Advanced Materials and Processes
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Lecture - 23
Strengthening Mechanisms Part – I

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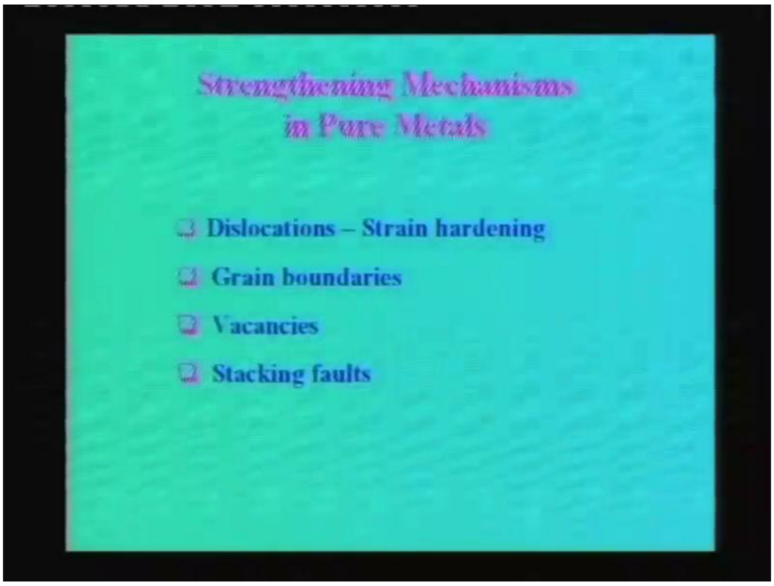

Strengthening Mechanisms in Pure Metals

- Dislocations – Strain hardening
- Grain boundaries
- Vacancies
- Stacking faults

We start now. So last class, we were talking about Strengthening Mechanisms. We talked about strengthening mechanisms in pure metals to some extent. We will continue with that, now and try to also look at the alloys. So just to recapitulate, some of the things, we started saying, what are the various strengthening mechanisms in pure metals.

We talked about the dislocations, acting as obstacles for the dislocations and even before talking about strengthening mechanisms. We talked about, how strength of a material can be increased; by increasing the difficulty for the dislocation moment, we talked about this. We talked about slip and things like that. And so dislocations, themselves can be obstacles for the other dislocations to move. So, this is what we talked about as strain hardening and the ill stress being proportional to the dislocation density to the power half.

And then the next obstacle is the grain boundaries, here also we talked about the hall petch relation. And we also talked about, how one can decrease the grain sizes. We will also look into a little more detail and the other possibility is vacancies. Vacancies themselves can be obstacles for the dislocation moment. When you have large number of vacancies, how do we generate large number of vacancies in a material.

Student: ((Refer Time: 02:15))

Quench it, yes this is what is called.

Student: ((Refer Time: 02:19))

Up quenching quenched in new revise can instead we say.

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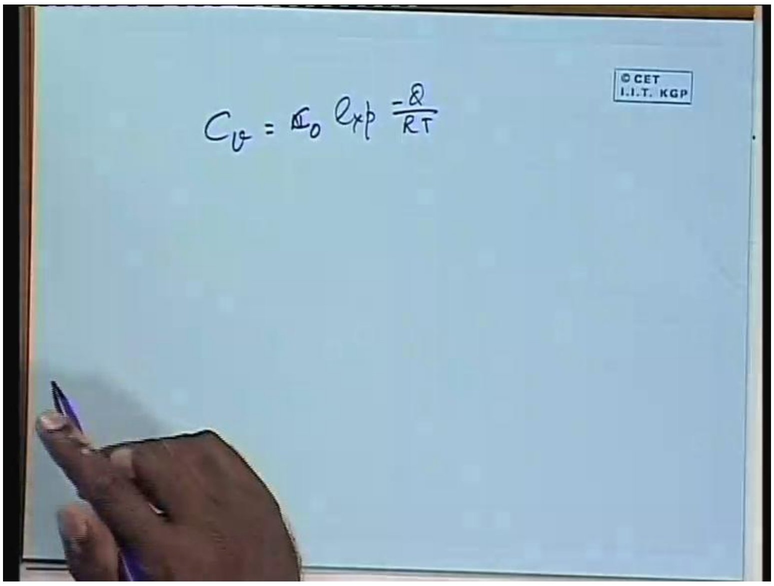

$$C_v = C_0 \exp \frac{-Q}{RT}$$

So, we know that the vacancy concentration is always a function of temperature. And I hope you must have seen expressions like this C v is equal to a some C not or n whatever you want to call it, exponential minus Q by RT, where Q is nothing but the activation energy for the creation of the vacancy. So, we know from that the vacancy concentration keeps on increasing with temperature.

And if you go to a higher temperature, you will have higher vacancy concentration. From their suddenly quench it to room temperature, you will have more vacancies. In fact, we many times use these vacancies as nucleating sites for the nuclei during the precipitation hardening. So, many times whenever you quench it from high temperature, then the nucleation rate increases.

Because, you have large number of vacancies available which can act as nucleating sides for precipitates? So, vacancies themselves can be obstacles for the dislocation moment, because why, because around every vacancy there is a strain field. Imagine you have atoms and in the centre of a number of atom, atoms which are regularly arranged. You have a vacant site the moment. You have a vacant site at the center, then immediately the atoms around that vacant site are pulled inside.

So, you have some kind of a compressive stresses there. So, you have a stress field around every vacancy like we say there is a stress field around every dislocation. So, similarly there is a stress field ever around every vacancy and this stress field is what acts as an obstacle for the dislocation to move. And so this is another possibility and another possibility is stacking faults, whenever you have stacking faults we know.

Those are the defects which are basically the distance between any two partials. Dislocation partials and this stacking fault width is the one which decides. Particularly, how difficult or how easy for a material to deform. And you must have heard about cross slip. Particularly, when we talk about high temperature. Deformation, so we know that. So, the two partials have to merge, and then only you can have the dislocation moment possible.

So that, you get a unit dislocation and that unit dislocation only can move partial dislocations cannot really move. So, as a result the smaller the distance between the two partials; that means, the thinner the stacking fault width it is the better for us, for the as per as the cross slip is concerned. So, that depends on something called stacking fault energy. You are all aware that the higher the stacking fault energy, you are all aware that the smaller is the width of the stacking fault.

So materials, which have high stacking, fault energy. The width is very small; that means, cross slip is very easy. So, those materials can easily deformed. The materials with very low stacking fault energy, for them the creep is more difficult, because the stacking faults are much wider. So, as a result the cross slip is very difficult. So whenever, we talk want to use a material for high temperature application.

We always look for materials with low stacking fault energy, that is why, we intentionally add also elements which can decrease the stacking fault energy. For example, nickel has very low stacking fault energy. So, when you add to iron nickel, iron nickel alloys have very low stacking fault energy and that is why, we use iron nickel alloys for high temperature application. For example, inconel is one such alloy which is nothing but an iron nickel alloy.

So, whenever you need high temperature strength. One way to improve the high temperature strength is to have low stacking fault energy. So, add all those elements which can reduce the stacking fault energy, that is as per as the alloys are concerned. But at the moment, we are talking of pure metals, so in the pure metals among the pure metals if you have more stacking faults.

If you can generate stacking faults inside a material, you can increase the obstacles for the dislocation moment. So, that is what, one way of increasing the strength of the alloy.

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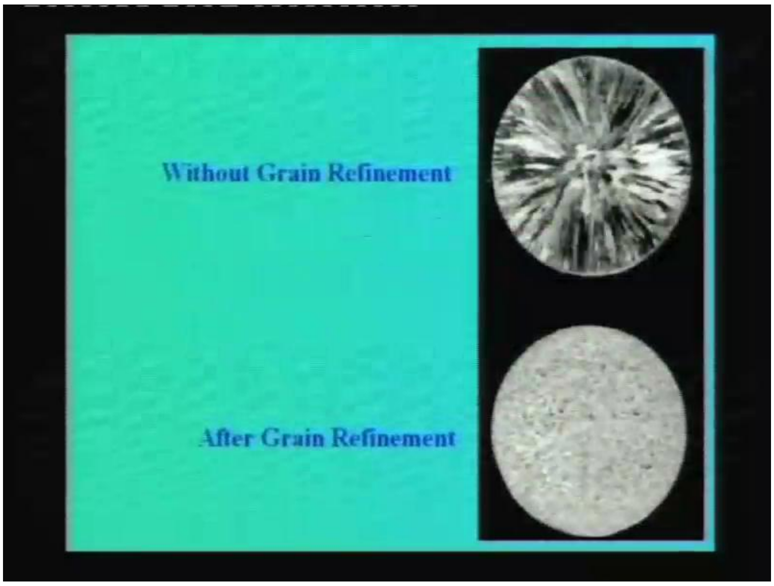

So, let us again look back some of these. So, we talked about the grain refinement and how by grain refinement, we can increase the strength. If you have fine grain material, the large number of grain boundaries is there. Each of this boundary acts as a nucleating acts as obstacle for the dislocation moment and hence you can increase the strength.

