Materials Science and Engineering
Dr. Vivek Pancholi
Department of Metallurgical & Materials Engineering
Indian Institute of Technology, Roorkee

Lecture – 27
Plastic deformation 1

Hello friends, now today's lecture we will start with now in this we will discuss in detail about plastic deformation. So, during uniaxial deformation, we have already seen through our tensile test that after yielding material undergo plastic deformation. So, we want to understand this whole process of plastic deformation and how it takes place so, to understand that what happens at the yielding. So, we will look at the 1 of the criterion that is Tresca criterion.

So, if you remember in your strength of materials course you must have gone through different yield criteria, and in that 1 of the yield criteria is Tresca criterion and the Tresca criterion says that, whenever the maximum shear in the system reaches the shear strength of the material, as your yield is a strength under shear of the material, then the yielding will takes place ok.

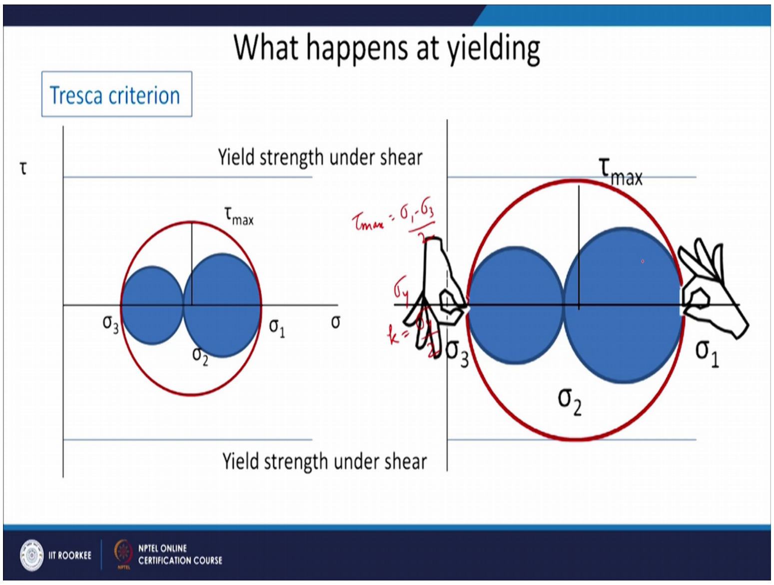
So, you can see that there are 3 principal stresses shown here sigma 1, sigma 2, sigma 3 and the maximum shear stress will be between sigma 1 and sigma 3. So, algebraically sigma 1 is maximum and sigma 3 is minimum because we are talking about 3 dimensional state of stress here you can see that I have drawn 3 more circle here; So, 1 between sigma 1 and sigma 2; another between sigma 2 and sigma 3 and 1 between sigma 1 and sigma 3.

So, tau max will be given by a sigma 1 minus sigma 3 divided by 2 that is the radius of this circle, where sigma 1 and minus sigma 3 is the diameter of this circle. So, when my this maximum stress in the system the maximum shear stress in the system reaches the yield strength of under of the material under shear, then the yielding will takes place.

So, yield strength we have seen till now under a tensile mode, and there we call it a sigma y and this yield stress is under shear. So, if you apply a shear stress on the material then also yielding will takes place. So, for that a torsion kind of experiments are there where you give a torsion torsion stress or torsion strain and the yielding will be taking place at under shear stress condition.

So, if there is a relationship between the whatever yield strength you get from simple shear kind of experiment, and the tensile experiment that will be k equal to sigma y by 2. So, this is what and actually what happens under yielding a we can see from this animation here. So, I am trying to show you that I am increasing the stress on the system ok.

