Mechanical Behaviour of Materials
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Lecture -20
Introduction to Dislocations – VIII

Hello, I am Professor S. Sankaran in the Department of Metallurgical and Materials Engineering.

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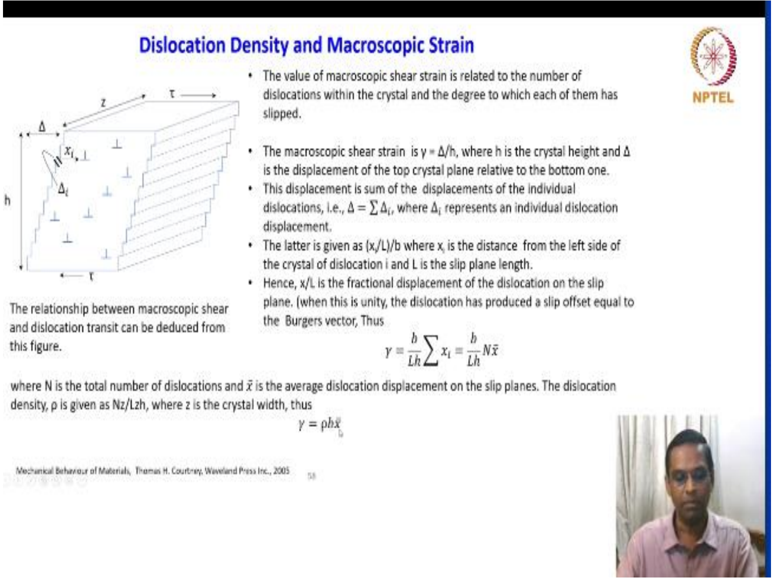

Dislocation Density and Macroscopic Strain

- The value of macroscopic shear strain is related to the number of dislocations within the crystal and the degree to which each of them has slipped.
- The macroscopic shear strain is $\gamma = \Delta/h$, where h is the crystal height and Δ is the displacement of the top crystal plane relative to the bottom one.
- This displacement is sum of the displacements of the individual dislocations, i.e., $\Delta = \sum \Delta_i$, where Δ_i represents an individual dislocation displacement.
- The latter is given as $(x_i/L)/b$ where x_i is the distance from the left side of the crystal of dislocation i and L is the slip plane length.
- Hence, x/L is the fractional displacement of the dislocation on the slip plane. (when this is unity, the dislocation has produced a slip offset equal to the Burgers vector, Thus

The relationship between macroscopic shear and dislocation transit can be deduced from this figure.

$$\gamma = \frac{b}{Lh}\sum x_i = \frac{b}{Lh}N\bar{x}$$

where N is the total number of dislocations and $\bar{x}$ is the average dislocation displacement on the slip planes. The dislocation density, ρ is given as Nz/Lzh, where z is the crystal width, thus

$$\gamma = \rho b\bar{x}$$

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

Now, I am turning to another important mechanics aspect of or macroscopic aspect of deformation. See when we say that the dislocation density is increased in the material and then we talked about how the material behaviour gets influenced by this and so on. So, what is it its influence on the macroscopic strain see ultimately when the strain I mean the dislocation produces, the shear strain in a very localised matter.

Suppose if you consider all the displacement produced by each dislocation in this material ultimately they should contribute to the total strain or a macroscopic strain. So, I just want to connect that aspect through this slide. So, the look at this the unit or crystallite it has slipped you can see the multiple slip line the whole crystallise slip because you know the meaning of this kind of a diagram now.

It is a shear complete shear and this is the height is h and displacement is Δ and dimension here is the length is z and the shear forces applied in these two directions. The relationship between macroscopic shear and a dislocation transit can be deduced from this figure. So, how do we understand this? The value of macroscopic shear strain is related to the number of dislocations within the crystal and the degree to which each of them has slipped.

So, the total strain stored in the material has something to do with what each individual dislocation experience inside the crystal that is the message the bottom line. So, the macroscopic shear strain is $\gamma = \Delta/ h$ this is straight forward from this displacement by the h, where h is the crystal height and Δ is the displacement of the top crystal plane relative to the bottom one because it is a pure shear.

