Nanotechnology Science and Applications
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Lecture - 11
Impact of the nanoscale on Mechanical properties

Hello, in this class we are going to look at the Impact of nanoscale on Mechanical Properties. Actually, it will be in this class and the next subsequent classes that follow that we will completely discuss this topic. So, to understand that and to completely figure out what is the effect of the nanoscale, we will begin by first looking at the mechanical properties themselves.

So, in this class, we will focus on the mechanical properties to understand what is that phenomenon that is a phenomenon or phenomena that are occurring at different size scales, which may impact the mechanical property. And once you get a sense of that, when you when we discuss the nanoscale, we will understand how or how the nanoscale is affecting the mechanical property, and also what is peculiar about the nanoscale about the impact of the nanoscale on the mechanical properties which is basically the crux of what we are trying to understand and discuss.

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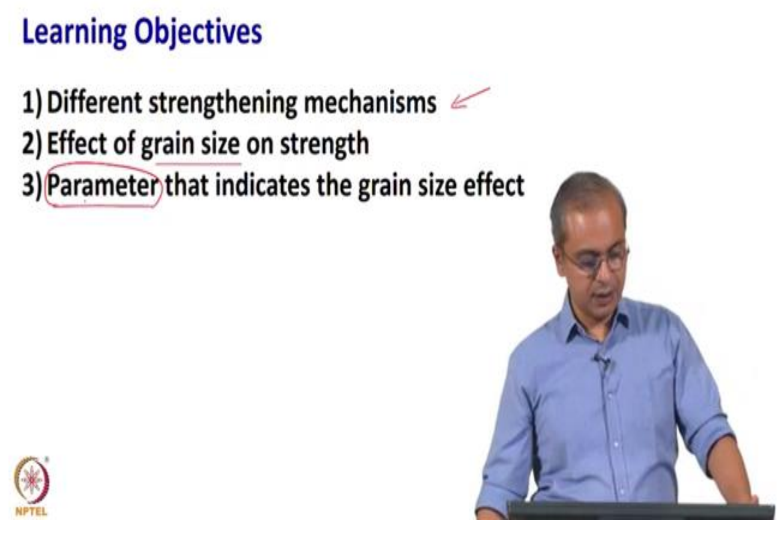

Learning Objectives

1) Different strengthening mechanisms
2) Effect of grain size on strength
3) Parameter that indicates the grain size effect

So, our learning objectives for today's class are to briefly look at different strengthening mechanisms. So, there a wide range of different mechanisms that are there. So, we will look at some of the significant strengthening mechanisms that are known to exist in the materials, and therefore, get a sense of how those strengthening mechanisms impact the property. We will look in particular we will focus on grain size. So, there is something called a grain size in a material, and then we will get a sense of what is the effect of the grain size on the strength.

Of course, some of these terms are very familiar to metallurgical and materials engineering students, perhaps if you are background is somewhat different, then this is not a term that will immediately be apparent to you, but it is not a very complicated term we will look at that.

And we will also look at a parameter that indicates this grain size effect. So, the grain size will have an effect on the property, but there is a parameter with a sort of captures it as a number; as a number that we can keep track of where we can compare it against different materials and get a sense of what is happening at in different materials. We will it is the same parameter that will also help us distinguish between the grain size-effect in the sort of macro-scale or even micro-scale as we may call it.

And the effect of the macro or micro scale versus the same effect happening at the nanoscale, and what is different about those two it is actually sort of captured by this particular parameter that we will briefly highlight, and then we will look at its impact data in this set of classes.

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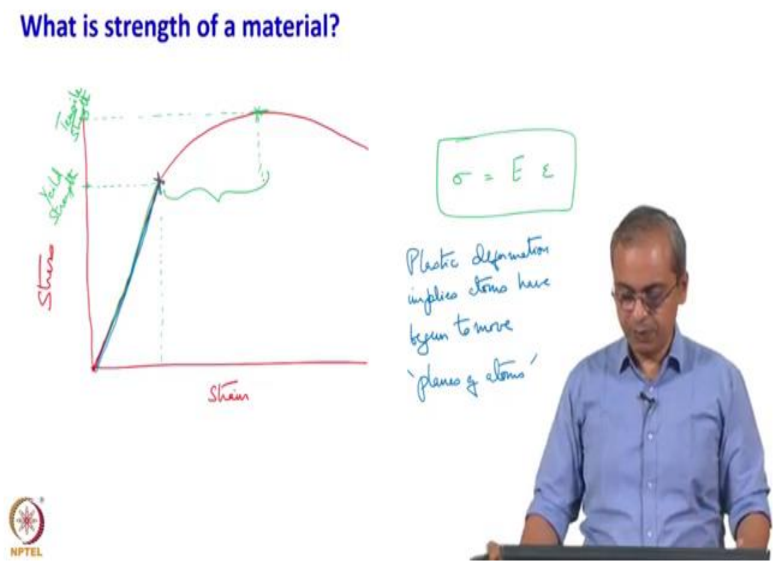

What is strength of a material?

$\sigma = E \varepsilon$

Plastic deformation implies atoms have begun to move 'planes of atoms'

So, we will first begin by asking ourselves what is the strength of a material, what exactly do we mean when we say strength of a material? So, to understand this we have we obviously, have a real-life perception of what strength of a material. So, we know when we see a material that is weak, we have some and which breaks easily, which bends easily things like that, we say it is weak. Whereas, some other material that really resists you try to put a lot of force, you try to do something to it, but it simply refuses to budge it's it is in its original shape so that is our sense of what is material that is strong versus a material that is weak.

Now, from a material science perspective, obviously, there are going to be some formal ways of doing this and formal ways of quantifying this material. And many of you must be familiar with it. We typically have a stress-strain curve. So, stress versus strain is what we will have. And the general and this curve itself can be drawn in a couple of different ways, so it depends on how we define our quantities. So, we can have true stress versus true strain, we can have engineering stress versus engineering strain and so on so. We will look at this version of it where basically we see as you increase the stress, you will see a linear increase in the strain.

And then, in general, there are going to be features which are very specific to different systems. So, I am not going to focus on system-specific features these are general features that we are going to look at. And from here you will see a behavior that looks like that, and then like that. So, this is the typical stress-strain curve that you will see for a wide range of at least metallic systems typically you will see this. And as I said there are exceptions, again if you go to polymeric systems, you can see a behavior that looks dramatically different; even within metallic systems there will be specific features that look ah very different.

