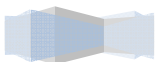


Module 27

Metal working: deformation processing I

Lecture 27

Metal working: deformation processing I



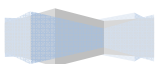
Keywords : Plastic deformation, hot & cold work, strain rate during forging, rolling, extrusion, wire drawing, deep drawing, stretch forming, bending, shearing, machining; effect of temperature on plastic deformation, flow stress, Zener – Hollomon parameter, workability of metals & alloy, effect of cold working on structure & properties, annealing, texture, preferred orientation

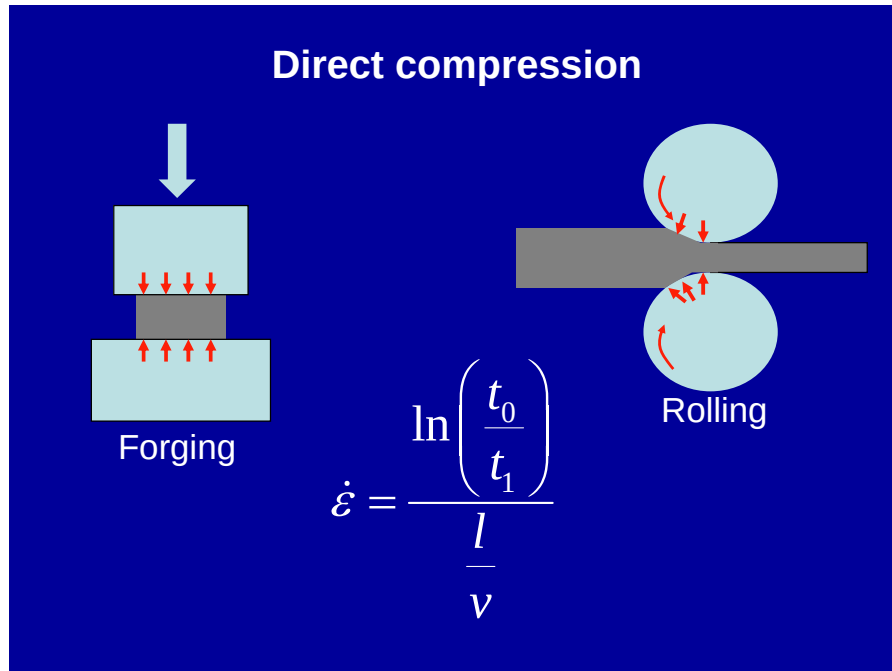
Introduction

We have looked at the evolution of structures in metals and alloys during solidification. Although it is possible to cast them in a variety of shapes and sizes, bulk of them are subjected to further processing before being put to use. This is because cast metals often do not have the desired properties because of the presence of a number of casting defects. Metals and alloys are ductile and malleable. They can be formed into various shapes by large plastic deformation. This helps not only in the healing of casting defects but also in the improvement of their structures and properties. In this lecture we shall learn about the methods by which metals can be deformed, what is the effect of temperature and strain rate on the structural changes that take place during the process, what types of microstructures of metals are more amenable to such processing and how the structure & properties can be restored or improved.

Plastic deformation:

Metals are known for its ductility. It can be formed into useful shapes by deformation processing. There are several ways by which metals can deformed into various shapes. The processes are often referred to as metal working. Deformation takes place under the influence of applied stress. Depending on the way the stress is applied to the work piece and its nature, metal working processes can be classified into different categories. These are (i) direct compression, (ii) indirect compression, (iii) tension, (iv) bending and (v) shearing.

