1- Introduction

Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces. Deformation results from the use of a tool, usually called a die in metal forming, which applies stresses that exceed the yield strength of the metal. The metal therefore deforms to take a shape determined by the geometry of the die. Stresses applied to plastically deform the metal are usually compressive. However, some forming processes stretch the metal, while others bend the metal, and still others apply shear stresses to the metal. To be successfully formed, a metal must possess certain properties. Desirable properties include low yield strength and high ductility. These properties are affected by temperature. Ductility is increased and yield strength is reduced when work temperature is raised. The effect of temperature gives rise to distinctions between cold working, warm working, and hot working. Strain rate and friction are additional factors that affect performance in metal forming.

2- Classification of Metal Forming Operations

Metal forming processes can be classified into two basic categories: bulk deformation processes and sheet metal working processes. Each category includes several major classes of shaping operations, as indicated in figure (1).

2.1 Bulk Deformation Processes: Bulk deformation processes are generally characterized by significant deformations and massive shape changes, and the surface area-to-volume of the work is relatively small. The term bulk describes the workparts that have this low area to-volume ratio. Starting work shapes for these
processes include cylindrical billets and rectangular bars. Figure (2) illustrates the following basic operations in bulk deformation:

- **Rolling.** This is a compressive deformation process in which the thickness of a slab or plate is reduced by two opposing cylindrical tools called rolls. The rolls rotate so as to draw the work into the gap between them and squeeze it.
- **Forging.** In forging, a workpiece is compressed between two opposing dies, so that the die shapes are imparted to the work. Forging is traditionally a hot working process, but many types of forging are performed cold.
- **Extrusion.** This is a compression process in which the work metal is forced to flow through a die opening, thereby taking the shape of the opening as its own cross section.
- **Drawing.** In this forming process, the diameter of a round wire or bar is reduced by pulling it through a die opening.
2.2 Sheet Metalworking: Sheet metalworking processes are forming and cutting operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is high; thus, this ratio is a useful means to distinguish bulk deformation from sheet metal processes.

Sheet metal operations are always performed as cold working processes and are usually accomplished using a set of tools called a punch and die. The punch is the positive portion and the die is the negative portion of the tool set. The basic sheet metal operations are sketched in figure (3) and are defined as follows:

- **Bending.** Bending involves straining of a metal sheet or plate to take an angle along a (usually) straight axis.
- **Drawing.** In sheet metalworking, drawing refers to the forming of a flat metal sheet into a hollow or concave shape, such as a cup, by stretching the metal. A blank holder is used to hold down the blank while the punch pushes
into the sheet metal, as shown in figure (3-b). To distinguish this operation from bar and wire drawing, the terms cup drawing or deep drawing are often used.

- Shearing. This process seems somewhat out-of-place in a list of deformation processes, because it involves cutting rather than forming. A shearing operation cuts the work using a punch and die, as in figure (3-c). Although it is not a forming process, it is included here because it is a necessary and very common operation in sheet metalworking.

The miscellaneous processes within the sheet metalworking classification in figure (1) include a variety of related shaping processes that do not use punch and die tooling. Examples of these processes are stretch forming, roll bending, spinning, and bending of tube stock.

**FIGURE 3** Basic sheet metalworking operations: (a) bending, (b) drawing, and (c) shearing: (1) as punch first contacts sheet, and (2) after cutting. Force and relative motion in these operations are indicated by $F$ and $v$. 
3- Material Behavior in Metal Forming

The typical stress–strain curve for most metals is divided into an elastic region and a plastic region. In metal forming, the plastic region is of primary interest because the material is plastically and permanently deformed in these processes.

The typical stress–strain relationship for a metal exhibits elasticity below the yield point and strain hardening above it. Figures (4 and 5) indicate this behavior in linear and logarithmic axes.

In the elastic region, the metal’s behavior is expressed by stress-strain curve and hooke’s law:

\[ E = \frac{\sigma}{\varepsilon} \] ............ 1

In the plastic region, the metal’s behavior is expressed by the flow curve:

\[ \sigma_T = k\varepsilon_T^n \] ............ 2

Where \( K \) = the strength coefficient, MPa; and \( n \) is the strain-hardening exponent. The stress \( (\sigma_T) \) and strain \( (\varepsilon_T) \) in the flow curve are true stress and true strain. The flow curve is generally valid as a relationship that defines a metal’s plastic behavior in cold working.

