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

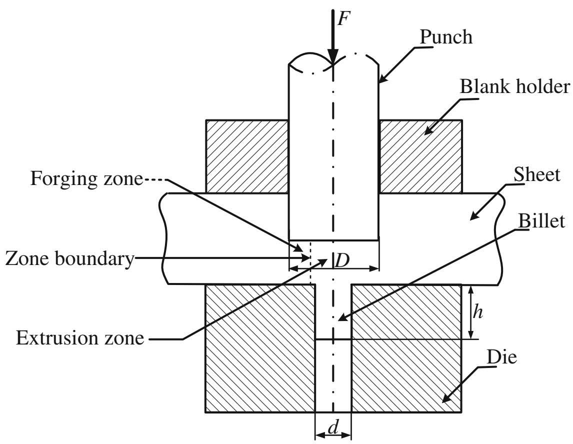

Fig. 5.1 A schematic view of microforging developed by Hirota. With permission from Jain et al. (2014b). Copyright IMechE 2014

(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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