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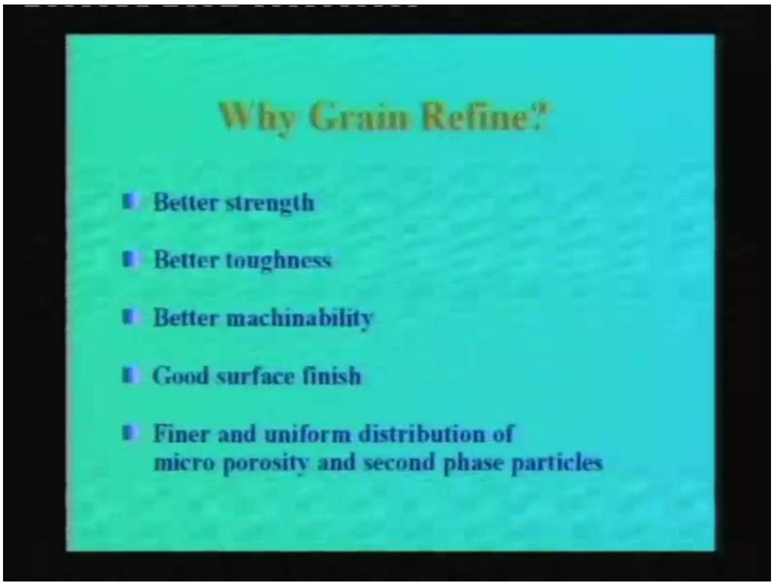

Why Grain Refine?

- Better strength
- Better toughness
- Better machinability
- Good surface finish
- Finer and uniform distribution of micro porosity and second phase particles

And there are a number of ways, to grain refine and before that, we also talked about why do you want to grain refine to improve the strength to improve the toughness to improve the machinability and the good surface finish.

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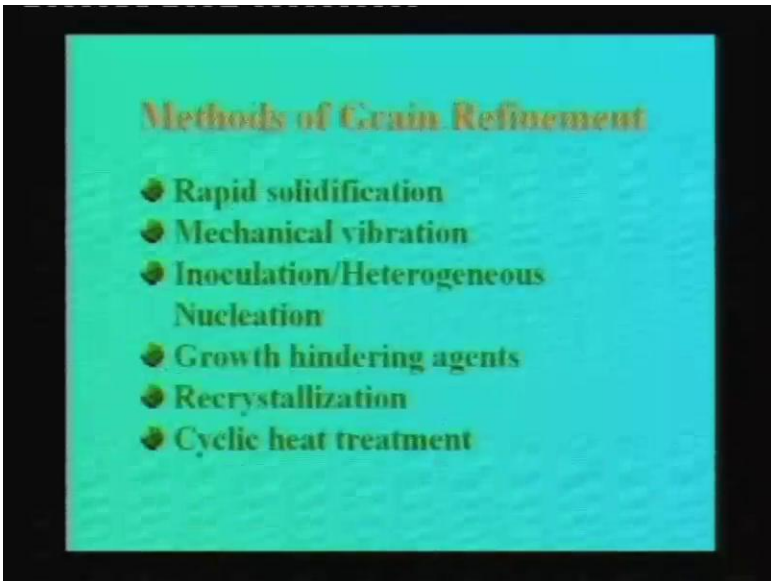

Methods of Grain Refinement

- Rapid solidification
- Mechanical vibration
- Inoculation/Heterogeneous Nucleation
- Growth hindering agents
- Recrystallization
- Cyclic heat treatment

And I told you, about various techniques to grain refine and the most popular technique is the heterogeneous nucleation.

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TiAl3 and TiB2 PARTICLES IN Al-5Ti-1B MASTER ALLOY

And, when you have a large number of this kind of heterogeneous nucleating site such as inter metallic particles such as TiAl 3 or TiB 2 particles which can act as nucleating sites for the aluminum during the solidification, when you add a master alloy like this aluminum 5 titanium 1 more on master alloy. Two a liquid metal and then start casting it. This liquid metal will contain these particles and these particles act as nucleating sites when the solidification starts. And that is, what gives you fine grain material.

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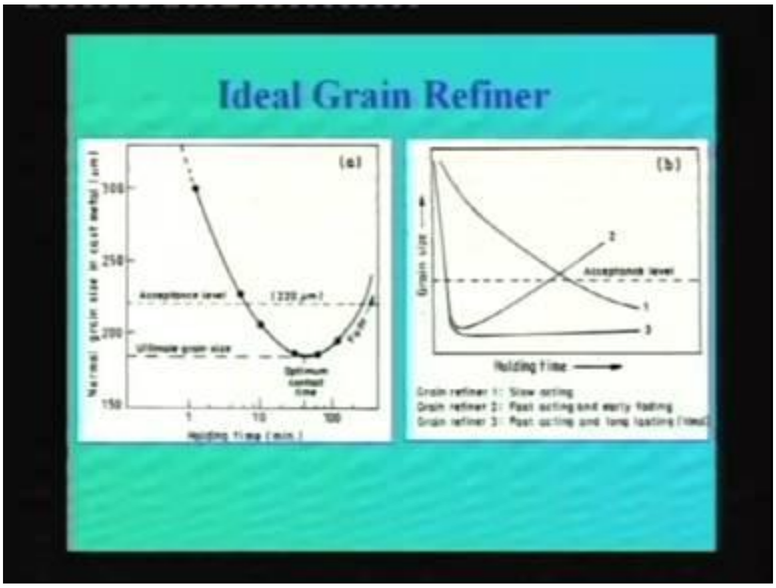

Ideal Grain Refiner

So, that is the most popular technique and we talked about, what is called the ideal grain refiner, the fast acting and the last long lasting.

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Development of an Ideal Grain Refiner

And we also talked about, the grain refiner that has been developed at IIT Kharagpur. And a comparison of the macro structures of aluminum achieved by adding this grain refiner and comparison with the imported grain refiner which is called London Scandinavian metals company. So, this is the most popular grain refiner as per as aluminum industries are concerned. We talked about, how we can get much finer grain size when compared to this.

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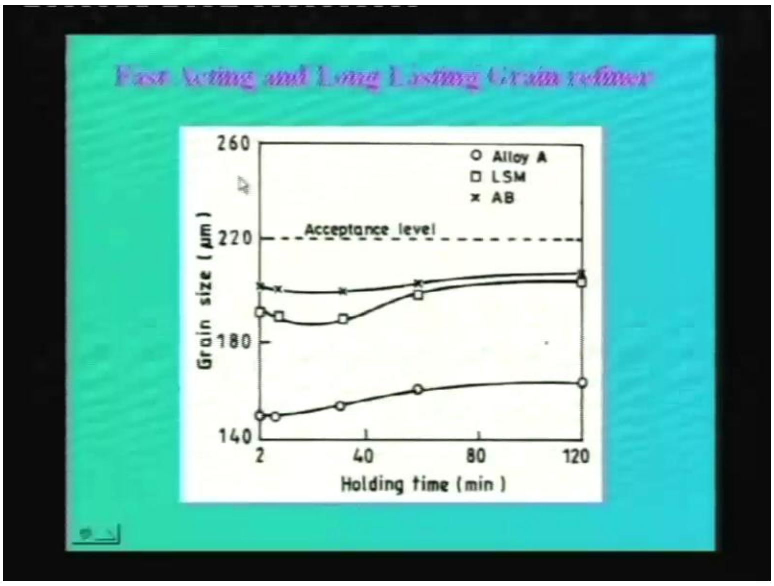

Fast Acting and Long Lasting Grain refiner

And if you look at the actual grain sizes which have been calculated, how do you measure the grain size of any material.

Student: ((Refer Time: 08:34))

Metallography method what kind of a technique you use.

Student: ((Refer Time: 08:39))

On a screen.

Student: ((Refer Time: 08:43))

Correct, what is this technique called.

Student: ((Refer Time: 08:48))

Linear intercept technique, linear intercept method is the one what we say. So, you have a line of a known length to you. And then try to see how many grains intersect that particular length of a known length line of a known length. And at a particular magnification usually people use 100 x as the magnification. So, at 100 x you try to see, how many intercepts are there, that is why we say linear intercept. And then if you see a number of such regions to have better statistics.

You can get an average grain size one can also talk about standard deviation. And things like that and get an average grain size. And if you look at the grain size of the alloy which is developed at IIT Kharagpur which is called alloy A which is having much finer grain size than the two imported alloys, whether it is LSM or Anglo Blackwell's .These are the two grain refiners, when you add those grain refiners to aluminum these are what the grain sizes that you get as a function of holding time.