Now, in this case, we are not basically accounting for changes in cross-sectional area. So, we will just leave that for the moment. What we need to keep in mind is that there is a certain section of this curve which is linear. So, up to here, it is linear; and then beyond this point it is so beyond this point, it is non-linear. So, this is the behavior that we see.

Now, generally the strength is a feature or an aspect of the material that we associate with this concept that you are applying, you are trying to change the shape of that material, but you have to keep applying more and more stress to do that. So, as long as you keep putting as long as you are required to put more and more stress to cause the material to change its shape, the material is getting stronger and stronger and stronger, so that is a general idea.

So, now there are a few points here. So, this linear region if you look at this the y-intercept of it, this is called the yield strength. And similarly, if you take the topmost point of this curve here, topmost point of this curve here, and you draw the take the y-intercept of this point, so this y-intercept of this point here, this is called tensile strength.

So, now you can see here what happens is you are applying some force to the on the material which I mean quantified in terms of once normalized to the surface area is being referred to as stress, so Newton’s per meter square we are applying some stress here. So, that stress is causing that material to change its shape.

Now, in the linear region of the so when we say something is changing its shape a few different things can happen. One is you have atoms which have in the crystal structure, they have got some bonding with respect to all their neighbors. And as you apply the stress, those bonds are being stretched. So, they are being stretched, but up to a certain point the bond is not being broken. So, it is being stretched, but not being broken. And then when you release the stress, they go back.

So, when you put the stress, the atoms move to as so they have an equilibrium position, you have pulled them out from the equilibrium position little bit apart from the equilibrium position, but you are not broken the bond, and then when you remove the stress they go back to the equilibrium position. So, you increase the stress, it goes out, decrease the remove the stress it goes back to its original position, so it is always able to go back to its original position.

And so this is this idea that you can put stress on material cause it to change its shape because if all the atoms move from whatever is their interatomic position they all move 2%, they increase the interatomic spacing goes up by 2% for all the atoms in the system. Because you are pulling the whole sample from left side to right side, you are extending it out that way. All the atoms accommodate that extension by moving apart from the nearest neighbor by 2%, then you will see an overall 2% strain. So, the material length will go up by about 2%. You release it, it will go back to its original length. So, this movement where you have not broken the bonds keeps this whole deformation process within what is referred to as the elastic regime. So, you reduce the force, it goes back to its original shape, and that is what is captured by this linear part of this stress-strain curve up to this yield strength.

So, up to that yield strength, it is what is happening is basically this you have not broken bonds, you are basically stretching the bond to some degree, and then you release it and then it goes back to its original thing. So, this is the yield strength. So, there you will simply have the stress that is being applied will be really related to the strain through the elastic modulus. So, this is from our Young’s modulus of elasticity kind of behavior. So, this is what you see here. Stress versus strain equation.

Now, as I said this equation captures the fact that you have to apply a certain amount of stress to get a certain amount of strain. So, now, clearly for some materials you have to apply even if you are within this elastic regime, where you are once you release the forces, it goes back to its original interatomic separation original size or the sample itself goes back to its original dimension.

Clearly this varies from material to material, some materials you have to put even more stress to get the same amount of deformation, and still stay assuming we are all still within the elastic regime, some material you will have to put less stress to get that elastic deformation to say 2% strain. And then another material we have to put much more stress to get the same 2% strain.

So, we have to see what is it that is happening in the material which causes this difference between the two materials in terms of how much stress you have to put to get the same 2% strain. As I said this is directly related to the interatomic bonding that is happening in the material.

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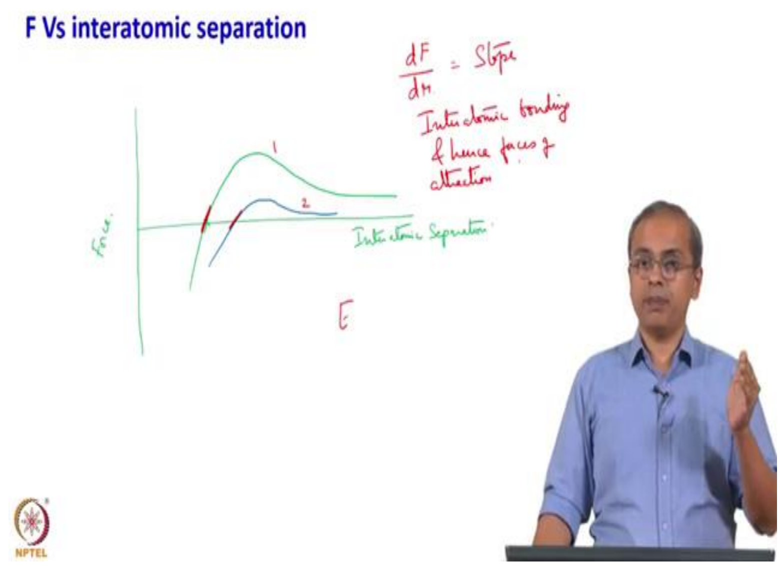
F Vs interatomic separation

So, for example, if you plot if you take a given material, they are called stress here. And this is inter-atomic I am sorry this is force, this is interatomic separation. So, you will see that there is an equilibrium spacing in the material, where the net force is 0; equilibrium spacing where the net force is 0. And what happens is if you try to compress the material, you get repulsive forces. You try to expand the material; you get attractive forces. So, you will see a behavior that looks like that something like this is what you will see the behavior that you will see.

You may have another material where you may see the behavior that looks like this. A general form will be similar but the exact shape may be different. So, you can see here for example, that this slope here is steeper than the slope here. The slope in the case of curve 1 is greater than the slope in case of curve 2. The slope is dF by d r that is the slope. And it is this the steepness of the slope that is basically getting reflected as our I know in the elastic modulus.

So, the steeper the slope the higher ratio elastic modulus; the more shallow the slope the less is your elastic modulus. And it has got to do with the interatomic forces. So, this is related to the interatomic forces, interatomic bonding, and hence forces of attraction. Attraction and repulsion based on whether you are compressing it and so on. So, this is where the elastic part of that stress-strain curve comes.

So, up to the yield strength, this is basically what we see. So, in particular up to the yield strength, up to this point here, if you load the sample, and if you release this release the load, you will go back to your original your strain will drop back to 0. So, you will trace this curve back and forth. So, we will simply trace this curve back and forth. So, you load the sample, you go up the curve, you unload the sample you come out from the curve. So, that is that reflects like I said the yield strength reflects something about the strength of the material, and you can have steeper and steeper lines here, and therefore, the E value is going up and it reflects a very strong material.