This displacement is some of the displacements of individual dislocations that is

$$\Delta = \sum \Delta i$$

where Δ_i represents an individual dislocation displacement very important. And it also gives a first perspective why we study the dislocation nature in terms of what material responses it produces. The latter is given as what is the latter here the individual dislocation displacement is given as $(x_i/L)/b$, where x_i is that distance from the left side of the crystal of the dislocation i and the L the slip plane length, so this is for any individual dislocations. Hence x/L is the fractional displacement of the dislocation on the slip plane when this is unity, the dislocation has produced a slip offset equal to the burgers vector. Thus, we can write that shear strain = b / Lh, what is b / Lh? We are taking these things from this total macroscopic shear and then we are substituting with individual displacement.

$$\gamma = \frac{b}{Lh} \sum x_i = \frac{b}{Lh} N\bar{x}$$

where N is the total number of dislocations and $\bar{x}$ is the average dislocation displacement on slip planes. The dislocation density rho is given us Nz/Lzh, where z is the crystal width, thus this we see that the γ, the macroscopic shear strain

$$\gamma = \rho b \bar{x}$$

this is one important expression relating the dislocation density with macroscopic shear strain.

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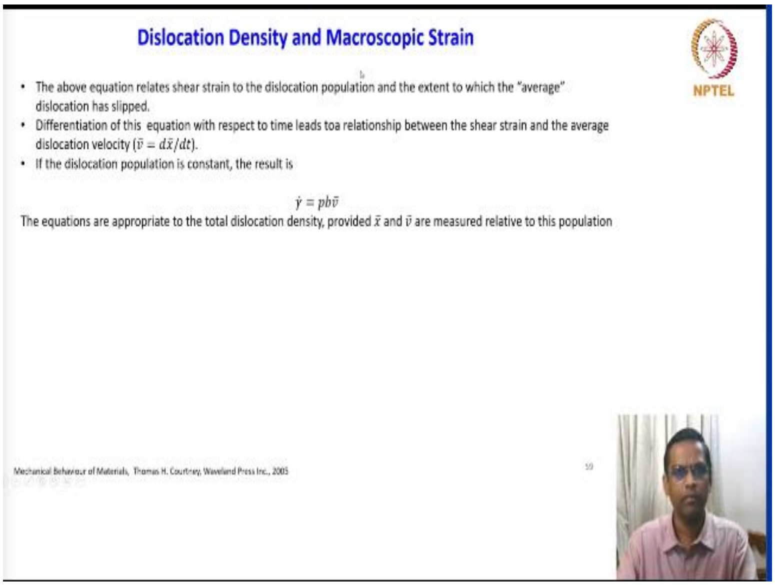

Dislocation Density and Macroscopic Strain

- The above equation relates shear strain to the dislocation population and the extent to which the "average" dislocation has slipped.
- Differentiation of this equation with respect to time leads toa relationship between the shear strain and the average dislocation velocity ($\bar{v} = d\bar{x}/dt$).
- If the dislocation population is constant, the result is

$$\dot{\gamma} = pb\bar{v}$$

The equations are appropriate to the total dislocation density, provided $\bar{x}$ and $\bar{v}$ are measured relative to this population

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

So, the above equation relates the shear strain for the dislocation population and the extent to which the average dislocation has slipped. And then differentiation of this equation with respect to the time leads to a relationship between a shear strain and an average dislocation velocity

$$\bar{v} = \frac{d\bar{x}}{dt}$$

this is again an interesting aspect. If the dislocation population is constant, then we can write that gamma shear rate gamma dot is equal to this is not p this is rho it is a type error here rho bv bar.

$$\dot{\gamma} = \rho b\bar{v}$$

So, this is a shear rate is related to the dislocation velocity, this is again a very interesting point to note. So, what we have that is the equations that are appropriate to the total dislocation density provided $\bar{x}$ and $\bar{v}$ are measured relative to this population. So, all these equations are valid for a total dislocation densities not pertaining to any particular type of dislocation of something it is a macroscopic strain just give you an idea of why, what is the connection between the dislocation density and the actual stock exchange that is another fundamental aspects that is why I wanted to discuss this.

