Production Technology: Theory and Practice
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Lecture - 02
Engineering Materials and Their Properties - 2

Welcome back to the discussion sessions. I will remind you that we were discussing in our last session the composite materials and the classification of the composite materials and we said that we have the laminar or layer composites then we have the particulate composites.

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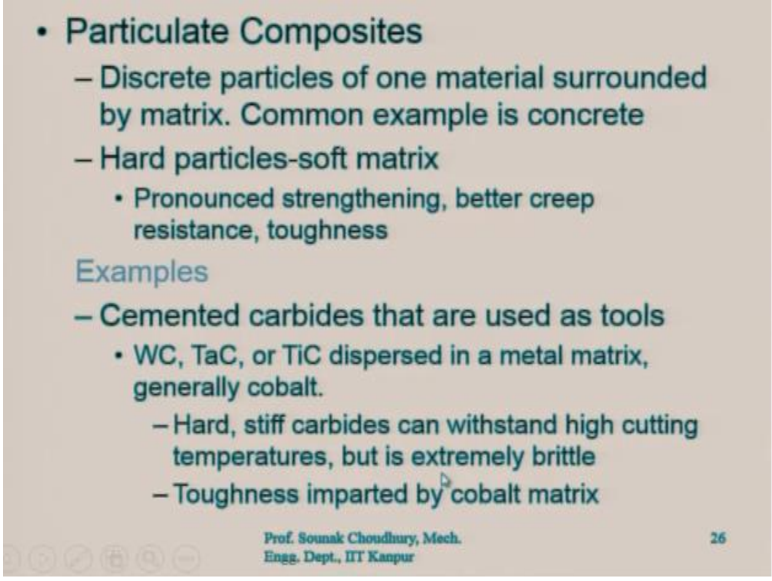

- Particulate Composites
  - Discrete particles of one material surrounded by matrix. Common example is concrete
  - Hard particles-soft matrix
    - Pronounced strengthening, better creep resistance, toughness

Examples
  - Cemented carbides that are used as tools
    - WC, TaC, or TiC dispersed in a metal matrix, generally cobalt.
      - Hard, stiff carbides can withstand high cutting temperatures, but is extremely brittle
      - Toughness imparted by cobalt matrix

Particulate composites are the discrete particles of one material surrounded by matrix and the common examples we said is the concrete, hard particles and the soft matrix this is the property pronounced strengthening, better creep resistance and the toughness. Examples are the cemented carbides that are used as tools. It is tungsten carbide, tantalum carbide or titanium carbide dispersed in the metal matrix.

Generally the cobalt is used for that kind of a metal matrix in the composite. They make very hard and stiff carbides which can withstand high cutting temperatures but they are extremely brittle and cannot withstand the shock load. Toughness is imparted by the cobalt matrix.

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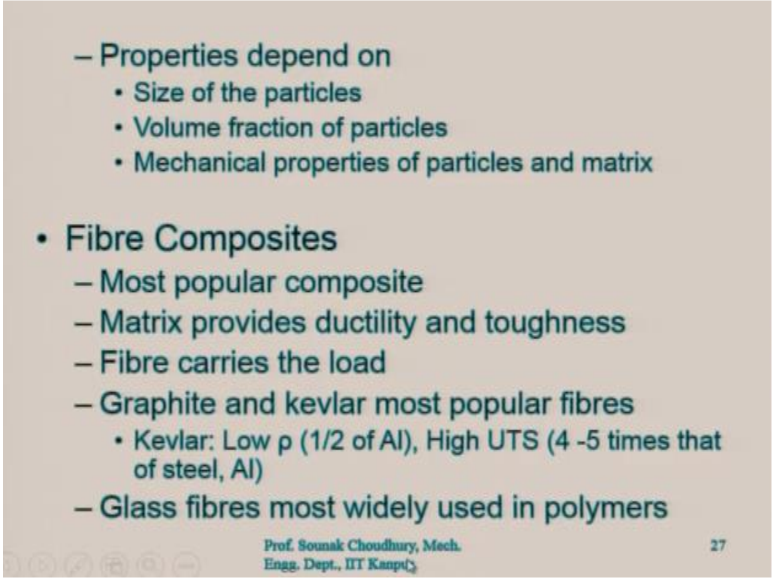

- Properties depend on
  - Size of the particles
  - Volume fraction of particles
  - Mechanical properties of particles and matrix

- Fibre Composites
  - Most popular composite
  - Matrix provides ductility and toughness
  - Fibre carries the load
  - Graphite and kevlar most popular fibres
    - Kevlar: Low ρ (1/2 of Al), High UTS (4 -5 times that of steel, Al)
  - Glass fibres most widely used in polymers

Now, I also discussed this in the last session that those properties depend on the size of the particles, volume fraction of particles and the mechanical properties of the particles and the matrix. And also I mentioned that the mechanical properties of the composite may not be the same as the properties of the particles and the matrix like in case of a solution. Now, next is the fibre composites, fibre composites are most popular composites, matrix provides ductility and toughness while the fibre carries the load.

So, in the fibre composites there are fibres of different materials and the matrix of different materials. Now, those matrices provide the ductility and the toughness and the load is carried by the fibres. Graphite and Kevlar are the most popular fibres, fibres are made of graphite and the Kevlar. Kevlar is the low density almost half of the aluminium having high ultimate tensile strength.

This is 4 to 5 times that of the steel that is very important or the aluminium. So, ultimate tensile strength particularly is important for the engineering materials and when it is more than steel by 4 to 5 times it is extremely important. Therefore, those kinds of composites are used in our field of mechanical engineering as tools and also for machining. For example, glass fibres most widely used in the polymers. Here we have the fibres as the graphite and the Kevlar, but the glass fibres are used in the polymers.

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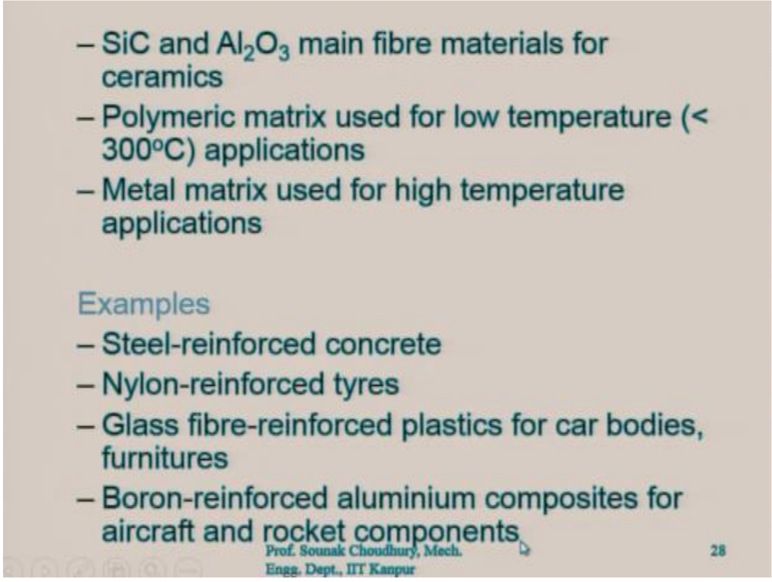

- SiC and Al_2O_3 main fibre materials for ceramics
- Polymeric matrix used for low temperature (< $300^{o}C$) applications
- Metal matrix used for high temperature applications

Examples

- Steel-reinforced concrete
- Nylon-reinforced tyres
- Glass fibre-reinforced plastics for car bodies, furnitures
- Boron-reinforced aluminium composites for aircraft and rocket components

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Silicon carbide and aluminium oxide are the main fibre materials for the ceramics by the way polymeric matrix used for the low temperature that is for the 300^0C when it is the polymeric matrix because otherwise they will melt but the metal matrix is also used for the high temperature applications when the temperature goes beyond 500, 600^0C.

There of course, the polymeric matrix cannot be used because they have low melting temperature melting point. Examples are the steel reinforced concrete that is the concrete where we have the steel rods in between. Nylon reinforced tyres, automobile tyres which have the nylons and they have the very thin metallic wires, they are reinforced.

Glass fibre reinforced plastics for car bodies furniture: those are the glass fibres. Boron reinforced aluminium composites for aircraft and the rocket components. Here we need the high temperature resistance. So, there the boron reinforced aluminium composites are used.

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- Sporting equipment such as tennis rackets, skis, fishing rods

Properties depend on

- Properties of fibres
- Volume fraction of fibres
- Aspect ratio of fibres
- Orientation of fibres
- Degree of bonding between matrix and fibres
- Properties of matrix

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Sporting equipment such as tennis rackets, skis, fishing rods - they need to have the highest strength; fishing rods need to have the fatigue resistance, they are bent many times so they cannot have the brittleness. Properties depend on the properties of the fibres, volume fraction of fibres, aspect ratio of fibres, orientation of fibres, i.e. in which way it is oriented.

So, initially we discussed that the strength and the required properties are obtained by different orientations of the fibre. We said that the properties depend on the orientation of fibres, and the degree of bonding between matrix and fibres how well they are bound properties of matrix. So, properties of fibres, properties of matrix, and how the volume fraction is made, what is the aspect ratio of the fibres orientation and so on. Now, let us see the properties of all those materials that we have discussed so far.

