cycle approaches that of the Carnot cycle. This is because in that case, both heat rejection and addition will effectively occur at constant temperature. Ericsson cycle consists of two isothermal and two isobaric processes. Regenerative cycle has the same efficiency as the Carnot cycle. Rankine cycle is called a vapor power cycle. Process 1–2 is reversible adiabatic (isentropic) compression, and process 3–4 is isentropic expansion. Process 2–3 is isobaric heat addition, and process 4–1 is isobaric heat rejection. Brayton cycle is the air standard cycle for the gas turbine power plant. The air is first compressed adiabatically in process 1–2. The process 2–3 is constant pressure heat addition. Air expands adiabatically in process 3–4, and the constant pressure heat rejection takes place in process 4–1. The air standard Otto cycle consists of two reversible adiabatic processes and two reversible isochoric processes. The Atkinson cycle consists of the following processes: isentropic compression (1–2), isochoric heating (2–3), isobaric heating (3–4), isentropic expansion (4–5), isochoric cooling (5–6), and isobaric cooling (6–1). The air standard Diesel cycle consists of two reversible adiabatic processes: one reversible isobaric process and one reversible isochoric process. Dual cycle differs from Diesel cycle in the sense that part of heat addition takes places at constant volume and at constant pressure. It was first introduced by Russian–German engineer Gustav Trinkler (http://www.google.com/patents/US828352).

4.6 Further Developments: Transformation to Quantitative Science

The pioneering works of Sadi Carnot, Clapeyron, James Prescott Joule, Clausius, Lord Kelvin, and Max Planck laid the foundation of the science of thermodynamics. Inspired by the works of their predecessors, James Clerk Maxwell, Josiah Willard Gibbs, Ludwig Boltzmann, and others continued advanced research contributing to evolution of thermodynamics to its modern form.

James Clerk Maxwell first conceived the statistical basis of the second law of thermodynamics in 1871, and he is considered the founder of statistical thermodynamics. He was also famous for his electromagnetic wave theory and kinetic theory of gases. Maxwell derived the 'Maxwell Relations' which were mathematical formulations used for advanced study of thermodynamics. Ludwig Boltzmann continued with Maxwell's kinetic theory of gases and arrived at important conclusions regarding dissipation of energy and increase in entropy.

Boltzmann precisely defined the relationship between entropy and molecular motion in 1875. The American physicist Josiah Willard Gibbs is considered one of the most important founders of modern thermodynamics. It is for the contributions of Gibbs that knowledge and possibility of energy transformation are extended to all fields of science. In 1875, Gibbs published his research in the paper 'On the Equilibrium of Heterogeneous Substances' in which he describes the science of thermodynamics as heterogeneous systems with chemical reactions. One of his greatest contributions was the formulation of the Gibbs free energy equation that gave the amount of useful work obtained from a system. The concept of enthalpy (total heat) H and Gibbs energy G was conceived by Gibbs. He proved that enthalpy changes with change in heat, and for equilibrium condition, the Gibbs energy G should be in its minimum value. Two other scientists Helmholtz and Van't Hoff followed in the footsteps of Gibbs and arrived at similar conclusions of free energy and equilibrium. Thus, the science of thermodynamics has evolved over the centuries to reach its modern state since the day Leonardo da Vinci drew a design for a steam-driven cannon. Mankind owes these tremendous developments in thermodynamics to the relentless research of some of the greatest scientific minds of the world.

4.7 A Note on Energy and Exergy

Energy is manifested in many different forms in the universe, and it is difficult to give a common definition of energy. A body has to possess energy to do work; therefore, in general, energy can be defined as the ability to do work. Different forms of energy may be mechanical, chemical, electrical, nuclear, radiant, magnetic, hydel, thermal, geothermal, tidal, gravitational, kinetic, potential, and many more. It is believed that the word 'energy' originates from the greek word 'energeia' used by Aristotle in the fourth century BC that meant 'activity.' The notion that energy is related to mass and motion of the constituent particles was first conceived by Leibniz in the late seventeenth century and later supported by Isaac Newton, Thomas Young, and other scientists. The word energy was first used much later in 1802 by Thomas Young.

In ancient times, people depended on the energy of the Sun, wind, water, and animals to perform different types of work. Invention of steam engine was the first epoch-making event that made mankind free from dependence on locality and natural sources for energy, thus opening up a world of possibility. Steam engine was used in locomotives, carriages, and factories as a source of energy. Gradually, the equivalence of different forms of energy, work, and heat was proved by scientists based on their relentless research. The terms kinetic energy and potential energy were coined by Coriolis and William Rankine in 1829 and 1853, respectively. The science of thermodynamics, which is basically the physics behind energy conversion through heat and work, progressed. The law of conservation of energy that energy cannot be created or destroyed, but can be converted from one form to another was established by Julius Robert von Mayer in 1842 and subsequently by Helmholtz in 1847 independent of Mayer (http://www.mhtl.uwaterloo.ca/courses/me354/past.html). By the middle of nineteenth century, it was widely accepted that heat, work, and energy are identical and only differed in their forms. Contributions of Sadi Carnot, Josiah Willard Gibbs, James Prescott Joule, Benoit Clapeyron, Lord Kelvin, Rudolf Clausius, Max Plank, Walther Nernst, Jožef Stefan, and William Rankine were invaluable in the all encompassing science of energy, heat, and work. It was a historic event when Thomas Alva Edison used electrical energy to produce light from incandescent lamp in New York in 1880. Gradually, hydroelectric plants were used to generate electricity. Potential of fossil fuels was harnessed as a source of energy. With the advancement of science, the power of nuclear energy was discovered and tapped that unleashed a host of possibilities. Hydrogen fuel cell is explored as a source of energy; however, it poses the risk of accident by explosion. Worldwide energy consumption is increasing at an alarming rate and expected to increase by 57 % from 2002 to 2025 (Kostic 2007). In the present global scenario, exploring green and renewable energy sources has become inevitable due to exhaustion of fossil fuel energy sources, hazards associated with nuclear fuel energy and to reduce green house gases and global warming. Presently, renewable energy sources contribute around 13 % of total global primary energy supply (Johansson 2013). Solar, wind, small-scale hydel, geothermal, tidal, and biofuel sources of energy are some options that can be harnessed without damaging the climate and ecology of planet earth.

Exergy is the amount of available and useful energy that can be converted into work. The quantity exergy is based on thermodynamic concepts as thermodynamics deals with energy conversion as well as finding the minimum amount of energy required to do work. In a sense, exergy can be considered as a property of a system. Assessing the performance/efficiency of energy conversion plants is an important issue in the industry. Exergy mainly helps in calculating the conversion (energy to work) efficiency of a process or a system. Ideally, exergy is the amount of work that can be obtained from an amount of energy under ideal conversion conditions using reversible processes. Once the available energy/exergy of a system is converted into work, the system comes to equilibrium with the surroundings and its exergy is zero. Exergy and energy are same in case of kinetic energy, potential energy, electrical energy, solar energy, etc., where complete conversion of energy to work is possible using reversible conversion methods with no associated change in temperature and no entropic loss. Exergy analysis is more relevant for the conversion of thermal energy, chemical energy, radiation energy, etc., where there is heat release and temperature change that reduce the available energy for doing work. Exergy analysis gives a more accurate and useful analysis of energy conversion efficiency of a system. The concept of exergy was first introduced by Josiah Willard Gibbs which was called Gibbs free energy. He showed that for equilibrium condition of a system after doing maximum possible work, value of Gibbs free energy is the minimum. Gibbs published his findings in 1873 which provided the foundation for research to other scientists such as Helmholtz and Van't Hoff who contributed more knowledge in the topic (Gibbs 1873). The term exergy was coined much later by Zoran Rant (1904–1972) in 1956. Application of exergy analysis is found in natural resource utilization, ecology and sustainability, calculating energy conversion efficiency of a system, etc.

4.8 Key Developments in Heat Transfer

Heat transfer is the indispensible part of thermodynamics, and there is constant reference of heat transfer among different systems in thermodynamics. The seeds of the science of heat transfer were sown by Sir Isaac Newton with his historic law of cooling in 1701, when he published a paper in Latin entitled 'Scala Graduum Caloris' ('A scale of the degrees of heat'). However, his pioneering works were published before that in Principia in 1687 (Bergles 1988; Cheng and Fujii 1998). Basic heat transfer principles, viz. Newton's law of cooling, Fourier's law, and Stefan–Boltzmann law, are necessary in addition to first law of thermodynamics to find heat transfer rate in a system. The fields of heat transfer and thermodynamics progressed simultaneously as the scientific study on heat transfer starting from late seventeenth century continued till twentieth century with contributions from some great scientists. Advanced research continued based on the works of Sadi Carnot and his contemporaries.

Franz Grashof (1826–1893), the German professor of Mechanical Engineering, was renowned for his valuable lectures in theory of heat, strength of materials, and hydraulics. Grashof was given the honor of having a dimensionless number in the study of convective heat transfer named after him. An equation for heat exchanger design is also named after him. Grashof was the founding member of the Society of German Engineers.

The Austrian physicist Josef Stefan (1835–1893) started his research with the flow of fluid through tubes and in 1874 presented the solution for evaporation of liquid in a vertical tube over which a gas flew. His apparatus called Stefan tube was often used to find diffusion coefficients. Following in the footsteps of James Clerk Maxwell for finding thermal conductivity of gases, Stefan experimentally determined the thermal conductivity of air, hydrogen, nitrous oxide, methane, carbon monoxide, and carbon dioxide. Josef Stefan is better known for his contributions in radiation heat transfer in black body in association with his student Ludwig Boltzmann (1844–1906). In 1879, Stefan established experimentally that the total flux of energy radiated from a black body depended on the absolute temperature and is proportional to the fourth power of its absolute temperature. His finding was explained theoretically by Ludwig Boltzmann in 1884 in the form of Stefan–Boltzmann law.

Ernst Mach (1838–1916), the Austrian physicist and philosopher, was well known for his progressive views on scientific research. He was a true scientist in the sense that he did not accept the views and theories of science unless it was subjected to rigorous empirical verification. His review works on thermometry before and after Newton had great impact on modern science. Mach advanced the concept that all knowledge is derived from sensation. He rejected the concept of absolute time and space. This paved the way for Albert Einstein's theory of relativity (http://www.britannica.com/biography/Ernst-Mach). Ernst Mach served as a professor of physics in several prestigious institutions. Mach number which is used to express the speed of matter relative to the speed of sound is named after this famous physicist.

The contributions of Osborne Reynolds (1842–1912), the English engineer and physicist, are invaluable in the field of heat transfer and fluid dynamics. His works on condensation and heat transfer between solids and fluids were considered revolutionary for the design of boilers and condensers with higher efficiency. The practical approach to determine the heat transfer coefficient in turbulent flow was first proposed by Reynolds in the form of the Reynolds analogy in 1874 (Cheng and Fujii 1998). He is also credited for offering explanation on radiometer and an early formulation of the mechanical equivalent of heat. Osborne Reynolds was a professor in the University of Manchester. Reynolds number is named after him as he discovered the laminar-turbulent transition during fluid flow in a tube. At low Reynolds numbers, a flow is laminar, and it becomes turbulent at high Reynolds numbers. Reynolds original laminar-turbulent flow experimental setup was used by the students of University of Manchester till 1970s. Some of his other important contributions are the law of resistance in parallel channels in 1883, the theory of lubrication in 1886, and Reynolds equations for turbulent flow in 1894.

Ludwig Boltzmann (1844–1906), the Austrian physicist, is famous for his outstanding contributions to heat transfer, thermodynamics, statistical mechanics, and kinetic theory of gases. Boltzmann was a student of Josef Stefan and received his doctoral degree in 1866 under his supervision. The Stefan–Boltzmann law (1884) for black body radiation is the result of the associated work of Josef Stefan and Boltzmann in the field of heat transfer. Boltzmann's most significant works were in kinetic theory of gases in the form of Maxwell–Boltzmann distribution and Maxwell–Boltzmann statistics in classical statistical mechanics.

Leo Graetz (1856–1941), the German physicist, focussed on the research of heat conduction and radiation in the early stages of his career. Later, his extensive works and publications on magnetism and electricity contributed greatly to this field which was at its nascent stage at that time. Max Planck (1858–1947), the distinguished Nobel Prize winner in Physics (1918), was famous for introducing the quantum theory. In addition to his contribution to the formulation of second and third laws of thermodynamics, he extended his study to black body radiation. Max Planck is credited for solving the problem of predicting how the intensity of electromagnetic emissive power of a black body depends on the frequency of the radiation. He published his findings in 1901 that formed the initial formulation of quantum mechanics. Planck black body radiation law and the quantity Planck's constant are widely used in radiation heat transfer problems.

British Engineer Thomas Edward Stanton (1865–1931) worked in the field of fluid flow, friction, and the related heat transfer phenomenon. He had the honor of having the dimensionless Stanton number named after him which is the ratio of actual heat flux to the fluid to the heat flux capacity of the fluid flow. It is equal to the heat transfer coefficient of a fluid in forced convection divided by the product of the specific heat at constant pressure, the fluid density and the fluid velocity. Stanton assisted in Osborne Reynolds laboratory in the University of Manchester for a long time.

Ludwig Prandtl (1875–1953), the German scientist, was famous for laying the foundation for the analysis of heat convection and his research in boundary layer in fluid dynamics. He earned his doctorate degree from the Technical University of Munich in 1900. In 1904, Prandtl presented his historic paper on boundary layer theory. He improved on Reynolds analogy for finding heat transfer coefficient in turbulent flow and presented Prandtl analogy for turbulent heat transfer in 1910. Prandtl's valuable findings on convective heat transfer in moving fluids are found in 'Essential of Fluid Dynamics' (Cheng and Fujii 1998). He also made important contributions to the fields of aeronautics.

Max Jakob (1879–1955), the German physicist, was an important figure in the field of heat transfer and thermodynamics in 1920s and 1930s. His research spread over measuring thermal conductivity, the mechanisms of boiling and condensation, flow in pipes and nozzles, and many more. Max Jakob was a professor at Illinois Institute of Technology, USA, and devoted his whole life to research in the field of heat transfer. He had over 500 publications in the form of books, technical papers, reviews, articles, and discussions to his credit. The dimensionless entity Jakob number was named after him in honor of his pioneering research in heat transfer during phase change. Jakob number is the ratio of maximum sensible heat absorbed by a liquid to the latent heat absorbed in a liquid–vapor phase change. The Max Jakob Memorial Award for distinguished service in the field of heat transfer is offered annually by ASME to commemorate his invaluable contributions.

Wilhelm Nusselt (1882–1957), the German engineer, is famous for his significant contributions to the field of heat transfer. He received his doctorate degree in mechanical engineering from the Technical University of Munich in 1907. Two most important contributions of Nusselt were dimensional analysis of heat convection and prediction of convective heat transfer during fluid film condensation. He is also credited for his contributions to heat exchanger design methodology, conductivity analysis of insulating materials, and heat and mass transfer in evaporation. In 1910, Nusselt developed the solutions for laminar heat transfer problem in the entrance region in tubes. In 1915, he published his historic paper 'The Basic Laws of Heat Transfer' in which he elaborated on the concept of heat transfer coefficient in forced and natural convection and proposed the dimensionless groups used for correlating the heat transfer results for various convective heat transfer problems. The dimensionless Nusselt number is named after him in honor of his fundamental works in convective heat transfer.

Ernst Schmidt (1892–1975), the German scientist, is known for his pioneering works in the fields of thermodynamics and heat and mass transfer. Some of his noteworthy contributions to heat and mass transfer were developing the analogy between heat and mass transfer, first measurement of velocity and temperature fields in natural convection boundary layer and heat transfer coefficient in droplet condensation, introduction of aluminum foil radiation shielding, and solution of unsteady state heat conduction problems (Lienhard and Lienhard 2008). The dimensionless quantity Schmidt number is named after him. In recognition of his outstanding work, he received the Max Jakob Memorial Award, the Grashof Commemorative Medal, and many more honors.

Thus, the quest for knowledge of heat transfer continued, and by the early part of the twentieth century, the foundation of heat transfer theory was established with proven laws and principles. With the progress of the twentieth century, those fundamental theories of heat transfer were gradually applied in thermal engineering and other engineering disciplines for the benefits of mankind.

4.9 Conclusion

A brief history of thermodynamics is presented in this chapter. It is often said that the thermodynamics is the daughter of steam engine. From that point of view, the origin of thermodynamics is in mechanical engineering. However, soon it was realized that the laws of thermodynamics are quite general. Nowadays, thermodynamics finds application in understanding not only mechanical processes, but also chemical processes. It is an integral part of the curricula of chemical and metallurgical engineering as well as science programs such as physics and chemistry. Heat transfer is very much related to thermodynamics. Thermodynamics studies the process in equilibrium, whereas the time for reaching the equilibrium can be obtained by heat transfer.

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Chapter 5
Manufacturing Through Ages

Abstract Manufacturing is integrally linked with the development of civilization. Some of the important manufacturing processes are machining, metal forming, casting, joining, powder metallurgy, and 3D printing. Power-driven machines for manufacturing became common since the first Industrial Revolution. In the nineteenth century, attempts were made to understand the physics of manufacturing processes. The predictive formulae for some of the processes were also developed. In the twentieth century, particularly in the second half of it, various advanced manufacturing processes were developed; notable among them are the laser-based manufacturing processes. In the twenty-first century, 3D printing technology has gained importance and is being further developed through continued research efforts. In the near future, mechanical engineers are expected to contribute a lot in developing green and sustainable manufacturing technologies.

Keywords Machining · Metal forming · Casting · Joining · Welding · Powder metallurgy · Advanced manufacturing · 3D printing

5.1 Introduction

Manufacturing is an integral part of mechanical engineering. The definition of mechanical engineering provided in Chap. 1 includes manufacturing. It is not enough to design a machine; it has to be fabricated. The world 'manufacture' originated from Latin words 'manu factum' meaning made by hand. Now, the word 'manufacture' may refer to made by hand or machine. Manufacturing is one of the oldest human activities. In the olden days, each family used to fabricate something as per the need of the family. With the division of labor, a class of craftsmen emerged. However, in ancient times, manufacturing was not considered a science. Today, manufacturing comprises science as well as art and the proportion of science is increasing day by day.

Often manufacturing is defined as an activity of adding value to raw material. In that sense, the scope of manufacturing is quite wide. Manufacturing of drugs, food

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items, textile, chemicals, and automobiles are the common manufacturing activities. Traditionally, construction of infrastructure such as roads, bridges, dams, and houses is not called manufacturing, although they also are constructed by the basic principles of manufacturing and various components used in these constructions are prepared by mechanical manufacturing processes. Nowadays, several buildings are prepared by prefabricated structures, and in future, it may be possible to construct a full house by 3D printing.

The discussion in this chapter will be limited to the history of main manufacturing processes that are used for making machines. Machines are usually made of metals. In the past, wood was an important engineering material. Presently plastics and composite materials represent their shares in machines. However, metals still dominate the mechanical products and they will continue their importance in future. Due to this reason, a significant portion of mechanical engineering curriculum includes metal manufacturing. The major metal manufacturing processes are machining, forming, casting, joining, powder metallurgy, and 3D printing. The heat treatment and surface coating may also be considered manufacturing processes. Manufacturing processes can be broadly classified into four parts—subtractive, mass containing, additive, and joining. In subtractive processes, the desired form of the product is obtained by removing the undesired raw material, e.g., in machining. In mass-containing processes, only the shape of raw material is changed, e.g., in metal forming. In additive process, the raw material is added as per the requirement of the product, e.g., in 3D printing. Welding and adhesive bonding fall in the category of joining processes. In these processes, two different parts are joined. The parts remain as they are except at the location of the joint. This chapter will discuss history of such type of metal manufacturing processes, although some reference will be made to plastic and composite manufacturing as well.

5.2 Machining

Machining is as old as human civilization. It is a metal removal process and may be called a subtractive manufacturing process. In traditional machining, the metal is removed in the form of chips using a tool. There are evidences of use of stone tools for cutting and chipping millions of year ago. Tool making started about 10 million years before present (McNeil 1990). Blades were invented about 35,000–12,000 years before present. However, most of the time, the machining either (of wood, stone, bone, and meat) was a household activity or was confined in the hands of artists. The tools were usually made of stone, and a lot of skill was required in obtaining the desired shape. This section is divided into two subsections. The first subsection discusses the evolution of machine tools and cutting tools. The second subsection discusses the research in metal cutting.

5.2.1 Evolution of Machine Tools and Cutting Tools

Nowadays, the most widely used machine tool is lathe, which is suitable for machining axisymmetric jobs. As per some records, the wooden lathe was in use around third century BC in Greek and Roman civilizations. The lathe was used to turn wood and bone (Trent and Wright 2000). One Eleusinian inscription dated circa 360 BC provides evidence for the use of lathe for turning of bronze (Darling 1990). Etruscan wooden bowl found in the tomb of the Warrior at Corneto dates back to about 700 BC (Corry 1990). The wood was the main engineering material, and it was turned in the lathe made of wood. Before the advent of lathes, the use of bow drills for making the holes was common (McNeil 1990). In fact, rock drilling process using the cord drive, in which an assistant manipulates cord wrapped around the vertical drill spindle to give it oscillating rotary motion, is a very old process. The treadle-operated lathe machines were in use in twelfth century AD. In late eighteenth century, the machining process was used to bore the cylinders of steam engines. Rapid development in machine tool industry took place starting from that period till late twentieth century.

A history of machine tools up to mid of twentieth century has been provided by Rolt (1965). Here, it will be briefly reviewed. As already discussed in Chap. 2, Leonardo da Vinci (1452–1519) was a great engineer and scientist. A drawing made by him in circa 1500 shows a screw-cutting lathe (Corry 1990). He also designed an internal grinding machine. One illustration by Jacques Besson shows an ornamental lathe for machining precision components. It has a template for guiding tool. Jacques Besson died in 1573 and was born perhaps in 1540. In 1571–1572, he had published a book entitled Theatrum Instrumentorum, which described many of his inventions in machine tool. A water-powered cannon boring mill was used in 1540. Christopher Polhem of Sweden built an iron-cutting lathe in circa 1716 that was driven by water wheel. There is not much development in seventeenth century, but after the advent of steam engines in eighteenth century, there was a boost in the growth of machine tools. John Smeaton (1724–1792), considered as the father of civil engineering, developed a cylindrical boring machine. John Wilkinson (1728–1808) developed a cannon boring mill in 1774.