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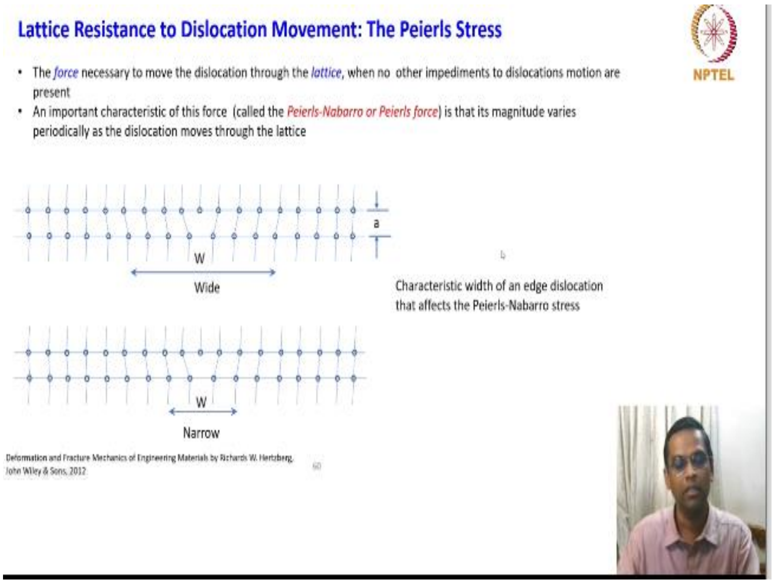

Lattice Resistance to Dislocation Movement: The Peierls Stress

- The *force* necessary to move the dislocation through the *lattice*, when no other impediments to dislocations motion are present
- An important characteristic of this force (called the *Peierls-Nabarro or Peierls force*) is that its magnitude varies periodically as the dislocation moves through the lattice

Characteristic width of an edge dislocation that affects the Peierls-Nabarro stress

Deformation and Fracture Mechanics of Engineering Materials by Richards W. Hertzberg, John Wiley & Sons, 2012

And finally, I want to introduce another interesting parameter lattice resistance to dislocation movement. So, the Peierls stress so, we have studied now what are the forces on dislocation, what is the stress field around dislocation, what is the minimum force that is required to move dislocation inside the crystal. Suppose, we have one just dislocation sitting in the perfect crystal, how much energy is required to move them or how much stress is required to move them in a lattice.

This is of very primary important conceptually not quantified for any systems, but conceptually this very important parameter. So, I thought you know this before we talk about dislocation motion economy, etcetera. The force necessary to move dislocation through the lattice when no other impediments to the dislocation motion are present. An important characteristic of this force called Peierls-Nabarro or Peierls force is that its magnitude varies periodically at the dislocation moving through the lattice.

So that means, the Peierls stress is not going to be a constant factor is going to vary and as you I mean, it is going to be very different depending upon the characteristic of which is that is what it means. So, look at this schematic is very interesting schematic, what is shown here is a characteristic width of an edge dislocation that affects the Peierls-Nabarro stress. Characteristic width, what is this characteristic width? So, this is a lattice and these are all straight bond which is continuing from the top and the bottom.

This is a lattice parameter a and something I have marked the here as W and the similar thing where I have returned wide and this is this W as Narrow. So, what is W? Let us try to understand that first. So, the extra half plane is inserted here and because of that there is a disturbance in the interatomic spacing the neighbourhood. So, if you look at this is straight bond this is straight, this is straight it started going incline the question incline, incline, incline.

So, suppose the extra half plane is inserted here how much distortion it creates or how far the distortion is going through. So, that is the measure of the W because of this edge dislocation got inserted how much disturbance it creates on both sides of the lattice. This is for a single dislocation because we are interested in studying this Peierls stress moving this dislocation. So, that means, if you look at this figure this if you look at the bond here they are all straight, but it starts distorting only from this point so, that is the W here.

So, compared to this and this this is a narrow width, this is a wider width so, what does it mean? It means it is going to be a characteristic of a material how it is going to distort its lattice in the presence of any dislocation. So, indirectly what is that we are saying? We are saying how much is the bond strength or the resistant force? Now, we go back to our fundamental idea the bond strength the resisting force.