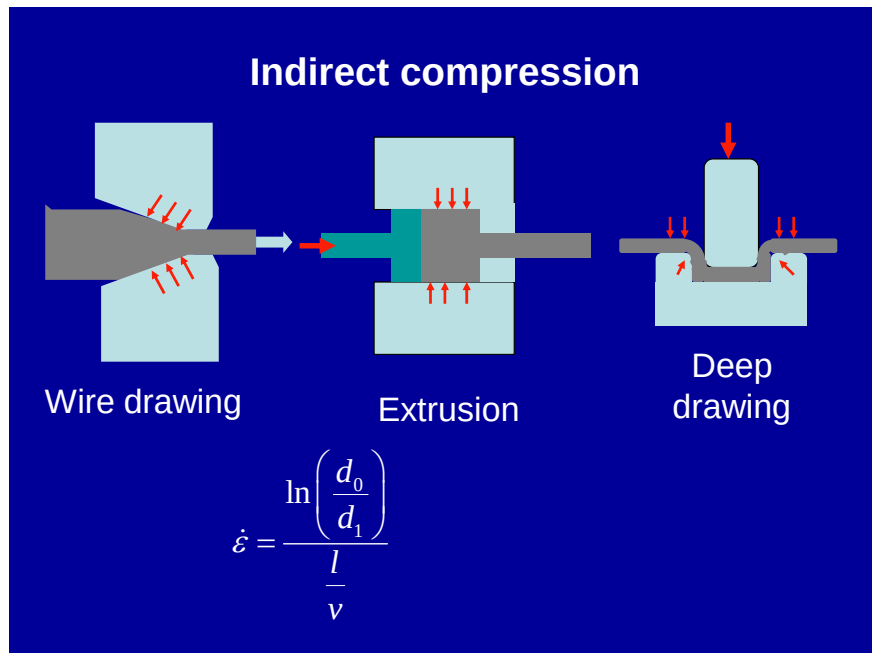




Slide 1

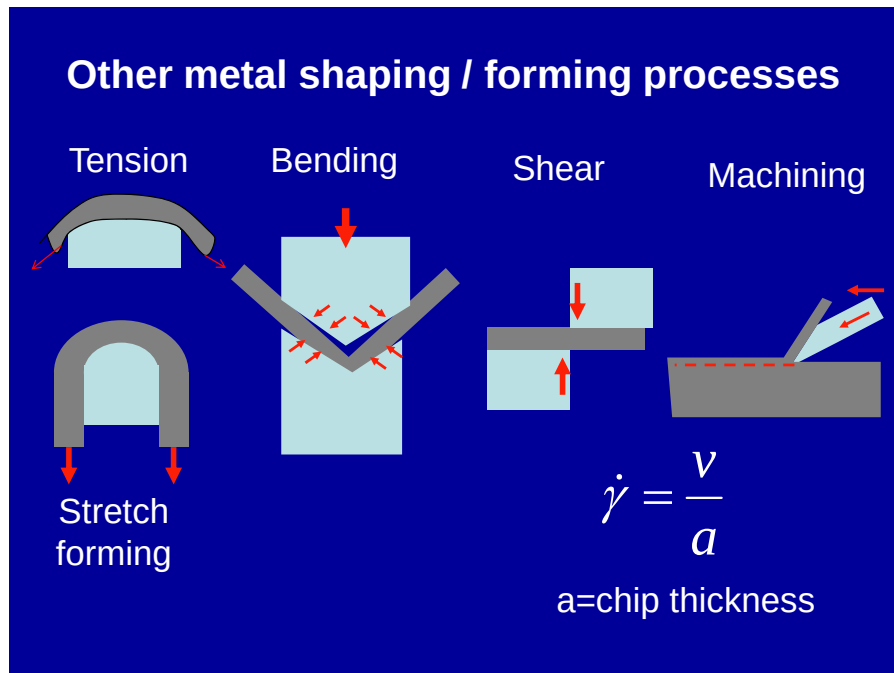
Slide 1 shows two common methods of metal working where the shape change occurs due to direct compression. These are forging and rolling. During forging the work piece is compressed by a pair of platens whereas in rolling the work piece passes through a pair of rolls rotating at a constant speed. In both of these there is a reduction in thickness and elongation in the other two directions. In the case of forging the elongation along the two directions are of the same order whereas during rolling the elongation along the width is negligible in comparison to that along the length. In all forms of plastic deformation the volume strain may be taken to be zero. Since the magnitude of deformation is large it is more appropriate to represent strain as true strain. It is given by $\ln\left(\frac{t_0}{t_1}\right)$ where t_0 is the thickness before deformation and t_1 is the thickness after the first stage of rolling or forging. Strain rate is an important parameter for deformation processing. How can it be estimated? During forging one of the platen moves at a constant velocity whereas the other remains fixed. If the velocity is v and the distance it has to move to reduce the thickness from t_0 to t_1 is l , the time required by the process is equal to l/v . The strain rate therefore should be given by:

$$\dot{\epsilon} = \frac{\ln\left(\frac{t_0}{t_1}\right)}{\left(\frac{l}{v}\right)} \quad (1)$$



Slide 2

Slide 2 shows schematic diagrams representing 3 common deformation processes where deformation occurs due to the compressive stress that develops within the die. These are wire drawing, extrusion and deep drawing. Wire rods are pulled through a die as shown. The applied load is tensile but deformation takes place due to the compressive stress that develops at the die / metal interface. In extrusion the work piece is pushed through a die as shown in slide 2. The work piece is subjected to compression from the die wall as well. In deep drawing a piece of sheet metal is pushed into a die by a mandrel as shown in the sketch in slide 2. The deformation occurs along the planar direction. The reduction in wall thickness is very little. This is possible only if the material has higher flow stress in the through thickness direction but lower flow stress along the planar direction. We will see in one of the subsequent modules what kind of processing can help develop different properties along different directions.



Slide 3

Slide 3 shows a set of sketches for several other deformation processes. In stretch forming the deformation is due to tensile stress. In bending the applied load is compressive but the stress on one side of the plate is compressive while that on the other is compressive. Shear forming is used to cut plates whereas machining gives the final shape of the product. Shear strain rate during machining is given by the tool speed over the thickness of the chip.

