Mechanical Behaviour of Materials
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Lecture - 24
Introduction to Plastic Deformation - III

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

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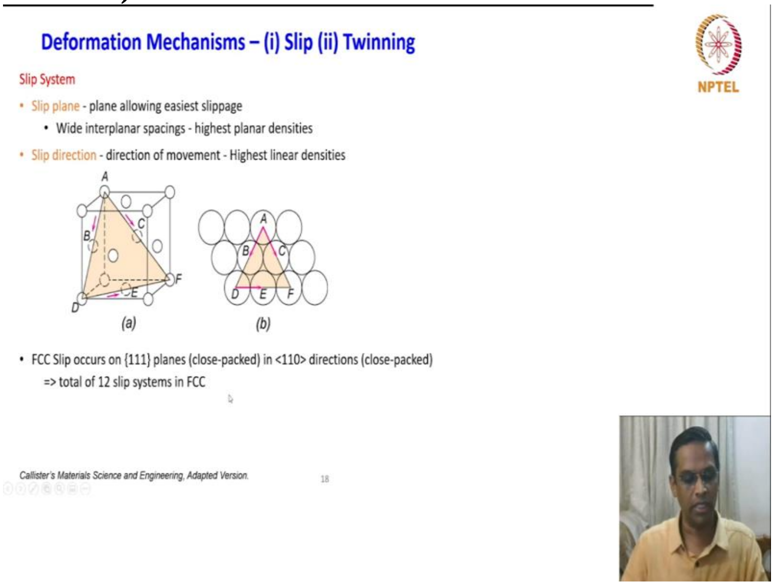

Hello, let us continue our discussion on this plastic deformation. In the last class we looked at what are all the fundamental issues with regard to yield criterion are fracture criterion and so on. We looked at two important yield criterion though there are different yield criterions are proposed, the popular ones are the Tresca criterion that is also called maximum shear stress criterion.

The other one is called von Mises yield or distortion energy criterion it is also called octahedral maximum shear stress criterion and so on. And then we also looked at the maximum principle normal stress fracture criterion which is mostly is suitable for brittle materials. On the other hand these two other criterions suitable for ductile materials. At the end, we also looked at the criterion which is these criterions how they are modified in the case of semi crystalline or polymeric materials or long molecule chain materials.

Incorporating this pressure effect how these expressions are modified and some new empirical models were proposed and this is what we have seen. So, now, we will move on to the deformation behaviour itself and the first topic we are going to addresses the deformation mechanisms of single crystals. And then we looked at we look at the what are all the aspects which describes the deformation mechanisms in a single crystal.

Then we will move on to poly crystal deformations. So, if you look at what are the primary mechanisms which governs the deformation is first slip risk training, we will first see what is slip? Slip in a crystallographic terms when you describe it the slipping of a large portion of crystal aggregate, so that is a slip normal slip and the slip is described by a term called slip system.

What is slip system? Slip system consists of two quantities 1 is slip plane, a plane allowing the easiest slippage, you know it is a simple term. Wide interplanar spacings and highest planar densities, these all the very important requirements for the easy slip that has to take place. And then slip direction, direction of the moment is highest linear density. So, a slip system consists of a slip plane and a slip direction and these are all the attributes.

Now, let us look at the example of you know highest dense plane and so, on. For example, here we have taken the face centred cubic crystal unit cell. And what you are seeing here is the 111 plane, which is also we have just seen in the previous lecture called octahedral plane and this plane has the highest planar density in a FCC system. And what you are seeing in that pink colour arrows indicating the direction you have a three directions.

Which can be easily identified from this. And if you take out this plane and then put it in a planar view and this is how it looks like this. So, there are A, B and then C type of atoms and then they are all stacked on the other end in the planar view but the top view I would say from this corner to C to all look like this ABC. So, FCC slip occurs on {111} planes that is you see that {111} is denoted by a flower bracket that means it is a family of planes.

They are also close packed planes in {110} direction this is also a family of directions also called closed pack direction. There are about twelve slip systems in face centred cubic lattice or face centred cubic crystal.