Suppose if you insert the dislocation how much it resists or how much it is allowing or how much it is responding indirectly that is one way of looking at it. So, this is going to decide the stress required or a force required to move a dislocation in the lattice. So, the characteristic width is going to decide.

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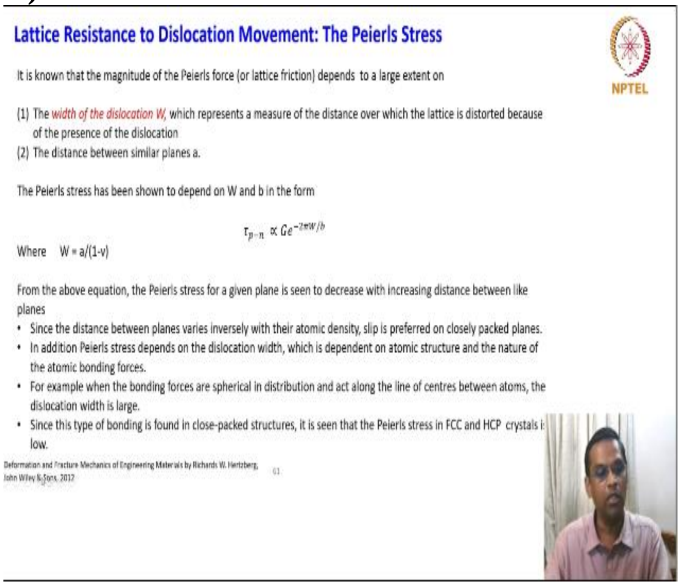

Lattice Resistance to Dislocation Movement: The Peierls Stress

It is known that the magnitude of the Peierls force (or lattice friction) depends to a large extent on

(1) The *width of the dislocation W*, which represents a measure of the distance over which the lattice is distorted because of the presence of the dislocation
(2) The distance between similar planes a.

The Peierls stress has been shown to depend on W and b in the form

$$\tau_{p-n} \propto G e^{-2\pi W/b}$$

Where W = a/(1-v)

From the above equation, the Peierls stress for a given plane is seen to decrease with increasing distance between like planes

- Since the distance between planes varies inversely with their atomic density, slip is preferred on closely packed planes.
- In addition Peierls stress depends on the dislocation width, which is dependent on atomic structure and the nature of the atomic bonding forces.
- For example when the bonding forces are spherical in distribution and act along the line of centres between atoms, the dislocation width is large.
- Since this type of bonding is found in close-packed structures, it is seen that the Peierls stress in FCC and HCP crystals i low.

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So, how it is going to decide? It is known that the magnitude of the Peierls stress or a lattice friction depends to a large extent on one the width of the dislocation W which represents a measure of distance over which the lattice is distorted because of the presence of dislocation. And the distance between the similar planes a that is extended. The Peierls stress has been shown to depend on W and b in the form

$$\tau_{p-n} \propto Ge^{-2\pi W/b}$$

Where,

$$W = a/(1-v),$$

$(1-v)$ you know it is because edge dislocation.

From the above equation, the Peierls stress for a given plane is seen to decrease with increasing distance between like planes. Since the distance between the planes varies inversely with their atomic density slip is preferred on it closely packed planes, these are all very fundamental ideas which gives us much more perspective about this concept. In addition, Peierls stress depends on the dislocation width which is dependent on atomic structure and the nature of atomic bonding forces.

So, now we are coming to a very fundamental idea bonding forces that is how we started this course. Now, where do we stand now we are now talking about the force required to move a dislocation lattice strongly connected to atomic bonding forces. For example in the bonding forces are spherical in distribution and act along the line of centres between the atoms the dislocation with this large. So, what does it mean?

Your bonding should not be directional in nature; the bonding should be spherical that means something like you have electron cloud in the matters. It is spherical around all that there is it is not like ionic or covalent bonds which are highly directional. So, in these kinds of situations the Peierls stress will be smaller, very important and nice idea. Since this type of bonding is found in close packed structures, it is seen that Peierls stress in FCC and HCP crystal is low.

