Advanced Materials and Processes
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Lecture - 20
Advanced Al Alloys Part – III

We start this class, last two classes, we have been talking about Advanced Aluminium alloys, these a little more in that direction.

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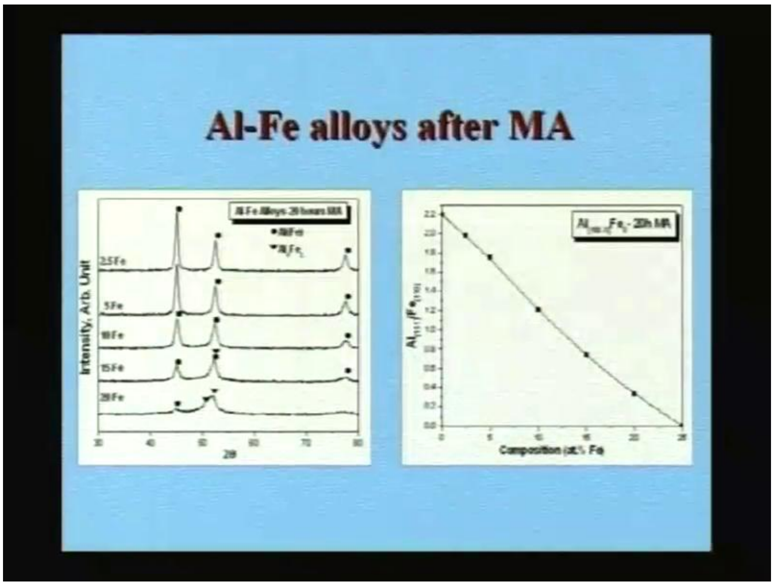

Al-Fe alloys after MA

We will continue today, and then go into the titanium based alloys. So, among all the alloys that we talked about, aluminium based alloy. We talked about amorphous aluminium based alloys, nano crystalline aluminium based alloys, nano quasicrystalline aluminium based alloys and nano composites. There are few more nano composites, which I thought literature is available. So, I thought, I would give you some more examples of that, one such thing is aluminium iron based alloys.

As I told you before, people want to put into aluminium, all kinds of high temperature materials, high temperature and high melting metals. One such example, you have already seen is titanium. So, why do, we put this, this is basically to improve the high temperature strength of aluminium. Because, when you put elements, which have high melting points, then these elements, their diffusivity is going to be low, at the temperature of the use.

And because of that, the creep is going to be much more difficult in those alloys. So, whenever, you add to aluminium, we know is a very low melting metal, 660. So, as a result, it is creep resistance is very poor, so creep is related to diffusion. So, we all know and grain boundary sliding. So, everything is related to high temperature, deformation is related to diffusion.

So, as a result, if you can somehow, constrain the diffusion or slow down the diffusion process, we can increase the creep life of any alloy. So, in that direction, people try to put a number of elements, for example, iron is 1; titanium is another; vanadium. For example, aluminium, iron, vanadium, silicon alloys is very popular alloys, for high temperature applications. Where, people try to put iron, vanadium, silicon and try to get a two phase microstructures, which can give you much high strength.

So, here is one strength example, aluminium iron, where different amounts of iron are added to the aluminium, 2.5 percent, 5 percent, 10 percent, 15 and 20 percent. And you know, as I told you, the most important compound in all these alloys is, what the Al 3, Fe, Al 3,, Ti, this type of a phase. The reason is, as I told you it is a high melting compound. In addition, it has large amount of aluminium in it and because of which, it is density is lower.

So, as a result, if you can have a Al 3, plus metal type of a compound Al 3, Ti, Al 3, Ni, Al 3, Fe, this kind of compounds, these are all aluminates. If you can have that kind of a compound as a precipitate in an aluminium matrix, one can achieve much higher strengths. So, keeping that in the mind, so people do not add too much of an alloying elements into it, those elements, which can give you, Al 3, Fe.