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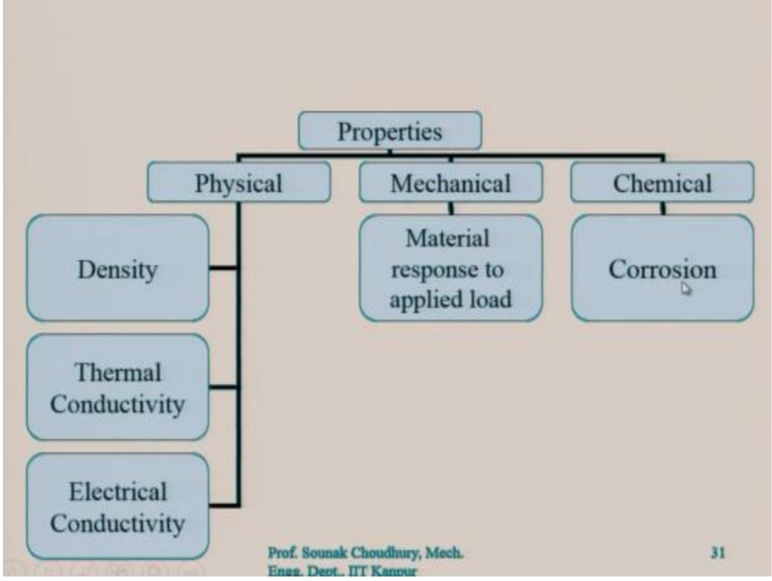

Properties

Physical

Mechanical

Chemical

Density

Thermal Conductivity

Electrical Conductivity

Material response to applied load

Corrosion

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Materials should have certain properties like physical, mechanical or chemical. The properties can be sub-categorised as the physical property, mechanical property or chemical property. In the physical property, we have the properties like density, thermal conductivity, electrical conductivity. In mechanical properties, we have the material response to the applied load bending, stress, strain and so on. In chemical properties there is corrosion, and many more, which we will look into details from now on.

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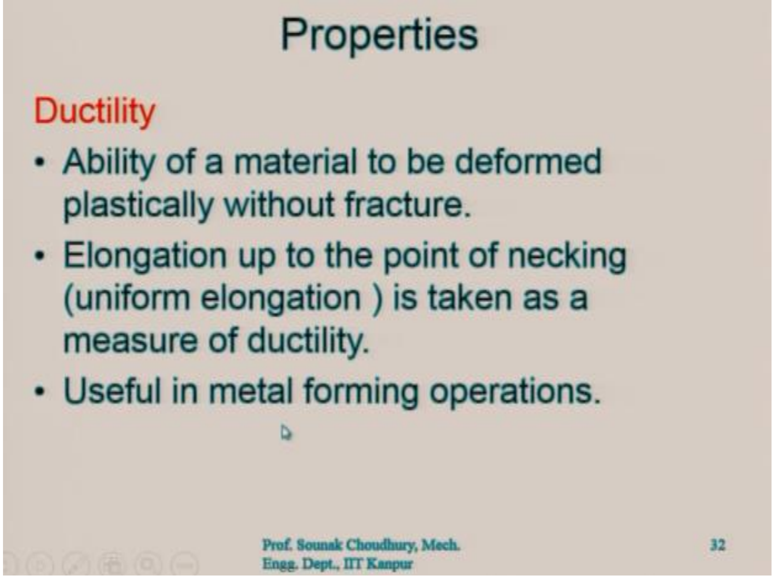

Properties

Ductility

- Ability of a material to be deformed plastically without fracture.
- Elongation up to the point of necking (uniform elongation) is taken as a measure of ductility.
- Useful in metal forming operations.

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Ductility: Mainly those properties we will discuss here, which are important in the field of engineering, particularly in the field of mechanical engineering. When we are designing the part, when you are using the material for the tools etc. So, we will be discussing those properties that are required and that are most popularly used in case of design and manufacturing .

Ductility: ductility is the ability of material to be deformed plastically without fracture. This I have shown it to you in the stress strain curve that it can actually go beyond the yielding point, those are the ductile materials like mild steel for example, whereas, the cast iron as the brittle material cannot go beyond that point, beyond the elastic range. It cannot have the plastic deformation. So, those materials which have the ability to be deformed plastically without being fractured, they are the ductile materials.

So, the ductility is defined by that elongation up to the point of naking, that is the uniform elongation is taken as a measure of ductility. How it is measured? This is how much it has been elongated, up to that necking point. Necking point is when the material is tested, you remember there is an ultimate tensile stress when you are testing or measuring - there you are actually pulling on both sides of the specimen and after some time there is a localised deformation and that localised deformation is the necking.

So, the elongation up to the point of necking and where it is uniform elongation of course, this is the measure of the ductility. This is useful in metal forming operation. There we have to have the ductile metal for the forming operation otherwise it will break; not only it will break, what will happen is that in the case of hot forming for example, the material is heated up so that the ductility becomes more, so that it can be easily formed. Therefore, we are saying that this ductility property is useful in the metal forming operation particularly.

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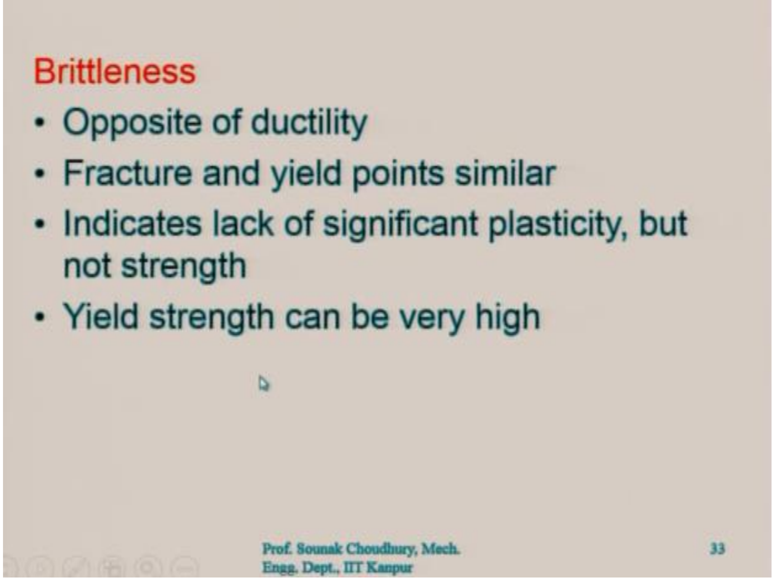

Brittleness

- Opposite of ductility
- Fracture and yield points similar
- Indicates lack of significant plasticity, but not strength
- Yield strength can be very high

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Brittleness: brittleness is opposite to ductility in the sense that those materials which will be ductile materials, they will not have the brittleness and vice versa. Brittle materials are not ductile materials, let us say not have the ductility, the cast iron for example, you cannot have its plastic deformation as I said. So, they are brittle materials for which fracture and yield points are similar.

Because they cannot go beyond the fracture indicating lack of significant plasticity but not strength, strength is high but due to lack of plasticity they cannot go beyond this point - it fractures. However, yield strength can be very high. This is one good property of those brittle materials that although they will not have the ductility, but they will have a very high yield strength for which those materials are also used in particular fields where the high yield strength is required.

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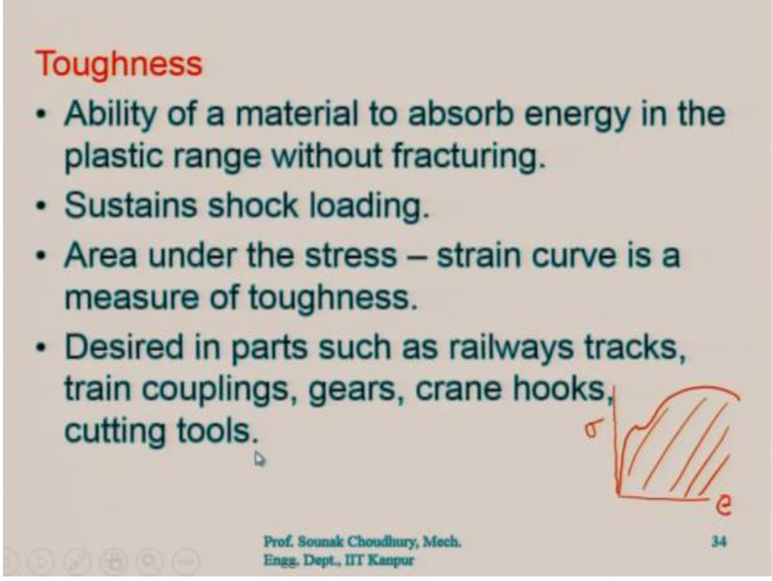

Toughness

- Ability of a material to absorb energy in the plastic range without fracturing.
- Sustains shock loading.
- Area under the stress – strain curve is a measure of toughness.
- Desired in parts such as railways tracks, train couplings, gears, crane hooks, cutting tools.

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Toughness: toughness is the ability of a material to absorb energy in the plastic range without fracturing in the plastic range. So, this is the absorbing energy, means that it will actually withstand shocks, sustains shock loading. It will absorb shock loading, that energy and it will not break, it will not fracture. The area under the stress strain curve is a measure of toughness.

Recall the stress strain curve that has been shown to you earlier. Along the Y-axis is the stress, and along the X-axis is the strain. Let us say it is ductile material. So, it will be something like this if this is the stress, so, this area under this curve, this is actually the measure of the toughness. This property of metarial is desired in parts such as railways track, train coupling, gears, crane hooks, cutting tools.

When the train moves at a very high speed it will have the shock loads, i.e. the fluctuation in the force, fluctuation in the load which is imparted on that train coupling. Similarly, gears will have tremendous shock loading when the gear teeth are engaging or disengaging, crane hooks or the cutting tools and so on. So, there the toughness property is very much required.

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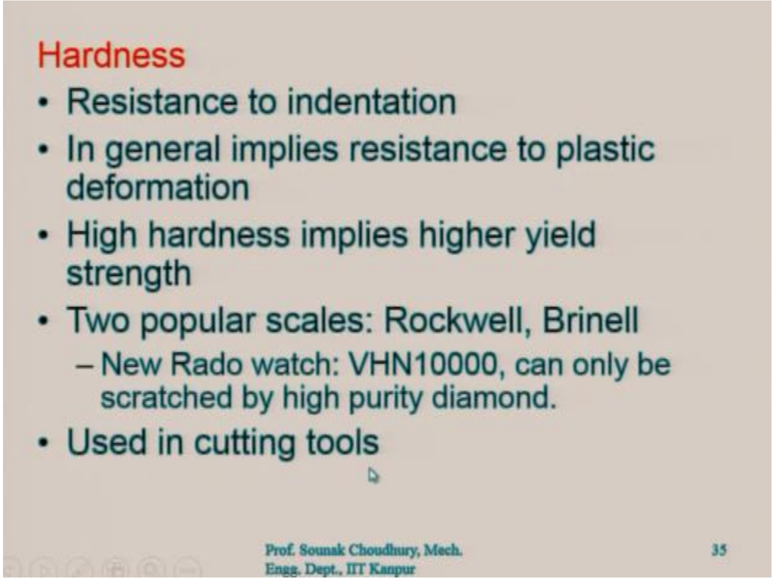

Hardness

- Resistance to indentation
- In general implies resistance to plastic deformation
- High hardness implies higher yield strength
- Two popular scales: Rockwell, Brinell
  - New Rado watch: VHN10000, can only be scratched by high purity diamond.
- Used in cutting tools

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Hardness is the resistance to indentation. When you cannot make any indentation, you cannot make a hole very easily or indentation on the material then we say that that has a very high hardness. Now, normally those materials which are brittle materials are also very hard. In general, hardness implies the resistance to plastic deformation that means, the hardness is overall plastic deformation when it resists those then it is harder. High hardness implies higher yield strength.

