

## Chapter Three – Metal Forming Processes

### Introduction:

- In metal forming processes, the plastic deformation is used to change the shape of the workpiece.
- Plastic deformation is resulted from use a **tool** usually called a "**die**", which applies stresses that exceed the metal yield strength.
- In advanced metal forming processes such as "**dieless drawing process**", the plastic deformation occurs without using a tool or die.
- Stresses applied in plastic deformation are compressive, tensile, bending and shearing stresses based on forming process which is applied.
- To achieve a successful forming process, a substantial desirable properties of the metal must be realized including low yield strength and high ductility.
- Ductility is increased and yield strength is reduced when temperature is raised.
- Strain rate and friction are additional parameters that affect performance in metal forming.

### Classification of Metal Forming Processes:

1. Bulk Deformation Processes
2. Sheet Metalworking Processes

Figure (3-1) states the metal forming processes.

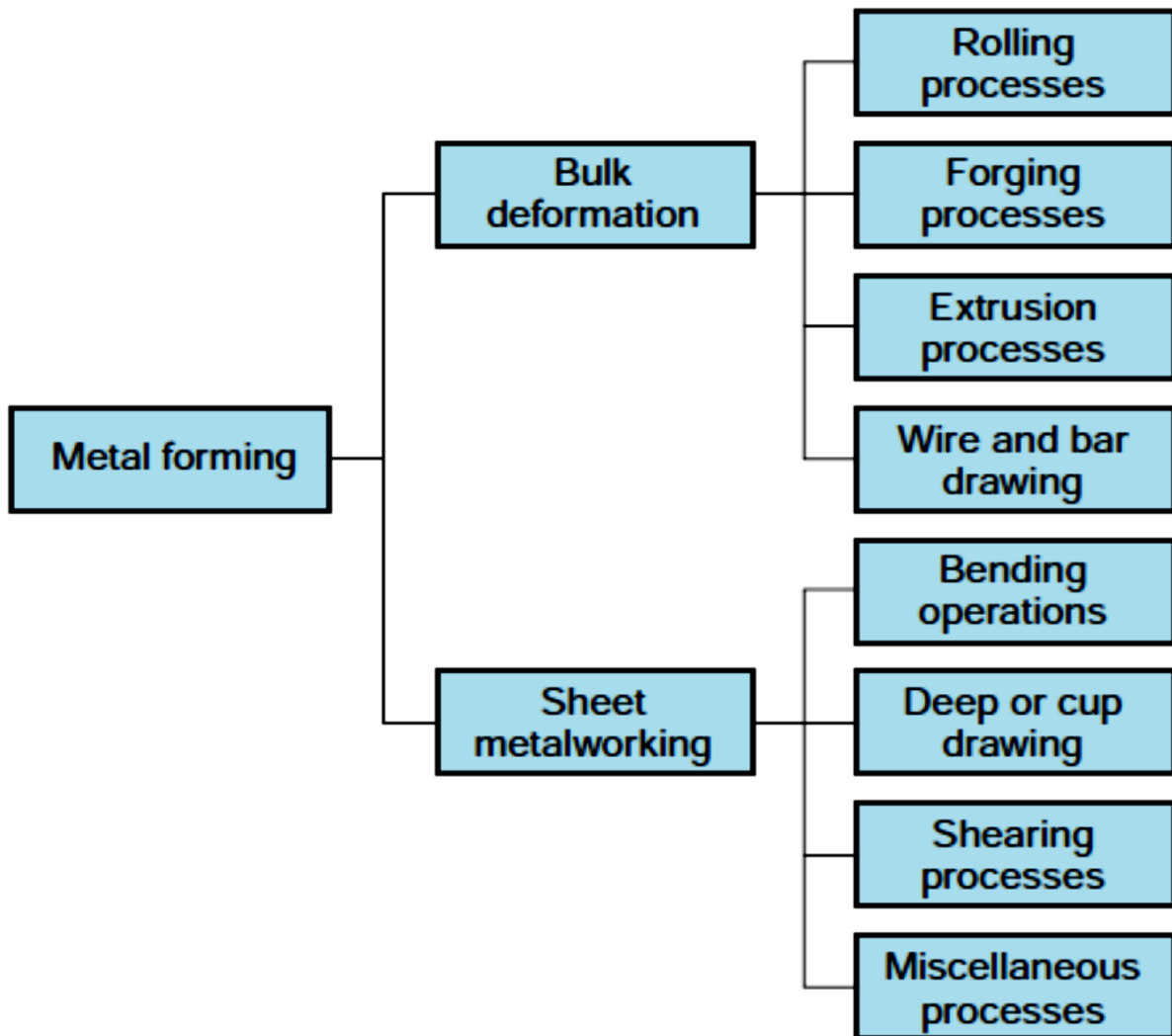


Figure (3-1) Metal Forming Processes Classification

## 1. Bulk Deformation Processes

- They are characterized by significant deformation and massive shape changes.
- The surface area-to-volume of the workpiece is relatively small.
- Term Bulk describes the workpiece parts that have this low area-to-volume ratio.

Figure (3-2) illustrates the bulk deformation processes.