So, that is the composition ranges people work on. So, that is why, we are still, below that 25 percent of iron into it. So, if you add this different alloying elements and this the technique; that people have used here is mechanical alloying. As I told you, all these nano composites can be produced by basically two techniques. One is the rapid solidification processing, another is mechanical alloying.

So, this particular example is for, what is called a mechanical alloying. And if we look at the XRD patterns, what you basically see that, after 24 of mechanical alloying of aluminium plus iron of different amounts of iron into it. You will basically see, only aluminium peaks. Suggesting that, it is the iron, which has dissolved into aluminium and what you have is, basically a solid solution. But, one interesting thing, that you look at this, more carefully, you will see that, the aluminium peak.

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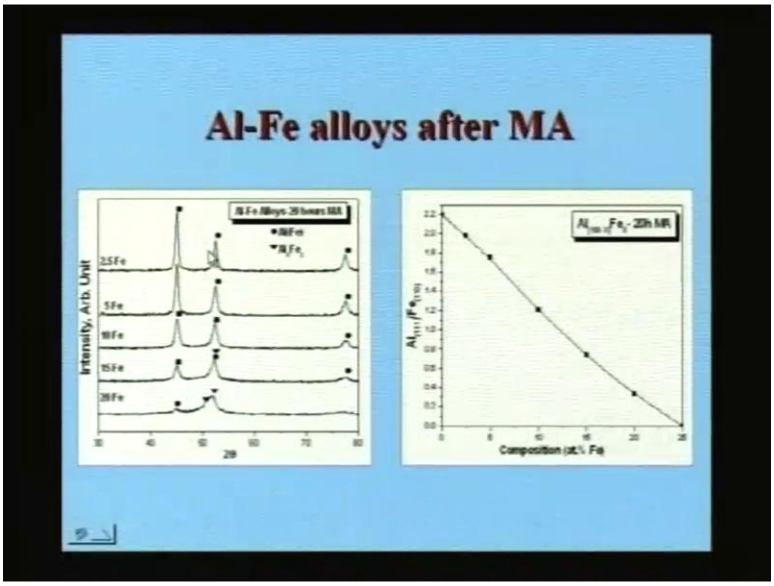

Al-Fe alloys after MA

The first peak, which is around 45degrees, which you see here is, aluminium 111 peak here. This peak which you see here, as aluminium 111 peak, it is intensity keeps on decreasing, as you increase the iron. And the second peak here, which you see is aluminium 200 peak. That intensity, with respect to the aluminium 111 intensity is increasing.

So, initially at 2.5 percent, you have the 111 peak, which is more intense than the 200 peak, which is what we expect for pure aluminium. When, you take a pure aluminium and do x-ray, always in an FCC metal, 111 peaks has a highest intensity than the 200 peak is it always true, do we have any exceptions. Usually, whenever you take a metal, mostly pure metals, you will see that, the first peak is the most intense peak. And the other peaks are lower intensity.

But, there are conditions, where it is possible for the second peak or the third peak being more intense than the first peak. When do you observe such a situation, any, no…

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Preferred orientation, that is it, texture. If you have a texture, let say you take iron and keep rolling it in a particular direction, let say 200 directions. Once, you do that, all grains are oriented in a 200 direction and take that and do an x-ray, you will not see 110 peak there, iron is BCC. So, 110 is suppose to be the most intense there. So, 110 will have a lower intensity than the 200.

So, unless, you have preferred orientation, if you have a random orientation, usually the first peak is the most intense peak and that is what you see here. And when you do mechanical alloying, which is a ball milling process, where the balls are hitting the powder. There is no chance of a preferred orientation coming into picture, because these are all random collisions of. So, it is not possible for the grains to be elongated in a particular direction; that kind of a chance does not exist.