Effect of temperature on plastic deformation:

Metals deform when the applied stress exceeds a critical stress called flow stress. This is a function of the alloy composition and temperature. Figure 1 shows the effect of temperature on the nature of the stress strain plot of a metal.

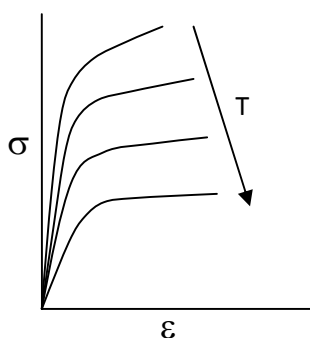
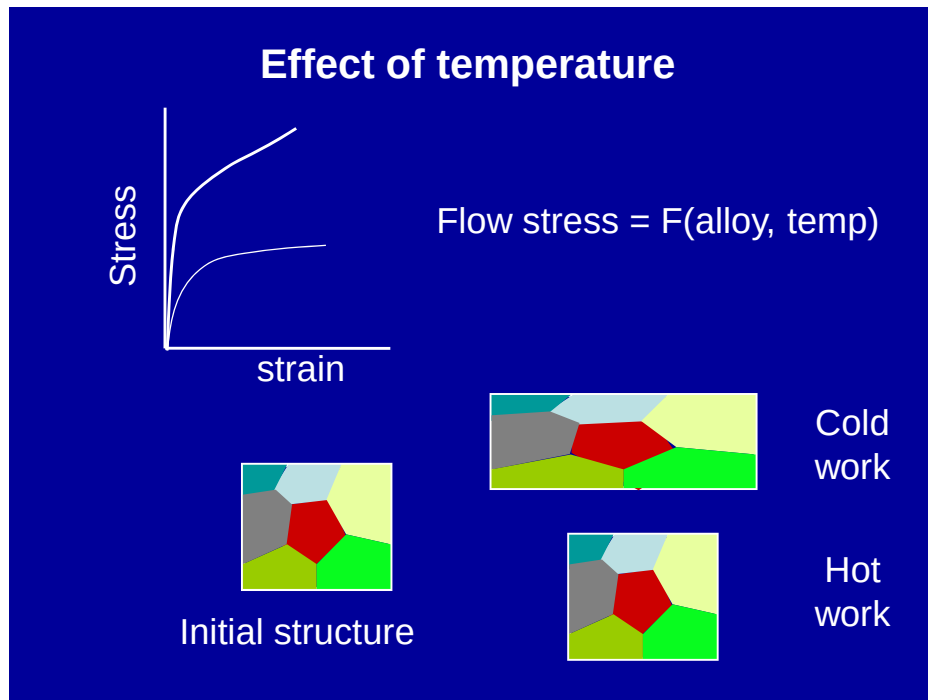


Fig 1: Shows the effect of temperature on the nature of stress (σ) strain (ϵ) plot of a metal. The initial part of the plot is linear. This denotes elastic part of the plot. The slope is the elastic modulus. It decreases with increasing temperature. The slope of the curve beyond the elastic limit decreases with the increasing strain. It is measure of strain hardening. With increasing temperature the stress at which the metal yields and its strain hardening rate keeps decreases.



Slide 4

Deformation in metals occurs by shear irrespective of the nature of the applied stress. A metal is made up of several grains. Deformation within the grains occurs through slip. It takes place when the magnitude of resolved shear stress on the slip plane exceeds a critical value known as critical resolved shear stress. The neighboring grains can also slide over one another. The process is known as grain boundary sliding. This too would need shear stress. We may therefore the mechanism of deformation is primarily by slip or shear.

Slide 4 shows the effect of plastic deformation at two different temperatures on the microstructure of metals. At a lower temperature the stress at which metal can deform or flow easily is high and it keeps increasing with increasing amount of deformation. The signs of deformation are left behind. This is known as cold working. Slide 4 also gives the microstructures of the metal before and after deformation. The initial structure has equiaxed grains having random orientation. As a result of cold working the grains become elongated along the direction of deformation as shown in slide 4. The dislocation density in cold worked state is much higher. The grains too get re-oriented along a preferred direction.