Now, after you cross this point after you cross this yield strength, the material has begun to deform. So, deformation means atoms have begun to move. So, deformation means atoms have begun to move, so especially plastic deformation, plastic deformation. So, in plastic deformation atoms have begun to move. So, more specifically these are planes of atoms, so planes of atoms have begun to move.

So, now, when you deform a material like that, if you stop the deformation, you will not recover all of the deformations. When you are within the elastic mode because you have not really broken bonds, you release the load, you go back to the original shape. Here when you release the load, you do not go back to the original shape. You will recover a little bit, you will recover whatever is the elastic part corresponding to that total deformation, but you will not recover the plastic part corresponding to the total deformation. So, what you will typically see.

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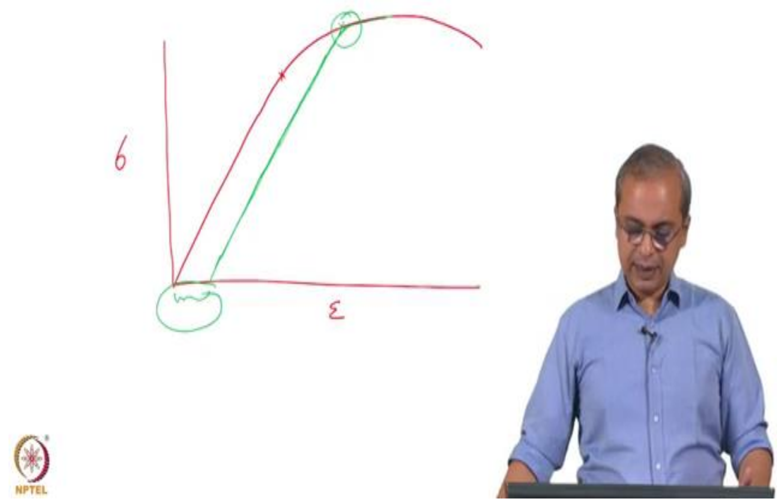

So, what you will typically see if you look at a stress-strain curve is that if you are in the plastic regime, so you have a stress-strain curve that looks like that. And this is the up to here is the elastic regime. So, then if you load it past the elastic regime, so you load it up to some higher load up to here. And at this point, you now release the load.

So, when you release the load, you will not get back the entire the deformation that you have done. You will simply get back some part of it. So, you will essentially trace a curve that looks something like this. So, there will be some permanent deformation that has happened, but still, there is some amount of elastic behaviour there. So, you will see something like this.

Now, if you load it up, you will again tray retrace this curve, in general, this is what will happen, and then you will again go back to this curve out here. So, for all practical purposes, it appears that the material has become stronger. And this is not some imagined thing, this is really something that happens and we utilize it. So, for example, if you take the body panels of an automobile, any car that you have, any automobile that you have. If you take the body panel, what is typically happened is that they would have gotten a block of material and that is put through a rolling process, it is put through rolls and that the material is made thinner and thinner and thinner.

So, during this process, you must remember that the shape is changing permanently. So, we are having permanent plastic deformation, so that is what is this. This is permanent plastic deformation; permanent plastic deformation that is happening, so that is happening in that material. And in the process that material is actually becoming stronger and stronger and stronger. So, that is this behavior that you see here. So, what it means is that during elastic deformation to the extent that the load is present the material is becoming stronger.

After the elastic deformation, when you start the plastic deformation for a fair bit into the plastic deformation for a fair stretch of the plastic deformation as you keep deforming the material, it also becomes stronger due to various other phenomena that is occurring in that material right, so that is how that material is becoming stronger.

So, what is that phenomenon that is happening in that material in this regime? So, here what is this phenomenon that is happening that is making it stronger. So, for the plastic deformation to occur as I said atoms of planes of atoms have to move. So, now, anything that you do which hinders the movement of planes of atoms makes it appear makes it show up to us in the macroscopic sense as a process that has made the material stronger.

If the atoms if the planes of atoms can move very freely, then it means that with very little extra stress, large planes of atoms will move large numbers of planes of atoms would move which basically means the shape of the material is changing because the atoms are moving so perhaps they were there was a top half of the sample, and bottom half of the sample and you are moving it. So, all of these atoms are beginning to move. So, they are all moving in different directions. And therefore, naturally, the shape of the sample is changing.

The more easily those planes of atoms move, the weaker is the material, and the deformation occurs much more easily. So, this is basically the idea here. So, certain types of mechanisms prevent that from happening from prevent the planes of atoms from moving. So, we will now see what are those strengthening mechanisms.

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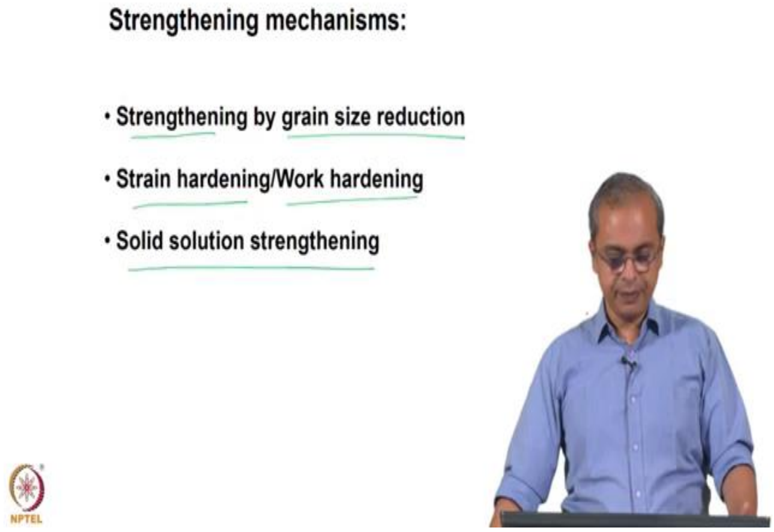

Strengthening mechanisms:

- Strengthening by grain size reduction
- Strain hardening/Work hardening
- Solid solution strengthening

So, basically, strengthening mechanisms occur by a few different ways. We have something referred to as strengthening by grain size reduction. So, this is one way in which you can strengthen the material. We can also have a strain hardening or work hardening that is another way in which you can strengthen the material. And you can have something called solid solution strengthening. So, these are three major ways in which we can strengthen a material. And you can see distinctly increased strength in that material. So, we will look at this one by one.