So, the possibility of second peak, becoming more intense than the first peak, does not arrives, because of the texture in this kind of material. So, what is the possible reason, why the second peak is becoming more intense than the first peak? That basically means some other phase is coming out. Unfortunately, that second phase, which is coming out overlaps with the first peak, if you carefully observe the 20 iron, you can see some kind of a shoulder on the left side.

And that shoulder, indicates that there is another phase, which is Al 5, Fe 2, this is interesting to note. That the composition is very close to Al 3, Fe, under equilibrium conditions the phase that you are suppose to expect is Al 3, Fe. But, you do not get Al 3, Fe, but you get another phase called Al 5 Fe 2. As Al 5, Fe 2 is a higher melting metastable phase, which can easily nucleate in an aluminium matrix than the Al 3, Fe. That is why; these are some metastable phases, which always come out.

Probably, if you take this alloy, and then heat treat it at high temperature for a long period. Again, you get back to the equilibrium conditions. So, this is, what you see here and to identify that, if you take the aluminium 111 peak and the iron 110 peak. And take the ratio of these two and plot it as a function of time or plot it as a function of composition.

You will see that at 25 percent, this should go to 0, why, at 25 percent, the aluminium 111 verses iron 110, if you take it, that ratio will go to 0. There reason is that 25 percent composition is equivalent to the Al 3, Fe composition. So, if you choose the Al 3, Fe composition and make an alloy of that composition, at that composition, you will not have any aluminium, you will have a single phase intermetallic compound in a phase diagram. This is nothing but like a Lever rule.

The volume fraction of the aluminium keeps on decreasing, as you keep on going towards the Al 3, Fe. And once you reach the Al 3, Fe composition, then there is no aluminium, it is only Al 3 Fe. So, that is what you see here as you keep on plotting this ratio, aluminium keeps on decreasing. And that is what you see, here in the x-ray also, the aluminium peak keeps on decreasing.

And when you go to 25 percent, it will completely vanish. There will be no aluminium, it will be only single phase inter metallic compound. So, one can produce this kind of phases, which are nano crystalline in nature, by mechanical alloying.

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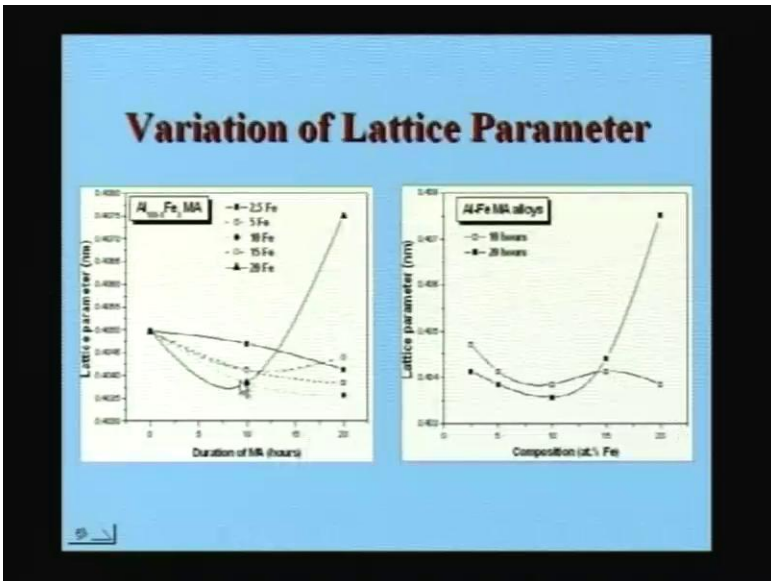

Variation of Lattice Parameter

And look at the lattice parameter, as I told you before, one can calculate the lattice parameters, based on. How do you, calculate the lattice parameter of various alloys, using an x-ray diffraction.

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Yes, just simply from the Bragg's Law and the relation between D spacing and the lattice parameter, one can do it. And if you look at the previous one, you can see that the peak, which you have aluminium peak keeps on shifting. Aluminium peak the position, if you look at it, the aluminium peak position at 2.5 percent is different from at 20 percent. So, this clearly, tells you, that there is some solubility of iron into aluminium.

