Dynamic Behaviour of Materials
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Lecture – 27
Fundamentals of Materials Science and Engineering

Hello everyone, so, today is lecture will discuss about Basic Material Science and we will quickly review the material science concepts which are required for this course dynamic behavior materials. So, as you have you have noticed in this course, we actually were discussing the things very slowly. So, we are going in a very slow pace, but now today I will be a little fast because these things are already you have studied in other courses.

So, what we will do we will just review. I will just highlight you know topics and probably if you are interested you can study and you can brush up your knowledge with your earlier textbooks of material science. And also, you can please feel free to send your queries into discussion forum. Okay. So, before I go to the topic, so I want to thank my M. Tech supervisor, Professor Alan Subramaniam from Indian Institute of Technology Kanpur.

And the Professor Mike Rigsby from North Carolina State University. So, these 2 professors taught me Materials Science and Engineering during my Masters and PhD. Some of the materials probably what I will discuss today.

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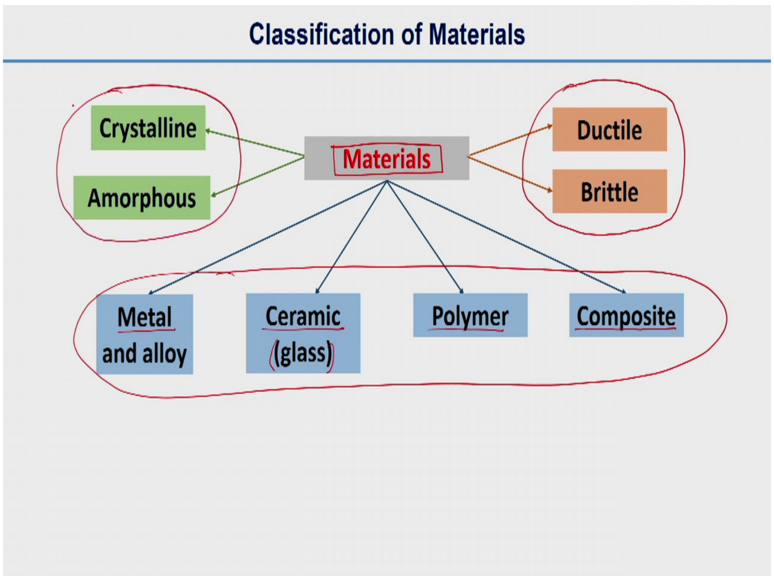

Probably from there influenced by their classes or classmates So, we first discussed about the classification of materials. So, we know that the common classification of materials you know is metals and alloys and ceramics that includes the classes as well. And then polymers and compose composites, which is a combination of ah 2 or more of these 3 classes of metal ceramics and polymers.

So, this is one classification and then enter classification is Ductile Brittle depending on the behavior of the material mechanical behavior of the material. So, that is another classification and the other one is Crystalline and Amorphous. So, these 3 classifications you already studied in some of your courses, probably basic material science courses or even some of these are mostly you studied in your High School standard.

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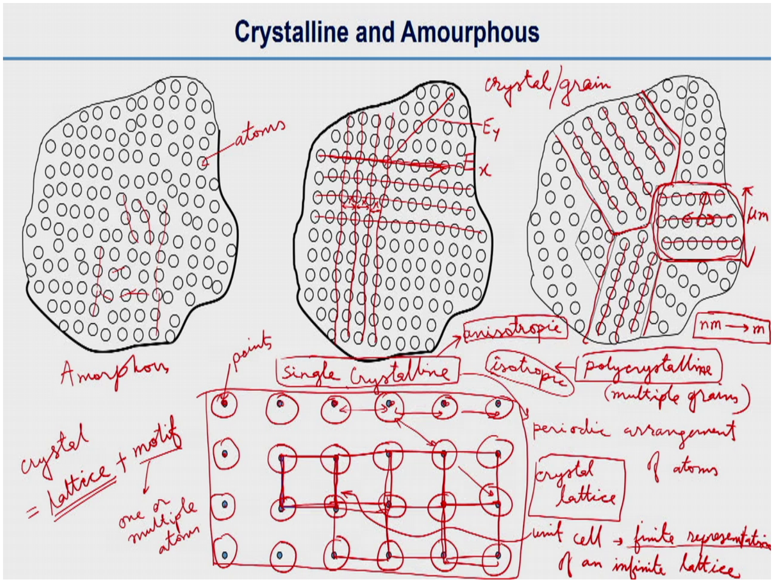

Will not just talk about the Crystalline and Amorphous materials. So, if you see here these atoms are in the left side it is Amorphous. So, in this few materials, if you see some in lines some of the ideas maybe in some, you know lines, but these are in not all the materials are you know it is in any particular order or but here in this case in the second case, it is we called Crystalline material.

So, why we call Crystalline material if you see there are you can draw some lines here and they are perfectly aligned and also the requirement for Crystalline material. We should tell that So, distance between these lines are also equally if this distance is x and if distance is again x and this distance is again x. So, similarly, you can draw lines in this direction as well. So, in that way also the periodic order will be maintained.

So, basically the crystalline material means, the periodic arrangement of atoms crystal. And it actually means, the periodic arrangement of atoms. How does these atoms are arranged? So, this is somehow, sometimes we call these are lattice points if you see this part of the slide. So, if you see that these points are, we let us say call them lattice points. So, now I will tell you this the crystal.

You will get this definition in our textbooks, not every textbook will discuss these things this way, but the crystal is equal to lattice plus motif, the motif sometimes it is called as basis as well. So, what is lattice here is? So, lattice is these points see what I showed you earlier here, these are atoms that you I am sure all of you understood this. So, these are atom but here, what we are showing is some mathematical points.

So, these are called the area of the mathematical points are called lattice. So, these points are lattice. And this lattice are as you can see that arranged in equal interval, if you see that way, or maybe some time you can see this world where it is very equal interval. Lattice is the only the mathematical points and a motif is 1 or multiple atoms. So, when you think about some atoms it is only one atom at one lattice point.

So, these are the atoms let us say on the lattice points. If you want to you know if you are now arranging some atoms and then arranging them, keeping them one atom at one lattice point, then this will be called as crystal. So, when you write the word lattice, you need to be careful because lattice only means the mathematical points. But when you write crystal lattice that will mean that okay.

This is something about the lattice of some atoms and the that is correct. So, lattice alone does not mean a crystal and also you know the in cell. So, you know this is the unit cell unit cell is the this is the unit cell unit cell, you can define it as a finite representation or when in finite lattice. So, that the lattice is them maintains the atoms it can be usefully in finite in. But when you have a unit cell that means you are having a finite representation.

How they are in one of these lattice and if you translate and this unit cell to here and then again you can translate this again to here and then you can you know represent the entire lattice. So, that is why it is a formal definition is some books will give you that way the finite representation of infinite lattice.

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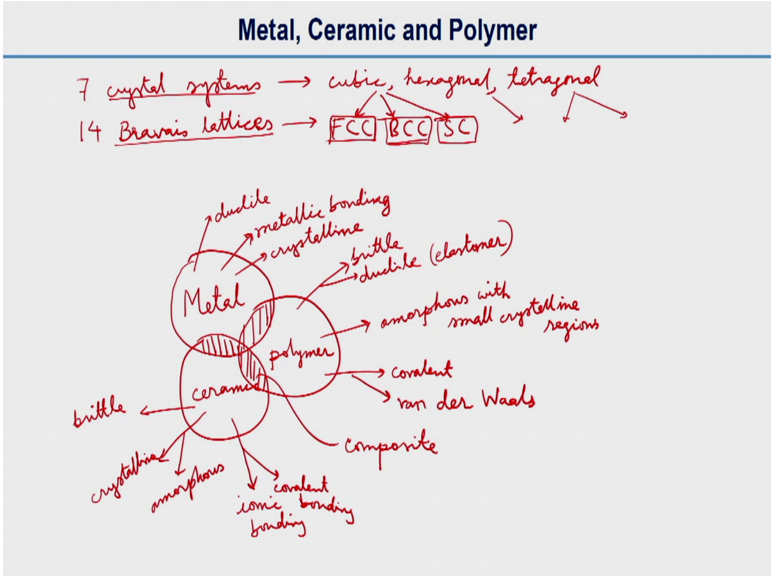

So, in this case also we want to tell you that we have 7 crystal systems and 14 Bravais lattices so, Bravais lattices 7 crystal systems you know the most common one is cubic or let us say hexagonal or tetragonal and orthorhombic, rhombohedral, monoclinic, triclinic. These are depending on the symmetries, how they atoms are arrange, but we are not going to discuss about the details.

But 14 Bravais lattices if you want to know this that is a FCC, BCC, SC there is a simple cubic these all are included in cubic crystal systems. Similarly, others you will be get you will get more here as well. So, that way it has there are 14 Bravais Lattices. So, what is the difference between crystal systems and Bravais Lattices is that the crystal systems are classified depending on the unit cells special unit cell parameters.

Which you call lattice parameters ABC or alpha, beta, gamma angles and the Bravais Lattices are from that those unit cells you need to know see how that atoms are arranged and depending on that we can get the FCC, BCC or simple cubic that you know that FCC has some atoms apart from the cube unit cell cube corners FCC has atoms on the 6 faces as when BCC has atom in the center. So, that you already probably know.

But then in this slide will mostly discussed about another classification let it on the metal that includes metal and alloy and then another one is ceramic. Ceramic will include as you know the glasses and then the third one is as you know is Polymer. So, and these areas will be common areas will be we can. We can represent the, you know, composite. So, very quickly, some important points about these materials are as you know, metal is mostly ductile material.