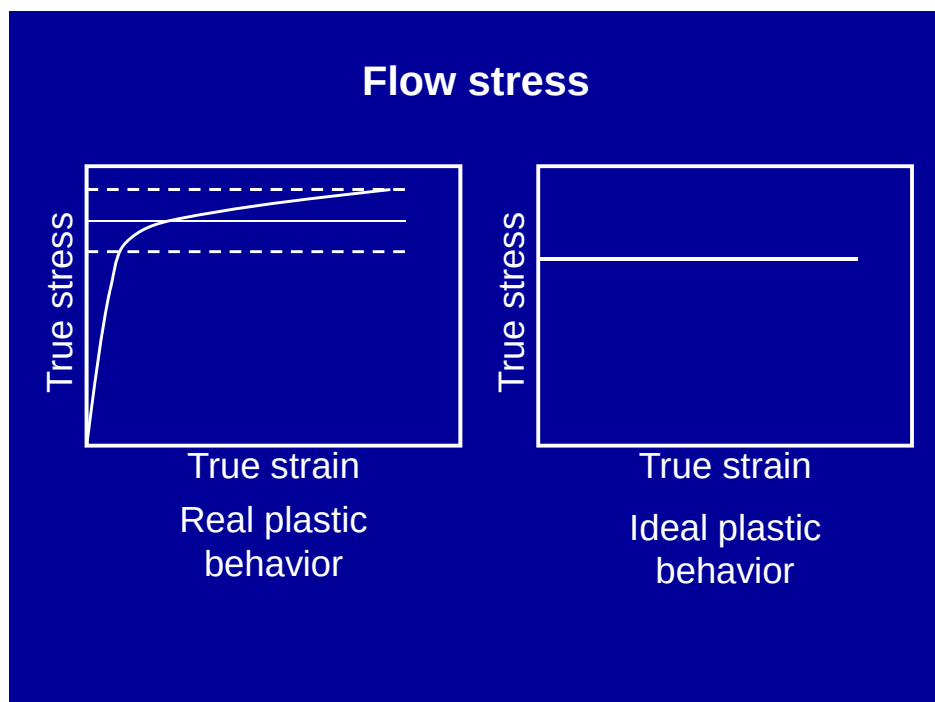
The flow stress at higher temperature is much lower. There is hardly any increase in the magnitude of the flow stress with increasing amounts of deformation (little strain hardening). This is because the strained grains get replaced by a new set of strain free grains. The process is known as re-crystallization. There may be some amount of grain refinement during hot working. However grains appear to be equiaxed having little sign of deformation. Appearance wise often the microstructures (shape & size of the grains) of metals before and after

deformation may be similar. However there are certain finger prints left behind in the metal by hot working. These are associated with the shape and size of the second phase particles in the matrix.

The area under the stress strain curve is a measure of the work done during deformation. Since the yield stress at high temperature is low the power required for hot working is low. Therefore primary working where large deformation is needed to remove the cast structure (segregation) is always done at high temperature.

Flow stress:

The mechanical properties that we look for the selection of metals and alloys for a given application are the yield strength or the tensile strength. We are satisfied with engineering stress strain diagrams since this is good enough to estimate these. However for metal working we need to know the true stress versus true strain plots. Slide 5 shows the sketch of such a plot for a material exhibiting real plastic.



Slide 5

The plot is linear till its yield stress. Thereafter the plot is nonlinear. The slope of the curve ($\frac{d\sigma}{d\epsilon}$) is a measure of its strain hardening. The two dotted horizontal lines represent the lowest and the highest stresses the material can withstand during plastic deformation. The average of the two is defined as its flow stress. An ideal plastic material has low flow stress and very little strain hardening. The second sketch in slide 5 represents the stress strain plot of an ideal plastic material. Note that there is no strain hardening.

Deformation takes place primarily through slip (shear) which occurs through dislocation glide at low temperatures. During the process dislocations multiply and the length of dislocations per unit volume (called dislocation density) increases. This makes further movement of dislocation more difficult. This is the reason why strain hardening takes place. At a higher temperature dislocations besides gliding can also move by a process called climb. This is the result of dislocation vacancy interaction in the metal. With increasing temperature the concentration of vacancy and its mobility (diffusivity) increases. As a result dislocations can climb and get annihilated so that the increase in its density is much less. In addition with increasing deformation the tendency of the grains to get replaced by a new set of strain free equiaxed grains (a process called re-crystallization) increases. These are the reasons why the extent of strain hardening is low at higher temperatures. Clearly there are two opposing phenomena during plastic deformation one that is controlled by the strain rate that pumps in more dislocations there by increasing the flow stress and the other that is controlled by temperature that tries to restore the structure by reducing the dislocation density or by replacing the old grains by a process called re-crystallization. Therefore the flow stress is a function of both strain rate ($\dot{\epsilon}$) and temperature (T). The combined parameter (Z) that is often used to describe flow stress (σ) is named after Zener – Hollomon. This is given by the following expression.

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A(\sinh \alpha \sigma)^n \approx A' \exp(\beta \sigma) \quad (2)$$

Where Q = activation energy, R = universal gas constant and α , β , n, A & A' are material parameters. The parameters can be estimated from a plot of stress against Z as shown in fig 2.

