Chapter 24
Tribology in Metal Forming

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Abstract The ability to produce a variety of shapes from a block of metal at high rates of production has been one of the real technological advances of the current century. This transition from hand-forming operations to mass-production methods has been an important factor in the great improvement in the standard of living, which occurred during the period. With these forming processes, it is possible to mechanically deform metal into a final shape with minimal material removal. The use of metal forming processes is widely spread over many different industries. In metal forming processes, friction forces between metal and forming tools play an important role because of their influence on the process performance and on the final product properties. In many instances, this frictional behavior is often taken into account by using a constant coefficient of friction in the simulation of metal forming processes. Several different types of instruments are constructed to measure the coefficient of friction for different materials. In this chapter, the fundamental concept of forming processes and the influence of friction in metal forming are discussed. A case study on the influence of friction based on surface texture during metal forming is also presented.

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1 Introduction

The basic understanding of sliding friction at dry contacts has been relatively well known since the early work of Coulomb in the seventeenth and eighteenth centuries. Friction is caused by the shearing of asperity junctions, by asperity interlocking between two surfaces, and by plastic deformation of the soft surface by hard asperity.

Friction has an important influence in metal forming operations. Friction arises during sliding of the workpiece against the tool. Friction between the tool and workpiece has a significant effect on material deformation, forming load, component surface finish, and die wear. It is also an essential input parameter for the ever-increasing use of finite element (FE) simulation for metal forming. The frictional conditions prevailing at the tool–workpiece interface greatly influence distribution of stresses and thereby the material flow. As friction plays a crucial role in metal forming, it is important to determine the friction as accurately as possible. Although a tremendous amount of work and discussion has gone into this subject over the decades, friction in metal forming is still not completely understood [1–3].

1.1 Fundamentals of Metal Forming

Metals can be formed into useful shapes, such as tubes, rods, and sheets, during metalworking. Useful shapes may be formed in three basic ways:

1. *By casting processes*: Here, the molten liquid is poured into a mold that holds the required shape, and allowing hardens the metal with or without external pressure. This process occurs in the liquid state.
2. *By plastic deformation or forming processes*: Here, the volume and mass of metal are preserved, and the metal is displaced from one location to another location by applying pressure. This process occurs in the solid state.
3. *By metal removal or machining processes*: Here, the material is removed in order to give it the required shape. This process also occurs in the solid state.

1.2 Classification of Metal Forming

Since the discovery of metal forming, hundreds of processes have been developed for specific metalworking applications. However, these processes may be classified into only a few classes on the basis of the type of forces applied to the workpiece as it is deformed into a particular shape as shown in Fig. 24.1 [4]. The classes are:

1. Direct-compression-type processes
2. Indirect-compression-type processes
3. Tension-type processes
4. Bending processes
5. Shearing processes

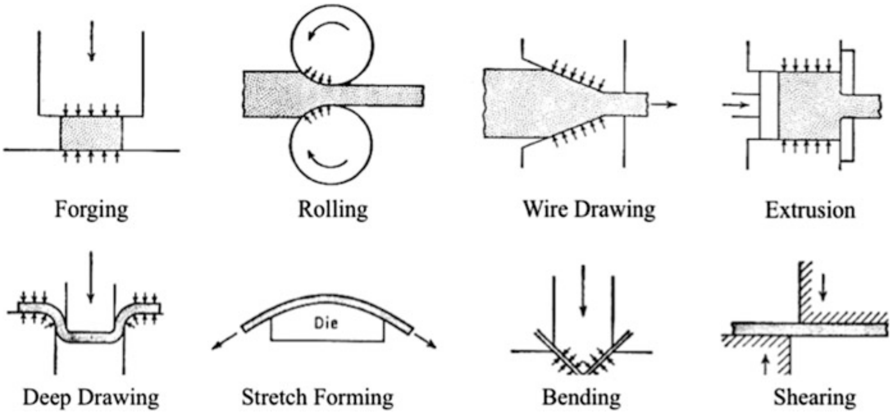


Fig. 24.1 Typical forming operations [4]

1. *Direct-compression-type processes*: In direct-compression-type processes, the force is applied to the surface of the workpiece, and the metal flows at right angles to the direction of the compression, for example, forging and rolling processes (see Fig. 24.1).
2. *Indirect-compression-type processes*: In indirect-compression-type processes, the primary applied forces are frequently tensile, but indirect compressive forces are developed by the reaction of the workpiece with the die. Therefore, the metal flows under the action of a combined stress state, which includes high compressive forces in at least one of the principal directions. Examples: wire drawing, tube drawing, deep drawing, and extrusion.
3. *Tension-type processes*: The best example of a tension-type forming process is stretch forming, where metal sheet is wrapped to the contour of a die under the application of tensile forces.
4. *Bending processes*: Bending involves the application of bending moments to the sheet.
5. *Shearing processes*: Shearing involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear.

The deformation processing system can be best viewed as shown in Fig. 24.2. The deformation zone can be analyzed with the distribution of stress, strain, particle velocities, and the overall pressure required to perform the operation. Foremost, the applied forces must develop yielding in the workpiece material, but the stresses must not locally create any fracture. During this process, the metallurgical phenomena, such as strain hardening, recrystallization, and fracture, are important. Often, other phenomena, such as strain rates and temperature, are also important under specialized process conditions. During the metalworking process, the workpiece will be in contact with the nondeforming tools or dies. The friction between the tool and the workpiece interface and the heat transfer from the workpiece to the tool are

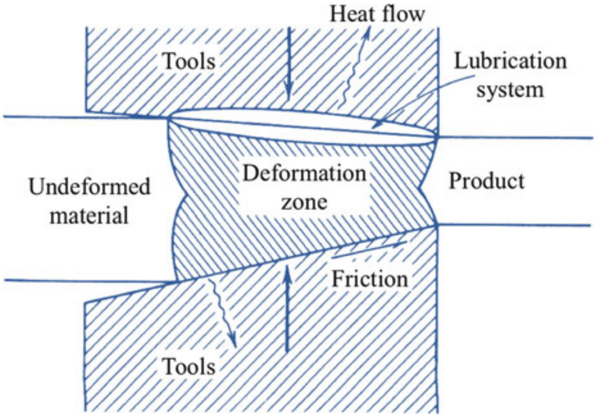


Fig. 24.2 Deformation processing system [4]

important considerations [4]. This is because tool wear and change in surface finish of the workpiece may occur during metal processing.

2 Metal Forming Processes

2.1 Manufacturing Processes

Metal manufacturing processes are those processes that are done to manipulate the size, shape, or appearance of materials. Many of the today's products require various manufacturing techniques to form, shape, and fabricate the necessary components. Raw materials are seldom useable immediately as they must be refined to separate impurities or unwanted materials from the more desirable materials, for example, iron ore must be refined to make steel. Secondary processes are procedures where prepared materials are used to manufacture more complex items. Most secondary processes result in products that are eventually bought and used by consumers or original equipment manufacturers to undergo more processes before being used by consumers.

In regard to metal forming processes, most metals, which are not used in cast form, are reduced to standard shapes for subsequent processing. Companies that manufacture metals often supply metals in the form of ingots, which are obtained by casting liquid metals into square cross sections known as slabs, billets, or blooms. Sometimes continuous casting methods are used to cast liquid metals into their appropriate shape. These shapes are further processed through rolling, forging, extrusion, or drawing to produce metal materials that are in standard form for distribution such as plates, sheets, tubes, rods, and various structural sections. Figure 24.3 details the sequence of operations for obtaining different shapes and the transformation from billets, blooms, and slabs to the final shapes often found by customers. In general, metal forming processes are carried out under hot-working or cold-working conditions. Hot-working is defined as the process of deformation of

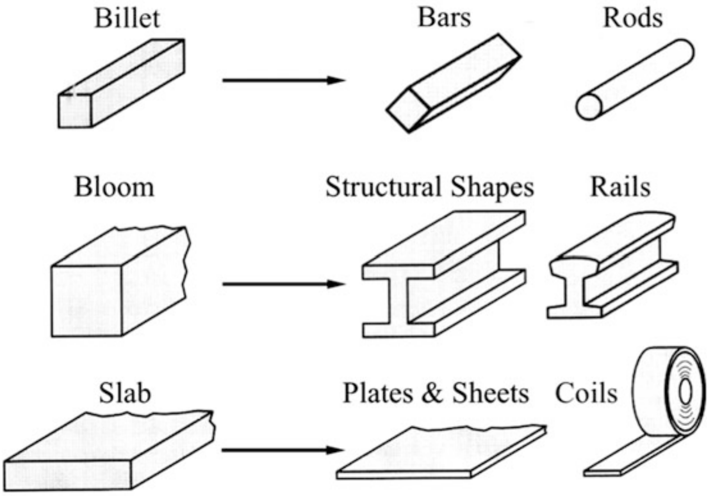


Fig. 24.3 Visualization from a billet, bloom, or slab to its final form

the workpiece under conditions of high temperature and strain rate such that the recovery process takes place along with the deformation of the workpiece. Cold-working is defined as the process of deformation under conditions where the recovery process is ineffective [4]. In hot-working, the strain hardening and distorted grain structure in the workpiece produced by deformation are transforming into new strain-free grains due to the recrystallization processes. For these reasons, very large deformations are possible in hot-working because the recovery processes occur simultaneously with the deformation. Hot-working processes occur at a constant flow stress within the workpiece, and these flow stresses decrease with an increase in temperature; thus, the energy required to deform the material is generally much less for hot-working than for cold-working [4]. Since the strain hardening is not relieved in cold-working, the flow stress increases with the deformation, therefore limiting the amount of deformation to the point of fracture. In cold-working, these limitations can be relieved by the process of annealing in between successive cold-working processes. It is important to note that the distinction between hot-working and cold-working is not an arbitrary temperature, but rather the processes occur at material-dependent temperature where recrystallization will occur. The primary metal forming processes that will be discussed are rolling, forging, extrusion, tube and wire drawing, and deep drawing.