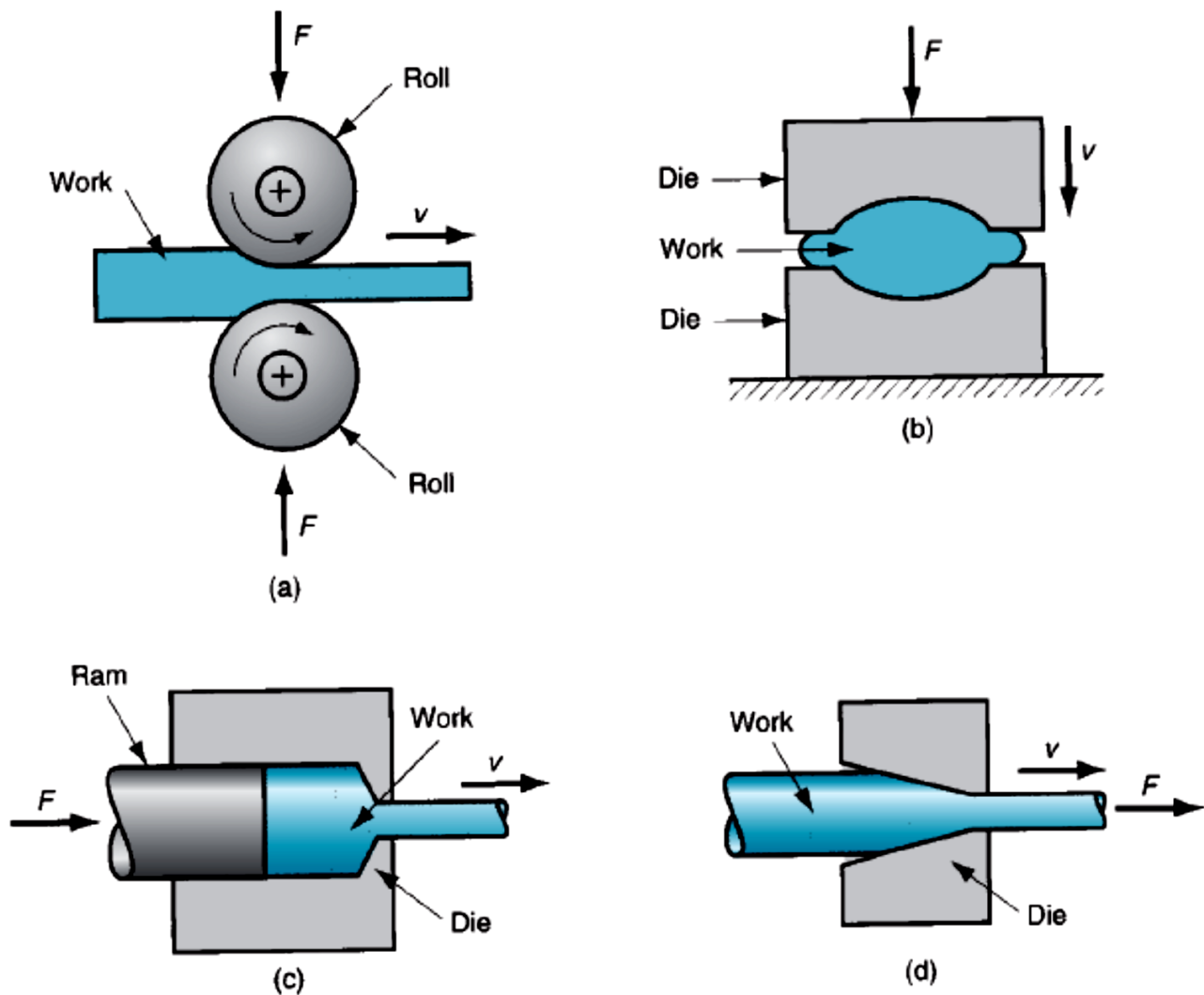


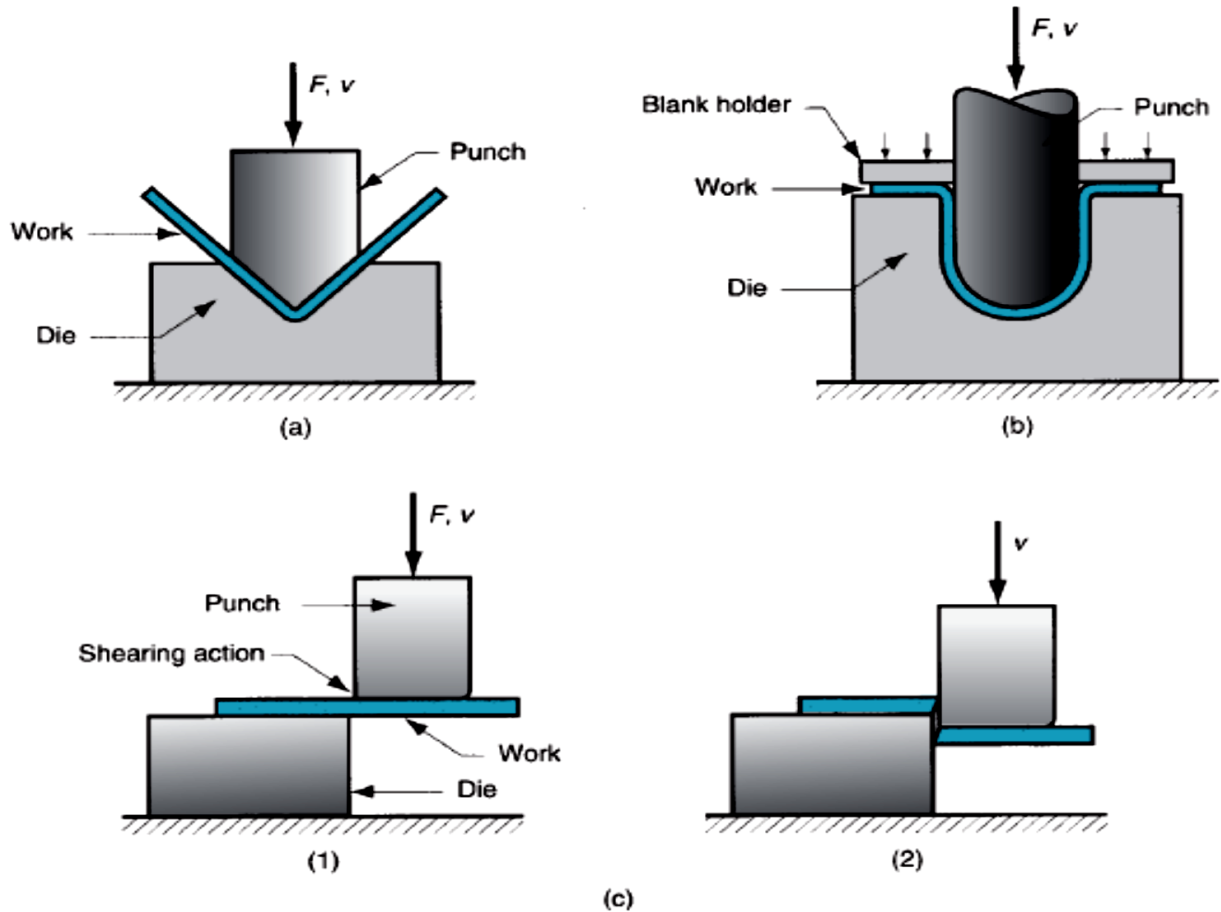
Figure (3-2) bulk deformation processes; (a) rolling, (b) forging, (c) extrusion, and (d) drawing