The hardnes can be very high for brittle materials. Cast iron is very brittle but its yield strength will be very high. So, the high hardness implies higher yield strength. Two popular scales are used to measure the hardness - Rockwell scale and Brinell scale.

New Rado watch is an example that this watch cover glass is scratch proof material. So the hardness has to be very high. Cutting tool materials have high hardness.

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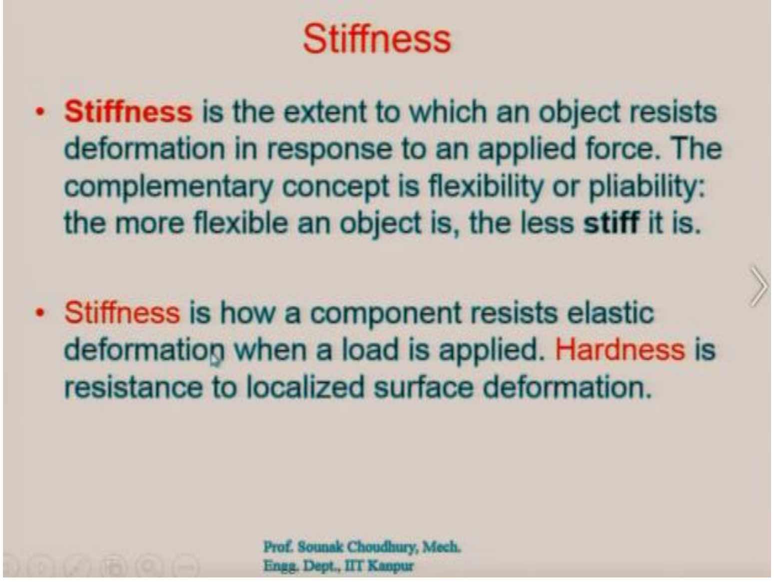

Stiffness

- **Stiffness** is the extent to which an object resists deformation in response to an applied force. The complementary concept is flexibility or pliability: the more flexible an object is, the less **stiff** it is.
- Stiffness is how a component resists elastic deformation when a load is applied. Hardness is resistance to localized surface deformation.

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Stiffness: stiffness is the extent to which an object resists deformation in response to an applied force. The complimentary concept of flexibility is pliability. The more flexible an object the less stiff it is. So, you can understand from this what is the stiffness. That means overall when the load is applied the deformation will be less. Those materials we call as stiff materials meaning that the material is difficult to bend.

So, the stiffness is how a component resists elastic deformation when a load is applied. In this curve, this is the elastic deformation and after that it is the plastic deformation. What we are saying is that, a component resists elastic deformation when a load is applied; hardness is resistance to localized surface deformation.

There is a very little difference between the stiffness and the hardness and you have to really distinguish the hardness from the stiffness. Once again, the stiffness is a component resistance to the elastic deformation when a load is applied. Hardness is the localized surface deformation resistance. When the material or the part is resisting to the localized surface deformation then it is the hardness.

So, hardness and stiffness are not the same. This is not to be confused.

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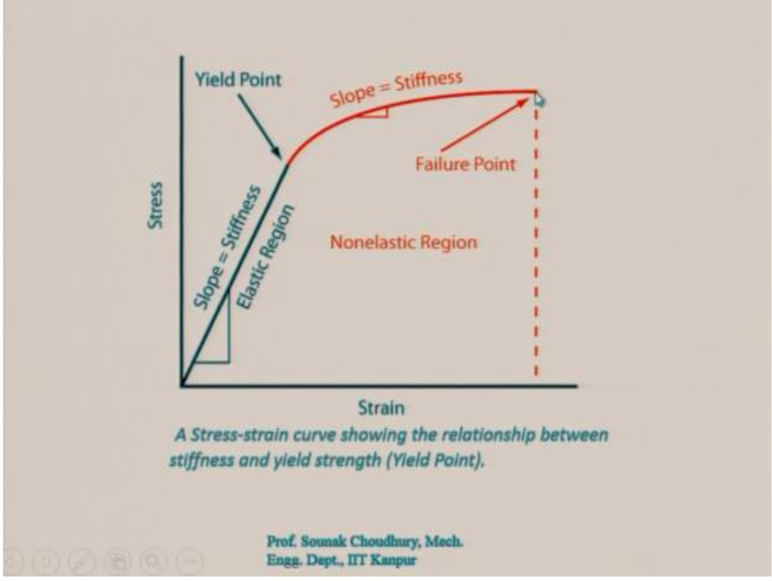

A Stress-strain curve showing the relationship between stiffness and yield strength (Yield Point).

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This is the stress-strain curve, along the y axis we have the stress, and along the x axis we have the strain. Stress-strain curve shows the relationship between the stiffness and the yield strength. This is the yield point; after that the plastic deformation starts here this is the elastic region. So, if you remember stiffness is the extent to which an object resists deformation in response to an applied force.

This is the elastic deformation when a load is applied, how the component resists is the stiffness. So, that is what we said that here the slope in the elastic region is the stiffness. And beyond that yield point is the plastic region and here the slope is the stiffness, this slope is the stiffness here, this is the non elastic region and here it can actually fail. Endpoint is here.

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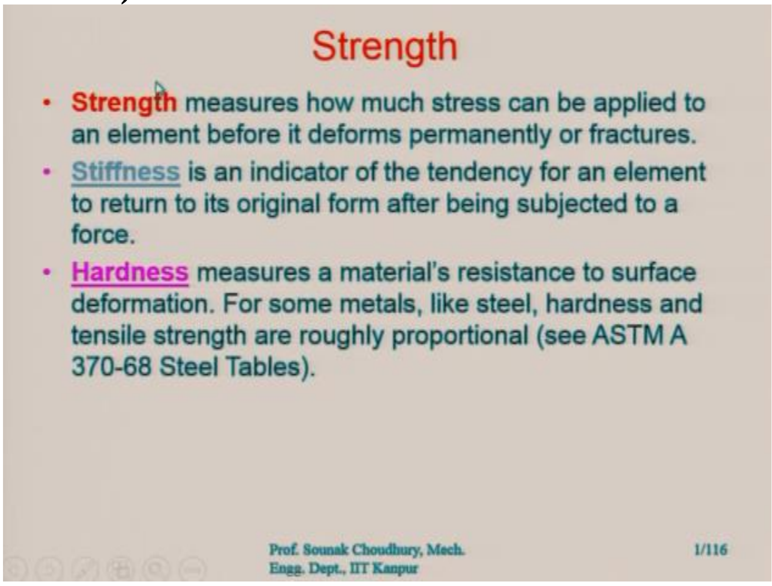

Strength

- **Strength** measures how much stress can be applied to an element before it deforms permanently or fractures.
- **Stiffness** is an indicator of the tendency for an element to return to its original form after being subjected to a force.
- **Hardness** measures a material's resistance to surface deformation. For some metals, like steel, hardness and tensile strength are roughly proportional (see ASTM A 370-68 Steel Tables).

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Now, the strength is measured by the amount of stress that can be applied to an element before it deforms permanently or fractures. This is the strength of material. That means it is the measurement of how stress can be applied before it deforms permanently. Stiffness is an indicator of the tendency of an element to return to its original form after being subjected to a force.

So, how much it is subjected to, I mean how much it can come back to this that is the indicator of the tendency of an element to return to its original form after being subjected to a force. Hardness measures materials resistance to surface deformation, we said earlier, I am repeating again so that you could understand the difference between the strength, stiffness and hardness.

These three concepts are different and these three definitions are put together here so that you would understand. Once again, the hardness is a measure of materials resistance to surface deformation. For some metals like steel, hardness and tensile strength are roughly proportional. American Society of the Steel has the table from where you can find out the actual values. So, this is the difference between strength, stiffness and hardness, and the definitions are noted down here.

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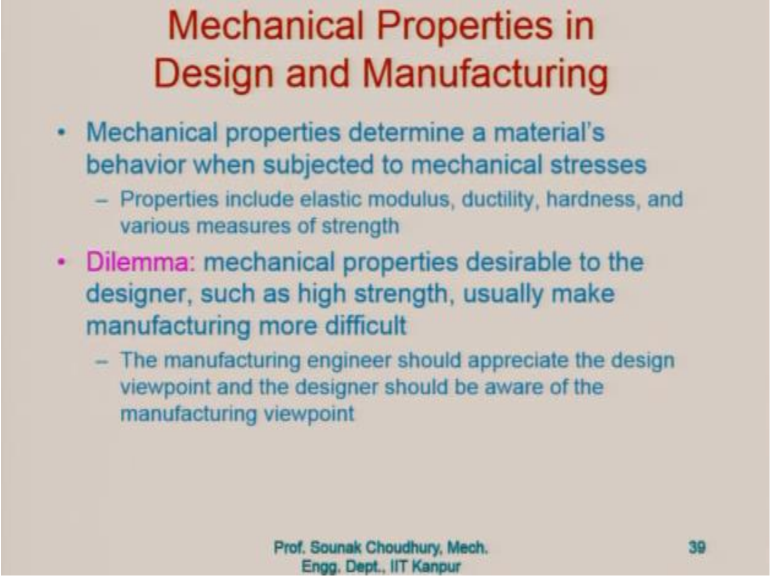

Mechanical Properties in Design and Manufacturing

- Mechanical properties determine a material's behavior when subjected to mechanical stresses
  - Properties include elastic modulus, ductility, hardness, and various measures of strength
- Dilemma: mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult
  - The manufacturing engineer should appreciate the design viewpoint and the designer should be aware of the manufacturing viewpoint

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Mechanical properties in design and manufacturing: mechanical properties determine a material behaviour when subjected to mechanical stresses. Properties include elastic modulus, ductility, hardness and various measures of strength. Here the dilemma becomes that mechanical properties, desirable to the designer such as strength usually make manufacturing more difficult, what we mean to say is that there is a concept of machinability which indicates the ease of machining.