3.1 Flow Stress: The flow curve describes the stress–strain relationship in the region in which metal forming takes place. It indicates the flow stress of the metal (the strength property that determines forces and power required to accomplish a particular forming operation).

For most metals at room temperature, the stress–strain plot of figure (5) indicates that as the metal is deformed, its strength increases due to strain hardening.
The stress required to continue deformation must be increased to match this increase in strength. **Flow stress** is defined as the instantaneous value of stress required to continue deforming the material to keep the metal "flowing". It is the yield strength of the metal as a function of strain, which can be expressed:

$$Y_f = k \varepsilon_f^n$$  

\[ \text{FIGURE 4 True stress–strain curve for the previous engineering stress–strain plot in Figure 3.3.} \]

\[ \text{FIGURE 5 True stress–strain curve plotted on log–log scale.} \]

\[ \text{The stress required to continue deformation must be increased to match this increase in strength. Flow stress is defined as the instantaneous value of stress required to continue deforming the material to keep the metal “flowing”. It is the yield strength of the metal as a function of strain, which can be expressed:} \]

\[ Y_f = k \varepsilon_f^n \]
Where $Y_f = \text{flow stress, MPa.}$

In the individual forming operations, the instantaneous flow stress can be used to analyze the process as it is occurring. For example, in certain forging operations, the instantaneous force during compression can be determined from the flow stress value. Maximum force can be calculated based on the flow stress that results from the final strain at the end of the forging stroke.

In other cases, the analysis is based on the average stresses and strains that occur during deformation rather than instantaneous values. Extrusion, rolling, and wire drawing are examples of this case.

3.2 Average Flow Stress: The average flow stress (also called the mean flow stress) is the average value of stress over the stress–strain curve from the beginning of strain to the final (maximum) value that occurs during deformation. The value is illustrated in the stress–strain plot of figure (6).

![Stress-strain curve indicating location of average flow stress $\bar{Y}_f$ in relation to yield strength $Y$ and final flow stress $Y_f$.](image_url)
The average flow stress is determined by integrating the flow curve equation, Eq. (3), between zero and the final strain value defining the range of interest. This yields the equation:

\[ \bar{\sigma}_f = \frac{K\varepsilon^n}{1+n} \]

Where \( \bar{\sigma}_f \) = average flow stress, MPa; and \( \varepsilon \) = maximum strain value during the deformation process.

**4- Temperature in Metal Forming**

The flow curve is a valid representation of stress–strain behavior of a metal during plastic deformation, particularly for cold working operations. For any metal, the values of \( K \) and \( n \) depend on temperature. Strength and strain hardening are both reduced at higher temperatures. These property changes are important because they result in lower forces and power during forming. In addition, ductility is increased at higher temperatures, which allows greater plastic deformation of the work metal.

We can distinguish three temperature ranges that are used in metal forming: cold, warm, and hot working.

**4.1 Cold Working:** Cold working (also known as cold forming) is metal forming performed at room temperature or slightly above. Significant advantages of cold forming compared to hot working are (1) greater accuracy, meaning closer tolerances can be achieved; (2) better surface finish; (3) higher strength and hardness of the part due to strain hardening; (4) grain flow during deformation provides the opportunity for desirable directional properties to be obtained in the resulting product; and (5) no heating of the work is required, which saves on furnace and fuel costs and permits higher production rates. Owing to this
combination of advantages, many cold forming processes have become important mass-production operations. They provide close tolerances and good surfaces, minimizing the amount of machining required so that these operations can be classified as net shape or near net shape processes.

There are certain disadvantages or limitations associated with cold forming operations: (1) higher forces and power are required to perform the operation; (2) care must be taken to ensure that the surfaces of the starting workpiece are free of scale and dirt; and (3) ductility and strain hardening of the work metal limit the amount of forming that can be done to the part. In some operations, the metal must be annealed in order to allow further deformation to be accomplished. In other cases, the metal is simply not ductile enough to be cold worked.