2.2 Rolling

Rolling is the most widely used metal forming process with nearly all metals undergoing this process because it allows for high production and close control of the final product [4]. Rolling is the process where a sheet or plate is drawn by means

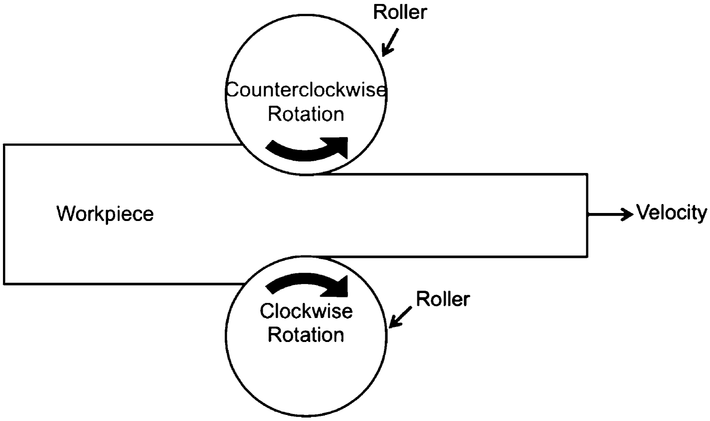


Fig. 24.4 Schematic of the rolling process for sheet and plates

of friction in between two rollers as shown in Fig. 24.4 [5]. The compressive forces applied by the rollers reduce the thickness of the workpiece while minimizing the cross-sectional area and causing the rolled material of the workpiece to elongate and spread. The final geometry of the workpiece depends on the contour of the roll gap, i.e., the distance between the rollers. Often the roller materials are cast iron, cast steel, or forged steel because of the high strength and wear resistance required. Generally, plates, sheets, rods, bars, pipes, rails, and other structural shapes undergo hot rolling, while sheets, strips, and foils with a good surface finish and increased mechanical strength undergo cold rolling [4]. Cold rolling also allows for a high degree of control over the final products dimensions and specifications. If the temperature of the workpiece is above its recrystallization temperature, then the process is termed as hot rolling. If the temperature of the workpiece is below its recrystallization temperature, the process is termed as cold rolling. In hot rolling, the rolls are generally rougher than in cold rolling, so that they can grasp the incoming workpiece and pull it through the roll gap. In cold rolling, the rolls are ground and polished for a smooth finish. During the rolling process, the grain size and structure change due to compression and the crystals of the rolled material become elongated in the rolling direction as shown in Fig. 24.5. In cold rolling, the crystals of the rolled material maintain the elongated shape, but in hot rolling, the crystals start reforming (due to recrystallization process) after coming out from the deformation zone (see Fig. 24.6).

As with many tribological applications, velocity and friction have an impact on the rolling process. If the peripheral velocity of rolls at entry exceeds that of the material to be rolled, which is dragged into the gap roll, this will cause the interface friction to be high. If in the deformation zone, the thickness of the material gets reduced, this elongates the material, thus increasing the linear speed at the exit, when leaving the gab roll. Within these variations, there exists a neutral point where roll speed and strip speeds are equal. At this point, the direction of the friction reverses.

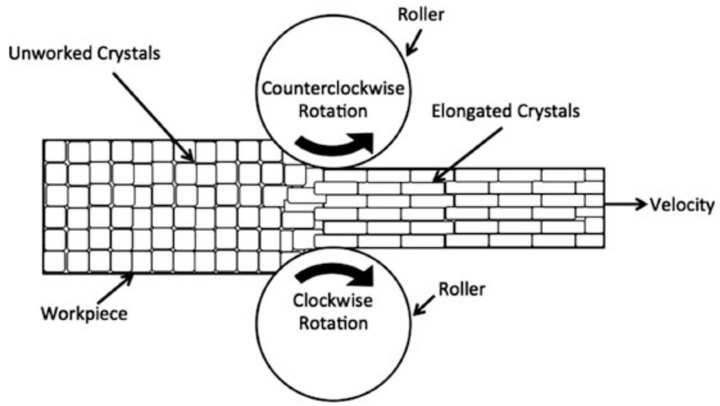


Fig. 24.5 Schematic of the grain or crystal elongation during the rolling process due to the compression and elongation of the rolled material

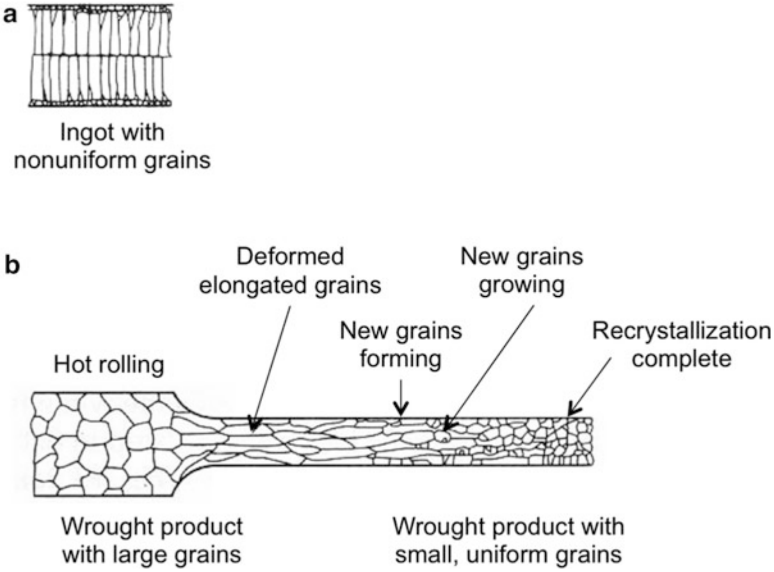


Fig. 24.6 Grain orientation in (**a**) ingot with nonuniform grains and (**b**) rolled material undergoing hot rolling

When the angle of contact α exceeds the friction angle λ, the rolls cannot draw fresh material, causing the roll torque and power input to increase with an increase in roll work contact length or roll radius. The pressure during rolling varies along the contact length in flat rolling. The peak pressure is often located at the neutral point. The friction in rolling is dependent on lubrication, work material, and also on the temperature. In cold rolling, the value of the coefficient of friction is around 0.1, and

Table 24.1 Typical lubricants and their coefficient of friction values in hot and cold rolling operations of various metals [6]

Material	Hot rolling—lubricant	Hot rolling—COF	Cold rolling—lubricant	Cold rolling—COF
Cu and Cu alloys	Emulsion, 2–8 % of mineral oil	0.3	2–10 % concentration of mineral oil with fat	0.01–0.03
Refractory metals	Dry	0.3	Mineral oil with boundary and EP additives	0.01–0.03
Steel	Water emulsion of fat + EP additive fat (ester) + EP	Sticking 0.4 0.3	3–6 % emulsion of palm oil	0.01–0.03
Ti alloys	Fat and water	Sticking	Esters or soap	0.2
				0.2
			Castor oil, compounded mineral oil	0.2
Al and Mg alloys	Emulsion, 2–15 % of mineral oil	0.4	Mineral oil with 1–5 % fatty acid	0.01–0.03

in warm rolling, the coefficient of friction is around 0.2. In either case, the use of lubricants is kept at a minimum to control friction and satisfy various surface finish requirements. In hot rolling, the coefficient of friction is around 0.4. In some instances of hot rolling, a friction condition occurs due to adhesion, which causes the coefficient of friction to increase to 0.7. Here, the hot rolling material surface adheres to the roller; thus, the central part of the material undergoes severe deformation. Lubricants are used extensively in hot rolling processes to control the adhesion between the workpiece and the rollers. Commonly, lubricants used in rolling processes are oil or water based with plenty of extreme pressure additives to aid in the lubrication process through a mixed-film lubricating mechanism [6]. Some of the common lubricants used in hot and cold rolling operations are presented in Table 24.1.

2.3 Forging

Forging is one of the oldest metalworking processes dating back many centuries to ancient times when metallic tools were made by blacksmiths who hammered heated metals against an anvil to form various shapes. Forging is the process of hammering or pressing material between two dies to achieve the desired shape and structure through plastic deformation. Since the Industrial Revolution, the development of machinery has replaced the physical presence of a blacksmith with a variety of forging machinery that is capable of forming anything from a bolt to a turbine rotor, to an entire airplane wing [4]. Forging operations generally occur through hot-working; however, some metals and metal alloys require cold-working. Forging

Fig. 24.7 Schematic of open-die forging of a billet

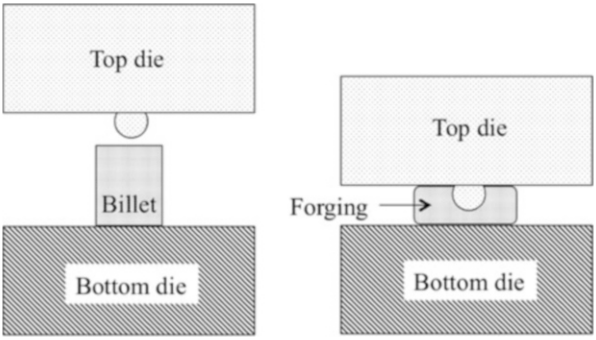
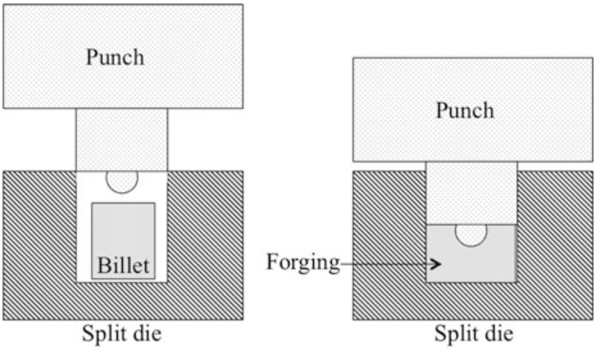


