Nanomaterials and their Properties

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Lecture - 17

Mechanical Properties of Nanomaterials (I)

So, students; we are going to start the new lecture that is the lecture number 17. And this is, obviously, in continuation of the previous lecture; lecture number 16.

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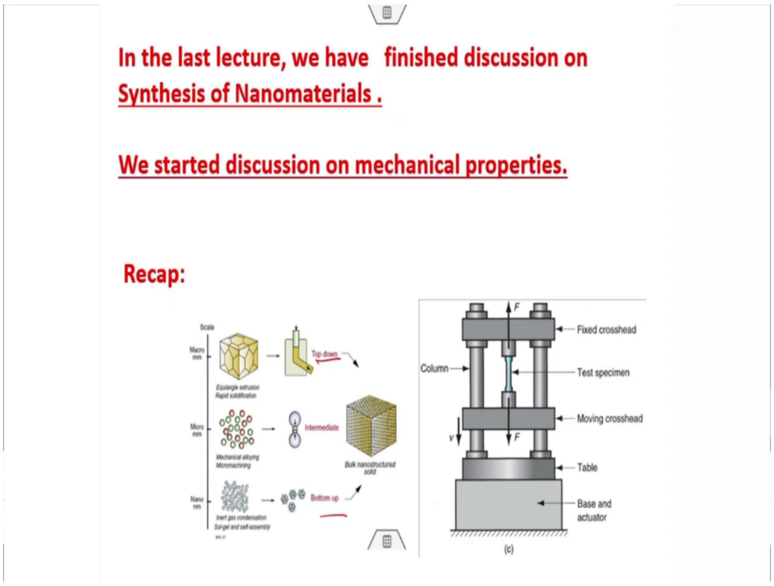

In the last lecture, we have finished discussion on Synthesis of Nanomaterials .

We started discussion on mechanical properties.

Recap:

And as you know in the lecture number 16 or the last lecture we have finished our discussions on Synthesis of Nanomaterials. We talked about various synthesis routes in a very brief and showed you how different ways you can produce zero dimensional, one, two and three dimensional nanomaterials correct.

And then on not only that we started also discussions on Mechanical Properties of Nanomaterials. And in that, I have only discussed about the basic things of mechanical behavior, mechanical properties. So, today we are going to continue on that and then slowly move into what is the effect of size on the mechanical properties.

So, in order to give you some recap we talked about various synthesis routes starting from top down ok to bottom up and also some intermediates like mechanical alloying other things ok.

And we also discussed something about mechanical properties how the mechanical properties can measure and all these aspects that was the main thing we discussed.

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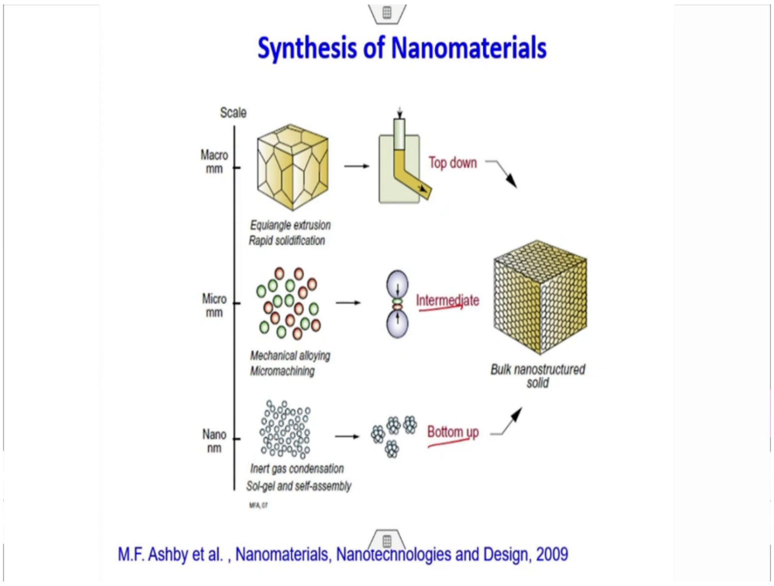

Synthesis of Nanomaterials

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

As you know synthesis of nanomaterials are done mostly by as a top down and bottom-up approaches, top down means you start with a big material large grain size break it down to smaller one. Bottom-up means start with molecules; molecules comes together they join with form clusters and the cluster leads to formation of nano materials.

Or you can also have intermediate things like mechanical alloying or micro machining you can produce powders of alloys or you can basically tweak chips up during the machining and that also contains nano particle, grain sizes and break them together and make powder. But nonetheless in case of bottom up and in case of intermediates you basically land up preparing powders.

So, you did not need to sinter it or you need to consolidate it to make the product or to make the three-dimensional product ok that is the bulk nanostructured solids and that is done basically by ultra-fast sintering techniques.

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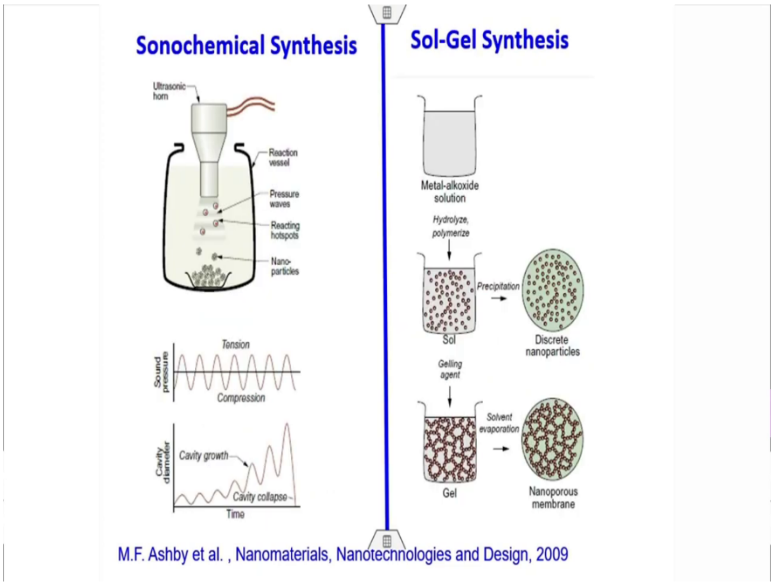

Sonochemical Synthesis

Sol-Gel Synthesis

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

So, a few of these techniques like in sonochemical which is used for zero-dimensional nano particle preparation they uses, sound wave or ultrasonic waves sol gel uses the mixture of sol and gel to prepare zero dimension nanoparticles ok.

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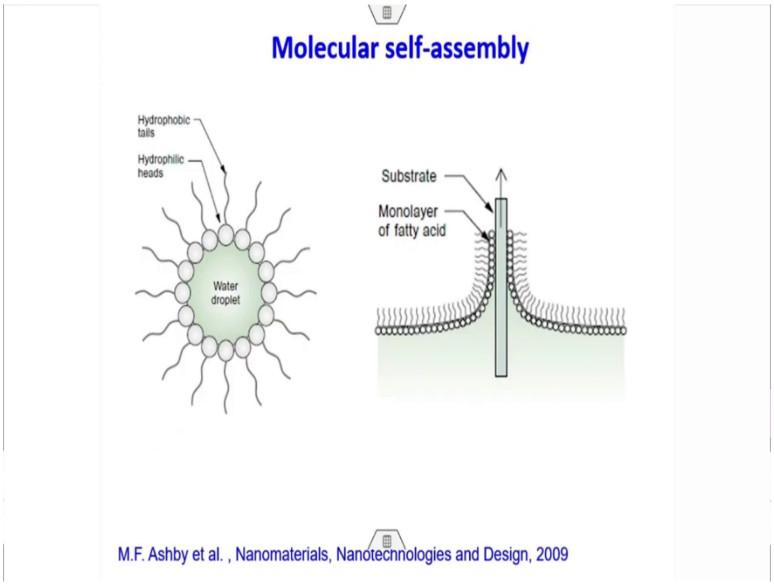

Molecular self-assembly

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

You can also do molecular self-assembly like muscles kind of roots, routes basically to prepare zero dimensional nanomaterials.

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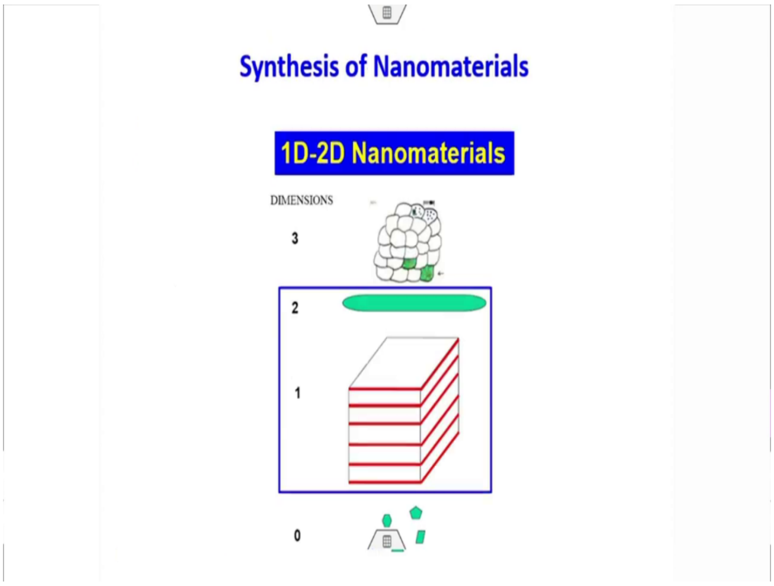

Synthesis of Nanomaterials

1D-2D Nanomaterials

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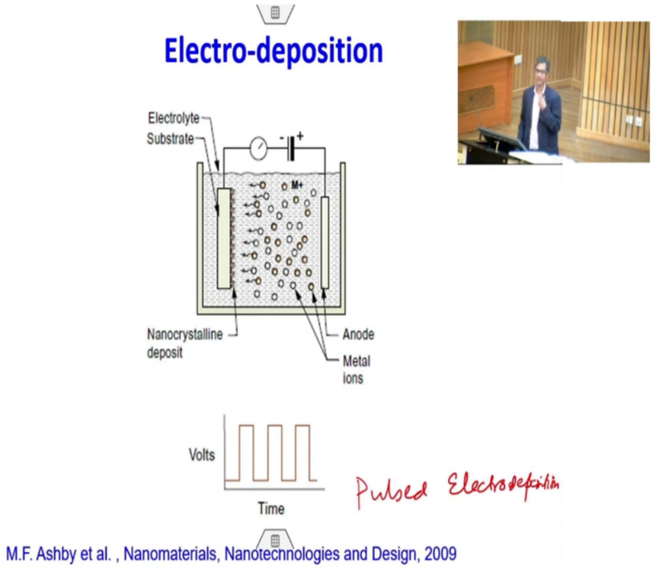

Electro-deposition

Pulsed Electrodeposition

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

You can also prepare 1 D and 2 D nanomaterials by using techniques like electro depositions which we discussed basically pulse electro depositions not electro deposition, pulse electro deposition. And pulse current or pulse voltage is used to prepare the nanomaterials. And this is same as like normal electro depositions only, but you are applying a pulse voltage correct. With high current density and usage of some kind of additives one can actually make nice 2 D nanomaterials.

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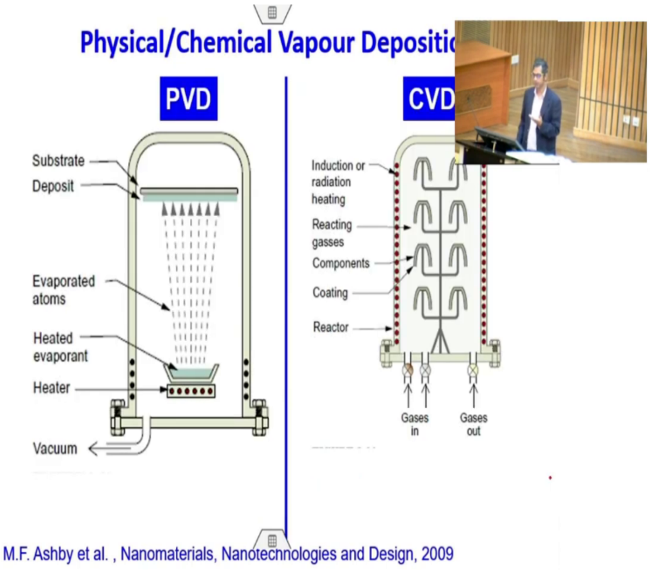

Physical/Chemical Vapour Depositi

PVD

CVD

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

You can use PVD or CVD like physical and chemical vapour depositions to create thin films which will have nano crystalline grains of thickness of the nano crystalline design. So, therefore, it is possible to prepare many 2 D nanomaterials.

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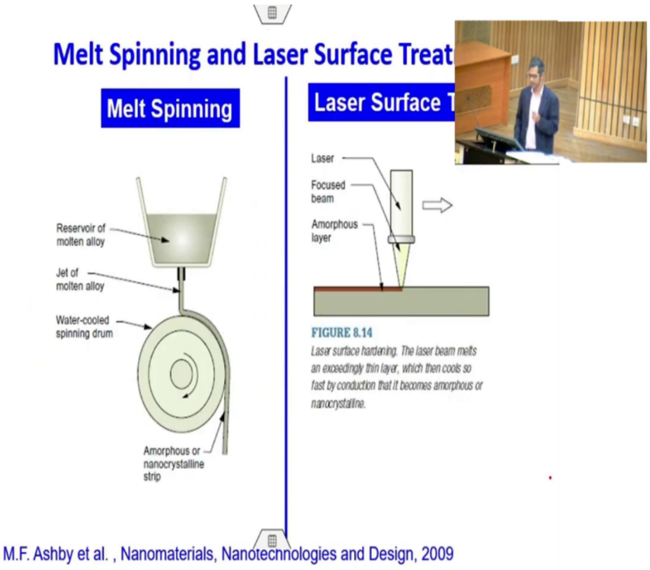

Melt Spinning and Laser Surface Treat

Melt Spinning

Laser Surface T

FIGURE 8.14

Laser surface hardening. The laser beam melts an exceedingly thin layer, which then cools so fast by conduction that it becomes amorphous or nanocrystalline.

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

Well, in case of 3D you can always do by melting roots like melt spinning or laser surface treatments ok melt spinning is a widely used technique to prepare this kind of nano materials which is you know we have discussed a lot on that and this is a rapid solidification route.

