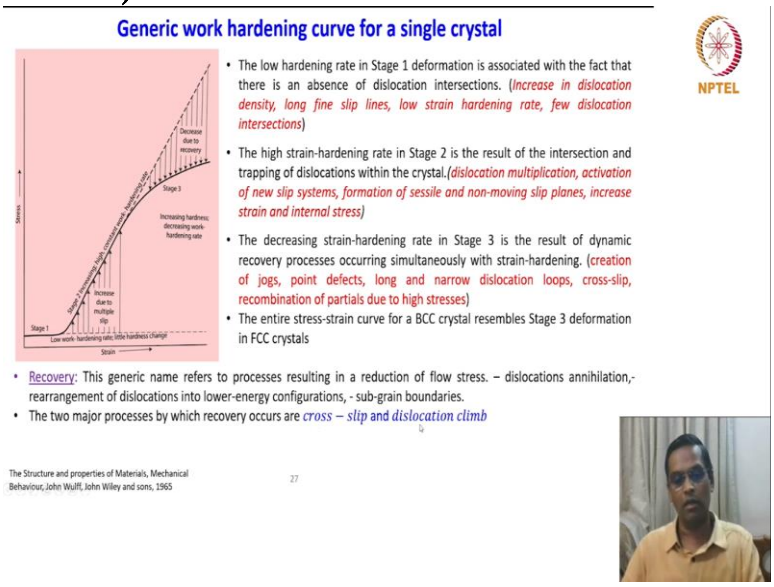
Mechanical Behaviour of Materials
Prof. S. Sankaran
Department of Metallurgical and Materials Engineering
Indian Institute of Technology - Madras

Lecture - 25
Introduction to Plastic deformation - IV

(Refer Slide Time: 00:17)



Hello, I am Professor S. Sankaran in the Department of Metallurgical and Materials Engineering. So, the other important aspect which we have to know about the single crystal plastic deformation is work hardening behaviour. So, what is this work hardening we have now seen that in a as I just mentioned in the beginning a few lectures back when we talk about you know crystalline plastic deformation.

The plasticity is always considered as dislocation mediated plasticity. So, we have also seen several dislocation characteristics in terms of generation, interaction, multiplication, intersections and dislocation, dislocation reaction and so on. So, all those concepts will come in handy here when we talk about work hardening. So, what is that I am showing some interesting plot that stress versus strain basically this is a critical resolved shear stress versus shear strain plot of a single crystal.

Let us look at that graph I mean plot a little more closely it conveys a lot of information so, we have to be very careful in looking at this and then try to understand this is most fundamental idea. So, what does it say this plot shows something called stage 1 as the strain increases in the beginning and then there is a steep increase in the stress and then after that its start slowly coming down.

So, again it has got about three stages the stage 1, stage 2 and then stage 3. So, stage 1 it is basically a low work hardening rate that means, we will see that the dislocation activity is the rate of dislocation, dislocation interaction and their activities slow and except that little hardness is changing in the material and the moment it start going to the stage 2 skills the moment it goes to stage 2.

You can see that the stress increases significantly due to multiple slips. And then it goes on and after some time the moment we start the stage 3 its start slowing down and then you can see that you know, in the stage 2 the increasing high constant work hardening rate the work hardening rates significantly increases and after some time it is staying constant and then after that it slows down.

So in this if you extend this straight line, then you appreciate that how much the decrease in the work hardening rate you can see that is given by this dashed line. Similarly, the increase in the work hardening is also given by this arrow hash line beautifully it illustrates the how the work hardening rate increases and then decreases. So, now we have to just understand in a single crystal why this happens.

And how do we understand this is a very basic and important fundamental idea, which you have to keep in mind I mean extrapolate these ideas to polycrystalline deformation or any other polycrystalline you know or deformation mechanisms and so on. So, the low hardening rate and stage 1 the deformation is associated with the fact that there is an absence of dislocation intersections.

