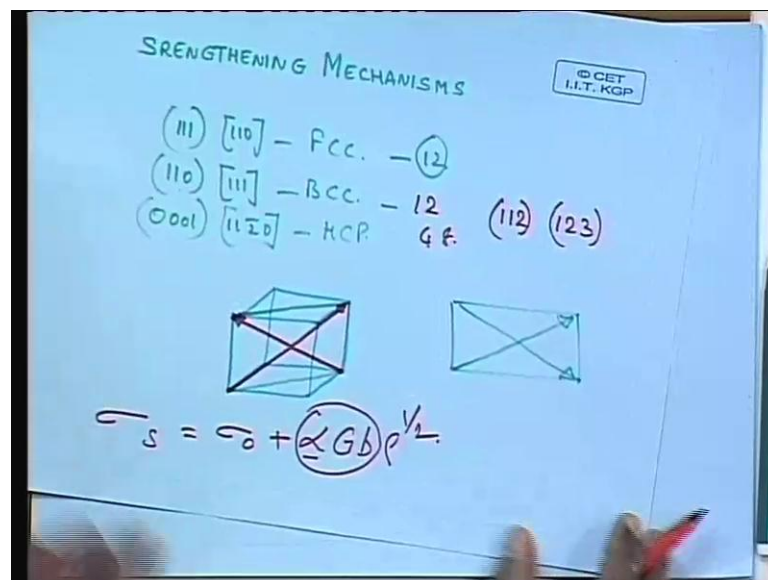


Advanced Materials and Processes
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Lecture - 22
Shape Memory Alloys

First of all... So, we were talking about strengthening mechanisms, and then trying to understand the basic deformation mechanism. And we know the basic deformation mechanism we slip, in most of the materials. And if we look at the slip the most crucial aspect is number of slip systems, which decide. Whether, a particular material is more easily deformable or not; so that is what we were looking at...

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And if you look at the FCC there are 12 slips systems, which are based on the 1 1 0 and 1 1 1 1 1 1 plain and 1 1 0 direction. And if you look at the BCC, the most close pack plain is 1 1 0 and the close pack direction is 1 1 1, 1 1 see. What important thing is, that the slip direction should be contained in the slip plain, it is very crucial.

So, when we say slip it is a moment of dislocation on a plain, in a direction in that plain. So, you should not consider any direction, which is not contained in the plain. The particular direction, there may be n number of closed packed directions, but the direction which is contained in the plain. For example, if I am looking at let us say a cubic crystal unit cell.

Let us look at any of the unit cell. If this is the unit cell, that I am looking at and the $1\ 1\ 0$ plain is nothing but this plain is not, it this is a $1\ 1\ 0$ plain. And what is a $1\ 1\ 1$ type of directions, which are contained in this plain? Which are nothing but the body diagonals. So, if we look at those body diagonals, this is one body diagonal, the other body diagonal is this. These are the two body diagonals, which are contained in the $1\ 1\ 0$ plain. So, those are the two closed pack directions, though there are a number of closed pack direction how many $1\ 1\ 1$ type of directions possible.

Student: 8.

8; obviously, because there are 8 corners in any cell unit cell. So; obviously, eight type of directions possible. Though, there are some direction which are nothing but is the same direction, one in one direction another in the opposite direction like $1\ 1\ 1$ direction. And then $\bar{1}\ \bar{1}\ \bar{1}$ direction, they are nothing but basically the same direction in the opposite direction is not it.

So, if you consider that there are again one can talk in terms of four sets of directions. So, here in this particular plain, these are the two directions. So, if you consider there are 6 parallel $1\ 1\ 0$ type of plains. And each plain containing two directions, you end up in 12 slip systems.

But, because these plains are not very close packed plains. And the directions are also not very close packed directions, when compare to the FCC type of system. As a result, we can also consider other slip systems, which are not really equally closed pack. But, close pack to an extent, which are similar to the other $1\ 1\ 0$ type of plains, and that kind of plains are nothing but $1\ 1\ 2$ and $1\ 2\ 3$.

So, if you consider those plains also. Then, total you end in 48 slip systems. So, though the number is very large, there nature of close packed let us if you consider, they are not as close pack as the FCC slip systems are. So, that is why BCC is less deformable, then FCC.

And again, if you come to HCP there the number of specimen systems are much lower, there is only one plain which is the close pack plain here which is the nothing but the Basal plain we call it $0\ 0\ 0\ 1$ plain. And there are two plains, basically within a unit shell. But, both are parallel to each other.

So, effectively we consider only one plain. And in that plain you have three directions possible $11\bar{2}0$ type of directions. And so 3 into 1 it becomes only 3 slip systems. So, as a result we say this HCP type of systems are those, where twinning can occur more favorably than slip. Particularly, because the number of slip systems are very few. And we know for a material to be easily deformable it should have a minimum of 5 slip systems all this you have gone through.

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So, if you look at this why we have gone through all this, is to know the deformation occurs by movement of dislocations. Deformation occurs by slip, in most of the metallic materials. So, as a result if you can make this slip more difficult than the material becomes stronger. If you are the strength of material is decided by what, is decided by how easily you can move over the dislocation is not it.

For example, if you say yield strength, yield strength defines what? It defines the minimum stress, that is required to induce plastic deformation, into material is not it. So, that is indirectly related to the stress required for the movement of dislocations. For example, we define what is called critical resolved shear stress. So, critical resolved shear stress is related to the yield strength of the material.

So, if we look at the yield strength, yield strength basically is a measure of is a macroscopic measure of the stress required to move the dislocations. So, as a result if you want have a material stronger, you should have a higher yield strength. So, if want to have a higher

heal strength for any material. It means, that you should somehow increase the stress required for the movement of the dislocation.