And because of which, the peaks are shifting. And from the peak shifts, one can calculate what is the solubilities also. So, when you plot the lattice parameter, what you see is that, the lattice parameter does not change much up to above 10 percent and from there. In fact, there is a decrease in the lattice parameter, as marginal decrease in the lattice parameter. As you increase the iron content up to 10 percent, because iron is slightly smaller a atom than the aluminium.

So, when iron goes into aluminium, the lattice parameter decreases or the overall atomic radius decreases. So, as a result, you can see a small decrease and but, later then this 10 percent, you see, suddenly there is an increase. And this increases, coming because of the formation of the second phase the Al 3, Fe. So, which overlaps, with that peak and because of which, one can find out that the peak, sudden increase in the lattice parameter is because of the formation of Al 5, Fe 2.

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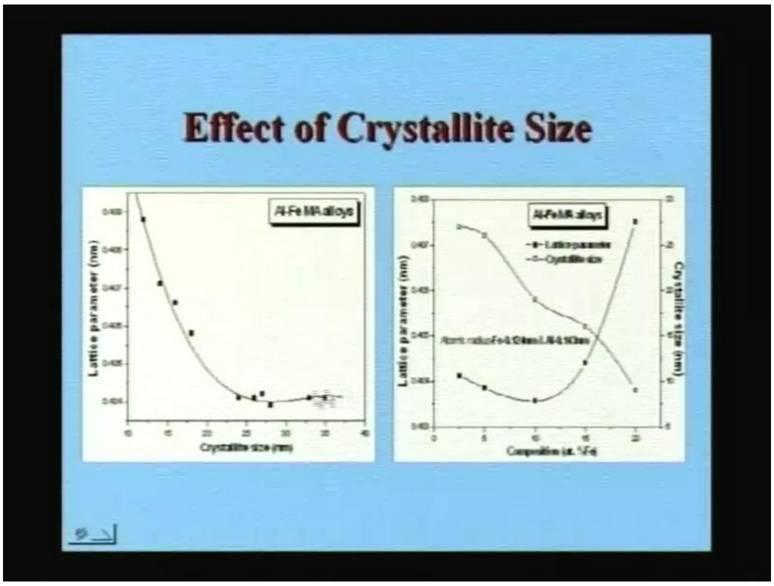

Effect of Crystallite Size

So, one can do this kind of lattice parameter calculations and also correlate the crystallite size to the lattice parameter. You can see as you keep on doing ball milling, the crystallite size decreases. And once, the crystallite size comes to above 20 nano meters or so suddenly the lattice parameters. Start changing up to that time, there is no change in the lattice parameter much. This is what, I told you long back also; nano crystallization is a prerequisite for alloying during mechanical alloying.

Unless it becomes nano crystal, it cannot become an alloy. So, nano crystal formation is crucial for the alloy to form. For one element to start diffusing into the other, because these diffuse is occurring at room temperature. Whereas, if you make this alloy, by normal conventional liquid metallurgy route. You are making alloy at high temperature, where the diffusion can easily occur.

So, here, you want to the diffusion to occur at room temperature, how the diffusion can occur at room temperature, where it has a large activation barrier. So, it can occur, only when you bring down the diffusional distances. So, if you can bring down the diffusion distance, the gradient becomes very large. Extremely, large because what you see d x, d c by d x becomes very large, when the d x becomes very small.

And that is what, you see, that even if the temperature is very low, the diffusion can occur at room temperature. Because, of the small crystallite size, that you have, if the crystallite becomes very small. Then, the diffusion can occur very easily and also, at those small crystallite sizes, the defects are so much inside the material, that the diffusion can occur very easily and the surface of these nano crystals being random in nature.