And you have a laser surface melting or laser surface treatment, you are melting a thin layer on the surface of the sample and this thin layer basically solidifies rapidly and that is so actually you can prepare nano materials correct.

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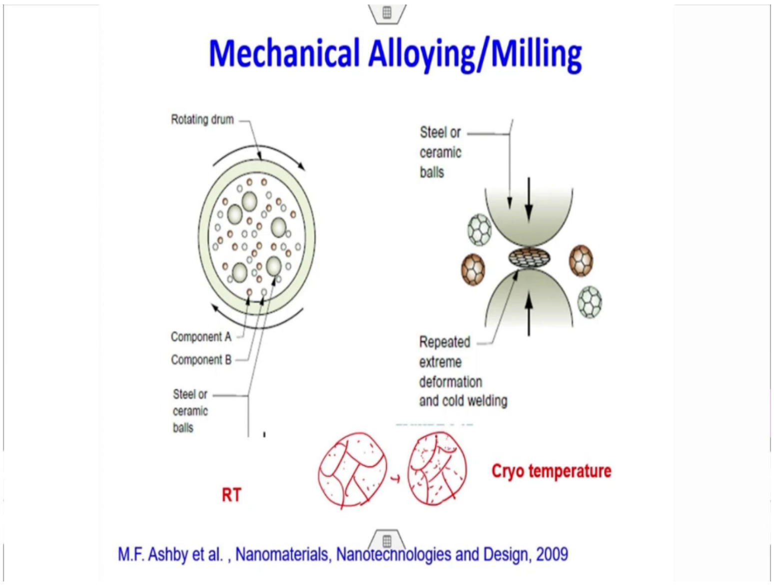

Mechanical Alloying/Milling

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

And then we have discussed about some of the techniques of you know mechanical alloying both at room temperature and as well as cryo temperatures in case of mechanical alloying of putting powder mixture, charging the powder mixture inside a drum, rotating drum with some balls and because of the actions of the balls and the powder mixture and you can create nanostructure materials very easily right.

And that is how then this leads to power production with nano powders, similarly you can do look cryo temperature also milling and then which you can break down actually the powders into pieces by accelerating the fracturing process at low temperature as well as you can actually make deformation induce nano crystallizations of the grains ok.

And this we have already discussed how it is done, you can always also basically generate a lot of defects inside the grains and these defects actually slowly align these defects which was nothing but dislocations they can align and produce such a kind of nano crystal grains easily ok. So, you can align them and prepare that ok, you can align them and prepare nano crystals and these grains actually are small angle can mount it correct. So, then become slowly become high angle boundaries.

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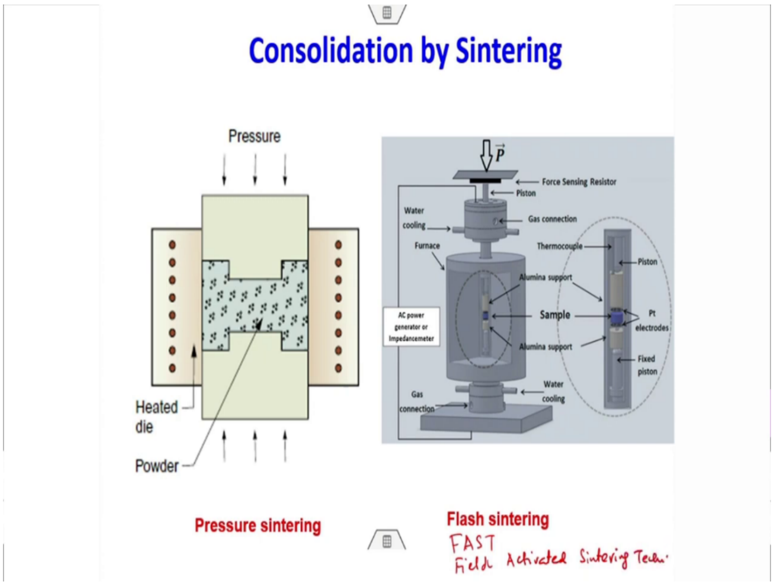

Consolidation by Sintering

Pressure sintering

Flash sintering

FAST
Field Activated Sintering Tech.

Well, as I said these techniques produces powder. So, you need to consolidate them and that can be done using flash sintering or spark plasma sintering ok. These are nothing but as routes known as a FAST fastest Field Activated Sintering Technique alright that is what is widely used.

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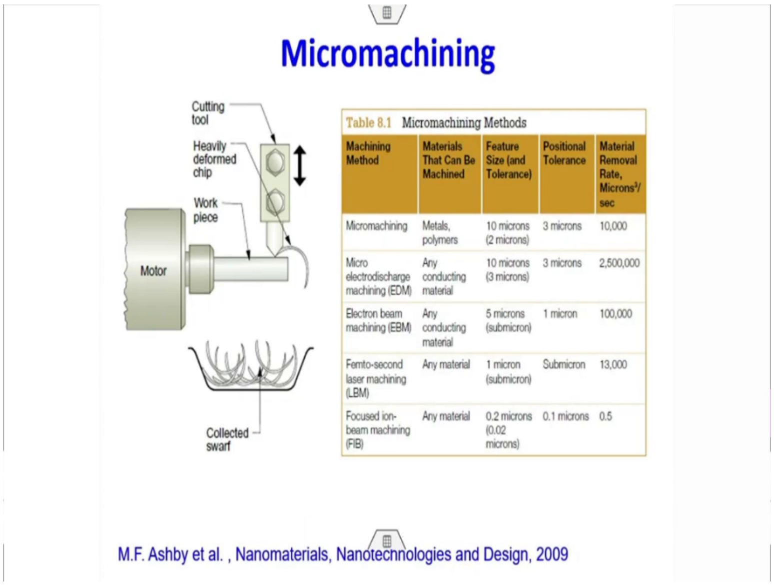

Micromachining

Table 8.1 Micromachining Methods

Machining Method	Materials That Can Be Machined	Feature Size (and Tolerance)	Positional Tolerance	Material Removal Rate, Microns^3/sec
Micromachining	Metals, polymers	10 microns (2 microns)	3 microns	10,000
Micro electrodischarge machining (EDM)	Any conducting material	10 microns (3 microns)	3 microns	2,500,000
Electron beam machining (EBM)	Any conducting material	5 microns (submicron)	1 micron	100,000
Femto-second laser machining (LBM)	Any material	1 micron (submicron)	Submicron	13,000
Focused ion-beam machining (FIB)	Any material	0.2 microns (0.02 microns)	0.1 microns	0.5

M.F. Ashby et al. , Nanomaterials, Nanotechnologies and Design, 2009

Well, then you can do micro machining which can lead to lot of chip formation and because of machining shear force is pretty high. So, therefore, this leads to a lot of you know nano crystallization in these chips unless the chips can be ground and made powder and the powder can be consolidated ok. So, there are many ways of machining routes I am not discussing again fine.

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MECHANICAL PROPERTIES OF MATERIALS

1. Stress-Strain Relationships
2. Hardness
3. Effect of Temperature on Properties
4. Fluid Properties
5. Viscoelastic Behavior of Polymers

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So, this is again when we come back to the original situations.

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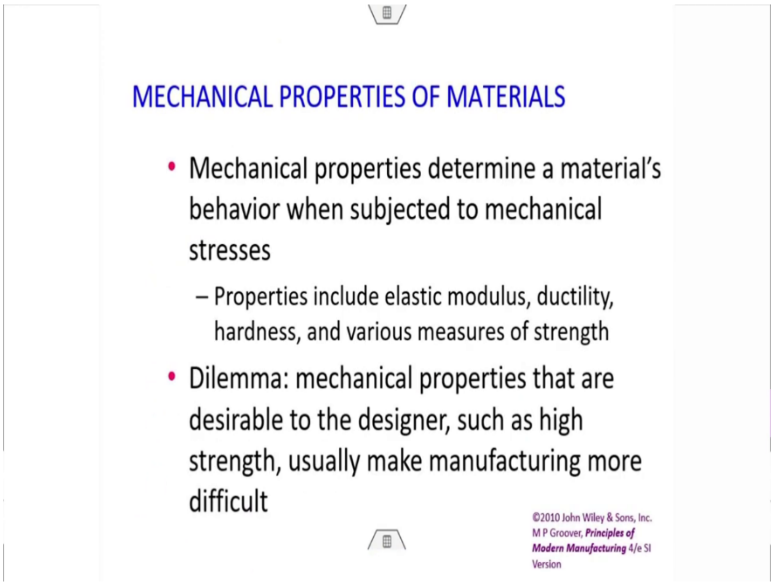

MECHANICAL PROPERTIES OF MATERIALS

- 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 that are desirable to the designer, such as high strength, usually make manufacturing more difficult

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Stress Strain Relationship

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

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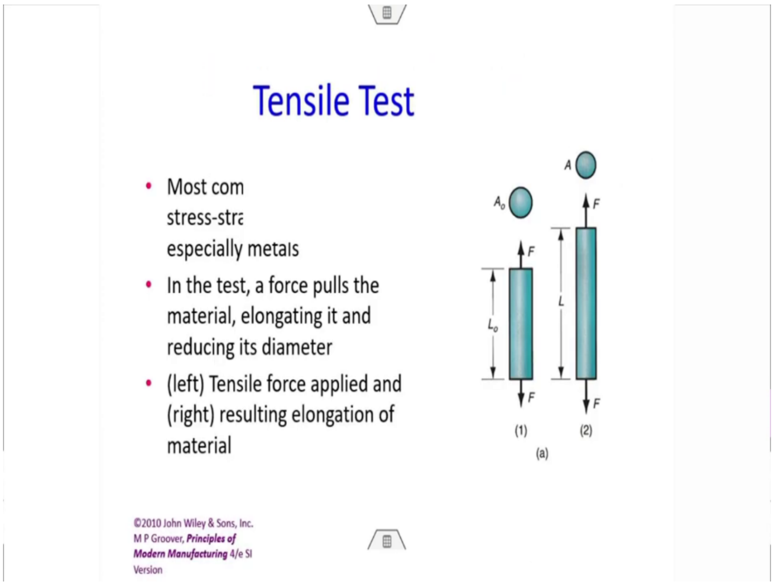

Tensile Test

- Most com stress-stra especially metals
- In the test, a force pulls the material, elongating it and reducing its diameter
- (left) Tensile force applied and (right) resulting elongation of material

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So, that is about this thing, then we discuss about some part of tensile test, how tensile tests are done.

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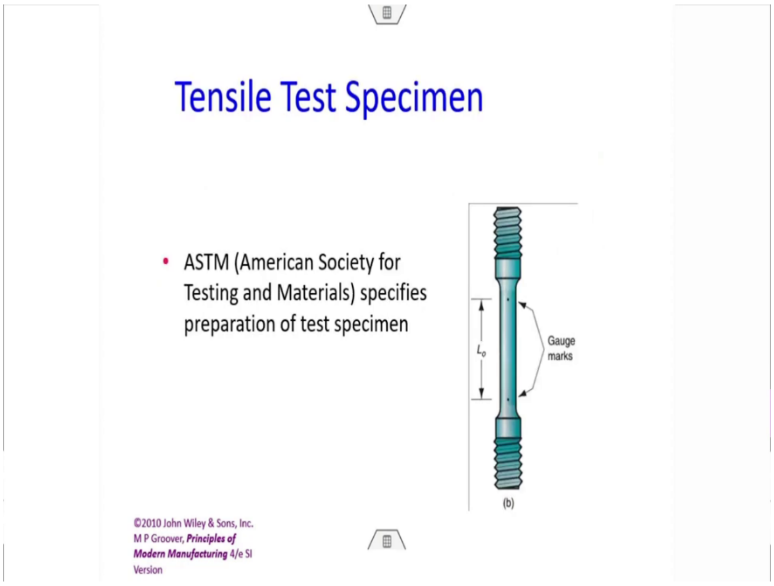

Tensile Test Specimen

- ASTM (American Society for Testing and Materials) specifies preparation of test specimen

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And what are the geometries you use ok, ASTM standards.

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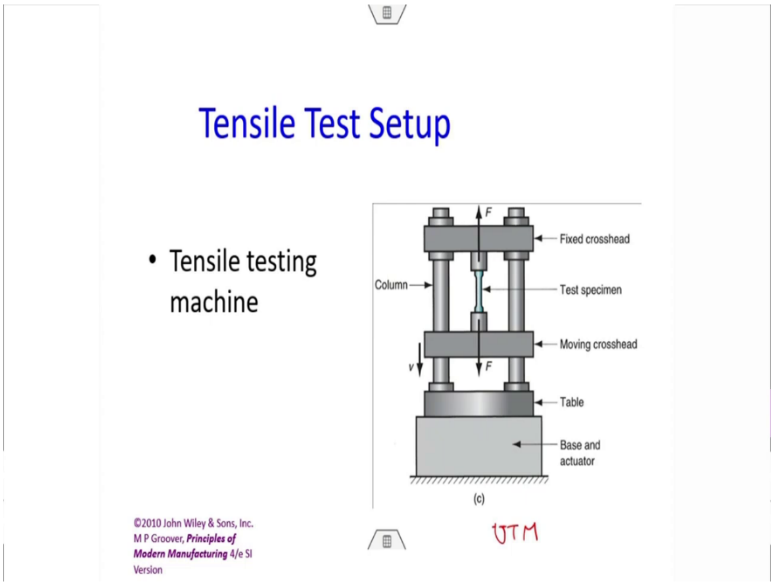

Tensile Test Setup

- Tensile testing machine

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And tensile test is done in a machine known as UTM or Universal Testing Machine ok and in this case sample is loaded into a jig and then pulled by applying forces F ok and then you can actually measure these elongation as well as the load and that can be convert it to strength stress and strain.