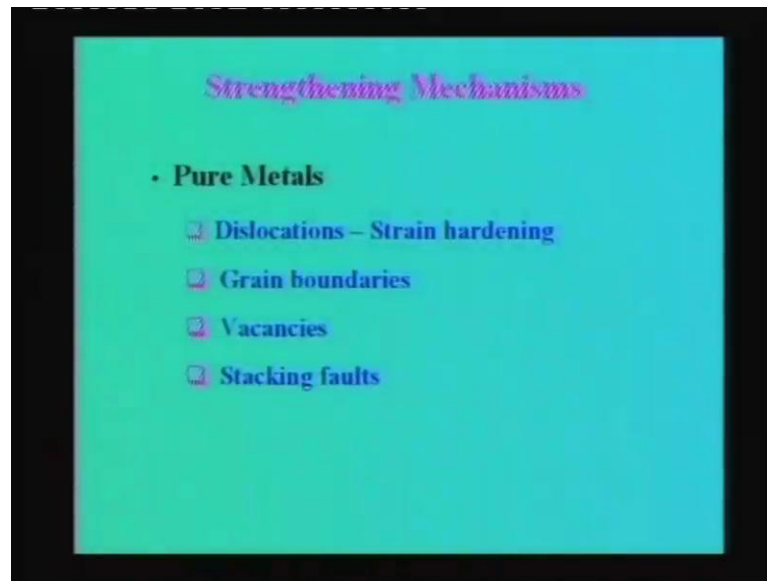
How do you increase the stress required for the movement of dislocation? If the dislocation movement is made more difficult than if you want to move the dislocation you have to put in more strain. And if you need to put in more stress to move the dislocation, we can say the material has become stronger.

So, strengthening mechanisms are all those mechanisms which make the dislocation movement difficult. So, that is the philosophy of strengthening mechanisms. So, once people have understood, the dislocations are the ones which are causing the deformation. Then, people started looking at how to make this dislocation movement more difficult. So, that we can make the materials stronger and stronger. But, at the same time the moment you start making the material stronger and stronger, you are also losing on one curve root which is nothing but the deformability of the material. The material becomes stronger, but less deformable.

Obviously, we know both cannot go hand in hand, because the deformability is related to dislocation movement. And the easier the dislocation can move, the more deformable the material is... And the strength of the material is related to how difficult it is for the dislocation to move.

So; obviously, both of them cannot leave together. So, as a result we see the moment we make a material more deformable, its ductility should be falling down. But there is another parameter, which we talked about when we were talking about the titanium based alloys, which measures to some extent about the difficulty for the materials to fail. That is called toughness. This is something which is different from the ductility. One can have high strength at the same time high toughness, one such example we will see is the grain boundaries.

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So, people have shown that one way to achieve high strength, at the same time high toughness is to make the grain size fine. So, if you look at pure metals, what are all the different strengthening mechanisms in pure metals. As we can see, one first and foremost is that we know there are dislocations in the material.

If we can increase the number of dislocations inside the material. Then dislocations themselves can act as obstacles for the other dislocations. It is similar to imagining, when there is a huge crowd trying to come out of a movie theater. Obviously, the rate of flow of the people out of the gate becomes restricted.

So, it is almost like that. So, when you have too many dislocations inside the material. Then, each dislocation movement is hindered by the existence of the other dislocations. And that is how you can have more obstacles for the dislocations. And how do we do that? We know dislocations can be generated. And when you deform a material, we have dislocation generation coming. Because of a special type of a mechanism called what?

Student: Frank resource.

Frank resource. So, there are number of Frank resources available, inside the material. Every material, whichever has some inclusions in it always act as a Frank resource. And because of which you can generate dislocations. And for generating dislocation, you need to put in some strain into the material.

So, that is why we call it as when you deform a material to some extent. During this deformation process, you are generating more dislocations. And these extra dislocations that have been generated will act as obstacles for the existing dislocations. And as a result the stress required for further deformation increases. And this is what we call it as, strain hardening or work hardening.

So, work hardening or strain hardening is related to the dislocations and this is given in terms of ((Refer Time: 11:46)) if we want to plot see how the yield stress is related. This gives you an idea of... What is the relation between the yield strength and the dislocation density ρ . Here ρ is the dislocation density and σ_0 is the yield stress of the material. What does it measure?

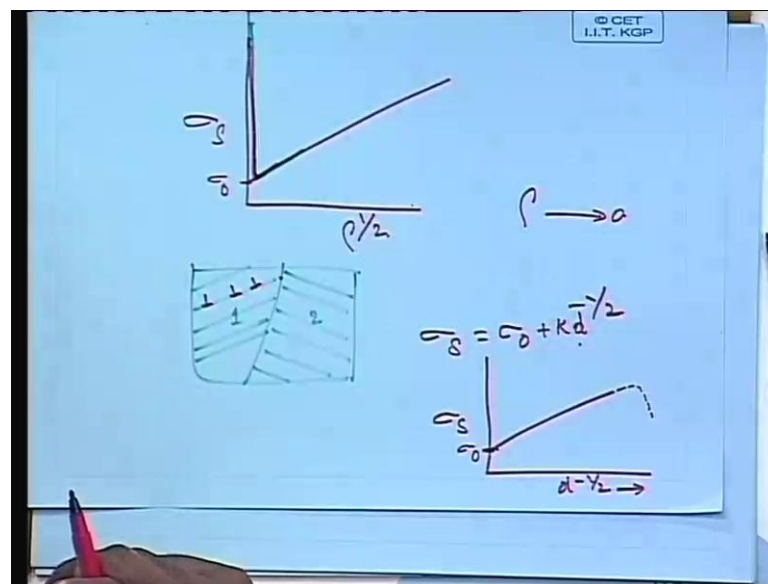
Student: Friction stress.

Friction stress, what does it mean physically?

Student: ((Refer Time: 12:09))

In a single crystal, if you assume the dislocation density is 0. Then, σ_s becomes σ_0 . So, you can consider σ_0 as the yield stress of material without any dislocations. So, if you keep on adding dislocations to the material. And you can see, there is direct relation between the yield strength of a material and dislocation density. But, at the same time when you make the dislocations 0, this formula does not really hold good. What does it say?

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If you look at this formula more closely. It shows that the yield strength, if you plot it as σ_y versus ρ is a straight line. There is a straight line intersection is not it. And here, you should see ((Refer Time: 13:04)) this α is nothing but a constant of the order of around 0.3 to 0.6 G is a shear modulus, b is the burgers vector.