Now, when you are designing a part you are also selecting the material. If the material has poor machinability, it is difficult to machine. For the designer it is easy to you know, and select that material because he needs particular properties for that. But for the manufacturer, it is very difficult to machine that particular part. So, the designer can actually have a substitute, if it is possible at all, of that material, instead of selecting the low machinability material.

He can select a substitute which will have reasonably good machinability so that it could be easier for the manufacturer to produce that part. This is the concept which is known as the design for manufacturability. That means, you have to design in such a way that the part can be manufactured in a proper way, it can be manufactured easily. There are certain features in the design that are created by the designer.

But those features are extremely difficult to manufacture. Now, it is up to the designers to substitute or change those features in the design so that it could be manufactured properly, and the designer can do that. So, then we say that designer is improving the manufacturability. The design should always be for manufacturability because ultimately the design will not remain on the paper, design will be manufactured. If you are designing a part, that part has to be manufactured.

So, you have to always understand that whatever you are designing, it should be easy for manufacturing, there should not be any conflicting feature in the drawings or in design parameters. That is the dilemma that mechanical properties desirable for the designer, high strength for example, that is very difficult to manufacture.

As I said, the manufacturing engineer should appreciate the design viewpoint and the designer should be aware of the manufacturing viewpoint similarly. So, this is in both way; as I was telling you that design should be for manufacturability at the same time the manufacturers should understand the designers as well.

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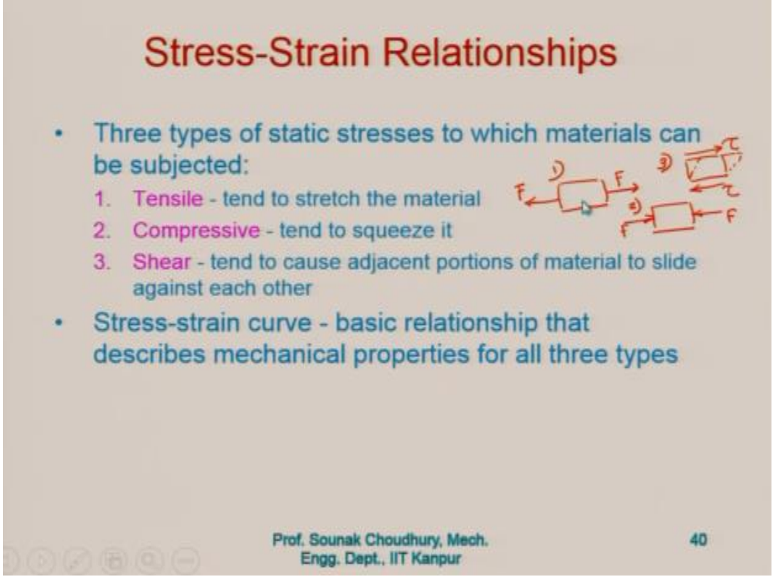

Stress-Strain Relationships

- Three types of static stresses to which materials can be subjected:
  1. Tensile - tend to stretch the material
  2. Compressive - tend to squeeze it
  3. Shear - tend to cause adjacent portions of material to slide against each other
- Stress-strain curve - basic relationship that describes mechanical properties for all three types

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Stress-stain relationship: There are three types of static stresses to which materials can be subjected. These are the tensile stress, tending to stretch the material, compressive stress tending to squeeze it, and the shear. So, overall, what you can say is that this is the tensile, when this force is applied here, now, when the force is trying to compress, this will create the compressive stress.

And if it is shearing, the force acts like this. This is the third case, shear is the first case, this is the second case, these are the forces acting. And this is the shear stress or the shear force. Now, shear tends to cause adjacent portions of materials to slide against each other. It means that it will elongate if the forces are applied like that, and it will be squizzed if the forces are applied this way.

These portions try to slide against each other. This is the stress strain curve, basic relationship that describes mechanical properties for all these three types, i.e. what are the mechanical properties when it is a tensile stress or it is a compressive stress or it is a shear stress?

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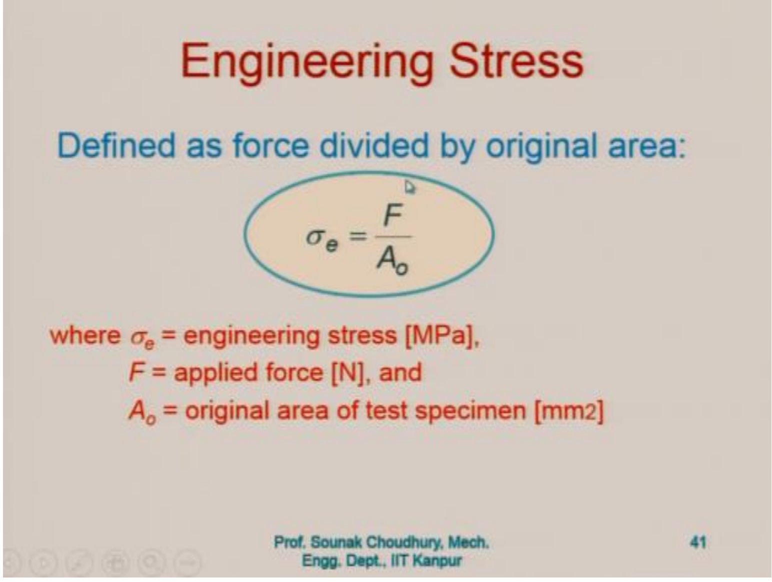

Engineering Stress

Defined as force divided by original area:

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

where σ_e = engineering stress [MPa],

F = applied force [N], and

A_o = original area of test specimen [mm2]

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Engineering stress is defined as force divided by original area. This is the engineering stress. It is measured in the mega Pascal (MPa) this is the force applied measured in the unit of Newton (N) and the original area of the test specimen is given in the millimetre square (mm^2). So, force upon area.

In case of engineering stress, this is the force applied by the original area of that test specimen. I will discuss later the difference between engineering stress and different other stresses.

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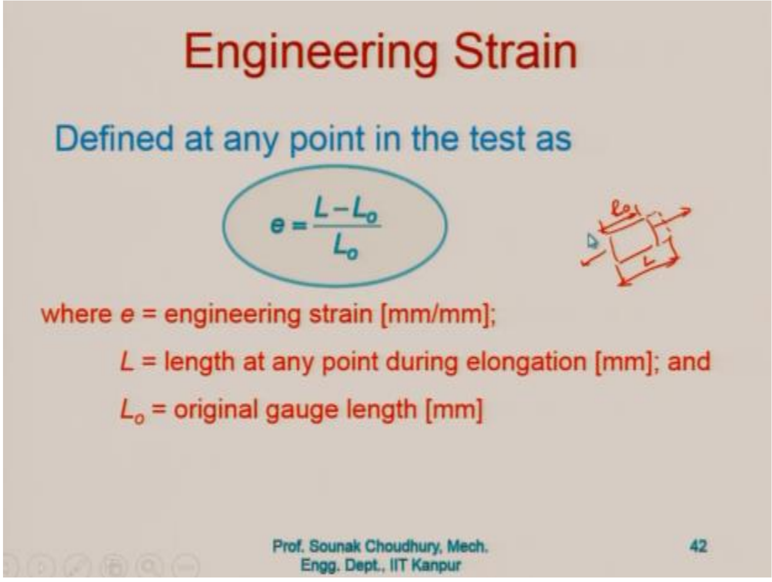

Engineering Strain

Defined at any point in the test as

$$e = \frac{L - L_o}{L_o}$$

where e = engineering strain [mm/mm];

L = length at any point during elongation [mm]; and

L_o = original gauge length [mm]

Engineering strain therefore, is defined at any point in the test as $\left(\frac{L-L_0}{L_0}\right)$, L_0 is the original gauge length and after the elongation the L_0 has become L, it has been elongated. Suppose this is L_0 and this is L after being elongated. So, this is the engineering strain.

It is dimensionless because $(L-L_0)$ is in millimetre divided by the original gauge length which is also in millimetre. Oce again, this is the original length, this is the length after the elongation and the engineering strain is given by the difference between them $(L-L_0)$ divided by the L_0 which is the initial gauge length.

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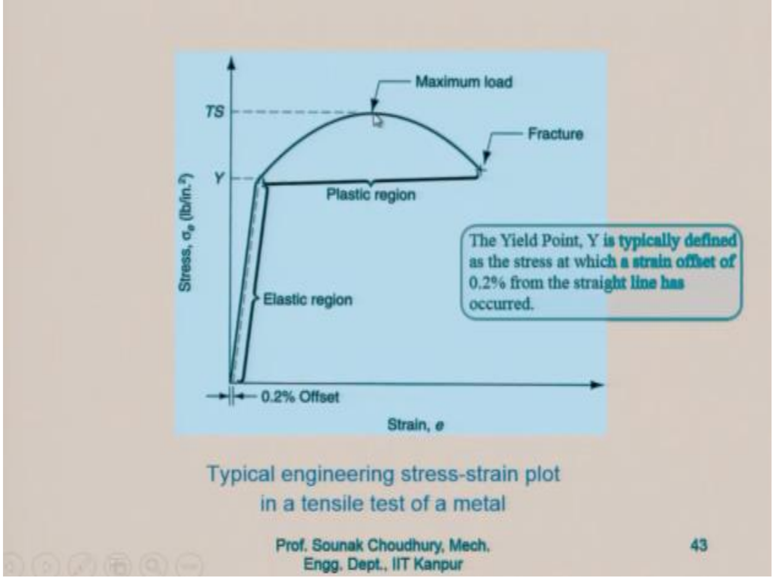

The Yield Point, Y is typically defined as the stress at which a strain offset of 0.2% from the straight line has occurred.