So this is belong to this region so, what does it mean this the key factor to notice increase in dislocation density and long fine slip lines and low strain hardening rate and few dislocation intersections. So, there we have seen that in the dislocation dynamics earlier or dislocation mechanics unless the dislocation, dislocation interact and then makes the intersections the formation of you know little harder dislocation success like king or a jog.

And no voids and other things are all not going to happen which are all the hard particles I mean will act as a hard particles they are not going to happen. So, that means they are all the signatures of high rate of dislocation interaction which is not taking place in this stage 1 the high strain hardening rate in the stage 2 is the result of intersection and trapping of dislocation within the crystal. So now, we are talking about intersection that means, the dislocation, dislocation start interacting with each other.

That means, after the initial glide that means, dislocate start gliding in a plane or glide plane without any hindrance and as the strain goes up this number of dislocation increases the number of dislocation per unit area increases and then as a result now intersection start happening. So, the primary signatures of the stage 2 is dislocation multiplication, activation of new slip systems, formation of sessile and non-moving slip planes increase in strain and internal stress.

You see, these descriptive are very, very important as you move to a second stage of work hardening rate you see the complete contrast in the dislocation and microstructure features if you look at the stage 3 the decreasing strain hardening rate is a result of dynamic recovery process occurring simultaneously with a strain hardening. So, you see you will have to now remember a strain hardening and then strain softening.

We can say that opposite word there is an another word we can use as a dynamic recovery also will act as a strain softening mechanisms you can consider it like that to start with we will give more importance to all this terminology and we will get into details as we proceed in the course but then it is easy to remember strain hardening taking place. So, that means it is getting reduced that means what something opposite to happen that is strain softening.

So, here we can consider the dynamic recovery, it is opposite to strain hardening. So, that is happening in the stage 3. So, what are the primary or key signatures here? Creation of jogs point defects long and narrow dislocation loops. So, you know now what is the jog you know what is a point defect or vacancy how it is getting generated interstitials how it forms all this descriptors you have some idea we have already seen in terms of dislocation reactions.

So, the dislocation loops and cross slip, cross slip you know 2 dislocation the 2 dislocation is only can undergo this kind of mechanisms that means, it can easily surpass the obstacles through these mechanisms. And recombination of partials due to high stresses. So, the stage 3 again shows very significant and very different signatures as compared to stage 2 in terms of this dislocation behaviour.

So, the entire stress strain curve for a BCC crystal resembles stage 3 deformation in FCC crystals. So, please understand this single crystal deformation behaviour what we have seen so, far stage 1, stage 2, stage 3 is for face centred cubic crystal system and for an BCC body centred cubic crystal system, the entire curve will look like stage 3 only. So, that means you have very you know different kinds of work hardening behaviour will be exhibited by the materials which has BCC crystal system.

And you know this kind of you know, work hardening behaviour will be exhibited by materials which shows or which has FCC crystal system very important basic understanding. So, I just use the word dynamic recovery suddenly what is recovery? Let us first see that, because we are now denoting the whole area as a decrease due to recovery what is recovery? Recovery means this generic name refers to a process resulting in a reduction of flow stress.

So, the reduction of flows stress the flow stress is coming down. So, what why does it comes down? Because the dislocation annihilation what is dislocation annihilation? Annihilation we have we have already seen what is this dislocation annihilation positive and negative edge dislocation glide on a same plane which is coming in opposite direction will form a perfect crystal.

That also we have shown in the dislocation dynamics. So, this process is dislocation annihilation. So, when the activities you know starts with this dislocation annihilation then what do you expect the total number of dislocation density will I mean total number of dislocations will come down as a result the density of dislocation itself will be decreasing as you proceed that is important aspect.

And secondly the rearrangement of dislocation into lower energy configurations that means, all the energy like see you know 1 example already we have just seen that how a dislocation will try to align themselves in especially a edge dislocation of a similar sign will align the one over the other because of the stress fields we have we have clearly shown how if it is more than you know 45° or less than 45° orientation know you have seen.

So it forms a low angle grain boundary that means, that is one a classical example of a low energy configuration like so, like that so many configurations are possible one of the primary is that cell, cell dislocation cell it will form a cells group of cells, that is always lower energy configurations. So, you could form a veins or string or dislocation wall cell all these things are descriptors of low energy configuration of dislocation.

