Production Technology: Theory and Practice

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Lecture - 03
Engineering Materials and Their Properties-3

Hello and welcome back to the discussion. We will continue our discussion on the engineering materials and their properties. We have discussed so far the true stress, true strain and compared engineering stress and engineering strain. We said that the true stress and the true strain are more realistic, because there what is considered is not the initial area but the area which is going through the stress or the elongation which has been taken finally. that value of elongation is taken in case of the true strain.

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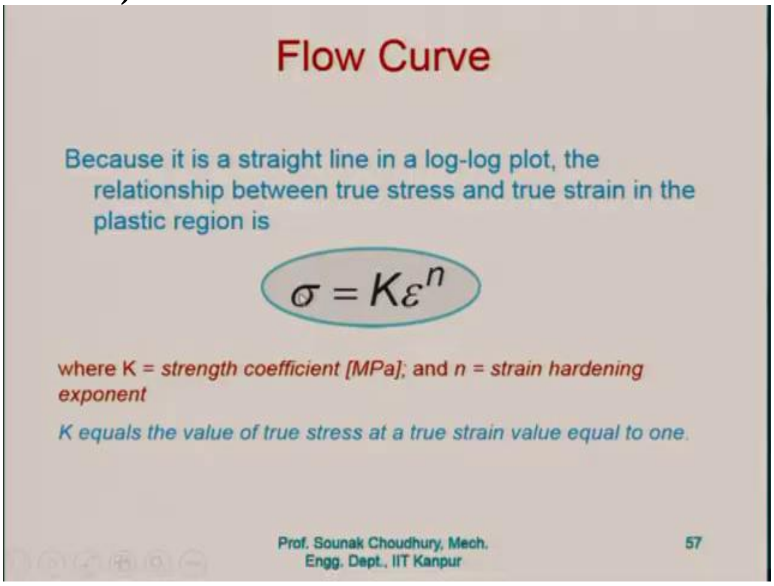

Flow Curve

Because it is a straight line in a log-log plot, the relationship between true stress and true strain in the plastic region is

$$\sigma = K\varepsilon^n$$

where K = *strength coefficient [MPa]*; and *n* = *strain hardening exponent*

K equals the value of true stress at a true strain value equal to one.

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57

The flow curve is the relationship between the true stress and the true strain through the strain hardening.

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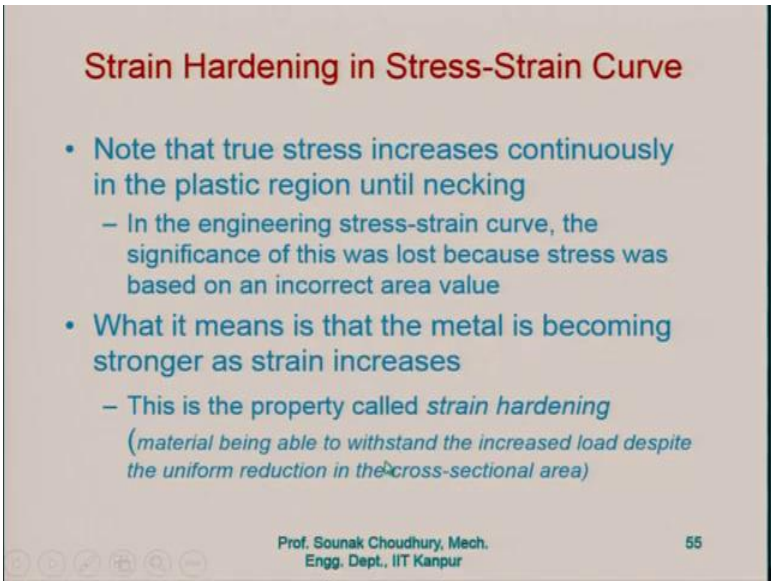

Strain Hardening in Stress-Strain Curve

- Note that true stress increases continuously in the plastic region until necking
  - In the engineering stress-strain curve, the significance of this was lost because stress was based on an incorrect area value
- What it means is that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening* (*material being able to withstand the increased load despite the uniform reduction in the cross-sectional area)*

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55

And we said that strain hardening is the ability of the material to withstand the increased load despite the uniform reduction in the cross-sectional area. this is the equation which is normally called the flow curve in engineering and here *K* is the strength coefficient in MPa. The strength coefficient means that this is the coefficient which actually defines the strength of the materials.

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Categories of Stress-Strain Relationship

1. Perfectly elastic
2. Elastic and perfectly plastic
3. Elastic and strain hardening

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58

Next in discussion are the categories of the stress-strain relationship. There are basically 3 categories that we can identify, e.g.perfectly elastic, elastic and perfectly plastic, and the third category is the elastic and strain hardening. By these categories we mean to say is that if we take the stress-strain relationship of a ductile material, we will have distinct 3 regions, e.g. perfectly elastic region then we have elastic and plastic, which is a small region and then we have elastic and the strain hardening region.

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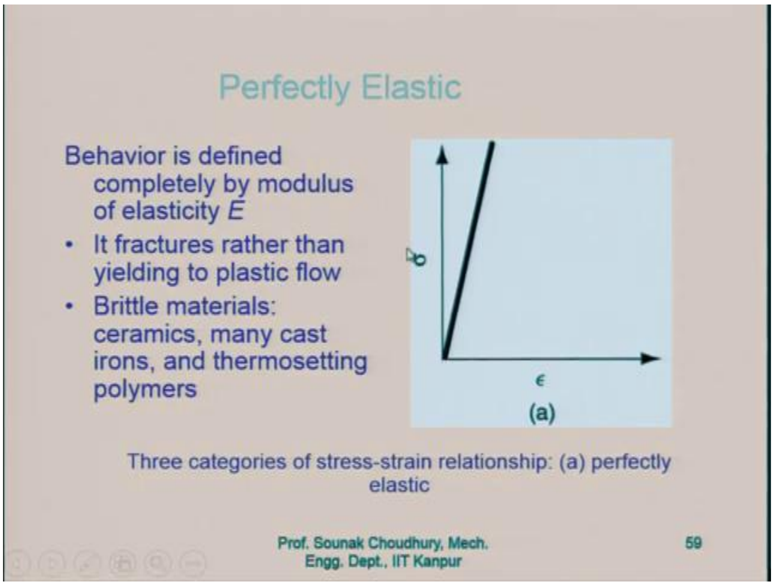

Perfectly Elastic

Behavior is defined completely by modulus of elasticity E

- It fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers

Three categories of stress-strain relationship: (a) perfectly elastic

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Let us see perfectly plastic category. This is a straight line when the stress is proportional to strain; behaviour is defined completely by modulus of elasticity. It fractures rather than yielding to plastic flow. It fractures here then it will not yield and it will not demonstrate the plastic flow as in case of the brittle material. Now, brittle materials, ceramics, many cast irons, thermosetting polymers, these are the materials which actually demonstrate this kind of a curve this is called perfectly elastic category of stress-strain relationship.

this is no more for the plastic material or for the ductile material, but this is for the materials like ceramics cast irons, thermosetting polymers and so on.

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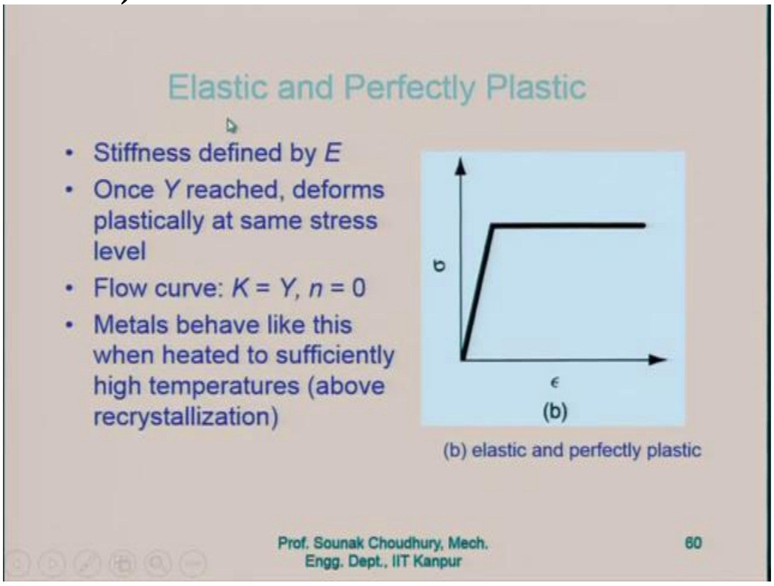

Elastic and Perfectly Plastic

- Stiffness defined by E
- Once Y reached, deforms plastically at same stress level
- Flow curve: $K = Y$, $n = 0$
- Metals behave like this when heated to sufficiently high temperatures (above recrystallization)

(b) elastic and perfectly plastic

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Second is the elastic and perfectly plastic. This is elastic and perfectly plastic. The stiffness is defined by E. This, as we said, is the modulus of elasticity. Once Y is reached that means this point is reached, material deforms plastically here at same stress level, the stress level is not changing. It is actually plastically deformed. Therefore, the flow curve is $K = Y$ because there is no strain hardening here $n = 0$ and therefore, the flow curve will be $K = Y$.

If you see the flow curve, the yield point is indicated by Y. Now, the metals behave like this when heated to sufficiently high temperatures. When a metal is at sufficiently high temperature and then the stress is applied, the stress strain curve will be this way. Initially it will be elastic and then it will be plastic without any stress being increased, at the same stress level. That means, the temperature of heating should be above the temperature of recrystallization.

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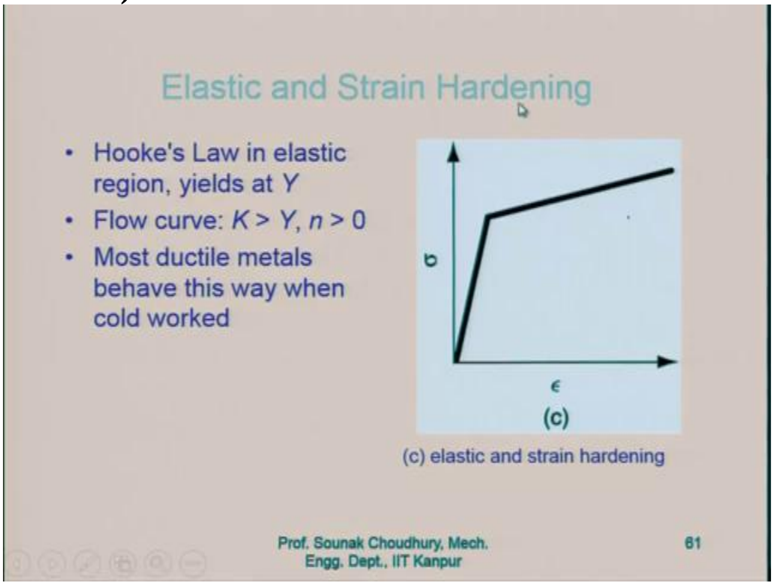

Elastic and Strain Hardening

- Hooke's Law in elastic region, yields at Y
- Flow curve: $K > Y$, $n > 0$
- Most ductile metals behave this way when cold worked

(c) elastic and strain hardening

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Elastic and the strain hardening: that is the third category; Hooke's law in elastic region, yields at Y. flow curve in this case will be $K > Y$ because n is positive $n > 0$ meaning that the strain hardening occurs. Most ductile metals behave this way during cold work without heating the material when the stress is applied. then the stress strain curve will be similar to what is shown here in this picture. This is the third category that is elastic and the strain hardening.

Now, I would like to repeat once again that these are the categories depending on the material. Depending on the material we can have the stress strain curve which is perfectly elastic, for example, it is for the brittle materials; depending on the material you can have the elastic and perfectly plastic material behaviour when the material is heated above the temperature of recrystallization or we can have the elastic and the strain hardening which is the case of most of the ductile materials when they are cold work without heating the material.

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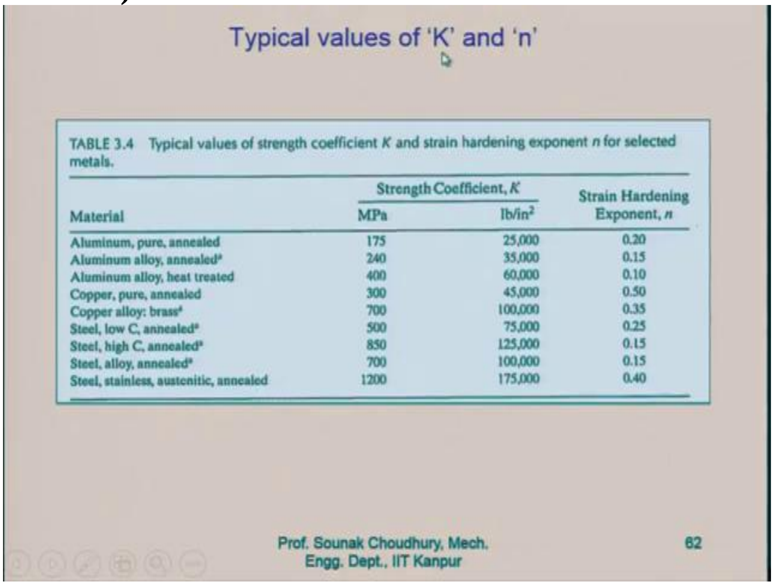

Typical values of 'K' and 'n'

TABLE 3.4 Typical values of strength coefficient *K* and strain hardening exponent *n* for selected metals.

Material	Strength Coefficient, *K* MPa	Strength Coefficient, *K* lb/in^2	Strain Hardening Exponent, *n*
Aluminum, pure, annealed	175	25,000	0.20
Aluminum alloy, annealed[a]	240	35,000	0.15
Aluminum alloy, heat treated	400	60,000	0.10
Copper, pure, annealed	300	45,000	0.50
Copper alloy: brass[a]	700	100,000	0.35
Steel, low C, annealed[a]	500	75,000	0.25
Steel, high C, annealed[a]	850	125,000	0.15
Steel, alloy, annealed[a]	700	100,000	0.15
Steel, stainless, austenitic, annealed	1200	175,000	0.40

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Typical values of the *K* and the *n*: *K* is the strength constant or the strength coefficient, *n* is the strain hardening; these are the values you can see here. This is for your comprehension and understanding that depending on the material, we can have the different strength coefficient as well as different strain hardening exponent values. the flow curve will be different. You can find out the flow curve for each of these materials when the stress-strain relationship has been made.

If you have the testing and you are measuring the strain for the stress, for the applied stress in that case, you can find out what will be the flow curve knowing the strength coefficient and the strain hardening exponent.