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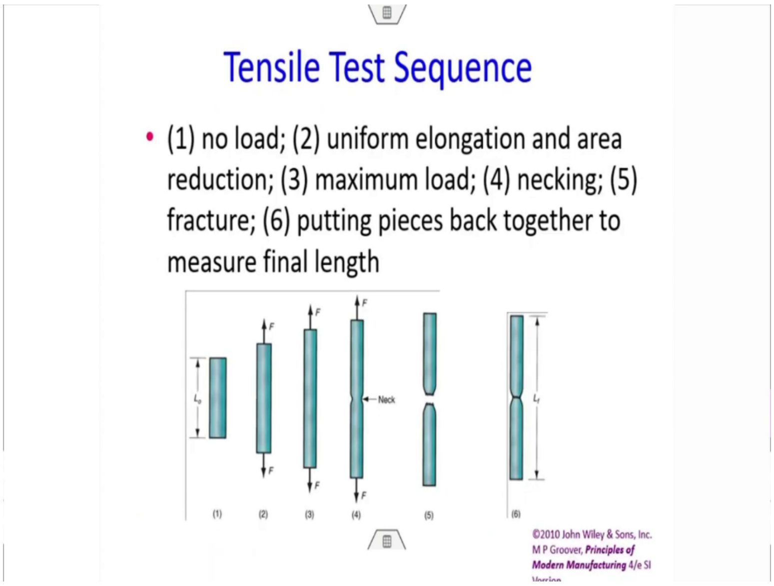

Tensile Test Sequence

- (1) no load; (2) uniform elongation and area reduction; (3) maximum load; (4) necking; (5) fracture; (6) putting pieces back together to measure final length

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This is a sequence of the tensile stress specimen ok.

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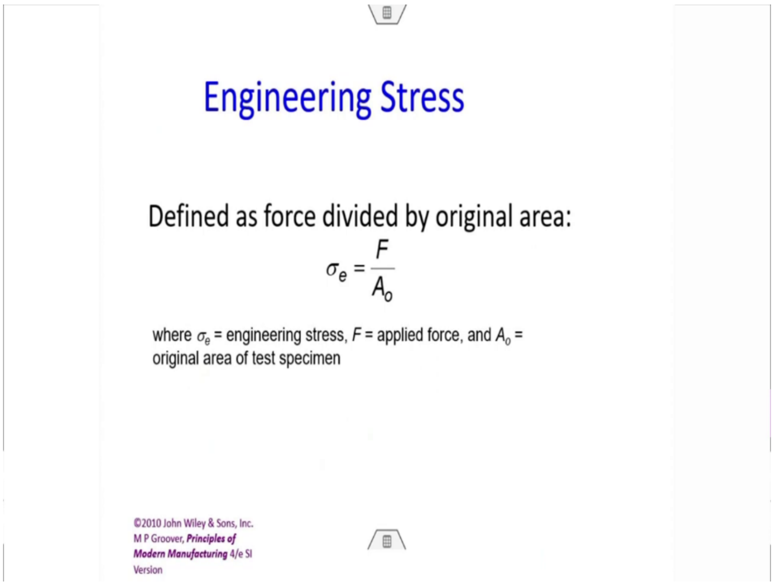

Engineering Stress

Defined as force divided by original area:

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

where σ_e = engineering stress, F = applied force, and A_o = original area of test specimen

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Now, let us come back to the some of the things which you need to know, as you know the stress is important things ok. The stress can be obtained by dividing the force by you know original area. So, engineering stress is nothing but force divide by the original area.

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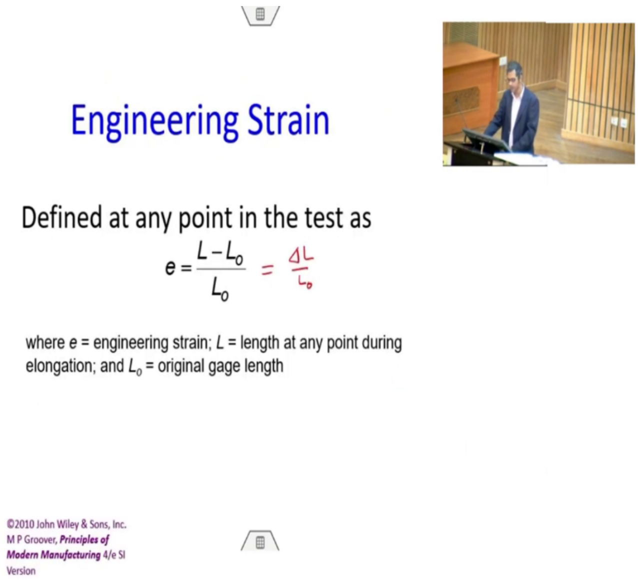

Engineering Strain

Defined at any point in the test as

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

where e = engineering strain; L = length at any point during elongation; and L_o = original gage length

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Strain engineering strain again is same it is basically length increased length divide by the original length ok. So, that is nothing but e = $\frac{L - L_0}{L_0}$, L is the length at any point of testing and

L_0 is the original length. So, these can also be written as $\frac{\Delta L}{L_0}$, you can always measure the elongations they during the start of the experiment at the end of the experiments change of length is what is known as elongation ok. So, that if you divide by original length is gives you the engineering strain.

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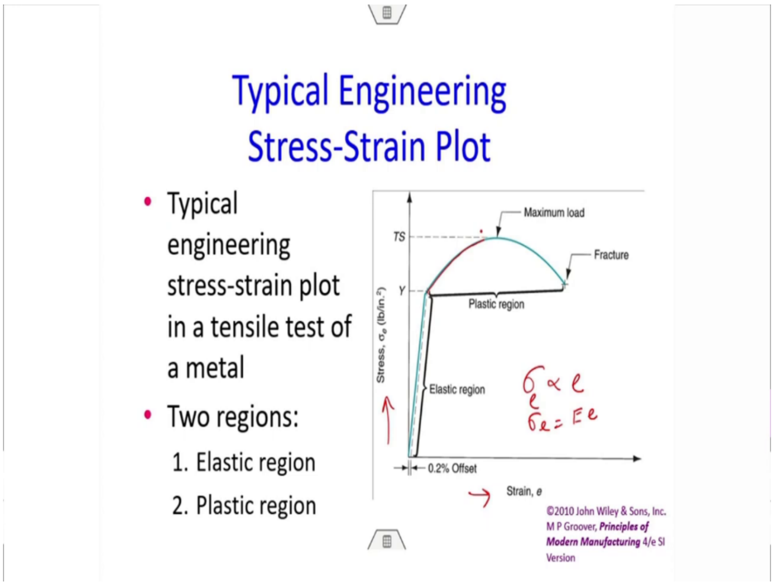

Typical Engineering Stress-Strain Plot

- Typical engineering stress-strain plot in a tensile test of a metal
- Two regions:
  1. Elastic region
  2. Plastic region

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Well, the typical stress strain plot will look like this. You can clearly see this is the stress on the Y axis, strain on the X axis right and in any typical engineering materials ok. Especially metals actually show such a kind of stress strain behavior there are two parts in this curve, one is an elastic region, other is the plastic region.

In the elastic region the stress and strain follow Hooke's law that is stress is proportional to strain and we know that this can be written as by Hooke's law ok which is nothing but stress is equal to elastic constant multiplied by the strain. So, we are not interested in this, we material scientists are mostly interested in the plastic region.

Elastic region is more widely used by the structural engineers like mechanical, civil engineering students or maybe the community, but material scientists are most interested in the plastic aspects. So, plastic portion of the curve or plastic region of the curve they are not plastic portion, plastic is normal plastic here.

This plastic means plastic deformation, plastic region starts with the yield strength that is what indicates the deviation from the linearity, you know this is a linear portion stress is proportional to strain. So, any deviation from that is indicated by the yield point or yield stress.

And then it goes to maxima that is correspond with the maximum load and that is what is known as a TS or Tensile Strength and then it follows a trajectory which is going downward finally, the material fractures. This is same as what I showed you here this snapshot views are reflected in terms of a stress strain plot correct.

So, in a nutshell what you understand that if you start deforming material initially, it will deform by elastic deformation. So, elastic deformation means any amount of strain happening in the material if you unload the material will go back to its original length original size basically. But the moment you cross the yield strength that is the point Y in this curve you are going to be region of irreversible strain.

So, you cannot if you need to unload the material at any point beyond UTS you will not be able to come back to the original point that is original shape and size this is not possible. There will be always a permanent strain remain in the material that is the thing happen in the plastic design and you keep on increasing these things a lot of many things lot of things happen which we will discuss one by one.

So, these are the two regions if you understand are going to happen when you test any material.

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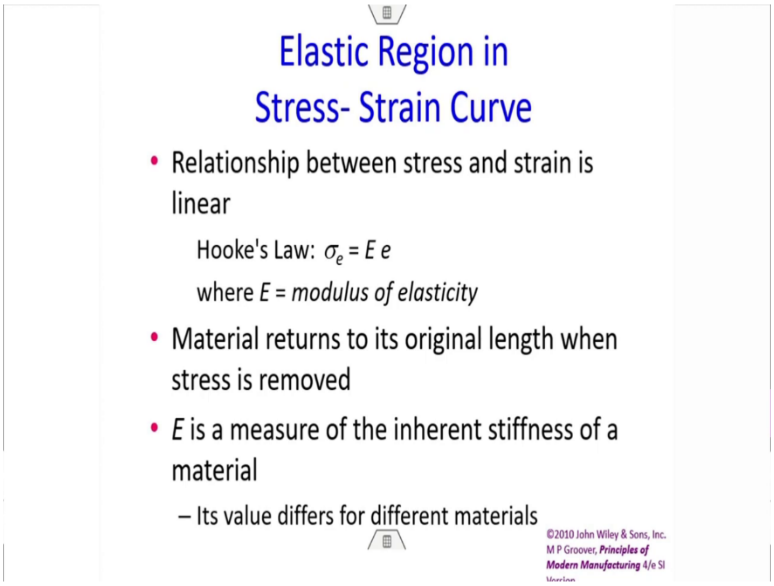

Elastic Region in Stress- Strain Curve

- Relationship between stress and strain is linear

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

  where E = *modulus of elasticity*
- Material returns to its original length when stress is removed
- *E* is a measure of the inherent stiffness of a material
  - Its value differs for different materials

So, therefore, relationship between stress and strain is given in elastic region is by Hooke's Law, $\sigma_e = E\epsilon$ and material returns to original length when the stress is removed. E is the measure of inherent stiffness of the material and its (Refer Time: 11:13) intensive property, it depends on the bond strain of the atoms in the materials. Its values differs for different materials that is because of these bonding naturally.

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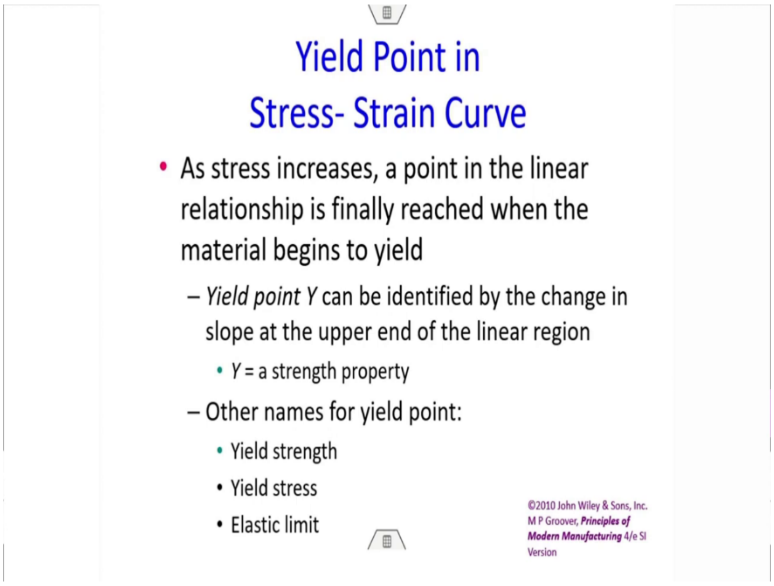

Yield Point in Stress- Strain Curve

- 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
    - Elastic limit

Well so, and then we talked about yield point or yield point is tested. As the stress increases a point appears in the stress strain curve where a linear relationship finally, breaks down and materials begins to yield. Yield point can be identified by the change in slope at the upper end of the linear region ok. Other names of the yield point is yield stress, elastic limit, group stress but do not worry about it; it is yield stress.

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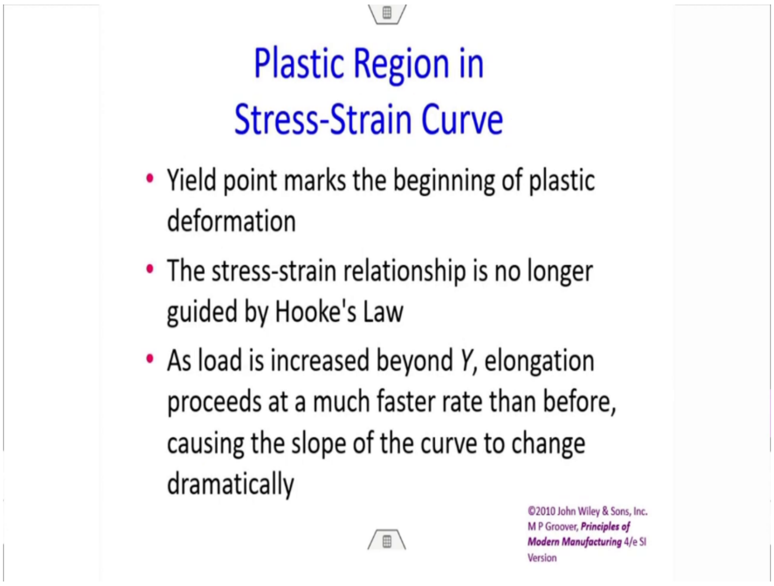

Plastic Region in Stress-Strain Curve

- 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

So, in the plastic region stress strain relationship no longer will be guided by Hooke’s Law. Load increases beyond Y, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically. That is what you have seen right, you have seen that, yes the slope has dramatically changed correct from the linear region.