## 2. Sheet Metalworking Processes

- They are forming and cutting operations performed on metal sheets (0.15-6.35mm), strips and coils.
- Plate is greater than 6.35mm and foil is smaller than 0.15mm.
- The surface area-to-volume ratio of the workpiece is high.
- They are always performed as cold working processes.
- They are 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.
- Shearing processes involve cutting rather than forming. Although it is not a forming process, it is included here because it is a necessary and very common operation in sheet metalworking.

- Miscellaneous processes represent that processes which do not use punch and die tooling such as stretch forming, roll bending, spinning and bending of tube.

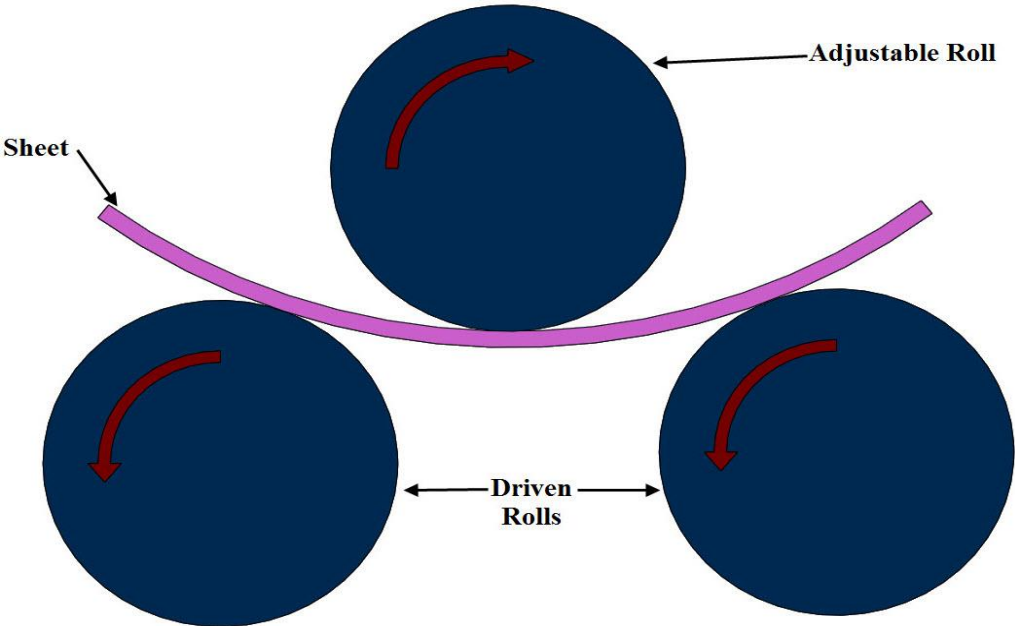
Figure (3-3) explains the sheet metalworking processes.



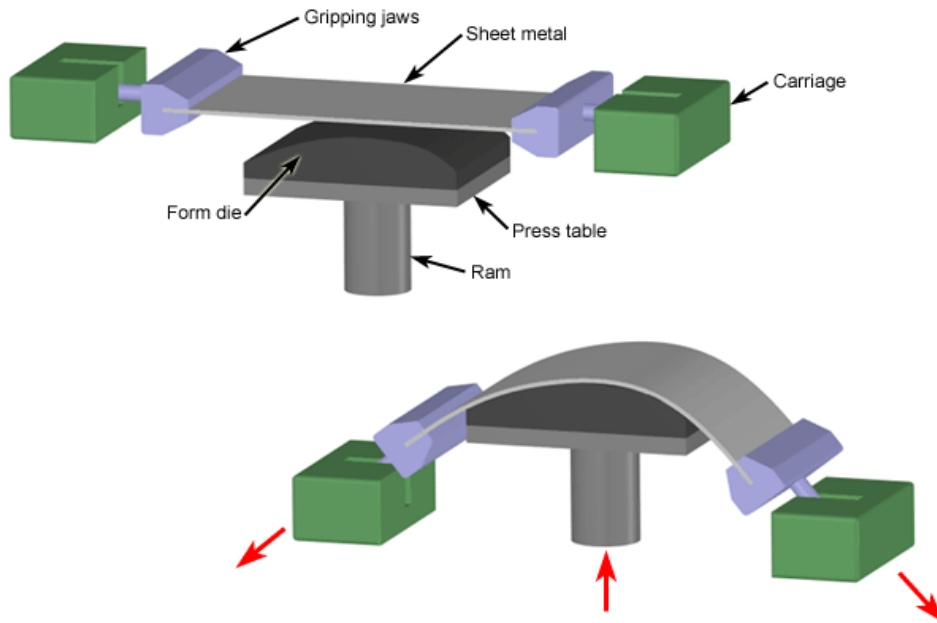
(d)