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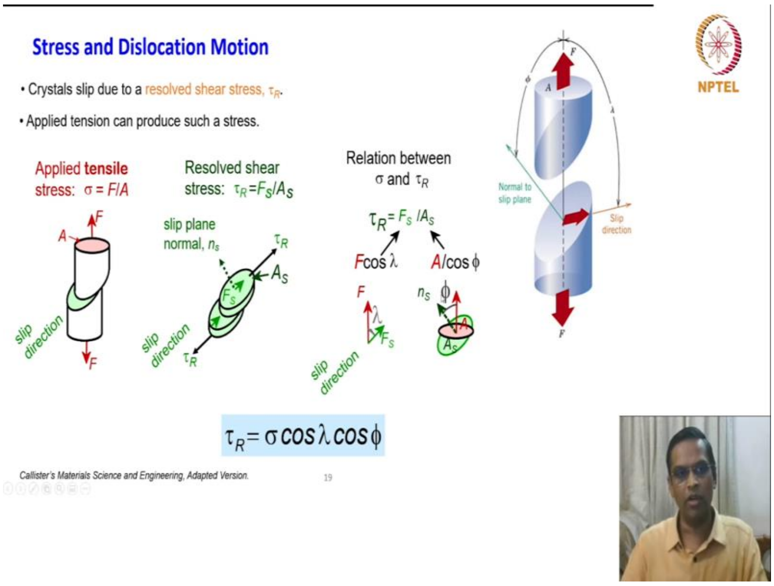

And then we will see how dislocation proceeds, dislocations proceeds so, because of the two aspects, first is because you are applying a load, which is measured as stress and because of that the dislocation moves in the crystal that is the primary action that takes place result in the deformation. So, this is a schematic which shows where we applied we apply the tensile force is F and the cylindrical member is getting slipped.

And the slipped area you can see that this is a slip direction and applied tensile stresses σ = F/A force by unit area. And we know that crystals slip due to a resolve shear stress τ_R, resolve shear stress. So, this we have already know that a total stress or normal stress can be resolved into shear stress and normal stress, total stress can be resolved into normal stress and shear stress.

So, slip I mean the shear causes by the resolved shear stress component of the stress applied stress. So, applying tension can produce such a stress and the resolved shear stress this τ_R is equal to the shear force (F_s) divided by the area (A_s) where the shear forces acting which will give the resolved shear stress. And if you look at the this schematic and it clearly depicts that the area which is subjected to the shear force as well as the plane on which the shear forces acting.

So, and then you see this n_s is a slip plane normal just to give the illustration clearly during this applied tensile stress versus resolve shear stress. And then if you look at the relation between sigma and τ_R we can just further you know expand this $\tau_R = F_s/A_s$. If you look at what is F_s and what is A_s and that for that I need to bring a more schematic here, this is a cylindrical member which is subjected to slip and then it is a slip plane and then this slip direction and the forces tensile force, uniaxial force and the area of the cylinder is A here.

And this is the green line is the normal to the slip plane which is kept at an angle 45° here. And the angle between the slip plane normal to the tensile axis is Φ and the angle between the slip direction and the tensile forces λ. So now, coming back to this relation between σ and τ_R and τ_R = F_s that is shear force divided by the area of the plane where the shear forces experience. So, F_s is F cosλ that means, the component the stress component which is contributing to this force in this λ that is in this direction.

The force which is perpendicular to this content the component which contributes to this slip plane is F cosλ. Similarly, the area this is A perpendicular I mean this is A which is where we see that you know the force is perpendicular to this plane but then the area which is actually subjected to the shear force is given by A/cosΦ because of this angular relationship. So, if you look at this substitutions then what you will see here is $\tau_R = \sigma \cos\lambda \cos\Phi$. So that is the kind of relation you get from the σ and τ_R. So, this is a fundamental requirement for the slip two takes place.