So, a lot of solute can dissolve into the surface of this. That is, we have see earlier also, that the grain boundary volume as it increases the solid solubility increases. So, that is what, you see in the nano meter. And all this occurs, below a certain crystallite size. So, we have to reach around 20 to 25 nano meters, for the lattice parameter to start increases.

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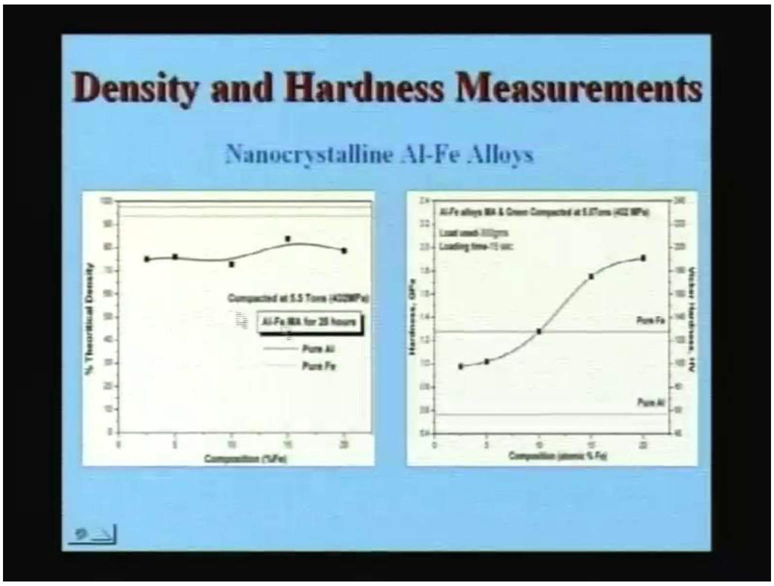

Density and Hardness Measurements

Nanocrystalline Al-Fe Alloys

And people have also tried to look at, what are the strength levels of these nano composites. And here, what you see is nothing but, the hardness, the Vickers hardness of these nano crystals, nano composites as a function of composition. You can see as a composition is increasing the hardness is increasing. And the hardness reaches almost about 2 Giga Pascal's and which is much higher, when compared to the hardness of most of the normal aluminium alloys.

Normal aluminium alloys, you get hardness of the order of around in terms of Vickers hardness, if you look at it, around 60, 70 Vickers hardness. You do not get much beyond that. So, here, you get around 200 Vickers hardness, which is equivalent to about 2 Giga Pascal's. And the densities of these alloys, grain densities, without any sintering, one can achieve about 85 percent or so. 75 to 85 percent of grain densities, one can achieve in these nano crystals.

This is one of the advantages of nano crystalline materials; people say, usually by normal powder metallurgy route, you have the problem, that achieving high densities is very difficult. You need to go to very high temperatures of sintering in a normal powder metallurgy; I think some of you are taking powder metallurgy course. So, you know that, compaction sintering and sintering at high temperatures is crucial and many times people do, what is called liquid phase sintering.

That one of the phases, present in the material melts and provides the required bonding, that is require for getting high dense compacts. Whereas, in a nano crystalline materials, material can flow more easily and you have large grain boundaries available, for achieving high densities and that is why, this you can even at normal grain compaction, you can achieve all mostly 85 percent. In a number of composites, people have achieved even 90, 95 percent, just by grain compaction. So, one can achieve high densities in these materials.