Typical engineering stress-strain plot in a tensile test of a metal

If you see this here, this is the stress strain curve, this is a very popular stress strain curve you must have seen and you must have studied that in some of your courses. This is the stress strain curve for material which is not brittle because the stress-strain curve for the brittle material obviously will be different.

Here, along the Y-axis we have the stress, and along the X- axis we have the strain. Now, the stress is given here in the American system, it is given in $\left(\frac{lb}{in^2}\right)$. We use $\left(\frac{kg}{cm^2}\right)$or $\left(\frac{N}{m^2}\right)$. Strain is the dimensionless because it is $\left(\frac{mm}{mm}\right)$.

So, here as the strain is applied, the stress increases proportionally. This is the friction force and this is the normal force. When the normal force is applied, the friction force increases. Similarly, when the strain increases, the stress increases proportionally to a certain level which we call as the elastic region.

After that elastic region the yielding starts and the material no longer remains in the elastic state and the plastic deformation starts. So, here what happens is that, in this elastic region after that yielding starts there is about 0.2% of offset between these points, from here and this actual curve, this is the offset which is about 0.2% then it goes to the plastic state; the curve will be like this.

The entire area is the plastic region, it will indicate the maximum load and sometimes after that the stress strain curve goes in this way and it fractures. How to define the yield point here? The yield point Y as it is written here as you can see from this slide is typically defined as the stress at which a strain offset of 0.2% from the straight line has occurred.

So, this is the exact identification of the yield point that it has to be 0.2% offset from this straight line that is in the elastic region and that will actually define where is the yield point and as I said that after the yield point it goes in a nonlinear way and maximum load occurs in the plastic region, then the necking occurs and it becomes unstable and at any point after the maximum load, the fracture occurs.

Fracture is basically the segregation of the material from the body. So, this is important to understand in case of machining particularly because in machining we actually segregate the excess material from the work piece and that excess material to be segregated as per this principle in case that material is of course, ductile material. In case of brittle material, it breaks in here. It does not go to the yield point, because it is a brittle material like cast iron for example.

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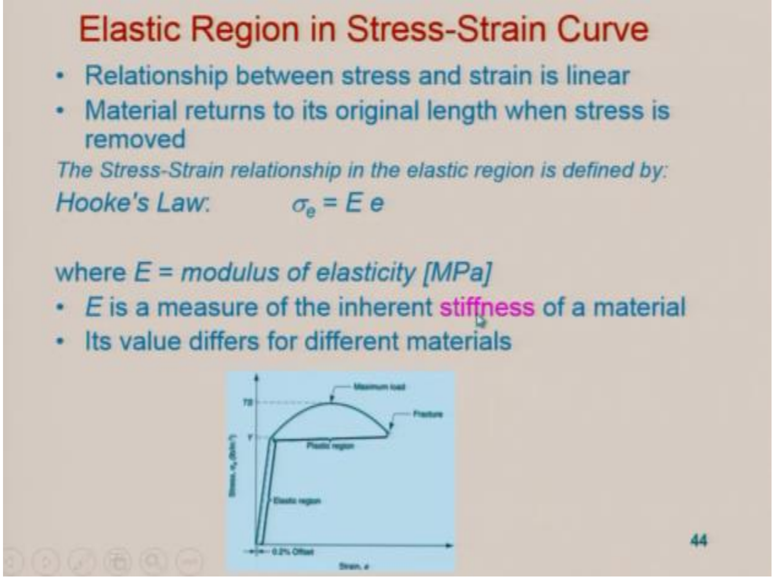

Elastic Region in Stress-Strain Curve

- Relationship between stress and strain is linear
- Material returns to its original length when stress is removed

The Stress-Strain relationship in the elastic region is defined by:

Hooke's Law: $\sigma_e = E e$

where *E = modulus of elasticity [MPa]*

- *E* is a measure of the inherent stiffness of a material
- Its value differs for different materials

Elastic region in stress strain curve: here the relationship between stress and strain is linear. So, the stress goes proportional to the strain. Second property is that the material returns to its original length when stress is removed.

So, material is deformed and that deformation may come back to the initial position, will come back to the initial position in case the strain is removed. These are the properties in the elastic region. The stress-strain relationship in the elastic region is defined by the Hooke's law as many of you might be knowing, the stress is proportional to E, that is the strain.

So, that stress is equal to a constant multiplied by E and this constant as you understand is the slope of this line which is called the modulus of elasticity and this slope is measured in a MPa unit. E, Young's modulus is a measure of the inherent stiffness of a material, its value differs for different materials like mild steel, we will have something alloy steel will have something else and so on. That depends on the material stiffness particularly.

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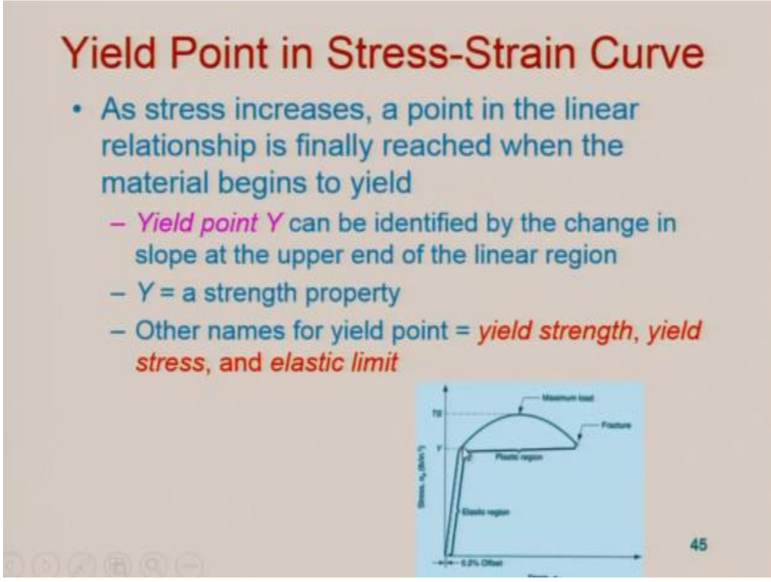

Yield Point in Stress-Strain Curve

- As stress increases, a point in the linear relationship is finally reached when the material begins to yield
  - *Yield point Y* can be identified by the change in slope at the upper end of the linear region
  - *Y* = a strength property
  - Other names for yield point = *yield strength*, *yield stress*, and *elastic limit*

Yield point: here once again, I will repeat that when it is 0.2% offset from the straight line. As stress increases, a point in the linear relationship is finally reached. In this linear relationship, a point finally reaches when the material begins to yield, yield point Y can be identified by the change in the slope. Since this is going in the other way, the slope does not remain the same as in case of the elastic region and the slope changes.

Therefore, the endpoint can be identified by the change in the slope at the upper end of the linear region. So, at this the slope will be different than in here. Why that yield point is a strength property? Meaning that yield point varies the location of the yield point varies between the materials of different strength. Yield point also indicates yield strength, it is also called yield stress also this called elastic limit, meaning that up to that point, the material is still elastic.

After this point the material deformation begins as a plastic deformation. Therefore, that yield point is also called as the yield strength of the material because this as I said is the strength property, yield point is a strain property of the material and different materials with different strains will have different location of the yield point this we have to understand and also it is called the yield stress or the elastic limit.

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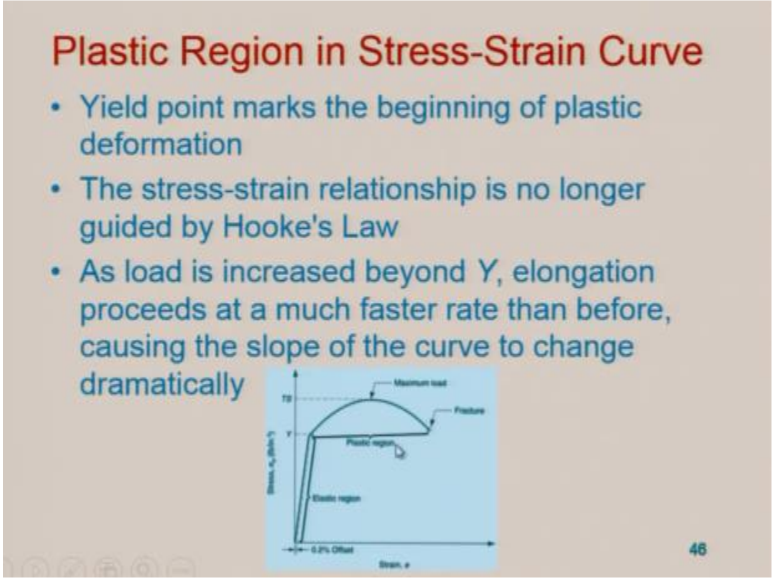

Plastic Region in Stress-Strain Curve

- Yield point marks the beginning of plastic deformation
- The stress-strain relationship is no longer guided by Hooke's Law
- As load is increased beyond *Y*, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically

Now, in the plastic regionof the stress-strain curve, yield point marks the beginning of the plastic region because below this point is the elastic deformation and beyond this point is the plastic deformation. Therefore, this is the yield point which is the beginning of the plastic deformation or the end of the elastic deformation.

Although, the stress strain relationship is then no longer guided by the Hooke’s law, because in the Hooke’s law which is applied in this region the stress is proportional to strain and it is a straight line. Therefore, the Hooke’s law which says the stress is equal to the Young's modulus and the strain that no more remains valid in the plastic region as load is increased beyond Y beyond this yield point elongation proceeds at a much faster rate, as you can see that it goes in a nonlinear way.

It goes at a faster rate than before causing the slope of the curve to change dramatically. Here at each point, you can see that the slope of the curve is changing; here the stress upon strain was constant, that is stress was proportional to strain and in this region it does not remain that way, that is stress is not any more proportional to strain in the plastic region.

