2

Metal Forming Processes

2.1 INTRODUCTION

Metal forming is the process which is used to change the size and shape of a part by the application of forces. The force has to be large so that stresses produced in the part are greater than its yield strength but it must be less than its fracture strength. It is necessary to strain the metal beyond its yield point so that the deformation and its new shape is maintained after the removal of force. Forming can be cold forming or hot forming. Forming is the fastest way to change the shape of a part. It is also the most economical process of manufacturing.

2.2 ELASTIC AND PLASTIC DEFORMATION

- **What do you understand by plastic flow of metals?**

Or

- **Describe elastic and plastic deformation behaviour of metals. (UPTU – 2008-9)**

1. Elastic and plastic deformation: Deformation is the change in dimensions or form of a material under the action of any applied force or load. The deformation can be (i) elastic or (ii) plastic. Elastic deformation disappears completely when load is removed. Plastic deformation is a permanent deformation without failure and takes place when elastic range of the deformation has been exceeded. The plastic deformation does not disappear when load is removed.

2. Plastic flow of metals: Metals show a permanent and non-recoverable deformation when stressed beyond a certain minimum stress. This deformation is called plastic deformation. The plastic deformation takes place as the result of permanent displacement of atoms, molecules or group of both atoms and molecules from their original position in the lattice. The displaced atoms and molecules do not return to their original position even after the removal of stress. Now, in case stresses are increased, the metal may show a continuously increasing deformation. This phenomenon is plastic flow of metals. The fluids always show flow when these are subjected to shearing stress but the metals exhibit flow when subjected to high load. In most metals, the elastic deformation precedes plastic deformation as shown in stress-strain diagram (Fig. 2.1). The material has elastic limit up to yield point (point *A*), in which the material has elastic and recoverable deformation. Beyond yield point the material has plastic and non-recoverable deformation (*a b*).

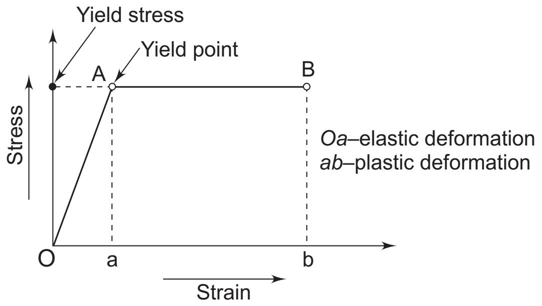

Fig. 2.1 Elastic and plastic deformation.

3. Mechanism of plastic deformation in crystalline and amorphous materials: Crystalline materials undergo plastic deformation as a result of slip along definite crystalline planes. However, in amorphous materials, plastic deformation occurs as groups of molecules slide past each other.

2.3 METAL FORMING

- **What is metal forming?**

Metal forming is a process in which the desired shape and size of a material is obtained by plastic deformation. In metal forming, stresses are induced in the material which are greater than its yield strength but lesser than its fracture strength, so that the material can be deformed into the desired shape and size. During plastic deformation, the material plastically flows and elongates in the direction of the flow of the material.

2.3.1 Features of Metal Forming

- **Describe the features of metal forming.**

The features of metal forming are:

(a) The stresses induced in the material are greater than its yield stress but these are less than its fracture strength.
(b) The material undergoes permanent and non-recoverable deformation.
(c) Plastic deformation depends upon (i) applied stress, (ii) temperature and (iii) strain rate.
(d) Plastic deformation involves distortion of the crystal and microstructure.

(e) When stresses increase beyond yield strength, the plastic deformation starts and the metal at this point begins to soften. The deformation starts spreading in the adjoining regions due to the presence of stress concentration between deformed and undeformed areas.

(f) The process of formation of new grains is known as *recrystallisation* and the temperature at which this recrystallisation takes place is called *recrystallisation temperature*. The plastic deformation at high temperature takes place at lower stresses as slip at crystalline planes and growing of new grains is much easier at elevated temperatures.

(g) In metal forming, metal is subjected to mechanical working with the purpose (i) to reduce the workpiece into the desired shape, (ii) to refine the grain size in the metal and (iii) to control the direction of flow lines in the metal.