And then as you know this classification is based on also the bonding, bonding between that atoms. So, this has metallic bonding, metallic bonding and also the metals are crystalline. Crystalline nature what we discuss in the last class last slide and then ceramics, ceramics are mostly the brittle and ceramics are sometimes it can be crystalline and sometimes it can be amorphous.

And these the bonding as you know it can be ionic bonding or it can be even covalent bonding as well. And the polymers are they can be brittle, they can be ductile even the very ductile are let us say elastomer and then it is amorphous with small crystalline and group so, sometimes it is called semi crystal and with small crystalline regions. So, sometimes it is maybe called semi crystalline.

And the bonds are mostly Covalent bond for a molecule and the inter molecule bonds are like secondary bonding Van der Waals bond. So, before going to the next slide so will again go back to the other slide. So, we have left something here so, this is the third one is the polycrystalline material, polycrystalline means the same crystalline material. So, in this case in the second diagram that is a single crystal let single crystal in this case.

And what is polycrystalline that all of you know that it has multiple crystals in it. So, we use the word crystal or mostly in mechanical engineering or mythology we may use the word grain. So, now, if you see this is one grain, so, how this gain the atom alignment or like this and if you enter into another grain. So, that atomy arrangements are a little different in a different orientation.

Similarly, the third grain so atomic elements are different. So, this is that is why this is multiple grain. And as you know that most materials most metallic materials are Polycrystalline because these grannies like in the order of micrometres like 10 micrometres to 100 micrometres. But sometimes you can make very big grains like for a turbine grease you can make series single crystal turbine grease.

So, engineers and also export they can make you a very big grains in centimeters or meters and they can also make very small grains like nanometer level. So, now the range of grains that is called nano crystalline material from nanometer to probably meter you can make grains depending on your expertise in metalogic, materials engineering. So, now one important thing to mention here is that for a metallic material for a crystal in material.

The single crystal is Anisotropic. As you know the definition of Anisotropic. I think that means the material properties are different in different directions and for a Polycrystalline material generally, we consider it is Anisotropic. Why it is anisotropic. Because in a single crystal, we think that the material properties let us say elastic properties in this direction.

Let us say E x and then let us see, and this direction elastic property is E y they are different. But in this case, as if you see only one grain, only one grain, then the material properties will be different in this direction in that direction. But, if you take the average of all the grains because there will be thousands of grains in a material, because it is only most grains are in micrometer level. So, then you can ever be out the properties. So, that means that is why you can get a material which can be considered as anisotropic.

But there are other cases of anisotropic that you can learn like isotropic material transversally Isotropic material and also if you take a single crystal of other crystal system like single crystals of cubic crystals tetragonal crystal, hexagonal they have all different kinds of symmetries and they anisotropic is very different than each other. So different from each other. So, they are not isotropic if you take a single crystal they are an anisotropic but the anisotropic is different. Cubic crystal is different tetragonal. Tetragonal is different from hexagonal.

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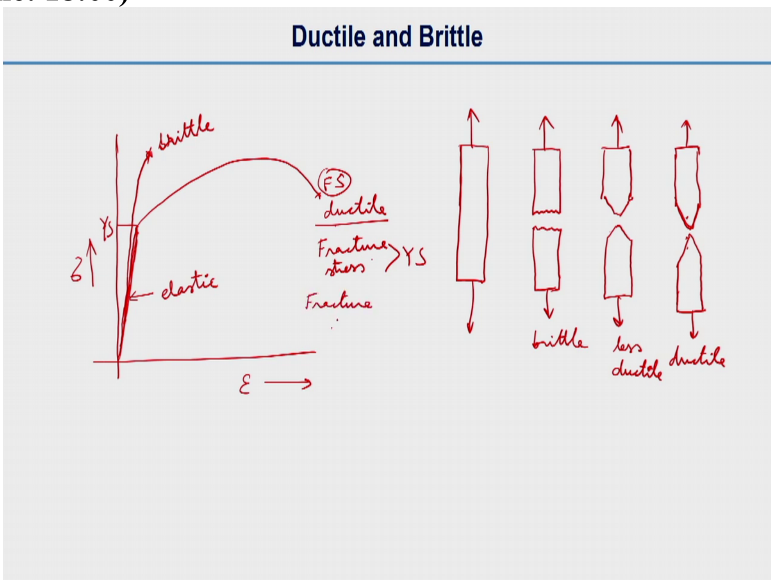

So, now, we want to talk about the ductile and brittle, what is the classification we discuss all of you know about that, but just to I know remind you the things you learned earlier. So, if you draw a stressed and curve as you know, the very common one general ductile, stressed in curve will look like this, this is ductile and if you draw another one for a brittle material. So, this brittle material will fracture it here.

So, this is for brittle. So that can be material, which is some ductile, but not exactly brittle. So, now, if you do a tension test, let us you have a specimen. You have, let us say, specimen like this and you were having a ductile this So, what will happen if it is a brittle material, so, the material will break at the middle you know a flat crack fracture will happen.

So, this is a brittle material. Similarly, for a ductile material, let us say aluminium all it is a very that kind of material gold. So, what will happen is you will get a nicking formation, nicking formation and the material will break like this. So, this is ductile and if you have a less ductile material less ductile material so, which probably nick portion will be not as long as the other one. So, it will look something like this. So, you can see that this is less ductile but not exactly brittle, but this is less ductile. So, these things you already know.

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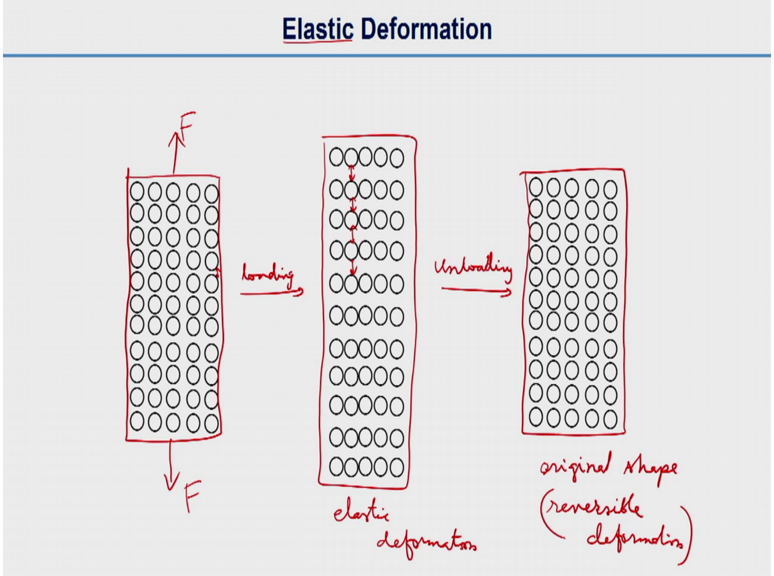

But then again, we will discuss about the elastic deformation here. So, as you know, in the stress strain curve and the stress strain curve, that is your ductile material, the elastic part of the stress strain curve is this one, that is the straight line mostly elastic. We are mostly in these lectures we will focus on only on metals, not on ceramics and polymers. So, that is why we are talking about this crystal in kind of metallic materials.

And we are showing these polly focus on that type of stress strain curve. So, this is a metal material and let us say your tensile specimen, we are drawing not many atoms. So, but just to show you what happened in these cases. So, what will happen after you do some, I know tensile tests. So, the material will elongate and so, that means, what will happen the distance between these atoms and the vertical.

You know, in the direction these will increase if you see the distance here is very less now, it is more. So, this will increase, so, that is the elastic deformation, Elastic Deformation and what will happen if you unloaded. So, this is what you did here is the loading and if you unloaded the material will take the original shape. So, what will happen this will be original shape that means the deformation is reversible deformation. So, the unloading is giving us the same shape of the original shape.

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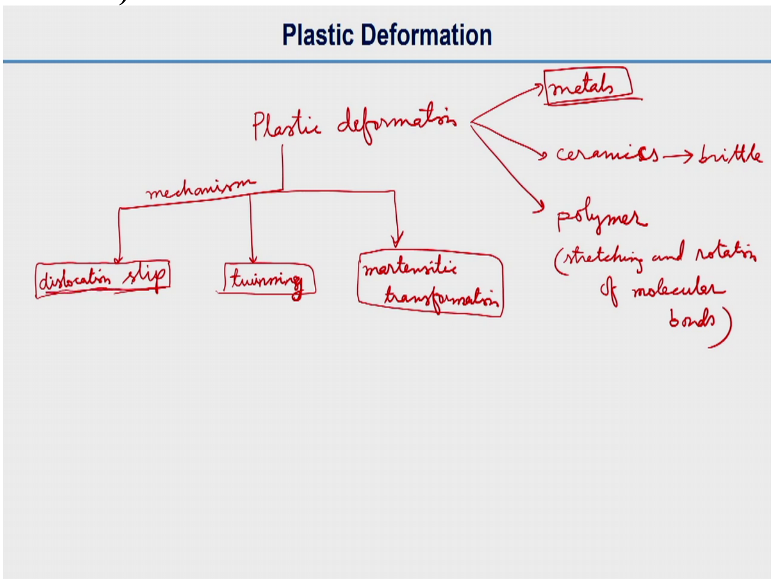

But that is not the case in plastic deformation, Plastic Deformation is different. So, plastic deformation, Plastic deformation probably anyways this these are different for different materials. So, mostly in this part we will discuss we will talk about metals and then we have ceramics. Ceramics also the plastic deformation mechanic mechanics and can be different and mostly as you know the ceramics are brittle by the way that will not have plastic deformation, much plastic deformation this is polymer is different.