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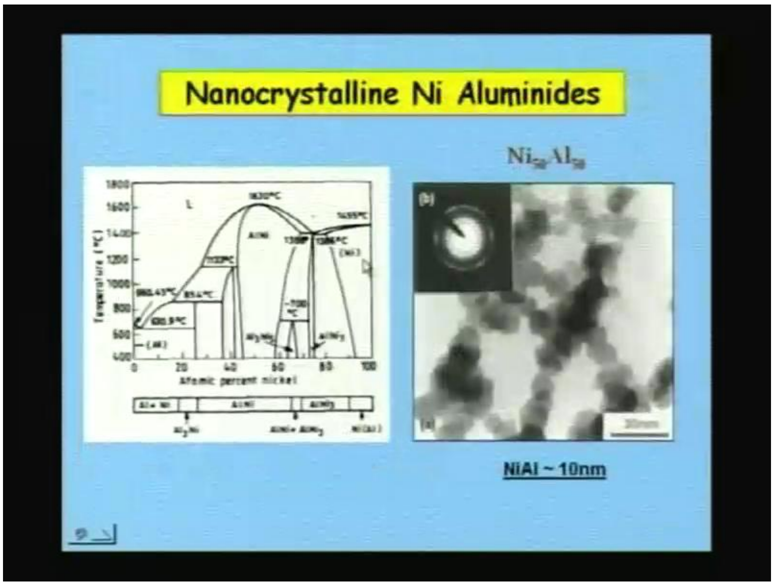

Nanocrystalline Ni Aluminides

$Ni_{50}Al_{50}$

NiAl ~ 10nm

Another possibility in these is to produce intermetallics. We have talked about so far composites, nano composites. One can also make nano crystalline single phase intermetallics, which can be useful for high temperature applications, when people want to look for high strengths at high temperature. Where, at the same time, you may say, how do we use nano materials at high temperature? Because nano materials usually grow at high temperatures.

So, one has to consider, how to control the growth of these nano grains, the grain coursing has to be controlled. So, one can controlled the grain coarsening, one can definitely achieve high strengths at high temperatures in these intermetallics. And these intermetallics, one more important point that you have note down is that. It is very difficult to make them by normal conventional route.

Because, I told you most of these intermetallics have very limited composition ranges. And one of the element has much lower melting point aluminium, the other element has much higher melting point. So, when you try to melt them together, before one of the elements starts melting. You may start seeing some evaporation of the second element and because of which, you lose lot of element.

So, one has to consider these loses and add additional excess element of aluminium. So, that, you can maintain this composition. So, maintaining the composition is very crucial in this kind of melting practice, where one of the elements has much higher melting pointing than the other. So, when the melting point difference between the 2 is largely different. It is very difficult to use liquid metallurgy route to make alloys.

And that is where, this kind of mechanical alloying, becomes very useful. Where, you can take the two elements and mix them together and do ball milling and produce nano crystalline intermetallics, such as, nickel aluminides shown here. Over, wide composition ranges, for example, Ni, Al, you can make only from 45 to 55 composition range parentage nickel in the equilibrium phase diagram. Whereas, one can produce from 25 percent to 65 percent, if you goes by this kind of non equilibrium processing route.

Whether it is a rapid solidification is mechanical alloying mechanical, alloying definitely gives you much wider composition ranges. And similarly Al Ni, Al 3, Ni which is a line compound here, can be made over a range of composition again by this mechanical alloying process. So, one can make this thing over wide composition ranges in a nano crystalline form, as you can see here, very fine grain sizes. And one can use them, for any application of interest.

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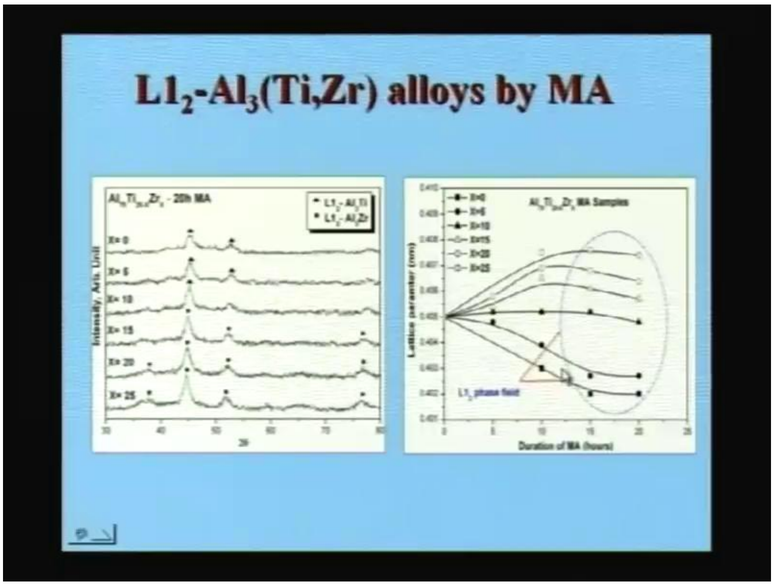