So, this low energy configurations will form and then as a result a sub grain boundaries will form so when I say low angle grain boundary that is also considered as a sub grain boundary. So, what recovery means is it consists of too many activities, which eventually reduces the effect density inside the system and reduce the energy of the system to the lower page so, these are all recovery.

When you say dynamic recovery, all these activities are expected to operate in a continuous fashion as the deformation proceeds it is happening continuously it is nonstop, that is why it is dynamic. So, we are talking about a room temperature deformation. Now, the same thing can happen at high temperature that means, you can imagine that thermally activated process also will contribute to this dislocation dynamics.

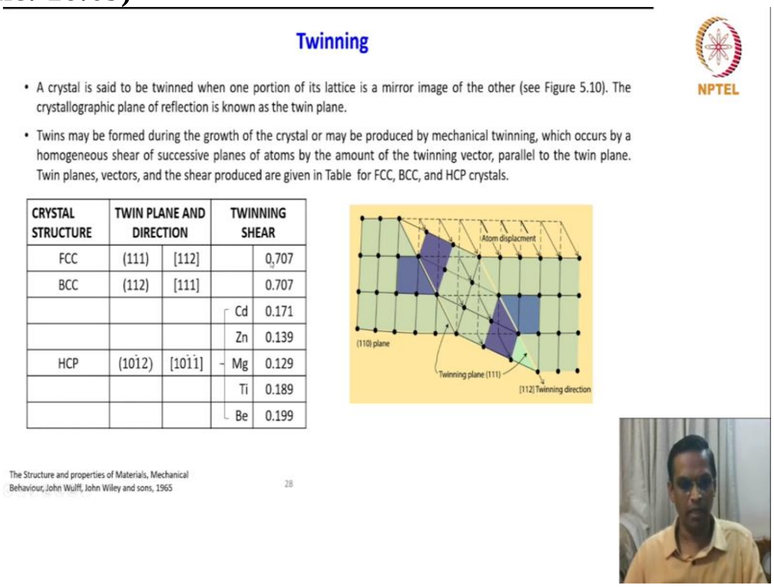
Then there again we will talk about dynamic recovery. So, the recovery means, these are all the activities and the dynamic recovery means, it acts simultaneously as the deformation proceeds too at the very higher stresses. So, what I am trying to convey through this slide is this is the first step we are seeing in a deformation of a single crystals, how what are all the you know, microstructural events that is going to happen in a very, very localised scale.

We in terms of dislocations, we are able to categorise them or describe them what are all the activities and then basically what we are trying to explain? We are trying to explain the stress response the stress response of a single crystal, how it behaves and why it behaves and what is the consequence of this deformation and so on so, this is very basic and fundamental. These ideas should remain intact in our mind, so, that we can relate this to the other crystals systems.

Already we are comparing this FCC with a BCC and BCC we are not going to see these kind of well defined stage behaviour rather it is a full stress strain curve is going to be similar to what is shown in the stage 3 that means, the very beginning of the deformation in self will involve all the activities. The dislocation activities or recovery activities, what we are seeing the stage 3 in the BCC that is how we should start at least you should start thinking in those direction.

And then we will get mature as we proceed and then the understanding will improve once you start from here. So the two major process by which recovery occurs are cross slip and dislocation climb, so, that we also have seen what is dislocation climb whether dislocation or vector moves up you can move up or you can move down depending upon the circumstances. So, the recovery by itself can take place by two primary mechanisms called cross slip and dislocation climb.