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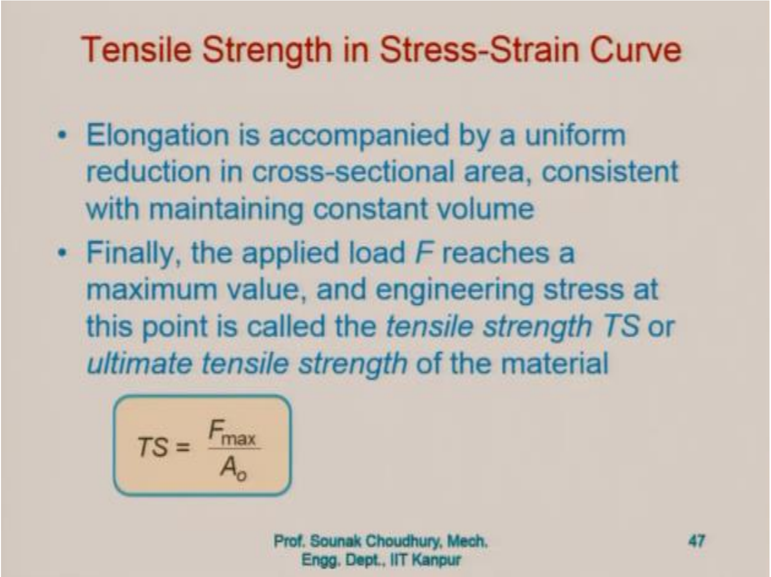

Tensile Strength in Stress-Strain Curve

- Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume
- Finally, the applied load *F* reaches a maximum value, and engineering stress at this point is called the *tensile strength TS* or *ultimate tensile strength* of the material

$$TS = \frac{F_{max}}{A_o}$$

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Tensile strength in the stress strain curve: elongation is accompanied by a uniform reduction in the cross-sectional area, consistent with maintaining the constant volume, because volume has to be constant. So, in the cross-sectional area, there is a uniform reduction as the elongation happens in the plastic region. Finally, the applied load F reaches a maximum value, this is the maximum value of the load that is being applied.

Engineering stress at this point is called the tensile strength. At this point whatever will be the engineering stress this is the tensile stress, tensile strength or ultimate tensile strength of the material. So, the tensile strength will be defined by the maximum of this force that is applied divided by the A_0 and A_0 is the original area of the test specimen because we are defining the engineering stress.

So, the ultimate tensile strength or the tensile strength in short as it is called, is the maximum force that has been applied divided by the original cross-sectional area.

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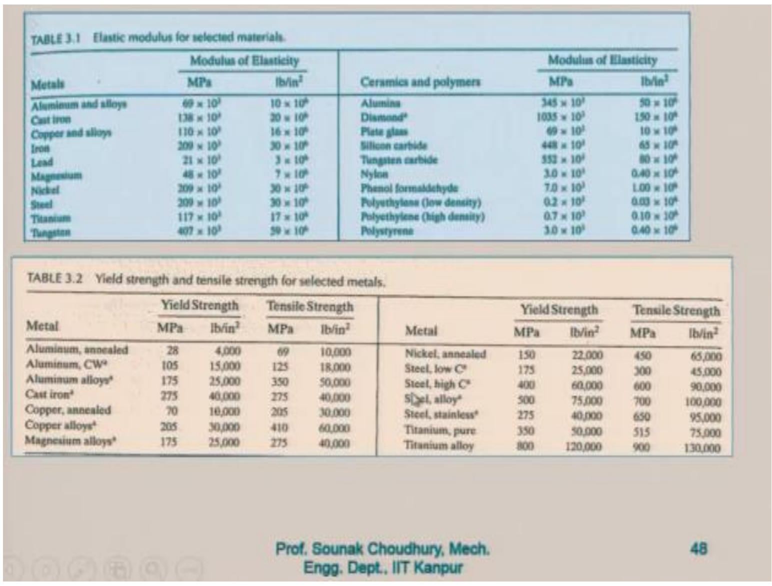

TABLE 3.1 Elastic modulus for selected materials.

Metals	Modulus of Elasticity		Ceramics and polymers	Modulus of Elasticity	
	MPa	lb/in^2		MPa	lb/in^2
Aluminum and alloys	69×10^3	10×10^6	Alumina	345×10^3	50×10^6
Cast iron	138×10^3	20×10^6	Diamond[a]	1035×10^3	150×10^6
Copper and alloys	110×10^3	16×10^6	Plate glass	69×10^3	10×10^6
Iron	209×10^3	30×10^6	Silicon carbide	448×10^3	65×10^6
Lead	21×10^3	3×10^6	Tungsten carbide	552×10^3	80×10^6
Magnesium	48×10^3	7×10^6	Nylon	3.0×10^3	0.40×10^6
Nickel	209×10^3	30×10^6	Phenol formaldehyde	7.0×10^3	1.00×10^6
Steel	209×10^3	30×10^6	Polyethylene (low density)	0.2×10^3	0.03×10^6
Titanium	117×10^3	17×10^6	Polyethylene (high density)	0.7×10^3	0.10×10^6
Tungsten	407×10^3	59×10^6	Polystyrene	3.0×10^3	0.40×10^6

TABLE 3.2 Yield strength and tensile strength for selected metals.

Metal	Yield Strength		Tensile Strength		Metal	Yield Strength		Tensile Strength	
	MPa	lb/in^2	MPa	lb/in^2		MPa	lb/in^2	MPa	lb/in^2
Aluminum, annealed	28	4,000	69	10,000	Nickel, annealed	150	22,000	450	65,000
Aluminum, CW[a]	105	15,000	125	18,000	Steel, low C[a]	175	25,000	300	45,000
Aluminum alloys[a]	175	25,000	350	50,000	Steel, high C[a]	400	60,000	600	90,000
Cast iron[a]	275	40,000	275	40,000	Steel, alloy[a]	500	75,000	700	100,000
Copper, annealed	70	10,000	205	30,000	Steel, stainless[a]	275	40,000	650	95,000
Copper alloys[a]	205	30,000	410	60,000	Titanium, pure	350	50,000	515	75,000
Magnesium alloys[a]	175	25,000	275	40,000	Titanium alloy	800	120,000	900	130,000

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Here these are the tables just for your understanding that these are the elastic modulus values E that is also called the elastic modulus or the modulus of elasticity. For example, you can compare the modulus of elasticity of aluminium and alloys this is in mega Pascal, cast iron is more as you can see, in comparison to cast iron and copper and alloys have less modulus of elasticity, but it is still more than the aluminium and the alloys as you can see here.

Now, the iron has much more than all of them. The lead is a very soft material. So here the modulus of elasticity is very low, probably the lowest in this table of metals whereas, the tungsten as I was telling during our discussion about the material, it is very hard material. So, the modulus of elasticity here is the maximum which is $407x10^3\ MPa$.

Now, for ceramics and polymers, if you compare the diamond, it will have the maximum value because it is the hardest material; it can scratch the brittle and hard material like glass for example. And next to that is the tungsten carbide here you can see the tungsten has the 407 and when it is in the form of the tungsten carbide it becomes even more this is 552 whereas, the lowest one in this table will be the polyethylene here is a very low density and the modulus of elasticity is only $0.2x10^3\ MPa$.

This is for your understanding on where the materials stand in terms of the modulus of elasticity and hardness. You can also compare the materials from the point of view of the modulus of elastic similarly, the yield strength. This is another table which shows the yield strength and tensile strength for the selected metals. Here is the yield strength which is in *MPa* and tensile strength in *MPa*.

You can compare aluminium annealed, aluminium, then the aluminium alloys, cast iron, copper annealed, copper alloys, magnesium alloys and so on. And here you can see the *MPa* wise what will be the yield strength. So, while calculating and designing the part, while calculating different kinds of design parameters, these tables are very useful because you have to know when you are using a particular material.

You have to know what is the modulus of elasticity of that particular material or what is the yield strength of that particular material. In this table you can find out the yield strength of the nickel, steel, stainless steel, and then a titanium alloy. You can see that the titanium alloy has the maximum yield strength.

Strength wise these alloys have very high value of yield strength and tensile strength in the table The tensile strength is also probably the maximum in this table among all these materials.

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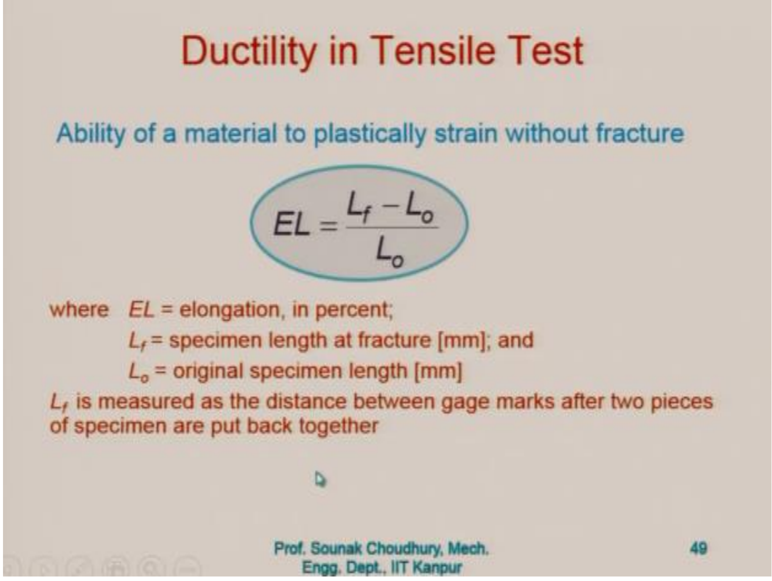

Ductility in Tensile Test

Ability of a material to plastically strain without fracture

$$EL = \frac{L_f - L_o}{L_o}$$

where EL = elongation, in percent;
L_f = specimen length at fracture [mm]; and
L_o = original specimen length [mm]

L_f is measured as the distance between gage marks after two pieces of specimen are put back together

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Let us see what is ductility in the tensile test? Ductility as we said is the ability of a material to plastically strain without fracture. Now, the elongation that is taken in percentage normally, how much it will be elongated that depends on the specimen length at fracture. So, when it is fracturing, what is the specimen length that exactly is taken?

Then the original specimen deducted from the L_f that divided by the original specimen length in millimetre gives you the elongation in the percentage, that of course, multiplied by

100. L_f is measured as the distance between the gage marks after two pieces of specimen are put back together. Now, what we mean to say is that L_f, how you measure it, it has already broken so, we are saying that this is the specimen length, just at fracture.