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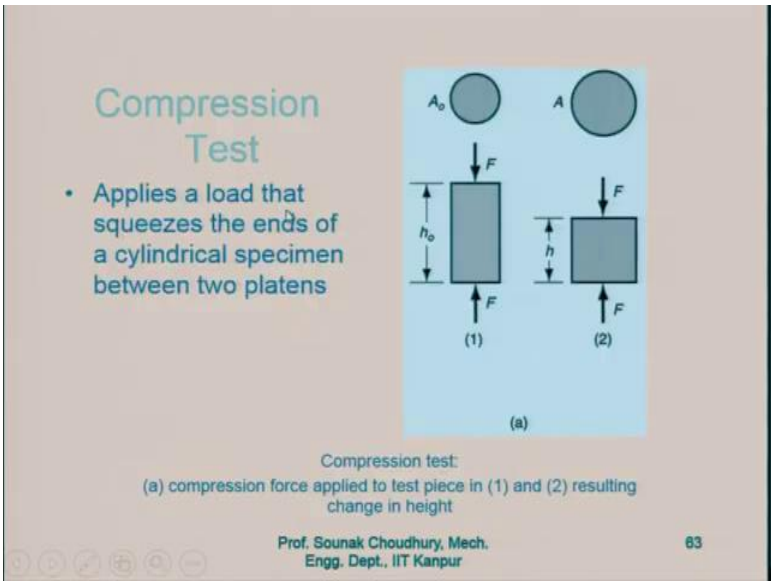

Compression Test

- Applies a load that squeezes the ends of a cylindrical specimen between two platens

Compression test:
(a) compression force applied to test piece in (1) and (2) resulting change in height

Now, let us see how the compression test is performed. During the test, a load is applied that squeezes the ends of a cylindrical specimen between the two platens. Let us say here there is a plate, this is a specimen and there is a plate here and if we actually put this load as it is shown in this direction, this will be compressed meaning that the height of this specimen will be reduced from h_0 to h because of the applied load as you can see.

However, the diameter of the cross-sectional area will be increased as you can see from here. This is the initial cross-sectional area before applying the load, and after the load is applied the compression happens and it reduces in the specimen, reduces in length and it is increased in the diameter.

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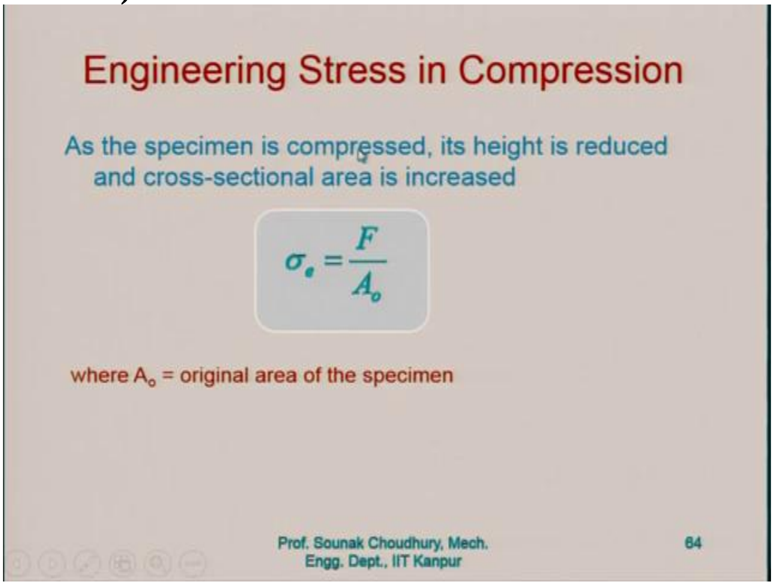

Engineering Stress in Compression

As the specimen is compressed, its height is reduced and cross-sectional area is increased

$$\sigma_e = \frac{F}{A_o}$$

where A_o = original area of the specimen

Engineering stress in compression: Describes engineering stress as the specimen is compressed, its height is reduced and cross sectional area is increased. In that case, the engineering stress will be $\frac{F}{A_0}$, A_0 is the original area of the specimen.

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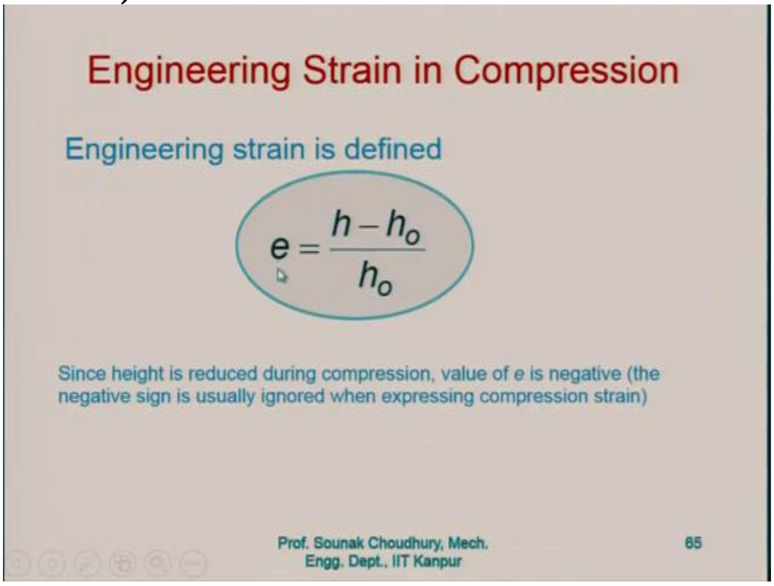

Engineering Strain in Compression

Engineering strain is defined

$$e = \frac{h - h_o}{h_o}$$

Since height is reduced during compression, value of *e* is negative (the negative sign is usually ignored when expressing compression strain)

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Engineering strain, in compression, will be $e = \frac{h - h_0}{h_0}$. h is the height after the compression, (compressive forces are applied) and h_0 is the initial length of it. it is still the initial length that we are using because it is the engineering stress and the engineering strain. Since height is reduced during the compression, the value of e is negative, when expressing the compression stain by negative we mean that this is the height is reduced. Negative value means it is a compression.

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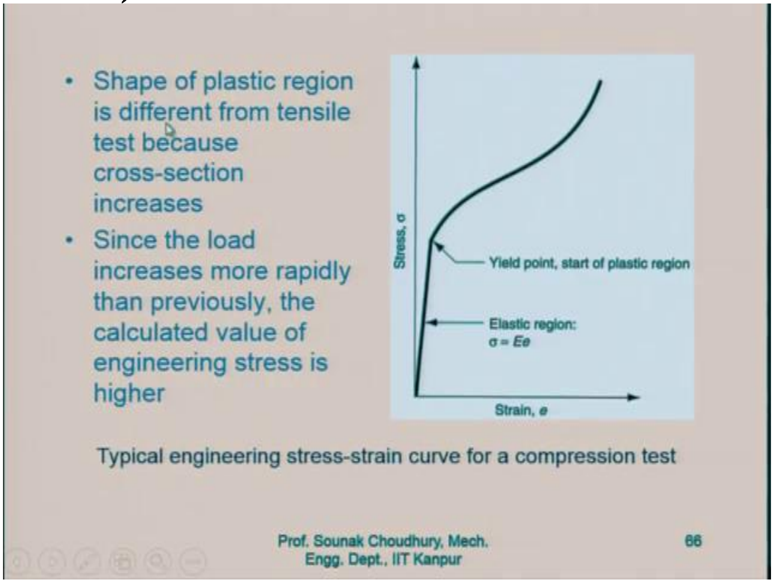

- Shape of plastic region is different from tensile test because cross-section increases
- Since the load increases more rapidly than previously, the calculated value of engineering stress is higher

Typical engineering stress-strain curve for a compression test

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Shape of plastic region is different from tensile tests because cross-section increases. We said this diameter is increasing, and the height is decreasing. the shape of the plastic region will be different. Since the load increases more rapidly than previously, the calculated value of engineering stress is higher. This is to be understood that the load increases rapidly. Therefore, as you calculate the value of the engineering stress it will not be higher. This is typical engineering stress-strain curve, but this is the engineering stress-strain. That is called as compressions test.

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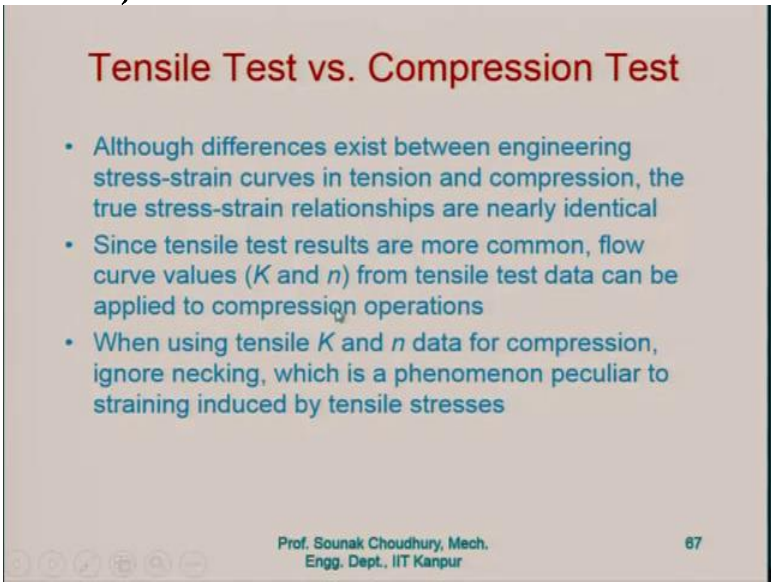

Tensile Test vs. Compression Test

- Although differences exist between engineering stress-strain curves in tension and compression, the true stress-strain relationships are nearly identical
- Since tensile test results are more common, flow curve values (*K* and *n*) from tensile test data can be applied to compression operations
- When using tensile *K* and *n* data for compression, ignore necking, which is a phenomenon peculiar to straining induced by tensile stresses

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67

Tensile test versus the compression test: We have discussed compression test, now it is a tensile test. Although differences exist between engineering stress-strain curves in tension and compression, the true stress-strain relationship is nearly identical. here this is very important and very unique because here the true strain and the stress relationship will be the same in case of the tension and compression.

Since tensile test results are more common, flow curve values, such as *K* and *n* - strength coefficient and the strain hardening from tensile test data can be applied to compression operation. When using tensile *K* and *n* data for compression, ignore necking, which is a phenomenon peculiar to straining induced by tensile stresses.

These are the data obtained by the tensile test and when it is used for the compression, ignore necking, which is a phenomena peculiar to the straining induced by the tensile stresses here that means you have to ignore because necking will be particularly for this situation and not for the compression. These are the recommendations when you compare the tensile test and the compression test results.

(Refer Slide Time: 12:14)

Testing of Brittle Materials

- Hard brittle materials (e.g., ceramics) possess elasticity but little or no plasticity
- Often tested by a *bending test* (also called *flexure test*)
  - Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center

Testing of brittle materials; How to do that? As we said that the stress-strain curve for the brittle materials is such that it does not go beyond the yield point. it does not yield and does not go beyond the elastic limit. Hard brittle materials like ceramics possess elasticity but little or no plasticity often tested by a bending test also called the flexure test. It is subjected to a bending force and the bending moment is measured. A specimen of rectangular cross section is positioned between the two supports and a load is applied at the center and the bending is measured.

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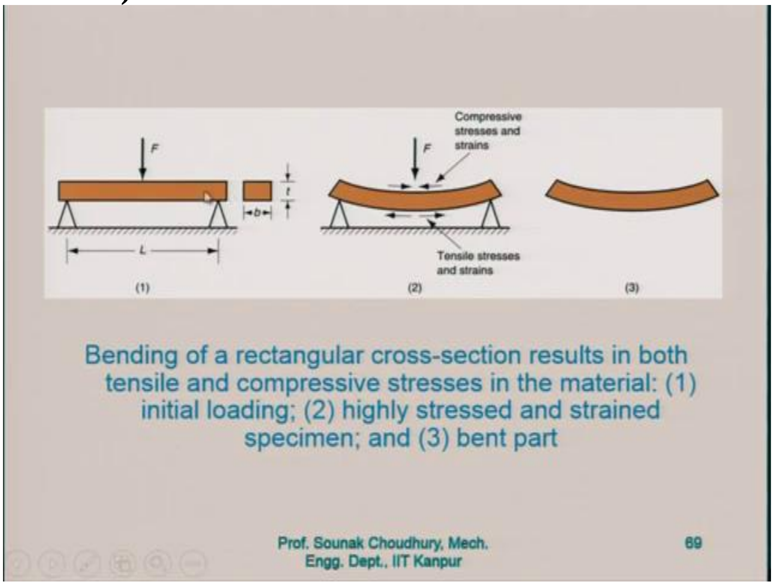

Bending of a rectangular cross-section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part

It is like as given in this figure. This is the testing of brittle materials, this is a cross section of the specimen shown and here is the load given which will bend the specimen. Compressive stress and the strain shown here acting on the opposite sides. These are the tensile stresses and the strains. Now; bending of a rectangular cross section results in both tensile and compressive stresses as it is shown here.

Once again, this will be the compressive stresses, and strains are on the opposite sides; it will be the tensile stresses.

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Testing of Brittle Materials

- Brittle materials do not flex
- They deform elastically until fracture
  - – Failure occurs because tensile strength of outer fibers of specimen are exceeded
  - – Failure type: *cleavage* - common with ceramics and metals at low temperatures, in which separation rather than slip occurs along certain crystallographic planes

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Discussion on the testing of brittle materials is continuing. Brittle materials do not flex. They deform elastically until fracture failure occurs because tensile strength of outer fibers of specimen are exceeded. Failure type can be called as cleavage, which is common with ceramics and metals at low temperatures in which the separation rather than the slip occurs along the certain crystallographic planes.

Now, the slip is a plastic deformation. Slip occurs when a plastic deformation occurs and along the slip line. Here it is a separation. That is why the failure is called the cleavage. This is commonly applied for the ceramics and metals at low temperatures.

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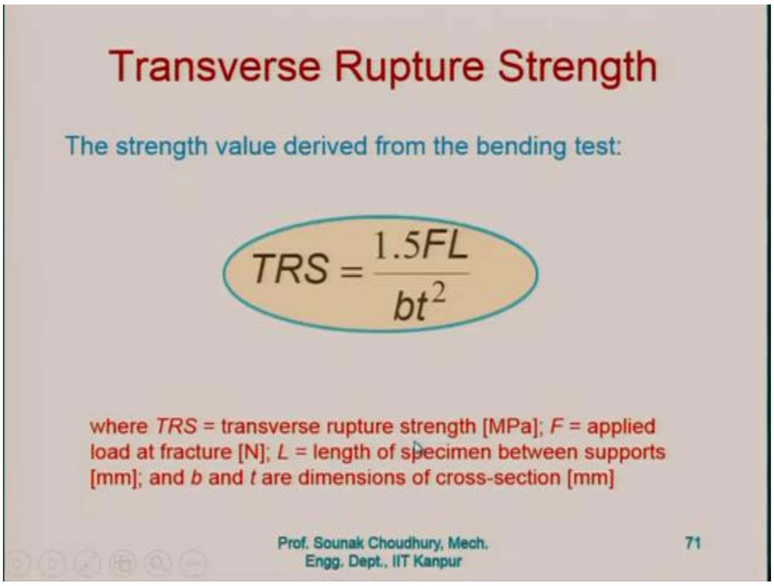

Transverse Rupture Strength

The strength value derived from the bending test:

$$TRS = \frac{1.5FL}{bt^2}$$

where TRS = transverse rupture strength [MPa]; F = applied load at fracture [N]; L = length of specimen between supports [mm]; and b and t are dimensions of cross-section [mm]

Transverse rupture strength: the strength value derived from the bending test is called the transverse rupture strength. This is equal to $\frac{1.5FL}{bt^2}$. F is that applied load, and L is the length of the specimen, and *b* and *t* as you can see from the figure, this is the *b* and this is the *t* shown in the cross section. This value is equal to the transverse rupture strength and this is expressed in the mega Pascal (MPa).