(h) Depending upon the temperature, the deformation processes can be classified as cold or hot working.

(i) Depending upon the type of operation, the deformation processes can be classified as (i) primary working on original workpiece (forging, rolling and extrusion) and (ii) secondary working on semi-finished product such as bolts, sheet metal parts and wire.

(j) Depending on size and shape of workpiece, the deformation processes can be classified as (i) bulk deformation or (ii) sheet forming.

2.3.2 Factors Affecting Plastic Deformation

- **Discuss the factors affecting the plastic deformation.** **(UPTU – 2008-9)**

Factors affecting the plastic deformation are:

(a) Applied stress: The plastic deformation depends upon the applied stress. The applied stress has to be higher than the yield strength and lower than the fracture strength. The plastic deformation increases with the applied stresses when these stresses are in between the yield strength and the fracture strength.

(b) Deformation temperature: The metal strength decreases as the temperature is increased. Metal plasticity is greatest when deformation temperature is above the recrystallisation temperature but below the melting point of the metal. Recrystallisation temperature is the temperature at which the material becomes sufficient plastic for deformation due to the formation of new grains which can flow in the direction of elongation.

(c) Strain rate: The change of deformation in a unit time is called strain rate. The plastic deformation is more at higher strain rate.

However, higher strain rate is possible at elevated temperature when metal becomes more plastic.

2.4 YIELD CRITERIA

- **Explain Tresca's yield criterion.** **(UPTU – 2009-10)**

Or

- **What do you understand by yield's criteria for ductile materials? Find out the relation between Von-Mises and Tresca's yield criteria. (UPTU – 2008-9)**

Or

Why yield criteria is needed? Show that shear strength k and tensile strength σ_0 are related as $k = \sigma_0/2$ and $k = \sigma_0/\sqrt{3}$ through Tresca's and Mises yield criteria respectively. (UPTU – 2007-8)

Or

- **What do you understand by the yield criteria? Express Tresca's yield criteria and compare it with Von-Mises yield criteria. (UPTU – 2006-7)**

Or

- **What is Von-Mises yield criteria and how does it differ from Tresca's yield criteria? Using Von-Mises yield criteria, show that shear stress σ of a material can be expressed as $\tau_0 = \sigma_y . \sqrt{3}$ where σ_y = tensile yield stress of the material. (UPTU – 2003-4)**

Or

- **What do you understand by yield criteria? Explain it with Von-Mises yield criteria.**

Or

- **Describe theories of plastic deformation (failure). (UPTU – 2004-5)**

Or

- **What are the two important yielding criteria for ductile metals, compare them and derive the basic governing equations of yielding criteria. (UPTU – 2005-6)**

1. Yield: The yield strength or yield point of a material is defined as the stress at which a material begins to deform plastically. For loading less than yield point, the material will deform elastically and it will return to original shape when the loading is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible. Knowledge of the yield point is vital when designing a component as it represents the upper limit to the load which can be applied on the component. The yield point is also important for the control of many manufacturing processes such as (i) forging, (ii) rolling and (iii) bending in which the material has to be plastically deformed.

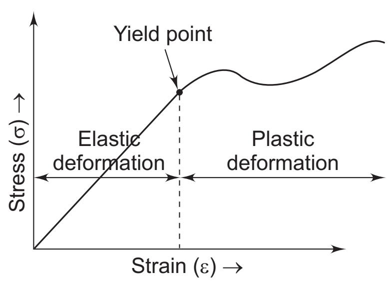

Fig. 2.2 Yielding

Graphically, the maximum shear stress criterion requires that the two principal stresses be within the shaded zone as shown shaded in Fig. 2.4.