(Refer Slide Time: 00:45)

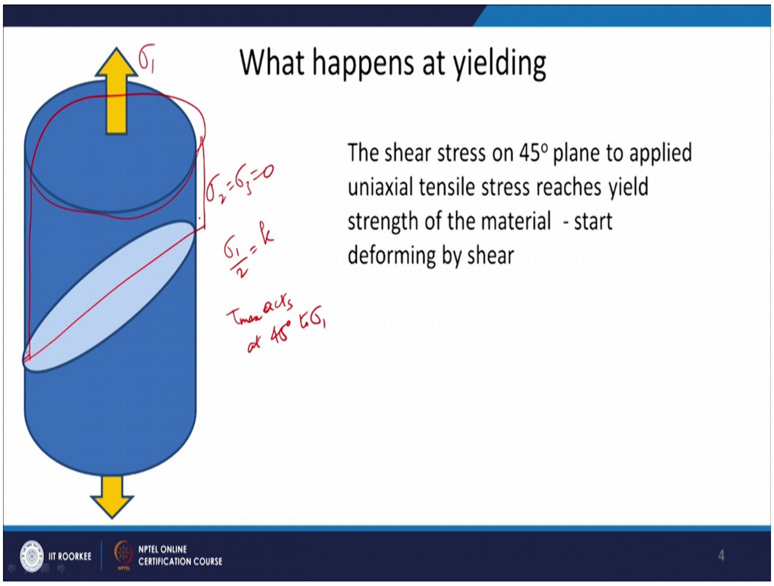


So, this is how I am increasing the stress on in the system, and you can see at some point when my maximum shear stress now reaches the yield strength under shear of course, yield strength of the material then the material will yield. So, if you see the a angle which tau max makes with the sigma 1 here, that is around 90 degree in more circle. So, in physical space it will be half of that, is 45 degree to the principal stress.

So, if you want to see it in terms of our experiment, where suppose we have taken a sample like this a cylindrical sample and I am applying stress sigma 1 in this direction it is a uniaxial deformation. So, sigma 2 and sigma 3 both are 0 then my yielding or my yielding under shear should takes place when my sigma 1 by 2 is equal to k, that is the shear strength of the or shield yield strength of the material. And that is also we have seen that this tau makes exact x at 45 degree to sigma 1 ok.

So, if this sigma 1 at 45 degree to that my maximum shear is acting and when it reaches the yield strength of the material or yield strength of the material under shear, then the then basically this upper part will slide ok.

(Refer Slide Time: 04:03)



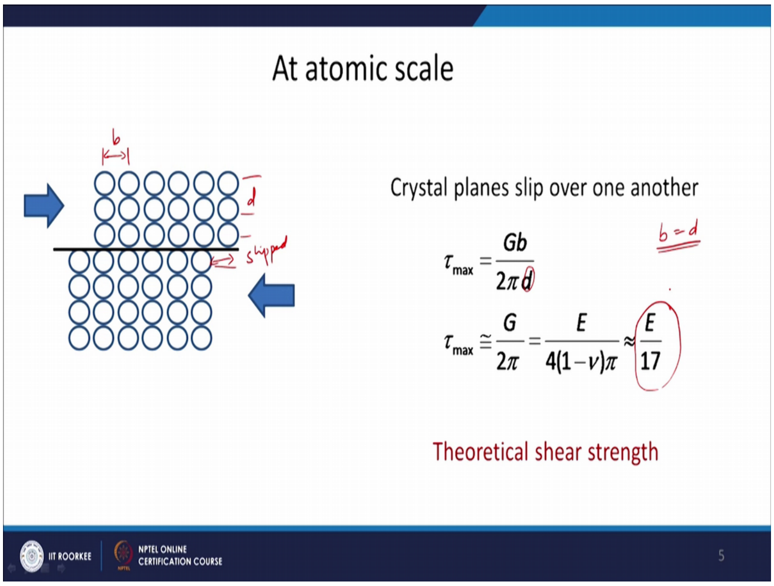
So, maybe I can just show you an offset here, maybe it will be something like this and here also there will be an offset and it will be like this something like this in this particular plane it is slided by some distance. So, there is a slip which is taking place and by which the upper part has slipped with respect to the lower part at 45 degree to sigma 1. So, when I reach the yield point, my material will shear and that is how it shears.