Normally during the testing the specimen is broken and then as soon as it breaks, those two pieces are joined together and the length is measured. So, that length will be the L_f that is the specimen length at fracture.

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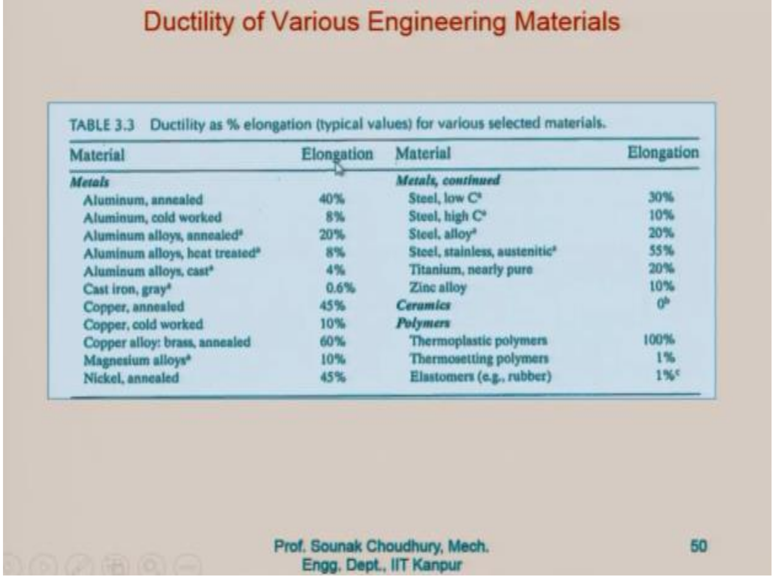

Ductility of Various Engineering Materials

TABLE 3.3 Ductility as % elongation (typical values) for various selected materials.

Material	Elongation	Material	Elongation
Metals		***Metals, continued***	
Aluminum, annealed	40%	Steel, low C[a]	30%
Aluminum, cold worked	8%	Steel, high C[a]	10%
Aluminum alloys, annealed[a]	20%	Steel, alloy[a]	20%
Aluminum alloys, heat treated[a]	8%	Steel, stainless, austenitic[a]	55%
Aluminum alloys, cast[a]	4%	Titanium, nearly pure	20%
Cast iron, gray[a]	0.6%	Zinc alloy	10%
Copper, annealed	45%	***Ceramics***	0[b]
Copper, cold worked	10%	***Polymers***	
Copper alloy: brass, annealed	60%	Thermoplastic polymers	100%
Magnesium alloys[a]	10%	Thermosetting polymers	1%
Nickel, annealed	45%	Elastomers (e.g., rubber)	1%[c]

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Here you can see the ductility of various engineering materials. This table is shown to you just for you to understand what are the typical values the ductility is given as the percentage of elongation, these are the typical values. Now, you can see that aluminium, aluminium alloys, cast iron, copper, magnesium, nickel, annealed metals containing still low carbon, high carbon, alloy steel and so on.

For example, cast iron cannot be elongated because it is the brittle material. So, here you can see that the ductility of cast iron is very less; it is 0.6% and similarly, the ceramics. Ductility of Ceramics is given as 0. So, it just cannot be elongated, it will break because ceramics are very brittle materials. Although, the ceramics, as I said earlier, is used for making cutting tools.

Because ceramics are very strong, and can withstand very high temperatures. Therefore, they are used as the tool material, however, these materials as you can see have 0% elongation, that means, they cannot withstand any shock or any fluctuation in the force. So, one has to be careful in case there is fluctuation in the forces or there is a shock during the machining process then the ceramic tools may not survive well.

Thermoplastic polymers can be stretched with the elongation value of 100%. So, you can have a fairly good idea about the materials in terms of their elongation, that which material is ductile, which material is brittle and so on. And how much brittleness is there, how much ductility is there that depends on what is the percentage of elongation one or the other material has.

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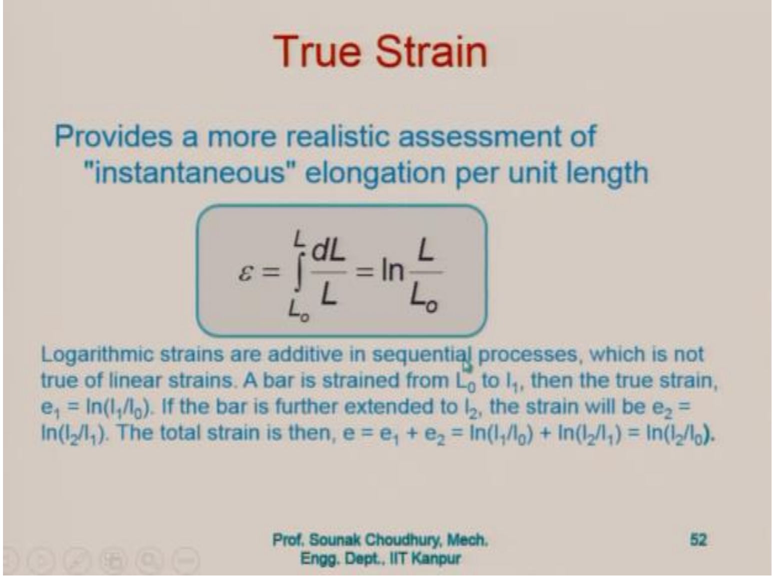

True Strain

Provides a more realistic assessment of "instantaneous" elongation per unit length

$$\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln \frac{L}{L_o}$$

Logarithmic strains are additive in sequential processes, which is not true of linear strains. A bar is strained from L_0 to l_1, then the true strain, $e_1 = \ln(l_1/l_0)$. If the bar is further extended to l_2, the strain will be $e_2 = \ln(l_2/l_1)$. The total strain is then, $e = e_1 + e_2 = \ln(l_1/l_0) + \ln(l_2/l_1) = \ln(l_2/l_0)$.

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Next is the **true stress** and the its value is obtained by dividing the instantaneous area into the applied load. So, you can find out the difference between the true stress and the engineering stress because this area (A) for the engineering stress was A_0. That was the initial cross section area, but A is the actual instantaneous area resisting the load, i.e. particularly that area which is resisting the load.

So, that area has to be taken care of in the case of true stress. It is called the true stress because in engineering stress, it is taken as the initial area. That area is not the actual area which resists the load and A is taken in mm^2, F is the force which is applied and for the true stress here this is $\left(\frac{F}{A}\right)$. This is taken as in case of engineering stress in MPa.

Similarly, the true strain differs from the engineering strain in the way that the true strain provides a more realistic assessment of the instantaneous elongation similar to the true stress that this is the instantaneous area resisting the load here also when we have to assess the instantaneous elongation per unit length, then the true strain has to be used, not the engineering strain.

So, true strain is given by $\int_{L_0}^{L}\left(\frac{dL}{L}\right)$ which is equal to $\ln\left(\frac{L}{L_0}\right)$. So, why it is taken in logarithmic scale? Because logarithmic strains are additive in the sequential processes. This is the advantage why the true strain is expressed in the logarithmic scale; this is not true in the linear stain in linear strain since it is not additive in the sequential process.

For example, a bar is strained from let us say l_0 to l_1., then the true strain is equal to as per this formula, this will be $\ln\left(\frac{l_1}{l_0}\right)$. Let us assume that the bar, after being elongated by up to l_1 is further extended to l_2.

In that case the true strain will be $\ln\left(\frac{l_2}{l_1}\right)$. Now, the total strain will be $e_1 + e_2 = \ln\left(\frac{l_1}{l_0}\right) + \ln\left(\frac{l_2}{l_1}\right) = \ln\left(\frac{l_2}{l_0}\right)$. So, what you can see is that it is easy, whatever stages you have of the elongation, what matters is the final length and the initial length and you take the ratio of that and logarithmic of that value will be equal to the total strain.

So, while estimating the total strain it is just the additive in the sequential process, that is what we said that logarithmic strains are additive in the sequential processes.

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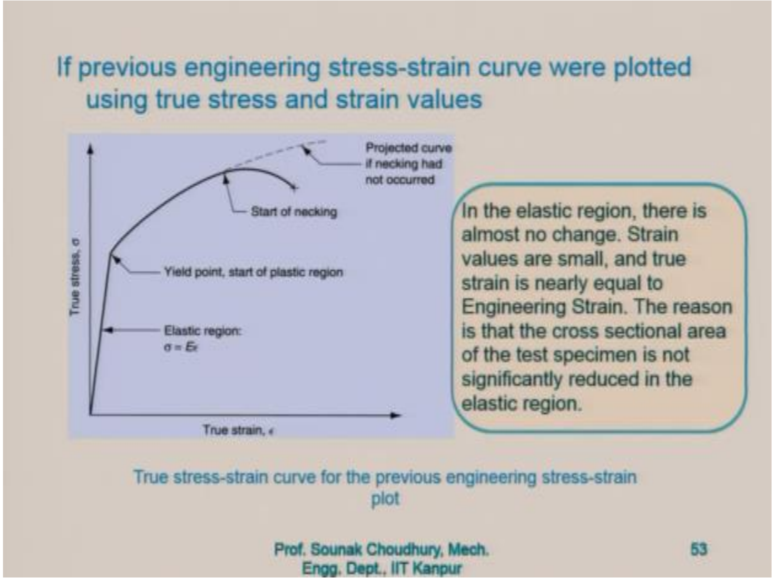

If previous engineering stress-strain curve were plotted using true stress and strain values

In the elastic region, there is almost no change. Strain values are small, and true strain is nearly equal to Engineering Strain. The reason is that the cross sectional area of the test specimen is not significantly reduced in the elastic region.

True stress-strain curve for the previous engineering stress-strain plot

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If previous engineering stress strain-curves were plotted using the true strain-true stress and the strain values, let us say now, we are putting their true stress here. And true strain here in the elastic region in here there is almost no change because this is the elastic deformation. Here the strain values are small and true strain is nearly equal to the engineering stress because of the small strain values. The reason is that the cross sectional area of the test specimen is not significantly reduced in the elastic region.