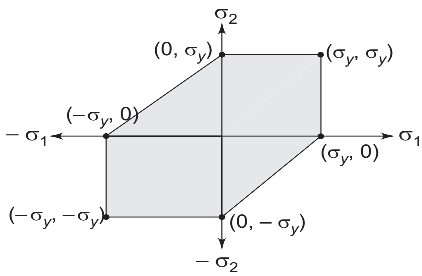

Fig. 2.4. Maximum shear stress criterion (Tresca's criterion)

3. Von-Mises criterion or distortion energy theory: This theory is also known as distortion energy theory. The theory states that plastic deformation of a material will occur when the total shear strain energy per unit volume in the strained body reaches a value equal to the strain energy per unit volume at the elastic limit in uniaxial tension. The strain energy per unit volume (U) is:

$$U = \frac{1}{12.G}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$$

where G = rigidity modulus = $\dfrac{E}{2(1+\nu)}$

For 2-D stress field $\sigma_3 = 0$, hence we have

$$U_2 = \frac{1}{12.G} \times 2(\sigma_1^2 + \sigma_1 \cdot \sigma_2 + \sigma_2^2) \qquad (i)$$

For uniaxial tension (σ_y), the strain energy is found out by taking $\sigma_x = \sigma_2 = 0$.

$$U_1 = \frac{1}{12.G}[(\sigma_y - 0)^2 + (0 - 0)^2 + (0 - \sigma_y)^2]$$

$$= 2.\frac{1}{12G} \cdot \sigma_y{}^2 \qquad (ii)$$

As per Von-Mises criterion to avoid deformation $U_1 \geq U_2$ and from equations (i) and (ii), we have:

$$\sigma_y^2 \geq \sigma_1^2 + \sigma_1\sigma_2 + \sigma_2^2$$

The above equation represents principal stresses as a ellipse as shown in Fig. 2.5. The figure also shows the maximum shear stress criterion or Tresca's criterion by dotted lines. Hence, Tresca's criterion is more conservative than Von-Mises criterion as it lies inside the Von-Mises ellipse. No

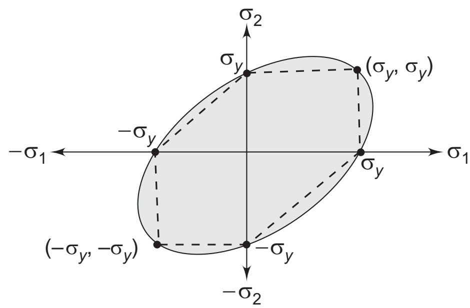

Fig. 2.5 Distortion energy theory (Von-Mises criterion).

deformation takes place in case principal stresses lie in the shaded region. In a uniaxial tensile loading, we have $\sigma_1 = \sigma_y$, $\sigma_2 = 0$, $\sigma_3 = 0$ and strain energy is

$$U = \frac{1}{12.G}[\sigma_y - 0)^2 + (0-0)^2 + (0-\sigma_y)^2]$$

$$= \frac{2.\sigma_y{}^2}{12.G}$$

or $$12.G\,U = 2\sigma_y{}^2 \qquad \ldots (iii)$$

In pure torsion, we have $\sigma_1 = k$, $\sigma_2 = 0$ and $\sigma_3 = k$ = shear yield stress. Hence,

$$U = \frac{1}{12.G}\{(k-0)^2 + [0-(-k)]^2 + [-k-(-k)]^2\}$$

$$= \frac{1}{12.G} \times 6k^2$$

From equations (*iii*) and (*iv*), we have:

or $$12.G.U = 6k^2 \qquad \ldots (iv)$$

$$2\sigma y^2 = 6k^2$$

or $$k = \frac{\sigma_y}{\sqrt{3}}$$

The comparison of Tresca and Von-Mises criterion is as per Table 2.1.

Table 2.1: Comparison between Tresca and Von-Mises criteria

Tresca's criterion	Van-Mises criterion
1. Plastic flow occurs when the maximum shear stress reaches a particular value $\tau_{max} = k = ½ (\sigma_1 - \sigma_3)$, $\sigma_y = 2k$ when $\sigma_1 = \sigma_4$ and $\sigma_3 = 0$.	1. Plastic flow occurs when strain energy reaches a value equal to the strain energy at elastic point in uniaxial tension (σ_y) $\sigma_y = \sqrt{3}.k$.
2. Simple to use.	2. Not simple.
3. Less accurate as σ_2 is not considered except σ_1 and σ_3 are considered.	3. More accurate as principal stresses σ_1, σ_2 and σ_3 are considered.
4. It is more conservative.	4. Less conservative.