Now, at atomic scale till now we were considering this whole system as a continuum, we were not saying that anything is there and it is a it is a continuum, there is there are no at atomic scale there is nothing there. But at atomic scale when we want to understand the deformation actually there are atoms and the sliding places and if you have a shear stress acting on the system, then the sliding play takes place of 1 crystal plane over another and that is how you can produce the slip. So, this a this upper part has slipped with respect to this lower part.

So, if I want to know that how much stress will be required for that. So, what will be the maximum stress shear stress will be required to do this kind of process, that will be equal to if I do a theoretical calculation, I am not doing the total derivation of this you can look it in there are lot of books in which this kind of derivation is given ok.

So, basically the maximum shear stress which is required to do this kind of slipping process will depend on the g shear modulus, b is basically the slip distance my upper plane has shifted by 1 a atomic distance here, d is your the distance between the or let us say I show it here inter planar spacing d and some constant 2 pi, which I can replace since in usually cubic material b and d are very very close to each other, the values are almost in the same order of magnitude ok.

(Refer Slide Time: 05:49).



So, I can just remove that. So, my atomics is now equal to G upon 2 pi and now I can use some conversion constants are there between the Young's modulus and the Shear modulus which uses to and the poisons ratio nu here. So, it will be E upon 4 1 minus nu pi. So, ultimately you will get a some value which is E by 17. So, this is the best theoretical shear strength of the material.

Now, if you compare the theoretical strength with the experimenter shear stress for example, for silver it is 12.6 gigapascal, but in experiments when we when people found out they found that it is only 0.37 megapascal. So, there are there is a almost like 3 or 4 mega order of magnitude difference. Let us say for copper it is 19.6, but experimentally it is only 0.49. So, what is the reason for that?

(Refer Slide Time: 08:45)

Material	Theoretical Shear Stress $G/2\pi$ (GPa)	Theoretical Shear Stress $G/2\pi$ (10^6 psi)	Experimental Shear Stress (MPa)	Experimental Shear Stress (psi)
Silver	12.6	1.83	0.37	55
Aluminum	11.3	1.64	0.78	115
Copper	19.6	2.84	0.49	70
Nickel	32	4.64	3.2-7.35	465-1,065
Iron	33.9	4.92	27.5	3,990
Molybdenum	54.1	7.85	71.6	10,385

Reduction in strength due to presence of dislocations

IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 6

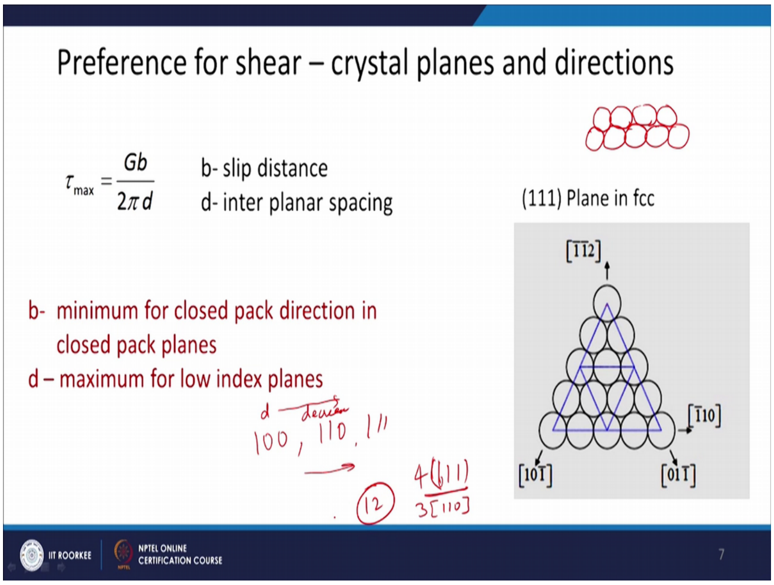
Already when we were discussing defects, we said that this difference between the theoretical strength what we calculated by equation in the previous slide and what you get experimentally the reason for this difference is that there are some defects present in the material, which are called dislocations and that brings down the shear strength of the material.