(e) tube bending

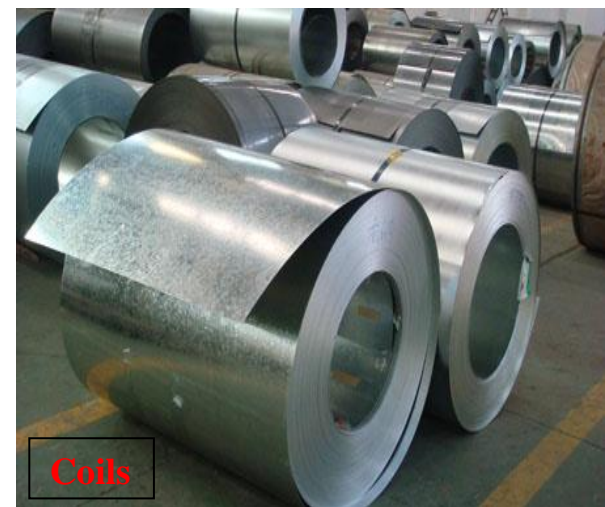
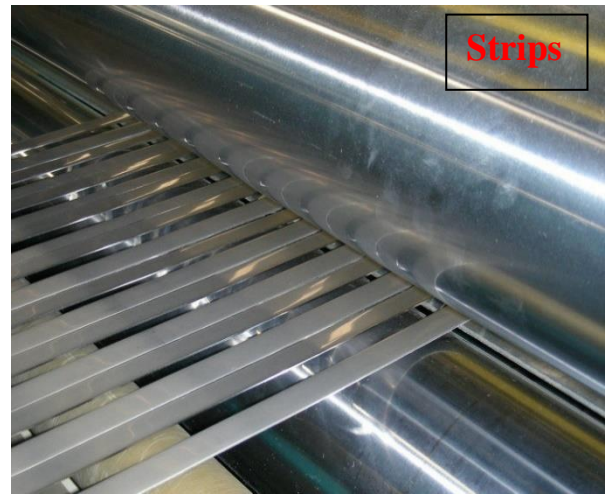


(f) roll bending



(g) stretch forming

Figure (3-3) sheet metalworking processes; (a) bending, (b) deep or cup drawing, (c) shearing (1) punch contacts sheet firstly. (2) after cutting, (d) spinning, (e) tube bending, (f) roll bending, (g) stretch forming



### **Type of Applied Stresses:**

- There are three types of static stresses to which materials can be subjected: tensile, compressive, and shear stresses.
- Tensile stresses tend to stretch the material.
- Compressive stresses tend to squeeze the material.
- Shear stresses tend to cause adjacent portions to slide against each other.
- The stress-strain curve is the basic relationship that describes the mechanical properties of materials for all types of stresses.

### **Stress-Strain Relationship in Tensile Loading:**

#### **Engineering Stress-Strain:**

- Figure (3-4) describes the engineering stress-strain curve.
- The engineering stress and strain are defined relative to the original area and length of test specimen.
- The engineering stress and strain are more important in design because the designer expects that generated strains will not significantly change its shape and the components are designed to withstand the anticipated stresses,