Fig. 24.8 Schematic of closed-die forging of a billet



can be classified into two classes of equipment: (1) the forging hammer or drop hammer, which delivers rapid impact blows to the surface of the workpiece, and (2) the forging press, which delivers slow-speed compressive forces to the workpiece. Depending upon the complexity of the part, forging is carried out as open-die forging or closed-die forging operation. Open-die forging, shown in Fig. 24.7, is the process where metal is compressed by hammering or pressing between flat or contoured dies either mechanically or manually, and the shape of the material is deformed through plastic deformation [5]. Open-die forging gets its name from the fact that the dies (the surfaces that are in contact with the workpiece) do not enclose the workpiece entirely, allowing the metal to flow except where contacted by the dies. Closed-die forging is the process where the metal is compressed between a shaped die and a hammer that presses the metal deforming it within the die causing the metal to flow and fill the die cavities as illustrated in Fig. 24.8 [5]. Two popular types of closed-die forging are drop forging and press forging. Drop forging is the repeated process of closed-die forging, where the hammer is dropped onto the metal workpiece and many successive strikes occur. In press forging, the metal is squeezed slowly by a hydraulic or mechanical press and the metal component is produced in a single strike. Open- and closed-die forging can be carried out as hot (temperatures above recrystallization temperature) or cold (temperatures below

Table 24.2 Typical lubricants and their coefficient of friction values in hot and cold forging operations of various metals [6]

Material	Hot forging—lubricant	Hot forging—COF	Cold forging—lubricant	Cold forging—COF
Cu and Cu alloys	Graphite in water	0.15	Fat: wax (lanolin), zinc stearate (soap), graphite or MoS_2 in grease	0.07 0.05 0.07
Refractory metals	Glass and graphite	0.05	N/A	N/A
Steel	Soap	0.3	Lime and oil	0.1
	Graphite in water	0.2	Copper and oil	0.1
	Salt solution	0.2	Phosphate and soap	0.05
Ti alloys	MoS_2	0.2	Zinc fluoride phosphate and soap	0.1 0.05
Al and Mg alloys	Graphite in water	0.3	Lanolin	0.07
			Phosphate and soap	0.05

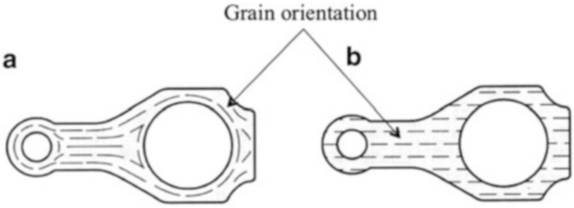


Fig. 24.9 Grain orientation in a (**a**) forged part and in a (**b**) machined part

recrystallization temperature) processes. In either hot or cold forging, lubricants are used to ensure proper material flow. Lubricants in forging are advantageous to prevent unwanted die wear and reduce local forging pressures on the die and forging material. Lubricants in cold forging typically consist of compounded oils and semi-solids such as fats, soaps, and waxes. In high-contact-pressure situations, MoS_2 is used as an extreme pressure additive. In hot forging, lubricants are composed of oil-based graphitic solutions or graphite-free solutions. Table 24.2 shows the typical lubricants used in hot and cold forging operations [6]. A benefit of forging, especially with the use of lubricants, is that the flow of material due to the plastic deformation produces desirable grain orientation of the metal when compared to standard machining processes. Figure 24.9 compares the grain orientation due to forging to the grain orientation produced by machining.

2.4 Extrusion

Extrusion is the process where a material is compressed in a chamber and the deformed material is forced to flow through a die orifice under high pressure.

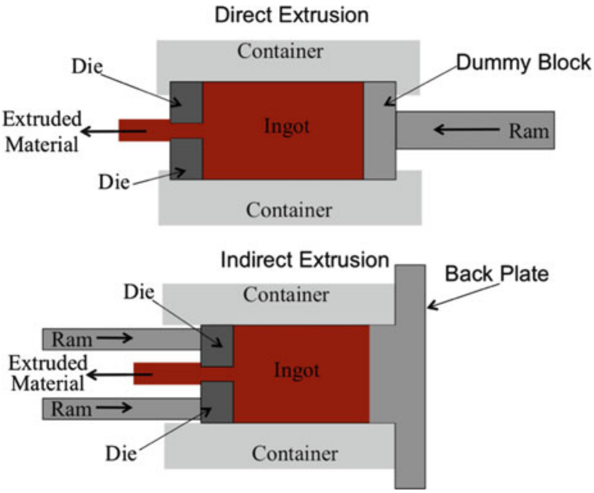


Fig. 24.10 Schematic of the tooling and metal flow for direct and indirect extrusion process

The die opening corresponds to the cross section of the required product. Extrusion is a relatively new process and its commercial exploitation started in the nineteenth century with the extrusion of lead pipes and later to copper, brass, and steel. The extrusion of steel became available in the 1930s, when extrusion chambers could be designed to withstand high temperatures and pressures. Extrusion is primarily a hot-working process due to the large forces and high amounts of deformation; however, for softer materials, cold extrusion is also performed and it has become an important commercial process. There are a few types of extrusion processes that are used extensively in industry: direct extrusion, indirect extrusion, impact extrusion, and hydrostatic extrusion. Direct extrusion illustrated in Fig. 24.10 is the process where the metal flows in the same direction as that of the ram. Due to the relative motion between the heated billet and the chamber walls, friction is severe and is reduced by using molten glass as a lubricant in the case of steels and high-temperature alloys at higher temperatures [5]. At lower temperatures, oils with graphite powder are used for lubrication. The indirect extrusion process shown in Fig. 24.10 allows the metal to flow in the opposite direction of the ram. It is more efficient since it reduces friction losses considerably [5]. The process, however, is not used extensively because it restricts the length of the extruded component. Impact extrusion is similar to indirect extrusion. Here, the punch descends rapidly on the blank, which gets indirectly extruded onto the punch to give a tubular cross section. The length of the tube formed is controlled by the amount of metal in the slug and by the blank thickness. Collapsible tubes for pastes are commonly extruded by this method. Hydrostatic extrusion is a process in which the billet is completely surrounded by a pressurized liquid, except where the billet contacts the die. This process can be done hot, warm, or cold; however, the temperature is limited by the stability of the fluid used. Hydrostatic extrusion must be carried out in a sealed cylinder to carry the hydrostatic medium. The fluid can be pressurized in two manners: (1) by constant-rate extrusion where a ram is used to pressurize the

Table 24.3 Typical lubricants and their coefficient of friction values in hot and cold extrusion operations of various metals [6]

Material	Hot extrusion—lubricant	Hot extrusion—COF	Cold extrusion—lubricant	Cold extrusion—COF
Cu and Cu alloys	Graphite	0.2	Castor oil	0.03
Refractory metals	Glass coating plus graphite on die	0.05	N/A	N/A
Steel	Graphite, molten glass, glass powder	0.2	Graphite	N/A
Ti alloys	Graphite	0.2	N/A	N/A
Al and Mg alloys	None	Sticking friction	Lanolin	0.07

fluid inside the container or (2) by constant-pressure extrusion where a pump is used, possibly with a pressure intensifier, to pressurize the fluid, which is then pumped to the container. In the hydrostatic extrusion process, the friction between the container wall and the billet is eliminated; however, this process has got limited applications in industry due to specialized equipment, tooling cost, and a low production rate due to a long setup time.

Extrusion operations are similar to many other metal forming operations where friction is undesirable. Friction on the die during the extrusion operation can cause increases in extrusion pressure and destroy the homogeneity of the extruded material. Friction on the die also contributes to heat generation and hinders the performance of the extrusion process by minimizing the speed of the process and attainable cross-sectional configurations of the extruded material. To thwart friction, lubricants are used in some cases. Extrusion can be unlubricated or lubricated. Unlubricated extrusions are used in the process of extruding tubes, hot aluminum alloys, and copper alloys. Table 24.3 details some of the common lubricants for various metals undergoing hot or cold extrusion operations [6].

2.5 *Drawing*

Drawing is a cold metalworking process that uses tensile forces to stretch metal into long rods, wires, and tubes. In this process, a material is pulled through a die to reduce it to a desired shape and size. Figure 24.11 reveals a schematic of the drawing process for a rod or wire and a tube. In a typical wire drawing operation, one end of the wire is reduced and passed through the opening of the die, pulling with it the metal to reduce its diameter. By successive drawing operations through dies of reducing diameter, a rod can be reduced to a very small diameter. Undergoing annealing heat treatment between each successive drawing operation permits larger area reductions in the drawn material. Tungsten carbide dies are used for drawing hard wires, and diamond dies are the choice for fine wires. When a

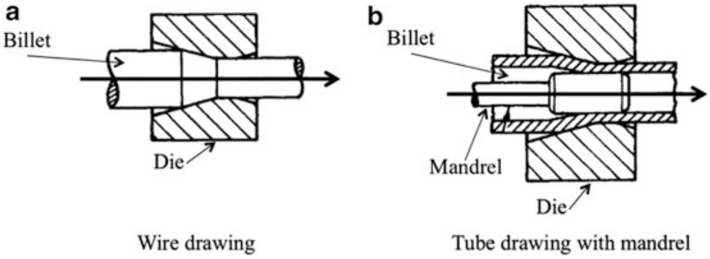


Fig. 24.11 Schematic of the drawing process of (**a**) rod or wire and (**b**) hollow tube

hollow tube is drawn through a die without any mandrel to support the inside of the tube, this process is known as tube sinking. When a mandrel or plug is used to support the inside diameter of the tube while being drawn through the die, this process is called tube drawing [4]. Tube drawing is similar to wire drawing, except that a mandrel is required to form the internal hole. As the blank is drawn into the die cavity, compressive stress is set up around the flange causing it to wrinkle or buckle the flange. Sheet metal drawing becomes deep drawing when the workpiece is drawing longer than its diameter. Figure 24.12 illustrates the deep drawing process where a sheet blank (hot or cold) is subjected to a peripheral hold-down pressure and is forced by a punch into and through the die to form a deep recessed part having a wall thickness the same as that of the blank [7]. This process is used to produce cylindrical or prismatic cups with or without a flange on the open end. Cylindrical-shaped parts such as cups, shells, or tubes from sheet metal can be redrawn to increase their length and to reduce their lateral dimensions. Along with deep drawing, it is common that the workpiece is also processed using other forming processes, such as piercing, ironing, necking, rolling, and beading.