Now, when you talk about shear, then is there any preference for certain crystal planes or direction? If you look at this equation here again tau max equal to G b by 2 pi d, where b is your slip distance and d is inter planar spacing. If you remember the when we were discussing about crystal structures and about planes and direction, we might have discussed that the slip distance is minimum for closed pack direction in closed pack planes. For example, this there is a 1 1 1 plane in fcc is shown here and the in the 1 1 1 plane of fcc this is the best packing you can get for a spherical atom, if you take any spherical object ok.

So, best packing you can get when you place another sphere in between the 2 here like this is not it and so on. So, this is going to be the best packing you cannot get better packing than this, and there is packing you see in the 1 1 1 plane of fcc arrangement. So, if you see this 1 1 1 plane of FCC, you can see in this 1 0 1 direction or 1 1 0 type of direction of FCC, you have the minimum distance between the atom. So, this atom when its slips it goes to the next position here.

So this is the distance it is going to travel. So, the yes I told the you cannot get best packing than this; that means, this is the minimum distance my atom has to travel and that is equal to your slip distance. We also discussed that you have maximum spacing inter planar spacing d, when you are talking about low index planes ok.

(Refer Slide Time: 09:39)



So, low index planes are 1 0 0, 1 1 0, 1 11 and so on.

So, in this direction now indexing is increasing. So, this will have the maximum d spacing and then d spacing will decrease in this direction. So, of course, but these 2 planes are not the closed pack plane. So, the best close packing you find in 1 1 1 plane and of course, d spacing will also be quite high in 1 1 1 plane. So, these type of planes are the preferred planes where the slipping is going to take place ok.

So, now not all at crystal planes and all crystal direction take part in the slipping process, there is a preference for shear during shear for certain planes and direction and those planes are the closed pack planes, and the directions are the closed pack direction and that is those are the going to have the minimum slip distance and maximum inter planar spacing.

For example slip system in different crystal structures if you want to see, just a another I want to tell you that in fcc cubic crystal, this is this is 111 plane, you will get 4 111 planes like this. When we were discussing indexing of planes and direction we discussed about that, that you will get 4 of these 111 planes and in each 111 plane you will have 3 1 1 0 directions. So, 3 1 1 0 type of directions will be there ok.

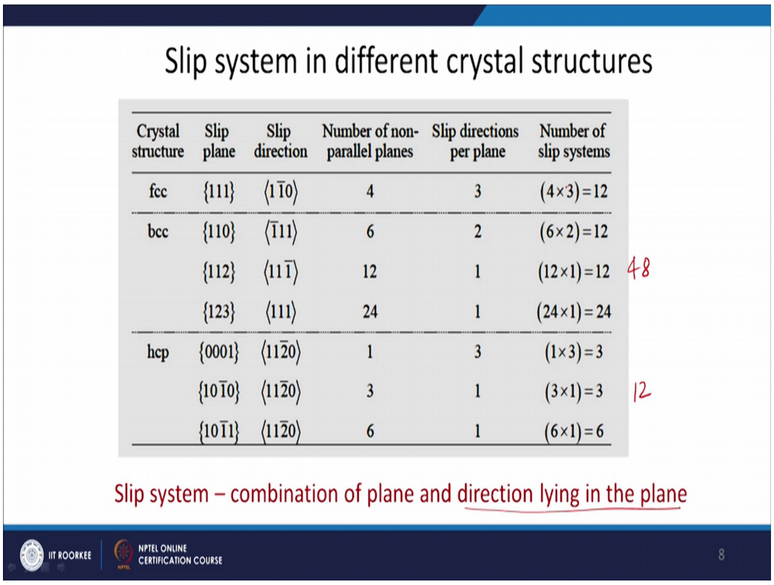
So, in combination if you look at the slip system, there will be 12 slip systems. So, that is what we want to tell you in that this next slide that slip system is a combination of plane and direction lying in the plane. So, direction which is lying in the plane and the plane, what is the combination of that so, slip plane in fcc we have told you that it is 111 plane closed pack plane in slip direction is 1 bar 1 0 type.