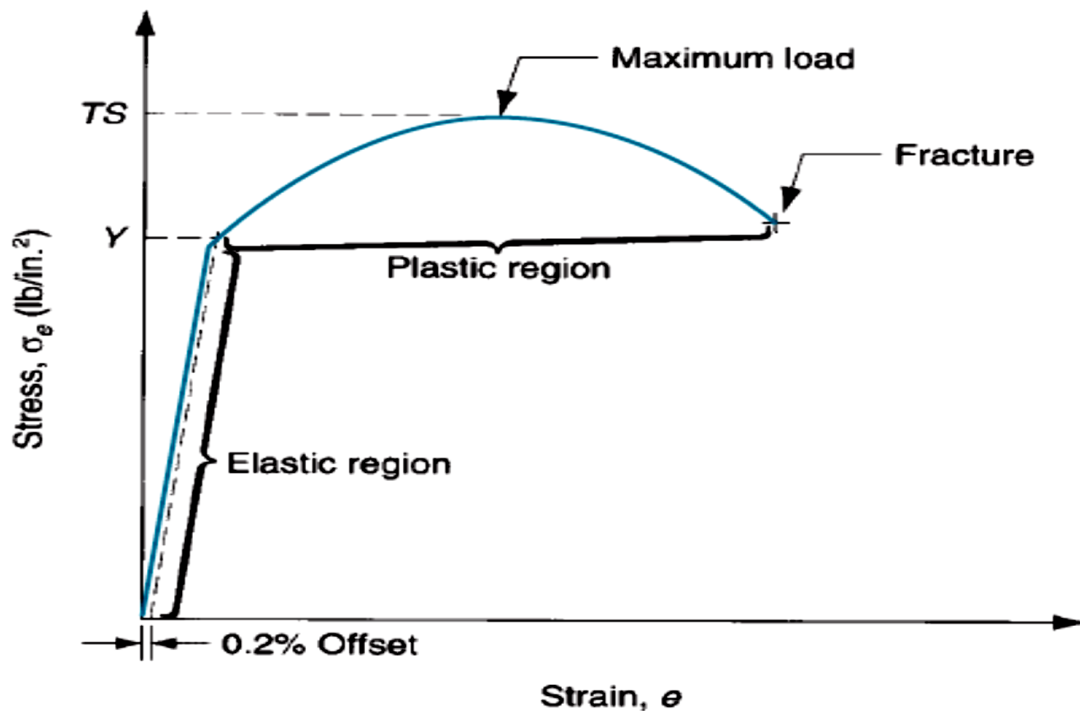


Figure (3-4) Engineering Stress-Strain Curve

**Engineering stress:**  $s = F/A_0$

s: engineering stress at any point on the curve

F: applied force in the test

$A_0$ : original area of the test specimen

**Engineering strain:**  $e = (L-L_0)/L_0$

e: engineering strain at any point in the test

L: length at any point during the elongation

$L_0$ : original gage length

**Elastic Region:**  $s = Ee$  (Hooke's Law)

E: elasticity modulus (measure of inherent stiffness of the material)

**Plastic Region:**  $TS = F_{\max}/A_0$  (tensile stress or ultimate tensile strength)

**Ultimate Tensile Strength (UTS):** it is a practical measure of the overall strength of a material.

**Ductility:** it is defined as ability of the material to plastically strain without fracture. Also, it is defined as how large a strain the material withstands before fracture. It can be defined by elongation or area reduction.

**Elongation:**  $EL = (L_f - L_0)/L_0$

$L_f$ : specimen length at fracture

**Area Reduction:**  $AR = (A_0 - A_f)/A_0$

$A_f$ : cross-section area at fracture

### True Stress-Strain:

- Figure (3-5) describes the True stress-strain curve.
- The true stress and strain are defined relative to the instantaneous area and length of test specimen.
- The true stress and strain are more important in manufacturing.

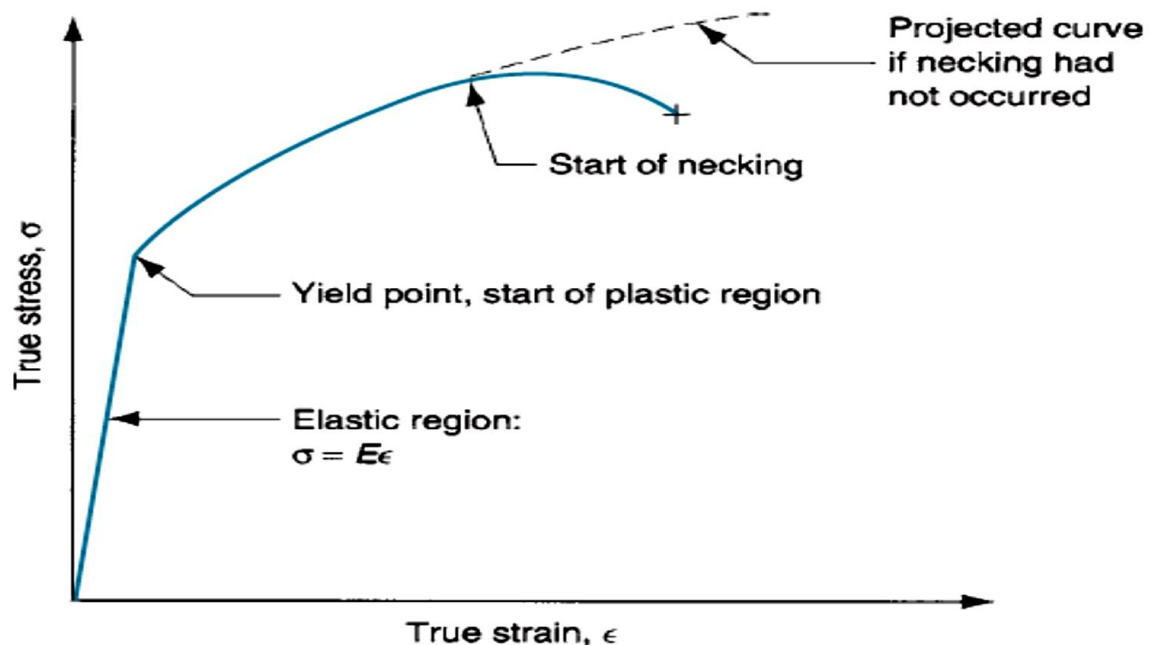


Figure (3-5) true stress-strain curve

**True stress:**  $\sigma = F/A$

$\sigma$ : true stress at any point on the curve

$F$ : applied force in the test

A: actual (instantaneous) area resisting the load

**True strain:** 
$$\epsilon = \int_{L_0}^L \frac{dL}{L} = \ln \frac{L}{L_0}$$

$\epsilon$ : true strain at any point in the test

L: instantaneous length at any moment during elongation

**Elastic Region:** 
$$\sigma = E\epsilon \quad \text{(Hooke's Law)}$$

**True-Engineering-Strain:** 
$$\epsilon = \ln(1+e)$$

**True-Engineering-Stress:** 
$$\sigma = s(1+e)$$

**Plastic Region:**

- In the plastic region (especially for cold working processes), the stress is increased with increase of strain until necking starts.
- The metal is becoming stronger as strain increases, this is because of strain hardening (work hardening) property.
- Figure (3-6) states the plastic region portion of the true stress-strain curve on a log-log scale. The relationship between true stress and true strain in the plastic region can be expressed as:

$$\sigma = K\epsilon^n \quad \text{(this equation is called the flow curve)}$$

K: strength coefficient (N/m<sup>2</sup>). n: strain hardening exponent (its value is directly related to a metal's tendency to work harden.