So, this $\alpha G b$ will be the slope of this curve, if you plot σ_y versus ρ to the power half. If you look at that when the ρ becomes 0, this is what is basically σ_0 is not it. And that tells you, that if there are no dislocations. The yield strength of the material is lower than what you have? When we have dislocations which is not really true.

When you to look at viscous, which do not have any dislocations at all. That means perfect crystals without any dislocation. Perfect crystals without any dislocation, their yield strength is much higher which we call theoretical cohesive strength. And so the moment you put a small number of dislocations in that the strength drastically drops, because now the deformation occurs by dislocation motion. And when there are no dislocations how does deformation occur.

Student: ((Refer Time: 14:22))

No, when there are no dislocations at all it is not ((Refer Time: 14:27)). It is the sharing of atoms one over the other, it is like a pack of cards. So, when you think of atoms, which are arranged as atomic planes. You imagine, one atomic plane sharing over the other atomic plane. And that is how the deformational occurs in a perfect crystal without any dislocations.

And that needs a much higher stress of the order of few giga Pascal's. When, compare to the actually stress required for the motion of dislocation. The yield strength of most of the metals are of the order of few MPA. For example, aluminum if you take aluminum yield strength is of the order of how much about 40 MPA.

Whereas, if you look at the aluminum without any dislocations. And think of what will be the yield strength of that or what will be strength of that theoretical cohesive strength. That will be of the order of few giga Pascal's particles. So, there is a sudden drop in the strength from the giga Pascal zone to a mega Pascal zone. By almost 3 orders or 2 orders at least, when you introduce dislocations into the material.

So, as a result this particular plot does not really hold good in this domain. When, the row becomes it tends to 0. This particular equation, what we have written here does not work. And so that in principle you will see should go more or less exponentially up, in that zone which is very close to 0 dislocation density. This more or less goes very steeply up, and reaches the value of theoretical cohesive strength, when the dislocation density goes to 0. So, in a small domain which is close to omega tending to 0. This particular equation does not work and it deviates from this linearity. Otherwise, when you have large number of dislocations this usually works very easily.

So, that one has to be remember that. So, there is a relation between the heal strength and the dislocation density, which works when you have more than a few dislocations, but when you have very little number of dislocations. This is one of the reasons, why people say nano cluster materials, how do we talk in terms of the ((Refer Time: 17:02)) people talk about it.

There is always what is people call now a day's as lattice softening can occur in nano materials. Because, the number of dislocations itself can be so few. So, how do we represent the strengthening of nano materials, when we come to grain boundary strengthening. This becomes a issue, how do we talk in terms of strengthening because of dislocations.

Probably there is more of grain boundary sliding when you have very few very small grain sizes of the order of around 5 nano meters or even less than that, because as you know that there has to be minimum distance between any two dislocations. Any two like dislocations should have a minimum distance between them, because there is always a repulsion between like dislocations.

So, as a result one has to maintain a certain distance between them. And if you think of about 5 nano meter length, as the diameter of particular nano material, within that 5 nano meter. If we can imagine, what is the distance between any two dislocations this is of order of around 5 inter atomic distances, if we consider f about 5 intern atomic distances. And intern atomic distance of the order of around 4 angstroms if you consider. Then, 5 intern atomic distances is becomes almost equivalent into 2 nano meters. So; that means, 5 nano meters, you can hardly have work 4 or 3 dislocations in one direction.

One can imagine, what is there in total volume that is the different thing. But, in a particular direction one cannot think of more than about 3 or 4 or 5 at the most. So, with

such few dislocations how can we really imagine a lot of strengthening coming. Because of a the Hal pitch relation. We know that usually, strength keep on increasing when you decrease the grain size we will come to that.

So, this is what is basically strain hardening, where because of the dislocations one can generate. The next type of hardening in pure metals, we are all talking of pure metals at this moment. We have not added any alloying element at the moment, to generate any additional type strengthening ((Refer Time: 19:16)).

So, in pure metals the other types strengthening is basically the grain boundaries. So, they are the other types of obstacles. Because, when we think of a slip plain, slip plain cannot be extended beyond the grain boundary. Obviously, grain boundary is a limit which distinguishes one grain from other. And what does how do we distinguish the two grains?

Student: ((Refer Time: 19:41))

With their orientation, we say there is a orientation difference. If there is a orientation deference definitely; that means, the slip plain. Let us say if we are considering 1 1 1 plane. 1 1 1 plane orientation in one grain is different from the it is orientation in another grain.

So, if I am considering 2 grains, grain 1 and grain 2 if in grain 1 if all 1 1 1 planes are oriented in this direction. And grain 2 they are oriented in a different direction. Otherwise, we cannot call them as two grains, we should call them only one grain. If there is no difference in the orientation. So, as a result if a dislocation is moving on this plain, the moment it comes here it has to stop. Because, the plain is not continuing further.

So, it has to stop and then you have to put in more stress. So, that you can induce dislocation moment in on the other plain on the same type of 1 1 1 plain in the other grain. So, as a result the stress required will be higher. And this increases, if you increase number of such boundaries. So, what is the way to increase number of such boundaries by making the grains finer.

If we can make the grain's finer, we can have much more obstacles for the dislocation moment. And this is usually given by an expression like this, which is usually called as

the Hall-Petch relation. All of us are aware of it. So, yield strength is related to the d to the power minus half by a relation which is similar to this.

So, if I plot the yield stress versus d to the power minus half, it looks something like this, as d to the power minus half increases. d to the power half increasing means what? d is decreasing. If the d decreases the strength increases. And the intercept here represents σ_0 within nothing but the yield strength of what?