So, now the numbers of non parallel planes are only 4, slip direction per plane these 3. So, number of slip system is 12. In bcc of course, none of the planes are the closed pack planes. So, only there is closest to closed pack arrangement that is what you see. So, the closest to cross pack arrangement you get in these 3 type of plane 1 1 0, 1 1 2 and 1 2 3 and these are the closed pack direction, but direction is of course, there is a closed pack direction is available ok.

So, number of non parallel planes for these type is these numbers are there, then in each slip direction per plane are also given. So, total 48 systems are there in bcc whereas, in fcc there are only 12. Though there are more slip system you may it appears there are more slip system available in bcc, but you have to keep in mind that these are not the closed pack planes ok.

So, though their number is high, but still they are not as effective as these 12 planes in the fcc system. In hcp of course, basal plane will be a closed pack plane and 1 1 bar to 0 direction will be closed pack direction. So, there are 3 actually which satisfy the closed pack plane and closed pack direction condition, the other two are not are similar to bcc type ok.

(Refer Slide Time: 13:17)



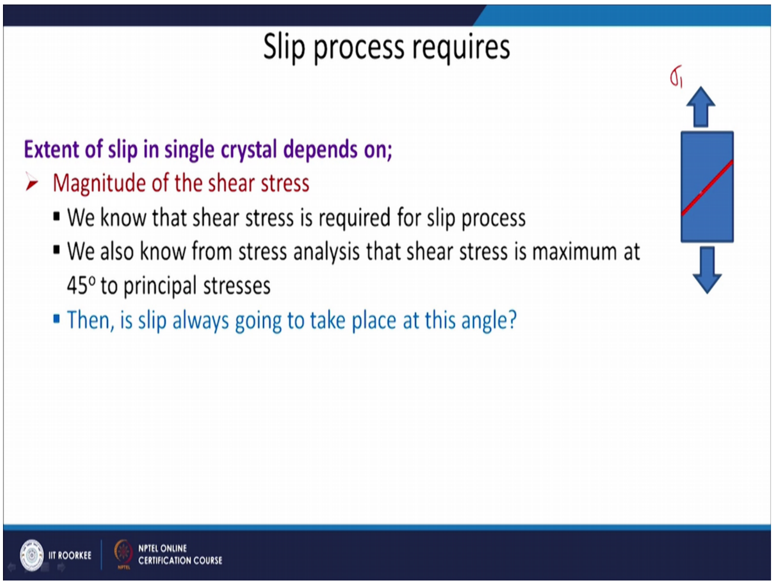
Crystal structure	Slip plane	Slip direction	Number of non-parallel planes	Slip directions per plane	Number of slip systems	
fcc	$\{111\}$	$\langle 1\bar{1}0\rangle$	4	3	$(4\times3)=12$	
bcc	$\{110\}$	$\langle \bar{1}11\rangle$	6	2	$(6\times2)=12$	
	$\{112\}$	$\langle 11\bar{1}\rangle$	12	1	$(12\times1)=12$	48
	$\{123\}$	$\langle 111\rangle$	24	1	$(24\times1)=24$	
hcp	$\{0001\}$	$\langle 11\bar{2}0\rangle$	1	3	$(1\times3)=3$	
	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3	1	$(3\times1)=3$	12
	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6	1	$(6\times1)=6$	

Slip system – combination of plane and direction lying in the plane

So, here also you get 12 systems. So, in this you can see that fcc has very efficient slip system. Now looking at the slip process, we slip process require a extent of slip in single crystal depends on magnitude of the shear stress as we have just discussed when we were discussing Tresca criterion, that what is the maximum magnitude of shear stress. We know that shear stress required for slip process, we also know from stress analysis that shear stress is maximum at 45 degree to principal stresses as we discussed during Tresca criterion.