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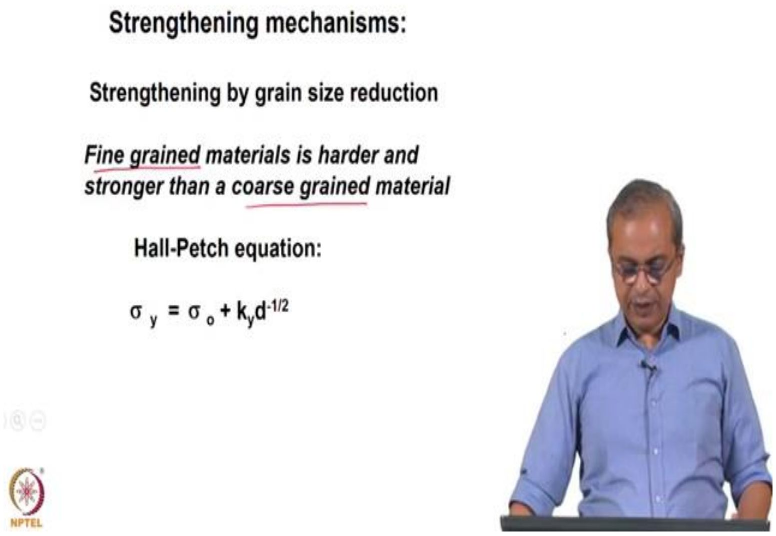

Strengthening mechanisms:

Strengthening by grain size reduction

Fine grained materials is harder and stronger than a coarse grained material

Hall-Petch equation:

$$\sigma_y = \sigma_o + k_y d^{-1/2}$$

So, when we say grain size reduction, so generally the idea here is that if you take a coarse-grained material, and take the same sample as a fine-grained material, you will find that the fine-grained material is typically harder and stronger than the coarse-grained material.

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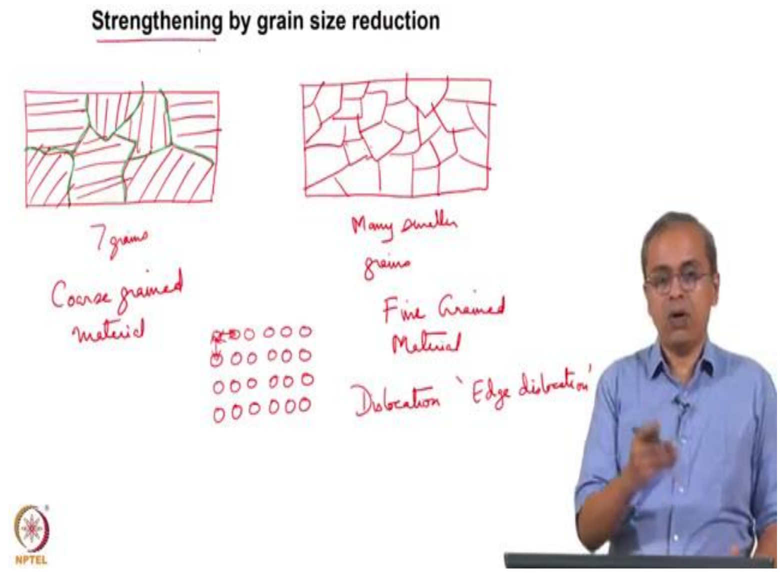

Strengthening by grain size reduction

So, to understand this first of all we need to have a quick idea of what is a grain which I have I mean which you may find at different places, but for sake of completion, we will just look at it here. So, you have a sample like this and another identical sample here it at least in terms of overall exterior size and dimensions.

Now, if you have atoms in perfect order from one side of the sample to the other side of the sample in perfect crystalline order, then there is a single crystal. So, usually, the samples that we get are not single crystals. You will not have them in perfect crystalline order from the left side of the sample to the right top to the bottom and so on. So, instead what you will have is, you will have various regions inside the sample something like this. So, within this you have all the planes of atoms in perfect order. Here you may have planes in a different orientation same plane let us assume.

So, there you go. So, this is a sample which has some number of grains I mean this is just too, in this case, it is coarse enough that we can count here we have 1, 2, 3, 4, 5, 6, 7 grains are out here. So, there are just 7 grains and the sample is of certain dimension. So, it has that many grains. So, a grain is a region within which the crystalline structure is maintained and so this is and then after that boundary which is this is called the grain boundary. So, this is referred to as the grain boundary across the grain boundary the orientation changes. So, all these are grain boundaries. So, across this the orientation will change.

You can have another sample where the exterior dimensions are the same as the sample that you just saw except that you have grains like this. So, I will not count the grains here, clearly, there is distinctly more in this particular case than they are on this. So, I will just say many grains many small grains smaller grains. So, there are many smaller grains in this sample, but the exterior dimension is the same and the concept is the same, within that grain there is a perfect crystalline order, across the grain boundary there is a change in ah the order which change in the orientation of the order, the order is still there, but it is in an oriented differently. So, you have smaller many numbers of smaller grains.

And in general, in fact, there would not be one unique value that you can say is the grain size there is usually be some distribution in the grain sizes, but generally the one on your left is a coarser-grained material, the one on your right is a finer-grained material. So, this is coarse-grained we will simply say this is coarse-grained, and this is a fine-grained material. And please remember this is a very descriptive term to use coarse-grained versus fine-grained, and in many ways, this is a relative term. So, based on what your starting grain is, and the other size that you are looking at you can have a fine-grained the sample.

And this is also something that we typically see in microscopes when you do metallography when you polish the sample and you clean it up I mean clean it up thoroughly, and then use an etchant, it will highlight all the boundaries, and then you can see it under the microscope and see it. Importantly you do not even it based on the sample; you may not even need a microscope to see it.

So, if you if you typically go and buy some iron sheet in or a stainless steel sheet a polished sheet in a hardware store, you will see patches which are physically visible to you or some will be like few centimeters across, you will see various patches, patch, patch, patch kind of arrangement, and to the extent that it is a clean surface then what patches that you are seeing are actually the grains. So, you can you do not even need a microscope to necessarily see, it is very visible, it based on the sample that you are picking up and looking at so anyway. So, this is a coarse-grained sample and then there is another thing called a fine-grained sample, we have put down some schematics associated with that.

Now, we spoke about the deformation process, the deformation process once you have gone into the plastic deformation process, then atoms or planes of atoms have to move. So, now, when planes of atoms move, then for them to continue moving, they need some kind of a similar environment ahead of them, so that they can it will have a certain size, and there should be a location which can accommodate the same sized set of planes of atoms. So, you move a plane of atoms which is say 10 atoms by 20 atoms that is the size, let us says it is a rectangular plane of atoms 10 atoms across. So, I will just draw a smaller version 6 by 4.