In 1798, Scottish engineer William Murdock (1754–1839) machined a 163-cm bore cylinder in the factory of English manufacturer Mathew Boulton. The machining of 163-cm bore took more than 27 days. Mathew Boulton (1728–1809) is famous for collaborating with James Watt for the commercial production of steam engine. In the final quarter of eighteenth century, hundreds of Boulton and Watt steam engines were installed at several places.

Henry Maudslay (1771–1831) is a well-known name in the history of machine tools. He developed many machine tools. In circa 1800 AD, he constructed a screw-cutting lathe. It was perhaps the first engine lathe with guide screw. David Wilkinson (1771–1852) is called the father of American machine tool industry. He designed a screw-cutting lathe in 1798 (https://www.asme.org/engineering-topics/articles/manufacturing-processing/david-wilkinson). James Fox (1780–1830) developed a big size planer machine in 1820. In the planer machine, the tool is stationary and the table on which the job is mounted carries out to and fro motion. Whereas turning machine, lathe, was used for machining the jobs with circular cross section, planer machine could produce plane rectangular surfaces. Fox constructed a second planer machine in 1825, where he could machine a square surface of 183 cm side. James Nasmyth (1808–1890), who is famous as an inventor of steam hammer, developed a nut milling fixture. He also developed a shaper in 1836. The shaper can machine similar components as machined by a planar; albeit of smaller sizes. In a shaper machine, the job is stationary and the tool carries out to and fro motion. A quick return mechanism for shaper was developed by Whitworth (1803–1887) who was born in Stockport. With quick return mechanism, the tool can machine the work at slow speed and can return with higher speed during its reciprocating motion. It is generally believed that Whitworth was the first to use scrapping process. Scrapping is basically a surface texturing process, which involves selectively removing the material by a hand or machine-operated scrapper. The purpose is to correct the surface and provide better tribological properties by providing the lubricating pockets. In 1835, Whitworth developed automatic cross-feed for the lathe. In 1836, he developed a measuring machine that was capable of detecting one millionth part of an inch. Around 1862, he developed a radial drilling machine. Multi-spindle lathes were developed around 1886 for enhancing the productivity.

In America, circa 1818, milling machines were used by English gun makers. Eli Whitney developed a milling machine in 1820. The oldest known milling machine to have vertical adjustment was built by Gay, Silver & Co. in circa 1837. Frederic W. Howe (1822–1891), an American inventor, designed a milling machine in 1848. Howe was the son of a blacksmith, and he designed a number of machine tools. For some period, he was the president of Brown & Sharpe Co. He is also famous for creating new sewing machines (http://www.britannica.com/biography/Frederick-Webster-Howe). Lincoln index milling was designed in 1850s by George S. Lincoln & Company (Roe 1916).

For the mass production purpose, turret laths were developed. In a turret lathe, a number of tools are mounted on an indexing turret. The first turret lathe machine was built by Stephen Fitch in 1848 (Robert 1989). With the advent of Computer Numerical Control Machining Center, turret lathe is gradually phasing out. Joseph R. Brown improved formed milling cutter for making gears. He conceived the idea of universal grinding machine in 1868, but it was developed by Brown & Sharpe machine shop in 1876. In 1871, Edward G. Parkhurst (1830–1901) patented a collet chuck and closing mechanism for automatic feeding of bar in a lathe machine. Edwin R. Fellows (1865–1945) developed gear-cutter grinder and bevel gear generator in 1897.

First scientific study of metal cutting was carried out by Frederic W. Taylor (1856–1915). He was employed in Midvale Steel Company. In 1886, he started experiments on metal cutting on a boring machine. He was trying to find out optimum cutting conditions and was encouraged by the president of Midvale, William Sellers. In 1889, Taylor left Midvale, but continued his project while working at Bethlehem steel. The project lasted for more than 2 decades, and it costed about \$200,000. In 1907, he published a famous 247-page paper on the art of metal cutting (Taylor 1907). He conducted about 50,000 experiments and consumed about 360 metric ton of metal. As a result of this study, several advancements were made. For example, the importance of coolant on the tool life was understood in a quantitative manner apart from the effect of cutting speed, depth of cut, and feed on the tool life. Effect of cutting speed is summarized in the form of Taylor's tool life equation:

$$VT^n = \text{Constant}, \tag{5.1}$$

where V is the cutting speed (surface speed of the job in lathe), T is tool life, and n is an index that depends on several factors. The extended Taylor's life equation is expressed as follows:

$$VT^n f^x d^y = \text{Constant}, \tag{5.2}$$

where f is the feed (traverse of the tool per revolution of job in lathe) and d is the depth of cut. The indices n, x, and y as well as the constant on the right-hand side are dependent on the tool–job combination, machine condition, and cutting environment (the presence and absence of cutting fluid). During the course of experiments, Taylor and White could develop a high-speed steel which increased productivity by 400 %. It was developed around 1900. The high-speed steel is still in use as a tool material. A common form is 18-4-1 high-speed steel containing 18 % tungsten, 4 % chromium, and 1 % vanadium. About 5 % cobalt is added as binder. This steel was introduced in 1910 (Bayer et al. 1989). Superhigh-speed steels contain 10–12 % cobalt along with high carbon and high vanadium. Such type of superhigh-speed steel was introduced around 1939. For further details, one can refer Bayer et al. (1989). Sintered carbides were first produced in 1914 by a German firm by sintering mixtures of WC and W_2C at temperatures close to their melting points. Tungsten carbide tools were produced by Krupps of Essen in circa 1931. It is said that the benefit of machining by tungsten carbide tool was first noted by a machine operator. In 1928, tungsten carbide tools were sold under the trade names Widia and Wimet in UK. In America, it was marketed as Carboloy. Around 1930, Widia introduced cemented carbide. The name Widia is the abridged form of Wie Diamant in German language that means like diamond. These tools contained about 94 % tungsten carbide and 6 % cobalt, which acted like a binder. During World War II, the tungsten carbide tools were used extensively, as it could machine the metal at high cutting speed. The tool was suitable for machining nonferrous materials and cast iron (Komanduri 1993). It was not suitable for the machining of steel and caused excessive crater wear. Due to this, multilayer carbides were developed. Use of TiC and TaC made the tool suitable for steel machining. Coated cemented carbide tools were introduced by 1960. Stellite is another cutting tool material, which is a trademark of Kennametal Stellite Company. It is basically a cobalt–chromium alloy and was originally patented in 1909 by Edward Haynes.

Grinding is also one of the oldest machining processes. Manually operated grinding machine was in use before 850 AD (Rolt 1965). However, electrically operated grinding machines emerged in twentieth century. James N. Heald (1846–1931) introduced a piston ring grinding with magnetic chuck in 1904 (Rolt 1965). Centerless grinder was perfected by L.R. Heim in 1915 (Rolt 1965). Centerless grinding can finish slender cylindrical jobs at a fast speed. In this, the workpiece is passed between two wheels—a grinding wheel and a regulating wheel. The regulating wheel is suitably inclined to provide the longitudinal feed to the workpiece. In 1933, the Heald Machine Company introduced an internal centerless grinder. Successful commercial application of surface grinder started in 1934.

Developments in gear machining took place in the nineteenth century. Initially, the gears were made on a milling machine using form cutters. In this method, one tooth was cut at a time and the job was indexed to cut another tooth. This process was quite slow. In 1840, English inventor Whitwoth developed a formed cutter for producing involute gears. Whitworth patented the first gear hobbing process in 1835 (http://www.ronsongears.com.au/a-brief-history-of-gears.php). In the hobbing process, a rotating cutter called hob, which is like a gear, generates its pair. Gears with different teeth may be generated by suitable adjustment of hob and blank rotations. In 1839, John Bodmer took a patent for a worm cutter. These were basically primitive hobs. They were used for cutting gears. A patent for surface broaching was taken in 1882. Lapointe broaching machine with screw feed was developed in 1903.

Several other patents were taken. However, the first hobbing machine capable of cutting both spur and helical gear was built by Robert Herman Pfauter (1854–1914) in 1897 in Germany (Maiuri 2009). Edwin R. Fellows (1865–1945) was an American inventor and entrepreneur from Torrington, Connecticut, who designed and built a new type of gear shaper in 1896. He left the Jones & Lamson Machine Company to jointly found the Fellows Gear Shaper Company in Springfield, Vermont, which became one of the leading firms in the gear-cutting. In Sunderland gear-shaping process, the cutter is in the form of rack.

After World War II (1939–1945), aircraft industry felt the need of accurate machining of complex shapes. The need was felt to develop machine tools that can operate as per the instructions. John Parsons, President of the Parsons Works of Traverse City, Michigan, developed a concept to produce integrally stiffened skin of aircraft (http://www.cmsna.com/blog/2013/01/history-of-cnc-machining-how-the-cnc-concept-was-born/). A series of research projects were given to Massachusetts Institute of Technology beginning in 1949. A Cincinnati milling machine was retrofitted with hydraulic drives and electronic control system with feedback under the leadership of Prof. J.F. Reintjes. The first NC milling machine could be developed in 1952–1953. Earlier NC machines were operated by giving instructions through punched tapes. Till 1959, there was a number of configuration and sizes of punched tapes used by various manufacturers of NC machine tools. In 1959, a standard format for tape size and configuration was issued by the Electronic Industries Association (EIA), USA, which is now universally accepted (Mehta 1996).

The history of automation is older than the history of NC machines. The first programmable loom controlled by punch cards was developed in France in circa 1720 (Deb 1994). In 1801, card programmable Jacquard loom was introduced in France for mass production. In 1822, Babbage completed the difference engine for automatic computation of tables in England. The Automate, a cam programmable lathe, was invented by Spencer in the USA. A programmable paint-spraying machine was developed by Pollard in the USA in circa 1938. Spray guns movable through predetermined paths were developed by Roselund also in the USA. The first NC machine built at MIT in 1952 consisted of vacuum tubes. In 1947, John Bardeen, Walter Brattain, and William Shockley invented transistors at Bell Labs (Transistor Museum 2009). These transistors were made of germanium, a semiconductor material. By 1954, silicon transistors were available from Texas Instruments. Nowadays, vacuum tubes are obsolete. Computer Numerical Control (CNC) machines were developed in 1960s. With the help of CNC machines, productivity and precision could be increased tremendously. Concepts of CNC machines have been employed in related field. For example, laser cutting machine employs a CNC table. The coordinate measuring machine (CMM) employs the concept of CNC machines. The first coordinate measuring machine was displayed at the International Machine Tool exhibition in Paris in 1959 by the British company Ferranti. The company is credited with delivering the world's first commercially available general purpose computer in 1951 (http://www.coord3-cmm.com/50-years-of-coordinate-measuring-machine-industry-developments-and-history/). With the advent of CNC machines, the concept of flexible manufacturing system (FMS) developed, where a lot of CNC machines assisted by material handling system, automated storage, and retrieval systems, and robotic manipulators make a complete setup for producing a variety of products. In FMS, software manages the sequence of machining and machining parameters. Future is toward developing artificially intelligent machine tools.

5.2.2 Research in Metal Cutting

Starting from later half of nineteenth century, researchers started investigating the science of metal cutting. Although F.W. Taylor carried out the most thorough investigation on metal cutting and provided the famous Taylor's tool life equation, his research does not throw light on the physics of metal cutting. Komanduri (1993, 2006) stated that the research on the science of metal cutting started from 1945 with the seminal paper of M. Eugene Merchant (1913–2006) on the basics of the metal cutting process. Merchant and his group published a series of papers on a single-shear plane model and cutting force calculation (Ernst and Merchant 1941, Merchant 1944, Merchant 1945a, b). However, this view is in disagreement with the view of Astakhov (2006). He points out that the first attempt to model metal cutting process was made by Time in 1870 (Time 1870) and Tresca in 1873 (Tresca 1873). Time proposed a model of metal cutting having a single-shear plane for plane strain condition (width of cut much greater than the thickness of the layer to be removed). In 1881, Mallock of Cambridge University, UK, attributed cutting action as being due to shear followed by the fracture of the cutting plane (Mallock 1881). Zorev (1966) pointed out that the single-shear plane model was actually developed by Zvorykin (1896) and was criticized by Briks in the same year in 1896. Briks (1896) suggested that the deformation zone consists of a family of shear planes. In 1900, the famous German engineer Reuleaux observed that during metal cutting, a crack was formed ahead of the tool so that chip was formed by a splitting operation just as in wood-cutting (Reuleaux 1900). The crack idea was immediately refuted by Kick. Kick (1901) stated that Reuleaux's observation was probably an optical illusion. However, later researchers confirmed the observation of Reuleaux. Brooks (1905) was one of the earliest to publish photographs of the chip roots for different stages of quick-stop test. After that, several researchers applied quick-stop test to study the machining behavior particularly the chip morphology. Later on, M.C. Shaw also pointed out that the material does not behave like a continuum and the microcracks along the shear plane play a significant role (Shaw 1984). Of course, it is possible not to observe any crack in many cases.

Ernst and Merchant published their paper on single-shear plane model in 1941 (Ernst and Merchant 1941). In the single-shear plane model, it is assumed that during metal cutting, shear takes place along a plane inclined to cutting velocity. In practice, there is a shear zone where most of plastic deformation occurs. In many cases, the zone is quite thick and single-shear plane model is far from reality. In the original solution, Ernst and Merchant made an assumption that the work material deforms when the shear stress on the shear plane reaches the shear strength of the work material. They did not consider strain hardening. In modified merchant solution, the shear stress is assumed to be linearly dependent on the normal stress. As the compressive normal stress increases, the shear strength increases. Simultaneously with Ernst and Merchant, Vaino Pissipanen in 1937 described the cutting process as the movement of deck of cards, where one card slides over the other (Pissipanen 1937). Pissipanen's paper was published in Finnish, due to which majority of research community was unaware about it. His analysis is similar to that of Merchant.

Several researchers tried to replace the single-shear plane model by a shear zone model. Lee and Shaffer (1951) provided a slip-line solution by applying the theory of plasticity. In the slip-line model, the metal is assumed to flow along the line of maximum shear lines. The slip-line field solution cannot be applied easily to three-dimensional as well as strain-hardening cases. Sidjanin and Kovac (1997) applied the concept of fracture mechanics in chip formation process. Atkins (2003) demonstrated that the work for creation of new surfaces in metal cutting is significant. He also points out that Shaw (1954) has shown this work to be insignificant. However, when this work is included based on the modern ductile fracture mechanics, even the Merchant analysis provides reasonable results.

The research in metal cutting is dominated by two-dimensional orthogonal machining, where the cutting edge is perpendicular to the cutting velocity. In practice, orthogonal cutting is seldom used. Many researchers attempted to study three-dimensional machining. Stabler (1951) developed a chip flow rule that facilitates the determination of the direction of the chip flow. The rule states that the chip flow angle is approximately equal to the inclination angle for a variety of tool and work materials, rake angles, and speeds. A detailed study of chip formation was conducted by Iwato and Ueda (1976). They concluded that a continuous chip is formed under very specific cutting conditions. Shaw et al. (1952) studied the mechanics of three-dimensional cutting operation and introduced the concept of effective rake angle. They applied this to practical machining operations such as milling and drilling.

Palmer and Oxley (1959) conducted low-speed orthogonal in situ machining using cinema films to record the path of individual grains on the side of a machined workpiece. They found the strain-hardening properties of the work material to have a profound effect on the hydrostatic stress distribution. Shaw and Finnie (1955) considered several factors that could influence the flow stress in cutting and found that the presence of normal stress on the shear plane and strain rates have negligible influence, but the strain hardening is significant. In fact, Drucker (1949) believed that effects of temperature and strain rate nullify each other in machining. Drucker introduced the concept of a random array of weak points to qualitatively demonstrate the increase in specific cutting energy with decrease in the depth of cut.

The machining process involves generation of heat mainly due to plastic deformation and friction. The pioneering work in the area of heat due to friction was done by Thames Benjamin, Count of Rumford, in 1798 (Benjamin 1798). Joule (1850) provided the equivalence between heat and work 50 years later. Benjamin had conducted systematic studies to ascertain how heat is actually generated by friction by a blunt boring bar rubbing against the bottom of the bore of a cylinder. Jaeger’s classical paper ‘Moving sources of heat and temperature at sliding contact’ (Jaegar 1942) laid the foundation for much of the analytical work. Kronenberg (1954) used the dimensional analysis to arrive at the cutting tool temperature. Rapier (1954) used analytical and finite difference method for the temperature distribution throughout the material. Boothroyd (1961) developed infrared photographic technique and was the first to determine the temperature distribution in the shear zone, and the chip and the tool in orthogonal machining.

Dwaihl (1940), Trent (1952) and Trigger and Cho (1956) conducted a number of fundamental studies on various aspects of tool wear of cemented carbide tools. There are mainly two types of wear, viz. flank wear and crater wear. Crater wear starts on the rake face at some distance away from the tool nose, as the maximum temperature is attained at this point. It is a diffusion-dominant wear, and temperature plays an excessive role in it. The flank wear occurs at the flank surface and affects the dimensional accuracy to a great extent. Recently, Astakhov (2004) has argued that the existing measures of flank wear are insufficient for its characterization and he has proposed new concepts.

A careful study of literature reveals that a lot of research on metal cutting mechanics has been carried out since last one and half century. Although a number of models were proposed for the estimation of cutting forces, most of the textbooks give more emphasis to Merchant’s analysis based on the single-shear plane model.

Other models are avoided due to their complexity and difficulty to get input parameters of the model. For surface roughness determination, some models were proposed. However, they were found inadequate. In 1980s, several empirical relations were proposed for the determination of surface finish. A brief review can be found in Risbood et al. (2003). With seminal paper of Rangwala and Dornfeld in 1989 (Rangwala and Dornfeld 1989), several people started applying neural networks and other soft computing techniques to machining. The soft computing methods mimic the behavior of human being and learn with experience. Now, many researchers are applying hybrid methods to model machining processes (Quiza et al. 2012).

5.3 Forming

Forming is also one of the oldest manufacturing processes. Whereas machining is a subtractive manufacturing process, forming is a mass-containing process. Metal forming may be divided into two parts—bulk metal forming and sheet metal forming. Bulk metal forming deforms the raw material having large volume-to-surface area ratio, whereas in sheet metal forming, the raw material is in the form of sheet and its thickness does not change significantly after deformation. In the rolling of thin sheets, the thickness of the sheet changes. Hence, it is not considered a sheet metal-forming process. On the other hand, tube-bending process is discussed in many books of sheet metal forming, although tube is not a sheet. The bending of tube is similar to the bending of sheet in the sense that there is no appreciable change in the thickness. Punching and blanking involve plastic deformation till fracture and are included in the sheet metal processes. In a sense, these are also mass-containing processes, as no material goes waste in the form of chips. The scarp material is in the form of sheet only and the sheet thickness does not change. In this section, first the evolution of various metal-forming processes is described followed by a brief history of theoretical studies on metal forming.

5.3.1 Evolution of Metal-Forming Processes

Perhaps, the forging is the oldest metal-forming process. Since ages, man has been using mace to hit the man, animals, and plants. Mace might have been used like hammer for shaping wood or metals. Cold forging was used more than 10,000 years before present. Small beads and pins of hammered copper found at Ali Kosh in western Iran and Cayönü Tepsi in Anatolia date from the period between the 9th and 7th millennia BC and were made from native, unmelted copper (Darling 1990). Around 1582, a London goldsmith John Brode was using hammers driven by water for shaping brass and copper. In the early eighteenth century, at Bristol, the brass ingots were beaten into sheet by hammering, although rolling was well established by that time. James Nasmyth (1808–1890) invented a steam hammer much later, but hammer was in use since a long period.

The wire drawing is also an old metal-forming technique. The word ‘wire’ has been used in the Old Testament of bible:

> And they did beat the gold into thin plates, and cut it into wires, to work it in the blue, and in the purple, and in the scarlet, and in the fine linen, with cunning work (Exodus, 39:3).

The wires might have been made by strip twisting technique, which involved cutting of thin strip of metal from sheet and twisting the sheet to form a wire (Newbury and Notis 2004). The twisted strips were rolled between two flat surfaces or drawn through a rudimentary die. This practice was prevalent up to about 1100 AD. Egyptian used to make wire by drawing very thin ribbon of metal through a metal or stone die. The modern form of wire drawing may have been started around 900 AD, but it took several years to develop. Around 1565, the Society of Mineral and Battery works was trying to introduce improved methods of wire drawing into England (Darling 1990). The society was involved in producing brass wires, but iron wires were also drawn around that period. In 1691, William Dockwra became the proprietor of a brass works at Esher in Surrey, which had initially been set up in 1649 by Jacob Mummer, a German immigrant. In this factory, brass ingots were rolled to sheet, slit, drawn to wire, and finally made into pins. In 1808, Humphry Davy electrolyzed a mixture of magnesia and cinnabar in naphtha to isolate magnesium. In 1864, Magnesium Metal Company was established at Patricroft. Sir William Matther worked in this company for some time and later headed the firm of Matther and Platt. He developed improved method for drawing magnesium wire. In 1906, A.L. Marsh introduced nickel–chromium and nickel–chromium–iron alloys as electrical heating element. A good combination was 80 % nickel and 20 % chromium, which was easily drawn in the form of wires.

Roberts (1978) has provided a history of rolling in his book. During the fourteenth century, small hand-driven rolls were used to flatten gold, silver, and possibly lead. Leonardo da Vinci designed a rolling mill circa 1480, but there is no evidence that this mill was fabricated. Brulier, a French man, rolled sheets of gold and silver for making coins. Circa 1578, Bevis Bulmer received a patent for a slitting mill that produced strips from a bar. A mill of this type was set up at Dartford in Kent in 1590. It was powered by waterwheels. In 1615, Salomon de Caus of France built a hand-operated mill for rolling of sheets and leads. Many authors consider Belgium and England as the birth place of rolling.