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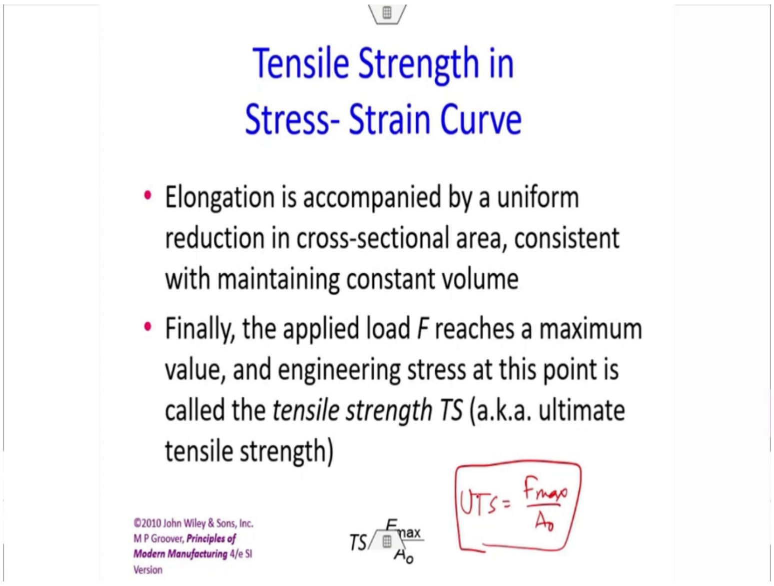

Tensile Strength in Stress- Strain Curve

- 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* (a.k.a. ultimate tensile strength)

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

$$\boxed{UTS = \frac{F_{max}}{A_0}}$$

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Elongation is accompanied by uniform reduction in the cross-sectional area, consistent with a meaning maintaining constant volume. Finally, a load appears let the load reaches a maximum value, engineering stress at this point is called the tensile strength or ultimate tensile strengths. This is nothing but UTS is equal to F_{max} by the original area, A_0, or it is also known as UTS, Ultimate Tensile Strength ok.

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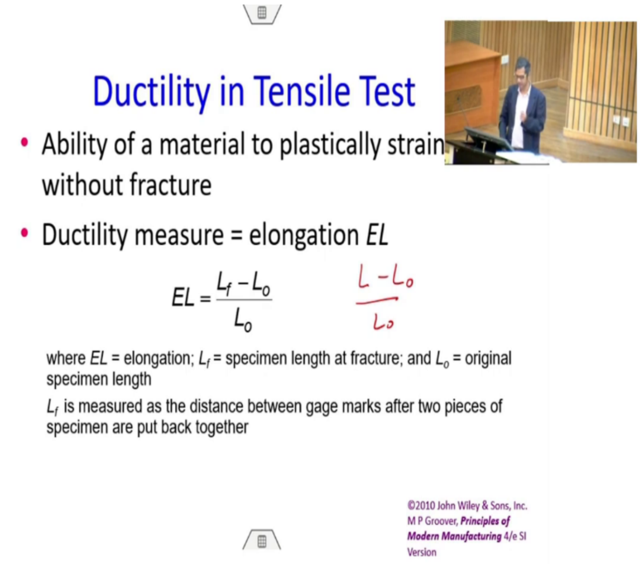

Ductility in Tensile Test

- Ability of a material to plastically strain without fracture
- Ductility measure = elongation *EL*

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

where *EL* = elongation; L_f = specimen length at fracture; and L_o = original specimen length

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

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That is about the strength, what about the ductility, how do you make the ductility? Ability of any material to plastically strain without fracture is what is known as a ductility. Ductility is basically measured by in terms of elongation divided by the original length, I already discussed it.

So, $L_f - L_0$ or $L - L_0$ whatever you define ok in the earlier slide you have defined $\frac{L-L_0}{L_0}$. L_f is the final length or L is a length at any point of time within the test and L_0 is the original length. So, L_f is measures of distance between the gauge marks as we have seen in the specimen geometry, I have shown this class also I have shown in the last class also right.

Specimen geometry as far as ASTM standards has two marks on the sample that is what is known as a gauge length that is corresponds to L_0 and L_f is whatever is increasing because of the application of this stress of course.

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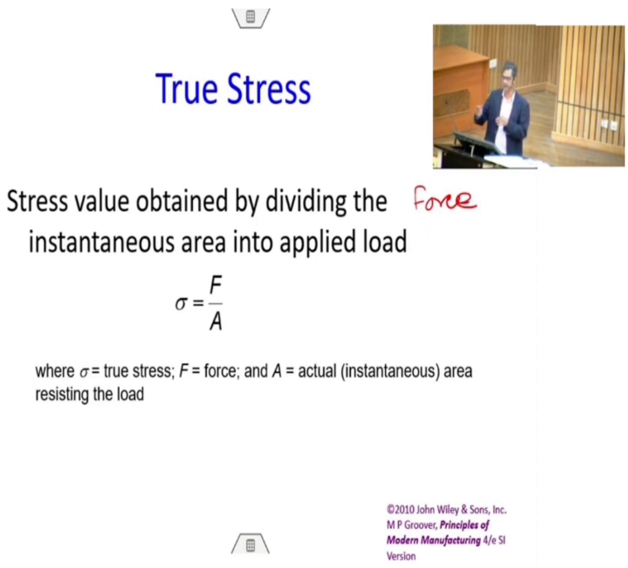

True Stress

Stress value obtained by dividing the Force instantaneous area into applied load

$$\sigma = \frac{F}{A}$$

where σ = true stress; F = force; and A = actual (instantaneous) area resisting the load

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And you know then you have something known as a true stress that is our engineering stress engineering strain, stress obtained by dividing the instantaneous you know dividing the force dividing the force by instantaneous area is known as the you know true stress.

So that means, the $\sigma = \frac{F}{A}$ at any point of time in the testing if you measure the area that is the instantaneous area. So, instantaneous area is used to know this true stress and F anyway you know how much force you are applying right.

So that means, you are using the actual area you had not the original area, original area was known before the beginning of the test, rather the test goes on the original area is changing that is what basically original area decreases because you are lengthening the sample, fine.

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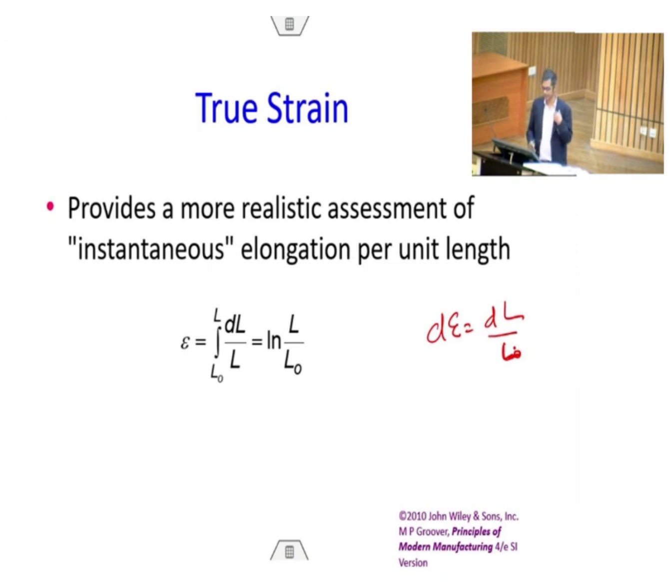

True Strain

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

$$\varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

$$d\varepsilon = \frac{dL}{L_0}$$

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So, similarly you have a true strain. True strain is nothing but written like this, $d\epsilon = \frac{dL}{L_0}$ correct. So, if dL is a small instantaneous change of length and if I divide it by original length that is what is sorry divide by the length ok at the time of this test that is what is known as this instantaneous change of strain or true strain.

And if you integrate it over L_0 to L you get $ln\frac{L}{L_0}$ that is what is your true strain. So, it gives you provides you more realistic assignments or assessment of the instantaneous elongation per unit length; that is what it provides you.

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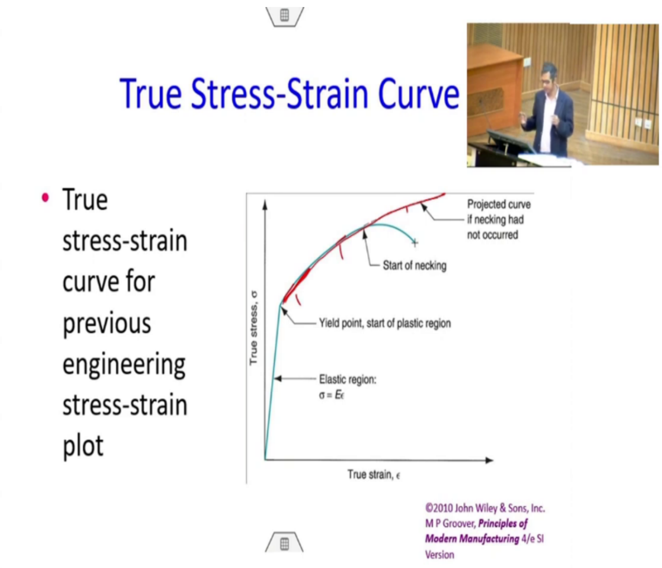

True Stress-Strain Curve

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

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So, if you plot this true stress true strain curve on the top of the engineering stress strain curve it looks like this ok. So, you can see here that you know if making does not appear this true stress true strain curve will keep on moving like this. That is a dotted curve which is showing, but engineering stress strain curve will be showing a deep and then it stops at the fracture point, am I clear.

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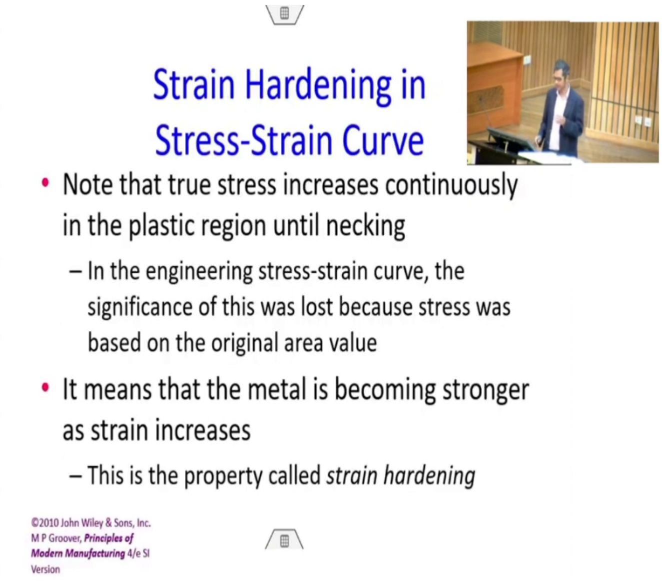

Strain Hardening in Stress-Strain Curve

- 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 the original area value
- It means that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening*

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Well, now let us talk about the slope of the stress strain curve after the yield stress. If you look at this true stress increases continuously in the plastic region until necking ok, you can see this true stress is increasing continuously until it fractures ok. So, that is what you are seeing.

Now you know in engineering stress strain curve the significance of this was lost because the stress was based on the original area. It means that metal is becoming more strong as the strain increases because your slope is increasing right and these properties known as strain hardening, what is it?

So, as you see here from here to here to here the slope of the curve is increasing; that means it is we require more amount of stress to deform the material by specified valued here, then here and then here that is what it is ok. So, that means, what? Material is becoming more harder and harder as becomes more and more hard.

See, you need more stress to get the specified amount of deformation and that is what is known as the strain hardening and this is something which is very unique in metals this happens because of the defect interaction in the material.

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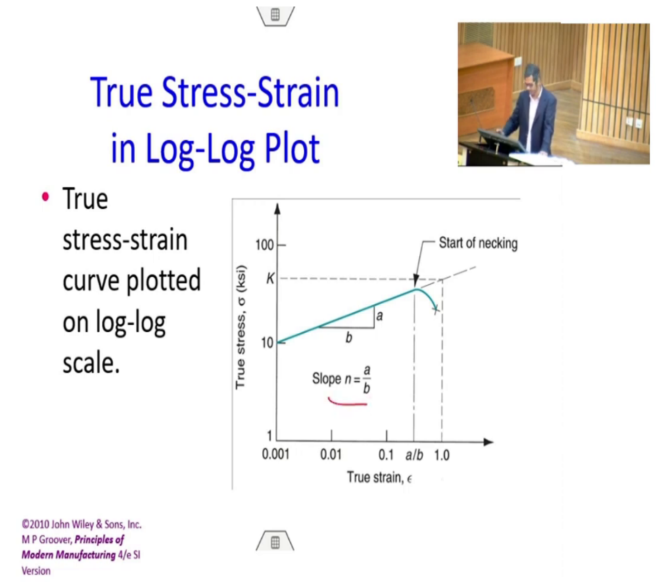

True Stress-Strain in Log-Log Plot

- True stress-strain curve plotted on log-log scale.

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So, if you plot this true strain behavior ok if you plot true stress true strain behavior like this and you can clearly see that you can measure. You can plot true stress versus true strain on logarithm plot then you can get a slope which is $n = \frac{a}{b}$ like this and that is what is known as the strain hardening coefficient ok.

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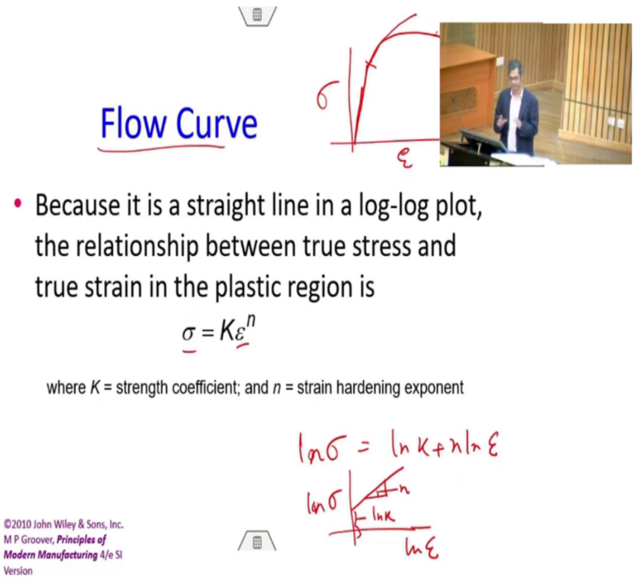

Flow Curve

- 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; and n = strain hardening exponent

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Now, how does it important? Because that gives you the equation of these deformation deformed curve in the plastic region what is known as a flow curve. So, flow curve is what is you see in this plot stress versus strain elastic portion then you have plastic portion, the equation of these curve from here to there are here this true stress true strain ok, that is this what is given by flow curve basically if flow curve is giving you true stress true strain behavior.

So, sigma and epsilon they are related by a constant K and exponent n, $\sigma = K\epsilon^n$ this exponent, n is known as the strain hardening coefficients and K is the strength coefficients which is also material property.