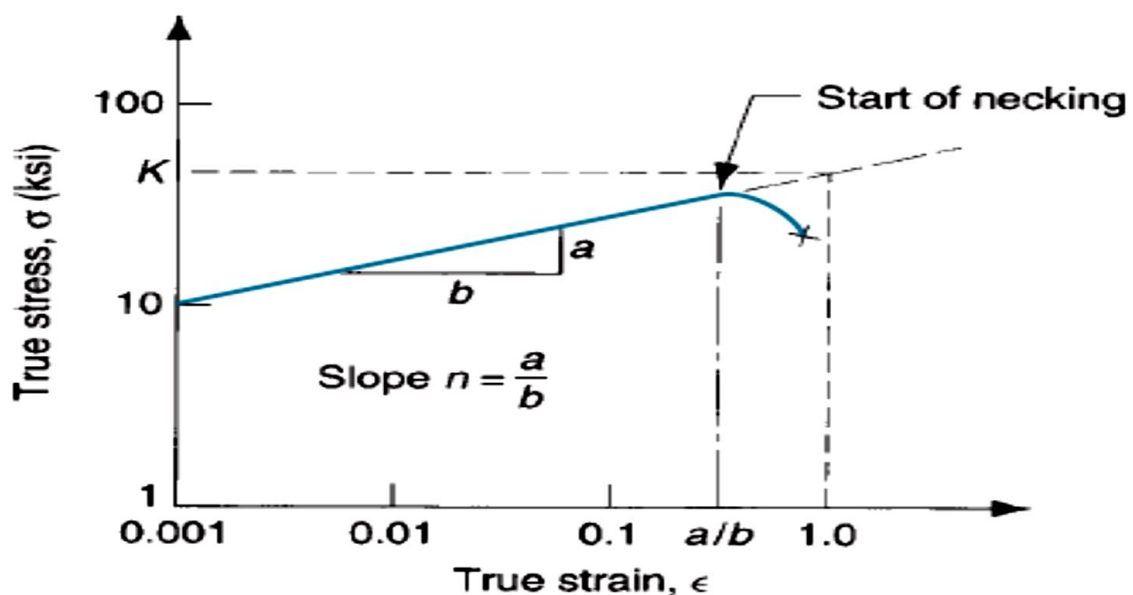


Figure (3-6) true stress-strain curve plotted on log-log scale.

## Material Behavior in Metal Forming:

- Behavior of metals during forming can be obtained from the true stress-true strain curve.
- In metal forming, the plastic region is very important, because the material is plastically and permanently deformed.
- In the plastic region, the metal obeys the flow curve equation ( $\sigma = K\varepsilon^n$ ).

## Flow Stress:

- It is the strength property that determines forces and power required to accomplish a particular forming operation.
- It is defined as the instantaneous value of stress required to continue deforming the material (to keep the metal "flowing").
- In certain forming operations like forging, the instantaneous force can be determined from the flow stress value, also, maximum force is calculated from the flow stress results from final strain.
- It is expressed as:

$$Y_f = K\varepsilon^n \quad (\text{yield strength of the metal as a function of strain})$$

$Y_f$ : flow stress.

## Average or Mean Flow Stress:

- In certain forming operations, like rolling, extrusion and drawing, the metal is gradually strain hardens to reach a maximum value.
- Determine the instantaneous stress-strain values in these operations, is difficult and limited interest.
- So, it is more useful to analyze the process based on average flow stress.
- Figure (3-7) states the average flow stress, which is determined by integrating the flow curve equation ( $Y_f = K\varepsilon^n$ ) between zero and final strain.

$$\bar{Y}_f = \frac{\int_0^\varepsilon Y_f d\varepsilon}{\varepsilon} = \frac{\int_0^\varepsilon K\varepsilon^n d\varepsilon}{\varepsilon} = \frac{K\varepsilon^n}{1+n}$$

$\bar{Y}_f$ : average flow stress

$\varepsilon$ : maximum strain value during the deformation process.