So, this is a plane of atom 6 atoms by 4 atoms that is trying to move. So, naturally, it needs another location which can accommodate 6 atoms by 4 atoms and then that is how it keeps moving. So, this plane of atoms that is moving, in fact, it is typically half a plane of atoms, and if it is assuming that it is like a movement along the in the manner that I am describing it is called a dislocation.

So, it is a plane of atoms typically a half-plane of atoms, it is a dislocation called an edge dislocation, in fact, so it is called an edge dislocation. You have other dislocation possible. For our purposes this is enough to understand what we are trying to describe here. So, this is an edge dislocation, it is trying to move.

So, now this edge dislocation for it to move, it needs to find another location which can accommodate these 6 by 4 set of atoms, and then that is how it moves. So, when you are deforming the material externally internally, this is what is happening. Many planes of atoms are moving and they are all trying to move, and they are all moving in to accommodate this force they are trying to move. And they need a similar location ahead of them for them to move into that location and that will happen because and 6 by 4 atoms set of atoms sitting in front of them will move to the location ahead of them. So, it is like a series process one plane moves, then the plane behind it moves and so on, so that is how it moves.

Now, every time a plane of atoms hits a boundary right, so a plane of atoms has some crystal structure it is a certain plane it is a 6 by 4 plane with some spacing here and some spacing in this direction, this direction and so on that is because that is a crystalline spacing of that material. When you hit a boundary, the orientation of that spacing is different on one side of the boundary relative to the spacing on the other side of the boundary. Therefore, this plane of atoms that arrives at that boundary is not able to easily move across that boundary. It arrives at that boundary and the boundary acts as a hindrance for it to move across. So, and therefore, this plane of the atom now struggles to cross the boundary, and therefore, resists the force even more.

So, you are now trying to put force on you are applying force on the sample, and you are trying to deform it further, it is already started changing shape we are trying to make it change shape even more. But for that to happen atoms have to move, they are trying to move, and they have started moving to some distance then they hit like a roadblock they are hitting a roadblock. The roadblock is basically the boundary, you are hitting the boundary the wall of that grain, and the plane of atoms is not able to move.

And therefore, it is now even though you are applying stress it is just pushing itself against that wall, but not able to go across and it is stuck there, and that reflects us as though the material has become stronger. All these planes of atoms go and hit various boundaries, and they start resisting our force even more and that is what makes the material appear stronger.

So, now naturally the more the boundaries that are present within the material the quicker will those planes of atoms hit those boundaries. So, it is no different than walking in a line of people walking in a large hall, so they can move from one end of the hall to the other end of the hall which is quite some distance before they hit the wall right; one end of the hall to the other end of the hall before they hit the wall.

On the other hand, the same hall if you put a lot of obstacles in the middle, the same line of people will start hitting the obstacles much sooner, and therefore, they will not be able to go through that easily. That is exactly the analogy that is valid here, you have this plane of atoms dislocation moving it hits the boundary, it does not move. And so, the more space you give it for it to move before it hits the boundary, it appears that the material deforms even more before it starts becoming stronger.

So, generally, you can strengthen the material or make the material resist deformation which is what we are calling as strengthening by reducing the grain size. Not reducing the sample size, in this case sample size is the same; the grains within the sample have become smaller in size. So, this is a strengthening process by grain size reduction.

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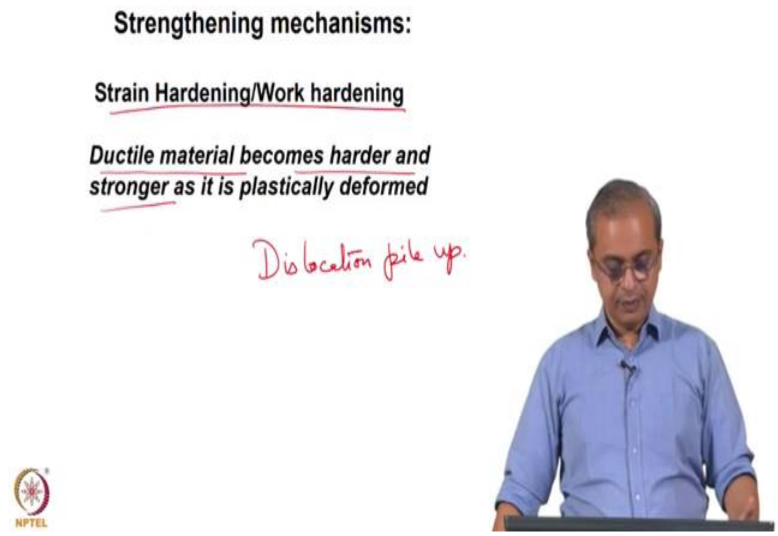

Strengthening mechanisms:

Strain Hardening/Work hardening

Ductile material becomes harder and stronger as it is plastically deformed

Dislocation pile up.

We could also have something called strain hardening or work hardening. Strain hardening or work hardening. And this is generally captured by this idea that a ductile material means a material that deforms very easily becomes harder and stronger as it is plastically deformed. So, the more you deform the material, the stronger it becomes. So, we already saw that one reason why it might become stronger is that the plane of atoms will now hit that boundary wall which is the grain boundary, and therefore it will start becoming stronger.

But it is also true that when you put that stress on that material, it is not necessary that only one plane of atoms should move in every grain, it does not work that way it is not that only one plane of atoms has to move, you may have multiple planes of atoms beginning to move. You have to understand that now there are competing processes happening there.

On the one hand, this is a crystalline material. And the crystalline material by definition has a lower energy state when it is in that crystalline state. It has to it would like to maintain certain interatomic distances in the x-direction, the y-direction, in the zdirection; it would also like to have that order over a longer period of a longer distance. So, this is what it is trying to do.

So, every time you break that you take or you start moving half a plane in one direction, you move another half a plane in some other direction, then you have a series of planes which are not series of atoms along the edge of that plane, along the edge of that plane that set of atoms do not have their bonds completed. So, every time you break a plane and start making it move, you are disrupting that crystalline order. So, it would like to go back to its crystalline order state. So, it is not particularly comfortable in this all broken upstate so to speak. It is not its lowest energy state.

So, now you have a plane of atoms moving that way, you have another plane of atoms moving this way, and they will come and hit each other. So, when they hit each other, this is called a dislocation pile-up. So, this is called a dislocation pile-up. So, the dislocations which are trying to enable the deformation of the material bump into each other. And in the process, they get they become a hindrance to each other, and in the process they the resists the deformation. So, the deformation itself is occurring because these dislocations are moving.