So, that is why we say this alloy is not only fast acting, but also long lasting. Because, it gives you for example, if you look at this within two minutes of adding this grain refiner you get much finer grain size from this to this, you can see what is what a dramatic change in the micro structure macro structure. And similarly, even if you hold it for a very long period of two hours you do not lose any of these grain refinements which you have achieved at a very short holding time that is why we call it also a long lasting grain refiner.

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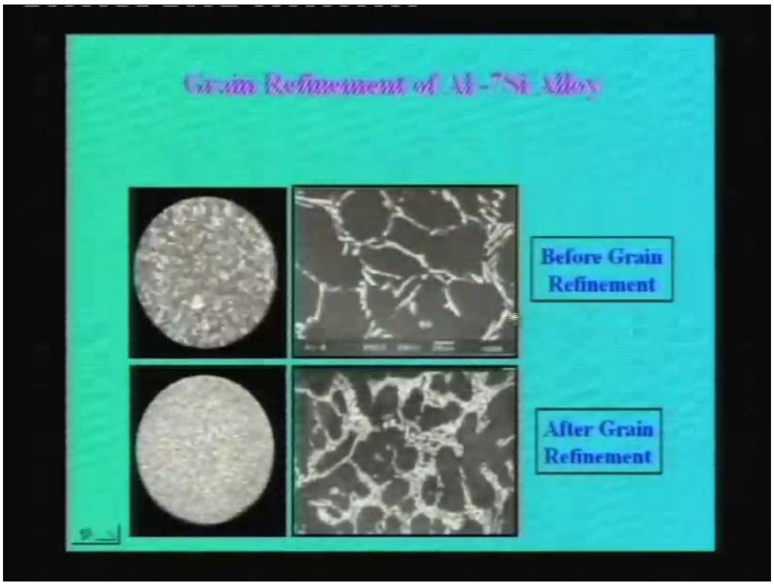

Grain Refinement of Al-7Si Alloy

Before Grain Refinement

After Grain Refinement

And if you look at that, on a aluminum 7 silicon alloy instead of only aluminum. This is where we are deviating for pure from pure metals and going into the alloys aluminum 7 silicon alloy many of you meteorologist. Now, it is basically a hypoeutectic alloy. Aluminum silicon is a eutectic system and you know where we use these silicon alloys.

Student: ((Refer Time: 10:44))

They are all casting alloys and where is the most

Student: ((Refer Time: 10:50))

Yes engine blocks in automobiles. So, the most popular and application of aluminum silicon alloys is a engine block application in automobiles. Most of the automobiles that you see, all the engine blocks are made with this. Because, you need a very high cast ability there, because if you carefully observe an engine block you have a very it is a very intricate casting.

Because you want to have high cooling rate possible, so that you provide lot of fins on the surface. And if you want to ma have such fins in a mold, if you create a mold with such fins; that means, you have very intricate holes into which the liquid metal has to flow so; that means, the liquid should have very high fluidity. If it does not have fluidity it does not flow into those regions and as a result you cannot get such a fine casting. So, that is one of the reason.

The second most important reason is aluminum silicon alloys have

Student: ((Refer Time: 11:47))

Yes, coefficient of thermal expansion is almost 0, that is another reason why we use them. So, if you look at that aluminum 7 silicon alloy. You have because it is a hypoeutectic alloy, it has two micro constituents; one is a pro eutectic phase which is the pro eutectic phase here, in a aluminum 7 silicon alloy.

Student: ((Refer Time: 12:07))

Alpha aluminum, it is a hypoeutectic in a aluminum silicon, hypoeutectic consist of alpha aluminum grains and eutectic mixture. And what is this eutectic mixture, it is nothing but aluminum plus silicon. And this silicon is usually in the form of needles and that is why this alloy is usually very brittle. So as a result, if we can somehow do two things; one is to make the grains finer alpha aluminum grains finer. And second, if you can make the silicon needles into spherical particles which is called modification.

So, if we one can do these two, one is the grain refinement, second is the modification. If we can do these two things, we can have an alloy which is not only strong, but at the same time quite ductile. And that is, what if you can try to see for example, this tells you about grain refinement. If you take aluminum 7 silicon alloy, if you try to take cast the alloy without any grain refinement. This is the type of micro structure that you get.

It will not be columnar grains as we have seen in the case of pure aluminum. The moment you have an alloying element, you will not always get the columnar grains. This is what is called constitutional super cooling; you must have read about it. So because of that, you will always get, what are called core squeaks grains, whenever you have alloys. In case of alloys, you rarely end up in columnar grains. Unless the alloy casting is too big. If it is a very big casting, then you will have some columnar grains and at the center again core squeaks grains.

So, this is a typical macrostructure and this is the microstructure that you get. And if you do grain refinement, you can see the fineness of grain sizes that you can achieve and also if you look at this the microstructure, you see finer grains, but what is important, you look at the grain boundaries. At the grain boundaries, you have this eutectic mixture and this eutectic mixture, if you look at the high magnification, those silicon needles which you have at the grain boundaries.

They do not get refined by the addition of the grain refiner. Because, grain refiner basically consists of particles which are TiAl 3 TiB 2 this kind of particles which can only act as nucleating site for aluminum? They cannot modify the silicon needles, what is the mechanism of modification of silicon needles; we add sodium on strontium kind of elements which are basically surface active agents. And these, surface active agents form as a coating on the silicon particle.

Once it nucleates and prevents it to grow in a direction which is most favorite direction for the growth of these materials. Because these are diamond cubic structure silicon is diamond cubic. So, it tends to grow in a particular direction giving it a needle like structure. So if you add, this kind of surface active agents likes sodium strontium antimony this kind of elements. These elements have you do not need to add very large quantities, very small amount 0.01 to 0.02 percent is the one amount that we usually add.

So, if you add just about 0.01 to 0.02 percent percent of either sodium or strontium. These elements will go into the liquid dissolve into the liquid and when the silicon starts nucleating. During the eutectic solidification at that point they will coat that silicon and then prevent it to grow as needles.

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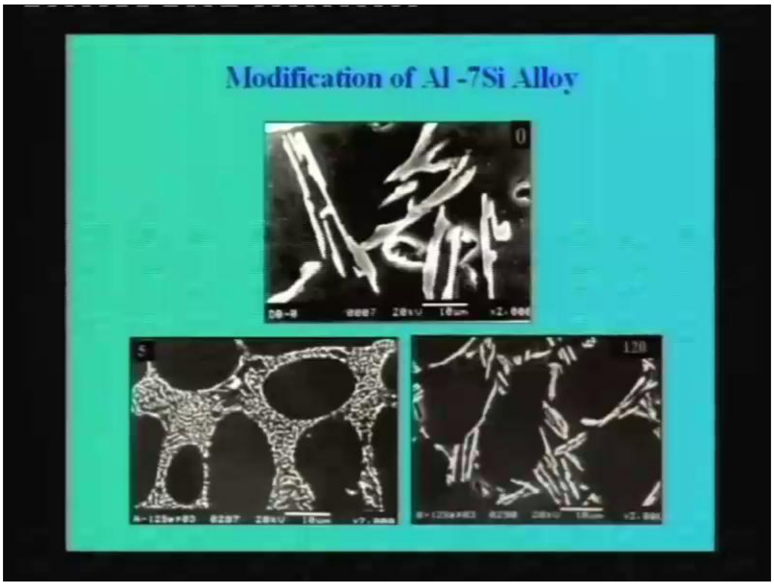

Modification of Al -7Si Alloy

And that is what; you try to see here, if you look at an aluminum silicon alloy and do not add any modifier. You see this is the type of silicon needles that you can get. This is a high magnification picture to show you what are the needle type of structure of silicon needles. And the moment you add 0.02 percent of strontium the same silicon has become very fine particles this is what we call modification.

And unfortunately, if you hold it for a very long period 120 minutes shown here. This one is after 5 minutes of adding the strontium on the right side, what you have is after 120 minutes of holding that strontium, when you add strontium into the liquid metal hold for a very long period. You lose whatever modification you have gained at a short holding time this is what is called fading, why does it happen? It happens because strontium has a tendency.

To form some complex compounds with aluminum. For example, Al 4 Sr is a compound which forms with aluminum. So, the moment you keep strontium which is inside the liquid for a long period this strontium will react with both the aluminum and also people have also found out recently some other complex compounds with both aluminum and silicon. They it is a complex compound of aluminum silicon strontium kind of a ternary compound.

So, once this compounds form the strontium is last from the liquid metal. So, all the strontium comes out of the liquid metal and forms these particles. And so there is not sufficient strontium left out in the liquid to form as a coating on the silicon during its growth and as a result you lose the strontium. In fact sometimes, we have also done adding access amount of strontium can overcome this kind of problem.