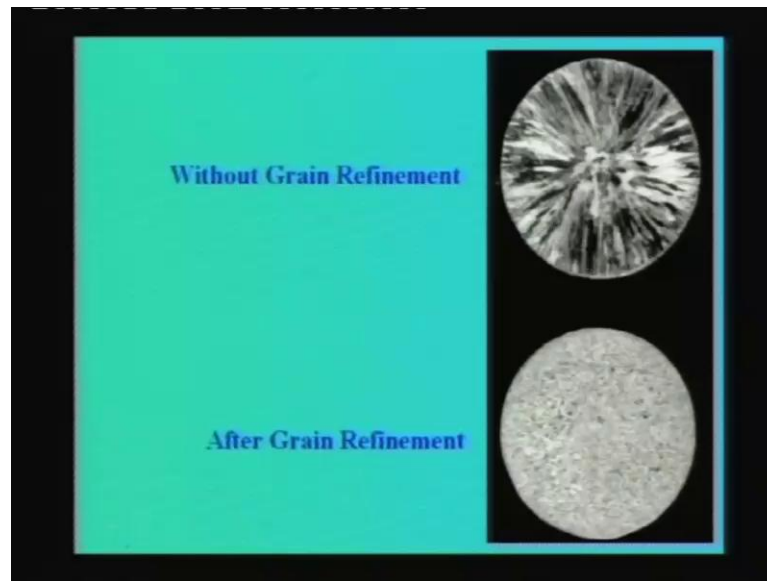
Student: Single crystal obviously.

Single crystal, obviously. You imagine when d to the power minus half goes to 0. What are you talking about it is a large grain, very large grain. In principle, which whose grain size infinite. That is, type of grain that we are talking about; that means, it is a single crystal, without any grain boundaries.

So, you can imagine a grain without any grain boundaries. The grain boundaries are so far of that we cannot physically see them. In such a case you start see only the surface of the material before seeing the grain boundary. So, in such a material which is nothing but single crystal. So, you can talk of this as a yield strength of that single crystal.

And now a day's people say that when you go to very fine grain sizes. There is a possibility of the yield stress dropping. And that is what we call as a lattice softening, though it has not been really proved in a number of systems. There are, few experimental evidences that are available, where people see that there is possibility of some a decrease in strength like that. So, this is the what is called grain boundary strain strengthening.

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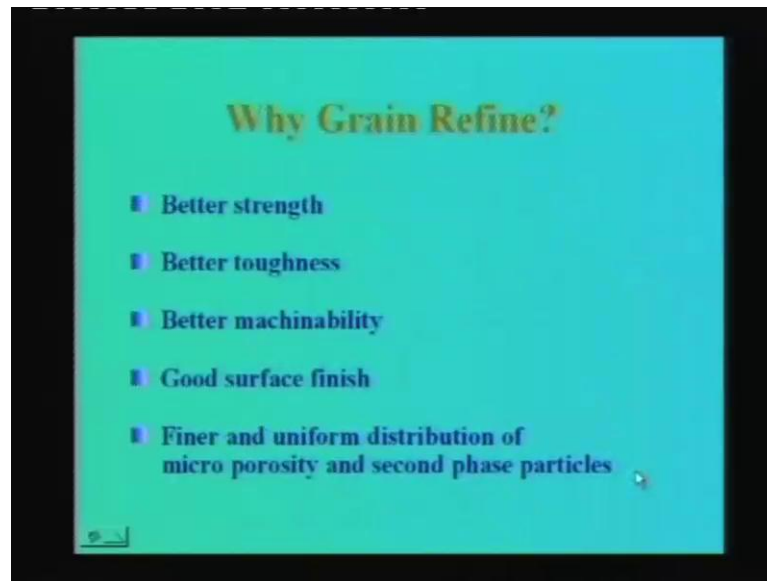
And how do you make the grain finer. And what is the grain refinement basically means, I am giving you some examples of this. If you look at a typical casting, a typical casting when you take liquid metal and solidify into a mould. And look at the cross section of such a cylindrical casting. The grain structure looks like this, this is what is called a macro structure.

And we know usually, that the grains are nucleated at the, where at the mould wall. And you will get innumerable number of those nuclei there. And some of these nucleuses start growing into the interior. And we call those fine grained structure, at the mold wall as the chilled zone.

And then you have this next zone columnar grains, which go either up to the centre or to certain extent depending on the type of material. That, we have considering and also depending on the type of thermal conditions there. If there is a high under cooling, there is a possibility of some other grains nucleating at the centre such as some ((Refer Time: 24:46)) structure.

Otherwise, usually you have this columnar grains going almost up to the centre. And this is a typical grain structure. And once you can achieve a grain refinement in this material, you can see the grains will be very fine uniformly distributed grain sizes, more or less homogeneous fine grain structure.

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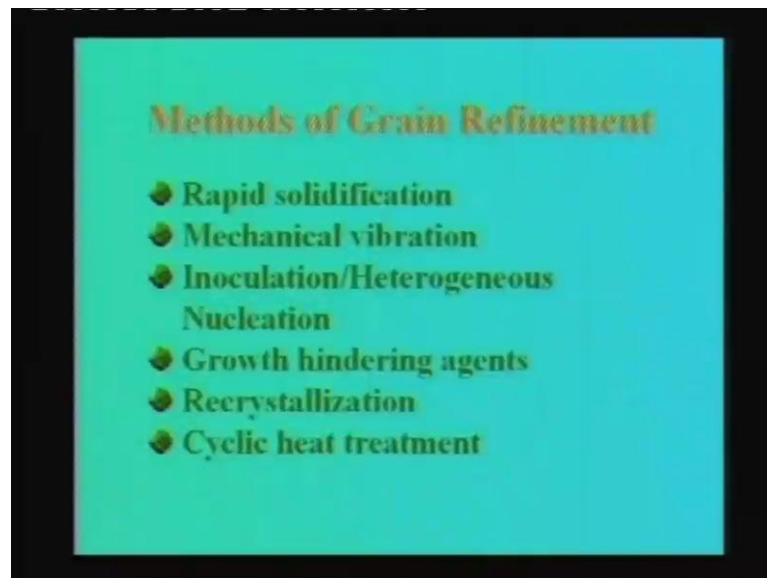
And how do achieve it, they are number of ways. And before we go that, we should see what do you achieve by doing that. As I told you, strength can be increased, we have seen Hal pitch relation already. And toughness can be increase, this is the only way by which you can increase both the strength and the toughness.