(Refer Slide Time: 16:09)



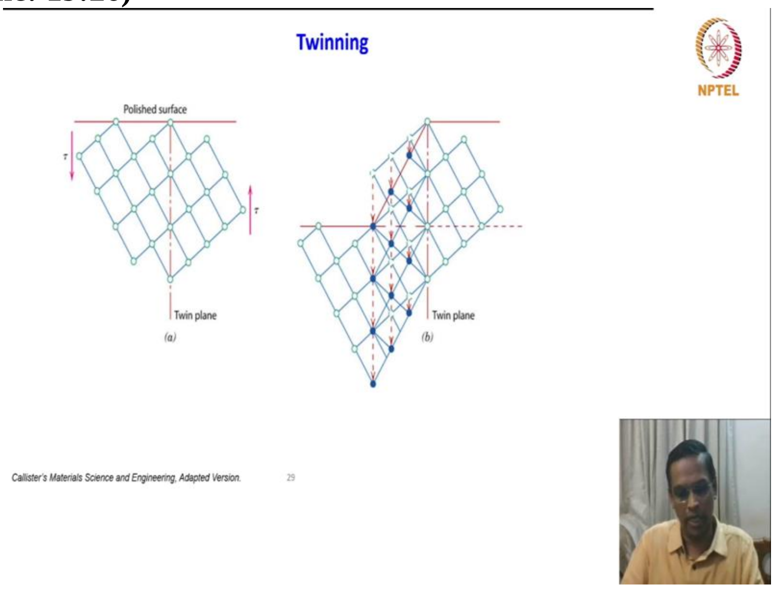
Next comes the important another mechanism is called twinning what is twinning? A crystal is said to be twin when one portion of its lattice is a mirror image of the other the crystallographic plane of reflection is known as the twin plane. So, you look at this image this is a crystal lattice of a cubic system and this is (110) plane and what you are seeing here is a twin region which shows a twin plane (111) and then the twin direction [112].

And then you can see this atom displacement is proportional to the from where the twin plane starts it is actually increasing from here the displacement increasing as you move from twin plane. So, this is a twin region and this is the kind of mirror image of this and here is the mirror image of this lattice. This is I will give a much more description of this in the next slide.

Twins may be formed during the growth of the crystal or maybe produced by mechanical twinning, which occurs by a homogeneous shear of successive planes of atoms by amount of the twinning vector parallel to the twin plane, twin planes vectors and the shear produced are given in table for a FCC, BCC and HCP crystals, what are this? So, like a slip system we have a twin system we can say that.

So, twin planar direction in FCC (111) and [112] direction this is a kind of amount of shear we can produce we can measure the shear this is 0.707 in BCC it is reverse 111, (112) planes and [111] direction and it also will produce a shear of equivalent to what is being produced in FCC. But in HCP it is $(10\bar{1}2)$ and the direction is $[10\bar{1}\bar{1}]$ examples are cadmium, zinc, magnesium, titanium, beryllium. And then you can see that the amount of twinning shear produced by these crystals systems or materials are significantly low compared to FCC and BCC. But, it is not that you know simple here.

(Refer Slide Time: 19:26)



I will just first describe this a little more for your understanding then we will move on to the next idea. So, what is the same thing a cubic (110) plane is shown here and this is a twin plane and this is a polished surface. So, this plane is oriented a little with an angle with the surface and then this is the shear force which is acting on this system. And this (110) plane is you know, it is on the plane of screen here.

And the twin plane is perpendicular to this plane of the screen and this is what the description for this and then if you look at this twinned region now, you see that the since the twin plane is perpendicular to the plane of the screen computer screen you can now see that this twin region also must be a an offset I mean, you can say that it could come out of the screen. If you look at real τ it should have twin regions should have come out of this plane of the screen computer screen.