To overcome the strain-hardening problem and reduce force and power requirements, many forming operations are performed at elevated temperatures. There are two elevated temperature ranges involved, warm working and hot working.

**4.2 Warm Working:** Because plastic deformation properties are normally enhanced by increasing workpiece temperature, forming operations are sometimes performed at temperatures somewhat above room temperature but below the recrystallization temperature. The term *warm working* is applied to this second temperature range. The dividing line between cold working and warm working is often expressed in terms of the melting point for the metal. The dividing line is usually taken to be 0.3 $T_m$, where $T_m$ is the melting point (absolute temperature) for the particular metal.

The lower strength and strain hardening at the intermediate temperatures, as well as higher ductility, provide warm working with the following advantages over cold
working: (1) lower forces and power, (2) more intricate work geometries possible, and (3) need for annealing may be reduced or eliminated.

4.3 Hot Working: Hot working (also called hot forming) involves deformation at temperatures above the recrystallization temperature \(T_R\). The recrystallization temperature for a given metal is about one-half of its melting point on the absolute scale. In practice, hot working is usually carried out at temperatures somewhat above 0.5\(T_m\). The work metal continues to soften as temperature is increased beyond 0.5 \(T_m\), thus enhancing the advantage of hot working above this level. However, the deformation process itself generates heat, which increases work temperatures in localized regions of the part. This can cause melting in these regions, which is highly undesirable. Also, scale on the work surface is accelerated at higher temperatures. Accordingly, hot working temperatures are usually maintained within the range 0.5Tm to 0.75Tm.

The most significant advantage of hot working is the capability to produce substantial plastic deformation of the metal (far more than is possible with cold working or warm working). The principal reason for this is that the flow curve of the hot-worked metal has a strength coefficient that is substantially less than at room temperature, the strain-hardening exponent is zero (at least theoretically), and the ductility of the metal is significantly increased. All of this results in the following advantages relative to cold working: (1) the shape of the workpart can be significantly altered, (2) lower forces and power are required to deform the metal, (3) metals that usually fracture in cold working can be hot formed, (4) strength properties are generally isotropic because of the absence of the oriented grain structure typically created in cold working, and (5) no strengthening of the part occurs from work hardening. This last advantage may seem inconsistent, since strengthening of the metal is often considered an advantage for cold working.
However, there are applications in which it is undesirable for the metal to be work hardened because it reduces ductility, for example, if the part is to be subsequently processed by cold forming.

Disadvantages of hot working include (1) lower dimensional accuracy, (2) higher total energy required (due to the thermal energy to heat the workpiece), (3) work surface oxidation (scale), (4) poorer surface finish, and (5) shorter tool life.

Recrystallization of the metal in hot working involves atomic diffusion, which is a time-dependent process. Metal forming operations are often performed at high speeds that do not allow sufficient time for complete recrystallization of the grain structure during the deformation cycle itself. However, because of the high temperatures, recrystallization eventually does occur. It may occur immediately following the forming process or later, as the workpiece cools. Even though recrystallization may occur after the actual deformation, its eventual occurrence, and the substantial softening of the metal at high temperatures, are the features that distinguish hot working from warm working or cold working.

Isothermal Forming: Certain metals, such as highly alloyed steels, many titanium alloys, and high-temperature nickel alloys, possess good hot hardness, a property that makes them useful for high-temperature service. However, this very property that makes them attractive in these applications also makes them difficult to form with conventional methods. The problem is that when these metals are heated to their hot working temperatures and then come in contact with the relatively cold forming tools, heat is quickly transferred away from the part surfaces, thus raising the strength in these regions. The variations in temperature and strength in different regions of the workpiece cause irregular flow patterns in the metal during deformation, leading to high residual stresses and possible surface cracking.
**Isothermal forming** refers to forming operations that are carried out in such a way as to eliminate surface cooling and the resulting thermal gradients in the workpart. It is accomplished by preheating the tools that come in contact with the part to the same temperature as the work metal. This weakens the tools and reduces tool life, but it avoids the problems described above when these difficult metals are formed by conventional methods. In some cases, isothermal forming represents the only way in which these work materials can be formed. The procedure is most closely associated with forging.