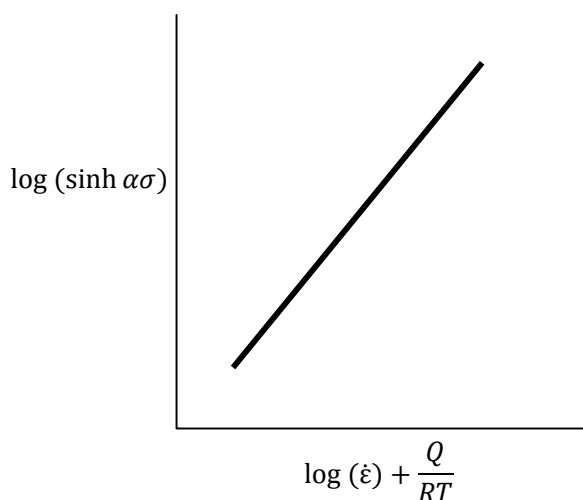
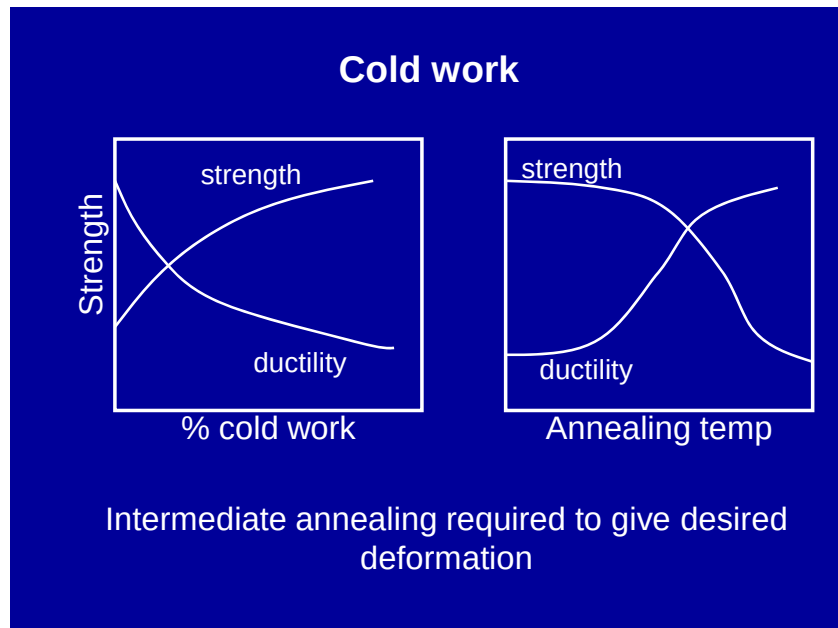


Fig 2: A plot of $\log(\sinh \alpha \sigma)$ against $\log(Z)$ is linear. The slope of the plot gives n and the intercept gives A. Activation energy and α can be estimated by iteration so that irrespective of test temperature and strain rate all data fall on the same trend line. Often $\sinh(\alpha \sigma)$ may be approximated as $\exp(\beta \sigma)$.

When a metal or an alloy is worked above a critical temperature the old deformed grains are replaced by a set of new strain free grains. It is known as hot working. Plastic deformation at a temperature lower than this is cold working. The critical temperature is known as re-crystallization temperature. It depends on the amount of stored strain energy, strain rate and the material. On an average the re-crystallization temperature of a metal is around 0.5 times the melting point of the metal in degree Kelvin ($0.5T_m$). The plastic deformation of metals having low melting point such as Pb or Sn at room temperature should be considered as hot working. Whereas metals like W even if it is worked at 1000°C , it amounts to cold working. Table 1 gives the range of strain, strain rate and temperature for various deformation processes.

The finger prints of cold work on metals include presence of elongated grains, preferred orientation (often called texture), high dislocation density, high hardness (high yield strength), and loss of ductility & toughness. It also leaves behind both micro and macro residual stresses. Some of these can be detected by non-destructive testing. Cold working has several advantages. It gives good surface finish and high strength. Loss of material due to oxidation is less. Often it is the last stage of forming. However because of work hardening the amount of deformation per pass is limited. If required the structure & properties of cold worked metal can be restored by giving annealing heat treatment. This is done by soaking it for around an hour or less in a furnace kept at a suitable temperature. In several cold working operations intermediate annealing becomes necessary to restore the ductility of the metal so that it can be given further deformation. It also helps reduce the load on the rolling mill by lowering its yield strength. Slide 6 gives two schematic sketches one showing the effect of cold work on the strength and ductility and the other showing the effect of annealing temperature on the strength and ductility. The structural change that takes place can be divided into 3 stages. The stage 1 is known as the recovery stage. This is where micro stress gets relieved, dislocation density decreases and they get rearranged leading to the formation of dislocation boundary. The stage two consists of re-crystallization. Deformed grains are replaced by a set of new strain free grains. The stage 3 consists of grain growth. This is undesirable because it is associated with loss of strength and toughness.