How toughness can be increase, is because when you have large number of grain boundaries. When a crack is nucleated the path for this crack propagation, becomes more torturous. The crack has to propagate along these grain boundaries. And when you have large number of these grain boundaries, the crack propagation becomes more difficult, particularly in metallic materials. If you have brittle materials, such as ceramics, then any way there is cohesion at the grain boundaries. So, as a result the crack propagation very easily occurs at the grain boundaries with... And gives you what is called inter granular cracking, in materials, whereas in metallic materials usually the cohesion is not that poor at the grain boundaries, and so if you have some good cohesion at the grain boundaries. If you can increase these grain boundaries, you are increasing the number of obstacles for the crack propagation as a result one can increase the toughness. So, the toughness can be improved the machinability can be improved. Particularly, in case of castings, it is very crucial. That machinability is a function of the grain size, if you have fine grains, you can have much easy machinability. Because, chip sizes chips become very fine. So, that easily it can be machine. And one can achieve good surface finish very easily.

And finally, one can have very fine uniform distribution of micro porosity and second phase particles. What is this micro porosity? Micro porosity comes because of the solidification of the liquid metal at the interdendritic region. We now that whenever a liquid is solidifying, the solid nucleates as dendrite. And at the interdendritic regions, you have some liquid left out and this liquid is the last liquid to solidify. And when it is solidifying, there is a shrinkage always, because liquid occupies usually a much higher volume than the solid. So, as a result you have the shrinkage, on a uniform scale, which occurs at the interdendritic regions. And this is what is called micro porosity, because it is porosity which you get, because of the shrinkage.

And because, it is on the micro level we call it as micro porosity. And if you can have a large number of fine grain material. So; that means, this liquid is distributed on a finer scale more or less uniformly. So, as a result this micro porosity is also distributed on a much finer scale instead of having on a large pockets of porosity in a few locations. You have a much more uniform distribution of micro porosity, that gives you much as strange.

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How do you achieve this. There are number of techniques, first technique which we have talked a lot earlier also, when we are taking of Rapid Solidification Processing RSP. The first most important technique is rapid solidification. And we now when we rapidly solidify, what do we achieve?

Student: High under cooling.

High under cooling, once we achieve high under cooling, then you have high nucleation rate and small critical nucleus. And that is what gives you fine grains a smaller critical nucleus and a higher nucleation rate is what we achieve by high under cooling. And that gives you a fine grain structure. And the second possibility is what is called mechanical vibration of the liquid. There are different techniques now a days available thick so casting.

Student: Rio casting.

Rio casting, these are all different casting techniques, where you take that whole casting and then vibrate this. And when we vibrate it, what happens is the dendrites which we have nucleated and start growing into the liquid they break. So, instead of a columnar grain, the columnar grains break into fine grains. So, the and then they get distributed uniformly into in the liquid as so that you get a fine grain structure.

So, here you are not really increasing the nucleation rate, what you are doing is... You are just breaking the already grown nuclei. And because of this breaking you each of the dendrite is broken into a number of parts. So, that the number of grains have increased. So, you are multiplying the grains by breaking the grains, this is similar to the high energy ball milling, where you are taking big crystals breaking them into nano crystals.

Though you do not really achieve nano crystals here, you can at least break columnar dendritic grains into more or less uniform grains. But, the problem is this kind of a technique is very difficult to be used, when you have large castings. If you have large casting say huge ingot is there, you want to really use this technique.

The whole ingot has to be placed on a vibrating platform and the whole thing has to be vibrated; obviously, it is not feasible practically. So, only on small casting sizes this is achievable. The most popular technique is the what is called Heterogeneous Nucleation or Inoculation. And which is very commonly used in a number of systems.

And particularly, in iron based systems and aluminum base systems, this has been very successfully adopted by a large number of investigators. These are all in the liquid state we have talked about so far. One can also achieve fine grain structures in the solid state.

That means, of obviously, whenever I am saying fine grain sizes, we are talking of solid state only.

But, the first three techniques are by controlling the solidification. Whereas, the last three techniques are in the solid state itself how to refine the grain size. One is by adding growth hindering agents after recrystallization. First of all, recrystallization is a way to refine the grain sizes, which is used in a number of rot alloys. Pparticularly, in case of cast alloys, because we do not deform the alloy.

As a result, you cannot use these solid state processing techniques. That is why one has to adopt only these first three techniques. Because, once a casting is obtained, you do not do anything else with the casting accepting giving a good surface finish to the casting in case of castings, whereas in case of rot alloys we are going to deform it.

So, as a result one can use recrystallization as a process. And one can also put certain growth hindering agents at the grain boundaries. For example, we know about High Strength Low Alloy steels HSLA or micro alloy steels, where people add certain particles, precipitate particles which can act as growth hindering agents called pinning agents.

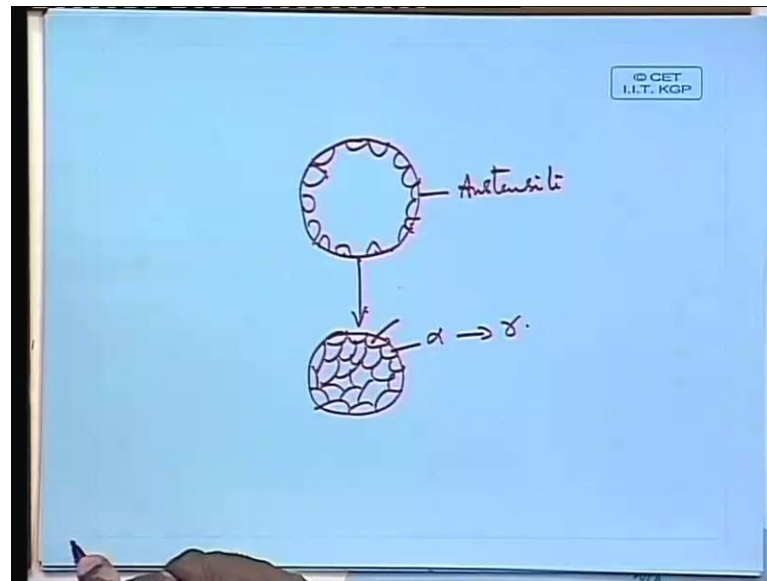
So, zener pinning. So, because of the zener pinning one can achieve much finer grain sizes. The other technique, which people have used particularly in steels is what is called cyclic heat treatment. The philosophy here is when you take an austenite. And start cooling it between the A_1 and A_3 zone, what is that called? Inter critical zone.