So, people sometimes add more amount of strontium. So, that at least some strontium is left out to act as a nucleating site. So, whenever somebody wants to use it for a long period of holding, he has to probably add higher amounts. But at the same time, one does not want to add too much of an amount. Because these particles which are forming. For example, Al 4 Sr or complex ternary compounds will act as probably as brittle compounds present in the matrix.

And act as, what are called stress concentrations inside the matrix, so that the strength of the ductility of the alloy might come down. So, nobody wants to add to much of strontium or any compound forming elements into an alloy. So, one has to remember that.

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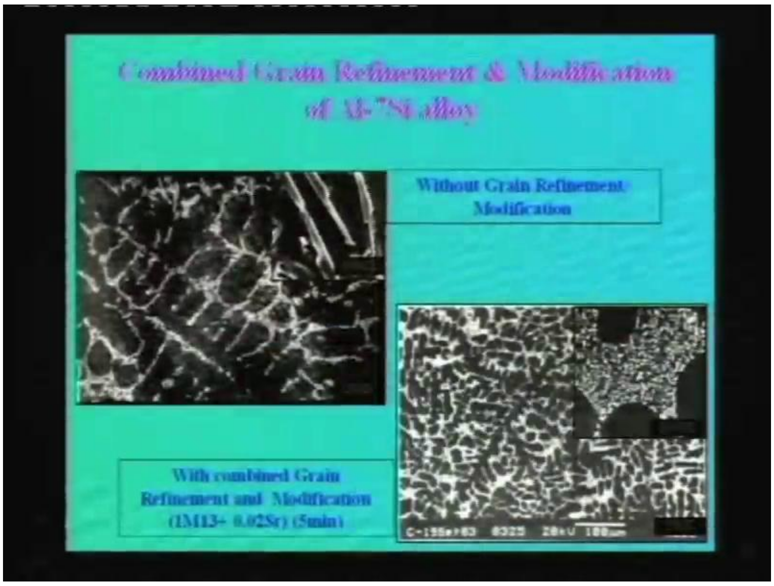

Combined Grain Refinement & Modification of Al-7Si alloy

Without Grain Refinement/ Modification

With combined Grain Refinement and Modification (1M13+ 0.02Sr) (5min)

So, if you do combined addition, what do you do, for example, if you do not add any grain refiner or any modifier? This is what you get; you get dendrites of aluminum and needles of silicon. So, this small picture which you see here is an enlargement of this eutectic mixture. So you see here, the dendrites of I mean the silicon needles in the magnified image here.

And similarly, if you do grain refinement come modification. You can see the grain size becomes very fine, from here to here you can see the grain refinement has taking place. And, in addition look at that any of those small region at the grain boundary magnify it. This is what you see, that the grain boundary magnified image shows you a complete modification of the silicon needles. So, one can have a combined effect of these two and once you do that the mechanical properties of such alloys are going to be much higher.

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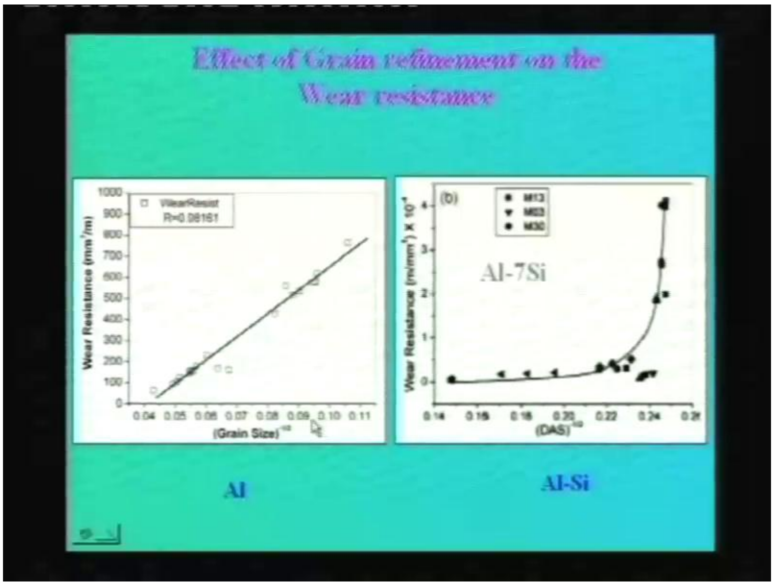

Effect of Grain refinement on the Wear resistance

Al

Al-Si

And that is what you see here, in terms of wear resistance. People have also done the ill strength of these alloys and then you can see that usually the ill strength follows a hall petch type of a relation. Here is an example which shows you the wear resistance of an alloy also, follows a hall petch type of a relation, how do we do this; you do aware test on an alloy with different grain sizes.

And once you know, how much wear has taken place, how do we measure wear, how does a person quantitatively measure wear.

Student: ((Refer Time: 20:01))

Loss, amount of the weight, weight loss or height loss depending on the type of machine that is available to you. Now a days, there are a number of machines which are available they can give you online height loss. So once, you measure the height loss, you convert it into volume loss. Once you know the cross section and from the volume loss one can also convert it into weight loss or volume loss itself can be represented as the extent of wear.

And this extent of wear ones, you know calculate the wear rate as a function of time and once you know the wear rate. Take the reciprocal of that wear race that is what will tell you what is called wear resistance. Reciprocal of wear rate is nothing but the wear resistance. And here we are trying to plot the wear resistance as a fine function of grain size to the power minus half. And you see exactly it gives you a hall petch type of a relation.

So, to show you not only the ill strength of the material, but also wear resistance of a material follows a hall petch a relation. And the fit is very good 0.98, so to tell you that all points. These are from a very small grain size means here, with d to the power minus half is very large means very small grain size. So, very large grain size is here. So, in a lay wide range of grain sizes one can show it is.

But the moment you go, from a pure metal aluminum to an aluminum silicon alloy. You do not see such kind of a hall petch relation here. The reason here is, it is not a single phase material any more. Aluminum silicon alloy has silicon particles along with aluminum grains. So as a result, if you plot the d to the power minus half here, if you carefully observe it is not the grain size which is plotted what is Das.

Student: ((Refer Time: 21:56))

Dendrite arm spacing, in case of alloys we do not measure the grain sizes, because we always get dendritic type of growth in case of alloys. So, and because of which we always measure inter dendritic spacing. And once, you get an average inter dendritic spacing you plot the inter spacing to the power minus half to the wear resistance and when you do that, you will see this kind of a relation parabolic kind of a relation. This comes basically because of the silicon particles which are present in.

So, you have a combination of the grains boundary, strengthening and particle strengthening; that means, precipitate kind of strengthening. So, a combination of these two will give you this kind of a thing. When you have very fine grain sizes, when you have grain size being very fine the particles are also very fine. Because, when you have large number of grains, you can see the grain boundary area is very small.

So because, the grain boundary areas; that means, the grain boundary thickness becoming very small. You will see that in that region the silicon particles will become very fine. So as a result, there is a possibility of silicon particles being very fine here in this domain. And as a result, you get much higher strength which is a combination of grain boundary strengthening and a precipitate kind of a strengthening or dispersion strengthening.

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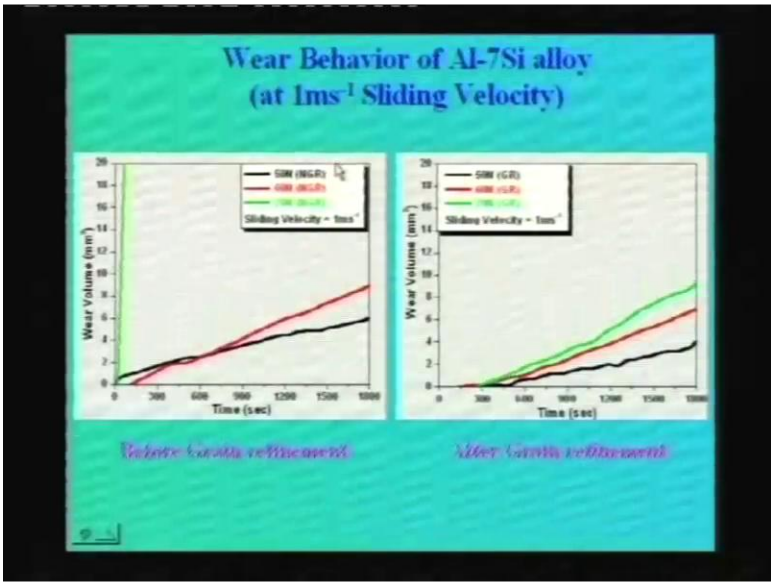

Wear Behavior of Al-7Si alloy
(at $1 ms^{-1}$ Sliding Velocity)

Before Grain refinement

After Grain refinement

So this is what you see and one can also improve, what is called the load bearing capacity; during wear properties particularly aluminum 7 silicon alloys because they are used for wear resistance applications, what is the effect of such kind of a grain refinement on the load bearing capacity if you look at it. So, if you try to take aluminum silicon alloy which is not grain refined.