$L1_2$-Al_3(Ti,Zr) alloys by MA

Another intermetallics that can also be produced is the Al 3 Ti, Al 3, Z r. Particularly, the L 12 type of compound, as I told you before, Al 3, Ti and Al 3, Z r; usually exist in the body centered tetragonal form. BCT type of compound and BCT type of compounds are more brittle. So, as a result, people wanted to make the cubic type of compounds by modifying the structure form the tetragonal to the cubic form.

And to do that people have done lot of process, one is what, I told you before, probably rapid solidification processing, where you can suppress the BCT to nucleate. And so that, the FCC can easily nucleate. FCC is a simpler structure, which can nucleate much more easily. Other possibility is to add certain alloying elements, which can stabilize the FCC structure, rather than the BCT type of structure. Such as, chromium, manganese, copper, nickel a number of these elements have a tendency to stabilize the L 12 phase.

So, that is one possibility, another possibility is to go through a process, such as, mechanical alloying, where one can easily produce these compounds. So, I told you in mechanical alloying the phases that comes out are always those with lower interfacial energy. So, and high symmetry element structures, such as, the cubic structures. High symmetry structures always have much lower interfacial energy. So, cubic structure can form much more easily.

So, you can see here, that if I take aluminium titanium zirconium type of a ternary mixture 75 percent aluminium, 25 minus x and zirconium x. So, keep on varying the amount of zirconium. So, when zirconium is 0, it is Al 3, Ti, when the zirconium is 25, it is Al 3, Z r. So, you are changing the composition in such a way, that you have all these ternary compound.

And in all the cases, you get the L 12 phase, after certain time of milling this is 20 hours. And here, we show you that lattice parameter, how does it change as a function of time for different compositions. You can see that, if the composition is less than about 15 percent. The lattice parameter decreases. That means, when titanium goes into aluminium, when the percentage zirconium is less than 10; that means, you are basically on the Al 3, Ti side, zirconium is low, titanium is more.

So, when the titanium is more and zirconium is low, you are on the Al 3, Ti side of the phase diagram. So, if you are on the Al 3, Ti side, you will see the effect of titanium here into that. So, as titanium goes into the aluminium, the lattice parameter decreases and beyond the certain time, it stabilizes and that is where the Al 3, Ti forms. So, after about 15 hours of milling Al 3, Ti forms and the lattice parameter get stabilized.

And if you use higher amount of zirconium, you see zirconium is a much bigger atom. And when a bigger atom goes into aluminium, then you will see that the lattice parameter increases and that is what you see here. And when you add some combination, proper combination of titanium and zirconium, the lattice parameter does not change much at all. And this lattice parameter is what, the starting lattice parameter is a lattice parameter of aluminium, we are talking about.

So, that means, the intermetallics compound that you are making has exactly the same lattice parameter, as that of the aluminium. And this is very crucial, when you want to make nano composites. If you want to make a nano composite of aluminium and Al 3, Z r or Al 3, Ti. If you can take a proper combination of a titanium and zirconium and make Al 3, Ti Z r kind of L 12 compound.