Then is slip always going to take place at this angle. So, this is the question which we should ask ourselves that if this is the case I am applying the stress like this which is sigma 1.

(Refer Slide Time: 15:23)

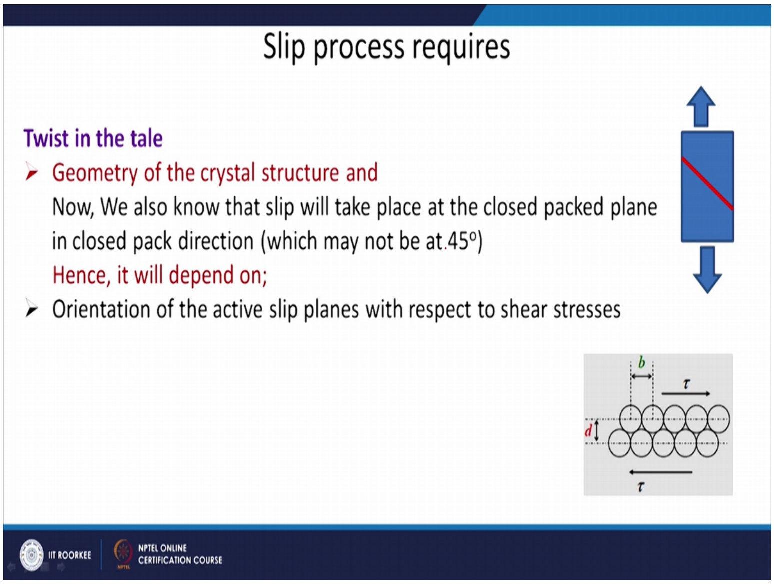


Principal stress in this direction, then according to the Tresca criterion though at 45 degree, I should get the maximum shear stress. So, now, the question is whether my material is going to slip in this 45 degree direction or not. The twist in the tail is that the geometry of the crystal structure and now we also know that slip will takes place at the closed pack plane in closed pack direction, we which may not be at 45 degree. If you look it as a as a continuum system, which does not have these atoms and it is a continuum ok.

Then this analysis actually tells you at 45 degree you should get the slip process, but now we also know that that which planes are going to take part in the slip process. So, in fcc for example, we know that closed pack planes and closed pack direction are going to be the 1 with where the slip is going to take place. So, it is not in any direction you will have a slip.

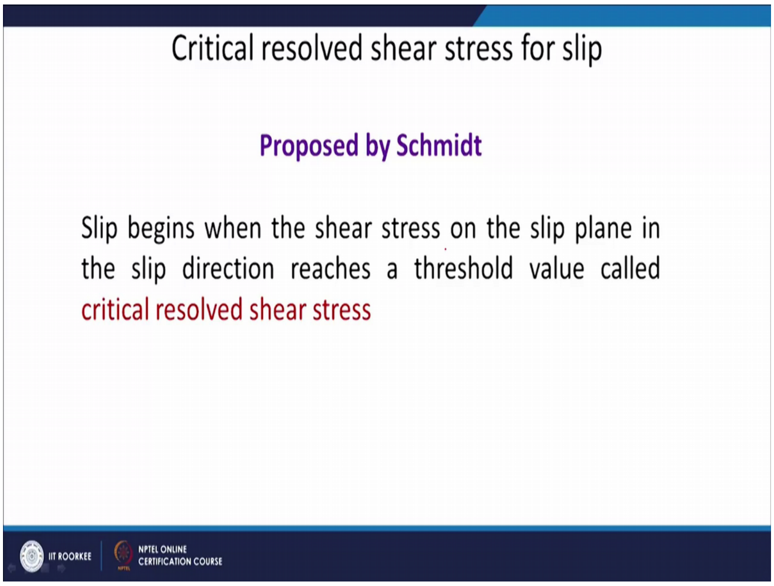
So, in 45 degrees direction of the maximum shear, if my 111 plane is not lying in that particular direction then slip is not going to take place in 45 degree direction ultimately what the slip is going to take place only in the plane, which is 111 how it is aligned with the maximum or how it is aligned with the shear stress direction. Hence it will depend on orientation of the active slip planes with respect to shear stresses.