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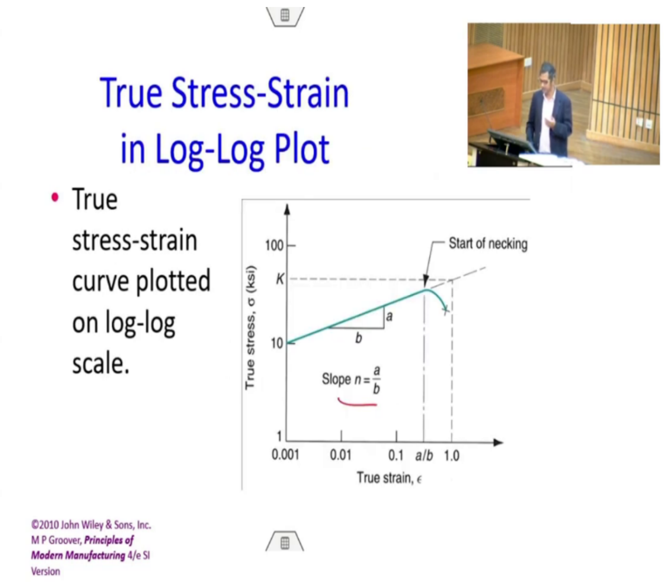

True Stress-Strain in Log-Log Plot

- True stress-strain curve plotted on log-log scale.

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So, strain hardening coefficient is measured like this way. So, if you plot log of true stress and log of true strain and then we will get a straight line that is very obvious. If I take log of $ln\sigma = lnK + nln\epsilon$, so, now, if I plot log $ln\sigma$, $ln\epsilon$ you get a straight line with a slope here and that is equal to lnK and the slope of this is basically n that is obvious right, that is mathematically what is possible.

So, you can measure the strain hardening coefficients by this way that is something which you should know very clearly.

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Categories of Stress-Strain Relationship: Perfectly Elast

- Behavior is defined completely by modulus of elasticity *E*
- Fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers

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Now, you know there are different types of materials in this world; you have plastic perfectly elastic material which has no plastic region, it goes and fractures. So, window glass is like that you just deform it will fracture after the elastic limit at the elastic limit ok. So, like ceramics many cast iron thermosetting polymers they are like that; that is the very.

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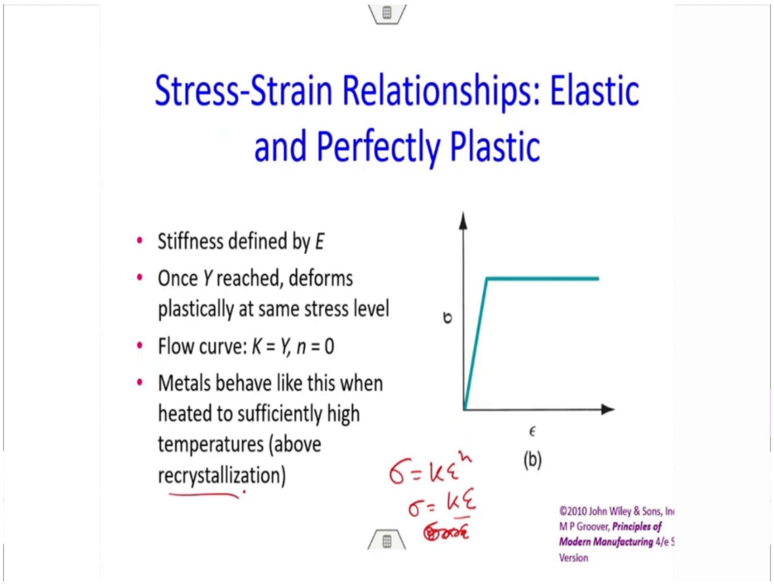

Stress-Strain Relationships: Elastic and Perfectly Plastic

- 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)

$\sigma = K\varepsilon^n$

$\sigma = K\underline{\varepsilon}$

[illegible]

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Then you can also have a perfectly plastic material ok; that means, you have a elastic and then a in the plastic regime the stress value remain constant so; that means, what in a flow curve n = 0 and K =Y. So, this flow curve $K\epsilon^n$, n is equal to 0, $\sigma = K\epsilon$, that means, what sigma is basically like a constant time ϵ, σ is proportional to. That is what you see here also, you see here also, basically here it is constant there is no change because K is a constant. So, therefore, for a material that will live on a flat.

So, metals behave like this when heated to sufficiently high temperature. So, you may not know about the crystallization, but that is ok high temperature if you heat it up it behaves like that otherwise you do not see such a kind of behavior.

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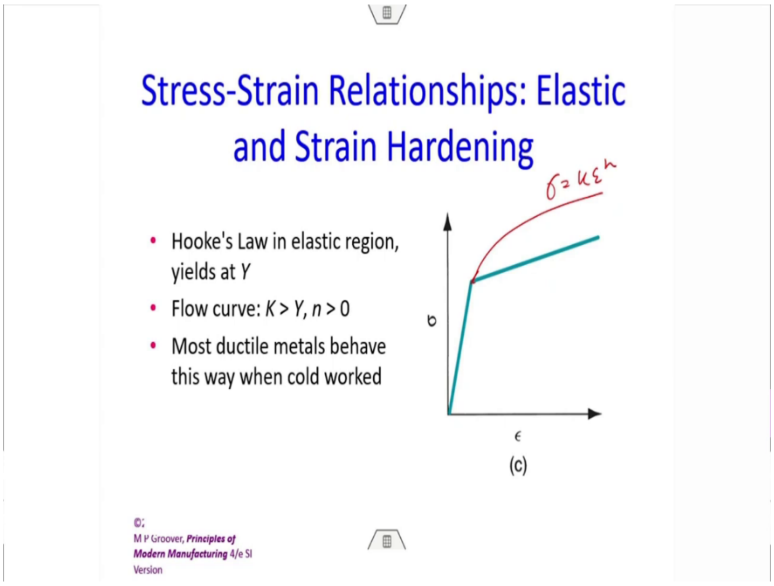

Stress-Strain Relationships: Elastic and Strain Hardening

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

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And then you can have elastic and strain hardening behavior which is more widely seen ok more with ductile metals behave like that. Here you see there is a elastic portion and there is a strain hardening portion ok. In fact, this looks like that ok not like a straight line, but a curved and that is the equation which is given as $K\epsilon^n$, right.

So, here flow for the flow curve K is Y, $K > Y$ and $n > 0$, but $n < 1$ also n is not more than 1.

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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

Mohr

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Well, you know most of the cases you may not be able to measure the you know do the tensile test. So, easiest way to understand or measure the mechanical property is hardness. You must know that you know diamond is the hardest material, because it can make scratch on anything and talc is the softest material that is why you apply talc on your body not only because of flavour, but also it is very soft.

So, in between there are 10 scale like you know the Mohr scale ok m o h r, he discovered the scale from diamond to talc 10 materials and the in terms of hard decreasing hardness ok. So, hardness is what? Resistance to permanent or plastic deformations. Good hardness generally means material is resistant to scratching and wear. Most tooling used in manufacturing must be hard against the scratch and the wear resistance that is what is very very important.

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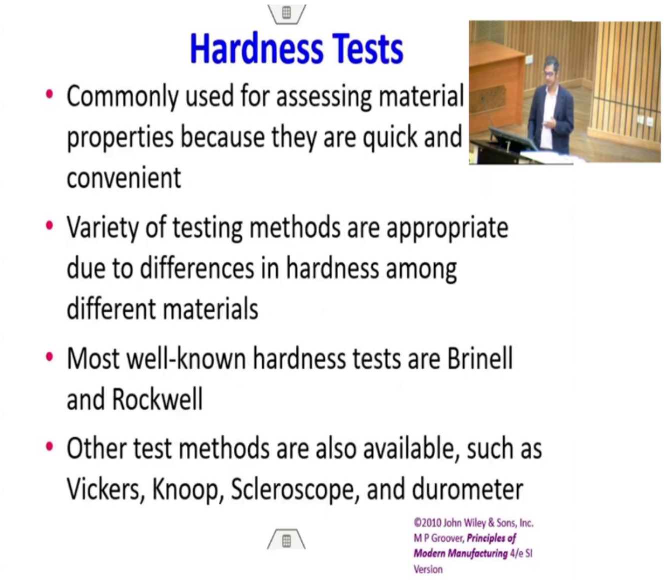

Hardness Tests

- 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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And you know commonly used hardness test processing material property are you know that is because hardness is very quick and convenient. There are various of testing methods available right. Most well-known is Brinell and Rockwell and also there are other tests available like Vickers, Knoop, Scleroscopes or even Durometer so, but you do not need not know all of this.

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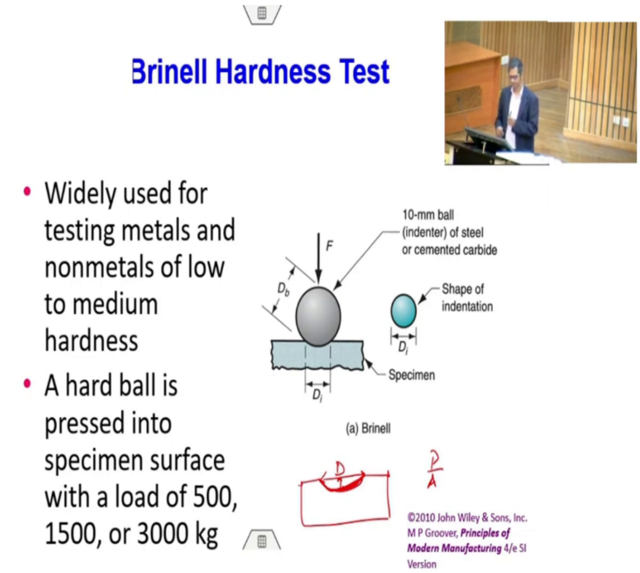

Brinell Hardness Test

- 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

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Vickers and Brinell is more widely used, and Vicker, Brinell hardness (Refer Time: 22:22) which is widely used technique, you use a ball indenter and apply force on the ball. So, the indenter goes and make a permanent mark in the material then you measure the diameter of that ok.

Once you measure diameter of that then you can measure the area it makes. So, if you know the area on the sample surface, sample surface will look like this. So, this is the because of the ball ok this is the indentation mark. So, if you know the diameter of that you can measure if you measure the area and if your load divide by area is what gives you the hardness again the same thing stress correct. So, hard balls pressed in the specimen surface. So 500, 1500, 3000 kgs very high load applied ok.

You know how to convert these kgs into load right, if you have to multiply with by the maybe gravity acceleration due to gravity right. If it is kg you have to multiply 9.8 newton per centimetre meter square then only you get what is the value of the force.

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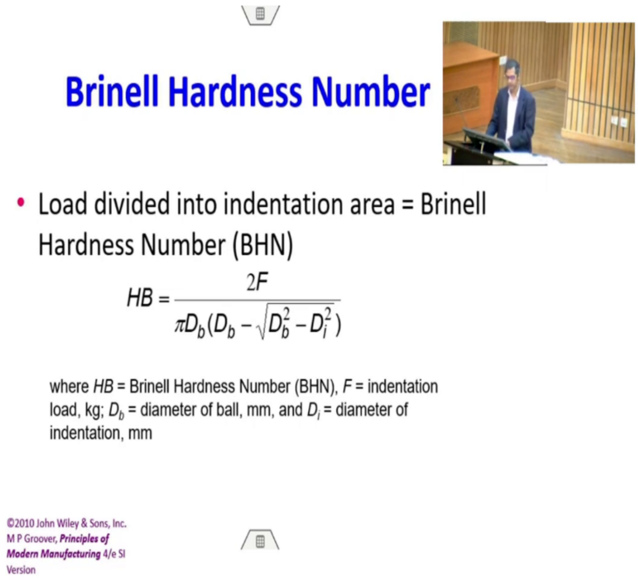

Brinell Hardness Number

- 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

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Brinell hardness tester is measured like this ok. You see this is what is the formula $\frac{2F}{\pi D_b(D_b - \sqrt{(D_b^2 - D_i^2)})}$ its basically it is not πD_b^2 square ok it is basically $\pi D_b\sqrt{(D_b^2 - D_i^2)}$ correct that is what is widely used.

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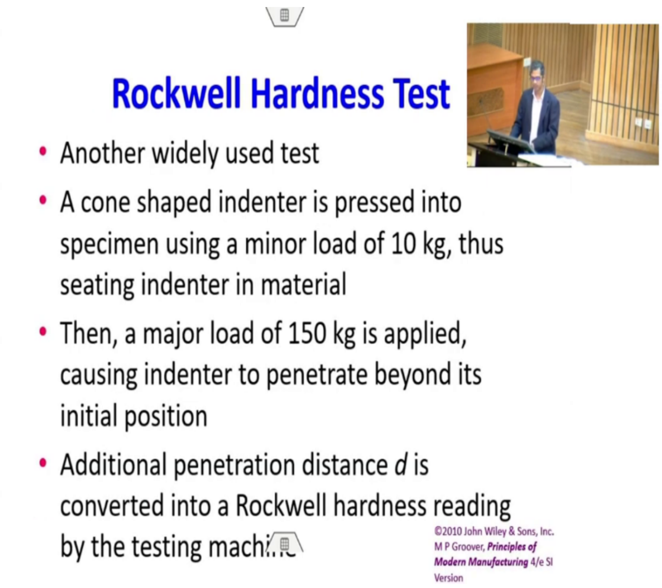

Rockwell Hardness Test

- 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

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Anyway, you can remember this formula, you can derive it. And Rockwell hardness testing does not measure anything, it measures basically depth does not measures area, but measure depth. A cone shaped indenter is pressed into specimen using a minor load of 10 kilograms or even less.

And that is what you know you can always apply higher load like 150 kilograms if you want to you know causing indenter to penetrate beyond the certain position it depends on the hardness of the material also. So, then you can measure the depth and from the depth you can calculate the hardness.

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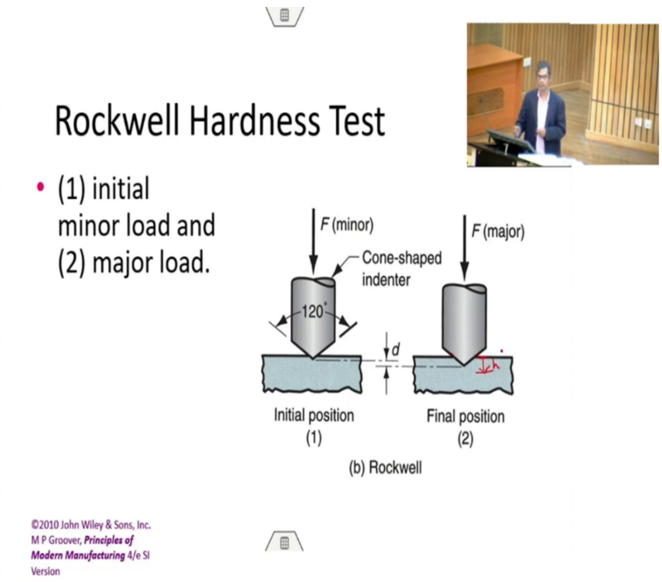

Rockwell Hardness Test

- (1) initial minor load and (2) major load.