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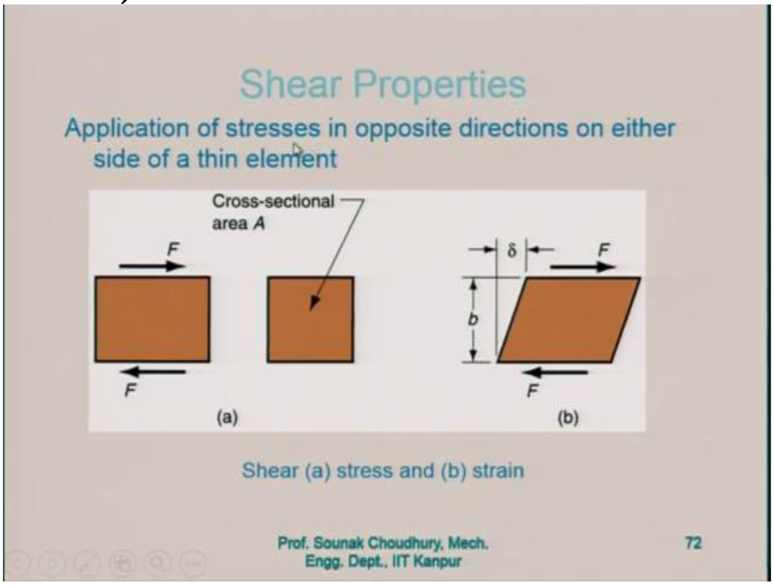

Shear Properties

Application of stresses in opposite directions on either side of a thin element

Shear (a) stress and (b) strain

Shear properties: the application of stresses in opposite directions on either side of a thin element is shown in the figure. this is a thin element and some shear force is applied . This will generate shear stress on the material and the material will be deformed as shown in the figure. This is the deformation that has occurred.

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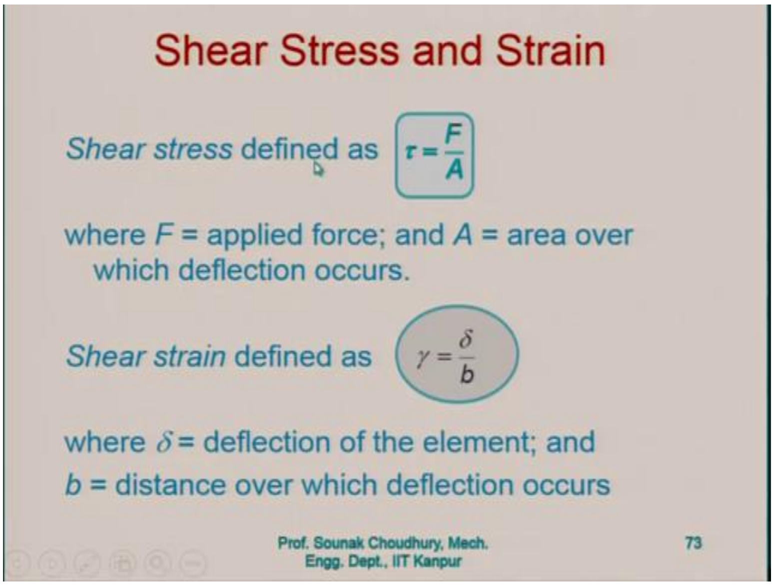

Shear Stress and Strain

Shear stress defined as $\boxed{\tau = \frac{F}{A}}$

where *F* = applied force; and *A* = area over which deflection occurs.

Shear strain defined as $\gamma = \frac{\delta}{b}$

where δ = deflection of the element; and *b* = distance over which deflection occurs

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Now, the shear stress is defined as $\left(\frac{F}{A}\right)$, F is the applied force. Earlier it was a normal force here we are having the shear force. Since the applied force is creating shear stress, this force is called the shear force, and *A* is the area over which the deflection occurs. Now, the shear strain, accordingly, is defined by $\left(\frac{\delta}{b}\right)$and *b* is the distance between the two layers. We consider that the upper layer is moving with respect to the lower layer in the opposite direction.

the distance between these two layers is *b* and the deflection of the element is δ. $\left(\frac{\delta}{b}\right)$will be the shear strain. This shear strain we will find out during the metal cutting because in metal cutting as you understand that the shear strain is very important phenomenon. There the high strain rate of deformation occurs and that is because of the shear stress applied and the shear strain produced at the work piece.

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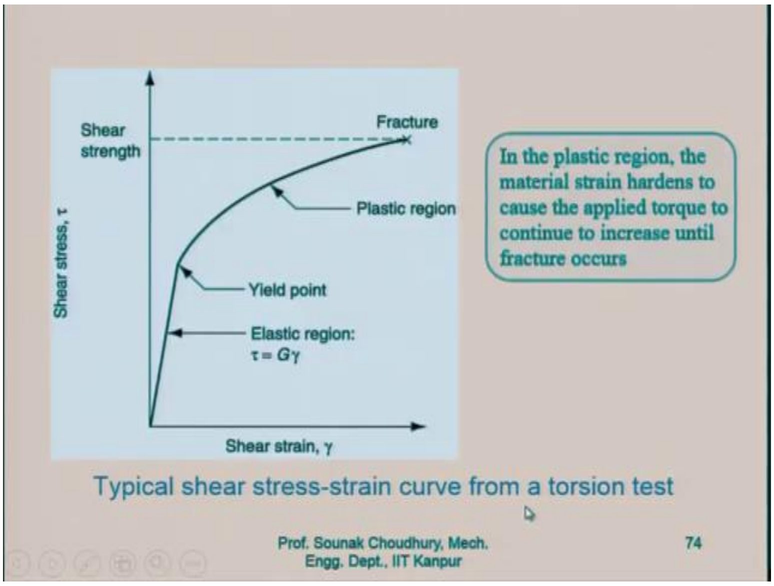

In the plastic region, the material strain hardens to cause the applied torque to continue to increase until fracture occurs

Typical shear stress-strain curve from a torsion test

This is the typical shear stress-strain curve from a torsion test. In the plastic region, the material stain hardens to cause the applied torque to continue to increase until the fracture occursat some point of time when the material is segregated from the actual base material. this is the shear strength or this point is defined as the shear strain and here along this Y- axis is the shear stress, along along the X- axis is the shear strain.

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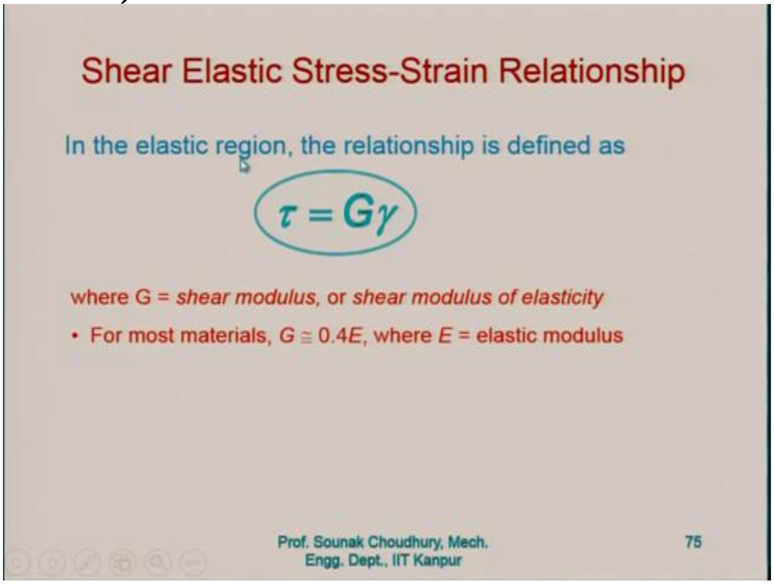

Shear Elastic Stress-Strain Relationship

In the elastic region, the relationship is defined as

$$\boxed{\tau = G\gamma}$$

where G = *shear modulus*, or *shear modulus of elasticity*

- For most materials, $G \cong 0.4E$, where E = elastic modulus

Shear elastic stress strain relationship is defined in the elastic region as $G\gamma$. G is the shear modulus. the shear stress is proportional to shear strain and this is equal to constant into the shear strain and this constant is called the shear modulus. For most materials, this G is equal to 40% of the elastic modulus that is about 0.4 multiplied by the elastic modulus (E).

this is not the same as the elastic modulus, but it is only the 40% of that value and this is the shear modulus. shear modulus and elastic modulus are different. As you can see that elastic modulus is more than the shear modulus. Shear modulus is only 40% of that.

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Shear Plastic Stress-Strain Relationship

- Relationship similar to flow curve
- Shear stress at fracture = *shear strength S*
  - Shear strength can be estimated from tensile strength: $S \cong 0.7(TS)$
- Since cross-sectional area of test specimen in torsion test does not change as in tensile and compression, engineering stress-strain curve for shear $\cong$ true stress-strain curve

Shear plastic stress-strain relationship is similar to flow curve relationship. Shear stress at fracture is equal to the shear strength. Shear strength can be estimated from tensile strength which is about 70% of the tensile strength. This is how you can find out that what is the shear strength which is about 70% of the tensile strength.

Now, since cross sectional area of test specimen in the torsion test does not change as in case of tensile and compression, engineering stress strain-curve for shear is equal to true stress strain curve. This is the reason why we said in the beginning that the engineering stress-strain curve for shear and the compression remains the same because of this reason that the cross-sectional area of the test specimen in the torsion test does not change as in case of the tensile and the compression.

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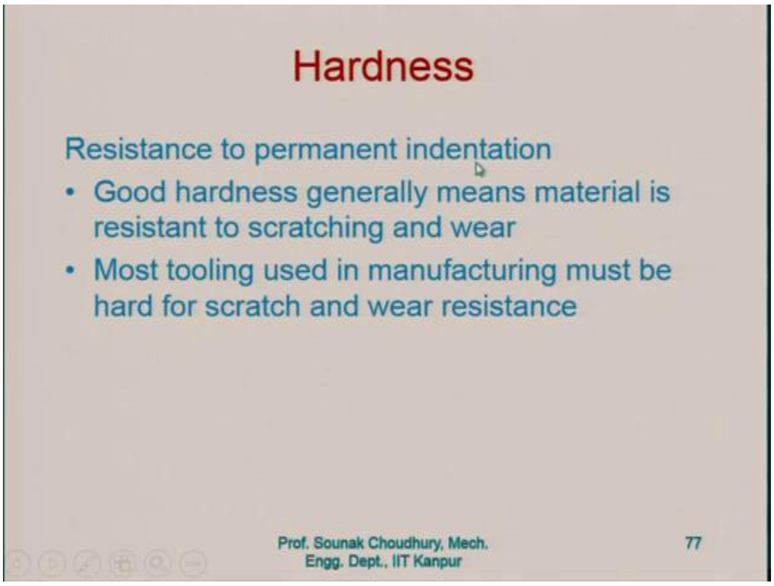

Hardness

Resistance to permanent indentation

- Good hardness generally means material is resistant to scratching and wear
- Most tooling used in manufacturing must be hard for scratch and wear resistance

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Hardness is the resistance to permanent indentation. the hardness does not allow the indentation so easily. Good hardness generally means the material is resistant to scratching and the wear. That is why it is desirable for the engineering parts that they cannot be scratched or the wearing action should be low, wear and tear should be low particularly in case of metal cutting tools.

Most tools used in manufacturing must be hard for scratch and wear resistant that the tool life could be very high.

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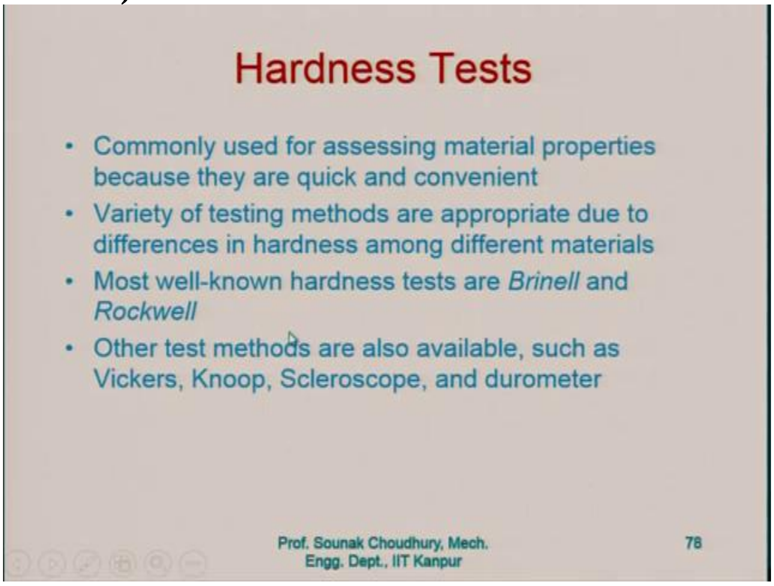

Hardness Tests

- Commonly used for assessing material properties because they are quick and convenient
- Variety of testing methods are appropriate due to differences in hardness among different materials
- Most well-known hardness tests are *Brinell* and *Rockwell*
- Other test methods are also available, such as Vickers, Knoop, Scleroscope, and durometer

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Hardness test commonly used for assessing the material properties, because they are normally quick and convenient and you can quickly find out what is the hardness of a particular material and that is required because this is the property we always use. Depending on the hardness value, we use it for a certain combination of work and the tool. In machining, variety of testing methods are appropriate due to difference in the hardness among different materials.

Mostly Brinell hardness or the Rockwell hardness is what we use to define the hardness of a particular material. this can be indicated as HRC or HB, Rockwell is the HRC Brinell is the HB and so on. Other test methods are also available such as Vickers, Knoop, Scleroscope and Durometer.

along with the popular Brinell and Rockwell hardness tests, other test methods like Vickers test, Knoop test Scleroscope and Durometer are also available. These are the instruments by which the hardness of a material can be measured.

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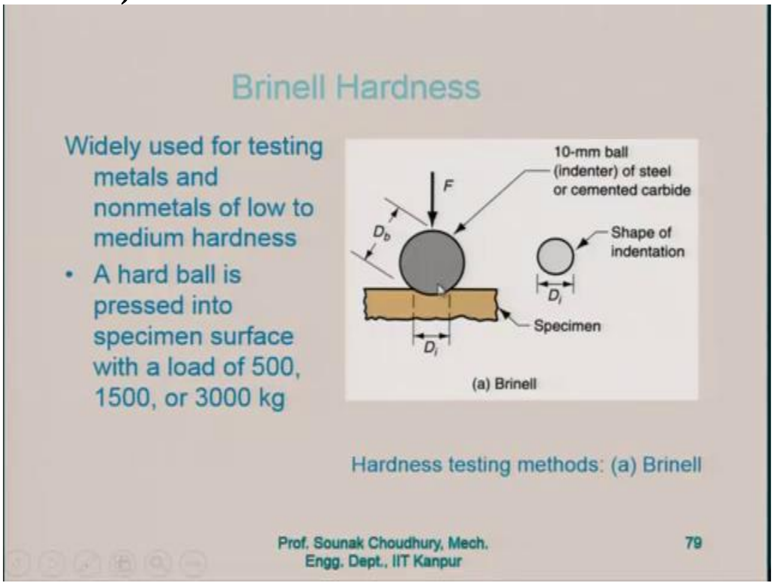

Brinell Hardness

Widely used for testing metals and nonmetals of low to medium hardness
- A hard ball is pressed into specimen surface with a load of 500, 1500, or 3000 kg

Hardness testing methods: (a) Brinell

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Now the Brinell hardness, how it can be done? This is a 10 millimeter steel ball. This is a standard procedure that is used all over the world. The Brinell hardness is measured by this. Whatever is the material specimen, the indenter material is a 10 millimeter steel or cemented carbide ball. The ball makes an indentation like it is shown in the figure.