From 1666, iron was rolled in thin flats in England. In 1679, a patent was granted for finishing of bolts by rolling. By 1682, large hot rolling mills were operational in England. John Hanbury began using rolling mill around 1697. They were driven by water. Christopher Pollhem (1720–1746) of Sweden designed a rolling mill with backup rolls. A reversing rolling mill was brought from France to England in 1728. In 1766, John Purnell received a patent for grooved rolls, and these turned in unison. Before this, both rolls used to roll independently and caused many defects in the rolled product. The first tandem rolling mill was designed by Richard Ford in 1766.

In 1798, a patent was granted to Henry Cort of Fontley Iron Mills, England, for utilizing grooved rolls for rolling irons. Several authors consider Henry as the father of modern rolling mills. By this time, steam engines started powering the rolling mills. In 1805, Sylvestor and Hobson of Sheffield first demonstrated the feasibility of producing zinc sheet by rolling. It was warm rolling. In Liége suburb of Saint Leonard, a rolling mill was producing zinc sheets 1.5 m long by 41 cm wide by 1811, and by 1813, the roof of St. Paul's Cathedral at Liége had been sheathed in zinc (Darling 1990). During nineteenth century, zinc sheet became a popular roofing material in its own right. John Birkenshaw set up first rail rolling mill in 1820. In 1831, the first T-rail was rolled in England. The first I-beam was rolled in Paris in 1849. At the British Great Exposition of 1851, a plate weighing about 511 kg was exhibited which was heaviest rolled plate till that time.

The first American rolling mill was built in 1751. The rolls of the mill were driven by water wheels. At the beginning of nineteenth century, Christopher Cowan built the first rolling mill in Western Pennsylvania, which was powered by steam. In 1820, Dr. Charles Lukes rolled boiler plates. By 1825, five rolling mills were operational in Pittsburg. By the middle of the nineteenth century, annual iron production in USA was 350,000 tons per year. The rolling of corrugated plates was patented in 1850. By 1875, steam engines were being built that were capable of delivering power up to 4000 HP. Aluminum was first refined in 1825. In 1882, Webster established the Aluminium Crown Metal Company at Hollywood. The aluminum produced by Webster was rolled into sheet, and the aluminum foil of high quality was produced by beating the metal (Darling 1990). Later part of nineteenth century saw the development of electric generators and motors. In 1903, two 1500 HP motors powered a light rail mill at the Edgar Thomson works at Braddock. The first reversing DC main drive motor was installed in the same year on a 36 in. (91.44 mm) universal plate rolling mill at South Works in Chicago.

A tandem cold rolling mill was built in 1904 in the West Leechburge Steel Company, and around World War II (1939–1945), the use of four-stand sheet rolling mill became common. In the 1960s, five-stand rolling mills were built. Since the 1960s, secondary rolling mills became common.

In 1797, Joseph Barmah patented the first extrusion process for making lead pipes. The metal used to be preheated and ram was hand-driven. In 1820, Thomas Burr built the first hydraulic power press that was to extrude lead pipes (Sheppard 2013). The process was called squirting. By the end of nineteenth century, the extrusion methods were also in use for copper and brass alloys. Alexander Dick invented a hot extrusion process for nonferrous metals in 1894. North America has its first aluminum extrusion process in 1904. In 1950s, Sejounet introduced molten glass as lubricant in extrusion process.

Deep drawing process also called eyelet dates back to 1800s. In this process, a sheet called blank is held at edges by a blank holder that is supposed to apply an optimum amount of force. The other portion of the sheet is forced by a punch into a die to provide a shape similar to a cup. It is possible to make a cup of complicated cross section. Necessary shapes can be provided to punch and die.

5.3.2 *Theoretical Studies on Metal-Forming Processes*

The modeling of metal forming started since twentieth century with the development in the theory of plasticity. Initial attempts were focused toward obtaining the forming load for a desired deformation or predicting the deformation for a prescribed load. Following are the commonly used methods for the modeling of metal forming: (i) slip-line field method, (ii) slab method, (iii) upper bound method (iv) visioplasticity method, and (v) finite element method.

Slip-line field was developed by Ludwig Prandtl (1870–1953) in 1920 for finding out the indentation pressure in flat punch indentation. Slip lines are the lines along which the shear stress is the maximum. It is assumed that the plastic flow takes place along the slip lines. At each point in the plane of plastic flow, there are two orthogonal slip lines. Heinrich Hencky (1885–1951) derived general theorems for the stress state in a slip-line field around 1923. Hilda Geiringer (1893–1973), an applied mathematician, developed equation for the velocity field. She was first working as an assistant to R. von Mises and married him in 1943. During World War II, Rodney Hill used a slip-line field method to determine the plastic deformation of a thick plate being penetrated by a bullet. Rodney Hill (1921–2011) published a book titled The Mathematical Theory of Plasticity in 1950, at the age of 29. In 1952, he became the editor in chief of the Journal of Mechanics and Physics of Solids. Hill is famous for his 1948 and 1979 anisotropic yield criteria (Hill 1948, 1979). His 1993 paper also discusses a useful anisotropic criterion (Hill 1993). Hill (1950) and Prager and Hodge (1951) presented a systematic account of slip-line field theory. During the 1950s and 1960, many new slip-line fields were proposed for extrusion, rolling, drawing, and machining. The slip-line field theory has the following limitations:

- It is suitable only for plane strain problems.
- The construction of a slip-line field is a difficult task.
- It is not easy to incorporate strain-hardening, strain-rate, and temperature effects in the slip-line field method.
- It is not possible to incorporate elastic effects in the model.

One of the simplest methods for analyzing the metal-forming problems is slab method. In this method, a slab of infinitesimal thickness is taken perpendicular to the flow direction at a general point in the deformation zone. Assumptions are made for the form of stress components. For example, it can be assumed that the stress varies only in the longitudinal direction. Force and momentum balance for the slab results in differential equations that may be solved analytically or numerically by employing proper boundary conditions. In 1923, Erich Siebel (1890–1961) published a paper on the analysis of forging based on the slab method (Siebel 1923). He calculated the average pressure for forging numerically and also discussed how to use the results for backward extrusion. A slab method for rolling was proposed by Theodore von Káráman (1881–1963) in 1925, although after that he never worked in this area (von Káráman 1925). Sachs (1927) used it for solving the wire drawing problem. Egon Orowan (1902–1989) proposed a more generalized differential equation than Káráman's equation (Orowan 1943).

Hill (1950) introduced the upper bound theorem. Prager and Hodge (1951) is one of the pioneers in formulating upper bound theorem. As per Hill, Markov applied the upper bound theorem in 1947 for rigid-perfectly plastic material. The paper was in the Russian language. In the upper bound method, a kinematical admissible velocity field is assumed. The velocity field need not be real. It may contain the tangential velocity discontinuities. However, in each zone of continuous velocity field, the volume constancy condition must be satisfied. It is also aimed to satisfy the velocity boundary conditions. From the continuously admissible velocity field, the power required for the plastic deformation can be obtained. If there is velocity discontinuity across a surface, power due to it will be the product of the shear strength of the material, magnitude of the tangential velocity discontinuity, and the surface area of the discontinuity. The power due to prescribed tractions can also be calculated. All these powers added together provide total power. The upper bound theorem states that the total power calculated this way will always be greater or equal to the actual power. If one can obtain the powers from all possible kinematically admissible velocity fields, the lowest power will be the actual power. Green (1951) applied upper bound theorem to plane strain compression between smooth plates and compared the results with the slip-line method. From the late 1950s, W. Johnson carried out extensive research work in the upper bound theorem for metal forming. Kudo and Avitzur also applied upper bound theorem. Kudo is one of the originators of the Japanese Society for the Technology of Plasticity (JSTP) and was its president in 1985–1986.

The visioplasticity method introduced by Thomsen et al. (1959) is a combination of experiments and analysis. In this method, a velocity field is obtained from a series of photographs of the instantaneous grid pattern during a metal-forming process. The strain rate, and strain and stress fields can then be obtained by kinematical, equilibrium, and constitutive equations. The calculations involved are time–consuming, and method has lost importance with the advent of other computational methods.

Nowadays, most of the metal-forming processes are modeled using finite element method (FEM). FEM is a numerical method to solve differential or integral equations. It was originally developed to solve structural problems. Courant (1943) used the variation form for solving torsion problems. Turner et al. (1956) used it for analyzing aircraft structure. The word finite element method was first coined by Clough (1960). Olgierd Zienkiewicz (1921–2009) was the first to write a popular book on FEM. He also modeled metal-forming problems by FEM. In the 1970s and 1980s, a number of processes were modeled using FEM. These were perfected in the 1990s. FEM has been used for modeling of machining processes, but the physics of machining processes is still not well understood. Hence, FEM modeling is not expected to provide very accurate results unless realistic governing equations are used.

5.4 Casting

Casting is also a very old manufacturing process. It is also a mass-containing manufacturing process, but differs from the metal-forming process. In a metal-forming process, the metal is brought to a plastic state so that it can be shaped easily. In casting, metal is transformed to a liquid state and allowed to adapt the desired shape in a mold, where it is solidified. The oldest known casting is a copper frog of circa 3200 BC from Mesopotamia. By 2500 BC, the Egyptians had developed considerable expertise in the production of hollow copper and bronze statuary. Hollow castings were produced by placing an internal sand core. Smaller castings were made by lost wax techniques, which had been mastered by Egyptian craftsman before 2200 BC (Darling 1990). Sand molding was common in China around 600 BC. Cast crucible steel was produced in India around 500 AD, and the process was reinvented by Benjamin Huntsman in 1750 AD in England. Vannoccio Biringuccio (1480–1539) is called the father of the foundry industry in Italy, who documented the foundry process. In 1813, Dony sent to Napoleon his bust in zinc, a casting weighing 74 kg (Darling 1990). Cupola furnace was invented by John Wilkinson in 1794. It can be used for melting cast iron. It was introduced in USA in 1815. American Foundrymen's Association (now American Foundry Society) was formed in 1896. The first electric arc furnace was used in USA in 1906. First stainless steel was melted in 1913. The first high-frequency induction furnace was installed in USA in 1930. In 1972, Wagner Castings Company produced Austempered Ductile Iron (ADI). In 1996, cast metal matrix composites were used in automobile sector.

Turbine blades were produced in the USA by vacuum melting and investment casting. The term investment casting denotes the production of industrial metal components via casting process that utilizes an expendable pattern. The expendable pattern, usually a proprietary form of blended waxes, is produced from a permanent mold. In some form, this process was in use around 4000 BC. It was used for the production of dental inlays and fillings at the end of nineteenth century. The industrial version of the process was developed in 1940s in the USA (Green-Spikesley 1979). During the World War II, investment cast gas turbine blades were produced from the cobalt-base alloy. In the late 1960s, blades were produced by nickel-based superalloys. In 1960, Pratt and Whitney Aircraft introduced directional solidification of investment cast superalloys.

5.5 Joining

A brief history of welding is presented in (http://literacy.kent.edu/eureka/EDR/5/Middletown/Industrial%20Fields/History%20of%20Welding.pdf). Joining metals by heat was practiced in the Bronze Age. The bronze, an alloy of copper and tin, has a low melting point (less than 1000 °C), and therefore, it could be fusion welded easily. During Iron Age, blacksmiths used to join metals by forge welding, which is a solid-state welding process. In the solid-state welding process, metals to be joined are not melted, but get deformed by the application of pressure and/or heat.

Priestley discovered oxygen in 1774. Edmund Davy produced acetylene in 1800. Linde devised a method for extracting oxygen from liquid air in 1893. Fouché and Picard invented oxyacetylene welding torch in 1903, which could achieve a flame temperature of 3250 °C. Since then, gas welding became an economical method for fusion welding of the metals as well as for cutting.

In 1800, Sir Humphry Davy produced an arc between two carbon electrodes using a battery. Satite and Auguste de Meritens filed a patent in 1849 for welding by electric arc with carbon electrodes. A Russian, Nikolai N. Benardos along with a fellow Russian, Stanislaus Olszewski, secured a British patent in 1885 and an American patent in 1887 for welding. The Russian, N.G. Slavianoff, used consumable bare steel rods in 1888. In 1909, Strohmenger used lime-coated electrodes. The coating of lime provided the stability of the arc. In 1907, Oscar Kjellberg (1870–1931) introduced the flux-coated electrodes. Earlier in 1886, resistance butt welding was invented by Elihu Tomson (Houldcroft 1986). It is a solid-state welding, in which heating is achieved by passing the current in the parts to be joined. Thermit welding was invented in Germany around 1893. Thermit welding usually uses the mixture red iron oxide called rust and aluminum to undergo exothermic reaction. It was very useful for welding railway tracks as it did not require electricity or gas.

In 1919, just after the World War I (1914–1918), Comfort Avery Adams founded American Welding Society. In the same year, C.J. Holstag invented alternating current welding, which was utilized by welding industry after 1930. Stud welding was developed in the 1930s, which was later replaced by submerged arc welding in ship industry. Gas Tungsten Arc Welding (GTAW), popularly known as TIG welding, was invented by Russell Meredith in 1941. It used a tungsten electrode and inert gas helium as the shielding gas. The gas shielded metal arc welding (GMAW) was developed in Battelle Memorial Institute in 1948. Friction welding was developed in 1956 in Soviet Union. Friction-stir welding was introduced by The Welding Institute in 1991. The Welding Institute was formed in London in 1923. Laser welding became popular in industry since the late 1980s. Electron beam welding was developed by the German physicist Karl-Heinz Steigerwald in 1958.

In the recent past, joining of materials with the help of adhesives called adhesive bonding has regained popularity, although it has been in use since more than 4000 BC (ESC Report 1991). Adhesive is any substance that is applied on the surface, or both surfaces, of two separate items that binds them together and resists their separation. Archeological evidences suggest that broken ceramic pots were glued with resins from tree sap. Wood gluing was in use during 1500–1000 BC. The first written document on art of gluing appeared in 200 BC. During 1–500 AD, the Romans and Greek developed the art of veneering, in which thin slices of wood were glued to core panels with the help of glue. The glue was developed from animal as well as vegetable sources. The first commercial glue factory was started in Holland to manufacture animal glue from hides. Circa 1750, the first glue patent was issued in Britain for fish glue. In 1910, Bakelite, a thermosetting plastic, was invented. After that, adhesive using thermosetting plastic was used. Epoxies are adhesive system prepared by a complex chemical reaction. Epoxy resin is mixed with a hardener or catalyst for curing. Epoxy adhesives can bond a wide variety of substances including metallic substances. The first production of epoxy resins was carried out by De Trey Frères SA of Switzerland. They licensed the process to Ciba AG in the early 1940s, and Ciba first demonstrated a product under the trade name Araldite at the Swiss Industries Fair in 1945. It was initially developed by Aero Research Limited (ARL), UK, hence the name araldite. Hot melt adhesives are thermoplastic polymers that are tough and solid at room temperature but are liquid at elevated temperature. They started to be used in the 1960s. Anaerobic adhesives are derived from methacrylates, a monomer, commonly known as Plexiglas. It can be hardened in the absence of air. Cynoacrylates are extremely rapid curing adhesives commonly called as superglues.

5.6 Powder Metallurgy

Powder metallurgy may have been used in prehistoric times. Around fifth century AD, Wayland the Smith used to employ some sort of powder metallurgy process for making the swords. It was used in pre-Columbian times by the Indians of Ecuador to prepare platinum blocks. The first truly ductile platinum was produced in 1773 by Rome Delisle, who found that if the platinum sponge, after calcination, was carefully washed and then reheated in a refractory crucible, it sintered to dull gray mass which could then be consolidated by careful forging at good red heat (Darling 1990). Density doubled to approximately 20,000 kg/m^3. Around 1800, William Hyde Wollaston started making ductile platinum by powder metallurgy route. In 1898, Welsbach proposed osmium as light filament material. It could be produced in the form of powder. The filament was produced by powder metallurgy and wire drawing. Ductile tantalum was first produced in 1903 by W. von Bolton. Ductile tungsten filaments were first produced W.D. Coolidge of the US General Electric Company at Schenectady in 1909. Fine tungsten powder was pressed into bars, which were then sintered by heating them electrically in a pure hydrogen environment with temperature around 3400 °C. In 1913, the American General Electric Company introduced sintered porous self-lubricated bronze bearings. In 1930, F. Skaupy devised a method of hydrostatic (isostatic) pressing. Isostatic pressing is now widely employed for the manufacture of smaller components.

5.7 Heat Treatment and Coating

Heat treatment is not supposed to change the geometry of a part, but is applied for improving the mechanical and metallurgical properties. Coatings are applied on the surface to protect the part from corrosion, improve its appearance, and make the surface stringer. Sorel attempted to apply zinc to the surface of rolled iron sheet, and in 1837, he and his associate named Ledru obtained a French Patent for iron protected against corrosion by a hot-dipped coating of zinc. The process was called galvanizing (Darling 1990). In 1837, the English patent for galvanizing was granted to Commander H.V. Craufurd RN. Galvanized corrugated iron is first mentioned in 1845 in a patent taken out by Edmund Morewood and George Rogers.

At the beginning of twentieth century, only steel was heat treated. In 1909, Dr. Alfred Wilm noted that an aluminum alloy had the ability to harden slowly at room temperature after it had been quenched from a temperature just below its melting point. This phenomenon is now called age hardening. During the World War I, large quantities of age-hardened aluminum alloys were used by the combatants, first for Zeppelins and then for other types of aircraft (Darling 1990). In 1919, Paul Merica, Waltenberg, and Scott provided an explanation for the age hardening of light alloys. In 1929, Professor P. Chevenard of the Imphy Steelworks observed that small quantity of aluminum in nickel–chromium alloys facilitated age hardening. Later in 1935, he observed that strengthening effect of aluminum could be augmented by small quantities of titanium. In 1934, Maurice Cook studied the precipitation hardening characteristics of 37 copper alloy systems. Induction hardening was developed around 1950. The research on heat treatment is mainly carried out by metallurgist, although it is an integral part of mechanical engineering as well.

5.8 Advanced Manufacturing

Advanced manufacturing refers to the processing of materials by non-traditional manufacturing processes. It may also refer to the use of advanced technology (e.g., software) to enhance the performance of traditional manufacturing processes. Advanced machining processes do not employ a wedge-shaped cutting tool. The material may be removed by mechanical force, melting/vaporizing by thermal energy or by chemical/electrochemical energy.

Ultrasonic machining is a non-traditional mechanical machining process. In this, a tool imparts high-frequency vibrations to an abrasive slurry (may contain abrasives in water), which removes material from a brittle material. Ultrasonic machining started with a paper by Wood and Loom in 1927, wherein the prospects of using high-frequency (about 70 kHz) sound waves were highlighted. A British patent was granted to Balmuth in 1945 (Jadoun 2014). Utrasonic machining is also known as ultrasonic impact grinding. It can be used to drill a hole smaller than 10 μm diameter in brittle materials.

Light amplification by stimulated emission of radiation (LASER) has been used for a variety of applications in manufacturing. Gordon Gould was the first person to use the word Laser. In 1917, Einstein had shown theoretically that lasing action should be possible. In 1960, Maiman invented the first ruby laser. Some argue that the first ruby laser was invented by Townes and Shawlow in 1957 (Chryssolouris 1991). First, CO_2 laser was built in 1964 in Bell laboratories. It used pure CO_2 and produced 1-mW power with an efficiency of 0.0001 %. By adding nitrogen, 200-mW power laser could be obtained, and by adding helium, a 100 W laser with efficiency of 6 % could be produced. Nowadays, CO_2 lasers up to 6-kW power with efficiency more than 10 % are common. CO_2 lasers up to 20 kW are available for welding. Lasing gas contains about 10 % CO_2, 35 % nitrogen, and rest helium. CO_2 gives molecular action to generate photon, and nitrogen reinforces and sustains the action and helium provides intra-cavity cooling. In 1964, Nd-YAG laser was also invented whose wavelength is one-tenth of the wavelength of CO_2 laser. Fiber laser was invented by Snitzer and his group between 1961 and 1964 (Snitzer 1961; Koester and Snitzer 1964). They doped rare earth Nd^{+++} ion in a barium crown glass to make the lasing material. This work was done in American Optical Company in USA. Starting from 1970s, lasers have been used for machining and welding. In machining, laser beam removes the material by melting and vaporization. Apart from thermal heating, heat is also generated by exothermic reaction of an assist gas that also flushes out the removed material. Laser beam also has been used for preheating the material in the conventional machining. A detailed review of laser beam machining is available in Dubey and Yadava (2008).

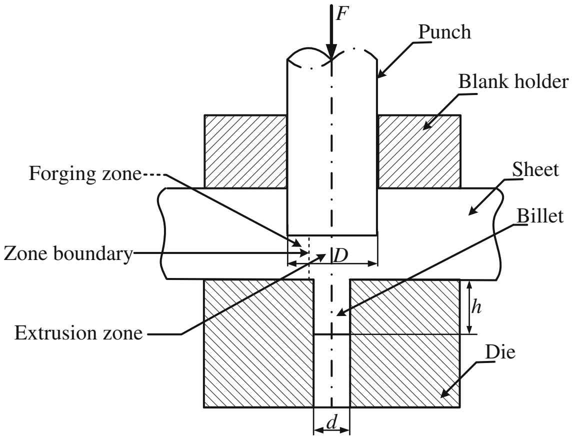
The forming of metal plates with the application of flame heating was initiated at the start of nineteenth century to shape the external metal plates of ship-hull. The process is man-hour intensive and dependent on the skill of personnel. It is difficult to control and focus the flame on a small area (Vollertsen and Sakkiettibutra 2010). These problems were solved by applying a laser beam instead of a gas flame to deform the metal sheets. First application of the laser forming for the automatic adjusting of the leads of the relays was patented by Martin in 1979 (Martin 1979). Further application of laser for sheet bending was reported by Kitamura in early 1980s (Kitamura 1983). Nowadays, fiber and diode laser are gaining popularity.