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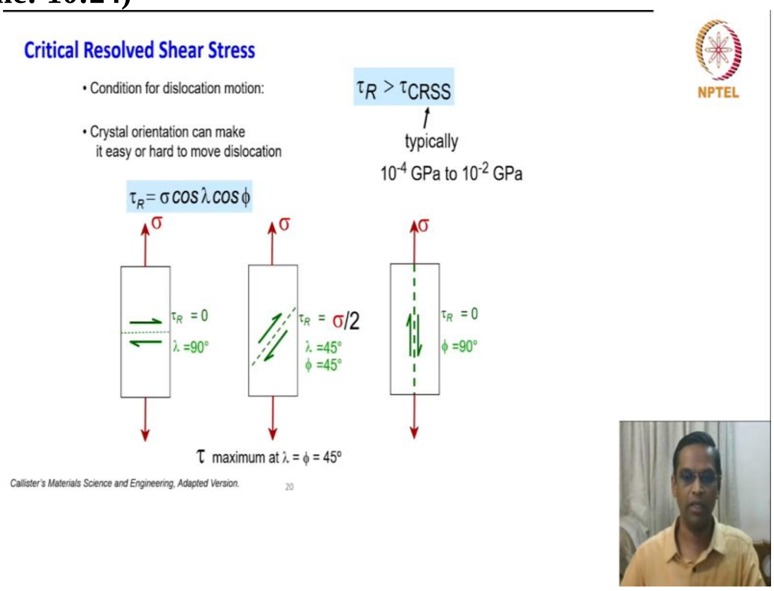

So, this is it is not that the resolved shear stress of any quantity will cause slip there is something called critical resolved shear stress that means, it is a kind of condition for dislocation motion, if you recall we have also seen that a stress required to move or dislocation suppose number equation if you recall it something similar to that you can you can relate that.

Of course, there it is assumed that the crystal is free of any other dislocation just one dislocation in a perfect crystal. But here we are talking about the bulk initial condition could be of any kind, but here also it is a single crystal a condition for dislocation motion the τ_R should be greater than τ or $\tau_R > \tau_{CRSS}$. So, it should be greater than the resolved shear stress should be greater than critical to resolved shear stress that is required to move in this location that is how you should look at it.

So, the critical resolved shear stress values are typically of 10^{-4} GPa to 10^{-2} GPa. The crystal orientation can make it easy or hard to move a dislocation, this is very important, we will look at the details as we move along and the $\tau_R = \sigma \cos\lambda \cos\Phi$. So, that clearly shows that the orientation is very important and we will show this by some schematic to explicitly arrive at the condition of a slip.

So, here you see that this rectangular member is subjected to a tensile force and then suppose if you assume that the λ is 90 degree and then what happens to the this critical results shear stress then it is 0 because λ will become 0 here and λ = 90 then this cos will become 0 and τ_R will become 0. On the other hand, if you take λ and Φ is 45 degree then it gives a value $\tau_R = \sigma/2$.

On the other hand, if you make Φ = 90 degree then also τ_R becomes 0. So, what it means is the τ maximum at λ and Φ = 45 degree. So, this is one simple substitutions which illustrates the maximum resolved shear stress is obtained at the angle of 45, this we have already seen in the yield criterion and even before that the shear stress plane and all that we have seen several times the maximum τ_{max} is 45 degree.

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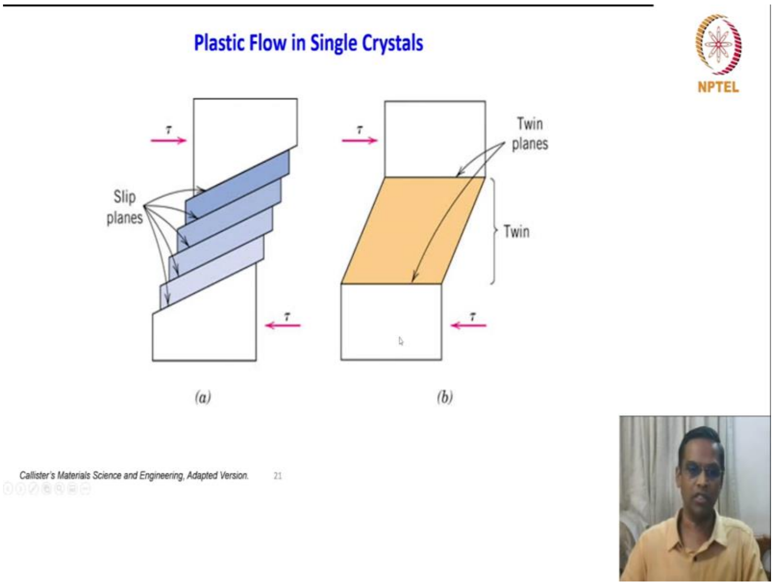

So, if you look at the plastic flow in a single crystal, so this is how the crystal will slip and then we can look at the slip planes the slip plane will appear like this against the shear force direction and each one will have the you know the slip planes may not be uniform like this it could be randomly I would say that it is a random aggregates of the slip plane will appear with the non uniform distance between them.