So, I just we go back to the earliest slides of the ductile and drittle and material slide. So, I probably forgot to tell you that and I am sure all of you know that. So, the ductile means, what does it means that fracture stress fracture stress is higher than the in strength here. So, this is the in strength and this is where the fracture happens, we need to this is fracture strength and that means, for the ductile material fracture happens.

After yielding after plastic deformation in this case, brittle material no yielding directly fracture. So, that is the difference that all of you know that. So, now if you come here, so, ceramics this mostly brittle and probably they will be very little plastic deformation, but some of the ceramics can so some plastic deformation and the polymers are deformation mechanism is very different.

And it is basically stretching and rotation of stretching and rotation of molecular bonds. So, this is for polymers, but as I told you, we are focusing on leon metals now. And then if you talk about metals. So, we can have a classification of the mechanisms. So, we are talking about the mechanisms of Plastic Deformation here mechanisms, the first one is slip second one is twinning, and the third one is martensitic transformation.

So, slip is very popular as you know. So, we sometimes call it as dislocation slip, because this involves movement of Dislocations and the most metals deform by plastically deform by this mechanism. But another mechanism is twinning less common and martensitic transformation is even not all materials also these kinds of transformation. So, dislocation slip is a called the common mechanism. So, we will discuss more on this and then we will discuss the other two the twinning and martensitic transformation, also little bit.

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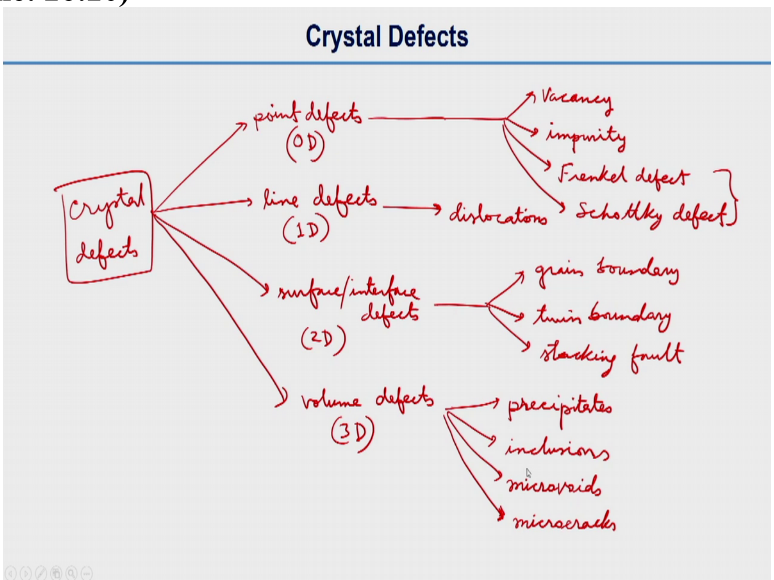

So, we will talk about Crystal Defects now. So, the Crystal Defects are can be classified into some categories that is also you studied in your probably in your material science class. So, the point defects which are call zero-dimensional defect and then line defects which is which are call 1D defect and then surface defect surface or actually interface defects, interface defects.

These are called also called 2D defects and then volume defects are the 3 dimensional defects. So, point defects, are Vacancy, Impurity atoms and Frenkel defect and Schottky defect. These 2 are for ionic materials and then line defect as you know very popular among metallises, this is this locations and then for surface defects that can be grain boundaries twin boundaries and then stacking fault and volume defects that can be precipitates, inclusions, voids whether we should call them a micro voids, why we are calling them a micro void.

Because another void is crystal refuse void which is in the atomic level in between that atom that is the interstitial sites and then another one is micro cracks that means not be cracks, micro cracks. So, in the atomic level that crack is in the atomic level. So, this is the, the mostly we are covering most of the defects here, this is the classification of defects, you can classify in terms of a 1D, 2D or zero-dimensional defect.

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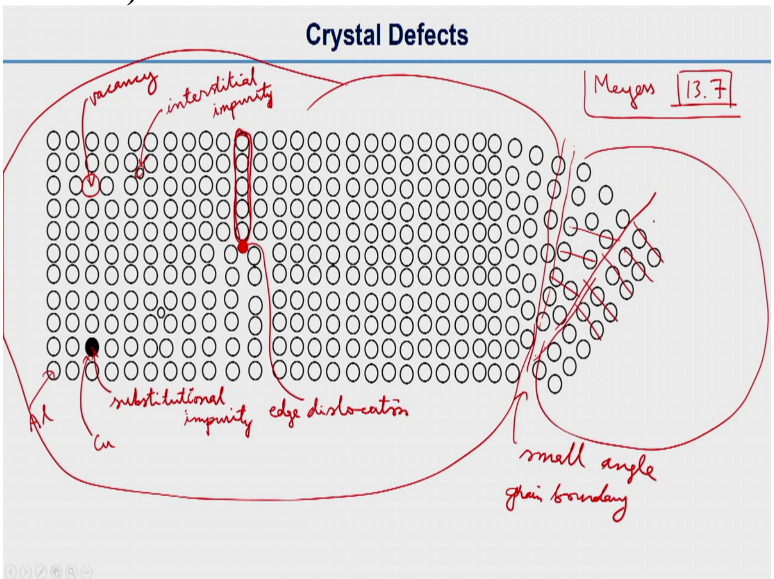

So, this figure is from Mark Meyers book 13.7 figure number probably that is the should be the same for all the books and that is the one additional 1994. So, now, there is 3 different kind of figures and I found it very interesting. So, what is happening here is it is shows different kind of defects in this in the same figure. So, this one is these are all atoms that you can understand, this is an interstitial impurity.

Interstitial impurity or interstitial sites are in between the regular analytics sites. And there is another one is, again one impurity that is called substitutional. Substitutional means that atom is different. Let us say the all other atoms are aluminium. And let us see one atom is cooper atom. So, that is why it is called substitutional impurity. They can be a lot of high number of impurities.

But we are showing only a one for each and then this is an extra half play we call that is the dislocation actually, dislocation is if you see in the perpendicular line perpendicular to the plane of this slide. So, that will be called as dislocation this is an actually edge dislocation edge dislocation. So, that this is called extra happened whatever I have drawn here, the dislocation line will be on this, whatever I am drawing now, and that will be perpendicular to the plane of the slide.

That means, you assuming 3 dimension what we are showing only 2 dimension and then there is one vacancy here, this is the vacancy there is no atom here. So, that is why it is called a vacancy. And then this part if you can see there is some boundaries here, this is these atoms are not arranged properly. So, this is a small angle grain boundary, small angle, boundary that means, actually the grain boundary,

If you have one more grain in this direction, so this is another, and this is one grain, let us see. So, now we can so some this is although not so clear, you can refer to the diagram. So, there is a twinning also showing here twinning will show in another slide as well. So, twinning that is not very easy to find from here probably better. This twinning boundary I am not discussing in these slides so will later we will discuss that.

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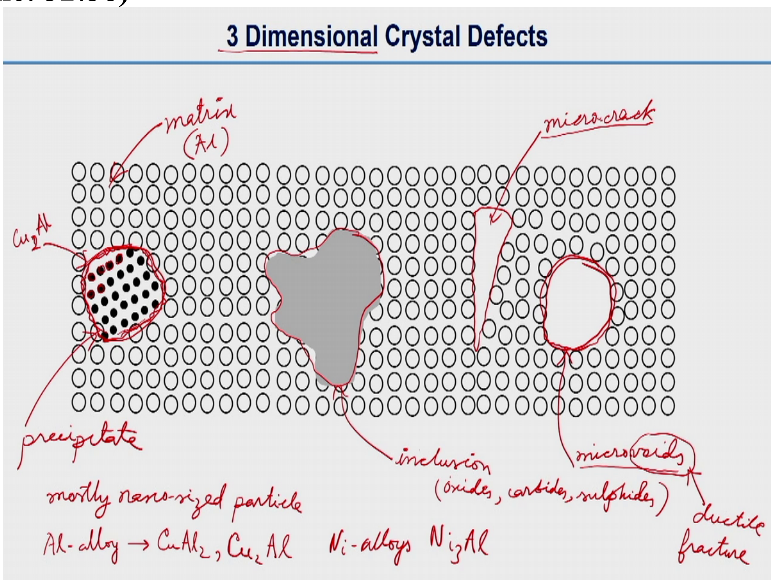

We are discussing about 3D Crystal Defects. So, this is the slide summarizes some of the 3 Dimensional Crystal Defects. So, this one is precipitate, mostly the sizes in a nanometer level. So, and they are mostly nano size particles. So, they are the primary strengthening is not in many alloys we will discuss about that. And suppose the precipitates are some compounds like for aluminium alloys.

Let us say these are the precipitate let us say CuAl 2 or Cu 2 Al. Similarly, for nickel alloys, the precipitate is Ni 3 Al. So, these are also what you can see is the dark colour are also atom although it shows in a different size of atoms but just to show you this structure, so this is the precipitate, as I told it is in general it is a nanometer level or it can be spherical or it can be applied shape or it can be rod shape.

So, that is in between the parent matrix. So, we call this part as matrix. So, if it is let us say if it is aluminium alloy, so, the matrix will be aluminium and let us say the precipitate will be Cu 2 sorry Cu 2 Al or something like that. So, now the big particle the bigger particle which is in mostly in let us say micron level, so, this is called inclusion. So, inclusions are mostly they are non-metallic oxides carbides and sulphites.

So, these inclusions are very different than the precipitate and also, we have some other defects. So, this one is a micro crack. So, there is some vacant space here. So, this is a micro crack very small crack these micro cracks in early do not grow very big. You know it always in material there are a good number of micro crack can exist, but the material failure generally does not happen from individual micro crack and similarly.