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So, you see that this is the indenter and if you apply load it make a depth ok you can see that this is a depth sorry this is a depth not this one. So, this depth is what is used for measure of hardness.

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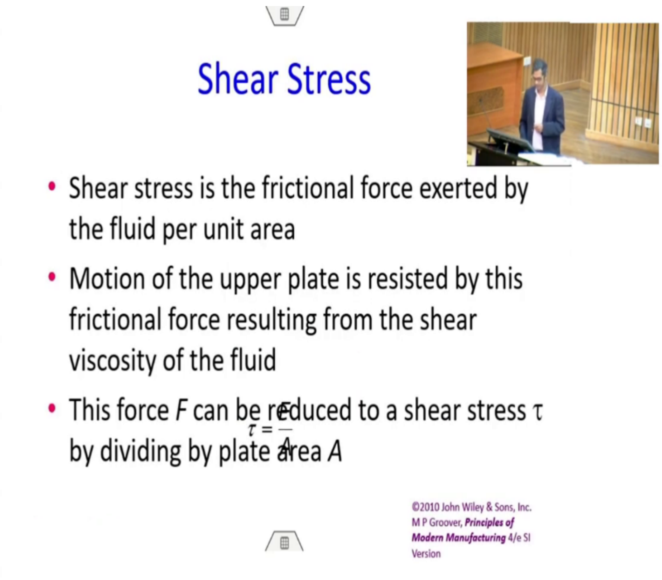

Shear Stress

- Shear stress is the frictional force exerted by the fluid per unit area
- Motion of the upper plate is resisted by this 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

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

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Well, another important aspect I said is the shear stress. Shear stress is frictional force exerted you know in a case of fluids, but in the solid it is this kind of stress which are applied. This force can be reduced to shear stress by dividing the area A ok.

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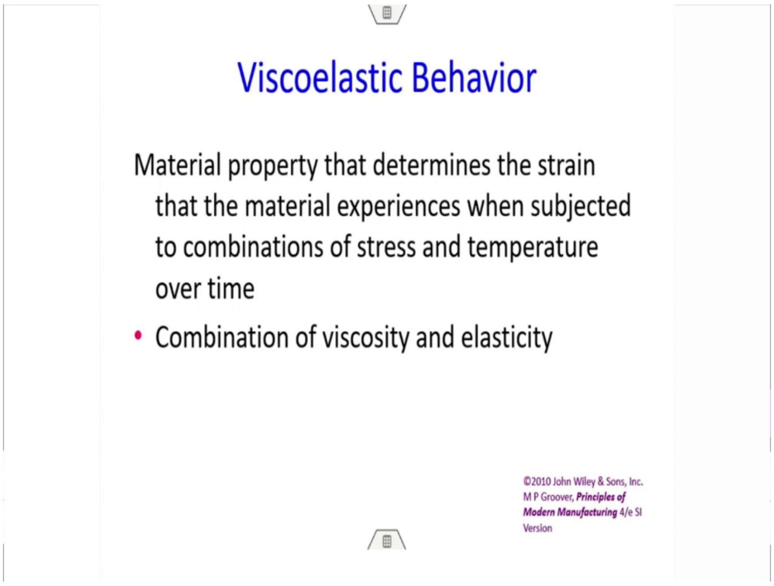

Viscoelastic Behavior

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

- Combination of viscosity and elasticity

Now, let us also discuss a bit of the viscoelastic behavior which is material observed in case of polymers. You know material property that determines a strain that material experiences when subjected to the combination of stress and temperature over time that is what is the viscoelastic there. Viscoelastic mean viscous and elastic is a combination of viscosity, elasticity. Many of you read about polymer sources behavior.

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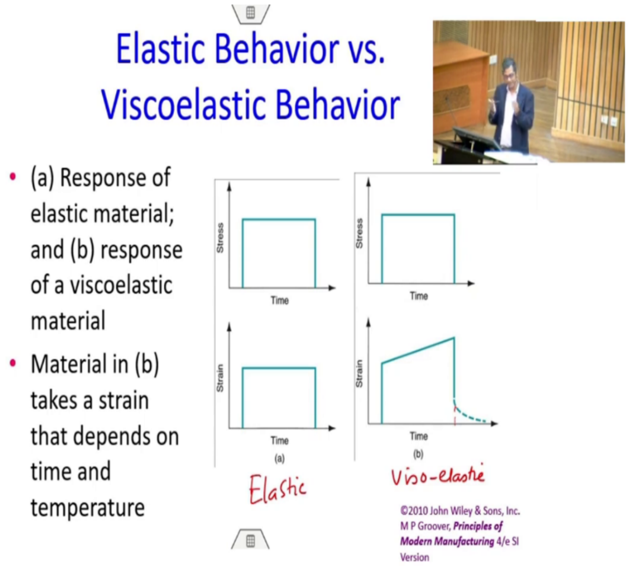

Elastic Behavior vs. Viscoelastic Behavior

- (a) Response of elastic material; and (b) response of a viscoelastic material
- Material in (b) takes a strain that depends on time and temperature

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So, this is the response of elastic material and response of a viscoelastic material, see this is the elastic and this is the viscoelastic. So, in case of elastic material if you apply a strain and then you keep it and you drop the load immediately it comes back. In case of viscoelastic it increases and once you drop it, it does not come back immediately right this part is missing, rather it is an elastic.

It depends on the time; this relaxation depends on the time. That is why it is called viscoelastic. It is because material is so viscous, the molecules once they stretch they take time to come back correct. So, all this elastic behavior the shape should come back to original positions, but it takes time to come back. In case of elastic materials it happens instantaneously it does not took it does not take time, but in case of viscoelastic it takes some time to come back.

That is mainly because of these you know viscous behavior of the liquid. You know although you have applied the load and if the molecules have extended they are stretched basically so, coming back to the unstress condition takes some time ok.

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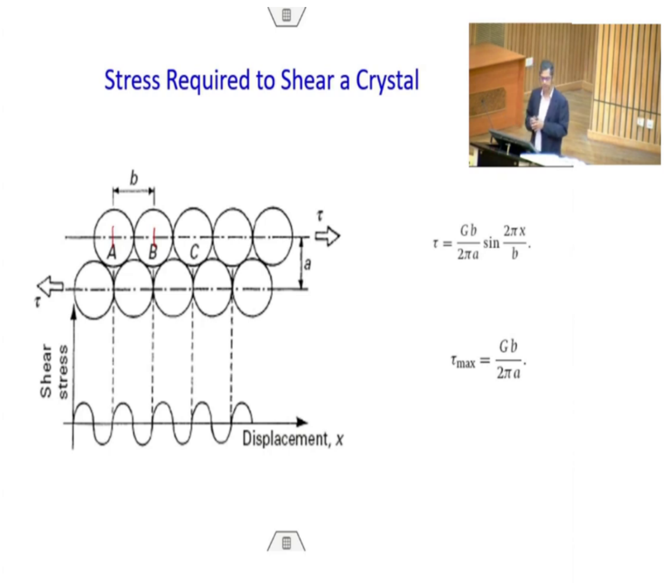

Stress Required to Shear a Crystal

$\tau = \frac{Gb}{2\pi a}\sin\frac{2\pi x}{b}.$

$\tau_{\max} = \frac{Gb}{2\pi a}.$

So, that is for the first part of the things which in which I have discussed about various aspects of stress strain, behavior, other material, how to measure it, tensile stress, hardness stress and a bit of viscoelastic behavior. Now it is important to for you to know also the defects in certain material, how these defects play a role and determine the mechanical behavior. To give an idea perspective why do you need the defects.

You know if you look at any material any crystalline material and if you want to shear the material and you know if really you want to shear the material without any defect you require a huge stress that is basically equal to given by $\frac{Gb}{2\pi a}$. What is why G? G is basically shear modulus and b is this distance from one centre of one atom to the other centre of the other atom and a is basically inter layer distance ok.

So, that is how actually one can calculate, but if you look at that this value is very high because b by a is basically is almost same constant, b by a will be almost close to 1. So, basically that means, it becomes $\frac{G}{2\,\pi}$ and π is 3.14; that means, say is $\frac{G}{6}$. So, that means, the theoretically speaking the material should have a strength equal to shear modulus divide by 6 or 7 basically if you consider that is fine 6 to 7.

But practically we do not see the material behaving showing such a high strength, practically you see the material show the strength of $\frac{G}{100}$ $\frac{G}{100}$; that means, materials actually break much lower stress. So, then what actually happening, why this is the; there is you know gap between measure and the theoretically you know calculated value based on this model what I discussed us now.

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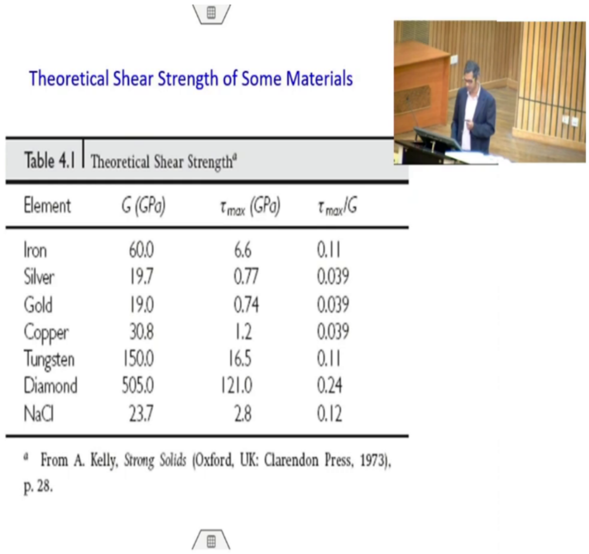

Theoretical Shear Strength of Some Materials

Table 4.1 Theoretical Shear Strength[a]

Element	G (GPa)	τ_{max} (GPa)	τ_{max}/G
Iron	60.0	6.6	0.11
Silver	19.7	0.77	0.039
Gold	19.0	0.74	0.039
Copper	30.8	1.2	0.039
Tungsten	150.0	16.5	0.11
Diamond	505.0	121.0	0.24
NaCl	23.7	2.8	0.12

[a] From A. Kelly, *Strong Solids* (Oxford, UK: Clarendon Press, 1973), p. 28.

That is was led to the defects in the material. So, if you look at this theoretical shear strengths of material like iron, silver even diamond and sodium chloride is very high extremely high. And you know it is in impossible this is what tabulated by Kelly in his classic book Strong Solids.

So, this is what the value normally you should get if you apply the formula for the theoretical shear strength and if you look at $\frac{\tau_{max}}{G}$ that is pretty high is close to many cases even in case of diamond is 24 percentage. That is impossible to get actually real materials because real materials have a lot of defects inside it. And this defects actually makes a material flow much earlier stress and fail also at much earlier stress that is what it is.

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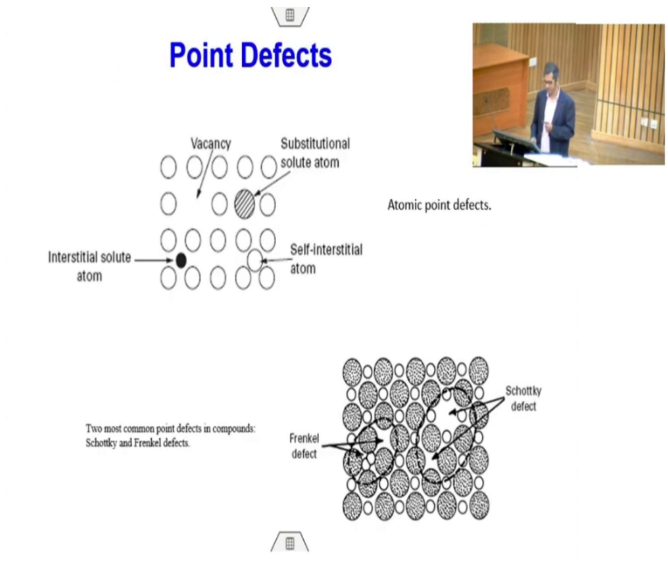

Point Defects

Vacancy

Substitutional solute atom

Interstitial solute atom

Self-interstitial atom

Atomic point defects.

Two most common point defects in compounds: Schottky and Frenkel defects.

Frenkel defect

Schottky defect

So, there are defects means you have point effects which are widely all of you know vacancy is a point defects you can have substitutional solute in alloy, you can also have self as interstitial atoms or you can have interstitial atoms or in case of ionic compounds you can have Frenkel defects or Schottky defects ok. Let us not discuss about those aspect these defects are known as point defect they are very important for various deformation behavior also.

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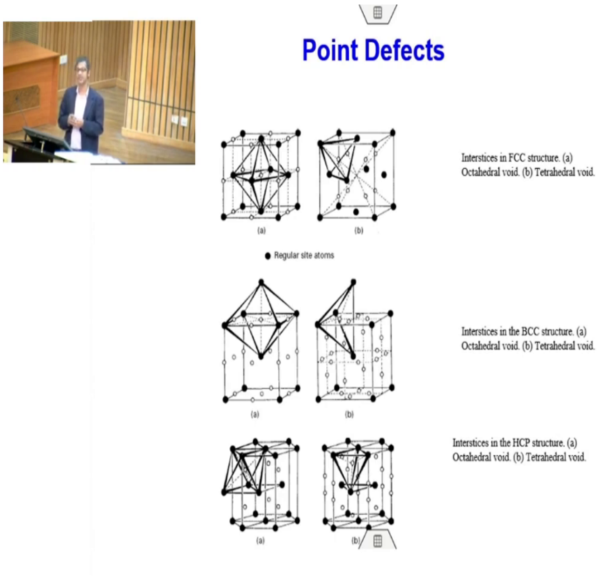

Point Defects

(a) (b)

● Regular site atoms

Interstices in FCC structure. (a) Octahedral void. (b) Tetrahedral void.

(a) (b)

Interstices in the BCC structure. (a) Octahedral void. (b) Tetrahedral void.

(a) (b)

Interstices in the HCP structure. (a) Octahedral void. (b) Tetrahedral void.