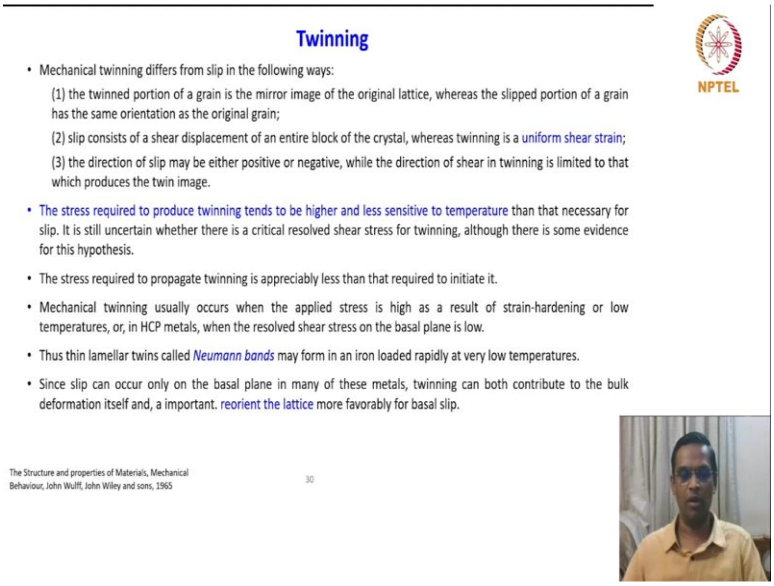
And then it also has created some a huge step on there above the polished surface. So, so, these descriptions will help you to imagine the three dimensionally how the twins takes place. So, now let us assume this polished surfaces are plane AA and this is a twin plane which is again not this twin region has come out of this screen. And then there are three circles one is open circle and a circle with a dashed line and the circle which is solid completely filled circle.

So, the open circle is untwined lattice the circle with the dashed line is the original position of the lattice point before it twin. So, you can see that the displacement of the atom you can see from here to here and here it is proportional to the distance from the twin plane. So, you can see that it is the displacement here is small slightly increased and slightly increased and like that.

So, it is proportional to the twin plane distance basically you can just understand like that, so, that it is easy to visualise. And another important point is suppose after it is a kind of surface relief you can say see this is a polished surface. That means this twin has created a step so, it is a kind of a relief surface relief. So, literally you can polish this and then you can remove this by polishing it will get removed, but still you will see that twin.

Because this orientation, the twinned orientation, since it is come out of this plane of the screen, it is completely different orientation as compared to the untwined region. So, even if you remove this portion above the polishing surface by polishing after etching you will be still able to see this twinned region because of the different orientation so in a polished surface and by etching you will be able to visualise the twins. So, these are all some of the very basic idea about the twinning.

(Refer Slide Time: 23:33)



So, what are the technical aspects? Let us now look at them a little more closely the twinning can happen by two ways one is by annealing another is by deformation the one which we are now looking at is mechanical twinning is by the shear force. So, the mechanical twinning differs from the slip. Now, since we are talking about deformation mechanisms we are comparing twinning versus slip the twinned portion of the grain is a mirror image of the original grain.

Whereas the slipped portion of the grain as the same orientation as the original grain very important point just know I demonstrated to you how this orientation is going to help because even by etching you can see it slip consists of a shear displacement of an entire block of the crystal whereas the twinning is a uniform shear strain please understand this, this is very uniform shear strain you look at the whole deformed region a twin region.

It is a cooperative movement of many atoms, but not to the extent of the slip vector, but it is only a fraction of that slip vector or inter atomic spacing that we will see the direction of the slip may be either positive or negative, while the direction of the shear and twinning is limited to that which produces that twin image so that it is clear now, very important point is the stress required to produce twinning tends to be higher and less sensitive to temperature than that necessary for slip very, very important point.