Therefore, engineering stress and true stress, true strain will be the same because it is either the initial length or it is the final length there is not much of a difference between them. Yield point starts off the plastic region and up to that point engineering stress strain curve and the true stress strain curve do not have much difference between them.

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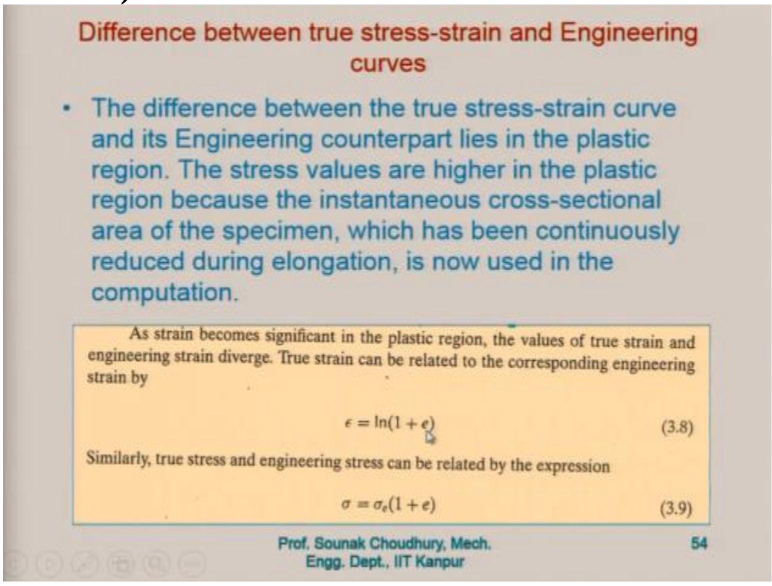

Difference between true stress-strain and Engineering curves

- The difference between the true stress-strain curve and its Engineering counterpart lies in the plastic region. The stress values are higher in the plastic region because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during elongation, is now used in the computation.

As strain becomes significant in the plastic region, the values of true strain and engineering strain diverge. True strain can be related to the corresponding engineering strain by

$$\epsilon = \ln(1 + e) \quad (3.8)$$

Similarly, true stress and engineering stress can be related by the expression

$$\sigma = \sigma_e(1 + e) \quad (3.9)$$

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let us discuss the difference between true stress strain and the engineering curve. In engineering counterpart in the plastic region lies the basic difference. We have seen that in the elastic region there is not much of a difference because the elongation does not happen very much. The stress values are higher in the plastic region, that is why the deformation has changed from the elastic to plastic.

Because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during the elongation is now used in the computation. This is the reason why the stress values are higher in the plastic region. So, as strain becomes significant in the plastic region, the values of true strain and engineering strain diverged; true strain can be related to the corresponding engineering strength.

So, the true strain equals to $\ln(1+e)$. Similarly, true stress and engineering stress can be related to this expression. So, this is the true stress and this is equal to the engineering stress multiplied by (1 + e), this is the difference. This small e is the engineering strain, this is the true strain. So, in case of stress it will be true stress is equal to engineering stress multiplied by 1 plus engineering strain.

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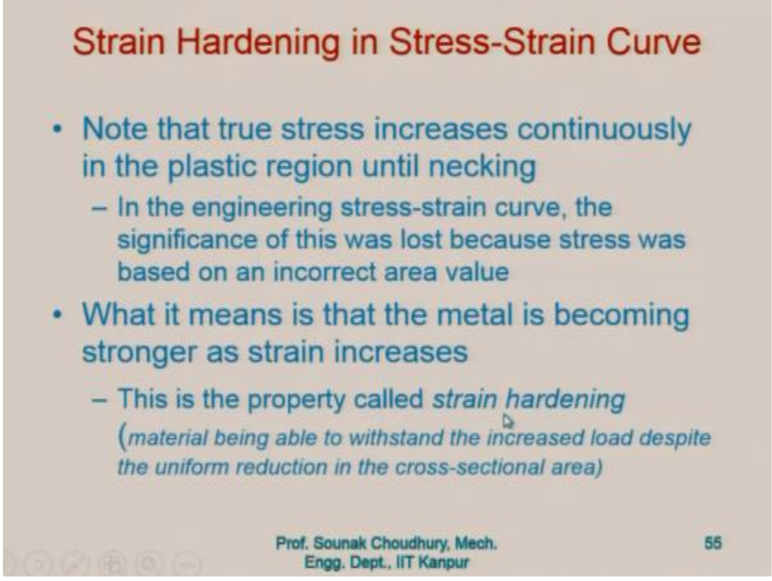

Strain Hardening in Stress-Strain Curve

- 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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Strain hardening & stress strain curve: this is another phenomenon which happens in the plastic region after the region crosses the yield point. Note that true stress increases continuously in the plastic region until the necking. In the engineering stress-strain curve the significance of this was lost because stress was based on the incorrect theory of value, meaning that when we are finding out the stress in the case of the engineering stress then the area we have taken as the initial area.

So, it has nothing to do with the area that is instantaneous. Therefore, in the engineering stress-strain curve the significance of this that the true stress increases continuously in the plastic region it was lost. What it means is that the metal is becoming stronger as the strain increases, this is something which has to be understood.

Because we are taking the instantaneous area and not as in the case of engineering stress or engineering strain, this is the property called the strain hardening. The definition of the strain hardening will be that this is the ability of the material being able to withstand the increased load despite the uniform reduction in the cross-sectional area which happens in the case of the plastic region after the yield point.

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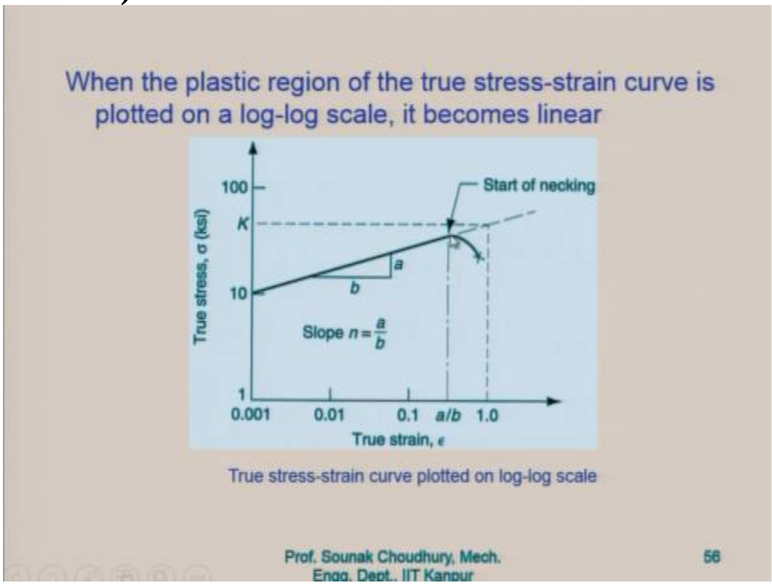
When the plastic region of the true stress-strain curve is plotted on a log-log scale, it becomes linear

True stress-strain curve plotted on log-log scale

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When the plastic region of the true stress strain curve is plotted on a log-log scale, here, along the Y-axis it is the true stress in the log scale and along the X-axis is the true strain in the log scale, it becomes linear. So, this is the necking up till that it is a linear and afterwards it will be fractured and it behaves in a very different way and in a very erratic way; in fact, it does not follow a certain rule.

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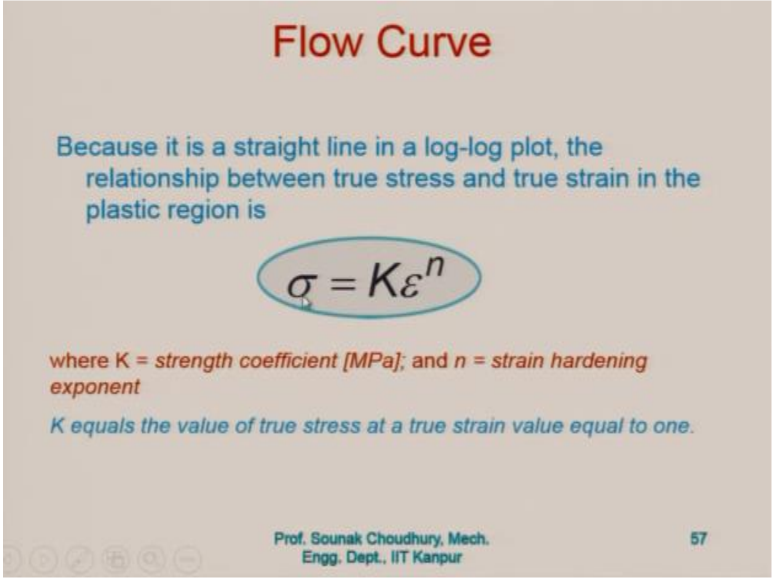

Flow Curve

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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Now, let us see what is flow curve? Because itis a straight line in a log-log plot, the relationship between the true stress and true strain in the plastic region can be expressed as $\sigma = K\varepsilon^n$. Here, K is the strength coefficient in *MPa*, and *n* is the strain hardening exponent.

The strength coefficient, K is actually a constant of proportionality taken in *MPa* to make the unit of the left side and the right side the same. The significance of K is the value of true stress at a true strain value equal to 1.

So, if you see in $\sigma = K\varepsilon^n$, for ε^n *=1*, σ will be equal to *K*. That is what we are saying that the K equals to the value of true stress at a true strain value equal to 1. This is equal to the value of the true stress. This is called the flow curve where the true stress is defined in terms of the true strain.

For that we have the factor which is called the strain hardening. And once again the strain hardening is the ability of the material to withstand the increased load despite the uniform reduction in the cross-sectional area. This does not happen before the unstable K point, i.e. not happens immediately at the yield point. It starts happening when the load becomes maximum and there the necking starts.

Despite the uniform reduction the material can withstand the increased load and this ability of the material or the property of the material. It is the strain hardening factor which is used here to express the relationship between the true stress and the true strength through a coefficient which is called the strength coefficient. So, the strength coefficient defines the strength of the material. Rest of the things we will discuss in our next discussion session. Thank you very much for your attention.