The shape of the indentation will be semi circular like this and this is the diameter D_i on the specimen this is measured after the force is removed and the ball is removed. this is how the Brinell hardness is tested. They are widely used for testing metals and non-metals of low to medium hardness normally. The ball is of hard material which is pressed against the specimen surface. Load, F is normally 500, 1500 or 3000 kilogram.

Load used for making the indentation has to be mentioned. In case it is a standard testing, then, a certain value will be used which needs to be specified.

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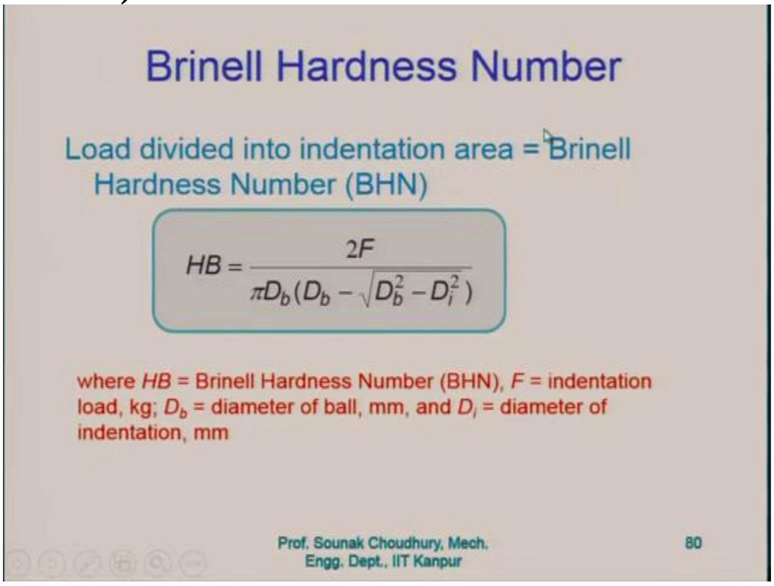

Brinell Hardness Number

Load divided into indentation area = Brinell Hardness Number (BHN)

$$HB = \frac{2F}{\pi D_b(D_b - \sqrt{D_b^2 - D_i^2})}$$

where *HB* = Brinell Hardness Number (BHN), *F* = indentation load, kg; D_b = diameter of ball, mm, and D_i = diameter of indentation, mm

Brinell hardness: Brinell hardness number is load divided by the indentation area. This is defined as $HB = \frac{2F}{\pi D_b(D_b - \sqrt{D_b^2 - D_i^2})}$ where, D_b is the diameter of the ball and D_i is the diameter of the indentation . Now, here you can see that the load, *F* will be defined, either it is 500 or 1500 or 3000 kg.

this will be the value for that particular material for which the Brinell hardness has to be specified.

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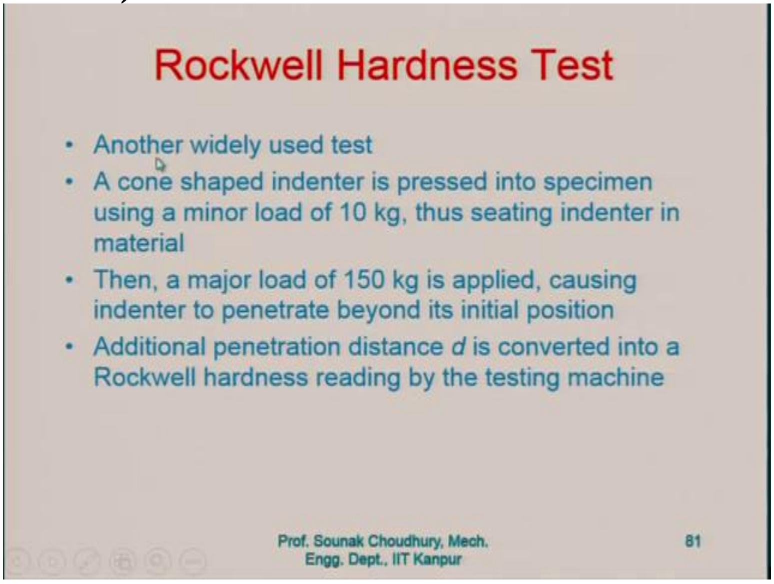

Rockwell Hardness Test

- Another widely used test
- A cone shaped indenter is pressed into specimen using a minor load of 10 kg, thus seating indenter in material
- Then, a major load of 150 kg is applied, causing indenter to penetrate beyond its initial position
- Additional penetration distance *d* is converted into a Rockwell hardness reading by the testing machine

Rockwell hardness test similarly, is another widely used test. In this case, a cone shaped indenter is pressed into the specimen. In case of determination of Brinell hardness, a hard ball is used as an indenter and here it is a cone shaped indenter which is placed into the specimen using a minor load of about 10 kilogram. in case of Brinell hardness, it was 500, 1500 and 3000 kg. Then a measure load of 150 kilogram is applied.

first a minor load of 10 kg is applied that there is a small indentation. that it could seat in the material and then a measure load of 150 kilogram on the same indenter is applied causing the indented to penetrate beyond its initial value. Additional penetration distance *d* is converted into a Rockwell hardness reading by the testing machine. here an indenter first presses the specimen lightly with a load of 10 kg.

When it has made an indentation, then the 150 kilogram of additional weight is applied so that the cone shaped indenter can penetrate the material deeper and that value is used by the testing machine to find out the Rockwell hardness reading. As you understand, the Rockwell hardness will be different than the Brinell hardness because the properties or the method of measuring these two hardness values are different.

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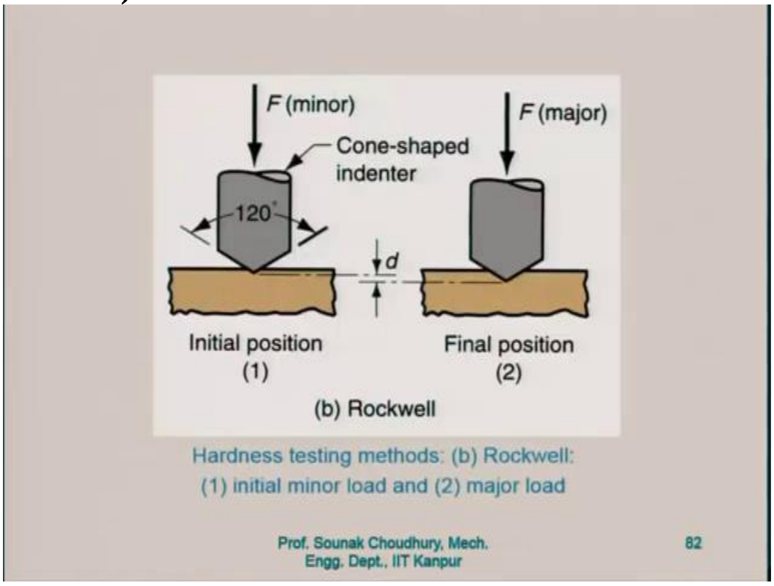

Hardness testing methods: (b) Rockwell: (1) initial minor load and (2) major load

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Here in the diagram it is shown that the cone shaped indenter will initially make an indentation. Standard cone will have an angle of 120^0 and this is the initial position where we have given a small load of 10 kilograms so that that indentation is made a lead and then the final load of 150 kilogram is applied so that it goes farther. the difference between these two indentations is measured. This value of *d* is used to find out the value of the Rockwell hardness and the machine will itself estimate that and it will determine what will be the Rockwell hardness.

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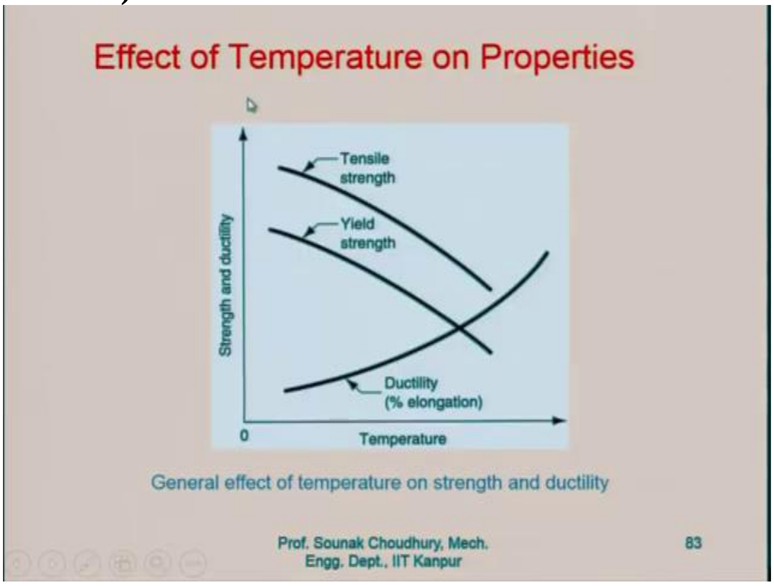

Effect of Temperature on Properties

General effect of temperature on strength and ductility

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83

Now, effect of temperature on properties; this is very important because most of engineering materials work to some extent at temperature more than or different than the ambient temperature. in case of manufacturing in the production, particularly we are bothered about our tool materials which work at a very high temperature. Therefore, what is the effect of the temperature on the properties of the material is very important to understand.

Let us say here along the Y-axis it is the strength and ductility and the temperature we will put it on the X-axis. Tensile strength, yield strength and the ductility are plotted. Ductility is given in percentage of elongation. Now, as you can see that they behave differently as the temperature is increased. When the temperature is increased, the ductility goes up, it goes up not linearly, but it is a nonlinear curve. Similarly, that tensile strength and the yield strength both fall as the temperature is increased.

Strength and ductility are along the y axis as we said yield strength and tensile strength both fall as the temperature increases. Now, here you can see that all these three curves are nonlinear because the equation between the temperature and the tensile strength, yield strength and the ductility separately if you consider then all three equations will be nonlinear equations.

Therefore, this is not a straight line. A major point that should be understood is that the tensile strength, yield strength fall, they decrease as the temperature increases, but the ductility increases. This is the gist of this curve.

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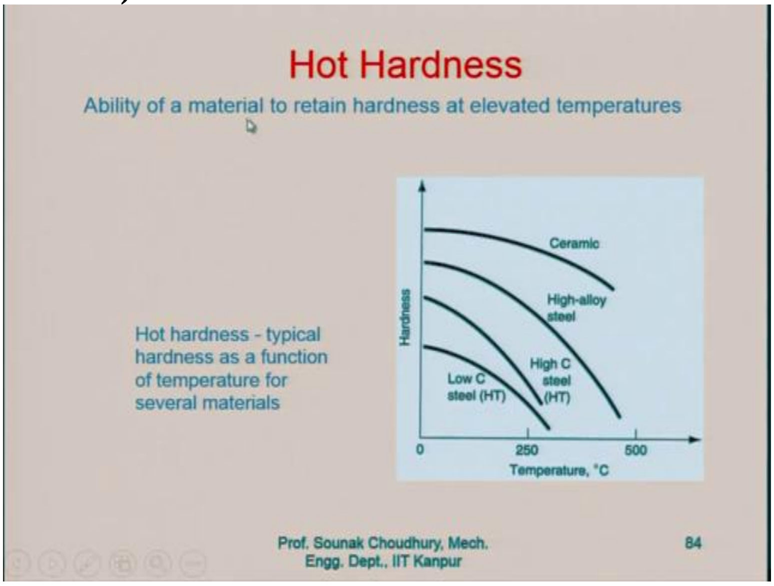

Hot Hardness

Ability of a material to retain hardness at elevated temperatures

Hot hardness - typical hardness as a function of temperature for several materials

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It was mentioned earlier that **hot hardness** is the ability of material to retain hardness at elevated temperature. If you consider the hardness here and at a higher temperature, as you can see that fall in hardness of ceramic is not as rapid as for example, high alloy steel or not as rapid as low carbon. Even at 500^{0}C the hardness of ceramic is maintained, but at this temperature in case of other materials, as shown in the graph, the hardness drops drastically.

This means that the not hardness of the ceramic is much more than any one of them then the high alloy steel or high carbon steel or the low carbon steel. The hardness as a function of temperature for several materials is shown here. These are the four different materials and ceramic being the best as long as the hot hardness is concerned and therefore, as I told you earlier also that ceramic material is one that we normally use when the high temperature is involved.

At a high speed, the ceramic cutting tool is used because at high speed cutting the temperature becomes very high and at that temperature the hardness of the tool material should not fall. So, hot hardness has to be more. Here you can see that for ceramic even at 500^{0}C the hardness is quite high. So, the hot hardness of ceramic is higher.

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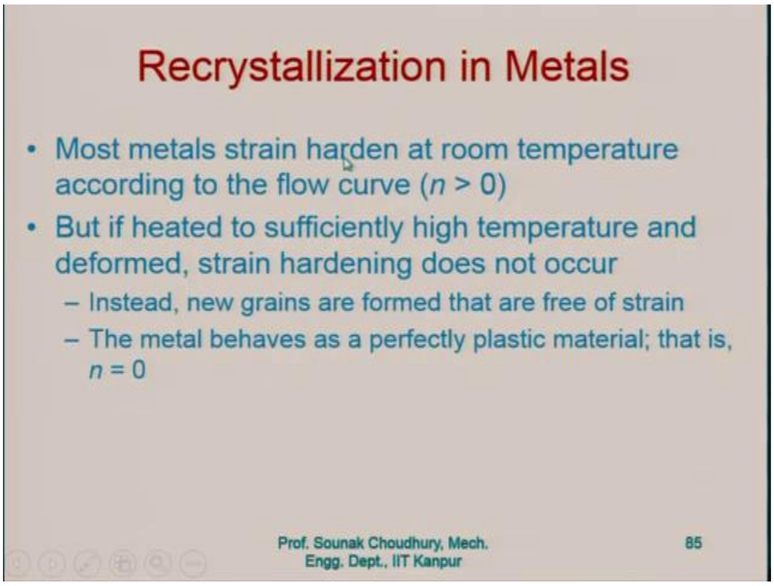

Recrystallization in Metals

- Most metals strain harden at room temperature according to the flow curve ($n > 0$)
- But if heated to sufficiently high temperature and deformed, strain hardening does not occur
  - Instead, new grains are formed that are free of strain
  - The metal behaves as a perfectly plastic material; that is, $n = 0$

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Recrystallization in metals: most metal strain hardened at room temperature according to the flow curve. For most of the metals, the *n* is more than 0, but if heated to sufficiently high temperature and deform then the strain hardening does not occur. This phenomenon is a very interesting phenomenon that when the metal is heated up to a sufficiently high temperature, and then deformed then the strain hardening does not occur.