Well, now you know there are also point defects like octahedral void, tetrahedral void these are solid atoms present in different kinds of lattices, BCC, FCC or HCP lattices this all you know. So, you can put atoms inside this they will act an interstitial, interstitial is a defect.

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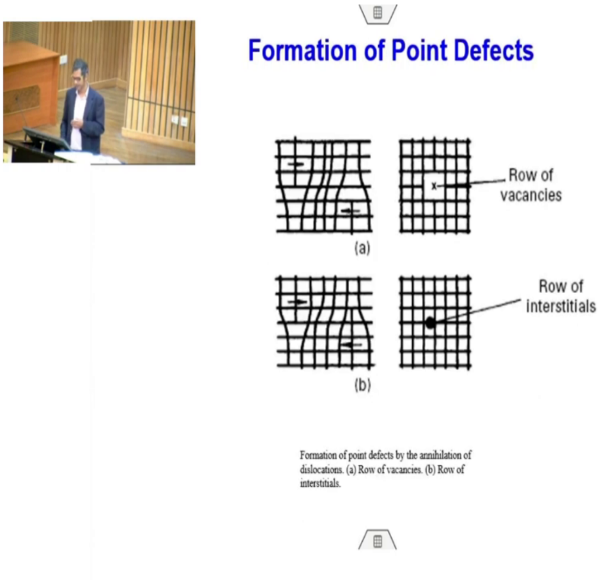

Formation of Point Defects

Formation of point defects by the annihilation of dislocations. (a) Row of vacancies. (b) Row of interstitials.

Well, they are sometimes the interstitial can come together and form a row of vacancies or it can form row of interstitials. So, defects can be extended also, this is all possible in case of different kinds of material.

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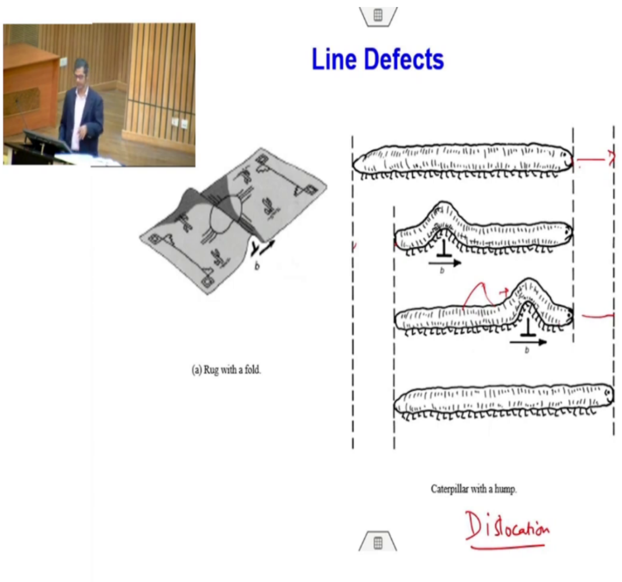

Line Defects

(a) Rug with a fold.

Caterpillar with a hump.

Dislocation

But the most important defects is the line defects ok. So, what is the line defects? In order to understand line defects all of you will have you know as you know mattresses in your home. So, whenever you want to unwrap a mattress you just open it up, but think of you know just if there is a fold in the mattress and you want to remove it. So, jerk it up. So, you will see that fold slowly moves from one end other ends, that is what is known as a rug enough with a fold ok.

So, dislocation is exactly like that, dislocation existence of the material and if you apply a shear force it moves in the material; that is what happens. And this also can be compared like a caterpillar; so, motion of a caterpillar. If you look at this is the caterpillar correct and now you wants to move from here to here.

So, it can jump, but they does not jump actually, caterpillars are very smart guys they want to spend least amount of energy to do that least. So, what they do? They just take a bend if they make a bend like this because there is a thousands of legs and then this bends actually move you can see by bending it, it has move from here to there right. So, this bends slowly then moves from here, there, then there ok and then on the stratum it reaches there.

So, dislocation also moves like that exactly like a rugged with a fold correct. That is how actually a dislocation motion happens in a material. And they are anyway by the way I already told you about dislocations, the dislocation is the most important line defect and we will be discussing more about it in the this lecture and maybe next couple of lecture also.

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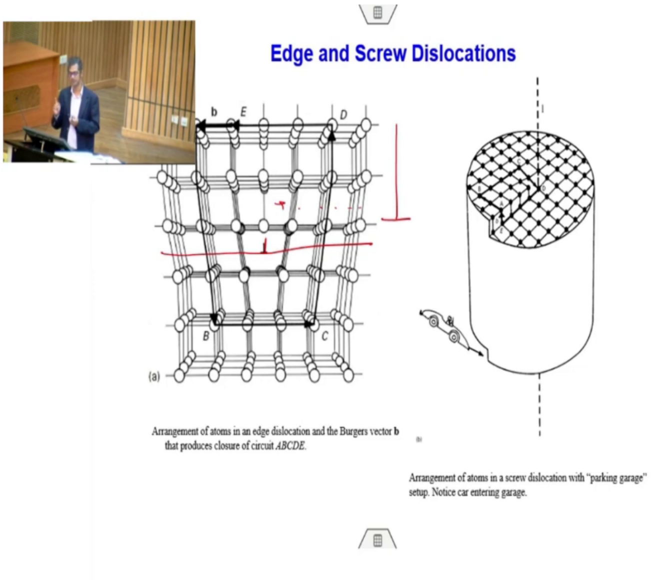

Edge and Screw Dislocations

Arrangement of atoms in an edge dislocation and the Burgers vector **b** that produces closure of circuit *ABCDE*.

Arrangement of atoms in a screw dislocation with "parking garage" setup. Notice car entering garage.

Dislocations can be two type edge and screw, edge dislocations has in a very simple way of looking it, they will have a this is the plane and this is the line they are perpendicular to each other and sheared in screw dislocation this is not true ok. Actually, sheared screw dislocations the line and the plane are parallel to each other correct. The extra half plane which is known as that this is they are parallel to each other.

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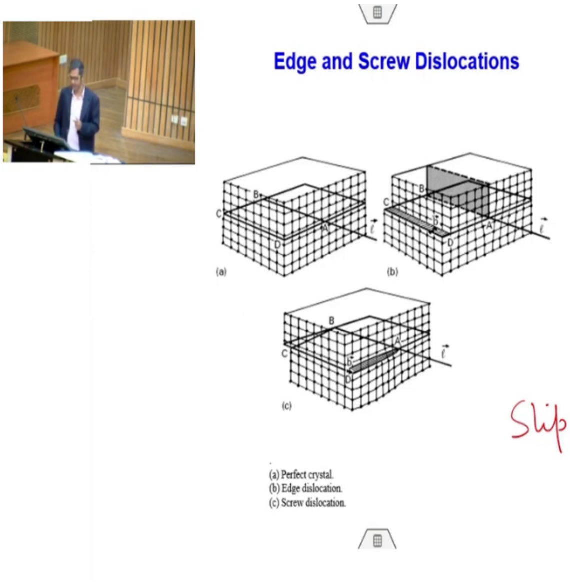

Edge and Screw Dislocations

(a) Perfect crystal.
(b) Edge dislocation.
(c) Screw dislocation.

Now, this can be explained in many ways, but nonetheless dislocation motion leads to what is known as a slip ok or extra step. It is very clear right, this extra plane as it moves from here to here to here, here and reaches the surface it will create extra step; that is understandable screw also same thing. So, why it is known as screw, because it looks like a screw from the top of the dislocation that is why it is known as a screw.

So, whatever you do dislocation motion when reaches to surface it creates a step and that step is known as slip ok. So, and by creating many many such steps you can deform a material, you can move a material from one person to other person, because it is moving by atomic columns, but still it is a movement of the material right.

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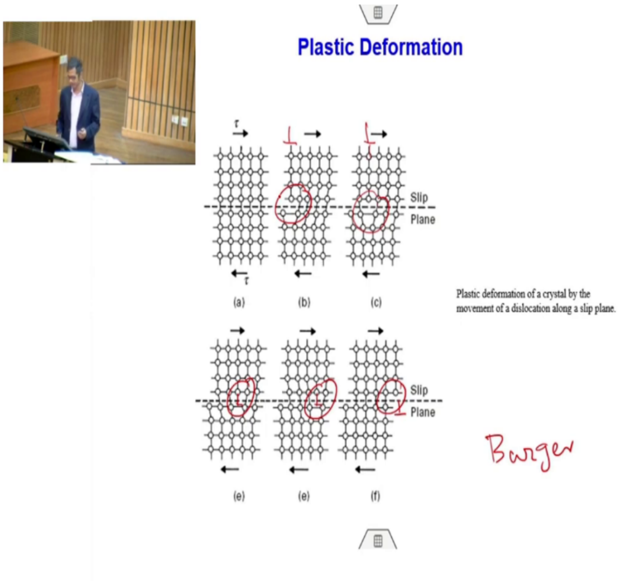

Plastic Deformation

Plastic deformation of a crystal by the movement of a dislocation along a slip plane.

So, that is what is shown here. You see that this is the you know this is the bond broken here, this is the perfectly crystal you apply shear force, you just broken a bond and create a dislocations ok. And then this row of atoms move to the next row equivalent dislocation moves here, you can see dislocations here, dislocation is over here and these bonds are joined.

And then again this dislocation moves here, dislocation moves here, dislocation move over the surface. So, it creates a step and this is the slip plane. And this is what happens in the edge dislocation, when you move a edge dislocations from one part of the crystal to the other part of the crystals as you can clearly see over a slip plane.

So, this step what is created here the end this step actually known as a slip step and this plastic is derived to something known as a Burger vector ok. This is the same Burger who discovered many things, same Burger vector who discovered many things.

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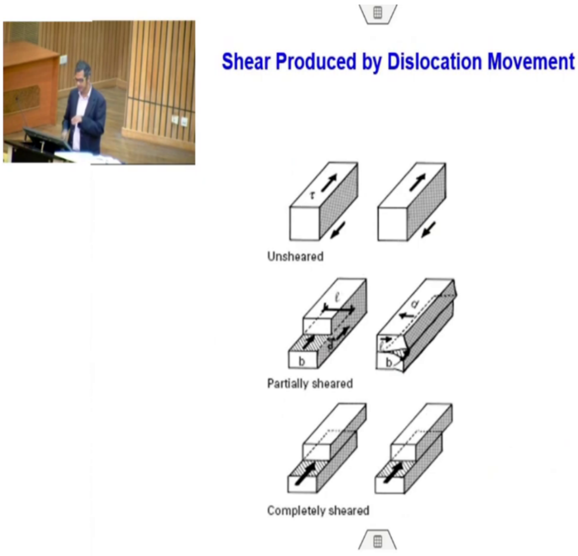

Shear Produced by Dislocation Movement

And you know it also produced shear ok let me also explain you. So, that is you have seen that this is because of the shear ok shear moments right. So, shear in a macroscopic scale if you apply shear it can produce a partially sheared region, you can see that and create a step that is very easy.

If you have two plates like this, if you move like that it creates a partially shear region that is what it does very easily right, very very easily it does like that. So, now, this is exactly what is true in many many cases.

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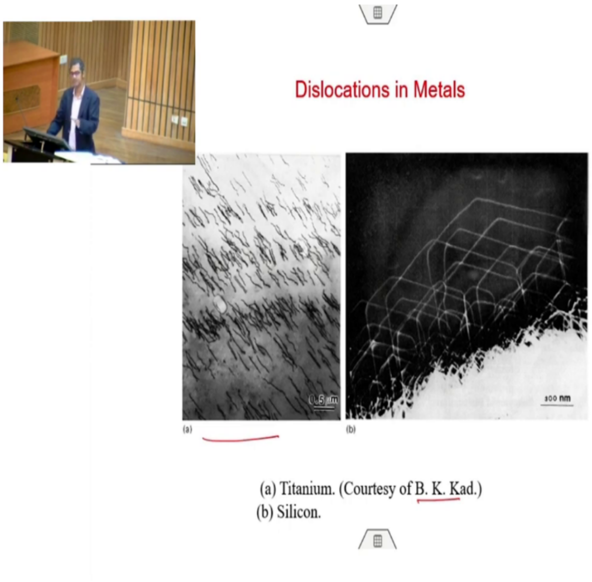

Dislocations in Metals

(a) Titanium. (Courtesy of B. K. Kad.)
(b) Silicon.

Well, how does the dislocation looks in the real materials? So let discuss about say 10 minutes or so and we can stop this lecture. Well, dislocations cannot be seen by any other technique other than TEM actually. It can be obtained idea can be obtained this was present by different kind of microscopic techniques, but transmission electron microscope is the only technique by which you can visualize a dislocation.

That is why it took some time to see that you can see dislocation looks like a line, this is the dislocations in a titanium and so, I am taking some pictures from such a kind of persons ok. So, and this is in a silicon. Silicon dislocations are more straight, but in a metal like titanium dislocations are like a curvy. This is something which because of the nature of the material, like in silicon bonding is different and then the titanium and that is why that this behavior is different.

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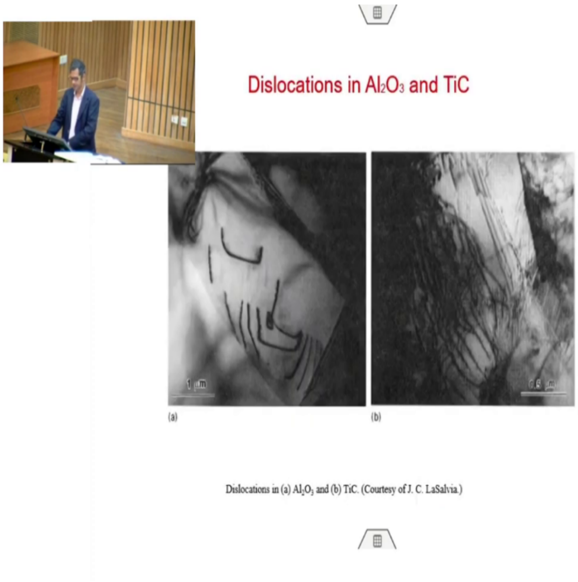

Dislocations in Al_2O_3 and TiC

Dislocations in (a) Al_2O_3 and (b) TiC. (Courtesy of J. C. LaSalvia.)

Well, you can also see some dislocations in ceramics like in an aluminium oxide or in a titanium carbide. In aluminium oxide also dislocations are curved, but; that means, the ceramics also deform by motion of dislocations. Although they are more less ductile than metals, but deformation is observed that is what I wanted to mean to say.