But if you have too many of these dislocations, they get in the way of each other, it becomes like a crowded room with lines of people trying to move in a wide range of different directions, and they are all bumping into each other. So, they have not even hit the boundary, they have not hit the boundary of that material, they have not hit the grain size, they are bumping into each other. And because they are bumping into each other they are it becomes more difficult for them to move in any coordinated manner, that is the idea that is leading to this strain hardening or work hardening which is because of this material having been deformed.

So, in fact, if you take this example that I gave you of this sheet metal that is being used for automobile applications, the more you roll it, generally, it is becoming stronger. Because you are putting in lot more dislocations into the system, and they are all sort of fighting each other and they are basically pinning each other down. And as a result, so you started with a 1-millimeter thick sheet, and you rolled it down to half a millimetre-thick sheet. And from half, if you want to go to quarter which is again 50% reduction, you will find the amount of stress that you require is much higher than what you required to go from one to half, so that process is called is dislocation pile up and strain hardening or work hardening.

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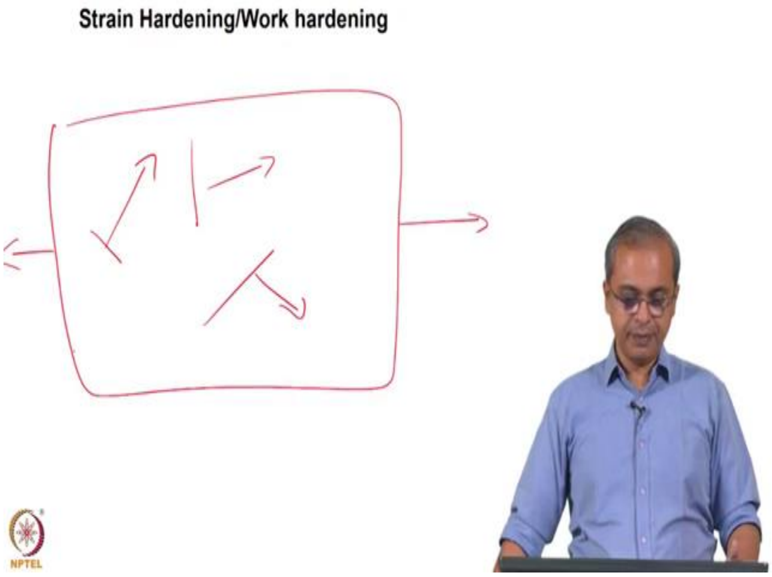

Strain Hardening/Work hardening

So, like I said the strain hardening or work hardening simply happens because you have this plane of atoms which is moving in that direction, another plane of atoms which may be moving in that direction, and a third plane of atoms which is moving in that direction, and they all start bumping into each other. And the overall material is trying to deform in this direction. So, they are all moving and they all start bumping into each other, and in that process, you have this strain hardening or work hardening that is happening.

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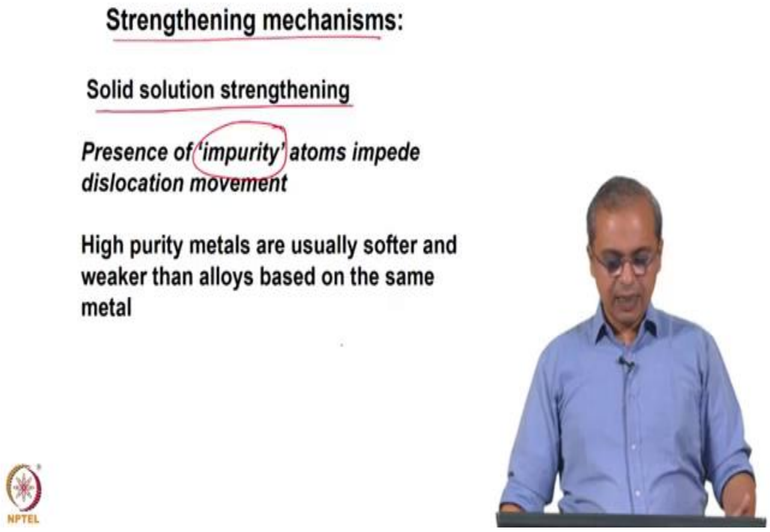

Strengthening mechanisms:

Solid solution strengthening

Presence of 'impurity' atoms impede dislocation movement

High purity metals are usually softer and weaker than alloys based on the same metal

There is one other way in which you could do the strengthening and that is called solid solution strengthening. So, solid solution strengthening is simply a material becoming stronger, because it is not pure. It has impurity atoms which have been inserted into it. Now, impurity is only a general term it does not I mean, in the English usage of it, it appears like it is a bad thing, but that is not necessarily true in this case. It in this case, when we say impurity, we simply mean an atom which is different from the primary set of atoms that are present there.

So, if you have nickel and copper, for example, you have some small% age of nickel and copper or something like that, then that nickel atom which is sitting in at a copper site is considered as an impurity Now, why does that lead to some strengthening. So, you can think of again an analogy which is no different than I mean it again comes down to this idea that planes of atoms have to move, and the more dissimilar the atoms that are present there, the more jarring is the movement of that plane of atoms. So, it is no different than moving on a smooth road. If you move on a if you drive on a smooth road, you are moving very smoothly know there is no you can basically drive at a fairly good speed.

On the other hand, if you have a road bump or if you have in even a pothole, it becomes a jarring experience. You are forced to slow down because there is a bump on the road, a speed breaker of some sort on the road, you are forced to slow down if there is a pothole and so on. And that is essentially what these impurity atoms are doing; they are creating a situation where one bond in that set of that line of atoms is either stronger or weaker than all the other bonds that are present there. Or you have one additional dangling bond which is trying to latch on to something else. So, you have something that is different at one location relative to all other locations.

So, when the set of atoms are beginning to move, this disparity at that location creates problems, and so the material does not move as smoothly as it is supposed to go. So, it does not the plane of atoms the dislocation does not move as smoothly as it is supposed to move, and that causes effectively a hindrance to the moment which reflects as though the material has become stronger and for all for all practical purposes we say that the material has become stronger. So, this is the strengthening mechanism associated with solid solution strengthening.