Instead, the new grains are formed that are free of strains. Normally, the metal behaves as a perfectly plastic material, that is the strain hardening is 0, because it has been heated up to a sufficiently high temperature.

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Recrystallization Temperature

- Formation of new strain-free grains is called *recrystallization*
- *Recrystallization temperature* of a given metal = about one-half its melting point ($0.5\ T_m$) as measured on an absolute temperature scale
- Recrystallization takes time - the recrystallization temperature is specified as the temperature at which new grains are formed in about one hour

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Recrystallization temperature: the formation of new strain free grains is called the recrystallization, meaning that when we say that, the new grains are formed that are free of strain when the metal is heated up at the sufficiently high temperature this will be at a temperature more than the temperature of recrystallization that is what we said earlier. This is the recrystallization temperature.

It is defined as when the formations of the new strain free grains happen, this is the recrystallization process and that temperature at which it happens is the recrystallization temperature of a given metal. This is about one half its melting point, $0.5T_m$. T_m is the melting point as measured on an absolute temperature scale. Now, recrystallization takes time. The recrystallization temperature is specified as the temperature at which new grains are formed in about 1 hour. That time is specified during which this recrystallization process takes place and the new grains are formed.

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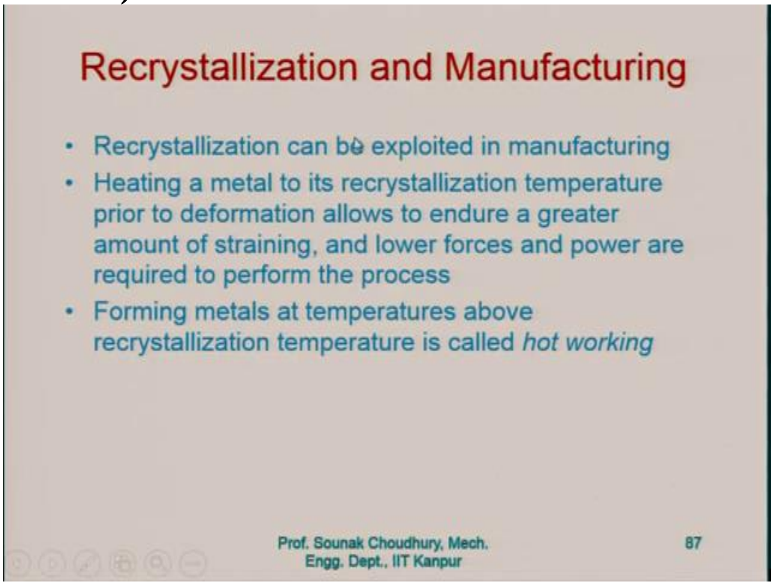

Recrystallization and Manufacturing

- Recrystallization can be exploited in manufacturing
- Heating a metal to its recrystallization temperature prior to deformation allows to endure a greater amount of straining, and lower forces and power are required to perform the process
- Forming metals at temperatures above recrystallization temperature is called *hot working*

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87

Recrystallization and manufacturing: how this recrystallization processes related or how it is important for the manufacturing? Recrystallization can be exploited in manufacturing in a way that heating a metal up to its recrystallization temperature prior to deformation allows to endure a greater amount of straining. This is very obvious because metal is being heated up prior to deformation the material and hence lower forces and power are required to perform the process.

Once again, as the metal is heated up to its recrystallization temperature or more than that prior to deformation, this will have greater straining of the material and therefore, the less force and power will be required. This is an advantage for the manufacturing because we always are bothered about the power of the machining; as less power is consumed, it is better; less force is to be applied for removing the material.

It is better because in that case the prime mover of the machine can be less powerful and this will be cheaper. In the area of machining some research is also being conducted on the hot machining, that is the during the cutting process the material is additionally heated up externally. This way the forces and the power consumption during the process will be less because the temperature at which the work piece has been heated up is more than the recrystallization temperature.

When the temperature of workpiece crosses the temperature of recrystallization only then it will happen that $n = 0$, forming metals at temperatures above recrystallization temperature. This is the hot working. It is very famous particularly in metal forming because in metal forming it is important that the force required in the die to be less. So, when it is worked in the hot working condition the deformation is easier and for metal forming operations it is a very big advantage.

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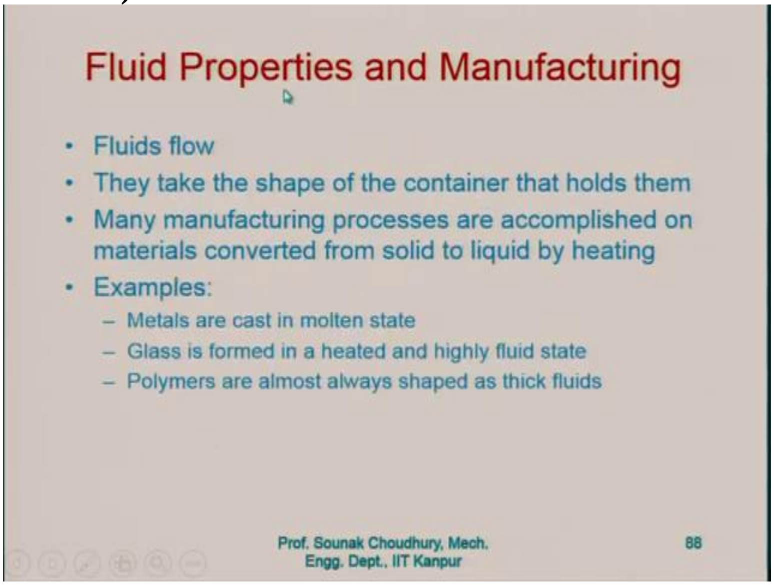

Fluid Properties and Manufacturing

- Fluids flow
- They take the shape of the container that holds them
- Many manufacturing processes are accomplished on materials converted from solid to liquid by heating
- Examples:
  - Metals are cast in molten state
  - Glass is formed in a heated and highly fluid state
  - Polymers are almost always shaped as thick fluids

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88

Fluid properties and manufacturing; fluids take the shape of the container that holds them that we all know and many manufacturing processes are accomplished on materials converted from solid to liquid by heating. Let us take some examples. Metals are cast in molten state otherwise the casting process cannot take place; glass is formed in a heated and highly fluid state. Initially it is heated up to bring it to the molten state and then it is poured in different kinds of forms.

That is how the glass products are manufactured. Polymers for example, are also almost always shaped as a thick fluid. However, there are some processes where polymers are being used in the solid state. Although, inside the machine it is melted. Therefore, as you can see that for casting, for glass forming, utensils, polymers, the raw material is always in the fluid state.

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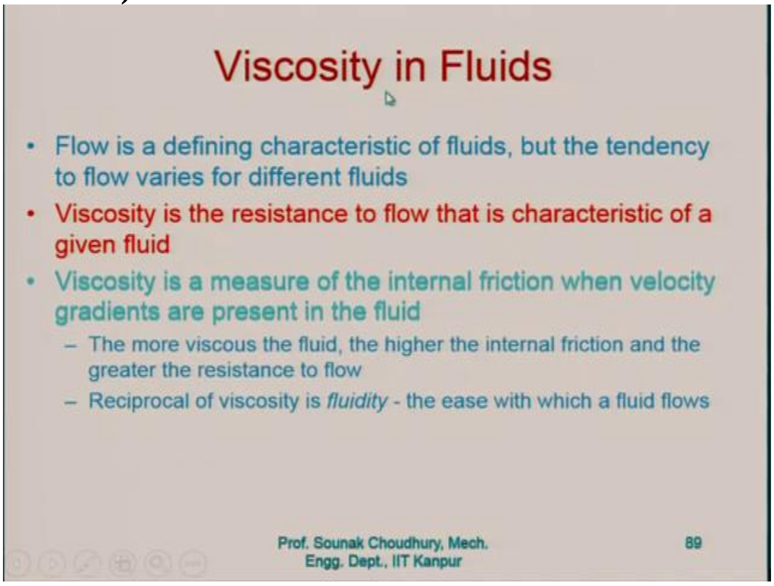

Viscosity in Fluids

- Flow is a defining characteristic of fluids, but the tendency to flow varies for different fluids
- Viscosity is the resistance to flow that is characteristic of a given fluid
- Viscosity is a measure of the internal friction when velocity gradients are present in the fluid
  - The more viscous the fluid, the higher the internal friction and the greater the resistance to flow
  - Reciprocal of viscosity is *fluidity* - the ease with which a fluid flows

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Let us see some of the properties of fluids. **viscosity in fluids**: flow is a defining characteristic of fluid. Of course, it flows as we said, but the tendency to flow varies for different fluids. Viscosity is the resistance to flow that is characteristic of a given fluid. So, if the fluid is very thick, you understand that it will not flow that easily that is, high or low viscosity fluid will flow in different ways.

So, thick fluid will flow less, if it is a more fluidic it will be flowing more rapidly. Therefore, viscosity is a measure of the internal friction when the velocity gradients are present in the fluid, the more viscous the fluid, the higher the internal friction and the greater the resistance to flow, more viscous material will have more resistance to flow.

In case of viscous fluid there will be more internal friction; that is why the resistance to flow will be more. Reciprocal of viscosity is fluidity. More the viscosity, less will be the fluidity; higher viscous fluids will not be flowing easily. We express in an engineering term that more viscous fluids will have less fluidity and vice versa less viscous fluids will have more fluidity, they will flow easily.

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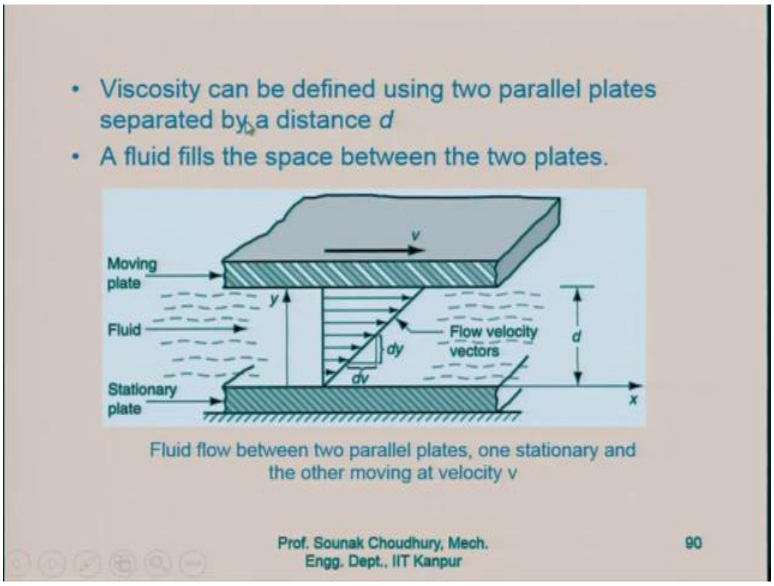

- Viscosity can be defined using two parallel plates separated by a distance *d*
- A fluid fills the space between the two plates.

Fluid flow between two parallel plates, one stationary and the other moving at velocity v

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Viscosity can be defined using two parallel plates separated by a distance *d*. Let us say there are two plates and this is the distance between them. Here we have a fluid which is flowing in between; this is the stationary plate and this is moving with respect to this stationary plate. A fluid fills the space between the two plates and this will be the flow velocity vector.

We have seen it in many other fluid mechanics courses that when the the fluid is flowing, the velocity is 0 here at the base and the maximum here and this is the flow velocity vector. For the slope to determine, this is *dy* and this is the *dv*. The velocity of the moving plate is *v*.

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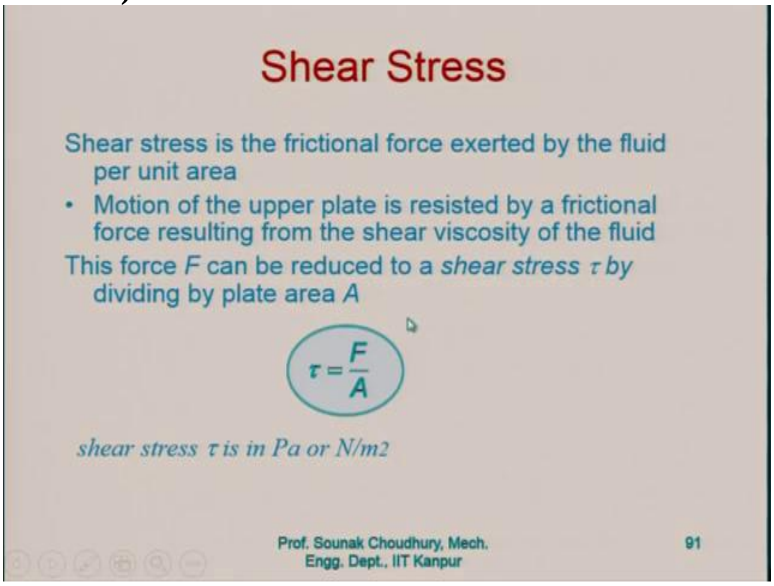

Shear Stress

Shear stress is the frictional force exerted by the fluid per unit area

- Motion of the upper plate is resisted by a frictional force resulting from the shear viscosity of the fluid

This force *F* can be reduced to a *shear stress* τ *by* dividing by plate area *A*

$$\boxed{\tau = \frac{F}{A}}$$

shear stress τ *is in Pa or N/m2*

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Shear stress is the frictional force exerted by the fluid per unit area. Now, the motion of the upper plate is resisted by a frictional force resulting from the shear velocity of the fluid. There is a shear velocity and because of that there is a frictional force and that frictional force resists the movement of the upper plate which is moving at a velocity *v*. This force *F* can be used to determine the shear stress as, $\tau = \dfrac{F}{A}$

This is how the shear stress can be defined. This is force divided by the plate area *A* and the shear stress τ is given in Pascal or $\dfrac{N}{m^2}$ Newton per meter square which is expressed in Pascal. Sometimes you find that this is also expressed in mega Pascal because the value of this stress is very high and therefore, it is expressed in mega Pascal.

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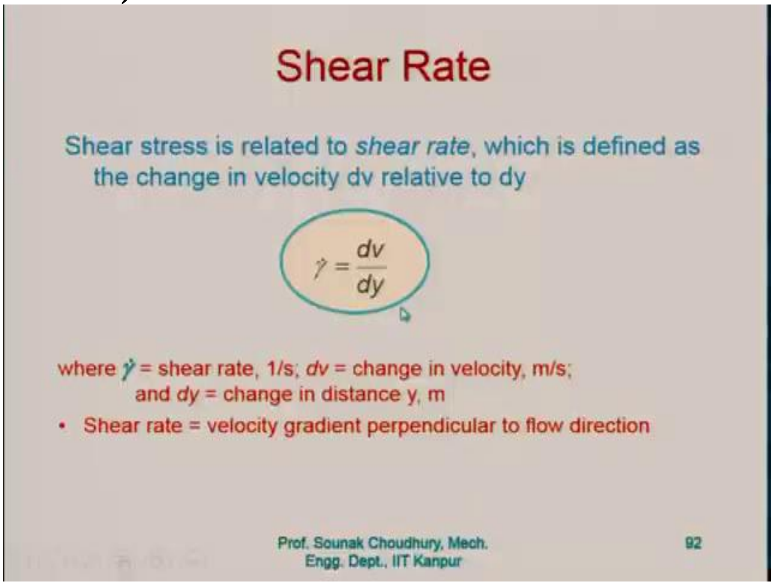

Shear Rate

Shear stress is related to *shear rate*, which is defined as the change in velocity dv relative to dy

$$\dot{\gamma} = \frac{dv}{dy}$$

where $\dot{\gamma}$ = shear rate, 1/s; *dv* = change in velocity, m/s; and *dy* = change in distance y, m

- Shear rate = velocity gradient perpendicular to flow direction

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Shear stress: Shear stress is related to shear rate which is defined as the change in the velocity *dv* relative to the *dy*. This is the change in the velocity with respect to the distance This is the shear rate because here the time will come into picture which is defined as the change in velocity *dv* relative to the *dy*.