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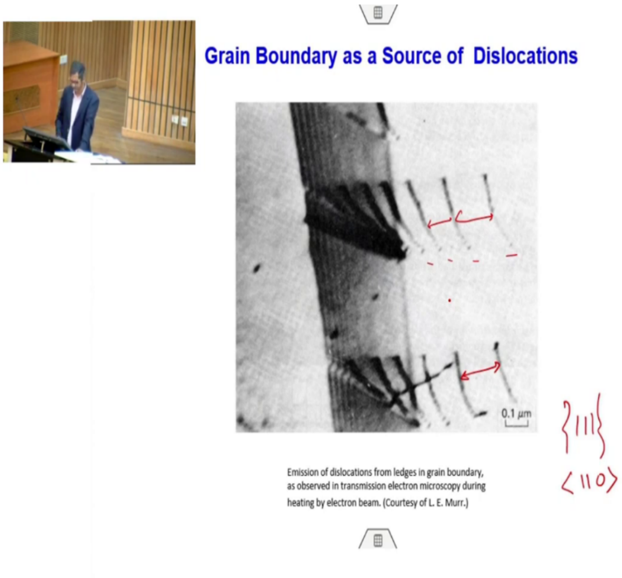

Grain Boundary as a Source of Dislocations

Emission of dislocations from ledges in grain boundary, as observed in transmission electron microscopy during heating by electron beam. (Courtesy of L. E. Murr.)

Well, you know how the dislocation is generated? Dislocation mostly generated by source or the grain boundaries in a mild polycrystalline material. That is what is normally seen in a polycrystalline material dislocations are generated from the grain boundaries. Grain boundaries as we discussed a lot in our previous few lectures in a polycrystalline material they are the main source of dislocation generation.

And here is a picture taken from L. E. Murr ok in a transmission microscopic images, correct, you can see here how dislocations are getting generated from the grain boundaries very easily. So, dislocation generates from the grain boundary and then slowly moves in the grain boundary you can see here one by one dislocation moving inside the grain correct.

So, there is a distance maintained between two dislocation you can see there ok, this distance must be maintained because there is a stress field associate dislocation this extra row of atoms as you have seen here extra row of atom and then this portion is bent actually. You can clearly see atoms are bent here extended here in this regime.

So, because of that because of this nature there will be there will be a lot of strain, now strain means there will be stress field around it. And the stress field will not allow dislocations to come close as close as possible ok. By the way the stress field will overlap and then it is not it will lead to increase of (Refer Time: 38:25) many things can happen there.

But it is not advisable or not possible rather to have this two-dislocation coming closer than certain distance. In fact, the distance can be also calculated knowing the stress field and other Burger vector and many other things ok.

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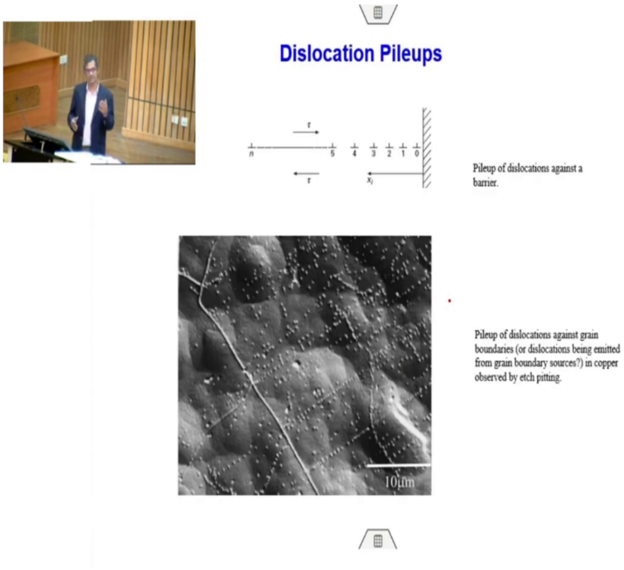

Dislocation Pileups

Pileup of dislocations against a barrier.

Pileup of dislocations against grain boundaries (or dislocations being emitted from grain boundary sources?) in copper observed by etch pitting.

So, now the dislocation generated like this they are moving inside the grain correct. So, then what will happen? They will go to the next grain boundary ok something like this, this dislocation which are coming they will go to the next grain boundary. And then at the grain boundary they will find an obstacle, you must be thinking why, that is very simple because grain and grain boundary structurally are different they are not same.

Secondly, each grain are crystallography oriented differently. So, fact that this dislocation moving on this grain; that means, this grain is oriented in such way these are the this is the slip plane; that is why they are moving. As you know in FCC the slip plane is 111 right, this is the closest packed plane 111 type of plane that is what we should do it ok. So, 111 type of planes are basically the slip plane and the direction is 110 right that is what it is.

So, in this case if this is a FCC material, then this plane must be oriented along 111 correct. So, then normal on this plane should be 111, but next grain may not be same that is why next grain is not same as this grain the orientations are different; that is how we define the different grains actually.

So, because of these two aspects, so, one is the grain boundary structure is different, other one is that the grains are not oriented same way. So, dislocations moving in a one grain will not be able to directly move into the other grain, so that means, what? Dislocations will find grain boundary as an obstacle to move.

Well, you can think, you can also imagine the dislocation can jump over and reach the other grain, that is not easy at normal temperatures. That happens only at high temperature when dislocation can climb over a ladder or over this kind of obstacles just like you know in case of hurdle races that the person comes and jump over each hurdle and move that is possible in dislocation at high temperature not at normal temperatures ok. So, nonetheless grain boundaries act as a pile up.

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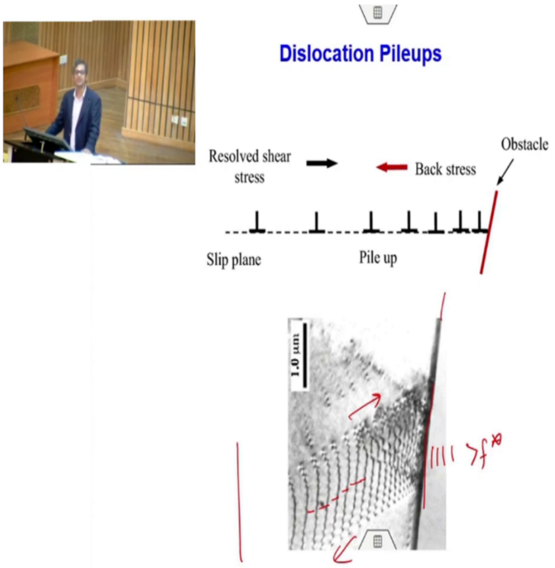

Dislocation Pileups

So, this is a picture which is showing you can see these are the dislocations which are going inside that grain and then comes at the grain boundary and they could not move farther. So, they then pile up just like a railway station. In Indian railway stations when some people are buying tickets you see the piling up of the passengers, right.

Passengers are standing one by one and slowly the line is increases and the piling up happens, it is routinely seen in case of railways railway ticket booking centres ok. So, same thing happens here. So, ticket counter action is now obstacle correct.

The moment the passenger at the front of the ticket counter buys the ticket, passenger leaves then the line moves. But most of the cases line does not change really its length remains almost constant and increases that is because passengers are more right.

So, here dislocation is moving inside the grain come and contact with the dislocation and stops. That is why we write this grain boundary as an obstacle and this as a pile up, but as you know as it piles up it creates a back stress. What is that? Very simple; if you are standing in a queue if the front guy is little bit moving you know like this there is a stress applied to the person behind him and this leads to a back stress.

The person sitting at the further sorry behind at the end of the line also feels feel a force that is what is known as the back stress correct. So, the resolved shear stress is acting like this and back stress is acting like this, this is known as the back stress because it is applying in the backward directions.

So, two things you understand, dislocation generate from the one grain boundary here, moved and reached the other side of the grain boundary and piled up. Pile up and lead to back stress the two things you must be very clear about it, very very clear about it why these are important ok.

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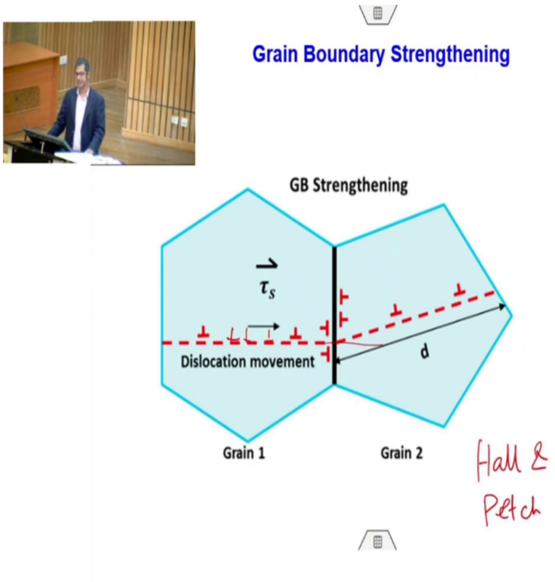

Grain Boundary Strengthening

Hall & Petch

Well, so these aspects looked very important concept what is known as a grain boundary strengthening ok, that means, what? Grain boundaries will act as a strengthening agent. This is increasing strength of the material, grain boundary is a defect, but you know defect is leading to increase of the strength. Why? That is just what I understandable here.

See this is the two grains or this is a two-grain model, you can see this is the plane slip plane, dislocation moving like this and then reach at the grain boundary pile ups correct. So, in order to start the dislocation motion on the other grain the enough stress should be applied.

So, that the other grain start deforming and dislocations start moving. Or it should be like that the two grains are the same kind of slip planes at a certain deviation from the angle it was like this correct, but normally that does not happen slip planes will not be arranged like that way.

So, therefore, dislocation will slowly pile up, as it pile ups it creates a stress on the boundary and this stress. So, it is a critical value then it will lead to generation of dislocations or movement of dislocation on the other grain, then deformation will proceeds. That is the model which is developed by Hall and Petch ok, two gentlemen very famous Hall and Petch coined this model that grain boundaries indeed act as a strengthening agents and this is how happens.

Now, if you go back here that is what you see here; the dislocations will maintain a distance in the pile up and then created a back stress on the grain boundary and if this back stress reaches a critical stress more than a critical stress this can lead to dislocation motion in the other grain.

Once it is successful to do that then the plastic deformation starts in the other grain and it follows up subsequent grains correct. So, that is because that this pile up has led to a pile up happened because of this grain boundary is the reason for strengthening correct that is the main reason for strengthening.

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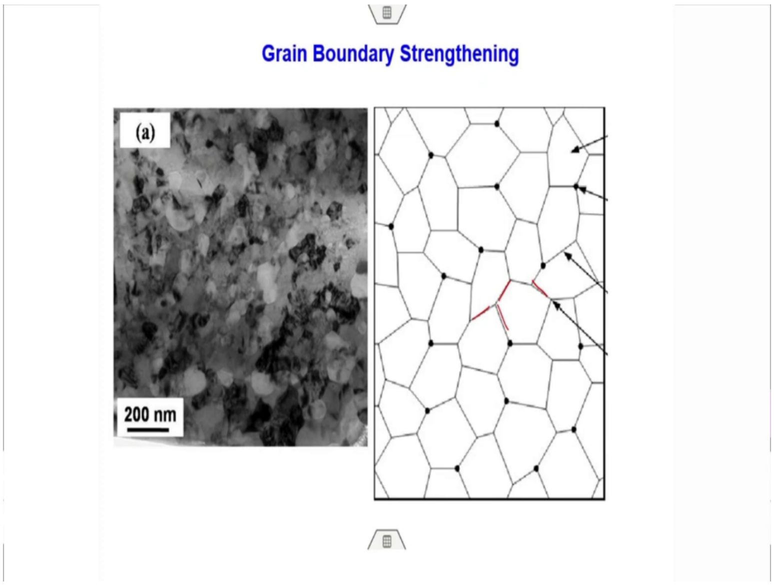

Grain Boundary Strengthening

Well, so as you know in a multi crystalline and nano crystalline material with milli grains, these are the grain, there are so many grain boundaries correct. Large amount of grain boundary area and this large grain boundary area will create large amount of pile up and that will lead to more hardening; this is expected correct, that is what is normally observed.

Now, can you model it? Yes, it is possible to model it, it is possible to develop equation to do that and that equation is known as Hall-Petch equations.

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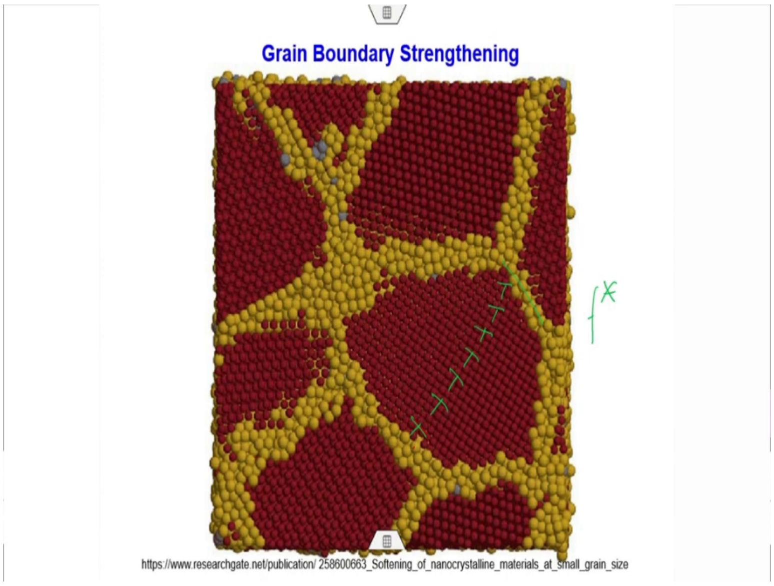

Grain Boundary Strengthening

https://www.researchgate.net/publication/ 258600663_Softening_of_nanocrystalline_materials_at_small_grain_size

So, let me tell you atomistically what can happen. You see the grain boundary which is more open structure is the grain. So, if you generate dislocations like that ok if you generate dislocation like this one here, another one, another one like that, you can see. Then this row of dislocations gets piled up at this other grain boundary and then in order to start the dislocations activity in this grain the sufficient amount of stress must be generated.

So, that dislocation activity will start in the neighbouring grain correct. So, that stress must be more than a critical stress this can be measured depending orientation of the grains also. So, let me stop here. In the next lecture we will discuss about this aspect more and then I will we will tell you how (Refer Time: 46:52).

Thank you.