There are voids that is mostly we call micro voids. So, these are as you know for ductile material and the failure depends on these voids or micro voids. So, there are many voids. So, individual voids are all also grow during deformation during plastic deformation and also the mini voids will come together and join to each other there is called void first nucleus and then it grow and then comes together as conquer lessons.

So, that way the ductile material fails. So, I just read right that is related to ductile fracture that means, the voids are responsible for ductile fracture or ductile failure or, or failure of ductile material. So, these are some 3 Dimensional Crystal Defects.

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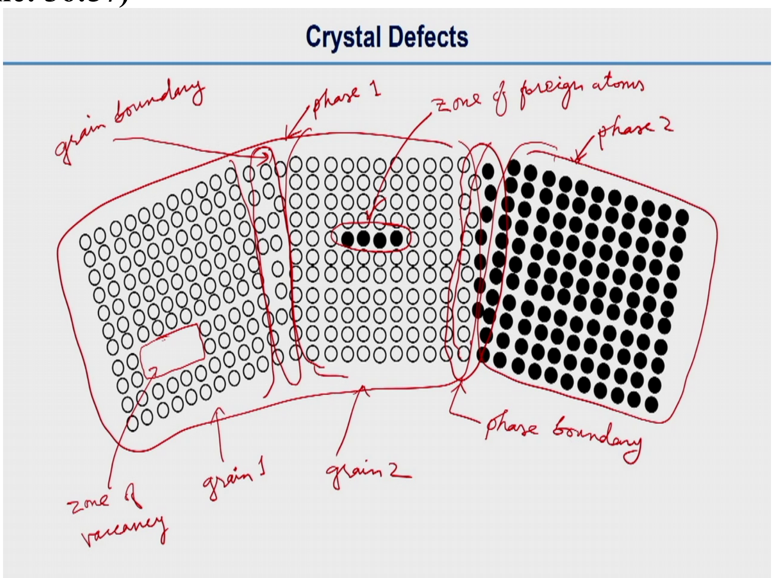

And then this is again some defects, let us say this is a different material and this is another material. So, this portion, where they are atoms are not very arranged in a periodic order some of these are some irregularity you can see. So, this is called phase boundary. Because let us say this one is phase 1, and this one is phase 2, they are different materials. So, this is the phase boundary. And similarly, there is 2 grains here actually.

So, this, this is in a phase 1, we have 2 grains, so, let us say grain 1, and then the second is grain 2. So, now, this portion which is does not have a very regular arrangement of atom. So, this is called the grain boundary. Grain boundaries also a crystal defect as you as we have discussed is a 2 Dimensional Crystal Defect. So, similarly, we have a vacancy zone so it is a group of vacancy or we can call zone of vacancy.

So, as I already told these 3 figures this these 2 slides and the earlier slides are these are from the Mark Meyers book that is figure number 13.7 zone of vacancy we can see and similarly, there are some foreign atoms the group together so, that is we can call zone of foreign atoms. So, these are some defects we discussed.

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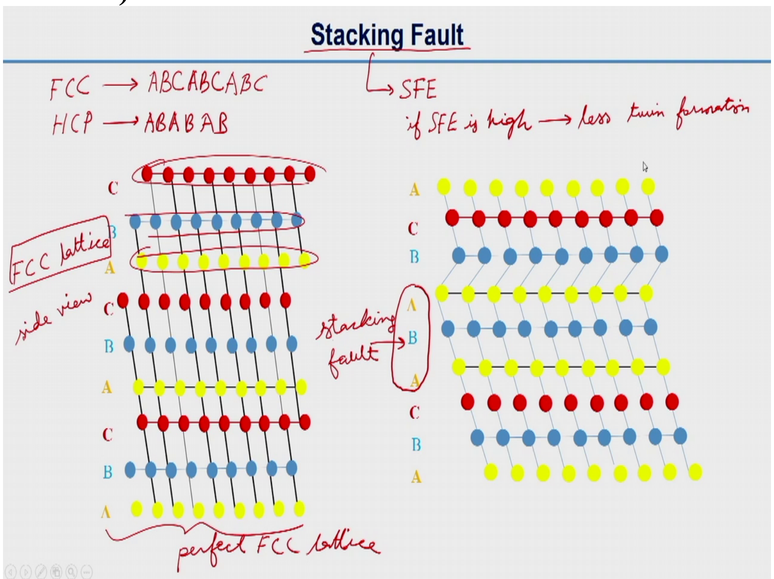

And another 2 dimensional defects. So that is called Stacking Fault we did not include in the earlier figure is schematics. So, the stacking fault is maybe a little difficult to understand. So, let us say we are seeing here in FCC lattice. And in side view, FCC, as you know, face center cubic. This is, let us say, a side view why we are calling side view, Is that, that you probably, I am sure that you studied, we do not have much time to describe all those about the packings.

How the they are packed in FCC and ACP. So, it is a little difficult now to you know, summarize it in a very less time, but you just please study these about this Stacking Fault. So, the FCC packing that means these are all atomic planes that you can understand. This is one atomic plane which is called B and this is C this is A. So, for FCC, the picking order is like that ABC ABC ABC. For hexagonal closed pick, the picking order is like AB AB AB. So, the are quite similar AB planes are there but C missing here.

So, now if you were talking about the FCC lattice, this is the perfect lattice without any defect, perfect FCC lattice, but sometimes what happened sometimes there will be some defect. So, there will be some missing. Let us see here. We have a plane missing here we are getting only AB AB picking there is no C plane. So that that is fault reason so that is called Stacking Fault.

So, in summary, so Stacking Fault is the fault in the stacking sequence of material like for this crystal in material. So, you can take this basic former material science textbook. So, the Stacking Fault has Stacking Fault energy I will just write SFE that means, E means energy. So, this Stacking Fault energy all the Crystal Defects not only Stacking Fault, but the dislocations other grain bond these 2 twin boundaries.

They have energy associated with it. So, like perfect crystal maybe at the minimum energy level, but these defects we increase the energy. So, stacking fault energy is related to mechanical twinning. If the stacking fault energy is high twinning, the chance of twinning is less. So, I would like less to information like, aluminium has high stacking fault energy and that is why it does not undergo much not doing deformation.

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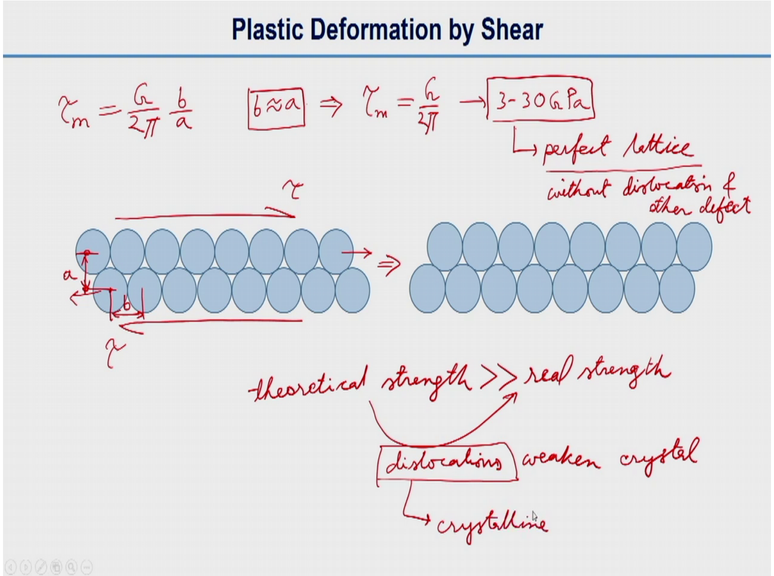

So, we will talk about this plastic deformation ratio. So, what we are doing there are 2 rows of atoms. So, if we share, apply some shear stress, like this, let us sit down with the shear stress. So, just you know, we are trying to shift these, let us say, plane or atom this way and the other plane in this way. So, what happened the result is the result is this one. So now, while doing this, so the maximum Shear Stress, Tau m that at which the slip will occur.

So, that will be equal to G by twice Pi Shear models and b by a So, if b equal to a we can assume b equal to a or sorry, I did not even tell you what is b sorry about that. So, b is nothing but the distance between 2 atoms in a plane and what is a, a is the distance between these 2 planes, so, inter atomic distance okay. So, if b is equal to a, and if it is not exactly equal also this will be in this is of the same order.

So that is where we are assuming b is almost equal to a. So, that will give us Tau m the maximum shear stress at reach the slip will walk out is equal to G by twice Pi, as you know the shear models is in giga pascal. So, for most metals this value will come like 3 to 30 giga pascal. So, this is a very high value that must shear stress is required. So, this is that is possible for a perfect lattice without any defect. Defect here mostly we will be discussing here now, Dislocations.

So, if it is a perfect lattice let us say without any in this dislocations or even other defects, dislocations and other defects. So, its strength will be this is the shear stress actually, the shear stress will be very high. So, this is theoretical shear stress. So, theoretical strength is much higher than what we get in experiments. So, that will be much much higher let us say it is 100 times or 1000 times higher real strength of the material.

To real strength you can determine from experiment. So, why this is happening? So, this happens mostly because of the dislocations. So, that means dislocations make the crystal weak make the material weak so, dislocations mostly as I told you this location is mostly for crystalline materials or metallic materials, or we can call this metals and alloys.