This is the shear rate. This is $\left(\dfrac{1}{\sec}\right)$ because this will have the time in picture, because *dv* is the change in the velocity the unit will be the same as the velocity, i.e. meter per second and *dy* is the change in the distance which is in meter, i.e. how that distance is changing where the change in the velocity is measured. This will be the slope of that curve or of that line and that is given by the shear rate.

Shear rate is the velocity gradient perpendicular to flow direction. This is the same as the velocity gradient, which is change in the velocity with respect to the distance and this is perpendicular to the flow direction. Flow direction is in this way and this is the change in the distance with respect to the flow direction, perpendicular to the flow direction.

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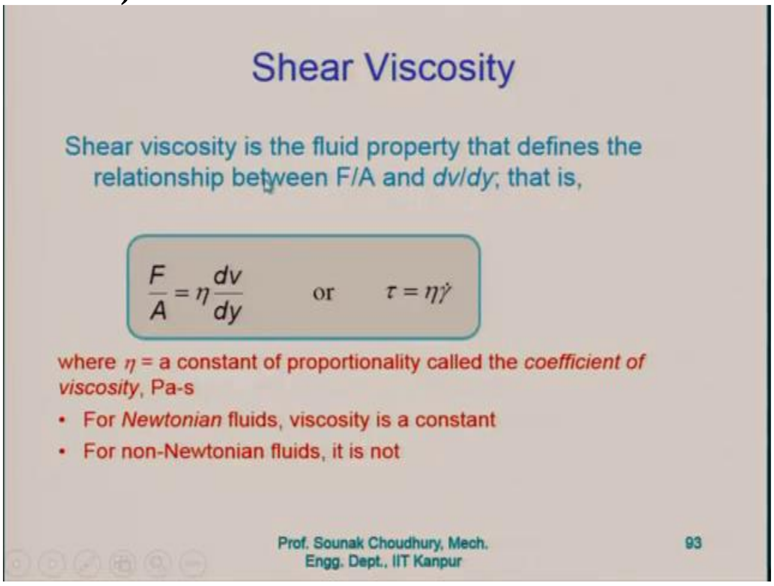

Shear Viscosity

Shear viscosity is the fluid property that defines the relationship between F/A and *dv/dy*; that is,

$$\frac{F}{A} = \eta \frac{dv}{dy} \quad \text{or} \quad \tau = \eta \dot{\gamma}$$

where η = a constant of proportionality called the *coefficient of viscosity*, Pa-s

- For *Newtonian* fluids, viscosity is a constant
- For non-Newtonian fluids, it is not

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93

Shear viscosity is the fluid property. This is one of the few properties that defines the relationship between the $\left(\frac{F}{A}\right)$ and the $\left(\frac{dv}{dy}\right)$ that is $\left(\frac{F}{A}\right) = \eta\left(\frac{dv}{dy}\right)$. This is the shear and this is the shear rate they are related by a constant of proportionality. This is called the coefficient of viscosity.

So, the shear stress is proportional to the shear rate and this will be therefore, equal to the constant of proportionality which is the coefficient of viscosity multiplied by the $\left(\frac{dv}{dy}\right)$ which is the shear rate. For Newtonian fluids, viscosity is a constant. When we talk about non-Newtonian or the Newtonian fluids, viscosity matters.

It is a Newtonian fluid and for fluids where the viscosity is not constant there those fluids are called the non-Newtonian fluids. We are discussing this because in the manufacturing the role of the fluids is very high particularly when we talk about the hydraulics. In hydraulics we have the pipelines through which the water or any other fluid flows. So, we have to understand the properties of such fluids, so that we can understand or design properly the hydraulic devices. That is why we need to understand the properties of fluid.

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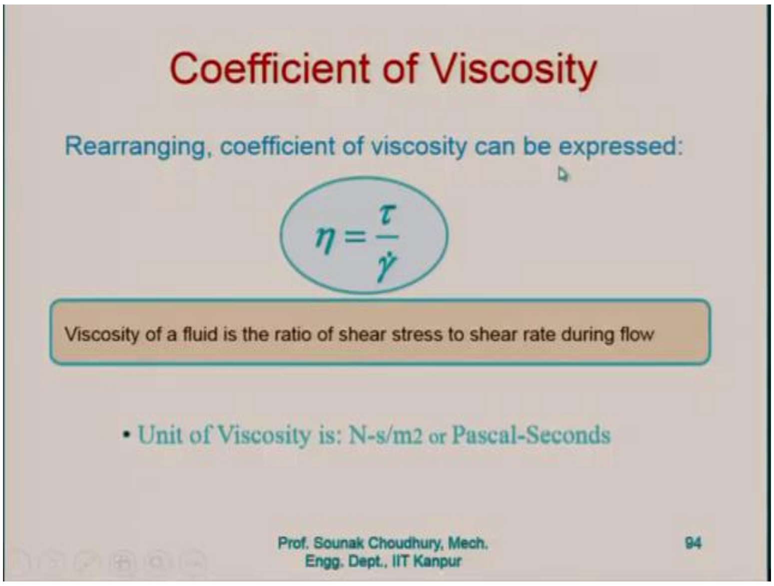

Coefficient of Viscosity

Rearranging, coefficient of viscosity can be expressed:

$$\eta = \frac{\tau}{\dot{\gamma}}$$

Viscosity of a fluid is the ratio of shear stress to shear rate during flow

- Unit of Viscosity is: N-s/m2 or Pascal-Seconds

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Coefficient of viscosity: rearranging, coefficient of viscosity can be therefore, expressed as $\eta = \frac{\tau}{\dot{\gamma}}$ i.e. shear stress to the shear rate during the flow. This is the viscosity of the fluid. This defines the viscosity that means, this is the ratio of the shear stress to the shear rate.

During the flow when the fluid is flowing, unit of viscosity is $\frac{N-s}{m^2}$. From here you can find out $\frac{N-s}{m^2}$ can be expressed as a Pascal second. This is the unit of viscosity.

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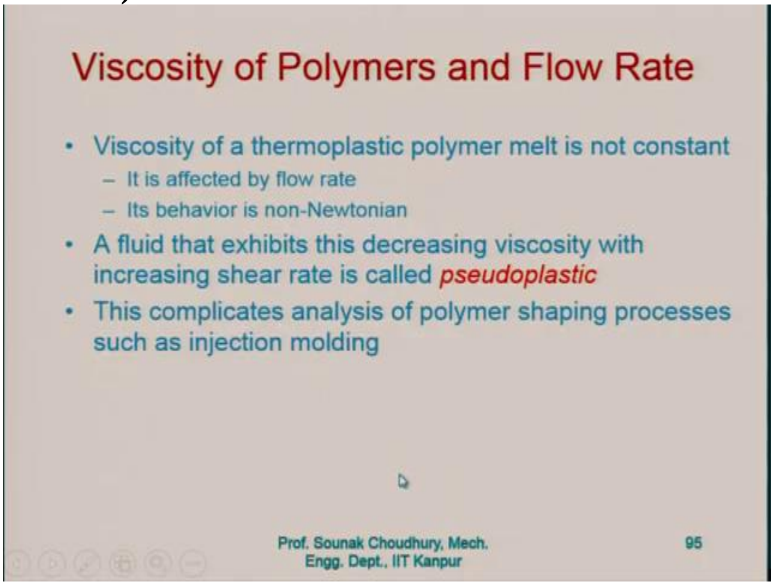

Viscosity of Polymers and Flow Rate

- Viscosity of a thermoplastic polymer melt is not constant
  - It is affected by flow rate
  - Its behavior is non-Newtonian
- A fluid that exhibits this decreasing viscosity with increasing shear rate is called *pseudoplastic*
- This complicates analysis of polymer shaping processes such as injection molding

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Viscosity of polymers and flow rate: viscosity of a thermoplastic polymer melt is not constant. It is affected by the flow rate and its behaviour is non-Newtonian. There the viscosity does not remain constant if you see this, for the non-Newtonian the viscosity is not constant. Now, you understand that this is a thermoplastic polymer we are talking about the melt is not constant. There is a fluid that exhibits this decreasing viscosity with increasing shear rate this is called pseudoplastic.

This is the concept of the material, that is a pseudo plastic material, where their viscosity decreases with the increasing of the shear rate. This complicates analysis of polymer shaping processes such as injection molding. The injection molding is directly related to the manufacturing and here if we have the pseudoplastics, this will actually complicate since we have to take care of this property of the pseudoplastic.

That the viscosity will be changing depending on the shear rate and we have to know before and that how much viscosity can be changed with the applied shear rate then only you can have the process of injection molding properly designed.

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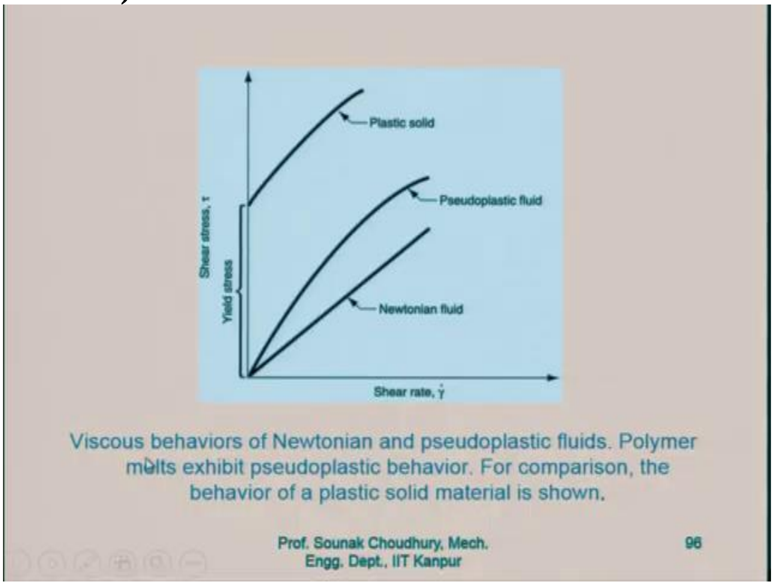

Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.

This is how it happens. Viscous behaviours of Newtonian and pseudoplastic fluids polymer melts exhibit pseudoplastic behaviour. This is Newtonian and this is non-Newtonian fluid and this is a plastic solid behaviour. For comparison the behaviour of the plastic material is given. This is the pseudoplastic fluid, which is non-Newtonian because the Newtonian fluid will behave this way, and this is the yield stress.

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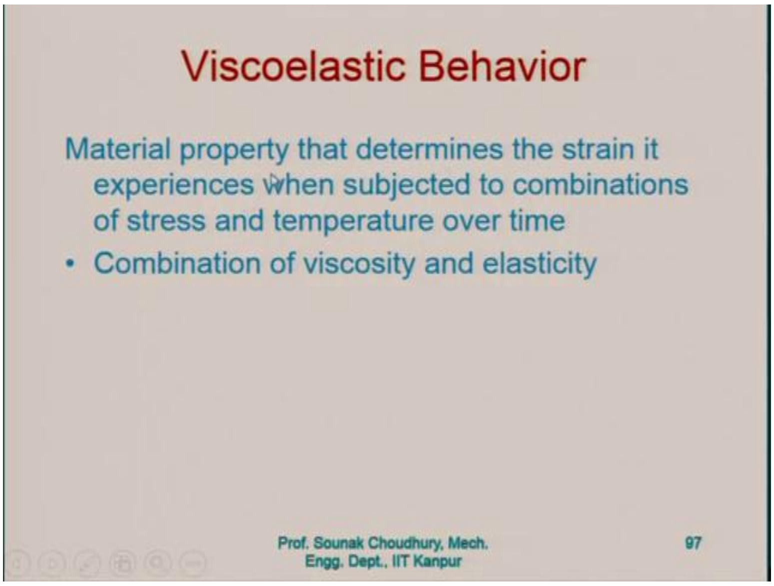

Viscoelastic Behavior

Material property that determines the strain it experiences when subjected to combinations of stress and temperature over time

- Combination of viscosity and elasticity

Viscoelastic behaviour: material property that determines the strain experiences when subjected to combination of stress and temperature over time. So, this is a combination of viscosity and elasticity, this is the concept that determines the strain experiences when subjected the combination of stress and temperature or time.

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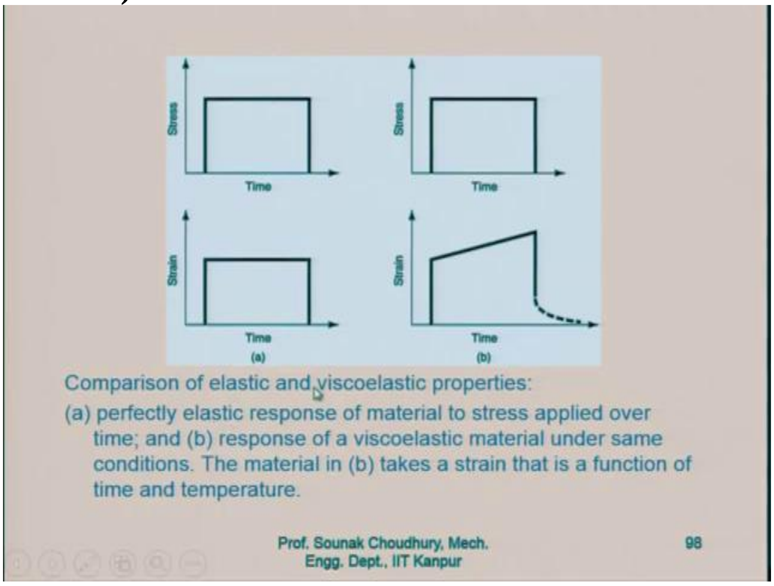

Comparison of elastic and viscoelastic properties:
(a) perfectly elastic response of material to stress applied over time; and (b) response of a viscoelastic material under same conditions. The material in (b) takes a strain that is a function of time and temperature.

Here is the comparison of elastic and the viscoelastic properties. Along the Y-axis we have the stress, and along the X-axis we have the time. This is a perfectly elastic response of a material to stress that is applied over time; here the response of viscoelastic material under the same condition, the material *b* here takes a strain that is a function of time and temperature as you can see from here.