Bar, wire, and tube drawing are often carried out at room temperature; however, because of the large compressive forces, which arise from the reduction of the metal with the die, significant deformations occur resulting in considerable temperature rises during the drawing operation [4]. These temperature rises along with increases in friction necessitate the use of lubricants during the drawing process. Drawing operations require lubricants to control the friction and to ensure adequate reductions in the size of the material. Lubricants are applied in drawing operations to reduce friction, wear, and heat generation. Drawing without lubricants results in material pickup, which can cause defects in the drawn material, large stresses in the deformation zones, fracture of the workpiece, or improper drawing processes. Minimal friction is required between the workpiece and the die in wire and tube drawing. Moderate friction is necessary in the process of drawing bars. Drawing operations can be performed with solid and liquid lubricants. Drawing under solid-lubricated conditions involves the use of soaps, whereas drawing under liquid-lubricated conditions involves the use of viscous oils or aqueous emulsions. Common applications of drawing utilize mixed-film regimes where lubricants are comprised of soaps with extreme additives. Table 24.4 presents the typically used lubricants for wire and tube drawing [6].

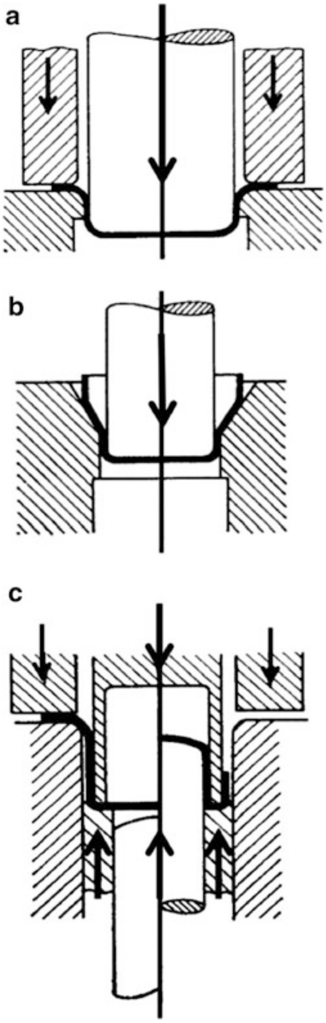


Fig. 24.12 Schematic of basic deep drawing processes with a rigid tool (**a**) first draw with a blankholder, (**b**) redraw without blankholder, and (**c**) reverse drawing

3 The Influence of Friction During Metal Forming

The knowledge of various parameters which control the friction forces is important in metalworking operations. Friction is an important process parameter that controls the tool load, product quality (geometry, tolerance, and surface finish), and tool wear. The coefficient of friction, if controlled properly, could generate the required stresses to deform the metal to the required shape. It could also lead to failure of the workpiece if not controlled properly, e.g., fracture of sheet in sheet metal forming.

In general, friction is controlled by many variables, such as surface texture, load, speed, temperature, lubricants, and material properties [8–16]. It is stated in the

Table 24.4 Typical lubricants and their coefficient of friction values in wire and tube drawing operations of various metals [6]

Material	Wire drawing—lubricant	Wire drawing—COF	Tube drawing—lubricant	Tube drawing—COF
Cu and Cu alloys	Mineral oil and fatty derivatives	0.03–0.15 (mixed film)	Soap film	0.05
Refractory metals	Copper and mineral oil	0.1	Copper and mineral oil	0.1
Steel	Mineral oil and fat and EP additives, phosphate and emulsion	0.07 0.1	Phosphate and soap	0.05
Ti alloys	Fluoride phosphate and soap	0.1	Metal and soap	0.07
Al and Mg alloys	Mineral oil and fatty derivatives	0.03–0.15 (mixed film)	Soap	0.07

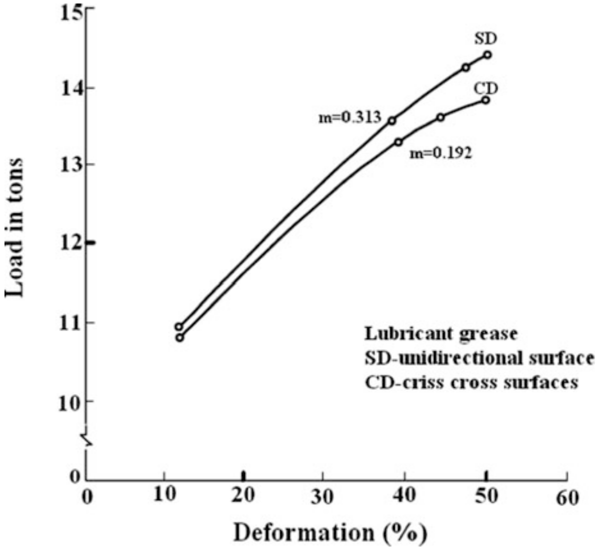
literature that surface texture of the die is one of the key factors that control friction during metal forming. The influence of surface texture on friction is not well established although some efforts have been made to study the effect of surface texture on friction during metal forming processes using experiments. In one of the earliest experimental steps towards understanding the effect of surface texture on lubrication during metal forming, Schey [17] demonstrated the effect of different machined surfaces but did not examine in detail the effect of surface topography as such. Later, Geiger et al. [18] identified two types of lubricant pockets, closed and connected. In their investigation of cold forging, they were able to determine the proportion of surface area at the interface; they comprised it by analysis of the surface texture. They compared the difference between two types of surface texture but not in terms of surface roughness.

Many researchers have carried out experiments on friction to characterize the metal forming process and to study the effect of surface texture on friction during metal forming. With sheet metal forming as an industrial backdrop, Wagner [19] studied the influence of tool surfaces, coating on tool surfaces, sheet metal surfaces, coating on sheet metal surfaces, and with the influence of the lubrication on the frictional behavior. Wagner [19] summarized that the tribological conditions at the contact zones between the sheet surface and the tool surface play an important role in determining the limits of the forming process. It was concluded that the friction in various tribologically relevant contact zones affects the flow of the material at the tool and hence it was used deliberately to control the drawing process. Bello and Walton [20] studied the combined effect of surface roughness and lubrication on friction at the tool–metal interface in sliding contact in the presence of lubricant. In their experiment, strips of commercial pure aluminum were pulled through steel dies designed to give partial simulation of the conditions that exist in the flange and die radius profile regions of the deep drawing process. They found that the conventional surface roughness parameters do not provide a satisfactory functional characterization of the surface in the context of the friction developed in sliding contact. They developed a new roughness parameter, which was found to be a better functional characteristic of the surface in regard to friction coefficient. Schedin [21] conducted experiments using U-bending test and strip drawing test to study the formation of transfer layer during forming processes. The experimental conditions resemble the contact conditions in sheet metal forming, where a hard and smooth tool surface will make repeated contacts with a soft and rough sheet surface. The research work inferred that it is impossible to completely avoid metal transfer in the sheet metal forming operation but that the growth of the transfer layer could be controlled by carefully designing the surface topography and using lubricants or coatings.

Rasp and Wichern [22] studied the effect of surface topography on frictional resistance using different kinds of surfaces. In their experiment, the five different specimen surfaces used were: as received, etched, coarse ground perpendicular to test direction, coarse ground parallel to test direction, and polished. It was found that the arithmetic roughness value (R_a) and lubrication regime have greater influence than the directionality of the surface lay. The influence of surface topography of the sheet material on the frictional characteristics of 3104 Al alloy sheet was investigated by Saha et al. [23] by stretching a strip around a cylindrical pin. They found that friction increased with the strain occurring during the contact, which supports the model relating friction to flattening of strip asperities and real area of contact. They also found that the coefficient of friction depends on the rolling direction of the strip. In all the above cases, the test material is deformable, so that the surface topography of deformable material cannot explain true friction values during metal forming process, and thus, it is important to have knowledge about the surface topography of tool material on the coefficient of friction.

A considerable amount of work has also been performed to study the effect of surface topography of harder materials on softer deformable materials during sliding in metal forming operations. Lakshmipathy and Sagar [24], in their industrial relevant study, tried to understand the influence of die grinding marks' directionality on friction in open-die forging under lubricated conditions. Two sets of dies, one with unidirectional grinding marks and other with crisscross grinding marks, were used. It was found for the same percentage of deformation that the dies with the crisscross ground pattern required lesser forging loads when compared with the die having unidirectionally ground pattern (Fig. 24.13). Lower friction value was also observed for the forging process when the die with the crisscross surface pattern was used. They concluded that the lubrication breakdown tendency is more when pressing is done with unidirectionally ground die than crisscross ground die. Malayappan and Narayanasamy [25] analyzed the bulging effect of aluminum solid cylinders by varying the frictional conditions at the flat die surfaces. Different machining processes like grinding, milling, electro-spark machining, and lathe turning with emery finish were produced on the flat dies to vary the frictional conditions. It was concluded that the barreling depends on friction and ultimately the surface texture.

Fig. 24.13 Forging load versus deformation at different die surfaces [24]



Määttä et al. [26] studied the friction of stainless steel strips against different tool steels and reported that the surface texture of the steel, rather than its composition, had the greatest effect on the friction at the tool and workpiece interface. Staph et al. [27] studied the effect of surface texture and surface roughness on scuffing using a caterpillar disk tester. The authors used steel disks of varying roughness and texture and concluded that both surface texture and surface roughness affect frictional behavior. Koura [28] studied the effect of surface texture on friction mechanism using a universal testing machine. Steel specimens were prepared to various degrees of roughness by grinding, lapping, and polishing. The results showed that the behavior of surfaces and thus friction during sliding depends on the degree of roughness. Costa and Hutchings [29] investigated the influence of surface texture on friction during metal forming processes. Figure 24.14 shows the variation of friction coefficients for the tests with dies of different surface textures. It was found that the friction was strongly influenced by the relative orientation between the grooves generated on the die surfaces and the drawing direction. Hu and Dean [30] analyzed the relation between friction behavior and surface texture using a ring upsetting test. The tests were carried out using either a liquid lubricant or under clean dry conditions. Two types of workpiece surfaces, random and directional, were prepared by either shot blasting or EDM or turning to different levels of surface finish. It was found that for random surfaces, smoother surfaces could retain more lubricant and decrease the friction resistance.