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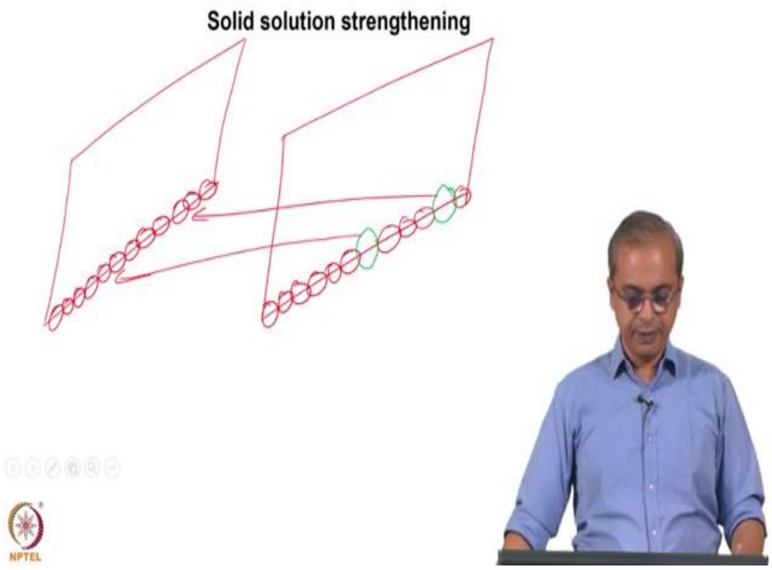

Solid solution strengthening

And like I said this is basically a player of atoms that is trying to move which is the dislocation. And all over here you have atoms of one particular type. And ever so often you have an atom of some other type. So, I will just make it slightly bigger. So, let us just say this is slightly bigger atom, and it is trying to move in a direction where you have another plane of atoms and that plane of atoms is all it is all in red. So, this is all the same kind of atoms. You have now this atom has to move here somewhere and that atom has to move somewhere there, and then that is going to cause a problem as you try to move this plane of atoms, and that is how you have this solid solution strengthening that is happening

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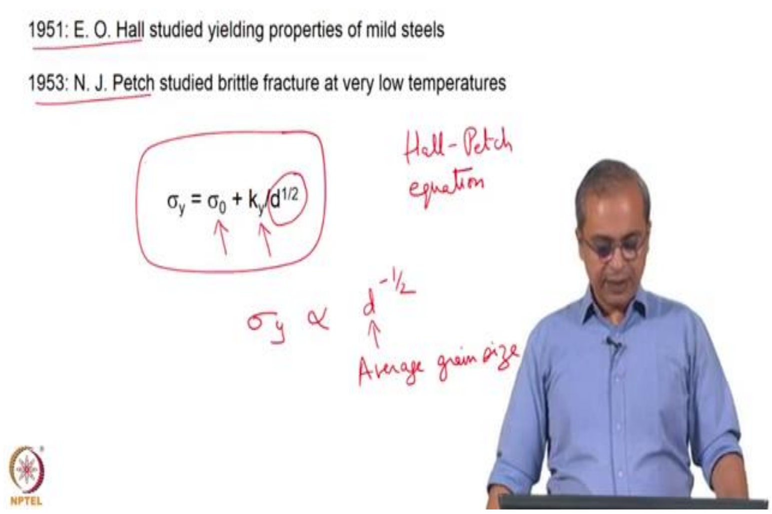

1951: E. O. Hall studied yielding properties of mild steels

1953: N. J. Petch studied brittle fracture at very low temperatures

$$\boxed{\sigma_y = \underset{\uparrow}{\sigma_0} + \underset{\uparrow}{k_y}/d^{1/2}}$$

Hall-Petch equation

$$\sigma_y \propto \underset{\substack{\uparrow \\ \text{Average grain size}}}{d^{-1/2}}$$

So, if you go back to what we looked at here on a stress-strain curve. So, up to here as I said up to the yield strength is elastic deformation. So, you release the load, it goes back. So, you have not actually had planes of atoms move. But you also have strengthening that is happening between the yield strength and the tensile strength which where planes of atoms have started to move, they have either started hitting boundaries grain boundaries because and that is something that would prevent it from deforming easily or they have started bumping into each other and so on.

And so, grains a grain size strengthening is a very significant part of a strengthening of the material and what was what has been done is there are people who have studied this in great detail, and it was studied in 1951 by Hall and 1953 by Petch. So, there is a relationship called the Hall-Petch relationship, Hall-Petch equation or Hall-Petch relationship. And you can, in fact, see science has changed quite a bit in all these years, this I mean there is a 2-year difference between the 2 the work submitted by these 2 people, but it is considered important enough that a contribution enough that they have been given both been given credit for it.

And essentially the relationship says that the yield strength of the material is associated with sort of lattice friction constant, and you have another constant here, and d power half d power minus half. So, sigma y is proportional to d power minus half, this is the basic equation we see, where d is the grain size, average grain size. And since the d is in the numerator sorry in the denominator, the smaller the d, value of d, larger is that value of the term, and therefore, your sigma y begins to climb up. And this is the Hall-Petch relationship.

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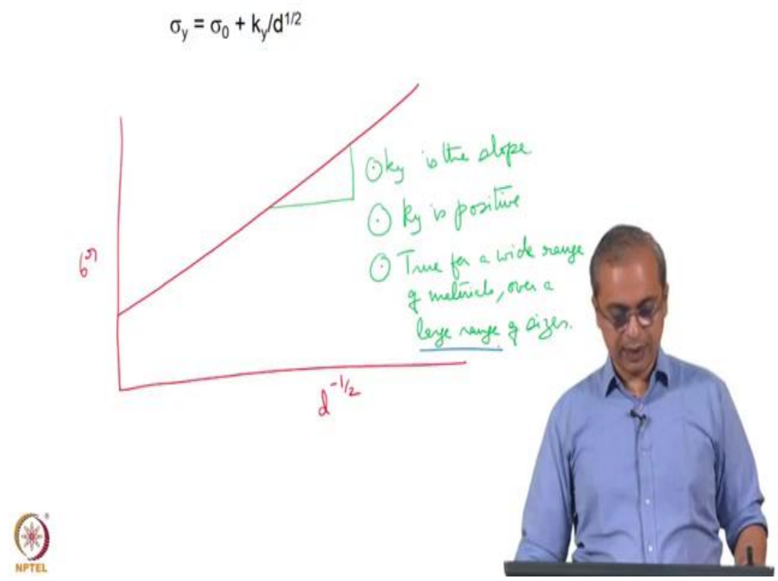

$\sigma_y = \sigma_0 + k_y/d^{1/2}$

① ky is the slope

② ky is positive

③ True for a wide range of materials, over a large range of sizes.

So, if you actually make a plot here of this equation. So, if I write d power minus half here, and we write sigma y here. So, you will see a plot that looks like that. So, this is the typical plot that you will see, you will see a value of ky which is the slope here, ky is the slope of this curve. Importantly the point you must remember is that the general idea of grain-size strengthening is that as you reduce the grain size, the material is becoming stronger. And therefore, ky is positive. So, it is positive.And this is the idea of the Hall-Petch relationship. It says that

$$\sigma_y = \sigma_0 + K_y d^{-1/2}$$

K_y is a positive constant.