So, in that inter critical zone, if you start cooling it what do you get? When a austenite is cooled through the inter critical zone, what is what do you get?

Student: ((Refer Time: 33:20))

Proeutectoid phase comes out. Whether, it is hypereutectoid or hypereutectoid depending on that some proeutectoid phase comes out. So, particularly in case of the hypereutectoid alloys, this has been very successfully used, where ferrite comes out. And when an austenite grain is there and ferrite is nucleating. And how many grains you expect out of one austenite grain. How many grains of ferrite do you expect is it one or more.

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Imagine an austenite grain is there, this is austenite. And when this is being cooled, what do you expect the ferrite grain size to be.

Student: ((Refer Time: 34:13))

Will it be equal to that austenite grain.

Student: ((Refer Time: 34:16))

Basically, because we know grain boundary acts as a nucleating site. As a result a number of nucleate can nucleate on the grain boundary, in different regions. And if a number of nuclei can form all these grow. And finally, cover up the whole of austenite. So, as a result each of this austenite grain is broken into a number of ferrite grains.

And at room temperature what are we bothered about, when we talk of grain size? It is the ferrite grain size, that is important to us not the really is the austenite grain size. Because, the actual deformation occurs if I we are talking of temperature strength of a steel. Room temperature strength of the steel, is related to the ferrite grain size are not related to the austenite grain size is not it.

So, as a result the we know that austenite gives one, I mean austenite gives one austenite grain gives a number of ferrite grains. And now if you take this ferrite which is there in the inter critical zone. And start heating it very rapidly, we know that each grain of ferrite will transform into one grain of austenite.

Because, you are heating it very rapidly. And because of which the whole grain of ferrite transform to the austenite grain. So, what happens if you take situation like this, which is having a large number of grains, let us say like this. And this particular situation, if you start heating it. It becomes again all of these grains, which are here get transformed to austenite. There are probably inside also some grains, we have not considered that still may be.

So, whatever grains that are there, the ferrite grains alpha grains. All alpha grains get converted to gamma grains. Now, you can see with this what we have done is that you are starting with one grain of austenite. You have cooled it to some temperature in a inter critical zone, and then heated back to austenite very rapidly. And while doing that, you have come back to the austenitic regime with a larger number of austenitic grains.

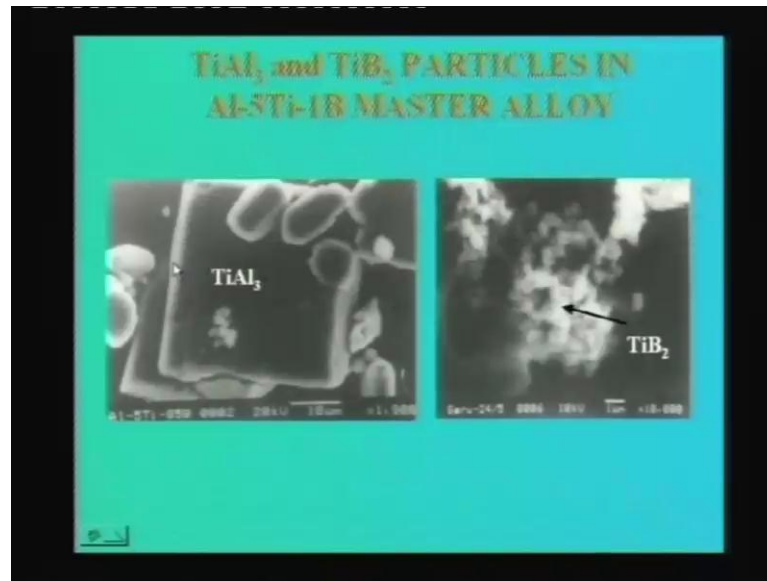
Starting with one grain of austenite, now you have generated a larger number of austenite grains. Because all of these ferrite grains have converted into austenite grains. And now if you can again cool this austenite grains, which are their larger number of them. Each one of these austenite grains can nucleate more number of ferrite grains again.

And again if you heat it rapidly, again all of them get converted to ferrite austenite grains. Like that, if one can do in a number of cycles 2 or 3 or 4 or 5 cycles. One can ultimately end up in very fine or ferrite grains. And people have adopted this technique in a number of cases, where grain size is a crucial aspect.

Because, definitely this means some economy has to be considered, because obviously, you are doing cyclic heating. So, you are putting in more energy into the system. So, obviously, some cost is involved in this process, but if that cost is going to give you a much finer ferrite grains, which is going to improve your strength and dramatically. So, people can go for that. So, this has been a technique where people have really used it ((Refer Time: 37:58)).

But, among all this techniques the most popular technique is the inoculation, number of people have done this.

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And in our own group, we have also done it in a very vigorous fashion, over the last 10 years. And particularly, the grain refinement of aluminum alloys. Aluminum alloys every aluminum alloy, that comes out of an aluminum industry is invariably grain refine by inoculation. And this inoculation is done by usually alloy such as aluminum, titanium, boron type of alloys.

For example, the most popular alloy is called aluminum 5 titanium 1 boron, which are called master alloys. And these alloys, if you look at the composition it has titanium and boron. And titanium reacts with aluminum and gives you T i A l 3 particles. And titanium and boron when they are together, they react with each other form T i B 2.

So, you have two types of particles T i A l 3 and T i B 2, in this type of a master alloy. And when you take this master alloy, add a small piece of it to a liquid aluminum. What does this master alloy contain? This master alloy basically contains aluminum matrix, you can see this is the aluminum matrix. And the particle such as T i A l 3, you can see different sizes of T i A l 3 particles here.