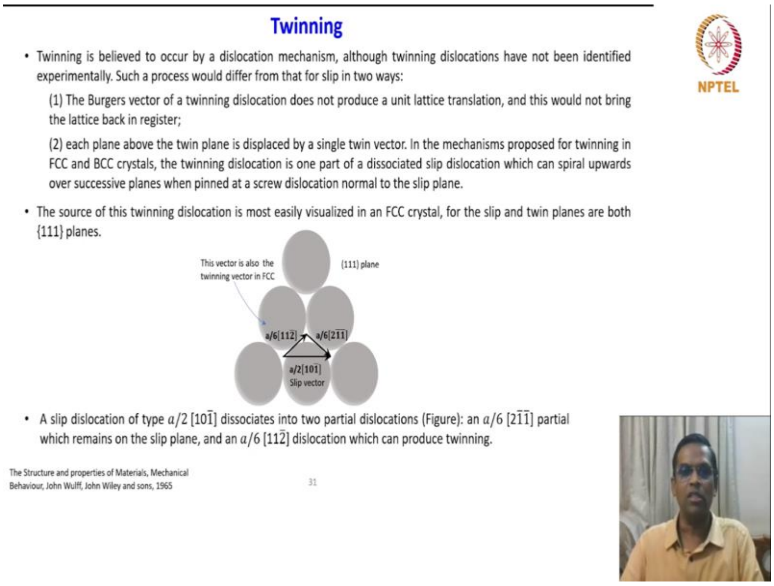
The stress required to produce the twinning is higher it is still uncertain whether there is a critical resolved shear stress for twinning another important point when we are comparing two mechanisms slip and twin about slip we talked to many things and it was very clear we established the mechanisms and how it takes place you know shear plane establishment we looked get octagonal planes you know and then critical result shear stress also we have seen that it is a characteristic of a material everything is clear.

But here still we do not know whether there is a critical result shear stress for twinning the stress required by to propagate twinning is appreciably less than that required to initiate it. Mechanical twinning usually occurs when the applied stress is high as a result of strain hardening or low temperatures or in HCP metals when the resolved shear stress on the basal plane is low.

So, this is a you know very fundamental idea and important idea because you cannot just like that formatting, it requires some conditions what are the conditions? Applied stress need to be at highest side as a result of strain hardening or at low temperature. So, either it should be temperature effect or the stress effects are the crystal system itself if it is a very different crystal system like HCP, where the number of slip systems available for slip is limited.

It is only basal slip it is not like on HCC where you have large number of high density planes we are not here in HCP. Thus thin lamellar twins called Neumann bands may form in the iron loaded rapidly at very low temperatures. This is one example how this forms since slip can occur only on the basal planes in many of these metals twinning can both contribute to the bulk deformation itself. And an important reorient the lattice more favourably for basal slip. So, this is again now we are trying to describe the deformation in the HCP kind of system to where the number of slip systems or favourable slip systems are limited.

(Refer Slide Time: 28:06)



Twinning is believed to occur by a dislocation mechanism. Although twinning dislocations have not been identified experimentally such a process would differ from that for a slip in two ways. The Burgers vector of a twinning dislocation does not produce a unit lattice translation and this would not bring a lattice back in register. So, this point is a very valid point and this is how we have been describing the slip.

Because the moment of the slip takes place and the lattice will experience a unit lattice translation by means of a lattice translation vector, but this is not going to happen while twinning. Each plane above the twin plane is displaced by a single twin vector in the mechanisms proposed for twinning in FCC and BBC crystals the twinning dislocation is one part of the dissociated slip dislocation which can spiral upwards over successive planes when pinned at screw dislocation normal to slip plane.

So, this is a kind of you know the hypothesis how twin can get generated. The source of this twinning dislocation is most easily visualised in an FCC crystal, for the slip and twin planes are both {111} planes. This is one advantage in FCC because here we see that both twin systems and slip systems we have seen that {111} planes are going to be the primary planes. So, what people believed is.

If you look at the octahedral planes the slip vector is $a/2[10\bar{1}]$ can dissociate into $a/6\ [11\bar{2}]$ and $a/6\ [2\bar{1}\bar{1}]$. So this particular slip vector can cause or can be a twin vector in an FCC this is one hypothesis to identify the origin of the twinning this is one kind of hypothesis a slip dissociation of a type $a/2[10\bar{1}]$ dissociates into two partial dislocations.

So, that is what is shown here a/6 $[2\bar{1}\bar{1}]$ partial which remains on the slip plane and a/6 $[11\bar{2}]$ are dislocation which can produce twinning. So, this is your slip vector here it is a twin vector it can be a twin vector in FCC crystal which can produce or cause a twin. So, what I am trying to say is though it is not well established the origin of dislocation activity in twinning. So, some of the hypothesis is available based on the experimental observations some hypothesis. We will stop here; we will continue this discussion in the next lecture. Thank you.