Electro-discharge-machining (EDM) is a popular thermal machining process. In this, metal is removed by the energy of sparks. The effect was observed by Joseph Priestly in 1770, but it was developed circa 1943 by Russians. CNC EDM machines were developed in 1980s. Electrochemical machining (ECM) was developed in early twentieth century. It is based on the principles developed by Michael Faraday (1791–1867). It removes the metal atom by atom, proving high surface finish with no heat-affected zone.

5.9 Micro- and Nanomanufacturing

In recent past, there is a drive to produce very small components. Process of manufacturing components or features whose one projection can be accommodated in a square of 1 mm side is called micromanufacturing. The attention toward micromanufacturing was focused starting from the 1980s. Micromanufacturing can be classified as subtractive, additive, mass containing, joining, and finishing (Jain et al. 2014a, b). Microversions of almost all manufacturing processes were developed. Hirota (2007) proposed a methodology to form billets (1 mm diameter) by extruding a sheet (2 mm thick) in the thickness direction. Here, the punch presses the sheet at the top surface; as a result, the material from the bottom surface extrudes in a die. The billet remains attached to the sheet surface and can be cut if required. The process is called as microforging. A schematic diagram of the process is shown in Fig. 5.1. In this process, one zone in the material undergoes forging and the other zone undergoes extrusion as shown. There have been a number of attempts to study the size effect on material flow and friction. Size effects can be grouped into three categories—density, shape, and microstructure size effects. Density-size effects occur, when the absolute number or integral value of features per unit volume is kept constant, independent of the size of the object. The features could be small pores, dislocation lines, or interface areas. One example of this size effect is the size dependence of the strength of brittle materials. As the probability of existence of defects (cracks etc.) decreases with decreasing size, the strength gets increased. This effect is expected to occur in the sample of size ranging from 1 to 10 mm. However, in the size range of 100 µm–1 mm, the strength decreases with decreasing size due to the dominance of shape–size effect. Shape–size effects are related to the surface area and volume. When shape is kept constant, due to the reduction in the size of an object, the ratio between total surface area and volume increases, because the volume of a part is proportional to cube of its size, while the surface area is proportional to square of its size. As per surface layer model theory

Fig. 5.1 A schematic view of microforging developed by Hirota. With permission from Jain et al. (2014b). Copyright IMechE 2014



(Engel and Eckstein 2002), the grains located at free surface are less restricted than the grains located inside the material. Therefore, it leads to less hardening and lower resistance against deformation of the surface grains and makes the surface grains deform easier than grains inside the material. For the same grain size with decreasing size of the specimen, the share of surface grains increases, which results in decreasing flow stress of the material. Some experiments showed that the flow stress of smaller piece is lower. The hardness is nearly proportional to flow stress. Hence, micro-indentation can be a viable method of assessing the flow stress of the smaller parts.

In microstructure size effect, the microstructural features are not scaled down in the same manner like the macroscopic size of the object. One example is the intrinsic material length which was introduced to include size effect in the constitutive laws. For each metal, there exists a particular intrinsic material length scale. For example, for a polycrystalline copper, it is 1.54 μm. Therefore, in the polycrystalline copper, the strain gradients of the order 1/1.54 $(\mu m)^{-1}$ are significant. The theory that takes into account the strain gradient effects is known as strain gradient plasticity, which emerged in late 1990 and was further developed in the beginning of this century. This effect is usually observed in the size range of 10 nm–100 μm.

The friction behavior between the die and work interface is greatly affected by the miniaturization. Effect of miniaturization by ring compression test and double-cup extrusion set up was investigated, and it was found that the value of friction factor increases as the size of the billet decreases. In an extrusion process, friction factor increased by 20 times for reduced size when using extrusion oil as lubricant. This behavior has been explained by the open and closed lubricant pockets model (Geiger et al. 2001). The closed pockets are those which are not connected to the edges of the specimen that can retain the lubricant during the process while others are known as open pockets. In a small component, the proportion of closed to open pockets is low. Hence, the lubricant is not retained effectively. Due to this, the real contact area between die and work material increases, which leads to increased coefficient of friction. This increases the friction force. When solid lubricants are used, the friction does not vary significantly with workpiece size. This confirms the model of closed and open lubricant pockets.

5.10 Robotics in Manufacturing

Idea of robots is very old. Puppets and mechanical toys have been found in 5000 year before at Indus Valley Civilization. German astronomer Johann Müller made an eagle that flew before the Emperor Maximillian when he entered Nurnbery (Deb 1994). The first use of the word robot appeared in 1921 in the play Rossum's Universal Robots (RUR) written by the Czech playwright Karel Capeck (1890–1938). The Czech word robota means forced labor. In 1940, Isacc Asimov wrote a science fiction, in which he projected robot as a helper of humankind. He postulated three basic laws for robots. These are as follows:

(1) A robot must not injure a human being. It should also not allow anyone to cause harm through its inaction.
(2) A robot must always obey human being, unless that is in conflict with the first law.
(3) A robot must protect itself from harm, unless that is in conflict with the first two laws.

Asimov also added zeroth law that states that neither a robot must harm humanity nor should allow humanity to come to harm. Fuller wrote the fourth law in his book, ‘A robot may take a human being’s job, but it should not leave the person jobless.’

Robot is defined as a reprogrammable and multi-functional manipulator designed to carry out a variety of tasks that is possible by the hands of a human being. Josheph F. Engelberger tried to develop robots in 1950 (Saha 2008). He and George C. Devol started UNIMATRON Robotics Company in the USA in 1958. UNIMATRON is the contraction of words universal and automation. The first UNIMATRON robot was installed in 1961 in the General Motor’s automobile factory in New Jersey, USA. It was basically a pick and place type of robot. Later on, mobile robots were developed. In 1964–1967, different robotics research laboratories were established at MIT, Stanford, and Edinburgh. The first version of the SHAKEY, an intelligent mobile robot, was built in 1968 at Stanford Research Institute. The second version was developed in 1971. In 1977, General Motors issued specifications for a Programmable Universal Machine for Assembly (PUMA). The first PUMA robot was built in 1978. In 1997, a Pathfinder lander and the microrover landed on Mars. It was developed by NASA.

5.11 3D Printing

Rapid prototyping started in 1980s. The literal meaning of rapid prototyping is that the prototype of a design can be developed very fast. However, commonly rapid prototyping is used for any additive manufacturing technology that deposits the material of the product layer by layer taking data from a CAD model. In 1986, 3D Systems, a California-based company, built a machine on Stereolithography Apparatus (SLA). Charles Hull is recognized as the father of rapid prototyping (Dutta 2010). SLA is a laser-based rapid prototyping process which builds parts directly from CAD by curing or hardening a photosensitive resin with a relatively low power laser. Fused deposition modeling (FDM) was developed by Stratasys company in 1988. Laminated object manufacturing (LOM) was developed by Helisis in USA. Solid ground curing was developed by Cubitol Corporation in Israel. In 1989, DTM of Austin developed Selective Laser Sintering. Multi-jet modeling was developed by 3D Systems. Solygen Incorporation developed 3D printing. After 8 years of selling, stereolithography systems, 3D systems sold its first 3D printer called Actua 2100 in 1996. It uses a technology that deposits wax material layer by layer using an inkjet printing machine. In 2009, 70 individuals from around the world met at the ASTM International headquarters to establish ASTM committee F42 on Additive Manufacturing Technologies. In 2010, Stratus and HP joined hands for manufacturing 3D printers (Wohlers Associates Inc. 2014).

3D printing technology is growing at an exponential rate. Huang et al. (2015) have provided a detailed review of additive manufacturing. Authors have identified 4 technology elements for a viable additive manufacturing—(1) materials development and evaluation, (2) design methodology and standards, (3) modeling, monitoring, control, and processes, and (4) characterization and certification. The current research is focusing on using proper engineering materials for making the 3D products.

5.12 Conclusion

In this chapter, a brief history of manufacturing is presented. New developments in manufacturing are taking place due to the advent of new materials and newer applications. Many new processes are being developed. However, traditional manufacturing processes are not losing their importance. They are getting rediscovered and improvised. There is a lot of expectation from 3D printing technologies and digital manufacturing. Digital manufacturing is the use of an integrated, computer-based system comprising simulation, three-dimensional (3D) visualization, analytics, and various collaboration tools to create product and manufacturing process definitions simultaneously. Also, attempt is being made to develop green and sustainable manufacturing processes.

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Chapter 6
Emergence of Production and Industrial Engineering

Abstract Production and industrial engineering are the offspring of mechanical engineering and started with factory system. The pioneers of these disciplines are Adam Smith, Eli Whitney, H.R. Towne, Henry Ford and Frederick Winslow Taylor. Taylor is often called the father of scientific management. After World War II lot of developments took place in the areas of operations research, quality and productivity. A lot of techniques were invented for enhancing the quality of products and services starting from quality guru Deming to Taguchi. Concepts of lean and agile manufacturing have given boost to productivity. Nowadays, there is increasing emphasis on the automation and use of information technology. Education and practice of production and industrial engineering is adapting to the rapid changes in technologies.

Keywords Quality · Productivity · Industrial engineering · Production engineering · TQM · Taguchi method · Operations research

6.1 Introduction

Production and industrial engineering are basically the offspring of mechanical engineering. They combine the essentials of mechanical engineering, manufacturing engineering and management science with a goal of higher productivity with proper integration of technology, knowledge, information, materials and manufacturing processes, and manpower. Although production and industrial engineering is considered as a combined discipline in many universities in Asia, there are separate disciplines for production engineering and industrial engineering in America, Europe and many parts of the world. Essentially, there is not much difference in the basics of production engineering and industrial engineering. In both the disciplines, manufacturing engineering and management science related topics are given prime importance. The knowledge of manufacturing technology and its proper management is the focus in addition to exposure to basic courses of mechanical engineering. Proper management of resources, manpower and money,

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quality control, optimization and decision making are some important aspects in both the disciplines.

In reality, the working domain of a production engineer and an industrial engineer overlap each other. A production engineer may be considered as an expert in manufacturing technology and its management, whereas an industrial engineer is more adept in utilizing the technology than in developing it. Production process transforms raw material into a product by utilizing the resources for the benefit of the end user. Resources include factories, machineries, equipment, human labor, intelligence and capability, and raw materials. A production engineer is supposed to possess knowledge about various manufacturing processes, machine tools, cutting tools, fixtures, and management issues related to production. His primary focus is to be on higher productivity with cost effective and high quality products. To ascertain smooth functioning of the whole production system, a production engineer has to check the feasibility of the design, compare different materials and manufacturing processes and select the optimum ones for a cost effective high quality product, produce prototype or simulate according to the requirement, ensure timely delivery and tackle all other issues related to production.

On the other hand, an industrial engineer makes an integrated engineering and management approach to analyze, design, and manage manufacturing and service processes, production planning and control, resource allocation and scheduling, eliminate waste, quality control, inventory control, and safety with the assurance of reliability, quality and performance. Moreover, he/she has to possess knowledge in various fields, problem solving capacity and good organizational and human relation skills. According to the Institute of Industrial Engineers, industrial engineers figure out how to do things better. They engineer processes and systems that improve quality and productivity. They work to eliminate the wastage of time, money, materials, energy and other commodities (http://www.iienet2.org/details.aspx?id=716). Industrial engineering is defined as a branch of engineering that deals with the optimization of complex processes and systems (Kahraman 2012). Definition of industrial engineering as given by Indian Institution of Industrial Engineering is, 'Industrial Engineering is concerned with the design, improvement and installation of integrated systems of men, materials and machines. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems (http://www.iiie-india.com/IIIE/industrial-engineering.php). Thus, higher productivity issue is given more importance by the production engineering professionals and overall integration of the production system for higher productivity is given more importance by the industrial engineering professionals. It can be said that production and industrial engineering is a multi-disciplinary approach to achieve higher productivity through optimum utilization of resources in an industry to meet the global challenges in the field. In order to achieve this goal, it is necessary for a manufacturing company to implement the concepts and principles of production and industrial engineering. In the following section, a brief history of the evolution of production and industrial engineering is presented with focus on the noteworthy developments on both the disciplines.

6.2 A Brief History of Production and Industrial Engineering

The history of production and industrial engineering dates back to the later part of the eighteenth century. From the middle ages to this period, all the products were fabricated by individual craftsmen and mechanics according to the specification set by the customer. Products were custom made manually either at home or at small workshops with hand-held tools. Manual, animal effort and flowing water were the sources of power. Historians around the world relate the emergence of production and industrial engineering with the Industrial Revolution (circa 1750–1850). Adam Smith from Scotland put forward his concept of 'division of labor' and laid the foundation for modern economic theory in his book entitled 'The Wealth of Nations' in 1776. His idea of enhancing efficiency and productivity by application of division of labor and specialization motivated many technological innovators of the Industrial Revolution to implement his concepts in factory system of production. Factory system with machines, workers and materials within a building for manufacturing products was established. As a result of the Industrial Revolution, new technologies replaced the traditional manual operations with mechanized ones thus enabling mass production. Some of the pioneers who shaped up this discipline of engineering are Adam Smith (1723–1790), Eli Whitney (1765–1825), H.R. Towne (1844–1924), Henry Ford (1863–1947) and Frederick Winslow Taylor (1856–1915).

The inception of the idea of production engineering can be attributed to the period well before the First World War. The name production engineering was coined as it emphasized on higher productivity with mass production. America was in fear of attack from the British and the French around 1790s. To be ready to face the war with weapons, the government asked Eli Whitney, a Yale graduate (and the cotton gin inventor) to produce 10,000 muskets in two years using jigs (Armytage 1961). This technique led to mass production of interchangeable parts thus saving on time, money and manpower. Later in 1812, 15,000 more muskets were ordered by the government. Simeon North (1765–1852) followed this technique to manufacture large number of pistols and supplied to the government for war. Thus mass production of interchangeable products gradually started. Eli Whitney invented the cotton gin (a machine for separating cotton fibers from their seed) in 1793 which had already revolutionized the cotton industry by replacing manual cleaning of cotton by machine cleaning. His cotton gin technology spread to European and Gulf states. Invention of 'flying shuttle' by John Kay in 1733 and 'spinning jenny' by a Lancashire spinner James Hargreaves in 1770 added to the growth of the textile industry. Richard Arkwright, the Englishman introduced water powered spinning mills thus replacing manual spinning. Turning raw cotton into cloth using a mill in 1812 by Paul Moody and F.C. Lowell had immense effect in the textile industry. Thus mechanization of spinning and weaving during the Industrial Revolution led to mass production and wide acceptance of the new technologies. The British engineer, Charles Babbage followed in the footsteps of Adam Smith by promoting Smith's idea that division of labour led to higher productivity. From the experiences of his visits to factories in England and the United States, he published his book 'On the Economy of Machinery and Manufacturers' in 1832 emphasizing on scientific time and motion study and analytical approach for improving manufacturing methods. Some of the noteworthy names in Britain in the field of production engineering and mass manufacture are Marc Brunel (1769–1849), Henry Maudslay (1771–1831), and Samual Bentham (1757–1831). Marc Brunel and Henry Maudslay invented machinery for mass production of ship's blocks which played a vital role in the war against Napoleon. Bentham helped Brunel and Maudslay in his capacity as a high rank navy officer and also took initiative in mass production of bakery food in a factory.

Henry R. Towne (1844–1924) of America was a pioneer in developing the field of industrial engineering (http://www.stamfordhistory.org/towne1905.htm). He initiated mass manufacture of different items like electric hoist, testing machines, cranes, etc. Towne's company contributed a lot to production and industrial engineering. He presented a paper 'The Engineer as Economist' to American Society of Mechanical Engineers (ASME) in 1886 emphasizing the need to combine production engineering and management for higher productivity.

Frederick Winslow Taylor (1856–1915) of United States is known as the father of industrial engineering (Copley 1923). He was born in Germantown, Philadelphia, Pennsylvania. His contributions may be acknowledged towards both production engineering as well as industrial engineering. In its early stage, industrial engineering mainly focused on improving productivity to which Taylor contributed in various manners. He was basically a mechanical engineer who studied different production processes and invented techniques for improving the efficiency of the production system. Taylor was highly praised for his outstanding invention of high speed steel (a cutting tool material that retains its hardness at elevated temperature) in the Paris World Fair in 1900 (Burstall 1963). He is best known for his efforts to find the 'efficiency' or 'capability' of men and use it in the best possible manner. His scientific approach to personnel management and productivity based on observations and tests with steelworkers in Pennsylvania is his greatest contribution to industrial engineering. By improving the method of working and focusing on efficiency and productivity, Taylor was able to extract higher work outputs from factory workers. Taylor was the first to evaluate human performance and organization in work and his technique was termed as 'scientific management' which was his best gift to the field of industrial engineering. His technique of enhancing work efficiency was based on better work methods, establishing work standards and setting standard time limits to carry out a work. In 1911, he published his book 'Principles of Scientific Management'.

Taylor's introduction of 'Time Study' in doing a work was later carried forward by the couple Frank Gilbreth and Lillian Gilbreth and they introduced 'Time and Motion Study'. Frank and Lillian Gilbreth were of the opinion that for every task, there could be only one best way of doing it. They divided each task into small elements and identified the best sequence (motion) of these elements for the maximum productivity. The philosophy of Taylor spread across America in the early part of twentieth century and industrial engineers across various organizations practically reaped the benefits of the principles. J.S. Lewis and A.J. Liversedge were two British industrialists who followed Taylor's concepts for better production. France, Vienna and Russia also followed suit. Henry Gantt, Elton Mayo, H. Fayol, L. Urwick, M. Weber are some of the names worth mentioning for the growth of production and industrial engineering (Nadler 1992). Henry Gantt developed an activity scheduling chart called 'Gantt Chart' in 1912 to demonstrate the proper schedule of the organizational activities and their relationships. A simplified Gantt chart for launching a new product is shown in Fig. 6.1. Henry Ford (1863–1947), the American giant in the automobile industry first introduced the concept of assembly line in his car company in 1913 and reduced the assembly time of a car significantly. The Ford Motor company enabled mass production of military aircrafts for use in the war. Henry Ford was also a pioneer in providing financial incentives for employees to increase productivity. Thus mass production technology was developed and accelerated after the First World War. There was diverse use of mass production techniques in metal industry, vehicles, electrical and chemical industries and shipbuilding. It spread to different parts of the world and 'Engineering Production' was studied as a subject in Britain. During 1920s, a new breed of mechanical engineers appeared who mostly focused on improving production techniques on the factory floor and they were named as production engineers. Most of the early production engineers were mechanical engineers. As per suggestions of H.E. Honer in 1920, the Institution of Production Engineers was formally formed in 1931 at Glassglow (Armytage 1961). After 1972, the Institute of Production Engineers became known as the Institution of

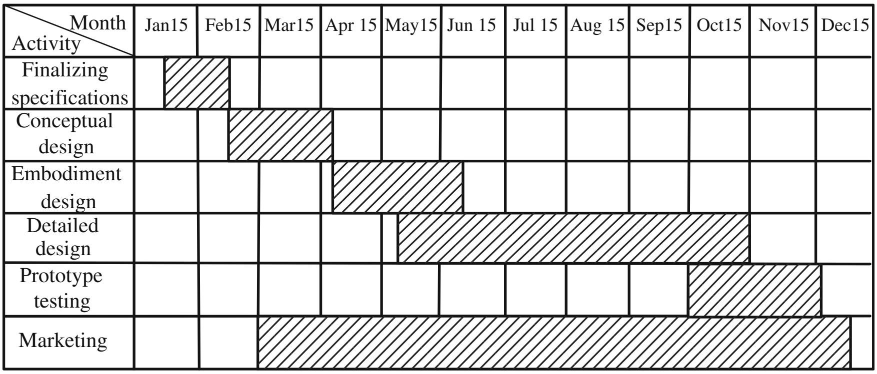


Fig. 6.1 Gantt chart for launching a new product

Manufacturing Engineers, which amalgamated with the Institution of Electrical Engineers in 1991.

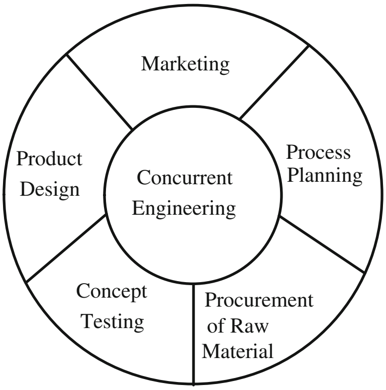
Elton Mayo (1880–1949) led the human relation movement of the 1930s by emphasizing on importance of human relations in industry and its significance for higher production. Elton Mayo, D. McGregor, A. Maslow were some of the prime contributors to the human relation movement. Abraham H. Maslow (1908–1970) was an American psychologist, who is best known for indentifying Maslow's need hierarchy. According to him, first a person wants to satisfy his/her physiological needs. After his/her physiological needs are satisfied, he/she needs safety and security. The third level of human needs is the need for love and belonging. After that he/she needs self-esteem. Finally, one needs to achieve self-actualization. It means that he/she wants to utilize his/her full potential and wants to be perfect. Later on, Maslow identified another need called Self-transcendence, which includes spiritualism and altruism.

Incentives, teamwork, energy expenditure, interpersonal relations, human behavioral aspects, worker's motivation and response, both mental and physical stress associated with work-load were identified as significant factors for productivity. The importance of human factor was identified for enhanced productivity. Thus production and industrial engineering emerged during the World War I and flourished until and after the World War II. There were significant developments in the production technologies during World War II and various war related equipment like automatic airplane pilots, gun-positioning systems, radar, etc. were designed. Different approaches for resource and personal management, layout, storing, scheduling were tried with the use of management science. To enable sharing of knowledge and progressing, American Institute of Industrial Engineers was founded in 1948, however, the word 'American' was dropped in 1981 (http://www.iienet2.org/). In 1950s and 1960s, quantitative management techniques were widely used utilizing mathematics, statistics and computation for modeling and simulation of complex processes. Decision support systems, PERT (Project Evaluation and Review Technique), CPM (Critical Path Method), LP (Linear Programming), OR (Operations Research) technique, MRP (Material Requirement Planning) are some of the techniques developed during this phase. The goal of higher productivity was combined with efficiency and personal management. The industrial engineer has to deal with both personal and organizational issues regarding production process. These developments initiated a new field in industrial engineering known as 'ergonomics' that takes care of the issues related to the human resources (workers). Nowadays, a broader term 'human factors engineering' is used interchangeably with ergonomics.