And T i B 2 particles are much finer of the order of around less than micron 0.5 micron are. So, such type of T i B 2 particles. So, you have a matrix of aluminum and find T i A l 3 and T i B 2 particles. So, if take a piece of this master alloy add it into liquid aluminum. What you see is that the matrix which is aluminum, melts away. Because, you have put it into a aluminum alloy.

So; obviously, this matrix which is aluminum immediately melts. And the TiAl₃ and TiB₂ particles get suspended in this liquid. So, you have a liquid aluminum now, in which you have added this master alloy pieces. And master alloy pieces out of that, whatever alpha aluminum, which is the matrix is there which dissolves TiAl₃. And TiB₂ particles get suspended.

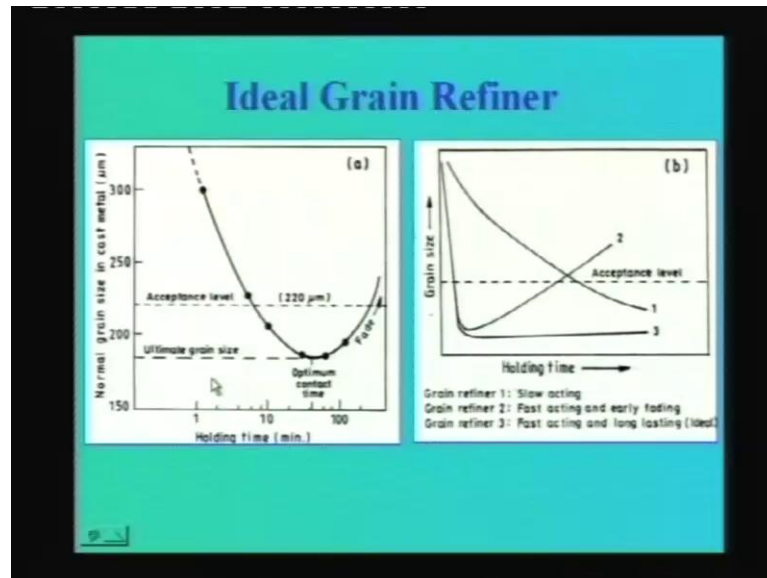
And this liquid containing this suspension of these particles, if you pour it into a mould, during the solidification these particles act as nucleating sites. And for a particle to act as nucleating site, there are number of condition have to be met. What are the conditions? First and for most is that, the structure of the particles should be similar to that of the structure of the solid, that is coming out.

There has to be some kind of an epitaxy epitaxial relation. That means, either the structure should be exactly the same or at least it is similar. For example, if you look at TiB₂, TiB₂ has a hexagonal structure. And aluminum which is for aluminum alloys we use this things. So, aluminum is an FCC. So; obviously, there is some relation between HCP and FCC.

Particularly, if you look at basal plain, the basal plain has a similar atomic arrangement as that of 111 plain in FCC. So, there is a lot of similarity between 111 plain of FCC and the basal plain. So, basal plain can act as a nucleating site for the 111 plain of the FCC. And similarly TiAl₃ is a BCc type of structure and bcc type of structure, we have talked about this Al₃Ti.

And it also has some plains which have some similarity with aluminum. So, it can also act as a nucleating site for aluminum. So, if you add this kind of particles to it, they act as nucleating sites. And once, these particles are uniformly distributed throughout the casting. You will have grains nucleating at each of this particles. And then as a result you will have ultimately the whole casting gets converted to very fine ((Refer Time: 42:17)) grains like this. ((Refer Time: 42:18)).

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And that can be shown in terms of the grain sizes. If one can measure the grain sizes, but usually when you add a grain refiner to the aluminum alloy. There is a minimum time that is required for the grain refiner to act as a grain refiner. This is what is called contact time, optimum contact time.

What happens is, when you add a grain refiner to the liquid. And immediately pour that liquid into a mould and cut it after it is solidify. And look at the grain size, you do not get very fine grain size. You have to hold this particles, inside the liquid for some time. So, that this particles get uniformly distributed into the liquid. And that particular liquid when you pour it into the mould, they start acting as nucleating sites.

So, as a result if you plot the grain size after holding the grain refiner into the liquid for different amounts of time. And then pouring the liquid into the mould, cutting that casting that you obtain and then looking at the grain sizes. So, after different holding times if you look at it, you will see grain size keeps on decreasing initially up to certain time.

And then later if you hold it again you start seeing that the grain size further increases. And this contact time optimum contact time is very crucial for any grain refiner, it keeps on changing for grain refiner to grain refiner. And one can control it by controlling the micro structure of the grain refiner. Particularly, it look depends on the size of the particles.

If the particles are very fine, then these particles immediately act as nucleating sites. If the particles are very big usually big particles never act as nucleating sites. So, when you hold these particles inside the liquid, they usually what happens is the particles start dissolving into the liquid. Because, Al₃Ti is soluble into the aluminum.

So, if you hold it inside the liquid, after some time the particles dissolve to some extent. So, their sizes decrease. And once, they decrease to certain size then they start acting as nucleating site. So, as a result there is a certain optimum contact time. But, if you hold it for a long period, then what happens is that the two things that happen, one is that these particles may completely dissolve into the liquid.

If they completely dissolve, then what happens you do not have any particles. If you do not have any particles you pour that liquid into the mould. So, there are no heterogeneous nucleating sites. So, they do not there is no grain refinement, that you can achieve. Second point is also, that these particles are usually heavier than the liquid metal.

For example, TiAl₃ or TiB₂ if you look at it, their densities are of the order of 3.5-4.2 are so. For example, TiAl₃ is about 3.5 TiB₂ is 4.2 are so... So, if you look at this kind of high densities, when compare to liquid metal. Liquid metal density of aluminum is about 2.4, thus aluminum is 2.7. But, when you liquefy aluminum the densities are much lower. In fact, it is about 2.35 or 2.4.