And try to conduct wear test at different loads 50 Newtons 60 Newtons and 70 Newtons. You see the moment, you use a low load this is a type of a wear volume loss as a function of time you will get. This is done at a one particular speed of the disc. Do you know, how people measure the wear properties, there is a particular machine people use it what is that called.

Student: ((Refer Time: 24:07))

Pin on disc correct, it is called pin on disc machine, where you have a disc which is rotating at high speed. You can control the speed of that disc and you put make your sample in the form of a pin. And allow it to come in contact with the disc and you measure as a function of time, how the height of this pin which is made in the form of a particular astm standard diameter. And, a particular height and this material allowed freely standing on the disc and keeping on increasing the load.

You can have various loads on this particular pin, so that we can study, what is the effect of load on the wear volume. And that is what if you do, it as you increase the load from

50 to 60 the wear volume increases and if you go to 70, then immediately the material seizes; that means, the wear volume becomes so high that the materials seizes; that means, the pin gets stuck to the disc and it does not move anymore.

And that is what you see, if you do not do grain refinement. If you do grain refinements you see there is no such seizing. But, what you see is that, with increasing load definitely the wear volume again increasing, but you can see after grain, one is able to increase the load bearing capacity of this. And if you go further, this is for 2 meters per second same conditions. Here you can see 50 Newtons alloy gives you a wear volume like this.

And, if you use 60 Newtons, again you have seizer. At a higher speed seizer occurs at a lower load. This is understandable very easily. Because, you are doing at very high speeds, so as a result tendency for material seize is for much higher the wear volume is also much higher.

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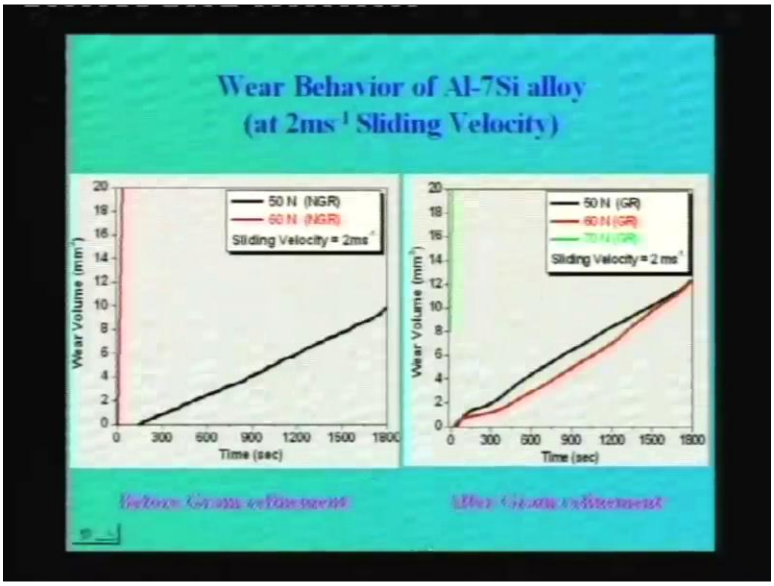

Wear Behavior of Al-7Si alloy
(at $2ms^{-1}$ Sliding Velocity)

Before Grain refinement

After Grain refinement

So, the same thing, if you do after grain refinement you can see 50 and 60 give you some wear volume, but 70 seizes here. So that means, even after grain refinement at certain load the material seizes.

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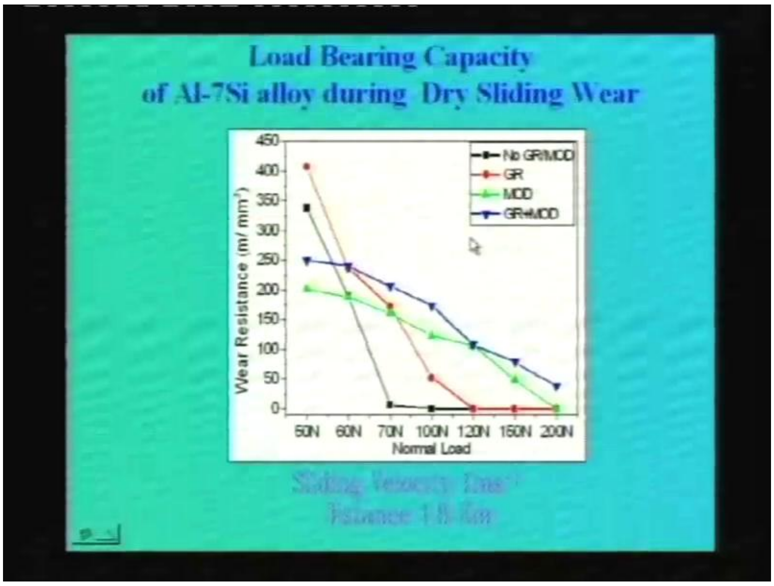

Load Bearing Capacity
of Al-7Si alloy during Dry Sliding Wear

Sliding Velocity 1ms^{-1}
Distance 1.8 km

So, one can do all this and here we show you the effect of all four conditions, one is without grain refinement and modification. If you do not do any grain refinement any modification, this alloy at a particular speed if you do it. You see after 70 Newtons it seizes, the wear the resistance becomes 0 after 70 Newtons.

Now, you do grain refinement, what happens at 70 Newtons? The material has certain wear as resistance is not 0. But, as you increase further, once you reach 120 Newtons. The material again seizes; that means the wear resistance reaches a zero value there. Now, you do modification only modification you can see the material again at 120 Newtons, it has some wear resistance.

So, actually you can see from these very clearly that the modification has a better improvement in the wear resistance than grain refinement. Grain refinement basically only decreasing the grain size where as modification is changing the silicon what particle morphology and silicon particle are the one which basically give you high wear resistance. Because, they are hard particles is like you take ductile material put hard particles into it you can improve wear resistance of a material.

So similarly here, you have a hard silicon particle inside the material. You can have a higher strength higher wear resistance. But you can see, if you do combination of these two grain refinement plus modification. Here, the only modified alloy seizes by 200 Newtons. Here a combination of these two even a 200 Newtons, it has not seized. It still has certain amount of though you can see clearly the wear resistance is decreasing with increasing load, but still it has some finite value of the wear resistance. So, this clearly tells us that a combination of a grain refinement plus modification will.

Not only the increase the ill strength of a material and also increase the toughness of the material. But, also improves the wear resistance of the material and load bearing capacity during wear. This is practically very important, whenever a somebody was to use such materials that is why grain refinement has become very important recently the DRDO labs are showing a lot of interest in improving the wear resistance of the materials of aluminum silicon alloys by a combination proper combination of grain refinement and modification.

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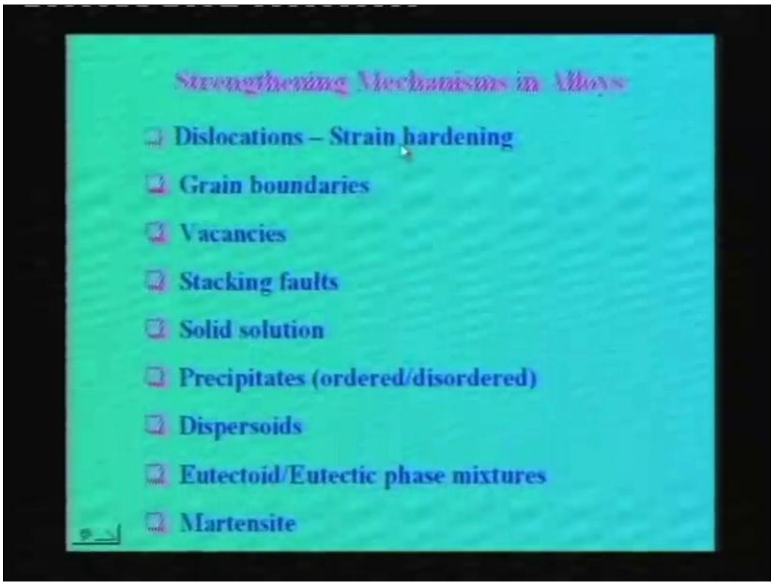

Strengthening Mechanisms in Alloys

- ☐ Dislocations – Strain hardening
- ☐ Grain boundaries
- ☐ Vacancies
- ☐ Stacking faults
- ☐ Solid solution
- ☐ Precipitates (ordered/disordered)
- ☐ Dispersoids
- ☐ Eutectoid/Eutectic phase mixtures
- ☐ Martensite

So, this as per as the pure metals and we looked at just one part which is the aluminum silicon. Let us look at a alloys in general, when look at a alloys in general, what are the strengthening mechanism. There are number of them. We start with the same things which you have already talked first four are the once we have already talked the exits even in pure material also. That, the dislocation strengthening grain boundaries strengthening vacancies and stacking faults.