Gradually, more importance was given to the quality of a product along with productivity and efficiency of the production system. During 1960s and 1970s, the emphasis shifted towards producing fewer and better products from producing in large quantities. The Japanese manufacturing technique 'just in time (JIT)' gained popularity which was conceived as a result of scarcity of manpower, and physical and financial resources after the World War II. JIT is a cost-effective manufacturing method that aimed to eliminate wastage in any form, e.g. wastage of raw materials, manpower, labor, scrap, over production of finished goods, unnecessary material handling, operations, work-in-progress, inventory, machining time, idle and waiting time to name a few. Japan was the pioneer in implementing modern management theories like 'Kaizen' and 'Kanban' and achieved continuous improvement in productivity as well as high quality of the products. These theories were used all over the world by the industries to reap their benefits. This phase is named as the quality revolution in the production system. It started in 1970s and continued till date. Although the concept of TQM (Total Quality Management) had developed much earlier, it gained momentum in 1980s. Pioneering quality gurus are William Edwards Deming (1900–1993), Joseph M. Juran (1904–2008), Philip B. Crosby (1926–2001) and Masaaki Imai (born, 1930).

A number of concepts like JIT, TQM, lean manufacturing, flexible manufacturing system (FMS), agile manufacturing, concurrent engineering, etc. were evolved with the goal of continuous improvement, better quality and minimum waste. JIT manufacturing promotes lean manufacturing instead of mass manufacturing. In lean manufacturing, value addition is done to the product at different stages to ensure the concept of 'quality at the source'. Value addition can be achieved by proper design of the product as well as the processes. Earlier, emphasis was given only on proper design of the product. Concurrent engineering encourages simultaneous working and active participation of all concerned departments such as design, manufacturing, quality control, marketing, finance, supplier, consumer, etc. during the design stage. The concept of concurrent engineering is depicted in Fig. 6.2, in which various engineering activities are carried out simultaneously. All are integrated together and work concurrently towards developing a product and related processes. 'Design for manufacturing (DFM)' and 'Design for assembly (DFA)' are two approaches related to concurrent engineering. Customer's requirements and preferences were considered the key factors for both products and services. There were attempts for total integration of all the components of the production system for efficient, flexible, economic and high quality products and processes. Invaluable contributions of the pioneers of the quality revolution such as

Fig. 6.2 Concept of concurrent engineering



Crosby, Ohno, Taguchi, Deming, Juran, etc. had elevated the industrial production system to a new height.

Beginning from the middle of 1900s, automation started gaining importance in the production industries enabling an entire production sequence to be performed without human intervention thus improving on productivity, quality, and variety. As the potential of Numerical Control (NC) technology for mass production and productivity was perceived, there was profound use of it in the manufacturing industry. NC machines were improved rapidly after the use of computers as the controlling unit and renamed as CNC (Computer Numerical Control) machines. The CNC technology is widely used in machining processes like turning, drilling, milling, shaping, etc. CNC technology has paved the way for computer aided engineering (CAE), computer aided design (CAD), and computer aided manufacturing (CAM) thus revolutionizing the production process. CAD/CAM enables faster design, modification, production, testing and redesign if needed. Computer aided process planning (CAPP) bridges the functional gap between CAD and CAM. Integration among different functional areas within a manufacturing industry is essential for improvements in quality, efficiency, cost and time. Computer integrated manufacturing (CIM) integrates human resource, machines and facilities, databases, and management thus building a network within the organization for sharing of related information. Each of design, process planning and production planning, manufacturing, quality control and other support functions act as a part of a unified system in CIM rather than a stand alone system. Certain standard protocols such as 'technical and office protocol (TOP)' and 'manufacturing automation protocol (MAP)' are followed for communication among different departments and offices in an organization. One of the major difficulties in integrating CAD-CAPP-CAM is the communication gap due to incompatibility of equipment and software. Over the last three decades, standard generic data exchange formats like IGES (Initial Graphics Exchange Standards), STEP (Standard for the Exchange of Product Model Data), DXF (Data eXchange Format) have been developed that can be used by all CAD-CAPP-CAM users for effective communication of information. Application of artificial intelligence (AI) techniques and robotics in production process is another milestone in its history.

With the advent of Internet technology and World Wide Web in 1990s, production and industrial engineering has reached a new milestone with globalization effects. Enhancing flexibility and customization, and catering to global population are the major achievements. The competitions among the organizations are stiff as global market is accessible to the customers all over the world. To deliver the best product at the minimum cost and at the shortest time, they have to implement methods for continuous improvements. With the ever changing customer's need and taste and change in the global market, manufacturing companies have to deal with these challenges to be in business. Customers now want both variety and quality in products. Moreover, their preferences change more frequently leading to shorter life cycle of a product. The manufacturing industries have to innovate ways to reduce the time taken to design, manufacture and market the product. Adaptation to the changing scenario is a crucial factor in this era of lean and agile manufacturing. Leagile manufacturing combines the advantages of both lean and agile manufacturing. There is continuous improvements and redesigning of products to meet the customer's demand. Flexibility is the call of the day and it is essential for a manufacturing organization to adapt to the changes in the product design, technology, environment, facilities, requirement, customer's preference and management rules. Cellular manufacturing system and reconfigurable manufacturing system (RMS) approaches are suitable for agile and flexible manufacturing environment. Reconfigurable machine tools play an important role in dynamic and adaptable manufacturing methods. Java and Web technologies provide a common platform for the collaborative design, manufacturing and marketing of a product enabling transfer of information among various organizations. Web-based production systems have been developed to facilitate sharing of production knowledge through the Internet. In this era of agile and virtual manufacturing, a part can be designed, manufactured and marketed in different sites across the globe. In 2000s, application of the state-of-the-art technology and modern techniques of management science has expanded the horizon of production and industrial engineering thus enabling to encompass diverse fields, viz. manufacturing and other industries, business enterprises, retail stores, educational institutes, banking, hospitals, healthcare and airlines.

6.3 Attempts to Improve Quality and Productivity in the Last 100 Years

The most of the research in industrial and production engineering is focused towards improving the quality of the product and productivity of the manufacturing system. There are several definitions of quality. A working definition can be as follows: "The quality of a product is good if it satisfies the customer's explicit and hidden expectations from the product." The productivity is the ratio of output to input. When a manufacturing system takes small amount of resources for making the product, it is said to be productive. There have been always attempts to improve quality and productivity, but real scientific approach started from the time of F.W. Taylor. Later on Walter A. Shewhart (1891–1967) introduced statistical quality control in 1924. In 1931, his book entitled "Economic Control of Quality of Manufactured Product" was published, in which the concept of control chart was introduced (Buffa and Sarin 1994). Control charts help to identify if any variation in the quality of the product is due to random causes or assignable causes and if the process is under control. Random causes are inherent in manufacturing system and there are so many of them. To reduce the effect of random causes, one needs to drastically improve the process or replace it by a better process. On the other hand, assignable causes are less in number and can be easily identified and eliminated. For example, when the parts are being machined on a lathe machine, there will be some variation in the dimensions of the components due to a variety of reasons.

The magnitude of these variations is dependent on the quality of the lathe machine. However, once the tool is sufficiently worn, there will be significant change in the dimensions and variation will no longer be confined within control zone. In that case, one can identify the cause and replace the tool. Shewhart is called as the father of statistical quality control by many.

After the concept of statistical quality control, the concept of total quality management (TQM) became popular in industries. TQM is an organization approach to management—an organization approach of managing for total quality, of managing for effectiveness and competitiveness, involving each and every activity and person at all levels in the organization (Logothetis 1992). William Edwards Deming (1900–1993) is a pioneering quality guru. He was born in Sioux City, Iowa on 14th October 1900. After obtaining a BS degree in electrical engineering at the University of Wyoming in 1921 and MS from the University of Colorado in 1925, he gained Ph.D. in mathematical physics at Yale in 1928. He worked up to 1939 at US department of Agriculture. During 1939–45, the American Bureau of Census and the US weapon industry were greatly benefitted by his advice. He first visited Japan in 1946 and returned there in 1948. He has provided consultancy to a number of Japanese firms. In his honor, Deming Prize was established in Japan in 1951.

Deming has provided 14 points guideline for the management. These are as follows:

(1) Create constancy of purpose for continual improvement. Long term planning is also implied in it.

(2) Learn a new philosophy for economic stability. Many a times a completely new management philosophy is needed for halting the continued decline of an industry.

(3) Do not depend on mass inspection. It implies that attempt should be to build quality in the product by improving the process, rather than inspecting each and every product. Sampling inspection may be carried out once there is confidence in the quality of a manufacturing system.

(4) Reduce the number of vendors. Long term business associating of loyalty and trust is desirable. It is not a good practice to award business to the firm quoting the lowest price.

(5) Improve constantly and continuously the system of production and services.

(6) Institute on-the-job training.

(7) Adopt and institute modern methods of supervision and leadership. Leadership and supervision should focus on making the workers take interest in the work. Continuous improvement should be carried out by the management.

(8) Drive out fear. Fear is barrier to improvement and innovation. Management by fear should be avoided.

(9) Break down barriers between departments and individuals. Everyone should work as a team.

(10) Eliminate the use of slogans, posters and exhortations. Instead of trying to preach the workers, system should be improved.

(11) Eliminate work standard and numerical targets. Eliminate management by objectives and by numerical goal. The focus should be on quality rather than on quantity.

(12) Let the workers take pride in their workmanship. Annual performance appraisal should be abolished as it creates fear in the mind of workers.

(13) Encourage the workers for learning new techniques. Hence, a vigorous system of education and training should be in place.

(14) Define top management's permanent commitment to ever-improving quality and productivity. Unless the top management is committed the quality cannot be achieved. According to Deming "Quality is made in the Board room and limitations on quality are also made in the board room."

Deming also identified 5 deadly sins. These are lack of constancy, short-term profits, performance appraisals, job-hopping and use of visible figures alone. Deming has proposed to use a cycle that he named the Shewhart cycle. It is also called PDCA (plan, do, check and act) cycle. Some of his famous quotations are as follows:

"The workers are handicapped by the system and system belongs to the management."

"Defects are not free; somebody makes it and gets paid to make them!"

"The job of management is not supervision but leadership."

"Secure: 'se' comes from Latin meaning "without", 'cure' means 'fear' or 'care'; 'secure' means 'without fear'. No one can give his best performance on the job unless he feels secure in the job."

"You do not have to do this; survival is not compulsory!"

Another famous quality guru is Dr. Joseph Juran (1904–2008) whose famous quotation is "Quality does not happen by accident; it has to be planned." He was born in Romania. In 1937, he created "Pareto Principle". It is the rule of "vital few and trivial few". For example, about 20 % causes might account for 80 % failure. Hence, one should concentrate on 20 % causes first. Dr. Juran helped a number of Japanese industries since 1954.

Philip B. Crosby (1926–2001) was born in West Virginia. In 1979, he wrote a best-seller book entitled "Quality is Free". His other famous books are "Quality without Tears" and "The Art of Getting Your Own Sweet Way". He provided the concept of "Zero Defects" and "Do it right first time." He has suggested 14 steps for quality improvement. These are as follows:

(1) Top management has to demonstrate commitment for quality.
(2) A quality improvement team must be formed in the organization.
(3) A proper method of measurement of quality must be in place.
(4) The proper estimation of cost of quality is required for drawing the attention of the management and proper planning.
(5) Awareness about the quality should be created.
(6) The corrective actions should be taken. They should be based on analysis of past data so that permanent solution can be found.
(7) Proper planning is needed for achieving zero defects.

(8) Education of employees for achieving quality is needed. The entire education system comprises “the six C’s”—comprehension, commitment, competence, communication, correction and continuance.
(9) A zero defect day should be celebrated. This contradicts the teachings of Deming who was against exhortations.
(10) The setting of a goal, for example achieving zero defects, is needed. On the other hand, Deming was against setting arbitrary targets.
(11) With a team effort, the cause of an error should be permanently removed.
(12) The persons responsible for improving quality should be recognized.
(13) Quality council should be formed to take appropriate steps for improving quality.
(14) Quality improvement is a continuous process and all the above steps should keep on repeating.

Another quality guru Masaaki Imai, born in 1930 in Japan, has provided the concept of kaizen that means continuous improvement. He has authored following popular books:

- The Japanese Businessman: An Introduction to His Behavior And Business Strategy (published in 1975)
- Never Take YES for an Answer—An Inside Look at Japanese Business for Foreign Businessmen (published in 1978)
- 16 Ways to Avoid Saying No (published in 1985)
- Kaizen: The key to Japan’s competitive success (published in 1986)
- Gemba Kaizen ((published in 1995)
- Gemba Kaizen: A Common Sense, Low-Cost Approach to Management (published in 1997)

Another famous person to propagate quality is Ishikawa, who developed cause and effect diagram (or Ishikawa or fishbone diagram). Figure 6.3 shows a typical fishbone diagram for the performance of a microforming system. The performance of a microforming system depends on the 4 main factors—equipment, material parameters, process parameters and tooling. Each of these factors comprises several sub-factors. This diagram helps to focus the attention on the responsible factors for improving the quality.

One famous name in the arena of quality is Dr. Genichi Taguchi (1924–2012). He was born in Tokamachi, Japan and studied textile engineering at Kiryu Technical College. After World War II, he worked for the Japanese Ministry of Public Health and Welfare. Taguchi has contributed a lot to applying statistical methods for offline and online quality control. Offline quality control involves taking suitable measures at the product or process design stage, whilst online quality control is carried out during actual production. In statistics, Taguchi was mentored by Prof. Masuyama.

Taguchi defined quality in a negative way. According to him, it is not enough that a product is within the specification limits. The moment a product deviates from the target, it incurs a loss that can be expressed in monetary terms. More the

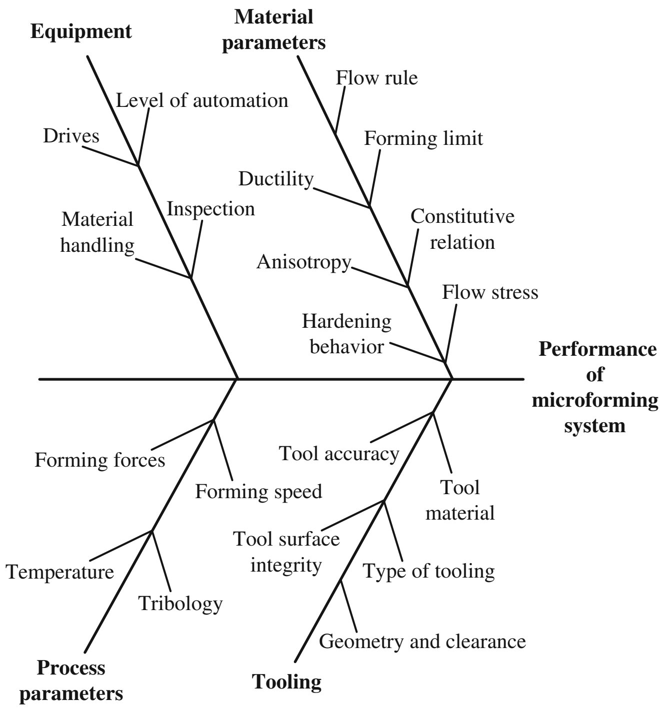


Fig. 6.3 A fishbone diagram showing the effect of various factors on the performance of a microforming system. With permission from Jain et al. (2014). Copyright IMechE 2014

deviation from the target, the more is the loss. Taguchi also provided a quadratic loss function that converts deviation into the corresponding monetary loss. It can be expressed as follows:

$$L = kd^2, \tag{6.1}$$

where L is the loss in dollar, d is the deviation and k is a constant. The constant can be easily evaluated. As a simple example, suppose the desired length of a component is 50 mm, but lower limit of 49 mm and upper limit of 51 mm is accepted. If the cost of component is \$100, we can consider that the loss is \$100 as soon as the deviation becomes 1 mm, because the component will be discarded as soon as the deviation exceeds 1 mm. Using Eq. (6.1), k comes out to be 100 \$/mm^2. If some component's length is 50.5 mm, Eq. (6.1) provides corresponding loss as \$25. The objective of quality control is to minimize the total loss.

Taguchi also suggested using orthogonal array in the design of experiments to find out the influence of various factors. There are two types of factors influencing the product quality—controllable (or design) factors and uncontrollable (or noise) factors. The controllable factors can be easily identified and adjusted. On the other hand uncontrollable factor are random factor and it may be difficult to control. Hence, the design itself may be made robust enough to tolerate uncontrollable/noise factors. For example, in a typical non-air-conditioned machine shop, the operator can easily choose cutting speed, feed and depth of cut, but the control of the temperature of machine shop is not in his hand. Therefore, the machining strategy should be designed in such a way such that machining accuracy is not affected significantly by the temperature of the machine shop.

Now suppose there are 6 factors in the process and each factor can take a high and a low value. In order to find out the best setting, one may carry out $2^6 = 64$ experiments. This is called full factorial design and suffers from the drawback of need to carry out huge number of experiments. Taguchi suggested using fractional factorial design with the help of so-called orthogonal arrays. Orthogonal arrays were introduced by Sir R.A. Fischer (1890–1962) in 1930s. Further developments were carried out by Plackett and Burman in 1946. Taguchi presented them in the simplified form so that practicing engineers could use it easily.

Other contributions of Taguchi include the concept of Signal to Noise ratio for assessing the relative effect of random factors. He suggested designing a product in a robust manner, so that the noise factors do not make significant change to performance. He also suggested the methods for proper tolerance design.

Significant developments for enhancing the productivity were carried out by Henry Ford (1863–1947) in automobile sector. He founded the Ford Motor Company in 1903. Ford employed the concept of assembly line production. In his autobiography published in 1922 (Ford 2006), he described the concept of Just-in-Time (JIT). JIT aims at achieving Zero inventory. Nowadays, JIT production is also known as Toyota Production System (TPS), which became very popular in Toyota Motor Corporation in 1960s and 1970s. Taiichi Ohno (1912–1990) may be called the father of TPS. He identified 7 types of Muda (waste)—defects in production, overproduction of goods, inventory, unnecessary processing, unnecessary movement of people, unnecessary transport of goods and waiting by the employees. Womack and Jones (2013) added eighth muda—design of goods and service that do not meet user's need. Elimination of Muda is an essential requirement of lean manufacturing. Mura (Japanese word for any variation leading to unbalanced situation, unevenness and inconsistency) and Muri (Japanese word for overburden) also need to be eliminated. Starting from 1990s, agile manufacturing has become very popular. Combination of lean and agile is called leagile.

Mathematical techniques for enhancing productivity were dominated by operations research starting from Second World War. In fact the name operations research pertains to application of optimization techniques in military operations. These included linear programming, transportation models, scheduling, queuing theory and network models. Nowadays, there is increasing emphasis on Big Data analysis and sustainable manufacturing. Sustainable manufacturing means the type of manufacturing which preserves the resources for future generations while meeting the needs of the present generations.

6.4 The Course Structure of Production and Industrial Engineering Discipline

Initially production engineering and industrial engineering were considered as two separate disciplines although both were combined to be named as production and industrial engineering at a later point of time. However, universities of different countries use different name for the discipline. Mostly, it is called industrial engineering in the western countries and production and industrial engineering in the Asian countries. The content of both the branches are similar and overlap each other and they strive for the same goal of higher productivity and quality.

There are several handbooks of industrial engineering for example, one by Nadler (1992), which provide excellent definitions of industrial engineering. Industrial engineers use the most effective ways to use man, machine, materials, money, information and energy for making a product or carrying out a service. They act as a bridge between management and core engineering. They need the knowledge of technology, management, economics and computer science.

Some important areas of industrial engineering are (http://www.iiie-india.com/IIIE/industrial-engineering.php):

- *Strategic Planning* involving research and development, technological, economical and market forecasts, investment analysis, manufacturing strategies, product/service range, global trend, etc.
- *Product/Service Design* involving innovation, customer needs, value analysis, product quality and reliability, process design, standardization, world standards, upgradation, replacement, etc.
- *Work System Design* involving operations analysis and design, plant layout and material handling, automation, cost, financial and budgetary controls, productive maintenance, FMS, TQM, employee training modernisation, global developments, etc.
- *Supply Chain Management* involving materials management, analysis of supply chains, transportation, facility, decisions-network and information technology (IT) in a supply chain.
- *Human Resource Management* involving skill analysis, forecasting, manpower planning, employee motivation and retention, redeployment, appraisal, counseling, personal development, etc.
- *Use of Communication and Information Technology* for quantitative analysis, information systems, networking, and all computer-assisted functions including CAD/CAPP/CAM.

Production and industrial engineering courses offer education both in engineering, management and business related topics. In addition to basic courses related to mechanical, production, and manufacturing engineering, management and business-oriented subjects like operations management, management science, operation research, project management, financial engineering, quality engineering, etc. are included. Although production and industrial engineering courses were offered much earlier in the western countries, it was introduced in the developing countries much later. Universities across the world offer bachelor, master, and doctoral degree in this branch. Production engineering courses became more popular after World War II. In India, the first department of Production Engineering was established in 1959 at Veermata Jijabai Technological Institute (VJTI), Mumbai. Initially it was known as Department of Industrial Engineering. In 1974, an undergraduate program in Industrial Engineering was offered in University of Roorkee. Some of the best institutions of global fame offering degree in industrial engineering are Georgia Institute of Technology, University of Michigan, and University of California.

Essentially, there is not much difference in the course structure of production engineering and industrial engineering. In both the disciplines, manufacturing engineering and management science related subjects are given prime importance in addition to exposure to basic courses of mechanical engineering. Syllabus for production and industrial engineering basically include the following subjects:

Engineering Mathematics containing Linear Algebra, Calculus, Differential Equations, Complex Variables, Probability and Statistics, and Numerical Methods.

General Engineering containing Engineering Materials, Applied Mechanics, Theory of Machines, Machine Design, and Fluids and Thermal Engineering.