2.5 HOT WORKING AND COLD WORKING

• **Differentiate briefly between hot working and cold working.**

(UPTU – 2001-2, 2003-4, 2005-6)

Or

• **Enlist various hot and cold working processes. Compare hot working and cold working processes.** **(UPTU – 2005-6)**

1. Hot working: Hot working is defined as the process which is done above the recrystallisation temperature but below the melting temperature of the metal. The recrystallisation temperature for lead and tin metals is always below the room temperature. Hence, the working of these metals at room temperature is always considered hot working. The recrystallisation temperature of steel is about 1000°C. Hence, working of steel below 1000°C is considered cold working. Hot rolling, hot forging and hot spinning are hot working processes.

2. Cold working: Cold working is defined as the process which is done below the recrystallisation temperature. Generally, recrystallisation temperature of metal varies between 30% to 50% of melting temperature.

3. Comparison between the hot and cold working.

Table 2.2: The comparison between the hot working and cold working

Hot working	Cold working
1. Working temperature is above the recrystallisation temperature.	1. Working temperature is below the recrystallisation temperature.
2. Hardening resulting from plastic deformation is completely eliminated by recovery and new grain formation.	2. Hardening is not eliminated due to low temperature.

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3. Poor surface finish due to oxidation and scaling.	3. Better surface finish is obtained.
4. Improvement in mechanical properties such as elongation, reduction of area and impact values.	4. Decreased mechanical properties such as elongation, reduction of area and impact.
5. Light equipment is used in hot working.	5. Powerful and heavy equipment are used for cold working.
6. Force required for deformation is less.	6. Force required for deformation is high.
7. Difficult to handle a hot workpiece.	7. Easier to handle a cold workpiece.
8. No internal or residual stress remains after working of part.	8. Internal and residual stresses remain after working of part.
9. No effect on ultimate tensile strength, yield point and hardness.	9. Increase in ultimate tensile strength, yield point and hardness.
10. Refinement of grain takes place.	10. Grains are enlarged.

2.5.1 Advantages and Disadvantages of Hot Working

- **What are the advantages and disadvantages of hot working? (UPTU – 2004-5, 2008-9)**

The advantages of hot working are:
(a) Homogenity of material is improved.
(b) Due to grain refinement, physical properties of material are improved.
(c) Material becomes soft at hot temperature, thereby change of shape can be easily achieved.
(d) Energy needed for deformation is much less as compared to cold working.
(e) Porosity of the material is largely eliminated.

The disadvantages of hot working are:
(a) Oxidation and scaling lead to poor surface finish.
(b) Dimensional accuracy is poor.
(c) Equipment and its maintenance for hot working are costly.
(d) Certain metals are brittle at high temperature and these metals cannot be hot worked.

2.5.2 Advantages and Disadvantages of Cold Working

- **What are the advantages and disadvantages of cold working? (UPTU – 2004-5, 2008-9)**

The advantages of cold working are:
(a) Cold working increases the strength and hardness of the material due to strain hardening.
(b) Good surface finish as oxidation or scaling takes place.
(c) Good dimensional accuracy is possible.
(d) Better mechanical properties are achieved.

(e) Economical for small parts.
(f) Handling of parts is easier.

The disadvantages of cold working are:
(a) Large parts are difficult to be worked.
(b) Residual stresses can be harmful.
(c) Suitable for ductile materials.
(d) Tooling cost is high where high production is required.
(e) High energy required for plastic deformation.

2.6 WORK TO PRODUCE YIELDING

- **Determine the work done to produce metal deformation.**

Consider a specimen of length l_0 and a load is applied uniaxially. The specimen length increased to 'l_1' due to plastic flow. Let yield stress is k corresponding to yield strain and A is area of cross-section.