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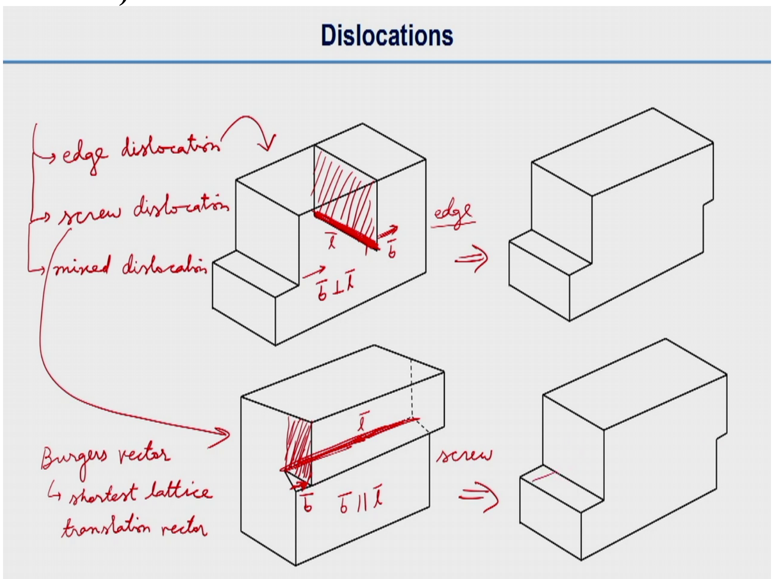

So, now we will see what are these dislocations are line deffects. So, there are different types of dislocations. So, first one is we call edge dislocations, I am sure all of you have read that but just for your review, and I am drawing doing this there is another one calls screw dislocations and the third one is called mix dislocation, which is in between these 2 screw an edge. So, first whatever we are drawing here is edge dislocation and the second one is a screw dislocation.

This is screw dislocation right here this is edge and this is screw dislocations we did not we do not have a mix dislocation here. So, what is happening here is the slip happens in this direction and the extra half blend that means an extra plane over atom will move in this direction for the dislocations this you can see that these part it just moved from this side, you know from left to right that you can I am sure you can understand this. So, this part of the material is shifted.

So, shear is sharing in this direction. So, when you call burgers vector which is the shortest, we call lattice translation vector, lattice translation vector. That means from one lattice point to another lattice point so this lattice translation vector. So, that is this is the b here so b in this direction is this one and then here the b direction is this one that is the slip directions in both the cases and then our dislocations line in this case and for l dislocation.

This is the dislocation line I will just write maybe l for dislocation line vector; this is the dislocation line and in this case in screw dislocations. So, this dislocation line is this one. So, that is why we say that the l dislocation the burgers vector is perpendicular to l the dislocation line here you can see and for screw dislocation burger vector is parallel to dislocation and you can see that the burgers vector direction.

And the dislocation line direction is the same and these 2 figuers on the right hand sides shows the result of these deformation. So, after this deformation you can get a step created here.

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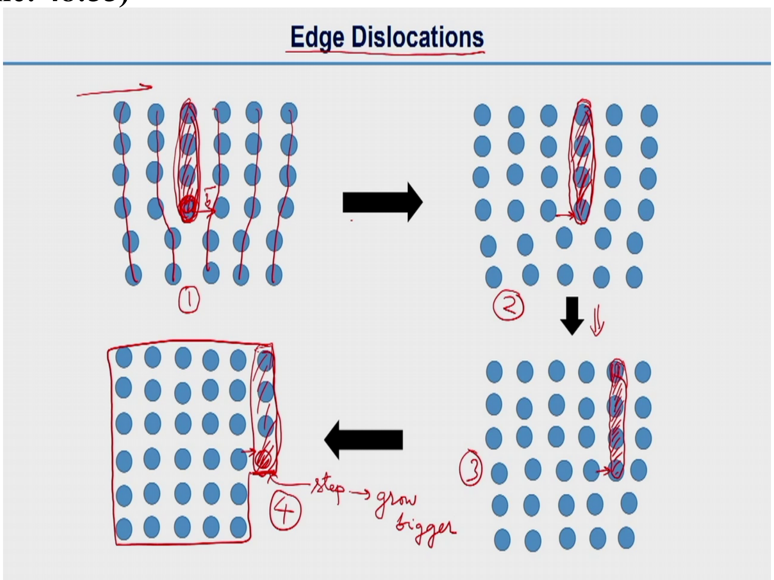

So, we will see now see about this edge dislocation. So, here, we can see that there is an extra half plane here the other lines of atoms are you can see the few going away from this. So, we have a one full plane over atom. But here in this case you have an extra half plane of atom so, that is actually dislocation and that this the slip direction on the burgers vector direction in this way and the l direction that the dislocation and direction is along at this point and in the perpendicular to the plane of the slide.

So, that is the dislocation line. And so, if you see after some time when you were sharing the material, so you are exerting some shear force. So, you are the extra half plane will shift a one atomic distance and towards the right and similarly, here if you if you shift more if you are exerting more sharing force, so, then the extra half line will go towards more right. And then at last it will be, this will be out of the, this crystal. So, now, what will happen there will be a straight formation.

So here we have probably one more item. So, there will be straight formation. So now, the entire body let us say, we are having showing only few atoms, but the entire body would look like this. So what happened here again, I am repeating this, so, extra half plane was here in this case, in the first step, and in the second step it has little displacement of these extra half plane and the and then again, this is the displacement and then again, and the third case, this is the third step.

So, what will happen, what happened and this is again one step towards the right. And in the fourth case, again one step towards right. So now, this dislocation comes out of the crystal, so that we are creating a step, we call it as the small step. So, this is very atomic level, it is very small. So, it is in the strong level, but if lot of dislocations like thousands of dislocations come out, and then what will happen is this step will grow, grow bigger,.

And then you can see some plastic deformation. So, the plastic deformation will be then we can see with our naked eye, so if a lot of dislocations, hundreds of thousands of dislocations come out and make a step like this,

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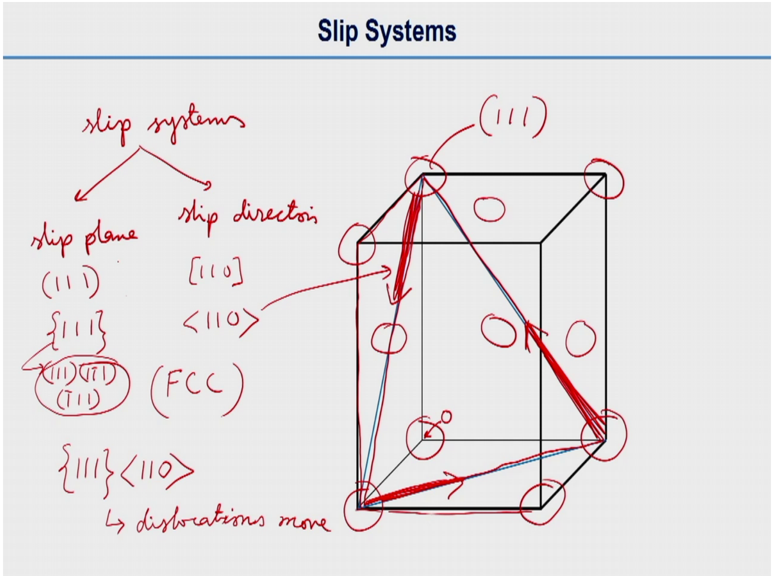

Make a big step on the on the surface. So, I just let you know what is slip system the slip systems are nothing but a combination of slip plane and slip direction. So, what is happening here is the black line, so the unit cell, so unit cell means let us say this FCC. FCC lattice and we have atoms at the corners and then we have atoms at the surface, the face center as well. It is something like this the face center as well.

So now what will happen is this plane this plane the blue line, this plane we call the 1 1 1 plane. So, considering this is the origin okay, so, so similarly for FCC material we are talking about FCC material here. FCC Slip System. So, 1 1 1 plane and we write actually the curly bracket because this is a family a plane and similarly family of directions is 1 1 0 in this case.

If you take this direction and or if you take this direction on the plane and or if you take you in this direction on the triangular plane and that is 1 1 1 you can take 3 directions which are like 1 1 0 directions. So, now, the combination of this 1 1 1, 1 1 0 So, that means, Why I am write why I am saying as a family, if it is a single slip direction, we write it like this. So, why we call the family because they are a combination of planes and combination of directions on which.

So, the dislocation moves so Dislocations moves on slip planes and in slip directions. Okay. So, this let us say the family or plane means it may be 1 1 1, or 1 -1 1. All let us say -1 1 1 or something like that. So that is that is why it is it family of plane.

So, these are the particular planes and directions that is crystallography directions and crystallography plane where the dislocation moves and that slip happens that that is the basis of plastic deformation.

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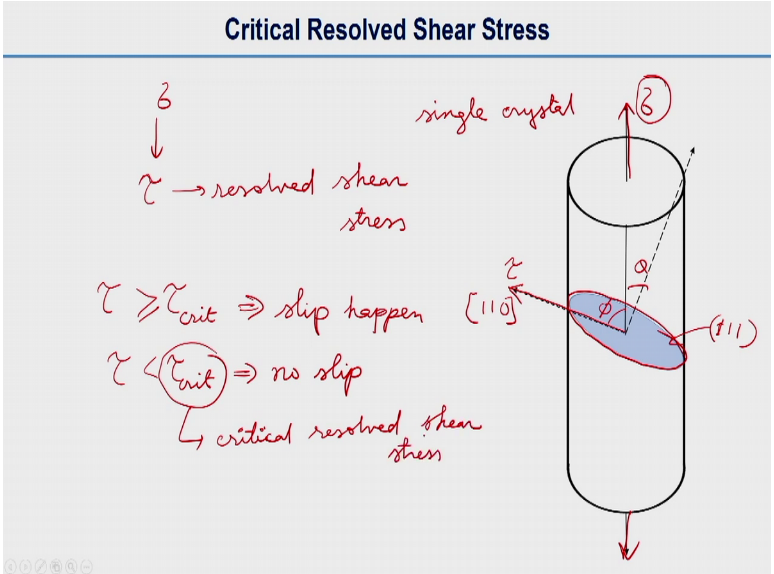

Now, again, coming to the same dislocation movement. So, if you have a let us say material and we exerting a force and let us say the normal stress sigma tensile stress, and if your slip plane is in direction, in this, this is the slip line in the material. Let us say we are assuming a single crystal here. Not very complex multiple crystals or polycrystal material. So, within the single crystal.