Production Engineering containing Metal Casting, Metal Forming, Metal Joining, Machining and Machine Tool Operations, Tool Engineering, Metrology and Inspection, Powder Metallurgy, Manufacturing Analysis, and Computer Integrated Manufacturing with CAD/CAM.

Industrial Engineering containing Product Design and Development, Engineering Economy and Costing, Work System Design, Facility Design, Production Planning and Inventory Control, Operation Research, Quality Management, Reliability and Maintenance Management, Information System, and Intellectual Property Rights.

6.5 The New Frontiers

Production and industrial engineering has come a long way from the primitive stage of home made products with hand-held tools. Fuelled by the latest inventions of science and technology, men's intelligence and the urge for continuous improvement have shaped it to its state-of-the-art form. Some of the cutting edge technologies and methods used in production and industrial engineering are briefly mentioned in this section.

Automation: Automation means performing functions without human intervention using the latest technologies. Automation in manufacturing refers to the application of robotics, CNC machines, and automated guided vehicles (AGV), etc. for production in an industry. Automation in manufacturing is mainly used in machining, welding, transportation, assembly, inspection, quality control, packaging, etc. Automation imparts higher consistency and quality, reduction of errors, lead time and delivery time, simplification of production process, minimum material handling, and improved work flow.

Robotics: Robotics was first introduced in the 1970s in the manufacturing industry. Robotics is the application of mechanical engineering, electrical engineering and mechatronics to create robots. A robot is a reprogrammable manipulator which is pre-programmed to interact with the environment for performing specific functions. A robot can carry out tasks done by a human being and may possess intelligence and decision making capability. Robots are very useful for tasks that are dangerous, unpleasant, repetitive and inaccessible for human beings. It is designed to perform different jobs such as moving materials, parts, tools and other specialized devices in an industry, welding, machining, assembly work, household tasks, perform surgery, cleaning, repairing, space exploration, and a variety of tasks through various programmed motions. Robots are used extensively in manufacturing engineering. Use of robotics imparts automation, saves labour, and ensures better quality.

CNC Machine: Automation is of supreme importance in the modern manufacturing industries for improved productivity, quality, novelty and variety in products. Computer Numerical Control (CNC) can be defined as a form of programmable automation which is used for the operation of different machine tools. CNC technology is widely used by the industry where a program of instructions (codes) is stored in the memory of a computer. Once the complete program is fed and activated in the CNC controller, the machine automatically performs the machining operations to achieve the final component. Computers provided an easier programming environment and flexibility. The use of CNC technology has led to higher state of automation thus reducing operator intervention. It can be operated automatically to produce components in large quantities thus improving productivity. CNC technology has paved the way for computer aided design (CAD) and computer aided manufacturing (CAM). CNC revolution accelerated in the 1970s and the 1980s with development of a number of CNC companies in the US and Germany followed by Japan. The latest CNC machines have microprocessor based control system with feedback for higher efficiency. Adaptive control is possible in the microprocessor based CNC machines to cope up with the changing environment. It incorporates feedback and optimal control through continuous monitoring and optimization of the machining parameters. Adaptive control is more accurate, precise and advantageous for machining complex shapes. CNC software programs like Enhanced Machine Controller (EMC) and Mach3 were made available as open source programs for personal use in 2003 (Groover and Zimmers 1984). Thus CNC technology has revolutionized the manufacturing industry.

Mechatronics: Mechatronics is the synergistic integration of mechanical engineering with electronics, electrical engineering and control engineering supported by computer engineering, information technology, and telecommunication engineering for better design, manufacture and operation of products and processes. During the 1970s, there was a change in the technology of products and equipment with incorporation of electronic components with the mechanical systems thus giving birth to mechatronic products. Mechatronics is applicable in production and industrial engineering field in several key areas, for example in robotics, intelligent motion control, automation, actuators and sensors, and modeling and design of product and processes. A CNC machine is a mechatronic product. Mechatronics played a pivotal role in the development in robotics in the 1970s. There has been tremendous application of mechatronics in production system such as in robotics, flexible manufacturing systems (FMS), CAD/CAM, automated guided vehicles (AGV), data communication systems, and the list goes on. Future of mechatronics has extreme potential as the application area of mechatronics encompasses all spheres of human lifestyle.

Rapid Prototyping: In today's competitive market, the industries have to innovate ways to reduce the time taken to design, manufacture and market the product. Recent technology like Rapid Prototyping (RP) can directly fabricate a scale model of a part from 3D CAD model thus enabling faster ways of manufacturing a part. Rapid Prototyping has emerged as a frontier technology in the recent times for its obvious benefits. It tremendously reduces the manufacturing lead time. In RP technique, need for prototype development is eliminated and parts are fabricated layer by layer using some additive manufacturing process. Another contribution of RP to the conventional manufacturing industry is the rapid production of complex shaped tools which is not possible by conventional machining processes. Moreover, the product data in the 3D CAD model can be used for performance and cost analysis, engineering analysis regarding strength, structure, etc., customization of the product and for interactive use during design and manufacturing stages. RP is preferred for customized products like ear plugs for hearing aids, prosthetics of body parts, cosmetic dentistry where the data from CT scan, MRI can be directly used for fabrication. RP technique has immense potential for the future and can be extended to other functions in engineering in addition to manufacturing. Research is going on to bring in a new era of e-manufacturing by improving the present RP techniques.

Flexible manufacturing system (FMS): Flexibility in manufacturing system allows some changes in the product without interruptions in production for incorporating the changes. It allows the manufacturing system to react to changes and modifications. Flexibility is a desired criterion in this age of ever changing customer's choice. Manufacturing systems that possess flexibility are called FMS. FMS can readily adapt to a new product design. To be flexible, a manufacturing system should have the capabilities of identification of the different work units, ability for quick changeover of operating instructions and physical setup, and shorter fixturing and tool changing time. FMS enables the ability to change the order of machining operations executed on a part and also the system's ability to absorb large-scale changes in volume, capacity, or capability. Most of the FMS systems comprise the facilities (machines and equipment), material handling system, and a computer to control all the functions. FMS is advantageous for managing manufacturing resources like time and effort in order to manufacture a new product.

Computer integrated manufacturing (CIM): CIM is the integration of all the functions associated with manufacturing using computers and data communications systems coupled with management science that improve organizational and personnel efficiency. It aims to integrate all of the operational and information processing functions in manufacturing from design through manufacture to product delivery. Development of computer numerical control played an important role in CIM. The use of computers in design and machining led to CAD and CAM. An integrated approach to computer-based automation with CAD and CAM gave rise to the concept of computer integrated manufacturing (CIM). This integration allows the processes to exchange information and to initiate actions among them. CIM was developed catering to the demands for more product variety, better quality, and lower prices in an ever changing global market. Application of CIM makes manufacturing faster and error-free. CIM integrates capital, manpower, technology, and equipment through effective communication for higher productivity and quality in products.

6.6 Conclusions

In this chapter, a brief history of the emergence of production and industrial engineering is presented. Significant developments in its evolution, education and course structure, and the profession of production and industrial engineering are highlighted. New technologies and their possible application for improving productivity and quality of product, process, and service are briefly discussed.

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Chapter 7
History of Mechatronics

Abstract In late twentieth century, a new discipline of engineering emerged as an offspring of mechanical engineering and electronics. The term mechatronics was coined by Tetsuro Mori and was trademark of Yasakawa Electric Corporation from 1971 to 1982. In order to understand the evolution of mechatronics, one needs to understand the evolution of mechanical, electrical, electronics, and computer engineering. A brief history of electrical, electronics, and computer engineering is presented in this chapter. The discipline of mechatronics is evolving. Some discussion about latest trend in technology is also presented.

Keywords Electrical engineering · Electronics · Computer engineering · Robotics · Magnetism · Smart sensors · Automated guided vehicles

7.1 Introduction

Mechanical Engineering is one of the oldest but perhaps the most dynamic discipline of engineering. Human beings have been using machines since times immemorial. Lever was used before the period of Aristotle (384–322 BC). In the beginning machines were powered by human power and later by animal power. Subsequently, use of air and water power gained popularity. Ships were moved by wind and flour mills were run by waterwheel. With the advent of steam engine, the industrial revolution (1750–1850) started. The use of human, animal, air, and water power diminished in favor of steam power. Today steam engine is obsolete, but steam is used as a power source to run steam turbines. In the nineteenth century, electrical motors were invented. They were found much superior to bulky and smoky steam engine. Hence, it was quite natural that use of electricity to power machines became common. Design, manufacturing, and maintenance of machines needed mechanical as well as electrical engineers. However, mechanical engineers took a leading role in the design of machines. Electrical engineers had to adapt as per the requirements of mechanical engineering and when they could not meet the requirements, mechanical engineers used to modify the design.

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Materials Forming, Machining and Tribology,
DOI 10.1007/978-3-319-42916-8_7

Meantime, the birth of electronics took place. The history of electronics started with the development of a primitive vacuum tube by Thomas Alva Edison (1847–1931) in 1883, but the momentum was gained after the invention of the transistor by John Bardeen, Walter Brattain, and William Shockley, who were jointly awarded the 1956 Noble Prize in physics for it. Integrated circuits were developed starting from 1950. Afterwards, electronics found extensive application in machine tool and robotics. Japanese engineer Tetsuro Mori of the Yasakawa Electric Corporation coined the term mechatronics. In 1971, the trademark rights for the term mechatronics was granted to Yaskawa, who abandoned the right in 1982. After that the term gained popularity as a separate discipline of engineering. It can be said that mechatronics was born by the marriage of mechanical and electronics. It has the genes of both but is different from mechanical as well as electronics. A mechatronic product is different from mechanical and electronics products. Nowadays, mechatronics encompasses several disciplines. It can be defined as follows (Dixit 2012):

> Mechatronics is the synergetic integration of mechanical engineering with electrical engineering and/or electronics and possibly with other disciplines for the purposes of design, manufacture, operation, and maintenance of a product.

The term 'synergetic' is very important in the definition. It indicates a concurrent and cooperative approach of various disciplines.

In this chapter, the growth of mechatronics starting from 1970s will be discussed. For the ease of understanding of the developments in mechatronics, brief histories of electrical and electronics engineering are also presented. Finally, the future trends are discussed.

7.2 A Brief History of Electrical Engineering

The knowledge of electricity dates back to sixth century BC. Thales of Miletus (circa 620 BC–circa 546 BC) observed that when amber is rubbed with fur, it gains the property of attracting other materials like feather. This phenomenon is due to static charge produced by friction. Amber is a fossilized tree resin of an extinct coniferous tree. The word electricity originated from the amber. In Greek, the word elektron is used for amber, which implies 'like a beaming sun'. Amber is a gold-like stone that looks orange and yellow in sunlight. In classical Latin, electrum means amber. In Latin, the word electricus means 'of amber'. William Gilbert (1544–1603) used the word electricus in his book De Magnete published in 1600. William Gilbert is regarded as the father of electrical engineering by many historians. Sir Thomas Browne (1605–1682) used the word electricity in 1646 in his book Pseudoxia Epidemica (first edition in 1646, the last edition in 1672), that includes his experiments with static electricity and magnetism.

The magnet was known to mankind since about 2660 BC. A naturally magnetized mineral magnetite was called lodestone. It can attract iron. The lode means 'journey way'. Sailors used to carry it for knowing the direction. The world magnetite might have come from the name of a shepherd, Magnes, whose shoe nails stuck to a rock containing magnetite. There is an alternate story about a region of Macedonia called Magnesia, where magnetite was found in abundance. First written reference to lodestone occurs in the writings of sixth century philosopher Thales of Miletus. The lodestone was used as a magnetic compass around 800 AD, but the written records date around 1200 AD. A letter written in 1269 by Peter Peregrinus gives instruction for making a compass (Bowers 1990).

William Gilbert started the scientific study of electricity and magnetism. He was born in Colchester and educated at Cambridge. In 1600, he became physician to Queen Elizabeth I. He discovered laws of magnetic repulsion and attraction and meaning behind magnetic dip. He also differentiated between attraction due to static electricity and that due to magnetism. He invented the first electroscope to detect charge, which was a pivoted needle called versorium.

Otto von Guericke (1602–1686) was the first person to develop an electrical machine for producing electricity. In 1663, he fabricated a machine, which had a spherical ball made of sulphur with a wooden rod passing through the middle of sphere. The ends of the rods were supported so that the sphere could easily rotate. When the rotating sphere was rubbed by hand, it developed electrostatic charge. The spherical ball was able to attract small objects like feathers. Otto von Guericke is famous for conducting an experiment in 1657, in which he sealed two hollow hemispheres and created the vacuum inside them. Eight horses on each side were employed to pull the hemispheres apart, but it could not be pulled. With this experiment he demonstrated that the theory that nature abhors vacuum is incorrect.

Stephan Gray (1666–1736) was the first to systematically study the conduction of electricity. He observed that some materials are the conductors of electricity, while some others were insulator. Until that time, there was no means to store electrical energy in a battery. In 1745, the Leyden Jar was invented, which is a primitive form of capacitor. It was invented independently by German cleric Ewald Georg von Kleist on 11 October, 1745 and by Dutch scientist Pieter van Musschenbroek of Leyden in 1745–1746. The invention was named on the name of the Leyden city. It is a city in the Dutch province of South Holland. In 1752, American statesman Benjamin Franklin (1706–1790) conducted a dangerous experiment to prove that lightening in a thunderstorm is basically electricity. He flew a big kite with the help of conducting threads. The kite reached up to the clouds. Lightening produced there was conducted through the threads into a Leyden jar. It was observed that the jar has charged. Thus, it was proved that the lighting is electricity, and also that it can be conducted. Franklin suggested protection of building by putting pointed lightening conductors. Pointed conductors will attract charge and pass on to the earth. Franklin's explanation about protection from lightning is not very accurate from the point of view of latest research. Current field studies suggest that the tips of the conductor need not be sharply pointed.

In 1787, Abraham Bennet (1749–1799) developed a gold-leaf electroscope to detect the electrical charge. The basic principle is to transfer some charge on two gold leaves, which repel each other after receiving the charge. Charles-Augustin de

Coulomb (1736–1806) and John Michell (1724–1793) independently invented torsion balance (also called torsion pendulum) to measure the weak forces. The torsion balance consists of a bar suspended from its middle by a thin fiber. The fiber acts like a very weak torsion spring. When a force is applied at the end of the bar, it undergoes an angular displacement proportional to the applied force. Coulomb used this instrument and arrived at his law of electric force in 1784. The law states that the force acting between two charges is directly proportional to the product of the charges and inversely proportional to the square of distance between them. Further, the like charges repel each other and unlike charges attract each other.

In early 1790s, Allessandro Volta (1745–1827), Professor of Natural Philosophy at Pavia, developed the first electric battery that could provide electric current to a circuit. Volta stacked several pairs of alternating copper and zinc discs separated by brine soaked cardboards, thus making a pile. The top and bottom of pile were connected by wires, and circuit was completed. In 1806, Sir Humphry Davy (1778–1829) proved the chemical nature of the voltaic cell (Krishnamurthy and Raghuveer 2001). Using electrolysis with the help of voltaic pile, he split common compounds to make many new elements. The first mass produced battery was designed by William Cruickshank after 1800 (Bowers 1990). Michael Faraday (1791–1867) used these batteries in his early researches and used a mixture of nitric acid, sulfuric acid, and water in volume ratio of 1:3:97 as an electrolyte.

In 1820, Danish physicist Orested provided a law that a steady electric current creates a magnetic field around it. It is the first law relating magnetism and electricity. Around the same time, Ampere provided a law that for any closed loop path, the sum of the length elements times the magnetic field in the direction of the length element is equal to the permeability times the electric current enclosed in the loop. The Biot–Savart law is used for computing the resultant magnetic field at a position generated by a steady current. William Sturgeon developed first electromagnet in 1825.

Michael Faraday (1791–1867) contributed a lot in the field of electromagnetism and electrochemistry. He is called the father of electricity by many. Initially, he worked as an assistant of Humphry Davy (1778–1829). In 1821, Faraday made two devices, which may be called the early electrical motors. These were of not practical value. In 1831, he provided laws of electromagnetic induction that establishes the basis for the design of electrical machines. The first law states that any change in the magnetic field of a coil of wire will cause an electromotive force to be induced in the coil. This electromotive force induced is called induced electromotive force and if the conductor circuit is closed, the current will also circulate through the circuit, and this current is called induced current. The second law states that the magnitude of electromotive force induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of number of turns in the coil and flux associated with the coil. Joseph Henry (1797–1878) discovered the phenomenon of self-inductance. Self-inductance is defined as the induction of a voltage in a current-carrying wire when the current in the wire itself is changing. In the case of self-inductance, the magnetic field created by a changing current in the circuit itself induces a voltage in the same circuit. Therefore, the voltage is self-induced. Heinrich Friderich Emil Lenz (1804–1865) was a Russian physicist who is popular for formulating Lenz's law of electrodynamics in 1833. It states that if induced current flows, its direction is always such that it will oppose the change which produced it. The symbol L is used for inductance in the honor of Lenz. Similarly, the unit of inductance is used as henry in the honor of Joseph Henry. The inductance of an inductor is one henry when an electric current changing at the rate of 1 A/s produces one volt of electromotive force across it.

Chemical cells were the main source of electricity until the advent of practical generators in 1860s. History of magnetoelectric generators started from 1830s. In 1832, Persian instrument maker Hippolyte Pixii (1808–1835) made a hand-turned magnetoelectric generator. William Sturgeon invented a metal commutator, which ensured that the current flowed as direct current. The magnetoelectric generators called magnetos were first used in the telegraph. Magneto uses permanent magnet and produces alternating current as it does not include commutator. Samuel Morse (1791–1872) invented telegraph and demonstrated it in 1837. He invented Morse code consisting of a set of dots and dashes which can be transmitted over a wire connecting the two stations. The first practical electric telegraph was installed by W.F. Cooke and C. Wheatstone in 1838. In 1840, Wheatstone used magneto for a new telegraph. In 1840s, a Birmingham chemist, J.S. Woolrich and the firm of Elkingtons used a large magneto for electroplating. Magnetos used to have permanent magnet. Wheatstone and Cook substituted electromagnets for permanent magnets to produce direct current. It was called dynamo. The first electric lighting company was formed in 1852. Around 1866, C.W. Siemens and others developed self-excited generators in which the current from electromagnet is supplied from the output of the machine itself. The first large scale practical generator was manufactured by the Belgian engineer Z.T. Gramme who worked in Paris. His machine used the ring armature known as Gramme Ring. Many of these machines were used in 1870s mainly for arc lighting. Today the electric arc is mainly used for welding, but it is interesting to observe that in the late nineteenth century, it was used for providing light in the streets. The first British generator manufacturer was R.E.B. Crompton (1845–1940). In 1882, Crompton patented compound field winding jointly with Gisbet Kapp. These machines were direct current (DC) generators. Afterwards alternating current (AC) generators were also made. As the speed of steam engines was limited to about 500 revolutions per minute (RPM), many poles of the magnet were required for producing a frequency of 50 or 60 Hz. Once the turbines were developed, the frequency could be achieved with lesser number of poles. The optimum frequency of 50 or 60 Hz is based on satisfying many conflicting objectives. The AC current had the advantage that its voltage can be magnified or attenuated with the help of a transformer. In order to reduce the losses, the transmission is carried out at high voltage. At the point of application, voltage can be attenuated. DC current had the advantage that batteries could be easily charged. With the development of induction motors in 1890, AC supply became attractive.

Electric motors started to be fabricated after Oersted's discovery in 1819 that a compass needle could be deflected in an electric current. In 1821, Michael Faraday showed that it is possible to produce continuous rotary motion by electromagnetism. William Sturgeon designed a motor in 1832. The first person to get a patent for electric motor (or electromagnetic engine) was Thomas Davenport in 1837. It was driven by a battery. In 1839, the Tsar gave a grant to Professor M.H. von Jacobi (1801–1874) of St. Petersburg for work on an electric motor. This was perhaps the first government grant for electrical engineering research. The Scotsman Robert Davidson developed an electrically driven carriage in 1842 that ran on the Edinburg and Glasgow railway. The first permanent public electric railway was opened at Lichterfelde in Germany in 1881. The first electric railway in UK ran between Portrush and Bushmills in Ireland. The mercury rectifier was introduced in 1928, which made it possible to transmit AC and convert it to DC for driving the motor. Universal motors operate both on AC and DC. The first practical AC motor was developed by Nikola Tesla (1856–1943) in 1888. Tesla worked for sometimes with Edison. Later on, both became rivals.

Alexander Graham Bell (1847–1922) invented the telephone in 1876. The incandescent light bulbs were developed independently by T.A. Edison (1847–1931) in the USA and by J.W. Swan (1828–1914) in England around 1879. In 1890s, electrical cookers, kettles, saucepans, iron, and heaters were common. Electric heaters used carbon filament lamp as the heating member. In 1906, nichrome, a mixture of nickel and chromium was developed. It does not oxide when red hot and most electric heaters use nichrome wire on fireclay support. In 1891, an electric table fan was developed. The first electric vacuum cleaner was made in around 1904. Before that bellow operated manual vacuum cleaners were invented around 1860. Food mixers and refrigerators came after World War I and became popular in 1950s. Various gas discharge lamps were made in the 1890s and neon lamps were introduced circa 1910. In 1930s, mercury and sodium lamps were in use. High pressure sodium lamps were in use in 1970s. Fluorescent lamps were developed just after World War II in Britain.

Today it is difficult to imagine life without electricity. The world produces about 24×10^{15} Wh electricity per annum. Attempts are being made to enhance the efficiency of electricity generation. In power plants electrical and mechanical engineers work in tandem. An offshoot of electrical engineering is electronics engineering, which is discussed in the Sect. 7.3.

7.3 A Brief History of Electronics and Computer Engineering

It is very difficult to provide a definition of electronics and also to clearly differentiate between electrical and electronics engineering. Many consider electronics as a part of electrical engineering, while some other consider them as two different disciplines. Both electrical and electronics engineers are concerned with the flow of electrons. Electrical engineers deal with mostly the flow of current in the conductors (mostly metallic). They are involved in the activities concerning the generation, distribution and utilization of electricity. Thus they work in power stations, in electricity boards and in places where electrical machines/gadgets such as motors find applications. Electronics engineers does not play primary role in the generation and distribution of electricity. They mainly utilize electricity for performing various tasks. In electronic devices, the electricity may flow in semiconductors, gases, and vacuums.