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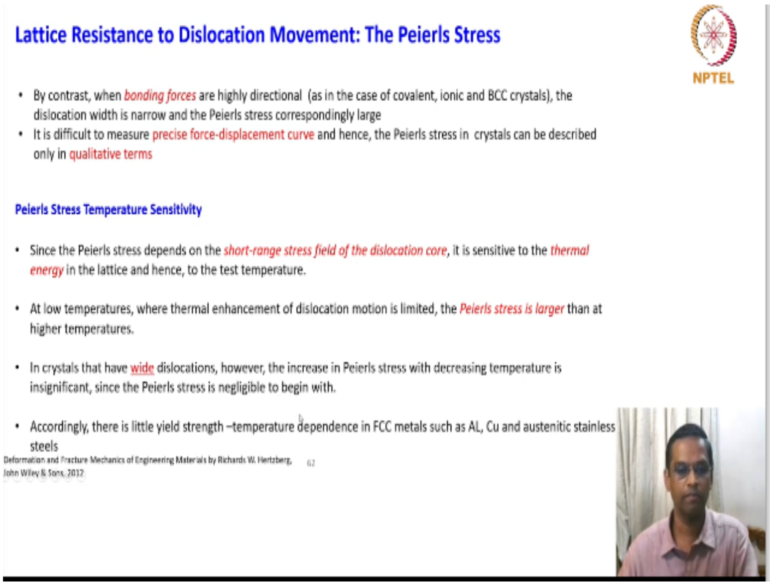

Lattice Resistance to Dislocation Movement: The Peierls Stress

- By contrast, when *bonding forces* are highly directional (as in the case of covalent, ionic and BCC crystals), the dislocation width is narrow and the Peierls stress correspondingly large
- It is difficult to measure precise force-displacement curve and hence, the Peierls stress in crystals can be described only in qualitative terms

Peierls Stress Temperature Sensitivity

- Since the Peierls stress depends on the *short-range stress field of the dislocation core*, it is sensitive to the *thermal energy* in the lattice and hence, to the test temperature.
- At low temperatures, where thermal enhancement of dislocation motion is limited, the *Peierls stress is larger* than at higher temperatures.
- In crystals that have wide dislocations, however, the increase in Peierls stress with decreasing temperature is insignificant, since the Peierls stress is negligible to begin with.
- Accordingly, there is little yield strength –temperature dependence in FCC metals such as AL, Cu and austenitic stainless steels

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By contrast, when bonding forces are highly directional, as in the case of covalent, ionic and BCC crystals, the dislocation with this narrow and Peierls stress correspondingly large very sharp connection between the very basic deformation characteristics and its bonding nature very important. It is difficult to measure precise force displacement curve for this I mean Peierls stress experiment. Hence the Peierls stress in crystals can be described only in qualitative terms not quantitative so far.

How was does, temperature affect the Peierls Stress temperature sensitivity? Since Peierls Stress depends on the short range stress field of dislocation core it is sensitive to the thermal energy in the lattice and hence the test temperature. At low temperature where thermal enhancement of dislocation motion is limited the Peierls Stress is larger than at high temperature. In crystals that have wide dislocations however, the increase in Peierls Stress with the decrease in temperature is insignificant.

Since the Peierls Stress is negligible to begin with for materials which is having a bite dislocation. Accordingly that is a little yield strength temperature dependence in FCC metals such as aluminium, copper and austenitic stainless steels. You see it has got immediate correlations we talk about you know wide dislocation what we thought the material will have wide dislocation typically the which is the material metals which causes FCC crystals to system like aluminium and copper and austenitic stainless steel.

They all will have very wide dislocation length w, the length of the w is quite large in this material and they do not have that much temperatures dependence Peierls stress.