So let us say this is we are FCC and this is this is a 1 1 1 plane and let us say this is the slip direction, which is 1 1 0 direction. So, now what we need to do is we will resolve this sigma along this plane or along on this plane along this direction is this is Tau. So, we will resolve this Tau we will calculate this Tau that is called resolved Shear Stress. So, we resolved it and calculate that stress from our sigma okay.

So, if you notice angle is Theta the angle what is made by these direction Phi so, then you can find out this Tau is Shear Stress Tau and if resolved Shear Stress is greater than a critical value. I will write Tau critical then the slip will happen them slip happened that means the dislocations moves below that. All we just write. Get it an equal Tau. So below that Tau if it is below Tau critical, so slip no slip, or we can write, yeah, no slip.

So that is why this Tau critical is called critical resolved shear stress. Yes, that is material dependent so it is a material property critical resolved shear stress.

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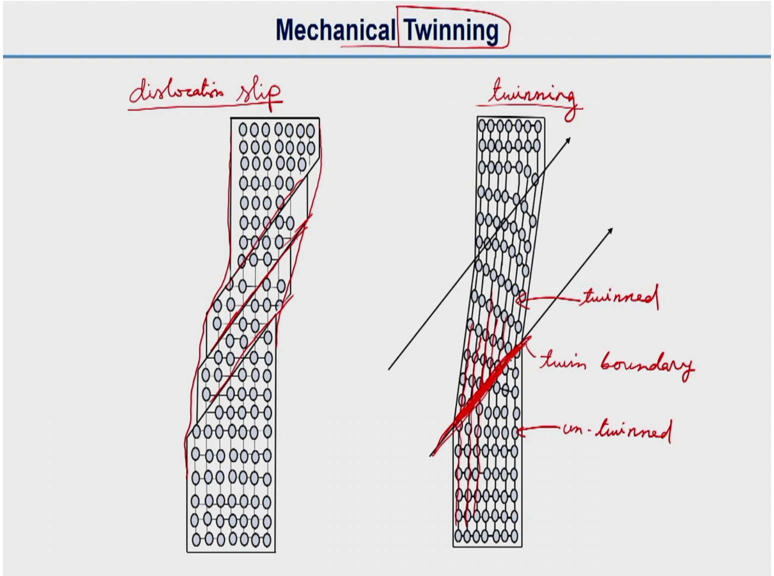

We are not talking about mechanical twinning as I told you the twinning is also a plastic deformation dechanism. Here on the left hand side we are showing you slip that means dislocation slip and on the right hand side, we are showing twinning mechanical, twinning for slip as I told you, these are some slip planes, where these are the planes let us say where the slip happens and ultimately, we are getting a deform shape like this.

So, this shape deform shape is form because of the many dislocations go out of the crystal and form these steps. So, now, what happened in a twinning is so, you can see that these are these atoms are aligned and suddenly when you were deforming the material, so, the alignment of this portion will be different suddenly it changes the orientation. So, now generally we in twinning we call that this is a twinning bound twin boundary.

So, that means, twin boundary form in between a twin region. So, this is twinned and this is untwinned, not twinned. So, this happens during plastic deformation as I told you and not all material will undergo probably twinning and this basically is a across the twinning plane, these atoms are like some symmetry reflectional symmetry that means mirroring is the one side will be that the other side of the twin boundary will be the mirror image that is called reflectional symmetry.

So, this is one way of plastic deformation, but is less common than dislocation slip. So, we have already discussed about 2 plastic deformation mechanisms, dislocations slip and mechanical twinning.

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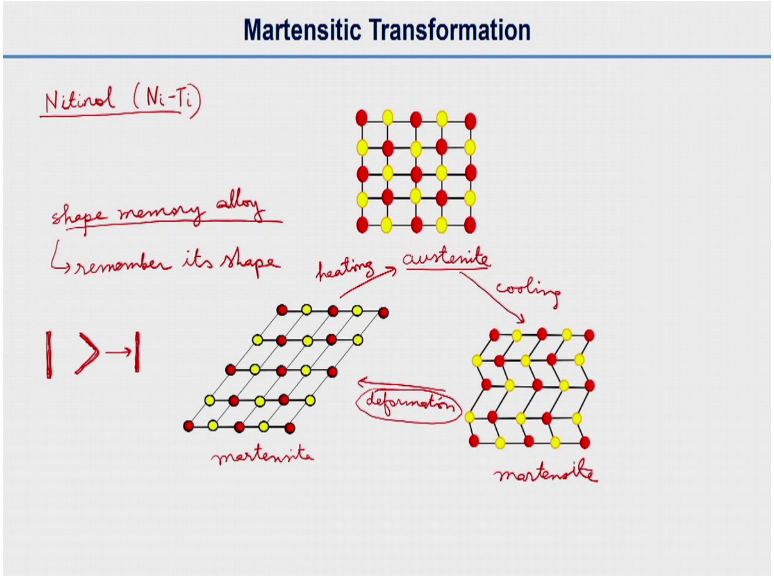

And the third one is martensitic transformation, martensitic transformation face transformation. So, solve the alloys like for example, nitinol is one example, which is nickel titanium alloy. So, this nitinol are some other materials. So, they undergo some crystal structure changes and the during the plastic deformation, so, here so, this material is in austenitic form and then when we cool it during after cooling, so, it will form martensite.

So, if we deform this martensite after the formation it will come to a different structure it is martensite, but it will have a different atomic arrangement and then if you again heat again it will go to their original austenitic structure. So, these kinds of alloys, some of these kinds of alloys are call shape memory alloys because when you call the material and you deform it and again you heat it you get the original shape. So, what it can does is, it can remember it is shaped.

Remember, it is shap suppose if you have a let us say wire or teen, a bar of that material and you are the bending the material like this bending the bar like this. And so, what if you heat, then the bar will come to its original shape. So that means the bar remembers its shape, and then it goes back to its original shape. So that is you can study about shape memory alloy, I am sure most of you know about shape memory alloy. But this is one of the plastic deformation mechanism.

So, the deformation is associated with the structure, crystals structure changes. So, we do not going to discuss details about this, but you can study in any material science textbook regarding this martensitic transformation. So now we will talk about the strengthening mechanisms of metals.

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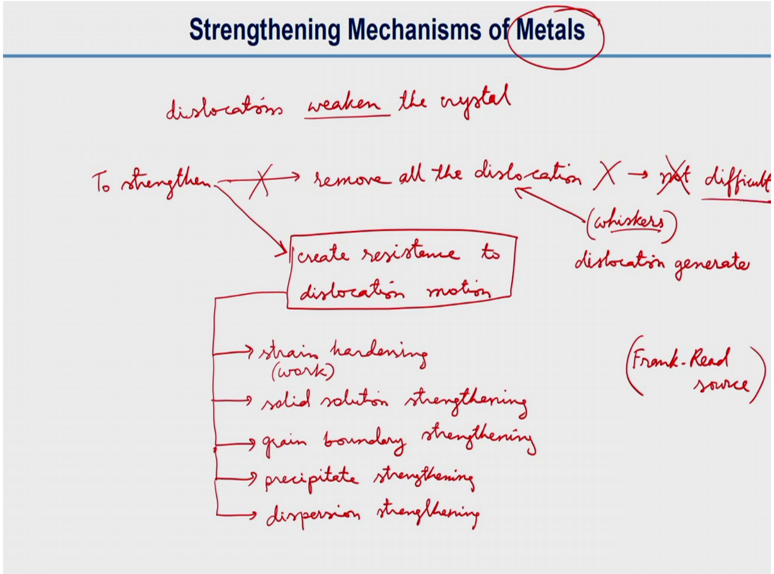

So, we for our applications. What we want to do is we want to strengthen our metal if it is not sufficiently strong. So, for that purpose strengthening means, we want to restrict the plastic deformation, so that we can exert higher load. So, for that reason, what we can do is in an earlier slide. So, what we found is that dislocations, which is one type of crystal defects and dislocations, we can crystal all the material the crystalline material and metallic material.

So, now, as we discussed that if you have a perfect crystal without any dislocations, so, you will the strength of the material will be much much higher than the crystal with a without dislocations. So, to strengthen the material what we can do is first, we can try to remove the dislocation remove all the dislocations so that we get a theoretical strength that is by doing not possible it is actually it can be possible but it is very difficult.

That you can probably make very small we call whiskers very small particles which may have the perfect crystal without any dislocations, but anyways if you if you deform more the more dislocation will generate. So, dislocations will generate even if you were starting with a perfect crystal dislocation will generate and then the mechanisms to generate dislocations lifetime to source you can study these, if you are interested, like frank read source of dislocation generation.

I am sure some of you already know about this. So, to remove all the dislocations for a bigger sample, it is impossible for small whiskers it can be possible, but again dislocation generates deformation. So, we are not going to use this technique or it is not possible. So, there can be another technique now, to strengthen the material to create resistance to dislocation motion. So, why we are saying that we are if we want to strengthen the material, we are we need to work on dislocations.