Wakuda et al. [31] studied the frictional properties of silicon nitride ceramic surfaces in which dimple patterns were machined with different size, density, and geometry against hardened steel using abrasive jet machining (AJM) and laser beam machining (LBM) techniques. Figure 24.15 shows the friction coefficient of

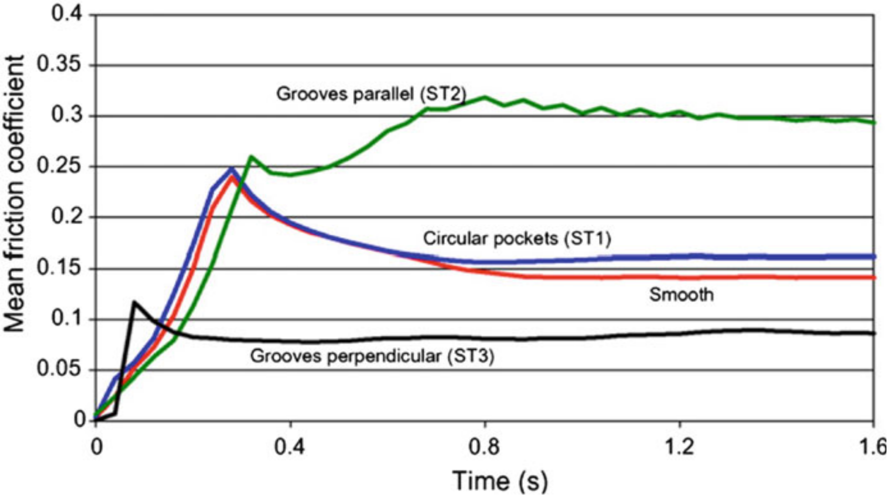
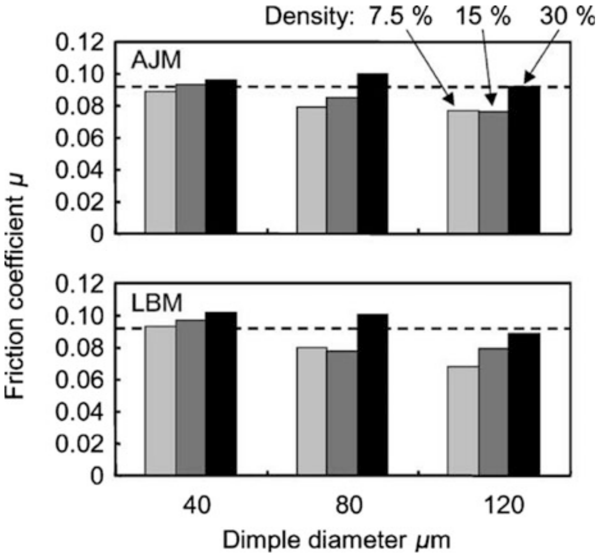


Fig. 24.14 Variation of friction coefficients for the tests with dies with different surface textures [29]

Fig. 24.15 Comparison of friction coefficient of the textured surfaces with different dimple diameter and density [31]



the textured surfaces with different dimple diameter and density. They found that surfaces with dimples show reductions in friction coefficient when compared to lapped smooth surfaces. It was concluded that the tribological characteristics depended greatly on the size and density of the micro-dimples rather than shape of the micro-dimples. Xie and Williams [32] proposed a model in order to predict the value of the overall coefficient of friction and wear rate, when the soft surface slid against a rough harder surface. This model points to the fact that both friction and wear depend essentially on the roughness characteristics of the harder surface, the mechanical properties of both surfaces, nominal contact pressure or load, and the state of lubrication. The influence of directionality of surface grinding marks on the coefficient of friction was studied [9, 10, 33–37]. It was observed that the friction depends primarily on the directionality of the grinding marks but was less dependent on the surface roughness of the harder tool surfaces.

In metal forming processes such as sheet metal forming, the control of the friction level has a significant role since it influences the stress and strain distribution in the sheet. It should be neither too high nor too low to obtain a sheet with desirable quality. Thus, the stability of tribological conditions in metal forming operation will, to a large extent, influence the productivity and the quality of the formed product. Friction between the tool and workpiece has a significant effect on material deformation, forming load, component surface finish, and die wear. It is also an essential input parameter for the ever-increasing use of finite element (FE) simulation for metal forming. It was reported earlier that surface texture of the die indeed plays an important role on coefficient of friction during forming. Further, ring compression tests have been conducted for evaluating the frictional effects in bulk metal forming [38, 39]. The result [38] showed that under frictionless conditions, the hole size of the hollow cylinder increases proportionately to the outer diameter. However, with increasing frictional constraint, the rate of expansion of the hole decreases, and eventually the compressive hoop stress developed at the hole causes the hole to contract.

Significant efforts have been made to understand the influence of friction in forming using numerical analysis [40–43]. Liu et al. [40] analyzed a three-dimensional upsetting process and reported that under frictionless conditions bulging does not appear, whereas it occurs when friction is present. Wang and Zhu [41] performed the numerical simulation of deep drawing process and concluded that the larger the coefficient of friction, the smaller the drawing limit. Wang et al. [42] studied the numerical research of the cold upsetting–extruding of tube flanges and reported that the friction conditions at the interface of the tube free end with the male or the female dies have an important influence on the material flow. Analysis of the deformation characteristics of spike-forging through finite element simulations and experiments was done by Xu and Rao [43] who concluded that friction at the tool–workpiece interface plays a significant role in forcing the material and thus the spike height. Thus, it is clear from the above discussion that the friction influences material deformation and ultimately stresses and strain rates in the workpiece material.

Efforts have also been made to study the effect of deformation and strain rate on microstructural evaluation [44–50]. Strain rate is one of the important factors that control the microstructure evolution of the deforming material. Depending on the combination of strain rate and temperature, various kinds of microstructural mechanisms will operate, leading to different microstructural evolution. Eghbali [45] studied the effect of strain rate on the microstructural development in micro-alloyed steel. It was found that the deformation strain rate has a significant influence on the flow behavior and deformed microstructure. Also, Li et al. [46] reported that the plastic deformation at higher strain rate in a Monel alloy induces dynamic recrystallization and ultimately affects the microstructure characteristics.

It is clear from the above discussion that by controlling the surface texture of the die, the interfacial friction can influence the net shape of the finished workpiece. The die surface and thus the friction can also affect the strain rate distribution in the workpiece, which is believed to ultimately determine the microstructure evolution of the deforming material. Thus, the die surface finish can be manipulated to obtain desired microstructure within the finished workpiece. The mechanical property and quality of the product depends on the microstructure of the workpiece material.

3.1 Effect of Surface Texture on Friction

Hence, efforts have been made to study the effect of surface texture of tool material on coefficient of friction using various soft materials during sliding under both dry and lubricated conditions [16, 51–60]. In these studies, various kinds of surface textures—namely, unidirectional grinding marks, 8-ground, and random—were prepared using simple metallographic techniques. Figure 24.16 shows the variation of coefficient of friction with surface textures when Al–Mg alloy pin slid on steel plate of different surface roughness [16]. It can be seen that the coefficient of friction depends on surface textures. It was found that the coefficient of friction was highest when sliding perpendicular to the unidirectional grinding marks (UPD) and lowest when tests were conducted on the random surfaces under both dry and lubricated conditions. For 8-ground and U-PL (sliding parallel to the unidirectional grinding marks) surface textures, the coefficient of friction lies in between these two extremes. The results obtained provide a basis for controlling the coefficient of friction across various locations along the interface between die and workpiece in metal forming process. These results may be employed to obtain a particular die surface finish in a particular area of the tool so as to obtain the desired coefficient of friction. By controlling the surface texture of the die, the friction at the interface and final shape can be controlled. This would affect the stresses and strain rates of the workpiece.

Thus, during the sliding tests, different friction values were obtained for the different surface textures. These friction values were subsequently used directly at the die–workpiece interfaces in finite element compression simulations to ascertain the state of stress, strain rate distribution, and the deformed shape in the workpiece. In the simulation work reported in literature for sheet metal and other forming operations [61–65], the coefficient of friction was assumed to be a constant at the interface or was set at different values at various locations. The criterion for choosing different values of coefficient of friction at different locations was made either arbitrarily or based on intuition.

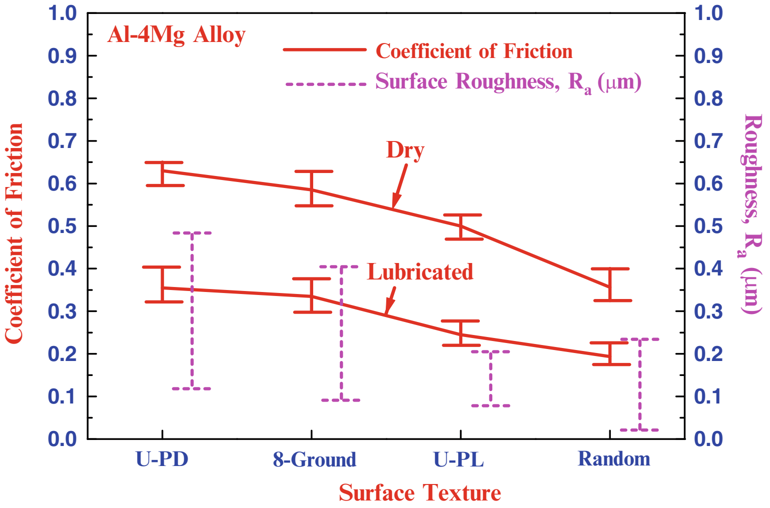


Fig. 24.16 Variation of average coefficient of friction and surface roughness (R_a) with surface texture for Al-4Mg alloy [8, 16]

3.2 *Effect of Friction During Metal Forming*

Attempts have been made to study the state of stress by implementing the obtained different coefficient of friction values at various locations between the die and workpiece during metal forming by using finite element (FE) analysis. In this simulation approach, the surface textures of various types [16] were not attained on the die surfaces. Instead, the coefficient of friction values, generated for these surface textures, were employed directly at the die–workpiece interfaces to study the state of stress in the workpiece and the deformed shape by conducting compression test using FE simulation.