So, with that density if you compare these particle densities, particles are denser. So, if you hold it for a long time, they settle down. If they settle down if you pour the liquid into the mould. So; obviously, the top liquid which you pour, will not contain any particles. So, they will not act as a nucleating site.

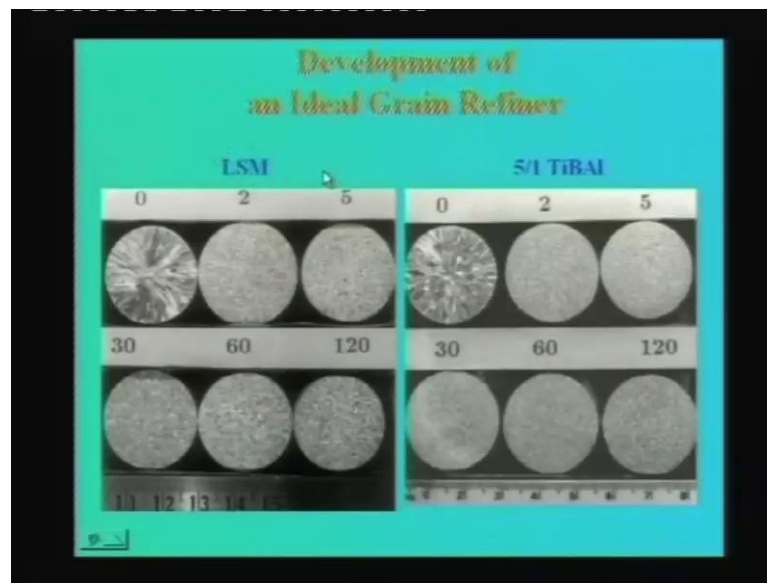
So, as a result what is crucial is that one has to identify this. And how to control this ((Refer Time: 46:14)). In this connection the grain refiners are usually broadly classified into three groups. One is called as slow acting grain refiner, this is number one which you see here. That means, this takes a long time for it to act as a good grain refiner.

And the second type of grain refiner is called fast acting grain refiner, but early fading grain refiner. That means, if you keep it inside the liquid metal, within a very short period it acts as a good grain refiner. But, if you hold it for a long period it loses its

efficiency. And the best grain refiner is what we call the ideal grain refiner, which is called fast acting and long lasting.

And this is crucial and this can be achieved by proper control of the particle sizes. If you have a good combination of fine and coarse particles, the fine particles act as good nucleating sites, within a very short period. And the big particles will act as nucleating sites on longer holding. So, as a result you can have a good combination of both and that is what we have achieved.

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And try to compare with, what is commercially available. Most of the aluminum industries, import the grain refiners. These aluminum, titanium, boron master alloys, they are all imported from basically one company called London Scandinavian Metals. This is a very popular company, which sells grain refiner to all these Nalco, Balco, Hindalco you take any aluminum company they all buy from that.

And in this particular institute at our department we have developed a grain refiner, which when you compare with this particular grain refiner. These all aluminum alloys, pure aluminum. For example, without this is not a aluminum alloy basically aluminum commercial purity aluminum. And without any grain refiner, these numbers which are given are time of holding 0 minutes, 2 minutes, 5 minutes, 30, 60, 120.

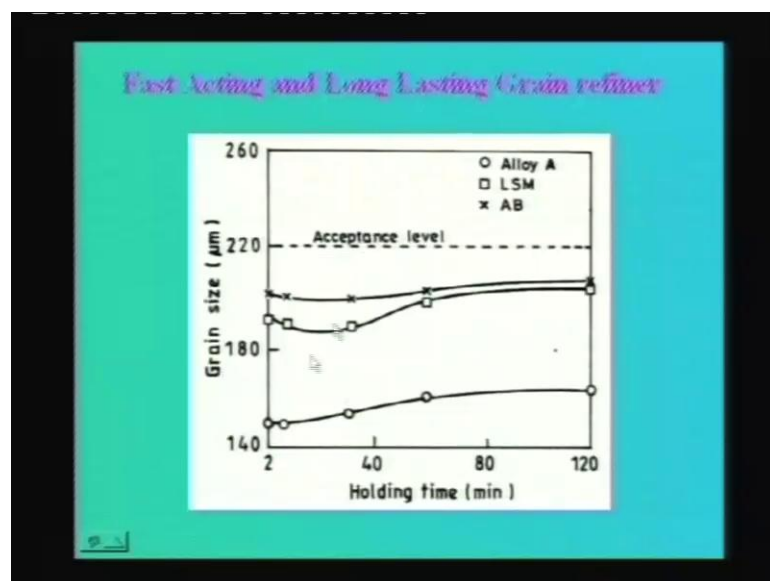
So, if you hold it for different timings. You can see initially you good grain refinement. But, on long holding this particular grain refiner is not good, you see start seeing the grain size starts increasing from here to here. Whereas, here you can see, the grain size is maintained even after 120 minutes.

We have even tested after 3 hours of holding. Why do you need to test for long hours? Because, basically when you take aluminum foundries, the way we people do grain refinement is they take the liquid metal in a ladle. And put the grain refiner into that ladle. And now you start pouring that liquid metal of ladle into different molds.

And sometimes you may have to pour into a large number of molds. So, from the first mould to the last mould the time of the pouring, might even take about 2 to 3 hours. So, as a result the last liquid which you are pouring should have sufficient number of nucleating sites present in them. So, that it can act as a nucleating site, whereas the some of the grain refiners do not work that way.

So, one has to consider this aspect. And this is where we can say that we have quite successful in this. This particular technology has already been patented one company in India, has already started making them on a large scale, started selling to Nalco, Balco and Hindalco. So, this is a real proven technology which has come out of our department.

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And if you look at the grain sizes and the alloy which is made here, which is called alloy A here, has much lower grain sizes, then either London Scandinavian Metal are the angle of black ((Refer Time: 49:58)). So, if you use any of these grain refiners, you do not get very good grain refinement. Though, they are also commercially used. But, this is much better and much chipper grain refiner than any of these commercial ((Refer Time: 50:11)). We will stop here and look at the other strengthening mechanisms in the next class.