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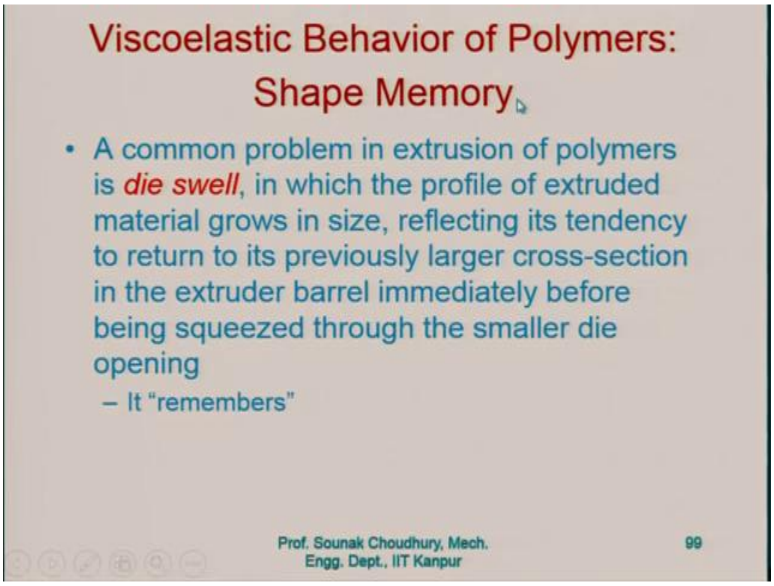

Viscoelastic Behavior of Polymers: Shape Memory

- A common problem in extrusion of polymers is *die swell*, in which the profile of extruded material grows in size, reflecting its tendency to return to its previously larger cross-section in the extruder barrel immediately before being squeezed through the smaller die opening
  - It "remembers"

Viscoelastic behaviour of polymers: This is a very important phenomena and a very important property that is being used very widely in the manufacturing and in many other industries; this is called the shape memory. Now, a common problem in extrusion of polymers is the die swell, in which the profile of extruded material grows in size reflecting its tendency to return to its previously larger cross section in the extruder barrel immediately before being squeezed through the smaller die opening.

These are some of the defects, in case of the extrusion of the materials and we have to take care of this. This is what happens - the material remembers the previous shape. When it goes through this smaller cross section, it remembers the earlier volume or the cross section and it immediately wants to come back to the initial shape. That is called the shape memory.

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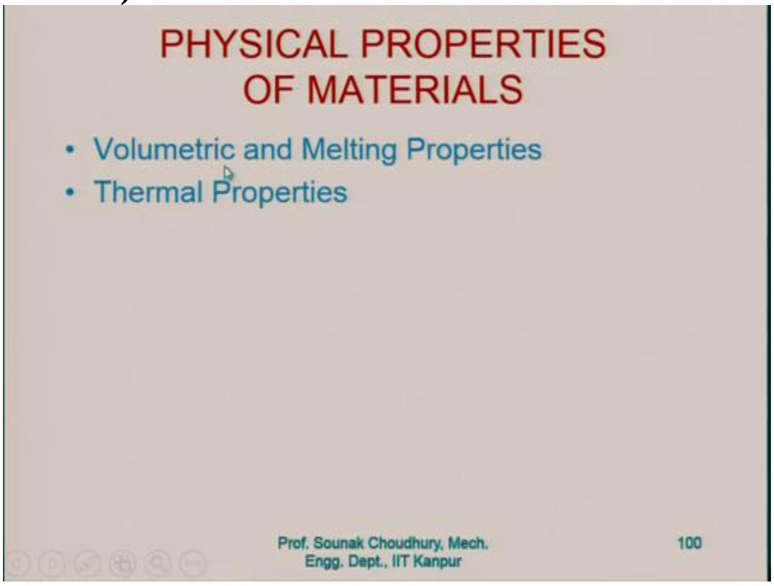

PHYSICAL PROPERTIES OF MATERIALS

- Volumetric and Melting Properties
- Thermal Properties

Physical properties of the material (continuing) These properties include volumetric and the melting properties, and thermal properties.

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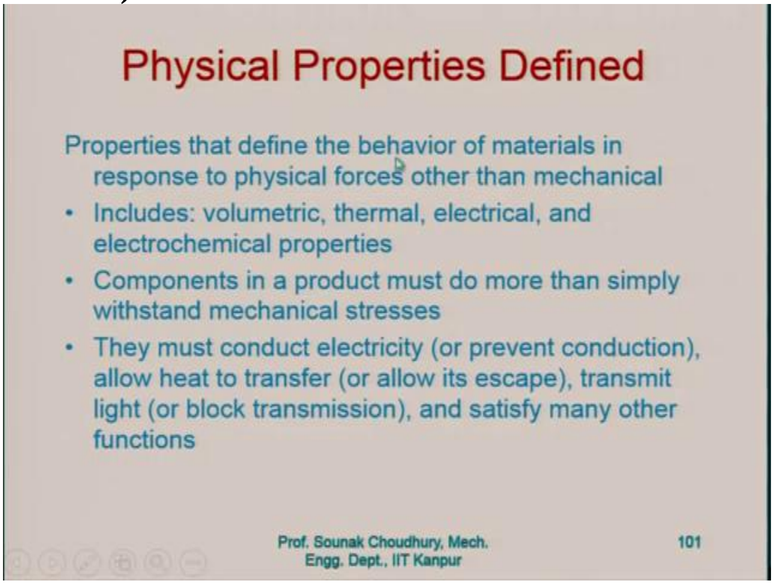

Physical Properties Defined

Properties that define the behavior of materials in response to physical forces other than mechanical

- Includes: volumetric, thermal, electrical, and electrochemical properties
- Components in a product must do more than simply withstand mechanical stresses
- They must conduct electricity (or prevent conduction), allow heat to transfer (or allow its escape), transmit light (or block transmission), and satisfy many other functions

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Physical Properties define the behaviour of materials in response to physical forces other than the mechanical. This includes volumetric, thermal, electrical and electro chemical properties. Now, components in a product must do more than simply withstand the mechanical stresses, like either they conduct electricity or prevent the conduction, allow heat to transfer or allow it to escape, transmit light or block the transmission and satisfy many other functions.

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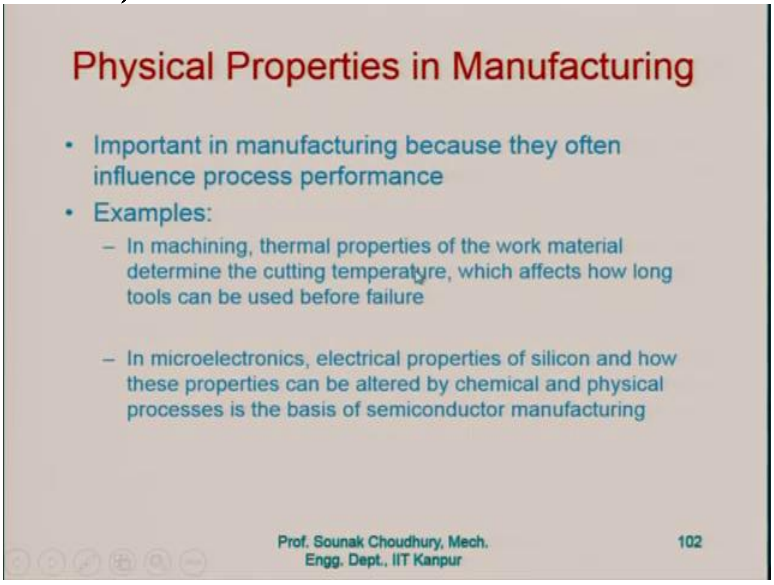

Physical Properties in Manufacturing

- Important in manufacturing because they often influence process performance
- Examples:
  - In machining, thermal properties of the work material determine the cutting temperature, which affects how long tools can be used before failure
  - In microelectronics, electrical properties of silicon and how these properties can be altered by chemical and physical processes is the basis of semiconductor manufacturing

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Physical properties in manufacturing are important in manufacturing because they often influence the process performance. I have given you enough examples in between indicating why these properties are important for the manufacturing. In machining for example, the thermal properties of the work material determine the cutting temperature which affects tool life, i.e. how long tools can be used before failure.

In micro electronics, electrical properties of silicon and how these properties can be altered by chemical and physical processes is the basis of semiconductor manufacturing. While manufacturing semiconductor or its machining all these physical properties are important.

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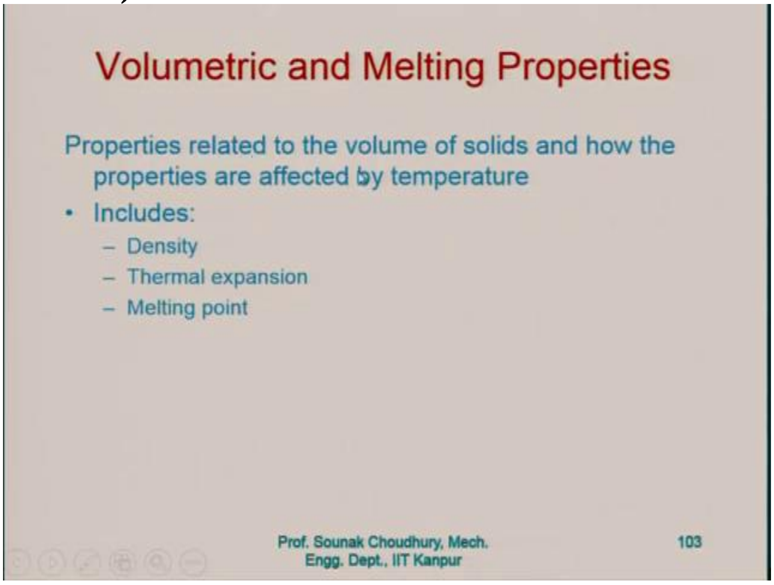

Volumetric and Melting Properties

Properties related to the volume of solids and how the properties are affected by temperature

- Includes:
  - Density
  - Thermal expansion
  - Melting point

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Volumetric and melting properties: These properties are related to the volume of solids and how the properties are affected by temperature that includes, density, thermal expansion, and melting point.

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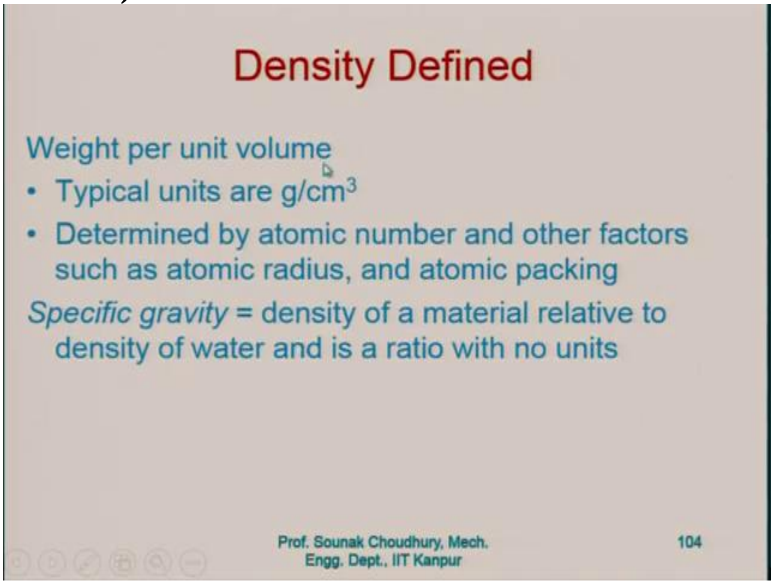

Density Defined

Weight per unit volume

- Typical units are g/cm^3
- Determined by atomic number and other factors such as atomic radius, and atomic packing

Specific gravity = density of a material relative to density of water and is a ratio with no units

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Density is defined by weight per unit volume expressed in gm/cm^3. Specific gravity is the density of material relative to density of water.

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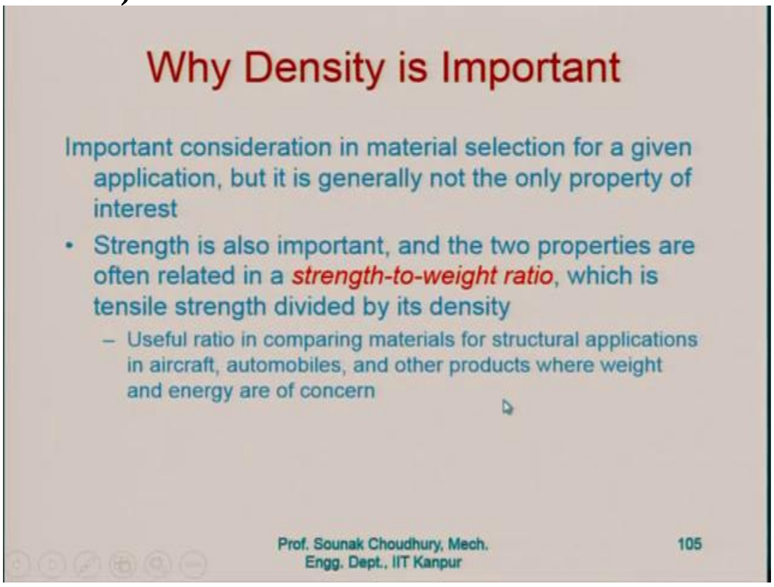

Why Density is Important

Important consideration in material selection for a given application, but it is generally not the only property of interest

- Strength is also important, and the two properties are often related in a *strength-to-weight ratio*, which is tensile strength divided by its density
  - Useful ratio in comparing materials for structural applications in aircraft, automobiles, and other products where weight and energy are of concern

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Density is an important consideration in material selection for a given application, but it is generally not the only property of interest. Strength-to-weight ratio is more important here which is tensile strength divided by the density.

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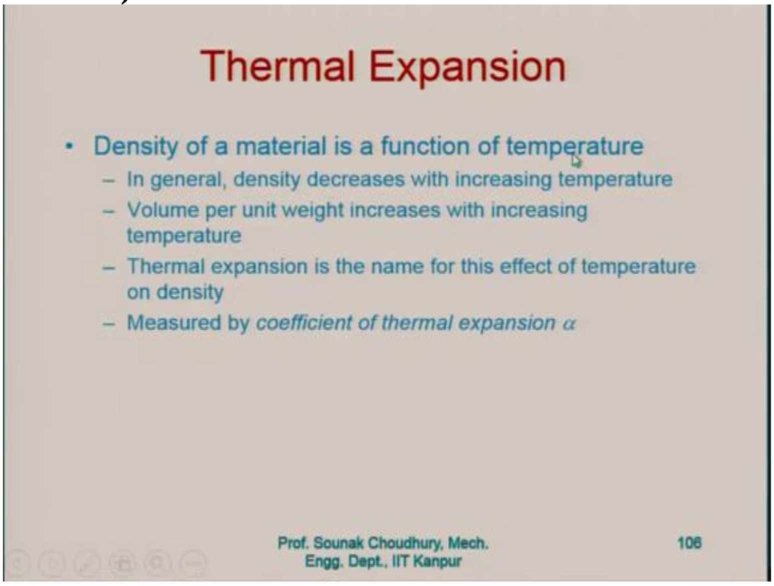

Thermal Expansion

- Density of a material is a function of temperature
  - In general, density decreases with increasing temperature
  - Volume per unit weight increases with increasing temperature
  - Thermal expansion is the name for this effect of temperature on density
  - Measured by *coefficient of thermal expansion* α

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Thermal expansion: density of material is a function of temperature. In general, density decreases with the increasing of temperature, the volume per unit weight increases with increasing temperatures. Thermal expansion is the name for this effect of the temperature or the density and this is measured by the coefficient of thermal expansion. Let us say that this is coefficient of thermal expansion given by α.