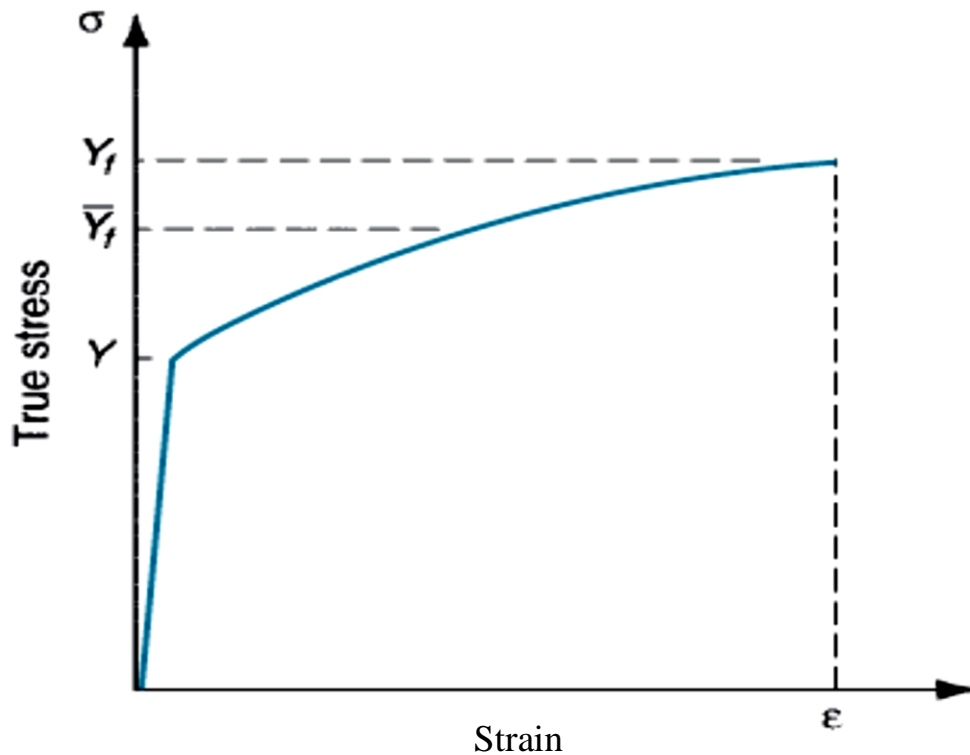


Figure (3-7) Average Flow Stress

### **Temperature in Metal Forming:**

- The flow curve figure (3-7) is valid particularly for cold working operations.
- K and n values depend on temperature.
- At higher temperature, strength and strain hardening are reduced, whereas, ductility is increased which permits greater plastic deformation.

There are three temperature ranges that are used in metal forming:

- 1- Cold working (cold forming).
- 2- Warm working.
- 3- Hot working (hot forming)

### **Cold Working:**

It is performed at room temperature or slightly above.

#### **Advantages:**

- Better accuracy (meaning closer tolerances).
- Better surface finish.
- Strain hardening increases strength and hardness of the product.
- Grain flow during deformation provides the opportunity for desirable directional properties to be obtained in the resulting product.

- No heating of the workpiece is needed which saves on furnace and fuel costs and allows higher production rates to be achieved.
- Minimizing the amount of machining required (can be classified as net shape or near net shape processes).

**Disadvantages:**

- Higher forces and power are needed.
- Care must be taken to ensure that the surfaces of the final product are free of scale and dirt.
- Ductility and strain hardening of the workpiece 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.

**Annealing:** heating a w.p. to a specific temperature range, holding it at that temperature for a time, and then cooling it at slow rate (say 10°C per hour).

**Warm Working:**

- By increasing the temperature, the plastic deformation properties are normally enhanced.
- It is carried out at temperatures somewhat above room temperature but below the recrystallization temperature.
- It is usually taken at  $0.3T_m$ , where  $T_m$  melting temperature at absolute scale.
- Recrystallization results in: 1- decrease in dislocations density, 2- lower strength, 3- higher ductility, 4- strain hardening lower.
- Metals recrystallize at room temperature do not strain harden.

**Advantages:**

- Lower strength and strain hardening at intermediate temperatures as well as higher ductility.
- Lower forces and power.
- More intricate geometries are possible.
- Annealing may be reduced or eliminated.

### **Hot Working:**

- It involves deformation at temperatures above the recrystallization temperature.
- In practice, hot working is carried out at temperatures above  $0.5T_m$ .
- Beyond  $0.5T_m$ , the metal is softened, thus enhancing the advantage of hot working.
- Due to (1) the deformation process itself generates heat which increases workpiece temperatures in localized regions and this can cause melting in these regions and (2) the rate on the workpiece is accelerated at higher temperatures. Therefore hot working temperatures are maintained within  $(0.5-0.75T_m)$ .

### **Advantages:**

- It has the capability to produce substantial plastic deformation of metal more than is possible with cold or warm working. Reasons for above: flow curve of hot working having a strength coefficient (K) less than at room temperature, strain hardening exponent (n) is zero and the ductility of metal is increased.
- The shape of workpiece can be significantly altered.
- Lower forces and power are required.
- Metals that usually fracture in cold working can be hot formed.
- Strength properties are generally isotropic because of absence of oriented grain structure typically created in cold working.
- No strengthening of workpiece occurs from work hardening.  
(This last advantage may seem inconsistent, since strengthening of metal is often considered an advantage for cold working. However, there are applications in which it is undesirable for metal to be work hardened because it reduces ductility, for example, if the part is to be subsequently processed by cold forming).

### **Disadvantages:**

- Lower dimensional accuracy.
- Higher total energy required (due to thermal energy to heat the workpiece).
- Work surface oxidation (scale).
- Poorer surface finish.
- Shorter tool life.

### Isothermal Forming:

- It is refer to forming operations that are carried out in such a way as to eliminate surface cooling and the resulting thermal gradients in the workpart. Since the heat is quickly transferred away from the part surface, 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.
- It is accomplished by preheating the tools that come in contact (during deformation process) with the part to the same temperature as the work metal.

### Strain Rate Sensitivity:

**Strain Rate:** the rate at which the metal is strained in a forming process is directly related to the speed of deformation. Thus:

$$\dot{\epsilon} = \frac{v}{h}$$

Where;

$\dot{\epsilon}$ : true strain rate (m/s/m), or simply  $s^{-1}$ .

$v$ : velocity of the ram or other moving element of the equipment, simply deformation speed (m/s).

$h$ : instantaneous height of the workpiece being deformed, (m).

- At the temperatures of hot working, flow stress depends on strain rate.
- The effect of strain rate on strength properties is known as strain rate sensitivity.
- The effect of strain rate on flow stress can be seen in figure (3-8).

Where;

$$Y_f = C\dot{\epsilon}^m$$

C: strength constant (N.s/m<sup>2</sup>),

m: strain rate sensitivity exponent

- At  $\dot{\epsilon}=1$ , the value of C is determined.
- Effect of temperature on flow stress is shown in figure (3-9).
- C is decreased with increasing of temperature, whereas, m (slope of each plot) is increased with increasing of temperature.