So, positive constant and that signifies that the Hall-Petch behavior is being displayed by that material. And it turns out that essentially this is true for a wide range of materials over a very large range of sizes. So, it is true for a wide range of materials over a large range of sizes.

Now, the important thing also to remember is that it is not true for all sizes. It is only for a true for a large range of sizes and that is something that people discovered only much later. So, it was when they experimented, they experimented over a range of sizes and this showed up very neatly as a straight line with a positive slope, and therefore, this was accepted as a law that the materials were displaying.

And the expectation was that this I mean even though they had investigated a certain set of sizes, because over the set of sizes and over a wide range of materials this was consistently being shown, the general feeling at least initially was that you would actually have this relationship hold over a much larger range of sizes. That there was no immediate evident reason why there would have to be a limit to this equation.

But as it is with the many aspects of science, people were later able to find some limits interesting limits to this the applicability of this equation. And you have seen behavior that is different from what is being described by the Hall-Petch equation and that is where the effect of the nanoscale comes. And this is something that we will see in our next class the effect of the nanoscale, and how that impacts the Hall-Petch equation.

And the and of course, once you now have a behavior that is different that is not described by the Hall-Petch equation, it is also equally important to try and understand what is the phenomenon that may be in operation in materials of in materials that are not displaying the Hall-Petch relationship, and under what conditions those phenomena are significant, and when can you expect or anticipate or predict that this non-Hall-Petch kind of behavior will begin to appear, so that is the effect of the nanoscale and which we will see in ah greater detail in our subsequent classes.

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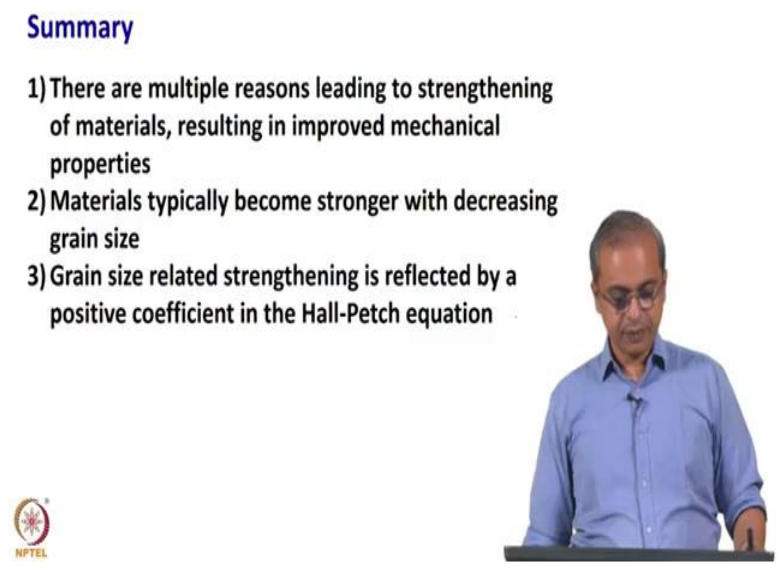

Summary

1) There are multiple reasons leading to strengthening of materials, resulting in improved mechanical properties
2) Materials typically become stronger with decreasing grain size
3) Grain size related strengthening is reflected by a positive coefficient in the Hall-Petch equation

So, in summary, there are multiple reasons for the for a material to become strong. And most of the time in an engineering sense, we are typically trying to make the material stronger. So, it is very nice for us to have multiple ways in which we can strengthen the material. So, most of the time we want the material to be strong in the final state that it is being put to use in. So, if it is finally, going to be a sheet, then in that final sheet shape it should have the stronger strength that you would like it to have so that it is in the final product it is a very strong material.

On the other hand, when you are actually working with the material to get it to that shape at that point you want the material to be weak, so that you can get it to that shape without wasting too much energy, without expending too much of energy. So, this is why it is very important to understand the strengthening mechanisms. If under what condition you can keep that material to be a soft material, then you will keep it as a soft material and change its shape to something complicated, nice and interesting for you for your end-use, and then when how to strengthen it, you will get it to that last final shape in that strong manner. So, that is why this mechanism is very important.

So, you can deliberately change the condition of that material to and there are various ways you can do this. Typically, in fact, in metallurgical processes, heat treatment is the standard way in which this is done. Using heat treatment, you can change the grain size without changing the overall shape of the sample. So, you can take a very small-grained sample, and then you can heat treated get larger grained sample.

So, therefore, the sample is now soft you can deform it, and do this process in a well thought out manner. So, that by the time you reach that final shape that you want the final dimensions that you want and the final shape that you want, it will again be a fine-grained material and which point you will hand off the product in a strong as a strong product, but having the correct shape. And in your processing that you have done to get there you have spent less energy or as little energy as possible because in all the processing in during all that processing that you were doing it was a soft material

So, anyway, so there are multiple reasons leading to a strengthening of materials. And typically, this results in improved mechanical properties or that is what is desired. So, you need to know the path to get to this improved ah mechanical properties. The materials typically become stronger with decreasing grain size. So, of the different mechanisms that we saw, we saw that there could be a solid solution strengthening, we saw that there could be strain hardening which is basically strengthening as the deformation is occurring. And this is also another possibility where the grain size is impacting the strength.

So, in the in this case, even though the total amount of deformation is the same, the smaller grain-sized material is displaying higher strength than the larger grain-sized material. So, if you have a grain size that is 10 times more than another one, or 9 times more than it is square root of that is there is a factor of 3 that is beginning to appear there, and then when you deform it you take on size and you make it like twice as long in both cases, you will see the difference in strength, even though everything else is the same. So, you may have the same amount of solid solution in it, you may have the same amount of dislocations in it, but one will be stronger than the other.

The grain size-related strengthening is reflected by a positive coefficient in the Hall-Petch equation. So, the Hall-Petch equation is what captures this grain size strengthening in the form of a relationship that conveys to us what is happening what we can expect when as the grain size changes. And it also captures this idea that it is getting to be a stronger material as the grain size is coming down, and that is captured by this positive coefficient that you get in that equation.

So, these are some of the concepts that we are interested in looking at when it comes to strengthening of materials. And in our next class, we will look at what is happening to this process when we go to the nanoscale, why is it different, how is it different, and why is it different. And with that, we will get a much better idea of what the nanoscale has done to this material.

Thank you.