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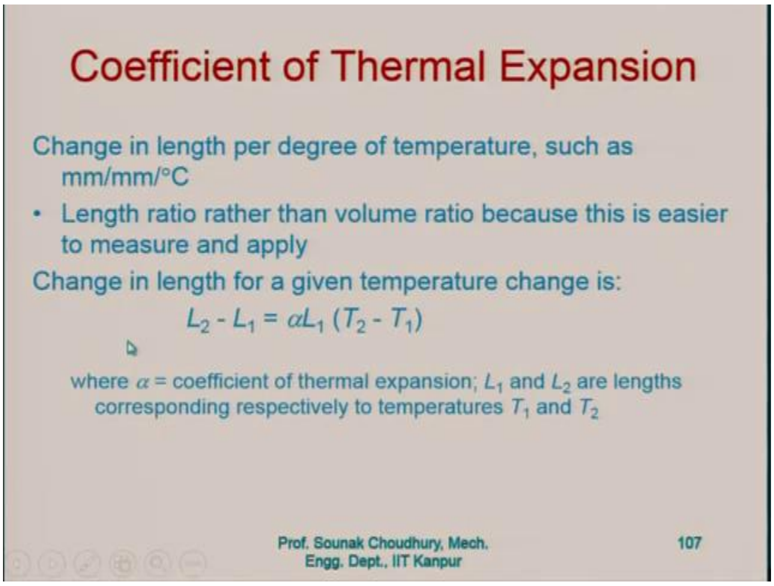

Coefficient of Thermal Expansion

Change in length per degree of temperature, such as mm/mm/°C

- Length ratio rather than volume ratio because this is easier to measure and apply

Change in length for a given temperature change is:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

where α = coefficient of thermal expansion; L_1 and L_2 are lengths corresponding respectively to temperatures T_1 and T_2

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This is the change in length for a given temperature. here is the coefficient of thermal expansion and L_1, L_2 are the lengths corresponding to the respective temperature. Let us say these are T_1 and T_2. So, these are the temperatures at which the length is L_2 at temperature T_2.

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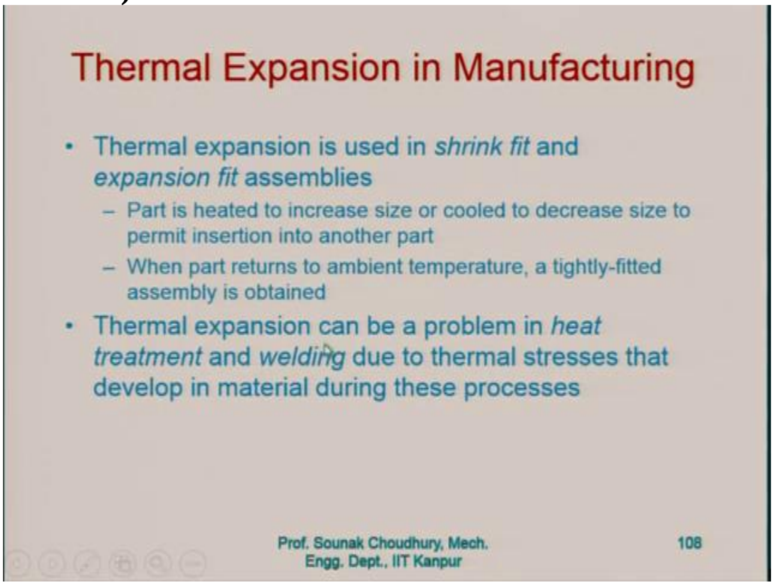

Thermal Expansion in Manufacturing

- Thermal expansion is used in *shrink fit* and *expansion fit* assemblies
  - Part is heated to increase size or cooled to decrease size to permit insertion into another part
  - When part returns to ambient temperature, a tightly-fitted assembly is obtained
- Thermal expansion can be a problem in *heat treatment* and *welding* due to thermal stresses that develop in material during these processes

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Thermal expansion in manufacturing: this is used in the shrink fit. During our discussion on fits and tolerances we will discuss it in more details. Part is heated to increase the size or cooled to decrease the size this permits the insertion into the another part.

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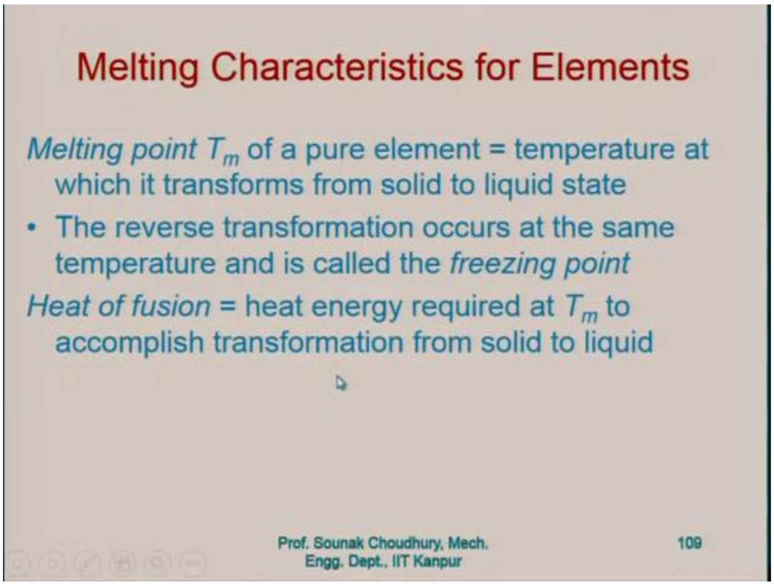

Melting Characteristics for Elements

Melting point T_m of a pure element = temperature at which it transforms from solid to liquid state

- The reverse transformation occurs at the same temperature and is called the *freezing point*

Heat of fusion = heat energy required at T_m to accomplish transformation from solid to liquid

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Melting point of a pure element is the temperature at which it transforms from solid to liquid state. Heat of fusion is the heat energy required at the melting point temperature to accomplish the transformation from solid to liquid.

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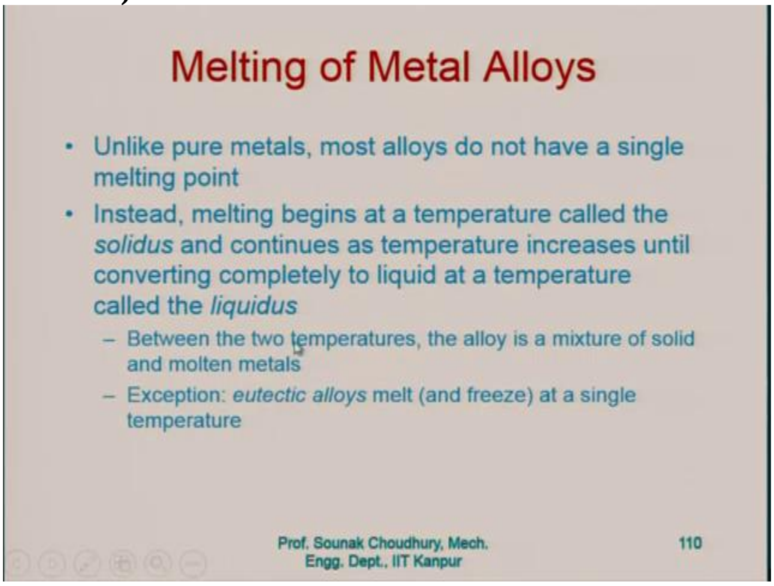

Melting of Metal Alloys

- Unlike pure metals, most alloys do not have a single melting point
- Instead, melting begins at a temperature called the *solidus* and continues as temperature increases until converting completely to liquid at a temperature called the *liquidus*
  - Between the two temperatures, the alloy is a mixture of solid and molten metals
  - Exception: *eutectic alloys* melt (and freeze) at a single temperature

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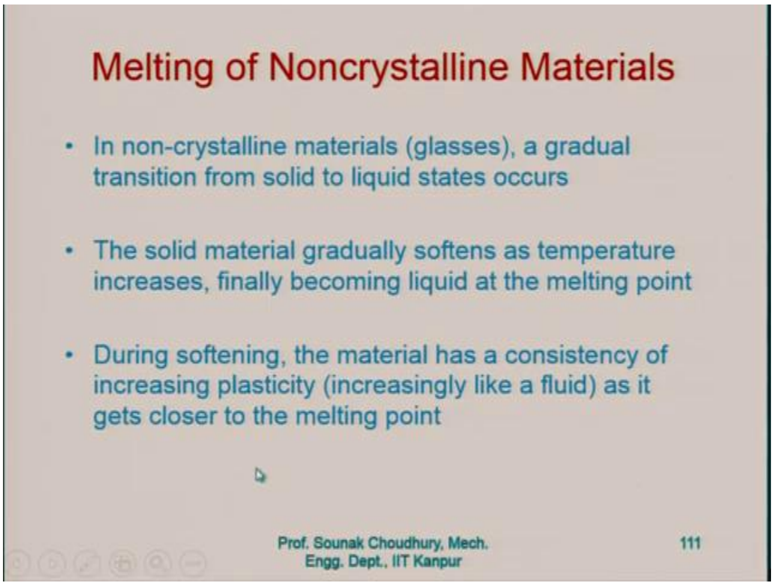

Melting of Noncrystalline Materials

- In non-crystalline materials (glasses), a gradual transition from solid to liquid states occurs
- The solid material gradually softens as temperature increases, finally becoming liquid at the melting point
- During softening, the material has a consistency of increasing plasticity (increasingly like a fluid) as it gets closer to the melting point

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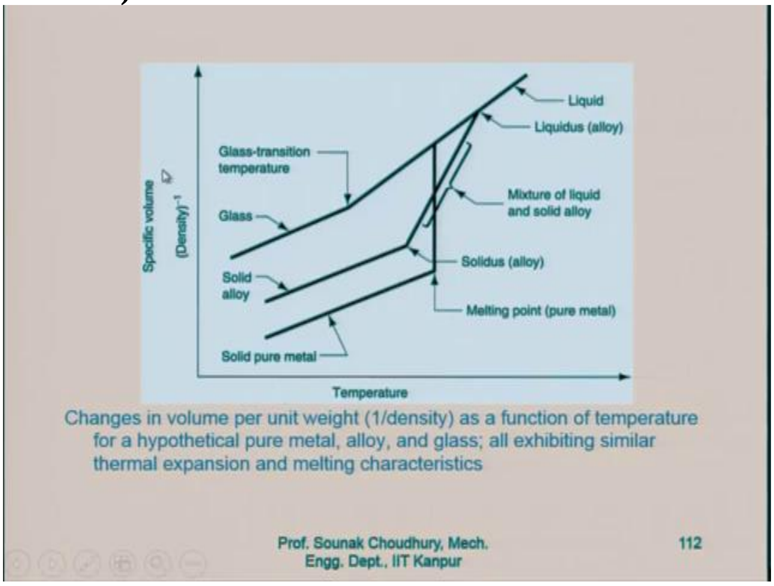

Changes in volume per unit weight (1/density) as a function of temperature for a hypothetical pure metal, alloy, and glass; all exhibiting similar thermal expansion and melting characteristics

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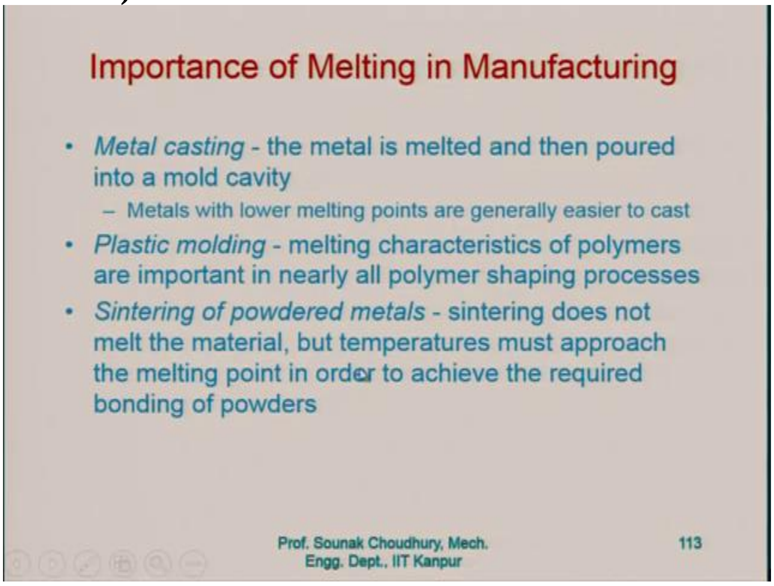

Importance of Melting in Manufacturing

- *Metal casting* - the metal is melted and then poured into a mold cavity
  - Metals with lower melting points are generally easier to cast
- *Plastic molding* - melting characteristics of polymers are important in nearly all polymer shaping processes
- *Sintering of powdered metals* - sintering does not melt the material, but temperatures must approach the melting point in order to achieve the required bonding of powders

This is melting of metal alloys, melting of non-crystalline materials. These are the simple definitions and this is the specific volume versus the temperatures shown and importance of the melting in manufacturing.

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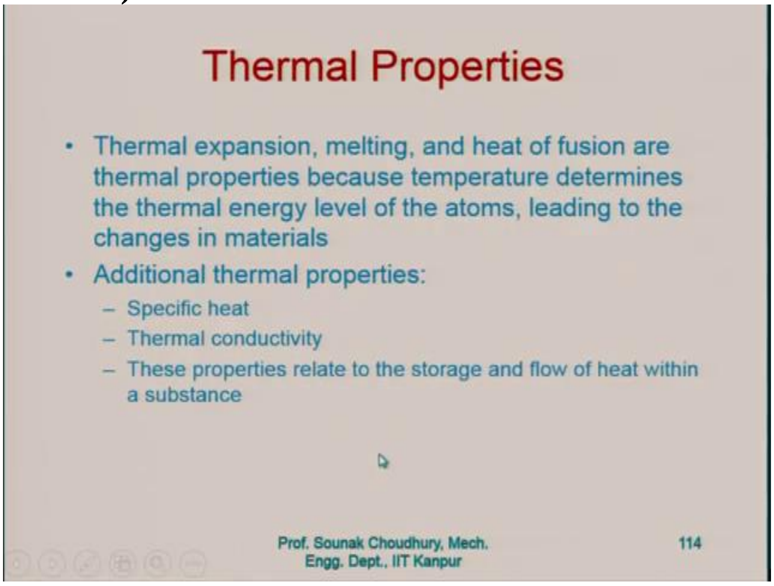

Thermal Properties

- Thermal expansion, melting, and heat of fusion are thermal properties because temperature determines the thermal energy level of the atoms, leading to the changes in materials
- Additional thermal properties:
  - Specific heat
  - Thermal conductivity
  - These properties relate to the storage and flow of heat within a substance

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The thermal properties also include specific heat, thermal conductivity and these properties relate to the storage and flow of heat within a substance. The rest of the material in this series of discussion, we will have in our next session of discussion. Thank you very much for your attention.