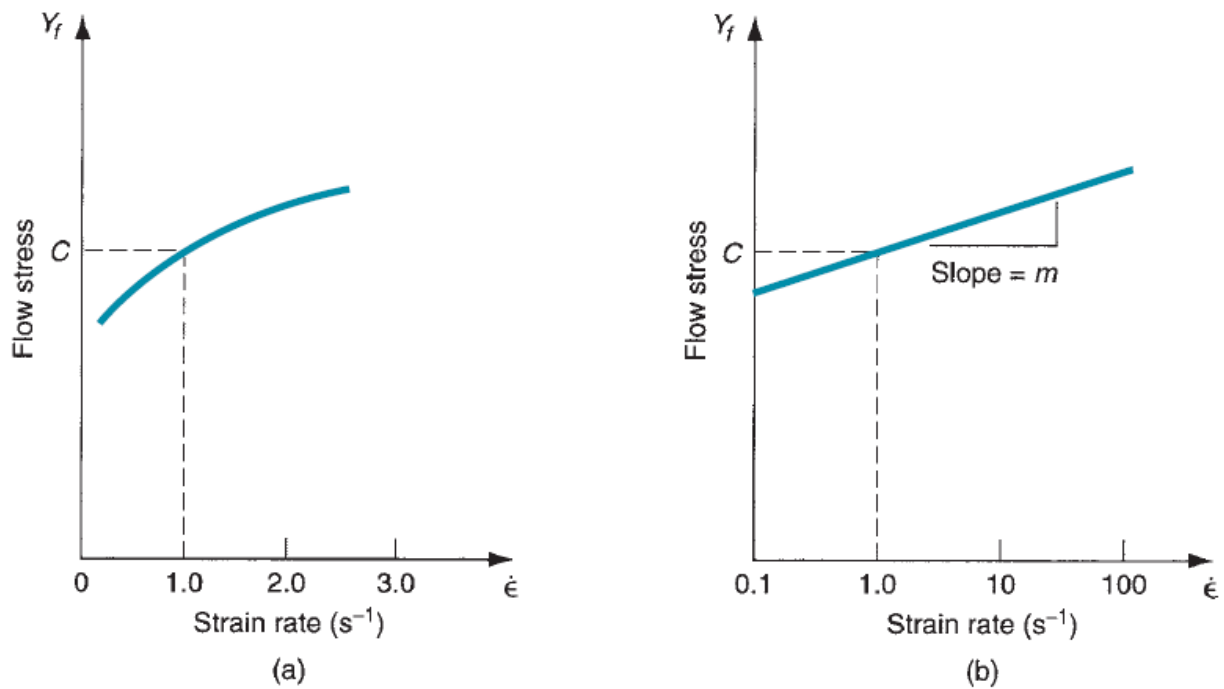


Figure (3-8) (a) effect of strain rate on flow stress at an elevated temperature, (b) same relationship plotted on log-log coordinates.

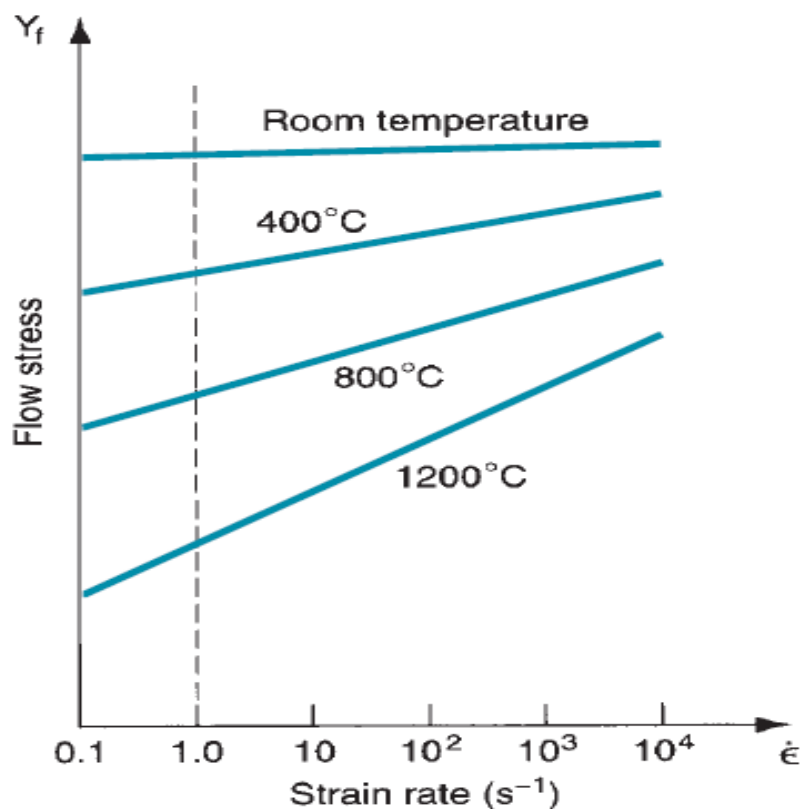


Figure (3-9) effect of temperature on flow stress

- In hot working processes, the strain rate is important since deformation resistance of w.p. increases as strain rate is increased.
- Even in cold working, the strain rate can have an effect, if small, on flow stress, whereas, in hot working the effect is significant.

- A complete formula for flow stress as a function of temperature, strain and strain rate is:

$$Y_f = A\varepsilon^n \dot{\varepsilon}^m$$

A: strength coefficient combining the effects of previous K and C values (N.s/m<sup>2</sup>) .

A, n, m: are temperature dependent.