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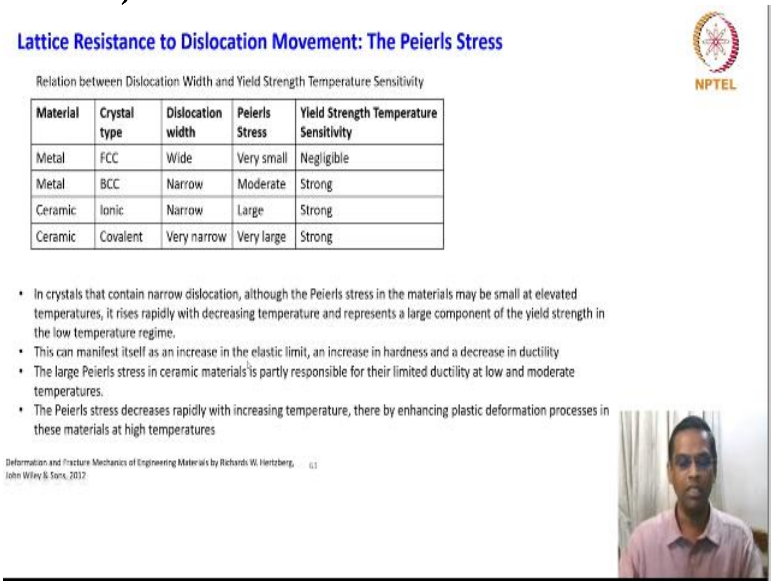

Lattice Resistance to Dislocation Movement: The Peierls Stress

Relation between Dislocation Width and Yield Strength Temperature Sensitivity

Material	Crystal type	Dislocation width	Peierls Stress	Yield Strength Temperature Sensitivity
Metal	FCC	Wide	Very small	Negligible
Metal	BCC	Narrow	Moderate	Strong
Ceramic	Ionic	Narrow	Large	Strong
Ceramic	Covalent	Very narrow	Very large	Strong

- In crystals that contain narrow dislocation, although the Peierls stress in the materials may be small at elevated temperatures, it rises rapidly with decreasing temperature and represents a large component of the yield strength in the low temperature regime.
- This can manifest itself as an increase in the elastic limit, an increase in hardness and a decrease in ductility
- The large Peierls stress in ceramic materials is partly responsible for their limited ductility at low and moderate temperatures.
- The Peierls stress decreases rapidly with increasing temperature, there by enhancing plastic deformation processes in these materials at high temperatures

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On the other hand, if you look at this table it is quite interesting. The relationship between dislocation width and yield strength temperature sensitivity. You take a material metal crystal type FCC, dislocation width wide, Peierls stress very small, yield strength temperature sensitivity negligible. You take a metal of BCC type dislocation with this narrow Peierls stress is moderate and temperature sensitivity strong.

So, even within these metals if it is BCC, FCC there is a huge difference in the Peierls stress so, it is very small it is moderate and temperature sensitive negligible adhere to them strong again. Coming to ceramic and if it is of ionic type the dislocation that is going to be narrow and the Peierls stress is large, very interesting and important point and then yield strength temperature sensitivity is also very very high.

And if you take ceramic which is of covalent bonded will have very narrow dislocation width and will have very large Peierls stress and very strong yield temperature sensitivity. So, what does it say in crystal that contain narrow dislocation although the Peierls stress in the materials may be small at elevated temperature, it raises rapidly with the decrease in temperature and represents a large component of the instant the low temperature regime.

This can manifest itself as an increase in the elastic limit an increase in the hardness and a decrease in ductility. So, now you can quickly connect these characteristics to the ceramic very high elastic modulus, very high hardness, very poor ductility. So, the large Peierls stress in ceramic material is partly responsible for the limited ductility at low and moderate temperatures. So, the Peierls stress decreases rapidly with increasing temperature thereby enhancing the plastic deformation process in these materials at high temperatures.

So, this is about material which is having ionic and covalent bonds, the Peierls stress decreases rapidly with increasing temperature. So, I think I have given you some prospects of you know dislocation and its various characteristics, how it is going to influence the material behaviour. I think this forms good background for proceeding further into this the core ideas of mechanical behaviour of materials.

So, from the next class I will get into the main ideas or main syllabus. So, I will go to the plastic deformation I will start with the plasticity theory principles very basic ideas and then we will proceed with the deformation characteristic of different kinds of materials. So, what we have looked at in all these lectures so far is we have I mean in principle I just took it as you know what all can be covered in theory of elasticity where all that is been used.

And how we describes that is why we looked at elastic stress line relations, elastic properties, and then anelasticity, description of dislocations and all this in you know domains, the theory of elasticity has contributed immensely in explaining all this behaviour. So, that is kind of you know careful domain we have covered and also it formed a very good starting point and background for the rest of this course. So, from next class onwards, we will deal with plastic deformation and we will start with the basic plasticity theory. Thank you.