The electronics engineering started with the invention of thermionic valve and a diode, by J.A. Fleming in 1904. A diode is like a check valve in hydraulic system. It allows the flow of current only in one direction. A thermionic valve works on the principle of Edison effect, which was proposed by Einstein in 1875 and refined by him in 1883. The effect was that in a vacuum, electrons flow from a heated element to a cooler metal plate. The term ‘thermionic emission’ which was used earlier to refer to Edison effect, is now also used to refer to any thermally-excited charge emission process, even when the charge is emitted from one solid-state region into another. The simplest form of thermionic valve consisted of two electrodes, a heated cathode and an anode. Everything was enclosed in an evacuated glass chamber. It was called diode. A schematic diagram of the diode is shown in Fig. 7.1. Lee de Forest (1873–1961) developed another thermionic valve called triode in America in 1906. It comprised three electrodes in an evacuated glass chamber—a heated filament (cathode), a grid, and a plate (anode). Grid can control the flow of electrons. A schematic diagram of triode is shown in Fig. 7.2. With the help of triode, signals could be amplified. Hence, it found application in radios as well as amplifiers in musical instruments.

Fig. 7.1 A schematic diagram of thermionic valve diode

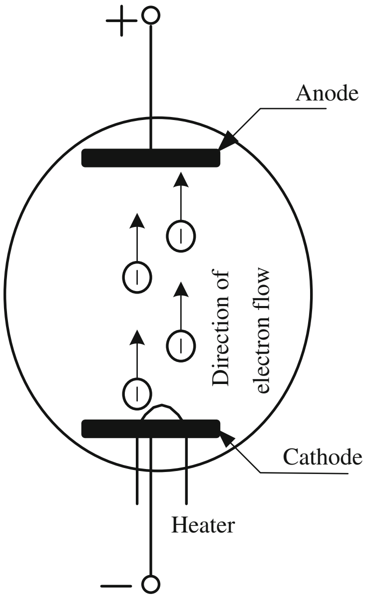
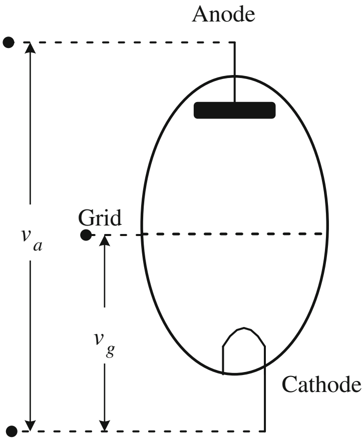


Fig. 7.2 A schematic diagram of thermionic valve triode



The first electronic computer ENIAC (Electronic Numerical Integrator and Calculator) developed in 1946 at the University of Pennsylvania had about 18,000 thermionic valves and consumed about 150 kW of electrical power. It was a huge machine weighing over 25,000 kg and filled a room. Initially, it was used for calculating artillery firing tables for the US Army's Ballistic Research Laboratory.

In December 1947, John Bardeen (1908–1991), Walter Brattain (1902–1987), and William B. Shockley (1910–1989) of Bell Laboratories invented transistor. It was announced to the public in June 1948. Transistors were much superior to vacuum tubes. They had very long life. They were small, lightweight and mechanically rugged. In 1950s, they were extensively used in telephone switching equipment, military computers, hearing aids, and portable radios. Earlier the transistors were made of germanium, which is a semiconductor. Later on, silicon became the main material for the fabrication of transistors. Transistors fabricated from silicon had superior performance at high temperatures. For the invention of transistor, John Bardeen, Walter Brattain, and William B. Shockley received Noble Prize in physics in 1956 (Riordan 2004). The first transistor was a point-contact transistor as the three metallic conductors were making contact with the surface of germanium. The three point contacts were named as emitter, collector, and base, respectively. By June 1948, Bell Laboratories have developed junction transistors, in which emitter, base, and collector were made in the germanium with three different layers. In 1951, Gordon Kidd Teal (1907–2003), a researcher in Bell Laboratories, grew single crystal of silicon and doped them with tiny impurities to make solid-state diode. Doping with arsenic and antimony produced n-type (negative type, with electrons as the majority carrier) and doping with boron and gallium produced p-type (positive type, with holes as the majority carrier) semiconductors. A hole indicates the deficiency of valance electrons and is ready to accept an electron. Combining the p and n type semiconductors, Teal and Buehler manufactured a p–n junction diode. On first January 1953, Teal joined Texas Instruments at Dallas in Texas with a primary reason to be near his home. He developed first silicon transistor there in 1954.

The concept of integrated circuits was proposed by Geoffrey W.A. Drummer (1909–2002) in 1952. Integrated circuit (IC) is an advanced electrical circuit comprising various electrical elements like transistor, diode, resister and capacitor. These elements are not connected by external wires but are internally connected in a substrate like silicon. As a result large number of elements can be accommodated in a small space. In 1958, Texas Instruments introduced the first commercial integrated circuit. Jack Kilby of Texas Instruments was awarded a patent for integrated circuit.

The first electronic calculator was introduced by the Bell Punch Company of the UK in 1961. This contained discrete components rather than ICs (Ohlman 1990). Universal Data Machines was the first American company to make electronic calculator using metal oxide semiconductor (MOS) chips from Texas Instruments. The first hand-held calculator was developed in 1967. In 1968, Burroughs produced the first computer to use an integrated circuit.

In the late 1960s, ARPAnet, a precursor to Internet, was developed at Advanced Research Projects Agency (ARPA), a military research agency of USA. Internet was perfected in 1970s. In 1971, Raymond Samuel Tomlinson (1941–2016) implemented the first e-mail program on the ARPAnet system. In 1971, Intel produced the first commercial microprocessor 4004. Intel, one of the world's largest electronic-chip manufacturing companies, was founded in 1968. Intel 4004 is a 4-bit central processing unit. It used 2300 transistors and had a clock speed of 108 kHz. It had about 1 KB of program memory and 4 KB of data memory. In 1980 Intel introduced the first 32-bit transistor. In 1981, IBM introduced a personal computer with disk operating system. In 1990, the World Wide Web (WWW) was set up by Tim Berners-Lee at the European Particle Physics Laboratory in Switzerland. Berners-Lee was born in 1955. Initially, he took a consulting job at CERN, the supercollider and particle physics laboratory near Geneva (Isaacson, 2014). There he created a computer program Enquire to link different projects. However, before the Enquire could be completed, he had to leave CERN. With the background of Enquire, Tim combined two technologies—internet and hypertext. Hypertext is a word or phrase that is coded so that when clicked, it sends the reader to another document or piece of content. It was named in 1963 by Ted Nelson (born in 1937 at Chicago). By the end of 1990, Tim crated Hypertext Translator Protocol (HTTP) to allow hypertext to be exchanged online, a Hypertext Markup Language (HTML) for creating pages and browser (a software application that enables the visit of websites). In the beginning of 1993, there were only 50 web servers. By October 1993, the number became 500. Now, the number is in millions.

In 1993, Intel introduced the Pentium Processor. In 2000, Intel introduced Pentium 4, which used about 42 million transistors and had a clock speed of 1.4 GHz. In 2006, Intel introduced the core 2 processor. In 2013, Core i7 were introduced. This reminds the observation of Gordon E. Moore in 1965 and then the director of research and development at Fairchild Semiconductor, that number of transistors in a dense integrated circuit doubles approximately every 2 years (Moore 1965).

7.4 Emergence of Mechatronics as a Separate Discipline

Mechatronics evolved from a marriage between mechanical and electronics. Before the 1960s, most of the industrial products and equipment were based on mechanical principles. The evolution of mechatronics started in the 1960s with the progress in the fields of electronics, development of semiconductors, and integrated circuits, microprocessors, and microcontrollers. Gradually, there was a change in the technology of products and equipment with incorporation of electronic components within the mechanical systems. In that sense, its origin can be traced to early 1950s when a numerical control (NC) machine tool was developed at MIT, USA in 1952. It was a retrofitted milling machine that used punched tap for feeding the programming instructions. As the potential of NC technology for mass production and productivity was perceived, there was profound interest in it among commercial machine tool manufacturers. However, research continued as there were certain disadvantages with the conventional NC machines. The new inventions of electronics, viz. miniature electronic tubes, solid-state circuits, and integrated circuits were gradually used in NC machines making it better, smaller, and more reliable. In 1957, the first computer numerical control (CNC) machine tool was developed at MIT. The control units with punched cards in the NC machines were replaced by the computers in the CNC machines. Computerized machine control unit led to software based control in the machine which is very flexible. Different programming languages like G-code were developed for CNC machines. In 1961, the part programming language Automatically Programmed Tool (APT) was released for CNC machines. This language defines the tool path for creating geometries on the workpiece. Raynold George, head of the Computer Applications Group of the Servomechanisms Laboratory at MIT is considered as the father of APT. The APT language is still in use in the industry, and it is also the basis of several modern programming languages. CNC technology has paved the way for computer aided design (CAD) and computer aided manufacturing (CAM) thus contributing to the growth of mechatronics.

Since late 1950s, the progress in the field of robotics started. Planet Corporation incorporated the first commercial robot based on limit switches and cams in 1959. Mechatronics played a pivotal role in development of robotics in the 1960s and 1970s. Extensive research were carried out in robotics in MIT, Stanford Research Institute, IBM, and General Motors resulting in building robots possessing various degrees of automation, movement, intelligence, degrees of freedom, and motion control. Robotics was first introduced in the 1970s in the manufacturing industry to perform different tasks such as moving materials, parts, and tools, and for welding, machining, and assembly work.

Other than manufacturing, application of mechatronics is diverse, e.g., in defence, medical, automobile, consumer products, and many more. For example, unmanned vehicles such as Drone, radar technology, jet engines, robotic surgery, active human implant devices, antilock braking system, cruise control and air bags in automobiles, and intelligent highways. Gradually through 1970s and 1980s, the advances in control theory, computation technology, servo technology, microprocessors, and integrated circuits enabled design of products such as auto-focus camera, automatic door opener, vending machine, sewing machine, digital watch, push button telephones, electronic type-writer, photocopiers, automatic washers and dryers, automatic ovens, and home security. Controlling and functioning of machines became much easier by the use of computer hardware and software enabling manufacturing of a product with high accuracy. Finally, since the 1990s, there has been tremendous progress in the field of mechatronics and its applications extended to flexible manufacturing systems (FMS), CAD/CAM, data communication systems, multi-point fuel ignition and digital engine control in automobiles, smart phones, microwave ovens, dish washers, vacuum cleaners, televisions, cameras and camcorders, video recorders, central heating controls, bar coding machines, automatic teller machines (ATM) and many more. The latest addition to the list is biometrics, automatic climate control, automatic unmanned vehicles, domestic and social robots, microbots, etc. Future of mechatronics has extreme potential as the application area of mechatronics encompasses all spheres of human lifestyle.

In 1991, *Mechatronics* journal was launched in the UK by Pergamon Press. This journal is being published by Elsevier. In 1996, IEEE/ASME launched a Transaction on Mechatronics. Today there are several journals in mechatronics. The education in mechatronics started since 1990s.

7.5 Current Developments

The mechatronics is an evolving field. Boundaries between various disciplines are vanishing with mechatronics approach. Many primarily mechanical products are becoming extinct for example mechanical watches, cams, and typewriters. At the same time, several mechanical products are incorporating a lot of electronics into it. In this section, a brief description of some mechatronic products and services is provided, which are going to dominate the technological world.

1. Smart sensors: Smart sensors are the sensors with integrated electronics that can perform one or more following function(s): (i) logic function, (ii) two way communication, and (iii) decision making. Smart sensors are defined by the IEEE 1451 standard as sensors with small memory and standardized physical connection to enable the communication with processor and data network. The smart sensors are evolving into intelligent sensors with the incorporation of artificial intelligence. The intelligent sensors possess more flexibility and can be configured to perform various functions. Smart sensors have become essential in various fields and industries, viz. process control, motion sensing and control, remote control, automobile, medical, defense, security systems, robotics, biometrics, prosthetic implants, self driven vehicles, and many more. Continuous research efforts have resulted in breakthrough in sensor technology innovating better, smarter, and more intelligent sensors. Presently, focus is on making micro-electromechanical system (MEMS) and nano-electromechanical system (NEMS) based integrated smart and intelligent sensors of miniature size. Challenge is to innovate sensors with increased accuracy, reliability, sensitivity, and adaptability that have multiple uses by various control systems. Self-adaptive intelligent sensors can adapt themselves automatically to the measurement task according to present conditions. New technology like System-in-Package (SiP) is emerging for designing smart sensors that offers various advantages (http://www.sensorsportal.com/HTML/DIGEST/E_27.htm). This is a promising field for the future (Giachino 1986).

2. **Machine vision**: Machine vision is the area of computer science and electronics in which intelligent decisions are made by employing camera. It started in 1950s, when pattern recognition was carried out based on two dimensional imaging. Today three-dimensional machine vision is gaining popularity in industry. Machine vision may be defined as the process of extracting, characterizing, and interpreting information from images of a three-dimensional object. Important fields of application of machine vision are 2-D image processing, computer graphics where 2-D images are rendered from 3-D models and computer vision where information is extracted from 2-D images and video. In machine vision, the image captured is converted to digital model and useful information about the image is extracted by using some algorithm. The information may be used for pattern recognition, inspection, and for positioning and orientation in robotics. Mobile robots fitted with laser scanners and cameras can build a 3-D map of their surrounding from the captured images of the environment. Rendering vision to machine is specially beneficial in applications such as space exploration, underwater missions, rescue operations in hazardous situations, war and defense, and robotic surgery. Application of machine vision encompasses various fields, viz. automotive, aerospace, electronics, pharmaceutical, robotics, printing, medical, manufacturing, monitoring, assembly, packaging, and inspection.

3. **Unmanned vehicles**: An unmanned vehicle moves without any driver or pilot. There are three types of unmanned vehicles, viz. unmanned aerial vehicles (UAV), unmanned ground vehicles (UGV), and unmanned underwater vehicles (UUV) which have a variety of applications in various fields. Although initial unmanned vehicles were remotely controlled, gradually it is replaced by autonomous control. Equipped with on-board advanced control system, artificial intelligence and decision making capability, sensors, camera, and machine vision, latest unmanned vehicles are capable of doing different types of tasks that were thought hitherto impossible.

Drone is a type of unmanned aerial vehicle (UAV). That was invented in 1974. Although drones are mostly used in military and defense services, gradually these are finding places in other applications such as search and rescue, disaster relief, aerial survey and surveillance, transportation of medicines and essentials to inaccessible regions, archaeology, agriculture, film making, and recreational uses. Sophisticated UAVs can create 3-D image of the landscape, it covers for future course of action. Unmanned spacecraft used for space exploration and gathering information of the Earth, Moon, and Mars is another important application of unmanned aerial vehicle. UAVs can be programmed to follow complex routes and to enable landing and perching on inclined surfaces. Advance research is going on around the globe resulting in micro- and nano-sized UAVs mimicking the movement of a fly with flapping wings. Solar powered UAVs are also in making, thus promising a brighter future for developments in this field.

Unmanned ground vehicles (UGV) are also in use. They can be operated by a remote control or can be programmed. USSR developed first ground vehicle in 1930s called Teletanks. UGVs are mainly used in areas where the presence of a human driver is dangerous or impossible. On-board sensors collect the required information, communicate with remote host, and take decision and action. It has varied use in hazardous situations as in diffusing explosives, work in nuclear plants, shooting and ground surveillance in military, rescue and recovery, and many other fields. Self-driving cars with artificial intelligence are developed which are run and controlled based on the feedback from current situations. Research is going on to impart UGVs with abilities of self-learning, self-repair, adaptation to unfamiliar situations, and even to develop ethical senses of the functions they perform.

Unmanned underwater vehicles (UUV) are the water based counterparts to UAVs and UGVs. The first UUV was developed in 1957 by Stan Murphy, Bob Francois, and Terry Ewart in Washington. UUVs can travel under the sea without an operator and can be remotely controlled and powered from a ship or ground. UUVs are mainly used for underwater oil and gas exploration, rescue operations in ship and aeroplane wreckages, study of ocean and marine living beings, military operations and surveillance, submarine warfare, underwater mining, repair works, etc. Latest UUVs are equipped with different sensors like depth sensor, position and navigation sensor, acoustic sensor, machine vision, and scanners and capable of undergoing unsupervised missions in the sea. Innovating designs of UUVs are tried by researchers by mimicking the motion of aquatic living beings like fish and frog. There are tremendous possibilities of innovations in the field of unmanned vehicles of all types in the near future.

4. Flexible robotic manipulators: The light and slender robotic manipulators in which there is a significant elastic deformation during operation are termed as flexible manipulators. They are being employed in nuclear industry, space exploration, and medical applications. Research in the area of flexible manipulators picked up in 1990s. Flexible robotic manipulator concept is relatively new compared to rigid robotic manipulator and its design and control pose challenges which need more research efforts. Although significant progress has been made in this field, further efforts and innovations in designing flexible robotic manipulators will contribute significantly to its use in robotic surgery, space mission, and other fields of robotics. In the future, advances in the design, modeling, and control of flexible manipulators are expected to accelerate.

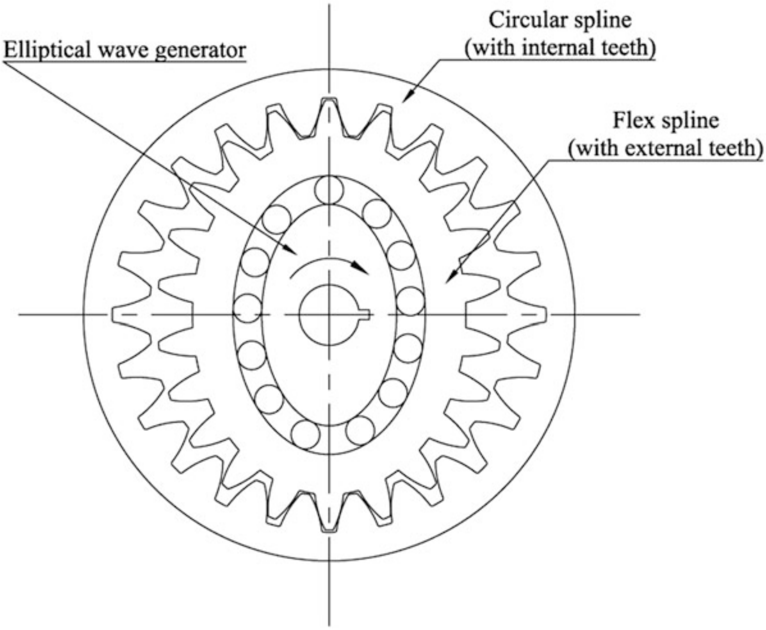


Fig. 7.3 A schematic diagram of harmonic drive

5. Harmonic drive: Harmonic drive is a type of strain wave gear, which is based on the elastic dynamics. It was invented by C.W. Musser in 1957. A schematic diagram of harmonic drive is shown in Fig. 7.3. It offers the advantages of high reduction ratios in a single stage, zero backlash and tooth wear, high precision, flexibility, minimum size and weight, and maximum output torque over conventional gear trains thus making it very useful for motion control and mechanical power transmission. Harmonic drive gears coupled with servomotors are used as high precision actuators that provide high force up to about 12,000 N and excellent sub-micron positional accuracy. Harmonic drive gears are used in highly compact designs of hollow shafts, bearing and flanges, and for a variety of robust and precision gear applications. It offers higher flexibility and integration in design of machine units. Harmonic drive gears are reversible and can be driven in the opposite direction. There are wide applications of harmonic drive in robotics and automation, medical equipments, measuring and testing equipments, semiconductor industry, aerospace, machine tools, and industrial motion control.

6. Direct Drive: In a Direct Drive mechanism, motor is directly mounted to the load to be driven; thus, eliminating the need for using any mechanical transmission system like gearbox, rack and pinions, chain and belt drives, pulleys, or lead screws. Direct coupling eliminates the disadvantages of mechanical losses, wear, noise, backlash, and higher weight and bigger size of conventional transmission systems. This leads to easier assembly, enhanced reliability and durability, minimum maintenance, reduced noise, lower power consumption, higher precision and an overall higher efficiency. Direct drive motors can deliver high torque over a wide range of speed and enable faster and precise positioning due to high torque and low inertia of the system. Direct drive mechanisms have wide applications in fans, turntables in CNC machines, washing machines, sewing machines, compact disc (CD) drives, gearless wind turbines, locomotives, etc.

7. Magnetic Bearings: Magnetic bearing is a mechatronic product which has wide use in different fields of engineering such as mechanical, electrical, and electronics. It was first conceived in around 1950. A magnetic bearing supports a rotating part (e.g., a shaft) by suspending it in the air without any physical contact with other machine elements with the help of an electrically controlled magnetic force. Magnetic bearings normally use electromagnets with continuous power input and a microprocessor as an active control system. As it is free of contact and hence free of mechanical wear, it enables lower maintenance costs and longer life. Very high speed can be obtained till the ultimate strength of the rotor is reached. Moreover, it has very low friction and able to run without lubrication and in a vacuum. Although a variety of magnetic bearings are developed, Active Magnetic Bearings (AMB) are widely used in the industry for their obvious benefits of high force on supported element, flexibility through software, faster performance, etc. Magnetic bearings are used in electrical power generation, semiconductor industry, vacuum technology, structural isolation, rotor dynamics, energy storage, turbo machines, machine tool operation, etc. Another important application of magnetic bearings is in artificial hearts used for transplantation. These bearing are also suitable for food processing industries due to absence of lubricants.