Slide 6

Table 1: The range of strain, velocity, strain rate and temperature range for various metal working processes

Process	True strain (ϵ)	Velocity, m/s	Strain rate, m/s	Temperature
Cold rolling & forging	0.1 – 0.5	0.1 - 100	$1 - 2 \times 10^3$	$< 0.5 T_m$ (Room temperature)
Hot rolling & forging	0.1 – 0.5	0.1 - 30	$1 - 1 \times 10^3$	$0.55 - 0.85 T_m$
Extrusion	~ 1	0.1 - 1	$0.1 - 1 \times 10^2$	$0.7 - 0.95 T_m$
Wire / tube drawing	0.05 – 0.5	0.1 - 100	$1 - 2 \times 10^4$	$RT < 0.3 T_m$

Finger prints of hot working left on the material depend on its initial structure. If the initial structure consists of equiaxed randomly oriented strain free homogeneous grains of a single phase there is very little detectable change. However hot working quite often is a primary working process. It is used to make the metal homogeneous and free from casting defects like segregation and porosity. Because of low flow stress at high temperature the load on the rolling mill is less. This is why exceedingly high amount of deformation can be given in a single pass. The presence of homogeneous equiaxed grains, aligned second phase particles such as inclusions and absence of gas porosity are some of signs of hot working. A major problem of hot rolling is the loss of metal due to scaling (oxidation) and poor surface finish. Hot rolled metals

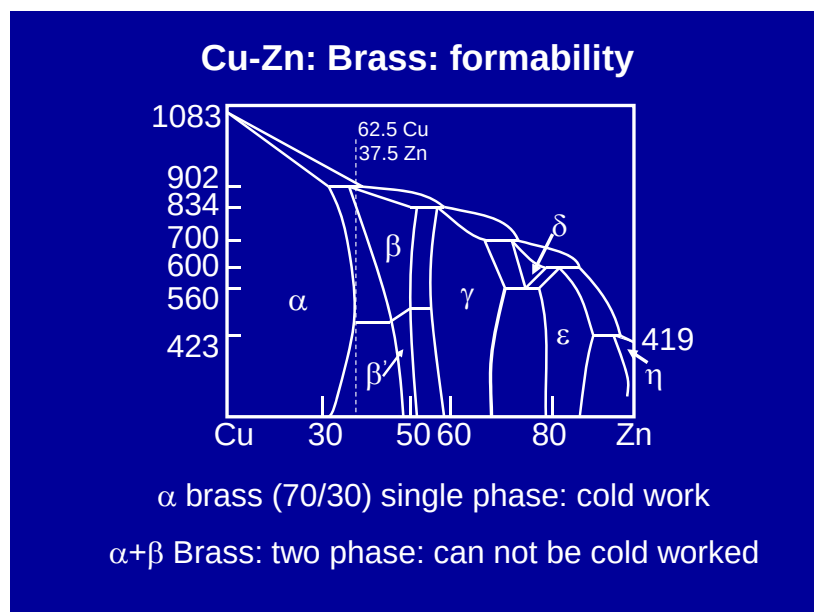
are subjected to pickling (a chemical cleaning process to remove oxide scale) before cold work. The table 2 gives the range of temperature for hot working of a few commercial alloys.

Table2: The usual temperature range for hot working of selected alloys in °C

Alloy:	Al alloys	Cu alloys	Pb alloys	Steel
Rolling & forging	320 - 450	450 - 900	100 - 200	800 - 1250
Extrusion	450 - 500	650 - 1050	200 - 250	1100 - 1300

Workability of metals & alloys:

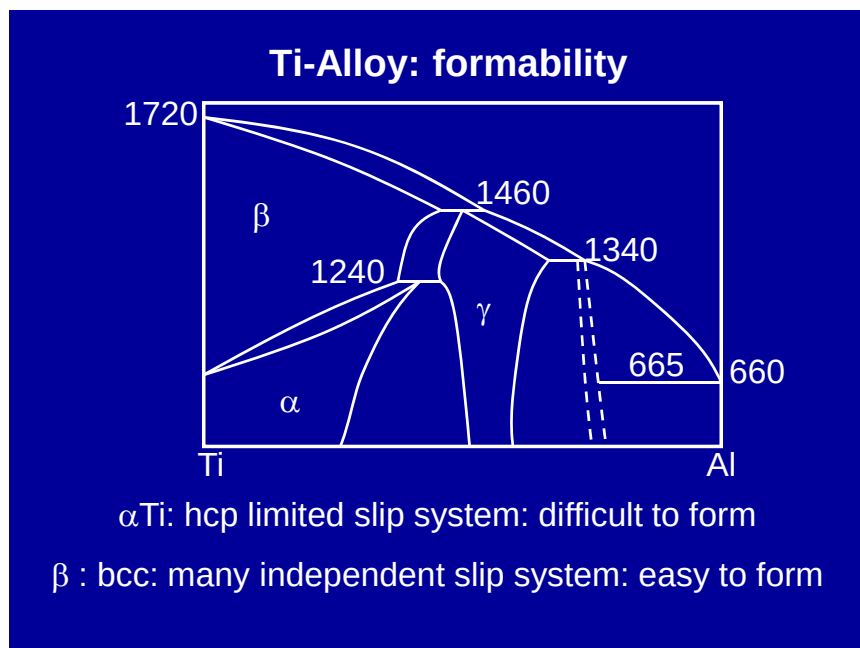
Pure metal is known for its ductility. Au & Al can be rolled down to very thin foils. Alloy addition is needed to improve its properties that would make it more suitable for various applications. Let us now look at how does alloy addition affects workability. Why is pure metal so malleable or ductile? This is because there is little resistance to dislocation glide because of the absence of any second phase, precipitate or solute atoms. The presence of brittle second phase makes plastic deformation difficult.