So, this is just a schematic which I am trying to show. So, this is how the slip plane will look like and the other hand the other mechanism stream will look like this. And we will see the details in a few minutes. But what you see here is this is a untwined plane and this is a twin planes and then in between you have the twin region and these are all the shear stress directions.

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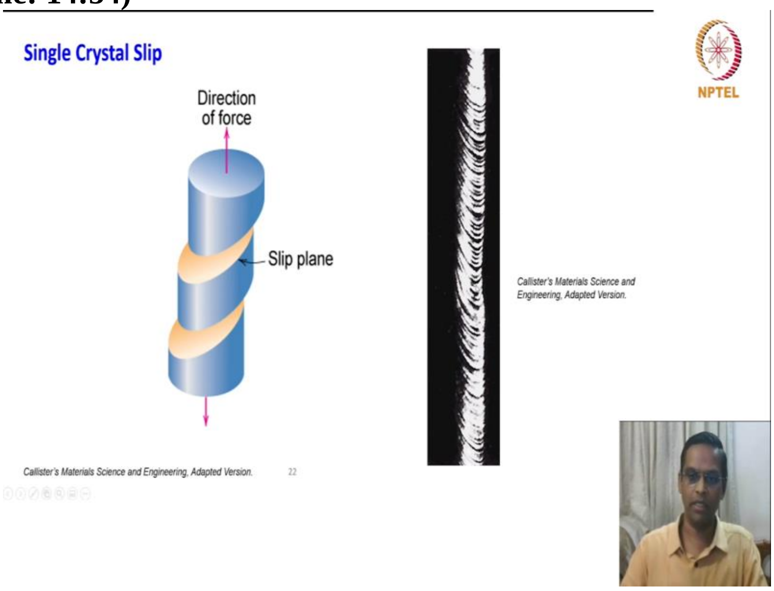

And this is a single crystal metallic's which you can see that the real time experiment which is given in this text I just brought to give an example how the slip planes exactly looking like what we have just shown in this schematic the real time slipped regions will exactly look like.

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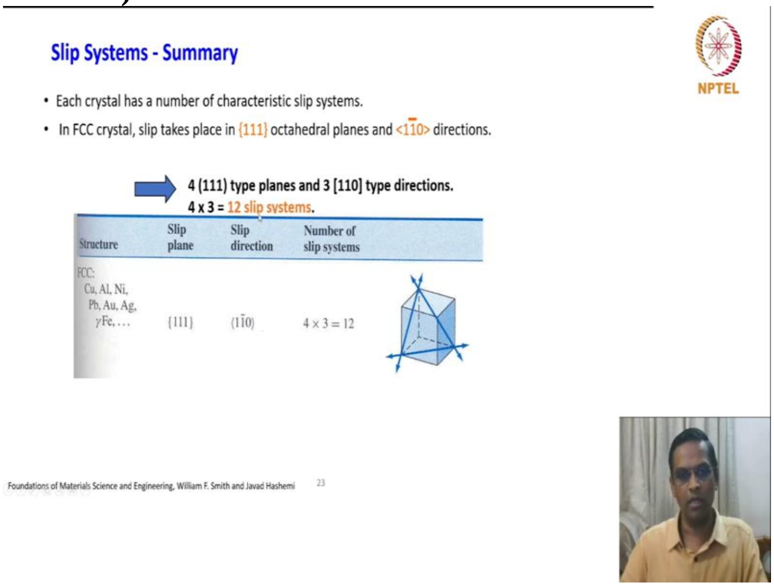

So, now we go a little more into the slip system each crystal has a number of characteristics slips systems. So, very important we are talking about a different type of crystal systems. So, each crystal system has got characteristics slip systems for example FCC will have already seen a slip takes place in {111} type of octahedral planes and <1$\bar{1}$0> directions and we have four types of (111) planes and three [110] direction. So, which is shown here in this schematic and four into three slip twelve slip systems. So, you have examples copper, nickel, aluminium, led, gold, silver, gamma iron and so on, they all belong to these kind of crystal systems.