Force = Yield stress × Area

$= k.A$

$$\text{Word done } (dW) = \text{Force} \times dl$$

$$= k.A.dl.$$

$$= k(A.l)\,\frac{dl}{l}$$

But $$A.l = \text{V} = \text{volume}$$

$\therefore$ $$dW = k.V.\,\frac{dl}{l}$$

On integration, we get

$$\int dW = KV\int_{l_0}^{l_1}\frac{dl}{l}$$

$$W = K.V.\log\frac{l_1}{l_0}$$

Case 3: $\sigma_1 = -85$, $\sigma_2 = 50$ and $\sigma_3 = 70$

Maximum stress = $\sigma_3 = 70$

Minimum stress = $\sigma_1 = -85$

$$\therefore \qquad \tau_{max} = \frac{70-(-85)}{2}$$

$$= \frac{70+85}{2} = \frac{155}{2}$$

$$= 77.5 \text{ MPa}$$

Hence, the material will yield both by Tresca's and Mises' criteria.

Case 4: $\sigma_1 = 75$, $\sigma_2 = -90$ and $\sigma_3 = 110$

Maximum stress $\sigma_3 = 110$

Minimum stress $\sigma_2 = -90$

$$\tau_{max} = \frac{\sigma_3 - \sigma_2}{2} = \frac{110+90}{2}$$

$$= 100$$

Hence, material will yield as per Tresca's and Mises' criteria.

Case 5: $\sigma_1 = 70$, $\sigma_2 = 80$, $\sigma_3 = 70$

Maximum stress = $\sigma_2 = 80$

Minimum stress = σ_1 or $\sigma_3 = 70$

$$\tau_{max} = \frac{80-70}{2} = 5$$

Hence, material will not yield both by Tresca's and Mises criteria.

- **A material with a yield stress of 100 MPa is subjected to principal (normal) stresses of σ_1, $\sigma_2 = 0$ and $\sigma_3 = -\sigma_1/2$. What is the value when the metal yields according to Von Mises criterion? What if $\sigma_2 = -\sigma_1/3$?**

As per Mises' criterion, we have:

$$k = \frac{\sigma_y}{\sqrt{3}} = \frac{100}{\sqrt{3}} = 57.74 \text{ MPa}$$

Maximum stress = σ_1

Minimum stress = $-\dfrac{\sigma_1}{2}$

$$\text{Mises' criterion, } k = \frac{\sigma_0}{\sqrt{3}} = \frac{130}{\sqrt{3}} = 75.05 \text{ MPa}$$

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \frac{134.55 - 58.45}{2}$$

$$= \frac{76.10}{2} = 38.05 \text{ MPa}$$

As τ_{max} is less than k value, hence material will not yield.

2.6.1 Applications of Hot Working and Cold Working

- **What are the applications of hot working and cold working?**

Or

- **Enlist the various hot and cold working processes.** **(UPTU – 2008-9)**

Applications of hot and cold working are as per Fig. 2.6. The applications of metal forming operations are as per Table 2.3.

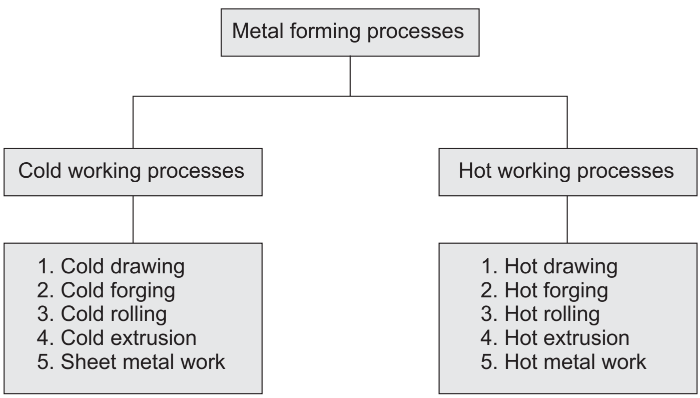

Fig. 2.6 Hot and cold working processes.

Table 2.3 Applications of metal forming operations.

Process	Applications
Cold Working	
1. Cold drawing	Wire drawing and tube drawing
2. Cold forging	Bolts, rivets, screws and similar headed items

Contd.