Slide 7

Look at the relevant part of the phase diagram of Cu-Zn system. It is reproduced again in slide 7. Two of the most common copper base alloys are 70/30 & 60/40 brass. The former is a single phase alloy whereas the latter is a two phase alloy. Single phase alloys have excellent ductility. This is because of the absence of second phase having entirely incompatible strength & ductility. Therefore 70/30 brass is amenable to both hot and cold work.

60/40 brass contains sizeable amounts of both FCC (α) & BCC (β) phase. The two have widely different strength and ductility. Therefore it has relatively low ductility at room temperature. Look at the phase diagram an alloy having a little higher than 36% Zn can be heated to a single phase region. Beta phase is BCC it has enough slip system. It can be deformed easily. 60/40 brass can be hot worked at a temperature where it is 100% beta.

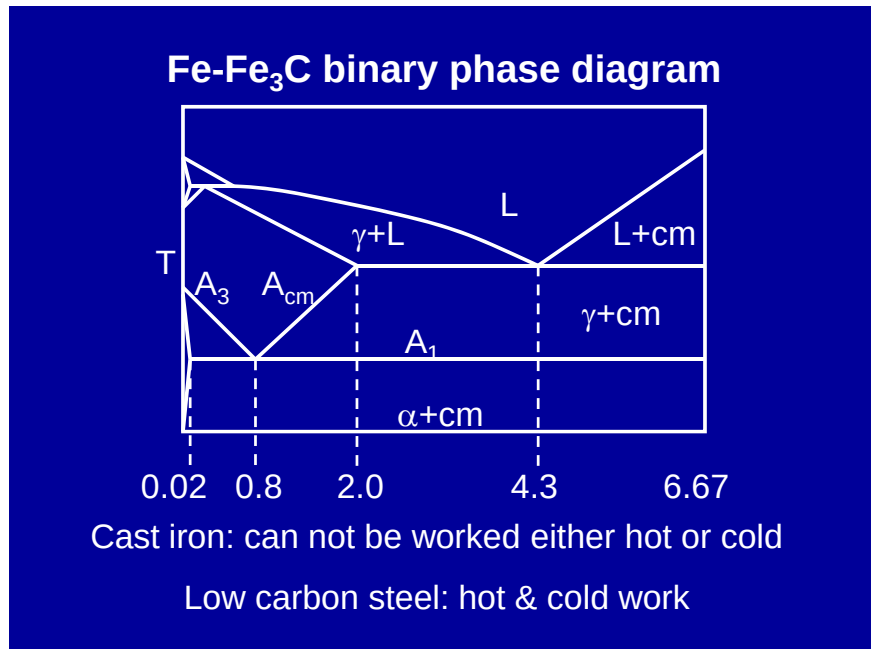


Slide 8

Let us now look at the formability of Ti alloys. Ti has two crystalline forms. At room temperature it is HCP whereas at higher temperature it is BCC. We know that HCP structure does not have 5 independent slip systems. This is an essential requirement to sustain arbitrary deformation. Therefore it is better to work (deform) polycrystalline alpha Ti alloy when it is beta state. Slide 8 shows the phase diagram of a Ti-Al alloy. Alloy addition is necessary to improve the strength of pure Ti. Al is an alpha stabilizer. It raises alpha beta transition temperature. There are other alloy elements like V which is a beta stabilizer. Ti-Al-V is one of the most popular commercial Ti alloy.