8. Mobile robots and AGV: Mobile robots and automated guided vehicles (AGV) are examples of mechatronic products. In a broader sense, AGV can be called one type of a variety of mobile robots. AGV is used to move materials from one place within a manufacturing industry to another efficiently, safely, and economically. In modern automated manufacturing plants, use of AGV is common for material handling and transportation for manufacture, assembly, and storage. The first AGV in the form of a modified towing truck was invented by the electronics engineer A.M. Barrett in 1954. It was guided by an overhead wire and used in a grocery warehouse. The advantages of an AGV are as follows: it is driverless, automatically controlled, enables minimum material handling, improves work flow, and has facilities for receiving and sending information. It navigates in predefined routes within the factory according to the functions it has to perform. The latest technology enables AGVs contactless inductive power transfer and data communication with the control unit for accurate guidance and positioning.

Although AGVs need some guiding devices, some mobile robots are capable of navigating around the environment without any guiding devices. Equipped with laser scanners and cameras, mobile robots can build a 3-D map of their environment and learn how to find their way to the required point in a facility. Mobile robots are invading many fields in commercial, industrial, and domestic areas, e.g., factories, warehouses, hospitals, supermarkets, military, security and safety, and households. Tracks, wheels, and legs provide mobility to land or ground robots. There are numerous examples of mobile robots doing tasks such as cleaning, transportation, repairing, household chores, and space and undersea explorations. Most of these robots move on wheels, e.g., vacuum cleaner, lawn mower, garden bot for watering plants. ASIMO (Advanced Step in Innovative Mobility) is a two legged robot that can walk, jog, and climb stairs (http://asimo.honda.com/downloads/pdf/honda-asimo-robot-fact-sheet.pdf). Humanoids are robots which are human lookalikes and can perform various tasks as performed by human beings. Both two legged and four legged robots are used in various fields like disaster response, mining, and offshore oil rigs where the environment is unknown. Flying robots are also designed to inspect a vast area with complex unknown environment. The latest addition in flying robots is an unmanned solar airplane that enable search and rescue from the air over large environments (http://www.icinco.org/KeynoteSpeakers.aspx). Incorporating artificial intelligence to robots has taken robotics to a new height. Intelligent robots are now used in almost all fields of human life.

9. Cloud Computing: The present trend in the world of computing is to use shared data and resources for one's personal computing in PCs. Centralized mainframe systems are replaced by personalized computers that can share information of another computer over the internet. Cloud computing enables users to access a shared computing resource and database according to their requirements using internet. The computing resources may be in the form of services, applications, storage, networks, and servers. It is provided as a service by another company and the user do not have to be concerned about the hardware and software of the facility provided. Everything is present in the 'Cloud' that is accessible over the internet. A simple example of cloud computing may be preparing an Excel spreadsheet or PowerPoint presentation by using some Web based software such as Google Documents instead of making it in Microsoft Office software in one's own PC in his office. Moreover, storage, backup, and keeping Google Documents software updated are also the responsibilities of Google. Different services of cloud computing are as follows: Infrastructure as a Service (IaaS) that provides access to computing hardware such as servers or storage, Software as a Service (SaaS) that provides facilities like Google Documents, e-mail services, and a variety of office applications online, and Platform as a Service (PaaS) that enables one to develop applications using Web-based tools (http://www.explainthatstuff.com/cloud-computing-introduction.html). Cloud computing has become very popular as it offers the advantages of high computing power, high performance, and easier accessibility at economic rate.

10. Household robots: Household robots have literally invaded the homes of Japan, China, The United States, and many other western countries. Incorporating artificial intelligence to robots has made it almost like a human being and the latest robots are able to work similarly and more closely with humans. Domestic robots can perform many household tasks such as vacuuming and floor washing, gardening, cleaning, ironing garments, repairing, kitchen works, home security, attending to children and elderly, and as butlers. Some examples are Pepper, the domestic helper that speaks Japanese and French; CaddyTrek, a golf bag carrying robot; Budgee, a load-carrying follow-me robot that help people shift heavy loads around their homes and communicate through phone; Jibo that can communicate over Wi-Fi; Sota with ability to communicate verbally and assist the user with health check-up, Furo-i Home, that can be verbally instructed to turn lights, music and heating on or off, and offer care to elderly persons and children; Otus that continually turns a tablet or smartphone to face the user; Atomobot that hunts the home for airborne dust and odours to remove to name a few (http://www.therobotreport.com/news/2016-will-be-a-big-year-for-social-robots, http://www.bbc.com/news/technology-30708953). Using artificial intelligence in the learning systems of these robots has enabled them to perform almost like a human. These robots can recognize voice and face and take verbal instructions, send text message, call, wake up an elderly and children and remind them to take medicine or eat breakfast, play with children, permit health-care workers to monitor patients at home via video call, plan schedule and suggest modifications, keep watch on house, read books, place order, and perform many more tasks. Human-like personal assistants and companions have become a reality now. Scientists have started incorporating emotions into robot learning system, for example Erica, the intelligent humanoid with emotions that can understand and respond to questions with humanlike changes in her facial expression (http://www.theguardian.com/technology/2015/dec/31/erica-the-most-beautiful-and-intelligent-android-ever-leads-japans-robot-revolution). The humanoid Nadine exhibits personality, moods, and emotions and works as a receptionist at Singapore's Nanyang University (http://www.wired.co.uk/news/archive/2016-01/04/robot-receptionist). Intelligent humanoids possessing human emotions and capability may do away with the need of human beings in the near future.

7.6 Conclusions

In this chapter, a brief history of the emergence of mechatronics is presented. As the root of mechatronics lies in electrical engineering and electronics engineering, significant developments in these two core engineering disciplines are also highlighted. New innovations in mechatronics, future perspectives, and their possible application for improving quality of product, process, and service are briefly discussed.

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Chapter 8
Future of Mechanical Engineering

Abstract Mechanical engineering is one of the oldest but evergreen branches of engineering. It is continuously evolving and adapting to new developments in science and technology. In the near future there will be more emphasis on developing sustainable technologies. Micro and nano technologies, biotechnology, mechatronics, and 3-D printing are some of the technologies that will grow tremendously in the twenty-first century. The world has become a global village now. The development of mechanical engineering will continue tackling global challenges.

Keywords Bioengineering · Mechatronics · Robotics · Nanotechnology · MEMS

8.1 Introduction

Mechanical engineering is one of the oldest branches of engineering. Evolution of mechanical engineering has been taking place through the centuries, and it is a continuous process. A number of epoch-making inventions in mechanical engineering have revolutionized the modern civilization. The invention of wheel was a landmark event in the mechanical engineering. Another landmark was the invention of steam engine, which played a major role in the industrial revolution. In the twentieth century, electronics played a major role in mechanical engineering. Nowadays, computers have become integral parts of mechanical engineering.

With the passage of time, the role and scope of the mechanical engineering is gradually transforming owing to the advancement of science and technology, new innovations, change in the need and expectations of human beings as well as their lifestyles, and globalization. These factors will serve as catalysts for significant changes within mechanical engineering in the near future. American Society of Mechanical Engineers (ASME) conducted a survey in 2011 among more than 1200 engineers (with at least two years experience in mechanical engineering related positions) to learn about the current status and the changes foreseen in mechanical engineering over the next two decades. The findings of the survey are presented in

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the report ‘The State of Mechanical Engineering: Today and Beyond’ which are important for the future of mechanical engineering in the coming days (https://www.asme.org/getmedia/752441b6-d335-4d93-9722-de8dc47321de/State-of-Mechanical-Engineering-Today-and-Beyond.aspx). Some of the key findings of the survey may be of interest to the readers. The survey mainly focussed on the emerging fields in engineering, the ability of the engineers to meet global challenges, state-of-the-art tools and techniques and their use, and professional and personal skill development. According to the survey, globalization is predicted to have a significant impact on the mechanical engineering field. Alternative energy, water, bioengineering, biomedical, environmental engineering, nanotechnology, robotics, mechatronics, latest computer technology, and electronics are expected to gain prominence in the near future. Energy, in particular, green/clean and renewable energy (solar/wind/hydraulic) will attain the maximum importance to deal with the issues of energy crisis and environmental protection. Some of the cutting-edge fields for the next twenty years are identified as virtual prototyping, motion simulation, animation, smart material, smart grid, Micro-Electro-Mechanical Systems (MEMS), green building technology, nano medicine, synthetic biology, greenhouse gas mitigation, etc. Importance of interdisciplinary skills, global team management, effective communication, computer/software skills, business skills, multilingual capability and sharing of data will remain. Social responsibility, diplomacy, leadership quality, and cost consciousness will also be important.

The history of mechanical engineering will continue to be written. As described in this book, the history of mechanical engineering started on the day when human being started using tools. The mechanical engineering got its separate identity in nineteenth century; Institution of Mechanical Engineers was formed in UK in 1847. In the near future, this distinct identity of mechanical engineering may be in danger in a positive sense. There will be more emphasis on interdisciplinary research and practice. The course structure of mechanical engineering will be dynamic depending on the changes in technology. The mechanical engineering students will have to be trained in a manner so that they are flexible, agile and have ability to grasp the knowledge of other disciplines quickly. Many may prefer to take minor degrees in other disciplines with mechanical engineering as a major.

8.2 Future Directions in Mechanical Engineering

The importance of engineering research and innovations, their applications, and applied hands-on engineering practice will play a major role for future developments of mechanical engineering. Cooperation and collaboration are required among nations, countries, educational institutions, and industries to meet the global challenges. Currently, mechanical engineering is perceived as a discipline that applies the principles of physics, design, manufacturing, and maintenance of mechanical systems (Davim 2014). For a mechanical engineer, the knowledge of the modern subjects is essential in addition to the fundamental subjects of classical mechanical engineering. Latest topics and technologies such as nanotechnology, nanomechanics, microelectronics, computational mechanics, mechatronics and robotics, alternative energy, and sustainability are gradually becoming widespread and relevant for the decades to come. Some topics that will attain prominence in the future are briefly presented here.

Sustainable energy: The growing demand for energy in the last two decades involving all spheres of human civilization is an alarming issue leading to energy crisis. The need arises to explore the means of sustainable energy for sustainable development. Moreover, to reduce harmful environmental effects, there are new industrial regulations of the government to go green. Research in sustainable energy is the call of the day to address the environmental issues. Without sustainable energy, overall global development will remain a dream. Efforts are on to extract energy from renewable sources such as wind, water, the Sun, and biomass which are inexhaustible and clean. Developing latest technologies to harness renewable energy is a promising research area. Additionally, importance should be given to energy efficiency, i.e., getting more from our existing resources. UN Secretary-General Ban Ki-moon has asked investors to at least double clean energy investments by 2020 to reduce climate risks, end energy poverty, and create a safer, more prosperous future for this and future generations (http://www.se4all.org/content/un-secretary-general-urges-doubling-clean-energy-investment-2020). The underlying philosophy of sustainable development is that for raising our present standard of living, the interests of future generations should not be sacrificed. Sustainability includes environmental, economical, and social aspects.

Nanotechnology: Emergence of nanotechnology has tremendous benefits on various fields of engineering and medical science. Nanomaterials have enhanced properties and are lighter and stronger compared to other materials. Some feel that nanotechnology will be the next industrial revolution (Bhushan 2010). Manufacturing with nanotechnology will reduce material requirements, time, and cost and also solve the problems of shortage of water and power. Effects of nanotechnology on life and health of people and on the environment are studied and green nano design principles are reported to have developed for positive environmental effects (http://www.nanowerk.com/spotlight/spotid=42342_1.php). Recently, nanotechnology is used to manufacture multipurpose fish shaped microrobots called microfish that can swim in liquids. Functional nanoparticles are added into the microfish body, and they can be used for detoxification, sensing, and drug delivery (http://phys.org/news/2015-08-3d-printing-microscopic-fish-team-method.html). A nanoparticle is an aggregate of atoms bonded together with a radius between 1 and 100 nm (1 nm = one billionth of a meter), typically consisting of 10–10^5 atoms. The diameter of a typical human hair is 75,000 nm. Nano electromechanical systems (NEMS) are typically less than 100 nm in size. A number of examples of advanced research in nanotechnology can be cited. Nano particles can be dispersed in the liquid for getting enhanced thermal conductivity. In a study, Eastman et al. (2001) has shown that when nanosized copper particles were dispersed in ethylene glycol, its thermal conductivity got enhanced by 40 %, when the concentration of nanoparticles was 0.3 vol.%, and the mean diameter was less than 10 nm. Nanotechnology has tremendous potential to be explored in the near future.

If only one length of a three-dimensional nanostructure is of nanodimension, the structure is called a quantum well. A quantum wire has two sides of nanometer length, and a quantum dot has all three dimensions in the nanorange (Bhushan 2010). The prefix quantum signifies the importance of quantum mechanics in understanding the nanotechnology. Although nanotechnology is a technology of twenty-first century, it was envisioned by Richard P. Feynman, a Nobel Laureate in physics, in a lecture in December 1959 (Feynman 1960).

Bioengineering and Biomechanics: Biomechanics is the application of the principles of mechanics to living biological beings. For example, it studies human body as a combination of links and connecting joints and analyze the functions of human body and the amount of stress, load and impact it can withstand. Bioengineering is mainly used for designing artificial replacements for various body parts of human beings based on the biomechanics analysis. With the advances in medical science and technology, now it is possible to replace vital body parts, thus giving relief to millions of patients across the globe. Bioengineering can produce customized products such as ear plugs for hearing aids, prosthetics of body parts, cosmetic dentistry, and artificial bone replacements in knee, jaw, and scalp in biomedical applications. Research is going on to produce artificial chests and necks. With the latest cutting edge technology, researchers are able to invent devices for brain activity monitoring, body function monitoring, drug delivery inside human body, and for many more functions. Bioengineers have developed a portable and wearable brain activity monitoring system that is equipped with sensors for collecting brain activity data and use for neuro-imaging, feedback, and clinical diagnostics (http://phys.org/news/2016-01-brain-lab.html). Another breakthrough in Bioengineering is the development of a tiny MEMS flow sensor that can be used for intravenous (IV) therapy for drug infusion in human being (http://phys.org/news/2016-01-iv-infusion-cave-fish-inspired-sensor.html). Bioengineering and biomechanics is one area where the mechanical engineering has a wonderful role to play to bring smiles to millions suffering from ailment. The area of synthetic biology is also picking up. Synthetic Biology comprises the design and construction of new biological parts, devices, and systems as well as the re-design of existing, natural biological systems for useful purposes (http://syntheticbiology.org/).

3-D Printing: 3-D printing has emerged as a frontier technology in the recent times in manufacturing sector for its obvious benefits. 3-D printing is an additive manufacturing process where parts are fabricated layer by layer from 3-D CAD model. This technique has immense potential for the future. The need for tooling is eliminated, and complex geometry can be directly manufactured from the digital model, thus enabling faster ways of manufacturing a part. It tremendously reduces the manufacturing lead time and very useful for customized products. Materials used for 3-D printing may be metal, plastic, ceramics, glass, and paper. Efforts are going on to achieve multi-material 3-D printing for fabrication. Recently, researchers at MIT's Computer Science and Artificial Intelligence Laboratory are reported to build a 3-D printer that can print ten different materials simultaneously by using 3-D scanning techniques (http://phys.org/news/2015-08-multifab3d-prints-materials-required-video.html). 3-D printing is also used to build microbots with complex shapes and functions. Experts are of the view that additive manufacturing is going to usher in the fourth industrial revolution, viz. 'Industry 4.0' that will revolutionize the production methods with the concept of 'Digital Transformation of Industries' (http://phys.org/news/2016-01-industry-additive.html). The 3-D printing technology has to be more advanced to meet the challenges of the fourth industrial revolution. Manufacturing will become leaner, faster, and customized catering to the customers' needs. Fast advances in research in 3-D printing technology are going to bring in a new era of e-manufacturing in the near future.

Robotics and Mechatronics: Mechatronics is essential for several key areas in mechanical engineering, for example robotics, intelligent motion control, automation, flexible manufacturing systems (FMS), CAD/CAM, automated guided vehicles (AGV), data communication systems, actuators, and sensors. There has been a tremendous progress in the field of mechatronics and advance research is going on. Some latest mechatronic products are biometrics, automatic climate control, automatic unmanned vehicles, microbots, etc. Robotics is the application of mechanical and electrical engineering and mechatronics to create robot which is a reprogrammable manipulator that can interact with the environment for performing specific functions. Incorporating artificial intelligence to robots has taken robotics to a new height. Intelligent robots are now used in almost all fields of human life, viz. manufacturing industry, household activities, medical surgery, space and undersea explorations, cleaning, and repairing. Recently, researchers have created a robotic finger with artificial skin that can detect pressure when a human finger touches the robotic finger and transmit the same to a nerve cell (http://phys.org/news/2015-10-artificial-skin-pressure-sensation-brain.html). It aims to give some sensory capabilities of human skin to prosthetic replacements. Robots such as ASIMO (Advanced Step in Innovative Mobility) can walk, jog, climb, and perform a variety of other tasks otherwise done by human beings (http://asimo.honda.com/downloads/pdf/honda-asimo-robot-fact-sheet.pdf). There is a tremendous advancement in robotics, and Japan is the pioneer in making robots that almost lookalike to human beings called humanoid. Hiroshi Ishiguro, the famous Japanese professor has developed several humanoids. For example, Geminoid F, the world's first humanoid film actor; Geminoid HI-1, a lookalike of professor Ishiguro; and the latest addition is Erica, the most beautiful and intelligent humanoid in the world according to the professor which has the ability to understand and respond to questions with humanlike changes in her facial expression (http://www.theguardian.com/technology/2015/dec/31/erica-the-most-beautiful-and-intelligent-android-ever-leads-japans-robot-revolution). The Japanese have started using robots in everyday life as receptionists, helper at home, companion for children and elderly, and hotel staff. The robot Nadine, named after her creator Professor Nadia Thalmann, works as a receptionist at Singapore's Nanyang University that exhibits personality, moods and emotions (http://www.wired.co.uk/news/archive/2016-01/04/robot-receptionist). Robotics and mechatronics have extreme potential for the future as their application area encompasses all spheres of human life. Intelligent humanoids possessing human emotions and capability may do away with the need of human beings in the near future.

In addition to the above, there are a number of fields where the application of mechanical engineering has significant scope for developments in future. Some of these are virtual prototyping, automation, motion simulation, animation, microelectronics, smart material, smart grid, Micro-Electro-Mechanical Systems (MEMS), biotechnology, intelligent machines, molecular manufacturing, lean and agile manufacturing, water resource management, environmental engineering, design for environment, green building technology, greenhouse gas mitigation, nanomedicine, synthetic biology, information technology, remote inspection, self driven automobiles, offshore technology, safety design engineering, and space science.

8.3 Challenges Ahead

Mechanical engineering has to invent the latest cutting edge technology in the near future by focusing on the following aspects:

- New innovations and continuous improvement of the product and service
- Global collaboration among countries, educational institutions, and industries
- The scarcity of water and energy
- Energy efficiency
- Alternative sources of clean/green energy
- Power generation and storage
- Environmental degradation
- Technologies to mitigate greenhouse gases and climate change.
- Environmentally friendly technology for sustainable development
- Emphasis on the issues of automation, networking, integration, knowledge sharing, and skill development

According to the ASME report, ‘2028 Vision for Mechanical Engineering’, mechanical engineering is entrusted with the responsibility of developing technologies that ensures a cleaner, healthier, safer, and sustainable global environment over the next two decades (http://newswise.com/articles/future-trends-in-mechanical-engineering). According to the report, nanotechnology and biotechnology will dominate the future in the next 20 years and will provide the building blocks to meet the challenges in the fields of medicine, energy, water management, aeronautics, agriculture, environmental management, farming and food production, housing, transportation, safety, security, healthcare, and water resources. Thus, mechanical engineering will be at the forefront of developing cutting-edge technology in the near future.

Although technology brings comfort to human beings, it comes with own side effects. Sometimes it brings disaster which may be attributed to man or nature. Future mechanical engineers should gear up for tackling various challenges including those created by existing technologies. Recently, sustainable engineering has become very popular. In simple words, sustainable engineering means providing engineering solutions without sacrificing the interest of future generations. It is necessary to use minimum resources of the nature and also produce minimum waste. Thus, the importance of optimization has increased drastically. Westkamper et al. (2000) has listed the following factors being confronted by the world:

1. A rising consumption of natural resources
2. The dramatic increase in world population
3. Environmental impacts, i.e., limited natural resources (energy and materials)
4. Global communication networks based on standards
5. An unstoppable worldwide globalization

They have advocated using life cycle management in an efficient manner.

Technology has profound influence on the culture and civilization. The influence is positive as well as negative. The first industrial civilization created a lot of economic disparity among people, although it made it possible to produce the goods at cheaper rates. In the age of information technology, there is a digital divide. Higher income group people have greater access to technology causing huge knowledge gap. There is a danger to our environment, ecology, and flora and fauna. Hence, there is an increasing emphasis on green or environmentally friendly manufacturing (Dixit et al. 2012). In the area of metal cutting, the minimum quantity lubrication (MQL) and dry machining have become popular.

Modern day mechanical engineers will have to look into all the aspects in totality. There is a realization about including a lot of subjects from humanities and social science including the subject on professional ethics in the engineering curricula. There is no looking back. Problems created by technology will be solved by technology only. Health, safety, and environment will be the part of all engineering curricula. In future, the focus will be on producing smart and intelligent machines and structures. The computational techniques like neural network, evolutionary optimization, and fuzzy logic will be important. However, the hardware sector will also be strengthened. Smart materials and structures will be able to identify their own faults and take corrective actions. Machines may be able to replicate themselves. Already there is a significant progress in self-assembly.

8.4 Conclusions

In this chapter, a brief description of the topics relevant to mechanical engineering in the near future is presented. The challenges and goals to be achieved by mechanical engineering in the coming decades are discussed in a nutshell. There are lots to do in mechanical engineering in the future for the welfare of mankind and our planet earth. The machines will always be there, but their avatars will be different. Wheels and levers are amongst the oldest components, which still find applications. However, at many places they have been replaced by electronic components. For example, unlike mechanical watches, electronic watches do not contain wheel and lever. Steam engines, which caused the first industrial revolution, are extinct now. Their place has been taken by turbines and electric motors. Mechanical engineering has to adapt to these changes, but its history will always continue as machines are integral part of human civilization.

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