Because the plastic deformities is mostly controlled by dislocation movement, if it is not mechanical twinning and martensitic transformation. So, most of the plastic deformation depends on dislocation movement. So, if we can restrict, the movement of dislocations then we can restrict the plastic deformation and that means, we are strengthening the material. So, we will now see how to create resistance to dislocation motion, there are different ways to do that.

So, that we will discuss one by one. Let us say first one is Strain Hardening or we call this a work hardening. Work hardening and the second one is solid solution strengthening or you can you can use the hardening and strengthening word actually interchangeably. This is what we are talking about metals this crystal materials. So, and another one is grain boundary strengthening and then precipitate strengthening and dispersion strengthening. So, we will now discuss one by one oh sorry, this is I should have wrote difficult.

Actually, initially I thought I will write not possible but this would be only difficult. It is not difficult. So, basically the remove all the dislocations is possible, but it is very difficult.

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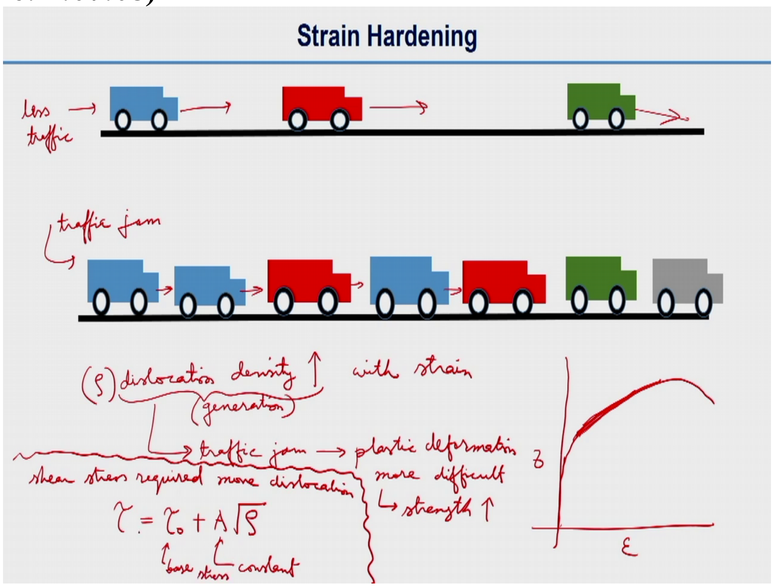

So, what is Strain Hardening? So, you can see some cars here. So, this is just to represent the strain hardening. So, what happens during strain hardening? So, as you know, during the plastic deformation, let us say this is engineering stressed and curve. So, this part is of this curve is we call it the strain hardening. So, what happens in this portion, so with strain with deformation.

So, dislocation density will increase dislocation density increases with deformation or weak strain. So, what happens if the dislocation density increases, it is something like this. This is like a traffic jam kind of situation. Traffic jam. So, here in this case in the earlier case, less traffic, though this is actually the dislocations movement can be compared to a traffic movement vehicle movement on a road.

So here in the first case, the less traffic and so it is very easier for the cars to move. So, and but here in this case, it is not very easy in a traffic jam kind of situation it is not very easy to move. So, similarly, when you strain more and more, so dislocation density will increase because of the dislocation generation like what we call one of the generation mechanisms is frank read source.

So, dislocation will generate and dislocation density will increase. So, this means dislocation increase of dislocation means traffic jam kind of situation traffic jam kind of situation. So, that will that means the plastic deformation is difficult plastic deformation is difficult more difficult and that means that the strength increases strength increases.

So, there is a relation its empirical relation first shear stress is required to move at dislocation. So, that is that looks like this. So, where this Rho is the dislocation density Rho is the dislocation density. This is shear stress required to move at dislocation move on dislocation. So, I will make a boundary here. So, this Rho is that dislocation density and the constant is A is a constant and then Tau 0 is the best stress to move at dislocation unique in the crystal in the absence of other dislocations if there is no other dislocations.

So, Tau Tau 0 is required. So, there is the we can check this relationship in the materials book. This is based stress when there is no other dislocations are no other interaction other dislocations. So, this is what we are showing is here it depends the shear stress required depend on the dislocation density. So, if Rho will increase, so if Rho increases, then Tau will also increase. So, that is what this relation shows. So, that is an empirical relation.

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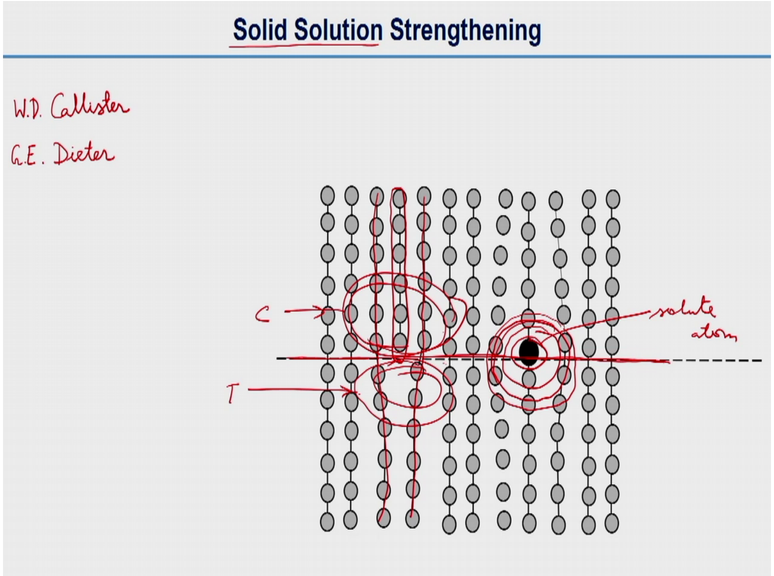

So now we will go to solid solution strengthening and you know, let us say we have a edge dislocation here, and if you see there are no planes below. So, here actually the slip plane is this plane perpendicular plane of the slide. So, and again this is a solute atom. So, what will happen now, so, there will be some dislike some stress field around this dislocation let us say in this region will be in comprehensive I write C for comprehensive and this region will experience some tensile stress and write T for tensile.

And similarly, the due to this solute atom the deck can be some stressful that can be comprehensive tensile depending on the solute atom. If it is a let us say smaller solid atom, then it can be probably even tensile stressful or if it is a bigger solid atom it can be comprehensive stressful. So, depending on that, they can there will be some stressful. So, if dislocation approaches is solid atom or a group of atoms solid atom. So, what will happen it will get some resistance.

So, this resistance will we increase the difficulty of dislocation moment and that will increase the strength of the material. So, this is called solid solution strengthening, I hope you most of you know that what is solid solution please refer to a standard material textbook like probably callister. So, I am just writing the callister book is good or otherwise, you can great classic book on metal mechanical metal G.E. Dieter. So, mechanical metal as a book so, and I writing W.D. Callister, these are the books probably you referred in your basic material science course.

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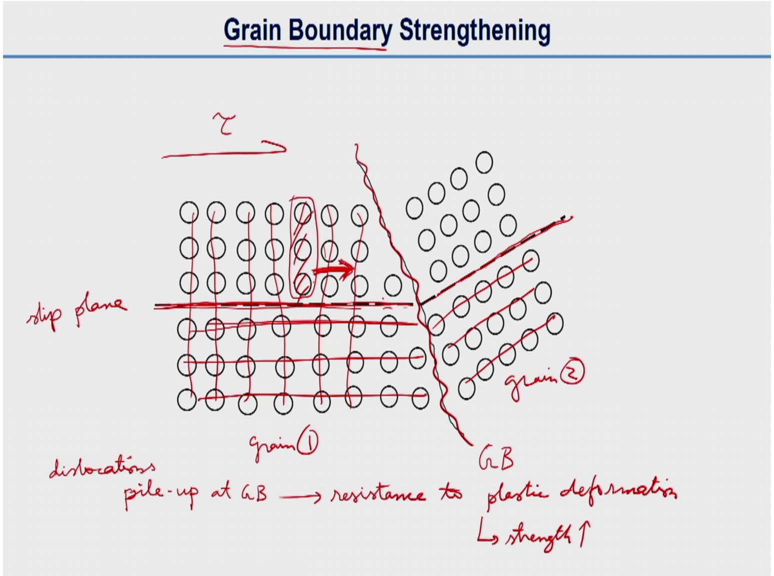

So, the next one is grain boundary strengthening, so, you are discussing about different strengthening mechanisms. So, this is the third strengthening mechanism we are discussing. So, here we have edge dislocations, if you see these are other planes or you know atoms, so, here we have edge dislocation, so, this is our extra half plane. And so, this is our slip plane, the dash line is our slip plane.

So, what happens is this is the grain boundary, as you can see that this is, I would write GB grain boundary. And as you can understand that the orientation of these atoms are different than the other grain. So, this is grain number sorry. So, this is grain 1 and this is grain 2. So, what happens when the dislocation the deformation let us see we exerting some Shear Stress and this extra half plane is moving towards right towards the grain boundary.

So, what will happen is when it tries to cross the grain boundary it will get some difficulty because the slip plane is oriented in a different direction. So, that is why what will happen is the dislocations will we call pile-up at the grain boundary. So, dislocations we pile-up like our vehicle pile-up that you can sometimes when some accident happens with several vehicles, generally we call them pile-up.

So, that vehicle pile-up at grain boundary and that means they are the resistance to plastic deformation that means the resistance to plastic deformation. Plastic deformation that means, that the strength we increase strength of the material will increase. So, dislocation movement restricted and that means the plastic deformation is restricted.