Only thing is the stacking faults, strengthening gets either enhanced are decreased depending on the alloying elements that you add. So in case of alloys, the stacking fault strengthening depends on the type of alloying elements that you are adding. Some alloying elements will increase the strengthening some alloying elements will decrease the strengthening depending on whether they are increasing the stacking fault energy or decreasing the stacking fault energy. That is going to decide the strengthening which is coming because of the stacking faults, where are dislocation strengthening again another point also one has to remember the alloying elements that you are adding can also act as pinning agent for the dislocation.

For example, I do not know whether you have read probably you must have read in detail about ill point phenomena. Ill point phenomena is just because of carbon atoms is not it. It is the carbon atoms give you a ill point phenomena. Even strain aging talk about strain aging is also related to carbon atoms, what is called drag? Cotton atmospheres, you have read about all this.

So, cotton atmospheres are nothing but the dislocation which has the strain field the stress the tensile. And compressive components strain fields above and below the dislocation. And once you have such kind of situation the moment a carbon item goes there are any other solute item goes there into those vacancies which are existing either below the positive dislocation are above the negative at this dislocation.

Once the solute atom goes there, then it nullifies that particular strain field and because of which it can lock of dislocation moment. So that is, why we talk about the strain aging cotton atmosphere causing. So, alloying elements can be a strong what are called strengthen us, one of the most important strengthening that comes from alloying elements is, what is called solid solution strengthening. And usually this solid solution strengthening looks something like this.

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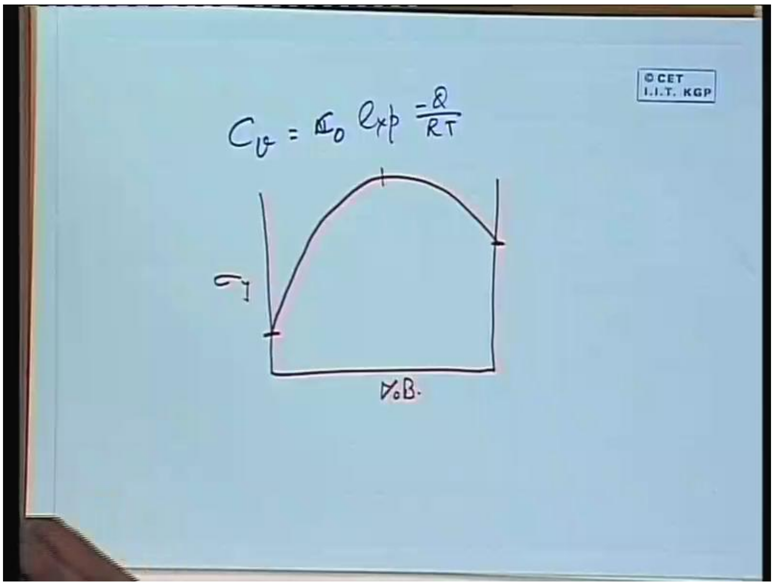

If you look at a strength ill strength as a function of percentage of B, let us say you will see this kind of a plot. If this is a ill strength of pure A, this is the ill strength of pure B. The strength reaches somewhere in the middle. It may not be exactly 50 50 depends on the type of A and type of B. But somewhere reaches maximum and that is basically because when B goes in to A. Element B always has a different atomic size and than that of element A. So, once that atomic size is different then there is a misfit strain and once this misfit strain is there that gives you strengthening and that strengthening we talk in terms of here.

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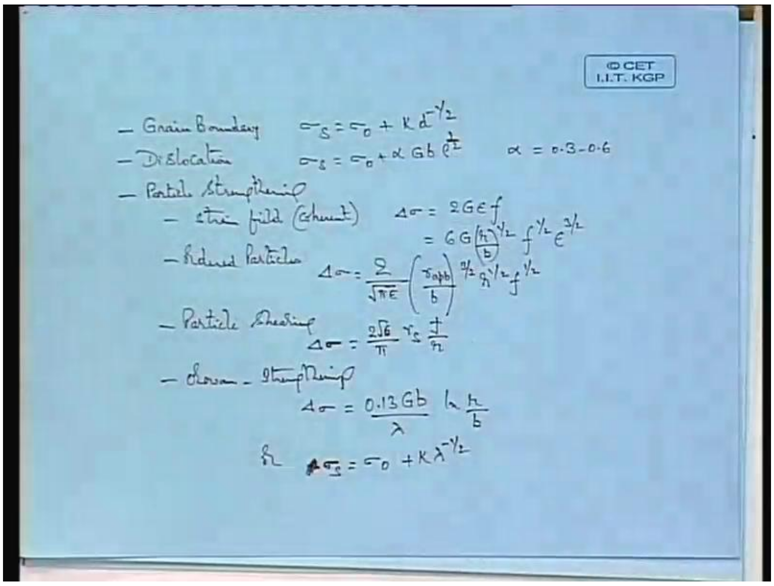

- Grain Boundary $\sigma_S = \sigma_0 + K d^{-1/2}$
- Dislocation $\sigma_s = \sigma_0 + \alpha G b \rho^{1/2}$ $\alpha = 0.3-0.6$
- Particle Strengthening
  - Strain field (coherent) $\Delta\sigma = 2G\epsilon f$
    $= 6G\left(\frac{r}{b}\right)^{1/2} f^{1/2} \epsilon^{3/2}$
  - Ordered Particles $\Delta\sigma = \frac{2}{\sqrt{\pi E}}\left(\frac{\gamma_{apb}}{b}\right)^{3/2} r^{1/2} f^{1/2}$
  - Particle Shearing $\Delta\sigma = \frac{2\sqrt{6}}{\pi}\gamma_s \frac{f}{r}$
  - Orowan - Strengthening
    $\Delta\sigma = \frac{0.13Gb}{\lambda} \ln\frac{r}{b}$
    Or $\sigma_s = \sigma_0 + K\lambda^{-1/2}$

We can also talk in terms of when you talk about particle sizes will keep it for the time being and then when you come to participate will talk more about it. So, this in general the strengthening that comes from because of the solid solution which is basically related to the misfit which is called delta parameter, what is delta parameter? Delta parameter is nothing but RA minus RB divided by RA mod of it multiplied by 100 in terms of percentage, where A is the solvent and B is the solute.

And, you normalize is it respect to the solvent all the time, so that is what is called misfit parameter. The higher misfit parameter the higher will be the strengthening. So, whenever you take a particular solute item and solvent item and keep on adding different types of solutes. The extent of strengthening is going to be different for different elements. Because, the misfit parameter is different for different elements, so for example, iron if you take ha the strengthening that you achieve because of various solute items is going to different for different elements.

So same thing, which will see when we talk about super alloys also the different alloying elements will give you, different solid solution strengthening, so which basically depends on this. And not only the solid, what are called substitution of solid solution, interstitial solid solution also give you strengthening in the same way that there also what is crucial is the misfit parameter once again. So, this as per as the solid solution strengthening is concerned.

Once you come to precipitates strengthening. There are two types precipitates ordered precipitates and disordered precipitates. And if you have ordered precipitates, you have the strengthening that one can a achieve is going to much higher than what can you achieve with disordered precipitates, why because when as dislocation has to move through a ordered precipitate. It has to break the precipitate cut through the precipitate particularly, if the precipitate very fine.

You must have heard about precipitation strengthening at some point of time, where we have two type of strengthening coming whenever you have participates. One when a precipitates is very fine, what is what we call precipitates shearing takes place, when the particles are very fine. When the particles are very big, we have, what is called bowing taking place moreover bowing which takes place and when the precipitates are very fine in the range of what are called gp zones.

You have the strengthening coming because of the strain field around those zones. There are really not any precipitates there we cannot really see precipitates. Because, they are so fine of just a few nanometers may be one or two nano meters. So, such zones can give you strengthening, because of what is called the strain field around that and (Refer Slide Time: 32:38) that is what is give here.

Whenever, you have a coherent strain field because of the particles and that gives you strengthening which is proportional to the misfit which is a epsilon here. And f which is the fraction of such zones, which is nothing but volume fraction precipitates we say. So here, they are not really precipitates, one cannot really see precipitates. If you go to a microscope, one can only see strain contrast in a even in a electron microscope.

To distinguish between they though, so called precipitates if you want call them that is why people do not call the as precipitate they would prefer to call them zones gp zones we call linear precipitate zones. So, the volume fraction of such zones and what is called the misfit parameters there. Here, the misfit parameters basically means lattice parameter mismatch. If you have a precipitates that is forming, what is the precipitate lattice parameter of the precipitate and the lattice parameter of the parent phase.