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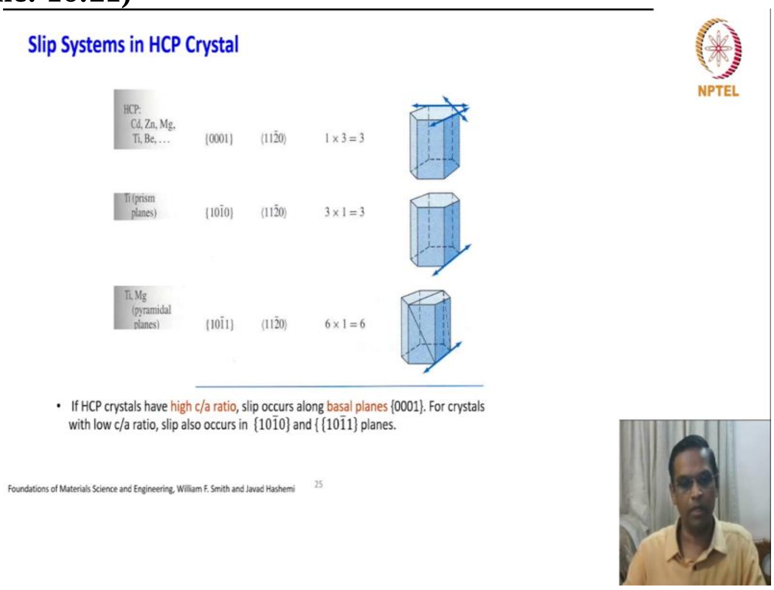

And if you go to BCC crystal that is body centred crystal lattice. So, you have {111} {110} plane and <111> direction of this one this type of slip system is a displayed by α iron tungsten, molybdenum, β brass. So, they have what about twelve systems and there are other system {211} is a plane and <111> direction, this slip systems also readily active in α iron, molybdenum, tungsten and sodium.

This again contributes to another twelve slip system. And the third slip system which exhibits which the BCC exhibits is {321} planes and <111> direction which is a loop which is giving rise to go twenty four system like α iron and potassium. So, all this directions are marked here for the quick reference. So, if you look at the number of slip systems as compared to FCC they are over, but the problem is BCC crystals are not close packed the slip predominantly occurs in {110} planes that has the highest atomic density. So, you have to remember that.

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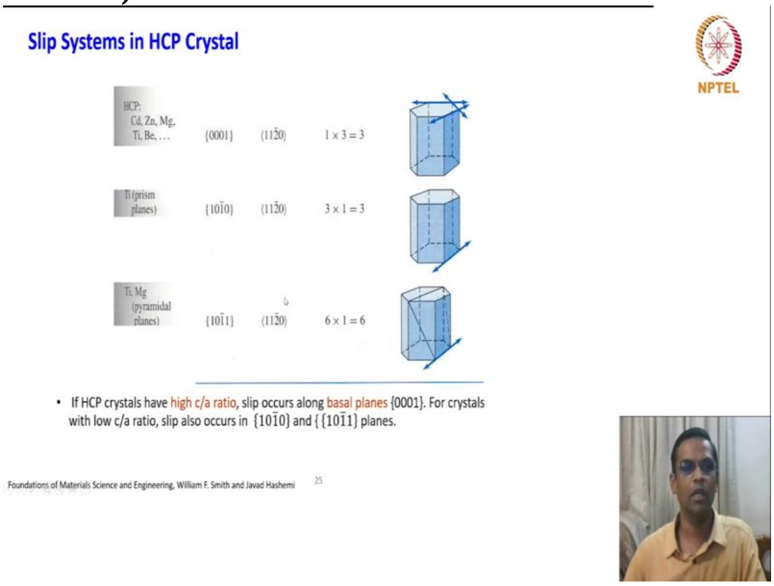

Similarly, if you look at the slip systems in hexagonal closed packed crystal and the primary slip systems are the basal plane. So, this can you see that it is a basal plane and directions are here three directions {0001} basal plane and <11$2\bar{0}$ > it is three directions. So, 1x3=3 examples of this kind of slip system exists in cadmium, zinc, magnesium, titanium, beryllium and another type of slip system {10$\bar{1}$0} slip planes and this is called prism plane.