Look at Fe-Fe₃C phase diagram (see slide 9). In this binary system Fe₃C (Cementite) is the hardest phase. It is very brittle as well. The amount of cementite in steel is very less. We shall look at the deformation processing of steel in greater detail in a subsequent module. Let us consider iron carbon alloys having higher than 2.0% carbon. It is known as cast iron. The name itself suggests that it is used in the form of casting. Cast iron has considerable amount of brittle cementite. Therefore it has poor ductility. It has poor workability. The phase diagram suggests that even if you heat it, it cannot be taken to a state where only one solid phase exists. This is the case even in the case of grey cast iron. By and large cast iron is not amenable to large

deformation processing. As against this low carbon steel can be subjected to both hot and cold work. This is because the volume fraction of hard carbide is very less. The steel can also be heated to a state where it is totally austenite. This makes it amenable to hot working.



Slide 9

Summary

In this module we learnt about deformation processing of metals. This is where the ability of metal to undergo plastic deformation is exploited to remove casting defects and give it the desired shape. The common deformation processes are forging, rolling, extrusion, drawing, stretch forming, bending, and deep drawing. Depending on the nature of applied stress the common deformation processes may be classified into different groups. We learnt about this classification. The deformation in metals takes place by shear. Shear strength of material decreases with increasing temperature. This is evaluated by uniaxial tensile or compression tests at different temperatures. This gives us an idea about the stress at which metal could flow easily. It is defined as the average of the yield and the maximum stress the metal can withstand. It is known as the flow stress of the material. Shear planes are oriented at 45° to the principal stresses. Therefore the flow stress in shear is around half of the tensile flow stress. We also looked at factors that determine flow stress. These are temperature, strain rate and the material (alloy). For a given material it best described by a combined strain rate temperature parameter. This is known as Zener Hollomon parameter. The flow stress decreases exponentially with temperature. It becomes negligible as it approaches its melting point. Therefore the load on the equipment is low if working is done at a temperature close to its melting point. As against this much higher amount of load is needed if working is done at a

lower temperature. The classification between hot and cold work is based on a critical temperature where re-crystallization takes place. This is a function of the material and the amount of stored strain energy within it. The concept was introduced in one of the earlier modules. It is around $0.5T_m$ where T_m is the melting point in °Kelvin. Deformation processing above this is hot working whereas the one below this is cold working. Hot worked structure consists of strain free re-crystallized grains whereas cold worked structure has elongated grains with high dislocation density. The properties of cold worked metals can be restored by annealing. If the amount of deformation to be given is large intermediate annealing may be required to restore its ability to withstand further deformation. In the end we looked at how phase diagrams help us judge the ability of alloys to undergo plastic deformation. This was explained with the help of binary phase diagrams of a few common commercial alloys.

Exercise:

1. List a few advantages & limitation of hot working.
2. List a few advantages and limitations of cold working.
3. Estimate energy required to extrude 250mm diameter billet of aluminium to 25mm diameter rod. Given flow stress of aluminium = 10MPa and therefore find out the amount of force needed. Process efficiency = 70%. Neglect work hardening.
4. If the maximum strain per pass in a wire drawing operation is 0.65 how many drawing passes will be required to draw wire of 0.25mm dia from 5mm wire rod?

Answers:

1. Advantages: Hotworking is done above recrystallisation temperature where flow stress is very low therefore it is possible to give large deformation with minimum effort (energy required is less). No further heat treatment is required. Product is in annealed / normalised state. Limitation: Metal tends to oxidise. Scaling leads to loss of material. Tool life is shortened because of abrasive scale, high temperature and lack of lubrication. Poor surface finish & difficulty in precise gauge control. It is necessary to pickle hot rolled sheets before cold rolling to remove oxide scale.
2. Advantages: Good surface finish & precise gauge control. Gives higher strength. Limitation: needs intermediate annealing because of work hardening, deformation / pass is limited by flow stress which increases with deformation, more energy intensive, needs more powerful equipment, Makes the material anisotropic.

3. Work done per unit volume = $\frac{1}{\mu} \int \sigma d\varepsilon = \frac{\sigma}{\mu} \ln\left(\frac{A_0}{A_f}\right) = \frac{\sigma}{\mu} 2 \ln\left(\frac{d_0}{d_f}\right) = \frac{10}{0.7} 2 \ln\left(\frac{250}{25}\right) \approx 66 \text{ MJ}/\text{m}^3$ where μ is efficiency. Stress required = 66 MPa. Force = stress x area = $66 \times \frac{\pi}{4} \times 0.25^2 = 3.24 \text{ MN}$
4. Strain in a single pass is = $\varepsilon = \ln\left(\frac{A_0}{A}\right) = 2 \ln\left(\frac{d_0}{d}\right)$. Using this it can be shown that diameter after n^{th} pass is given by $d_n = d_0 \exp\left(-\frac{n\varepsilon}{2}\right)$. Therefore number of pass = $\frac{2}{\varepsilon} \ln\left(\frac{d_0}{d_n}\right) = \frac{2}{0.65} \ln\left(\frac{5}{0.25}\right) = 9.3$. This means successive dies should be so chosen that in 10 passes the wire could be drawn.