(Refer Slide Time: 16:27)



So, basically this is what we are saying that atomic ultimately atomic arrangement is the 1 which is going to decide whether you are going to get deformation or slip process in that particular direction or not. So, to resolve this problem Schmidt 1 scientist he proposed that slip begins when the shear stress on the slip plane in the slip direction reaches a threshold value called critical resolved shear stress ok.

(Refer Slide Time: 18:16)



So, he said that when the a resolved stress in that particular plane and in that particular direction, when it reaches a critical value then the shear then the slip process will take place in that particular plane in direction. So, this is what the idea is now. So, instead of that 45 degree which is given by the Tresca criterion, ultimately we have to see that whether my closed pack plane and closed pack direction are lying in that particular direction or not ok.

So, first we will resolve the shear stress. So, now, we are resolving the shear stress here. So, let phi is the angles between normal to the closed pack plane and tensile exist. So, this is my plane, and now this may not be at 45 degree to the principal plane principal direction, but it is making some angle with the tensile axis and that I am calling as phi. So, phi is the angle between normal to the closed pack plane, this is my normal and tensile axis. So, this angle is phi.

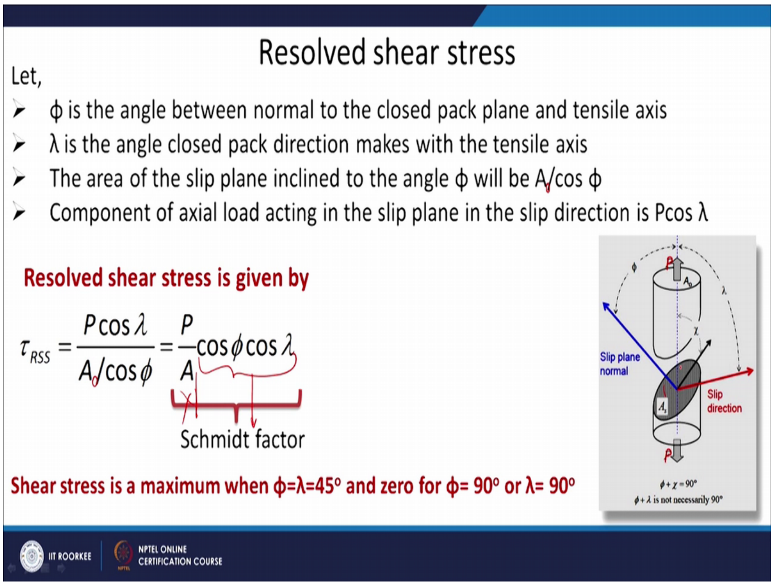
Lambda is the angle closed pack direction makes with the tensile axis. And this lambda here is the angle, which the slip direction is making with the tensile axis. The area of the slip plane inclined to the angle phi will be A upon cos phi. Component of x shell load acting in the slip plane in the ship direction is P cos lambda. So, now basically we are resolving the load P and in these 2 directions. So, I think instead of f I will say it as P because that is what we are saying.

So, it will be P the area and this is my area A naught, but my shear stress is acting on the area which is given by a s. So, the area which I am resolving here will be A upon cos phi that is what I am writing there let us say that this is A naught here. And this slip direction is the your tensile I am resolving the P for stress in the direction of slip. So, this will be P cos lambda.

So, now my shear stress is acting in this plane in this direction. So, and of course this direction will be lying in the plane. So, this is going to be of course, going to be shear stress. So, shear stress is acting in this plane in this direction and plane is given by A and A naught divided by cos phi. So, my resolved shear stress will be P cos lambda divided by the area. So, this is my force resolve force in that plane, and this is my area of that plane and that will be P A upon cos phi into cos lambda. So, this cos phi cos lambda is the estimate vector; not this one only up to here.