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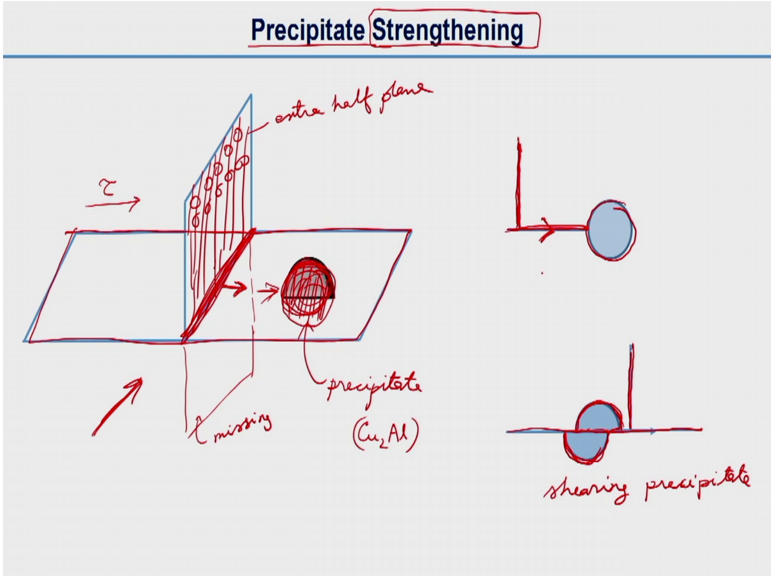

So, the another one is precipitate strengthening, so, as you know precipitates are small particles I discussed earlier also, this is one particle this is not very clear here but it is a spherical particle and we are having these as an extra half plane please try to understand this from the earlier figure. So, here somewhere I showed you here I showed you this one is the extra half plane in 2 dimensional case and I told you this horizontal line is the slip plane.

And here we are discussing the 3 dimensional case but without any atoms. So, atoms, like let us say that atom will be here, but we are not showing we are not showing the atoms. So, this is the extra half plane that means a plane under that is missing. So, this plane is missing under that it is missing plane. That is why it is called extra half plane. And now this one is the slip plane, because of dislocation will move on the slip plane this is the dislocation line.

This is the dislocation line. And this dislocation line will move from left to right. So, let us say it is because of some shear stress, this is some we are exerting some shear stress. And the dislocation line is moving from left to right now there is an obstacle this is the precipitate. So, what happened the precipitate is a small particle mostly generally the precipitates are nano sized particle.

But they are probably intermetallic, as I told you for a let us say, aluminium alloy, the precipitate can be Cu 2 Al. So, the structure is different, the crystal structure is different sometimes it can be similar same crystal structure or let us say aluminium is also FCC and this precipitate may also be FCC sometimes the precipitate that may be BCC or hexagonal closed precipitate.

So, what will happen is this dislocation line we will face some difficulty to cross the precipitate. So, what will happen this is the dislocation line again we are showing from 2 dimensional viewed from this side, the side view we are showing here this is the slip plane. And dislocation is going this way. So, this is the extra half plane actually dislocation line will be perpendicular to that. So, this is the precipitate.

So, after some time what will happen this extra half plane, we cross and precipitate will be sheared this is called shearing a precipitate, this is called shearing of precipitate. So, during this shearing there are 2 results. So, that is the surface area of the precipitate increases and also the force required for the dislocation line to you know cross the precipitate actually it increases.

So, there are more force required so, that is why the strengthening happens need to precipitate, but these are the precipitate which are we call coherent precipitate coherent please check it, what is coherent and incoherent. So, just to I mean you know very you know simple language the coherent precipitate are easier to cross for these dislocations.

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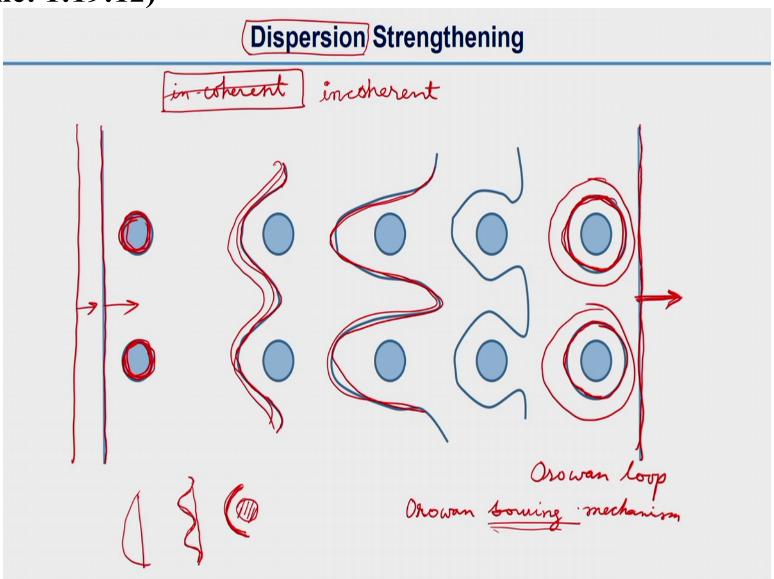

But there can be some incoherent particles and this is now we are coming to this dispersion strengthening these can be these are some particles that can be some inherent or incoherent sorry probably I told you inherent that should be incoherent. So, this incoherent particles that can be some inclusions or some dispersion particles are some can be incoherent precipitate. So, this line is the dislocation line.

So, dislocation lines here is trying to move towards the right side. And then what will happen it because these precipitates are incoherent that means, this is difficult to cross or difficult to cut through or sheared through then it will form like this. And finally, it will you know, try to form a loop and finally, it will form a loop around the precipitate or whatever particle it is and incoherent particle and then dislocation line and it will move.

So, what happens this location lines circles around these precipitates and then again it will be new straight line. Straight dislocation line will be move towards right crossing that. So, subsequent dislocation line if you think that there will be one more dislocation line behind these which is also traveling in the right direction. Then there can be one more circle around it and these circles are loops on the dislocation loops or call orowan loop or it is sometimes called orowan bowing mechanism.

It is like it is it is make it bow like shape special here you can see this bow like shape. So, this call all orwan bowing mechanism sorry, this incoherent is not kind of a separate word separated by dash. So incoherent this is the correct word and also there when I told about the bowing mechanism. So, I told that this is the bow but the nearly bowing I mean bow shape, although this is also a bow shape, but the nearly here the bowing means simply you know shape like this so do not confuse with that.

So simply, I mean, when you have a particle, and then simply the distribution line takes a shape like to this or that is we call bowing. Not exactly this type of bow shape which nearly we sometimes you know, imagine the bow like that but even this is also a bow, this is also a bow. So, both the planes are bow shape but do not confuse that you know there are 2 arcs needed for a pause on a simple single arc is also enough for to call it as a bowing mechanism. These are a strengthening mechanism of metals.
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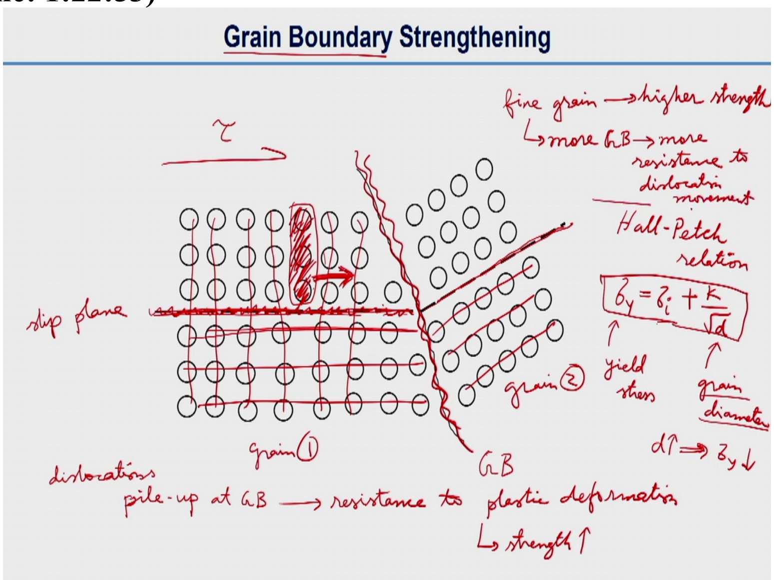

So just I want to tell you one more thing that I forgot here in the grain boundary strengthening the grain boundary strengthening also one mathematical relation that is called Hall-Petch relation. With the help of that relation we can show you know the quantify the grain boundary strengthening that is sigma y equal to sigma i plus k root d. So, d the grain diameter here, so, grain diameter and k is a constant and then sigma i is also a kind of the base stress we discussed earlier.

So, that is the stress to move a dislocation in a single crystal sigma i and the Sigma y is the yield stress, so, yield stress we decrease if we have a bigger grain that means if the grain diameter So, if these higher that means, sigma y will be lower. So, for the for that reason, so, if you have a fine grain structure fine gains means smaller grain structure, the material will have higher strength. So, material will have higher strength.

So, you can probably understand that, if it is fine grain, there is more grain boundary more means, the length of the grain boundary will be more or we should not call it a length. Because, what we are seeing here the grain boundary is in 2 dimensional there is in 2 dimensional surface. So, more grain boundary area so, that is why more resistance to dislocation, movement.

So, that is why the strength increases, we actually completed this lecture on material science basics. So, this is I was quite fast in this lecture, I was not going in space like what we followed in earlier lectures because I believe most of you already learned these concepts of material science in your basic materials courses. Probably in your second or third year of your bachelor's degree.

So, I think these are the mostly the basics we are using or we will be using in our then you will be ever materials course, but there can be some more concepts, we may require. So, in during our subsequent lectures we will try to discuss very briefly about those concepts. After these, we will talk about the phase transformations that is induced by shock wave. So, that is all for today. Thank you.