And this misfit is what gives you the strengthening there. And, if one does more detailed modeling, he gets equations like this which is given here. This is a rough estimate and here you can see not only the volume fraction of the precipitates. But the misfit parameter, but also the size of the precipitates comes a zones come into picture and burgers vector are also come into picture.

And the shear modulus of the matrix comes into picture. So, this is what is the strengthening that one can achieve as because of strain field. And once, the particles become slightly bigger. But still finer and that you have still some kind of semi coherent or coherent precipitate present they you have two possibility. One is shearing whenever you have particle shearing take place this is what type of strengthening that you can achieve.

The delta sigma is given by 2 under root six by pie which is geometric is a factor, because we are assuming either spherical particles or any type of elongated particles by changing the shape of particles. One can change this geometric factor and what is important, here is gamma which is called the surface energy are the interfacial energy why this is important, it is important because when you take a particle.

And if dislocation which is moving on a plane shears this particle what kind of a situation you have, you have a situation like this. The particles get sheared when a particle get a sheared. Then, you creating a new surface and this new surface is given here this is the new surface that you are creating. If I enlarge this and this portion is the new surface that you have created.

So, once you have created a new surface for creating any new surface. You need some energy to be spending that is why we say nucleation during solidification also. We always say there is under certain cooling required for nucleation because surface has to be created. So similarly, because the surface has to be crated there one has to provide extra stress to create that surface.

And that is why strengthening will increase and that is why here it is very important to talk in terms of the surface energy. Surface energy is very is directly the strengthening that you can achieve is directly proportional to surface energy. The higher the surface energy for a unit area, the amount of energy that you have to spend is going to be higher. So, the amount of stress that you have to given is going to be higher.

Similarly, it is also a function of the volume fraction directly proportional to the volume fraction. And, in directly proportional to the volume fraction and indirectly proportional to the size why proportion to size, because surface area to volume ratio is going to be higher finer the size. And, we are taking the new surface being created. So, as a result the total amount of surface to be created is going to be higher the finer the particles.

So, that is why the finer particle will have higher strengthening coming into picture. And this is for shearing. And once the particles became much bigger, you have what is called dislocation bending taking place around the particles, because now particles are much bigger. So, shearing is very difficult. So, dislocations cannot shear. So, instead they would like to bend around the particles and that when they try to bend around the particles.

You call it as or wan bowing, Or wan is the person who has talked about this. And this particular or wan bowing can be represented in this form, where delta sigma, delta sigma is what is sigma is ill tress minus sigma not basically. So, that is the increment in strengthening that is taking place because of such precipitation. If do not have precipitate you have a certain strength if you have precipitate what is the extra strengthening that you get. So, that is why in all these cases whatever we are talking about is a delta sigma.

In the extent of strengthening additional strengthening that we are going get. And that is proportional to g barges vector and inversely proportional to the lambda, what is the lambda here, inter particle spacing. Whenever, you have precipitate strengthening one of the most crucial aspects. In fact, I would say there are three aspects which are very important. Whenever you are talking of precipitate strengthening, one is the volume fraction of precipitate, two the size of the precipitate, three inter particle spacing.

And of course, the fourth one which is also crucial is the surface energy which you have talked about it just now. So, these are the four important parameters which decide the extent strengthening that one can. So, here the lambda is very crucial. So, as you can clearly see lambda comes in the denominator; obviously, it has to come in the denominator. Because if the lambda is smaller; that means, inter particle spacing is smaller; that means, number of particle in a unit volume is higher is not it.

So, inter particle spacing being smaller means the number of particles in a unit volume is higher or in a particular direction even if you think of in a particular unit direction. Unit length also is going to be higher if the lambda is smaller is not it. So, lambda is wave length and wave number is in inversely proportion to the wave line. So, the wave number is going to be larger if lambda is smaller.

So, as a result the numbers of obstacles are going to be higher. If the lambda is smaller, so that is why lambda comes in the denominator. And again, the particle size also comes in the picture. And, the one can also talk in terms of a hall petch type of relation. In case of precipitates in terms of lambda, lambda to the power minus half. So, one can plot the ill strength of a material as a function of lambda which is the per minus half and get again a linear relation. So, this is as per as precipitate strengthening is concerned. And one can also talk about, ordered precipitates which we have not talked so for. And in case of ordered precipitates you get additional parameter here which is called gamma a p b what is this a p b.

Student: ((Refer Time: 43:31))

Anti faced boundary energy. So, whenever an ordered particle is there if an ordered particle is shared by dislocation. So, you are creating an anti phase boundary. So, anti phase boundary has to be created, again as I told before like a particle shearing one has to create certain new surface. So, one has to spend energy. The extent of energy that you have spend is going to depend on how much is anti phased boundary energy. If the anti phased boundary energy is higher you have spend more energy; that means, more stress.

So, that is why you can see this comes in the numerator it does not come in the denominator this is very crucial for you to understand. So, any strengthening what comes in denominator, what come in the numerator is very important. So, this is and again r comes in to picture the size of the precipitate particle the volume fraction of the particles. So, this is what is called precipitate strengthening then let us talk in terms of the other aspects.

Once precipitate strengthening has occurred, we know that the precipitate strengthening.

Student: ((Refer Time: 44:45))

Yes, it depends on here in case of these particles. If the particles are bigger, here in this particular case if the particles are bigger, what would be bigger you tell me.

Student: ((Refer Time: 45:03))

They then that is why I am saying, you can see delta sigma is increasing with r. Only thing is not directly proportional it to the power half. So, you can clearly see that the strengthening that you can achieve because of r is much smaller than the strengthening that you can achieve because of gamma. So, that is why gamma is much more crucial here. So, anti phased boundary energy because it is 3 by 2. So, one has to considered that.

So, once we have this particles and once we go to higher temperature we come into problem of particle coarsen is not it. Once particle coarsen, what is going to happen, the number of particles are going to decrease. Because, the total volume fraction of the particles has to remain the same is not it. The total volume fraction of the particles has to it. In fact you will see, this is one important point that one has remember. Thus the volume fraction will remain the same once you increase the temperature in principle it will decrease, why does it decrease.

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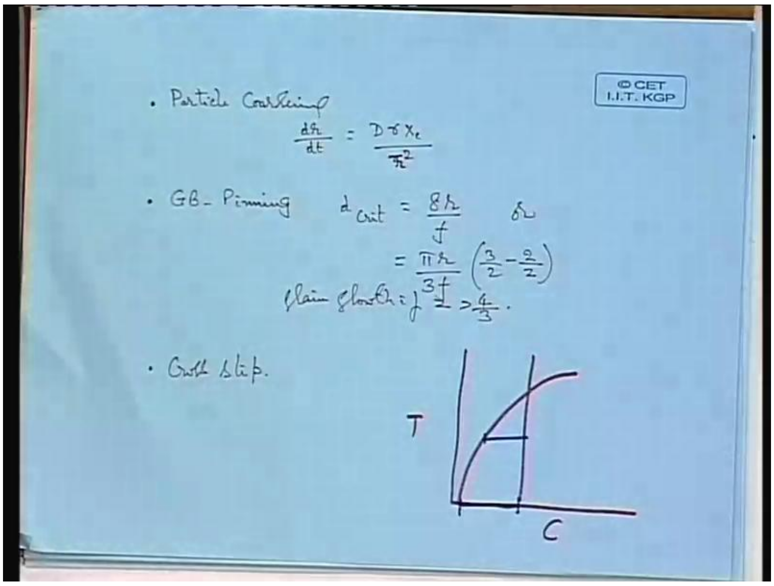

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- Particle Coarsening

$$\frac{dr}{dt} = \frac{D\gamma X_e}{r^2}$$

- GB- Pinning $d_{crit} = \frac{8r}{f}$ or

$$= \frac{\pi r}{3f}\left(\frac{3}{2} - \frac{2}{z}\right)$$

Grain Growth : $z > \frac{4}{3}$.

- Cross slip.

You think of your phase diagram temperature versus concentration. Look at this salvo’s line, you consider a particular alloy. And the extent of super saturation at room temperature is this. And the extent of super saturation at high temperature is this for the same alloy. So, if the super saturation is decreasing, volume fraction is decreasing.

In addition for a given volume fraction, if the particle size is increasing. It means that some particles are becoming bigger. At the expense of; obviously, some other particles we have talked about this during thermodynamics class that some particles dissolve and some particle grow. And as a result, the number of particles decrease, when the particle size increases for a given volume fraction. So, if the number of particles decrease, then the inter particle spacing is going to increase is not it.

So, if the inter particle spacing increases, then the strengthening is going to come down. So, two things are going to happen, when we go to high temperature. One is the volume fraction is decreasing because the particles are dissolving. Second the particles are becoming a bigger, because of which delta is decreasing. And if the delta decreases then you can see the strengthening decreases.

As result our goal is to how to control the particle course name and that is where lot of people have done lot of studies.