In this study, the influence of friction between the tool and workpiece on the metal flow behavior was studied by simulating compression tests on cylindrical Al–Mg alloy using finite element method (FEM) technique. This has been done by changing the coefficient of friction values at different location on the die. Process simulation of compression tests was performed using commercially available nonlinear finite element code, DEFORM 3D, a general-purpose program performing both elastic–plastic and rigid–plastic analyses. The package is capable of simulating metal flow during forging, extrusion, rolling, drawing, and stamping operations.

In the simulation, the coefficient of friction values, generated for various surface textures, were employed directly at the die–workpiece interfaces. It was observed from Fig. 24.16 that the variation of friction with surface textures under both dry and lubricated conditions follows the same trend (i.e., the coefficient of friction values are high when sliding tests were performed perpendicular to the

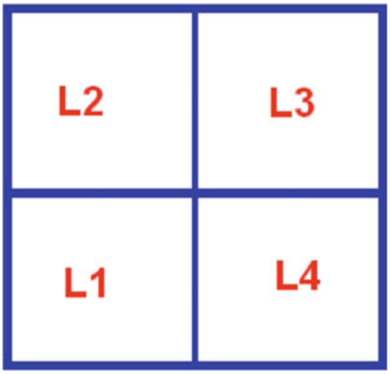


Fig. 24.17 Schematic diagram of lower die (top view) [66]

Table 24.5 Coefficient of friction values at four zones between the lower die and the workpiece interface [66]

	Friction at different zones			
Tests	L1	L2	L3	L4
First	0.65	0.65	0.65	0.65
Second	0.65	0.65	0.35	0.35
Third	0.65	0.35	0.65	0.35

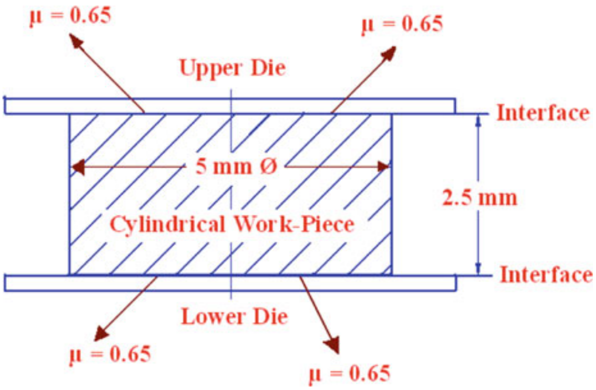
unidirectional grinding marks and low for the tests conducted on the random surfaces) [8, 16]. Hence, in the simulation, the coefficient of friction values, obtained for the unidirectional and random surfaces under dry conditions, namely, 0.65 and 0.35, were considered.

Three kinds of compression tests were considered wherein a constant coefficient of friction (i.e., 0.65) was employed at upper die–workpiece interface. However, the coefficient of friction between the lower die–workpiece interfaces was varied in the tests. Thus, to vary the friction between lower die and workpiece interface, the lower die was divided into four zones, namely, L1, L2, L3, and L4. A schematic diagram of the lower die with four zones is shown in Fig. 24.17. Table 24.5 shows the different coefficient of friction values employed at different zones between lower die and workpiece interface for different tests. A schematic diagram of the compression tests is shown in Fig. 24.18 with similar friction values at the contacting interface as shown in the first test of Table 24.5.

The coefficient of friction values incorporated in this study were obtained for the case of Al–Mg alloy which is slid against steel counterface [16], and Al–Mg alloy material properties were assigned to the workpiece. The material parameters were obtained from the database library of DEFORM. All tests were performed by reducing the height of the workpiece by 70 %.

Figure 24.19 shows the variation of load with stroke for all the three tests. It can be seen from the figure that higher loads are required for the first test when compared to the second and third tests, since the coefficient of friction values are more in all the four zones (i.e., L1 = L2 = L3 = L4 = 0.65) of the lower die for this first test when compared to the second and third tests where half of the

Fig. 24.18 Schematic diagram of compression test [66]



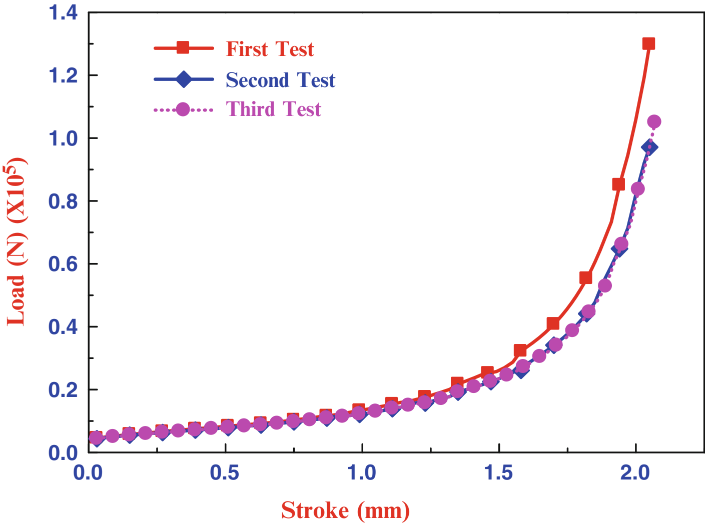


Fig. 24.19 Load–stroke curves for compression tests [66]

workpiece (two zones) experiences low coefficient of friction (i.e., L1 = L2 = 0.65; L3 = L4 = 0.35 for the second test and L1 = L3 = 0.65; L2 = L4 = 0.35 for the third test). For this reason, the second and third tests experience similar load–stroke curves and lower values of load when compared to the first test. Here, it is interesting to note that the variation in load is independent of the friction conditions at lower strokes and the difference in loads is greater at higher strokes. Another interesting fact is that there is almost no variation in load (Fig. 24.19) when the friction conditions are as per the second and third tests [66].

Figure 24.20a, b depicts the distribution of the stresses and strain rates for the simulation when the workpiece was compressed to 50 % [67, 68]. Here, the coefficient of friction values were the same (0.65) between all contacting surfaces.

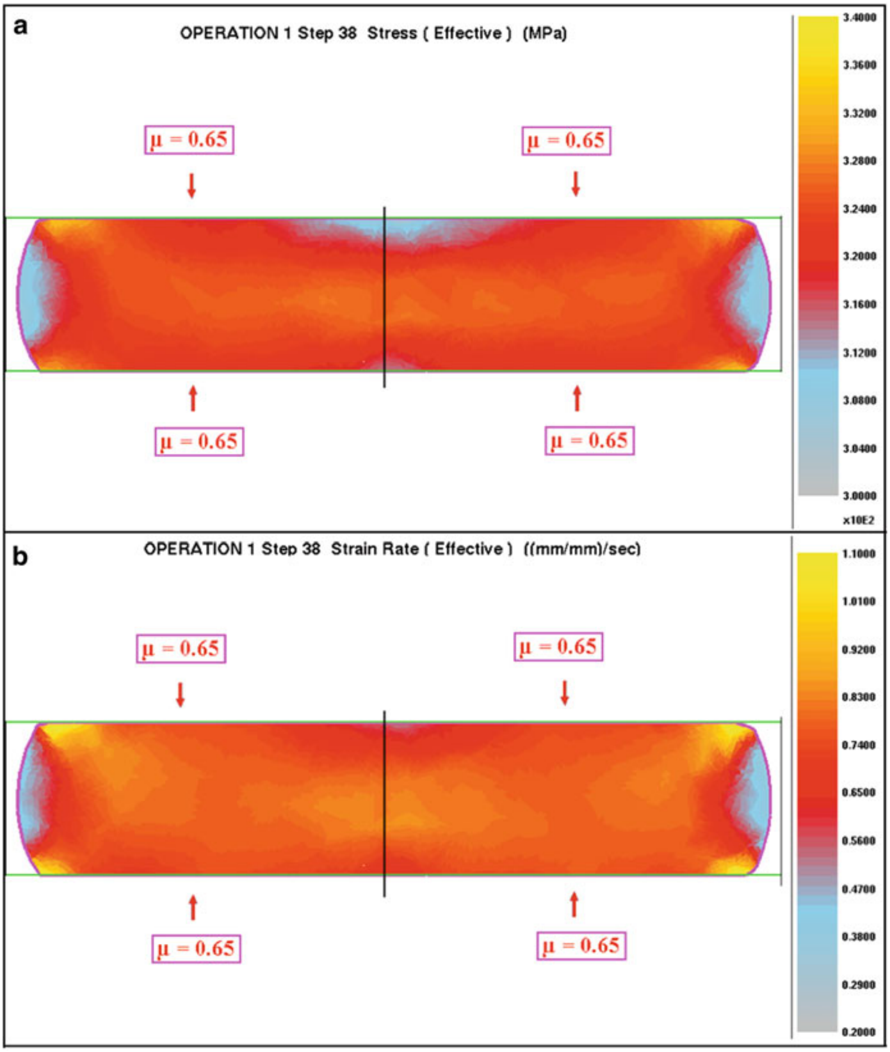


Fig. 24.20 Variation of (**a**) stresses and (**b**) strain rates when same friction values were assigned at the lower die–workpiece interface [67, 68]

It can be observed that the stress and strain rate distribution, as expected, is the same (i.e., the side view after sectioning perpendicular to the axes along the major diameter) for both the left-hand and right-hand sides near to the lower interface. In these regions, the friction values were assigned to be the same in both halves of the die–workpiece interface.