So, cos phi into cos lambda is your Schmidt factor. Shear stress is a maximum when phi and lambda both will make angle of 45 degree. If I take 45 degree and 45 degree here this is going to give me the maximum shear stress, and will be 0 if phi is equal to 90 degrees. So, phi 90 degree means the plane is almost the plane is parallel to the tensile axis ok.

(Refer Slide Time: 18:43)



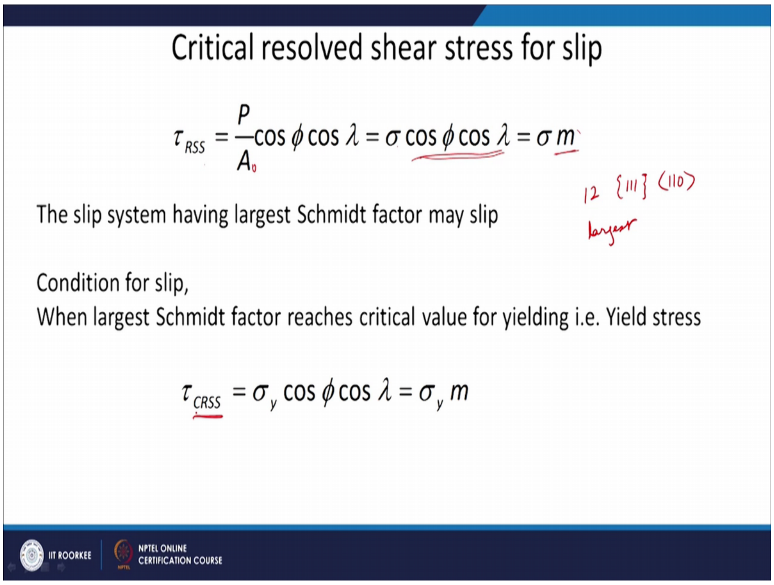
So, it cannot you cannot have shear in this direction, because in this direction your maximum principal stress is acting. Similarly delta 90 degree means delta 90 degree becomes the 90 when the plane is in this condition. So, now, principal plane is acting like this. So, when this plane now shear stress cannot be maximum because only the normal stress is acting there. So, in this 2 configuration of planes, my shear stress is going to be 0 and it is going to be maximum for 5 and lambda equal to 45 degree.

So, tau the resolved shear stress is P A P by A cos phi cos lambda let us say I call it as a A naught because in the figure it is written as a not. So, it is sigma cos phi cos lambda as the P upon A naught is equal to sigma into cos phi cos lambda equal to sigma into m. We are representing this factor as m here the shear stress having largest mid factor may slip. So, now, what we will do is we have to 12 slip system and 12 arrangement of 111 plane and 1 1 0 direction.

Now, we do not know for which 1 this is going to be maximum the tau RSS. So, what we will do; we will determine this particular factor for all the planes, with respect to the tensile axis and for whichever it is going to be maximum, that is that the system is of interest to us. So, condition for sleep is when largest Schmidt factor. So, largest of this 12 whichever comes. So, out of this 12 one will be the largest obviously.

So, when the largest Schmidt factor reaches critical value for yielding. So, that yield stress. So, then it these tau RSS become tau CRSS critical resolved shear stress when I am replacing sigma by sigma y now and cos phi cos lambda the m when it is the maximum for whichever is this.

(Refer Slide Time: 22:50)



If this factor reaches the critical resolved shear stress, then the slip is going to take place.

So, now you can understand that that idea of 45 degree to the principal plane, now we have brought in the idea of crystal planes and crystal direction in this whole thing and now we are able to tell you that which planes are going to take part in the slip process. So, when we will do the assignment this will be more clear to you, that how we can a use this relation to find out this aspect.

So, thank you and we will take the another lecture on plastic deformation, where we will discuss about other mechanism of deformation that is twin, and we will also see in the slight detail that how the deformation takes place in the single crystal ok.

Thank you.