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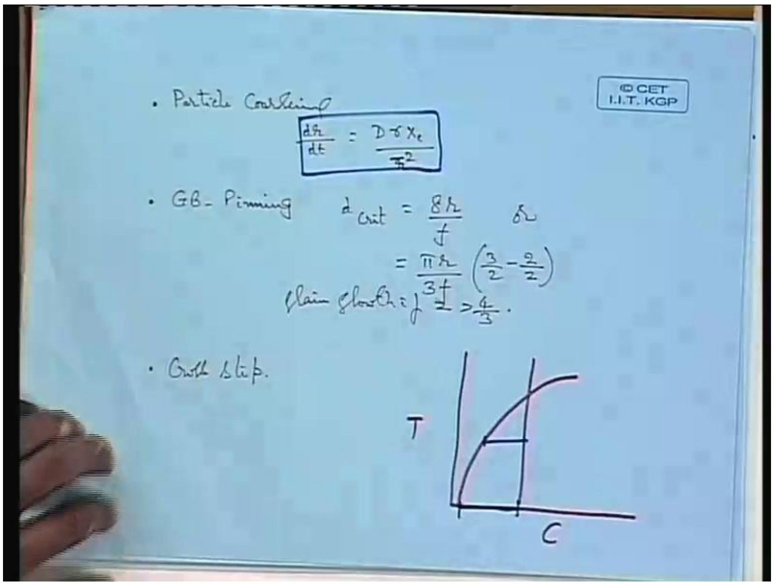

- Particle Coarsening

$$\boxed{\frac{dr}{dt} = \frac{D\gamma x_e}{r^2}}$$

- GB- Pinning $d_{crit} = \frac{8r}{f}$ or
$= \frac{\pi r}{3f}\left(\frac{3}{2} - \frac{2}{z}\right)$
Grain growth: $z > \frac{4}{3}$.

- Cross slip.

And people have come up with an expression of this kind where dr by dt tells you what

Student: ((Refer Time: 47:54))

Rate of increase in the particles size; that means, grain particle coarsening I should not call in grain coarsening here the particle coarsening. So, you have a number of particles and these particles are trying to coarsen. So, the rate of coarsening of the particles is the dr by dt and that is proportional to d, what is d, diffusivity or obviously, it is very easy to understand, why should be proportional to the diffusivity.

If the higher the diffusivity the faster is the diffusion so easy a particle coarsening. Because, particle of coarsening occurs only because of diffusion, otherwise if there is no diffusion, there is no particle coarsening. Then the second thing gamma the higher the surface energy the easy for the growth coarsen. In fact, that is reason why if somebody wants gray particle coarsening not to occur you need to create particles which have very low interfacial energies.

Ordered coherent particles do not grow as fast as non coherent particles. In coherent particles grow very fast and semi coherent and coherent particles do not grow. Because they have lower interfacial energies that is why that is very important second thing is the solubility x e is the equilibrium solubility. If the equilibrium solubility is very large, then particle will coarsen is very easily.

If the solubility is very small then they do not coarsen. Because for coarsening of some particles some particles have to dissolved is not it. So, as a result solubility is going to decide on the coarsening indirectly. So, that is why, the if you have to different phase diagrams.

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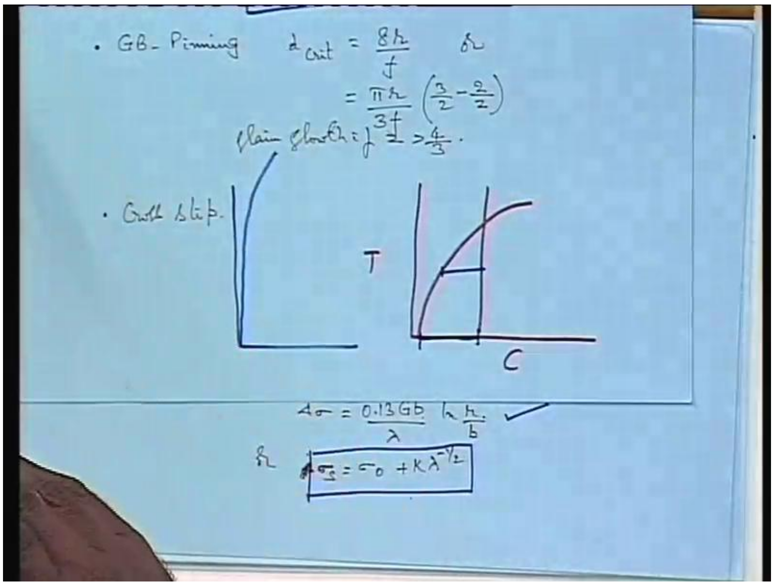

One phase diagram like this, another phase diagram which is like this, where the solves line is much more steeper. This kind of phase diagram in this alloys the coarsening will not occur very easily. In this alloys coarsening will occur very easily. So, solubility is very crucial. And it is also inversely proportional to the average particle size, square of average particle size; that means, if the average particle size is very large, then the coarsening is lower is average particle size is very fine, then the coarsening is higher.

Fine particles have a greater tendency to coarsen is not it. So, because of high surface area to volume ratio, so that is why this is going to be very important. So, all this factors have to be considered and that is why when somebody thinks of alloy design people considered all these. For example why do we use dispersion strengthening, because of these. For example, one important thing for dispersion strengthening is this X c is almost 0, but definitely gamma is going to be higher. So, one has considered that aspect also.

So, how are we going to have an advantage or a disadvantage one has to look at the actual numbers and then decide whether we are going to higher strengthening.

Student: ((Refer Time: 51:09))

Definitely.

So, whatever may be the gamma if X c is 0, then dr by dt is 0 is not it. So, that also one has to considered. So, other way is also that grain boundary coarsening is also is very important, because we now the strengthening comes because of grain boundaries. So, if at higher temperature grains also tend to grow. So, we have to think of how to prevent grain growth.

So, for that one way is to do what is called grain boundary pinning and this grain boundary pinning ha dependence on the particles. So, if you put hard particle which can go to the grain boundaries and can pin the grain boundaries and the volume fraction of particles and the size of particle are going to decide, what is the critical diameter of the grain size that you can achieve. If you have a large volume fraction then you have a smaller grain size if you have very small.

If for example, if the volume fraction goes to the 0 you can see d is almost goes to infinity; that means, grain growth can occur very easily, if you do not have particles. So, if you have large volume fraction particles, then the grain growth is completely controlled. So, that the d is very small, so that is why one can also control the grain growth by controlling. In terms of the grain boundary pinning agents that is what you see in case of high strength low alloy steels or micro alloy steels.

In micro alloy steels, we add certain alloying elements such as niobium vanadium titanium which form carbides and nitrides go to the grin boundaries and prevent the grain growth. So, this what is precipitates and dispersoids.

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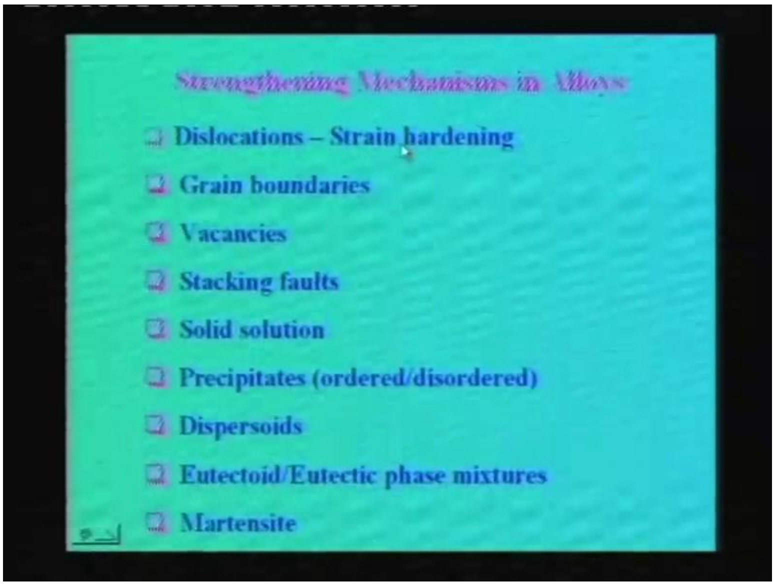

Strengthening Mechanisms in Alloys

- ❑ Dislocations – Strain hardening
- ❑ Grain boundaries
- ❑ Vacancies
- ❑ Stacking faults
- ❑ Solid solution
- ❑ Precipitates (ordered/disordered)
- ❑ Dispersoids
- ❑ Eutectoid/Eutectic phase mixtures
- ❑ Martensite

And the other possibilities the second phase mixtures, the eutectic or eutectoid mixtures whenever you have a second phase we get strengthening and finally, marten site. You all know that marten site also gives to. So, these all are various strengthening mechanisms we stop here and consider the super alloys in the next class.

Thank you very much.