Another simulation was carried out by assigning different friction values at different locations on the lower die–workpiece interface. In these simulations, the friction values assigned for the left and right halves of the die–workpiece interface

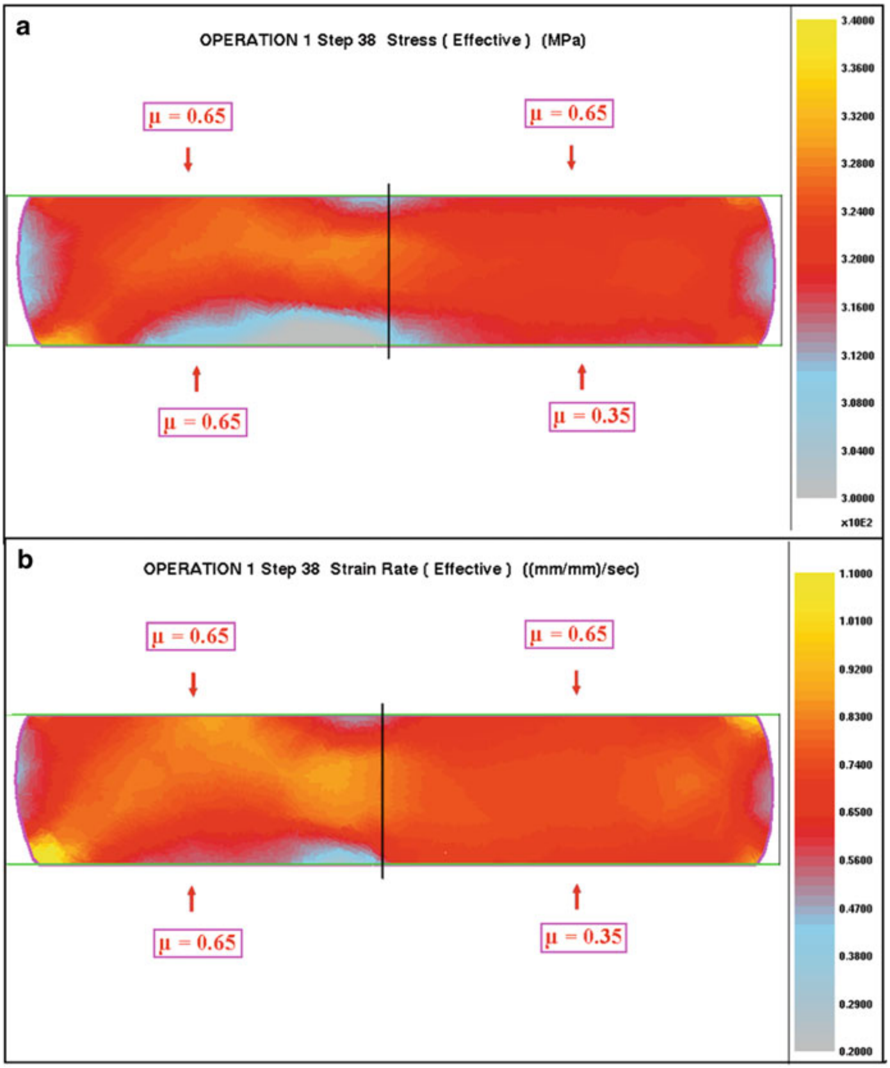


Fig. 24.21 Variation of (**a**) stresses and (**b**) strain rates when different friction values were assigned at the lower die–workpiece interface [67, 68]

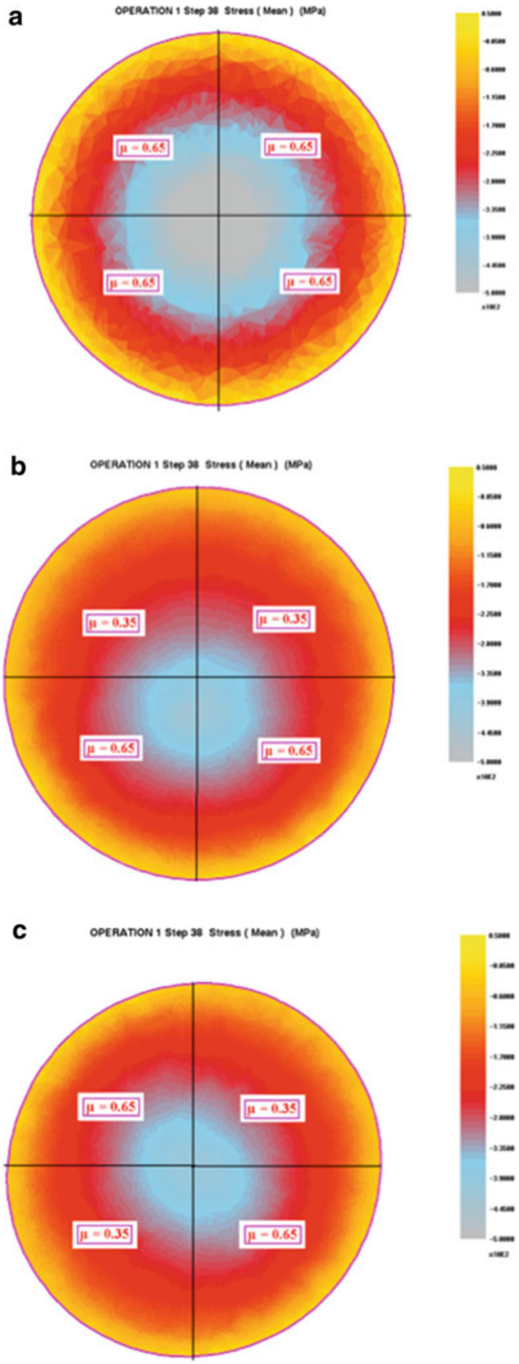
were 0.65 and 0.35, respectively. The friction value was 0.65 between upper die and workpiece interface. Figure 24.21a, b shows that the distribution of stresses and strain rates was significantly different for the left-hand and right-hand sides near the lower interface where the friction is different. Low effective stress and strain rate is observed at the left half and near to lower die–workpiece interface when high friction value is assigned. However, high effective stress and strain rate is observed at the right side and near to the lower die–workpiece interface when low friction value is assigned. In addition, it can be seen that the high stress and strain rate region in the core of the workpiece in the first simulation (Fig. 24.20a, b) shifts towards the region of higher die–workpiece friction in the second simulation (Fig. 24.21a, b). Furthermore, the shape at the periphery of the workpiece is the same for the first simulation (Fig. 24.20a, b) and different for the second variable friction simulation (Fig. 24.21a, b) [67, 68].

Having seen the stress distributions for different coefficient of friction values at the cross section of the cylindrical workpiece, now results on the changes in shape of the cylindrical workpiece when compressed to 50 % in the compression test for different coefficient of friction values will be presented. Figure 24.22a shows the distribution of mean stresses for the first test. It can be seen from the figure that the shape of the workpiece remains circular when similar coefficient of friction values are assigned to all the four zones. In addition, the tension zone was observed at the periphery of the workpiece, while the compression zone was observed at the center of the workpiece. Figure 24.22b shows the distribution of mean stresses for the second test. It can be observed from this figure that the shape of the workpiece is different when different coefficient of friction values are assigned to each zone. The flow of the workpiece was much larger for the one half of the workpiece where lower coefficient of friction values were assigned at the interface when compared to the other half of the workpiece where higher coefficient of friction values were assigned. In addition, the compression zone changed its shape and the stress contours shift towards the half of the workpiece where high coefficient of friction values are assigned.

Figure 24.22c shows the distribution of mean stresses for the third test. In this case, as explained earlier, the compression test was conducted by assigning coefficient of friction values of 0.35 and 0.65 that are assigned alternatively to each quarter (zone) of the lower die–workpiece interface. It can be seen from Fig. 24.22c that the flow of the workpiece is much larger when low coefficient of friction values are assigned at the die–workpiece interface than when high coefficient of friction values are assigned. In addition, the compression zone becomes elliptical in shape with its semimajor axis aligned in direction of the quarters (of the workpieces) where high coefficient of friction values are assigned and its semiminor axis aligned in the direction of the quadrants where low coefficient of friction values are assigned. From this it can be inferred that the flow of metal and thus the changes in shape of the workpiece depend on coefficient of friction at the interface [37]. Similar observations were also reported in the literature using both experimental [25] and numerical analysis [40] methods for the upsetting process. In these efforts, it was reported that the shape of the workpiece depends on the coefficient of friction at the interface between the die and workpiece.

By controlling the surface texture and the friction at the die, the stress and strain rate can be controlled. Strain rate is one of the important factors that control the microstructure evolution of the deforming material [37, 44, 69–75]. Thus, desired microstructures can be derived by controlling the friction values at the die–workpiece interface. Depending on the combination of strain rate and temperature, various kinds of microstructural mechanisms will operate leading to different

Fig. 24.22 Distribution of mean stresses for the (**a**) first test, (**b**) second test, and (**c**) third test when the workpiece is compressed to 50 % [67, 68]



microstructural evolution. The different microstructural mechanisms that operate include dynamic recrystallization (DRX), dynamic recovery (DRY), adiabatic shear banding (ASB), wedge cracking (WC), void formation (VF), superplastic deformation (SPD), intercrystalline cracking (ICC), and prior particle boundary (PPB) cracking. In some of these mechanisms, including DRX, DRY, and SPD, the microstructural evolution leads to a more desirable microstructure. Other mechanisms, such as ASB, WC, SPD, VF, PPB and ICC, can lead to an undesirable microstructure. It is also important to have the desirable microstructures at preferred locations. In metal forming, the locations and area in the workpiece covered by a particular microstructure can be completely altered by just changing the die–workpiece friction.

3.3 Effect of Surface Texture on Metal Forming

Similar to finite element analysis, laboratory uniaxial compression tests were performed on cylindrical Al-4Mg alloy at constant true strain rates of 4 s^{-1} at room temperature. Instead of assigning different friction values from the experiments, in this study, different surface textures (unidirectional and random) were generated at each halves on the lower die surface so that the workpiece would experience variable friction at the interface. In the compression experiments, the random texture generated on the die surface was similar to the texture generated on the friction test sample [16]. However, the unidirectional texture on the die was prepared by creating circular grinding marks on the die surfaces by maintaining the same roughness level as that of friction test samples. This was done to maintain similar material flow (i.e., perpendicular to the die grinding marks' direction) of the cylindrical sample at the contacting interface. After the experiments, the deformed workpiece was sectioned along the compression axis. The sectioned half was then metallographically polished, etched to reveal the microstructure prior to optical microscopy examination.