And <112 bar 0> direction you have three planes like this and one direction. So, three slip systems titanium, magnesium they also show pyramidal planes you can see that pyramidal planes shown here this is pyramidal planes and the same direction. So, you have six pyramidal planes of similar direction, so six systems. So, you see again in HCP have bought twelve slip systems. But the problem with the HCP is it is a very sensitive to the c/a ratio, HCP crystals those have high c/a ratio slip occurs along basal planes that is {0001} type of planes.

For crystals with the low c/a ratio slip also occurs in this type of prism planes. So, this is one thing you have to remember. So, you see that compared to FCC, both BCC and FCC do not have high density plane. That is a bottom line.

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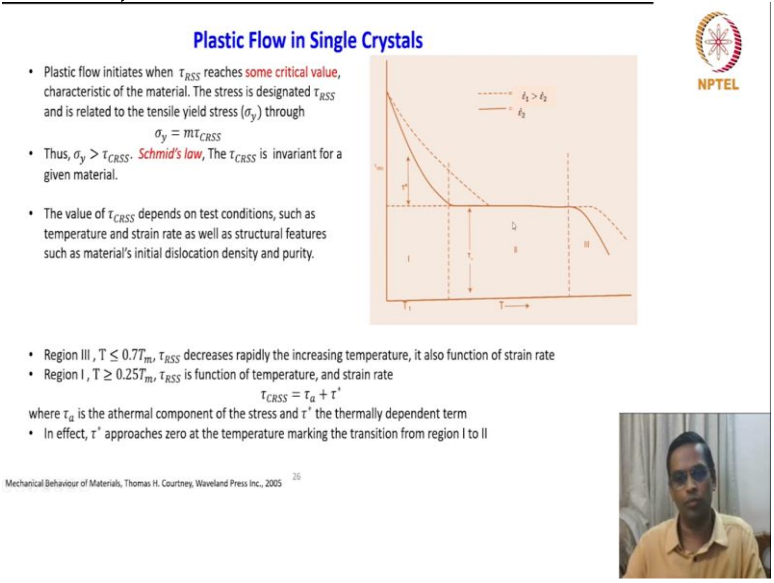

So, if you look at a little more detail about this plastic flow in single crystals. So, we have seen that the plastic flow initiates when τ_{CRSS} reaches some critical value characteristic of the material. So, the stress is designated τ_{CRSS} and it is related to the tensile yield stress σ through this relation that is $\sigma_y = m\tau_{CRSS}$. So, this is also known as a Schmid's law.

So, τ_{CRSS} is invariant for a given material. So, the value of τ_{CRSS} depends on test conditions such as temperature and strain rate as well as the structural features such as materials initial dislocation density and purity. So, here is an important plot that we need to keep in mind when we as with regards to the critical resolved shear stresses concern. So, the critical resolved shear stress is plotted here against the temperature τ_{CRSS} versus T plot.

You can see that it is not only showing the temperature variable there is also a strain rate variable, the dashed line is $\dot{\varepsilon}_1 > \dot{\varepsilon}_2$. So, the solid line is $\dot{\varepsilon}_2$ that is so, it shows both the effects temperature effect as well as strain rate effect. So, what does it show. It is very interesting actually, you can see that this plot exhibits almost the three regions the region 1, region 2 and region 3.

And then what are the critical points to be noted, what are the critical points in region 3 what is that we are seeing the $T \leq 0.7\ T_m$ τ_{CRSS} decreases rapidly with the increasing temperature. So, you can see that the region 3, the τ_{CRSS} decreases rapidly with increasing the temperature. It is also function of strain rate where strain rate is also it is a function of strain rate.

So, that means in both strain rates they look different. So, that means it is sensitive to strain rate as well. If you compare the region 1 where the $T \geq 0.25\ T_m \tau_{CRSS}$ is function of temperature and strain rate we can rewrite this $\tau_{CRSS} = \tau_a + \tau^*$, what is this τ_a? Where the τ_a is the athermal component of the stress and τ^* is the thermally dependent term very important term.

So, you have a temperature dependent term and athermal component temperature independent term, the τ_{CRSS} has got two τ 's τ_a and τ^*. In effect tau star approaches 0 at the temperature marking the transition from region 1 to 2 this is true because the moment it reaches this τ to then you start the region 2 till the end it is 0 the temperature dependent component τ^* is 0 in the region 2.