Figure 24.23a shows the photograph of the cross section of compressed workpiece. The arrows indicate the type of texture generated on the low die surfaces. It can be observed that the material flow was found to be greater at the right-hand side of the workpiece that experiences low friction coefficient due to random surface texture. The optical micrographs taken near the interface are also presented in the figure (see Fig. 24.23b, c). It can be seen that microstructural features are different in both sides of the workpiece. More specifically, coarse-grained structure was observed at the left half and near the lower die–workpiece interface (Fig. 24.23b), while a fine-grained structure was observed at the right half and near the lower die–workpiece interface (Fig. 24.23c). Thus, it can be inferred that the grain size of the samples near the interface is largely influenced by the surface texture of the die.

From the above analysis, it is evident that low effective strain rate was observed when a high coefficient of friction value was assigned at the interface due to constraint to flow of the workpiece material. In contrast, high effective strain rate

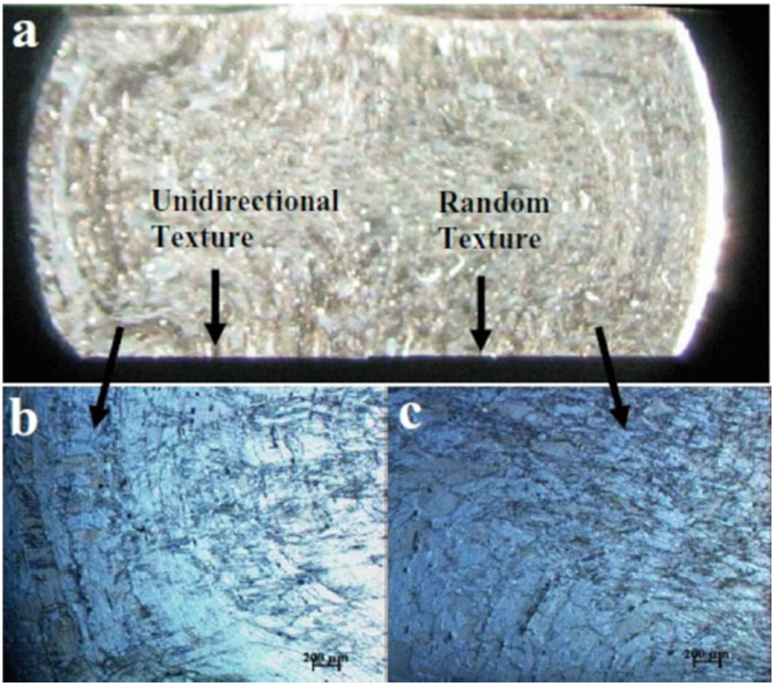


Fig. 24.23 (**a**) Photograph of the cross section of the workpiece, (**b**) the microstructure of the workpiece compressed against a unidirectional texture, (**c**) the microstructure of the workpiece compressed against a random texture [68]

was observed when a low coefficient of friction value was assigned at the interface due to less constraint to flow as shown in the simulation results. Hence, coarse-grained structure was observed at low strain rate region, and fine-grained structure was observed at high strain rate region as revealed in the microstructure of the compression test samples.

The surface texturing technology can be utilized in metal forming process to design a particular texture at different locations of the die so that the coefficient of friction could be varied according to the requirement. In locations where the coefficient of friction needs to be high, a unidirectionally ground surface with the flow perpendicular to the grinding marks can be machined, and in locations where the coefficient of friction needs to be low, a randomly ground surface can be machined. Designing textures on the die may also enable the reduction of conventional lubricants that are needed to achieve the required friction. The die–workpiece friction affects material flow, stresses, and strain rate distribution in the deformed material, which in turn influences the microstructural evolution in the material. The microstructure evolution will affect the mechanical properties of the formed product. The mechanical properties of the formed product at different locations depending on the requirements can also be tailored by designing proper surface texture.

4 Conclusions

Friction in metal forming processes is a very complex phenomenon as it depends on many parameters. Metal forming is a vital part to the way in which industries, applications, and consumers utilize and create metal components. Companies that manufacture metals often supply materials in the form of ingots, which are obtained by casting liquid metals into square cross sections known as slabs, billets, or blooms. These shapes are further processed through rolling, forging, extrusion, or drawing to produce metal materials that are in standard form for distribution in the form of plates, sheets, tubes, rods, and various structural sections. As with many applications, the ability to control the friction forces is important, especially in metalworking operations. Friction is an important process parameter, which controls the tool load, product, and tool wear. The coefficient of friction, if controlled properly, could generate the required stresses to deform the metal to the required shape. It could also lead to failure of the workpiece if not controlled properly. In general, friction is controlled by many variables, such as surface texture, load, speed, temperature, lubricants, and material properties. The influence of surface texture on friction was investigated in this chapter and revealed to be an important parameter that influences metal forming. Designing textures on workpieces enables the reduction of conventional lubricants that are needed to achieve the required friction within a metal forming process. The change in friction affects material flow, stresses, and strain rate distribution in deformed materials, which in turn influences the microstructural evolution in the materials. The microstructure evolution will affect the mechanical properties of the formed products. Thus, the mechanical properties of formed products can be tailored by designing proper surface texture.

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Questions

1. What are the three manufacturing processes?
2. Explain direct-compression-type processes and indirect-compression-type processes.
3. Describe tension-type processes, bending processes, and shearing processes.
4. Describe the rolling process.
5. Describe the forging process. Explain two types of forging.
6. Describe the extrusion processes. List four types of extrusion techniques.
7. Describe the drawing process.
8. Explain how surface texture affects friction and the relevance this has on metal forming processes.
9. How does surface texturing influence metal forming and affect the microstructure of the die workpiece?
10. What are primary and secondary metal forming processes?
11. What are hot-working and cold-working processes?

Answers

1. The three manufacturing processes are casting, forming, and machining. Casting is the process where molten liquid is poured into a mold that holds the required shape, and allowing hardens the metal with or without external pressure. This process occurs in the liquid state. Forming is a process where the volume and mass of metal are preserved and the metal is displaced from one location to another location by applying pressure. This process occurs in the solid state. Machining is the process where material is removed in order to give it the required shape. This process also occurs in the solid state.
2. A direct-compression-type process is one in which the force is applied to the surface of the workpiece and the metal flows at right angles to the direction of the compression. An indirect-compression-type process is one in which the primary applied forces are frequently tensile, but indirect compressive forces are developed by the reaction of the workpiece with the die. Therefore, the metal flows under the action of a combined stress state, which includes high compressive forces in at least one of the principal directions.
3. A tension-type forming process is stretch forming, where a metal sheet is wrapped to the contour of a die under the application of tensile forces. A bending process involves the application of bending moments to the sheet. A shearing involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear.
4. Rolling is the process where a sheet or plate is drawn by means of friction in between two rollers. The compressive forces applied by the rollers reduce the thickness of the material while minimizing the cross-sectional area and causing the rolled material to elongate and spread.

5. Forging is the process of hammering or pressing material between two dies to achieve the desired shape and structure through plastic deformation. Two types of forging are open-die forging and closed-die forging. Open-die forging is the process where metal is compressed by hammering or pressing between flat or contoured dies either mechanically or manually and the shape of the material is deformed through plastic deformation. Open-die forging gets its name from the fact that the dies (the surfaces that are in contact with the workpiece) do not enclose the workpiece, allowing the metal to flow except where contacted by the dies. Closed-die forging is the process where the metal is compressed between a shaped die and a hammer that presses the metal deforming it within the die causing the metal to flow and fill the die cavities.
6. Extrusion is the process where a material is compressed in a chamber and the deformed material is forced to flow through a die. The die opening corresponds to the cross section of the required product. Extrusion is primarily a hot-working process; however, for softer materials, cold extrusion is also performed. There are a few types of extrusion processes that are used extensively in industry: direct extrusion, indirect extrusion, impact extrusion, and hydrostatic extrusion.
7. Drawing is a cold metalworking process that uses tensile forces to stretch metal into long rods, wires, and tubes. In this process, a material is pulled through a die to reduce it to a desired shape and size. In a typical wire drawing operation, one end of the wire is reduced and passed through the opening of the die, pulling with it the metal to reduce its diameter. By successive drawing operations through dies of reducing diameter, a rod can be reduced to a very small diameter.
8. The coefficient of friction depends on surface textures. Research shows that the coefficient of friction was highest when sliding perpendicular to the unidirectional grinding marks and lowest when tests were conducted on the random surfaces under both dry and lubricated conditions. In the test conducted for 8-ground and U-PL (sliding parallel to the unidirectional grinding marks) surface textures, the coefficient of friction values were in between these two extremes. The results obtained provide a basis for controlling the coefficient of friction across various locations along the interface between die and workpiece in metal forming process. These results may be employed to obtain a particular die surface finish in a particular area of the tool so as to obtain the desired coefficient of friction. By controlling the surface texture of the die, the friction at the interface and final shape can be controlled. This would affect the stresses and strain rates of the workpiece.
9. The surface texturing technology can be utilized in metal forming process to design a particular texture at different locations of the die so that the coefficient of friction could be varied according to the requirement. In locations where the coefficient of friction needs to be high, a unidirectionally ground surface with the flow perpendicular to the grinding marks can be machined, and in locations where the coefficient of friction needs to be low, a randomly ground surface can be machined. Designing textures on the die may also enable the reduction of

conventional lubricants that are needed to achieve the required friction. The die–workpiece friction affects material flow, stresses, and strain rate distribution in the deformed material, which in turn influences the microstructural evolution in the material. The microstructure evolution will affect the mechanical properties of the formed product. The mechanical properties of the formed product at different locations depending on the requirements can also be tailored by designing proper surface texture.

10. The plastic working processes, which are designed to reduce an ingot or billet to a standard mill product of simple shape, such as sheet, plate, and bar, are known as primary mechanical working processes. Forming methods, which produce a part of a final finished shape, are called secondary mechanical working processes. Most sheet metal forming operations, wire drawing, and tube drawing are secondary processes.
11. Hot-working is defined as the process of deformation of the workpiece under conditions of high temperature and strain rate such that the recovery process takes place along with the deformation of the workpiece. Cold-working is defined as the process of deformation under conditions where the recovery process is ineffective.