Now, you have an FCC compound, in FCC matrix, whose lattice parameters are exactly similar. So, you have matrix, whose lattice parameter is same as that of intermetallics compound. And if you have that kind of a situation, you have prefect coherent precipitate possible. Because, as I told you, when you want to have coherent or semi coherent precipitate, what you need is that, the misfit should as small as possible. The lattice parameter, difference between the matrix and precipitates should be minimizing. And if that is small, then you can have a, what are called the coherent precipitates or semi coherent precipitates.

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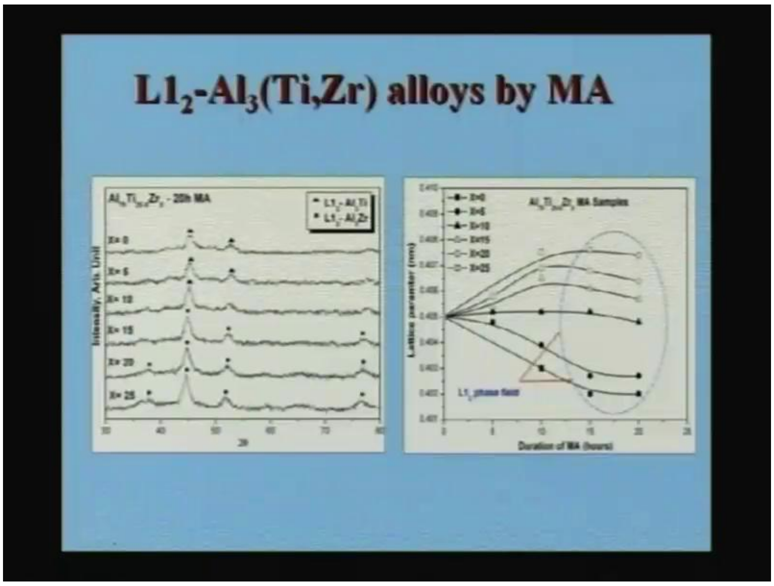

L1$_2$-Al$_3$(Ti,Zr) alloys by MA

And this is, one way a to engineer or the tailor, the lattice parameter of the compound, such that, the lattice parameter of the compound becomes close to the lattice parameter of the matrix. So, with this kind of the possibility, people have been able to make nano composites with different amounts of titanium and zirconium into it. So, that one can make Al 3, Z r Ti, kind of ternary compound, which is the cubic structure in an aluminium matrix, which has again a cubic structure. The only difference is one is ordered cubic, another is a disordered cubic, that is only difference.

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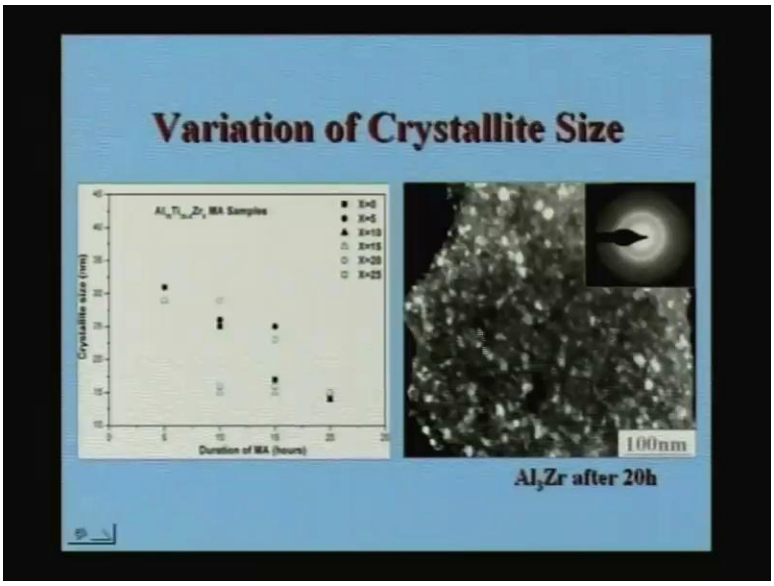

Variation of Crystallite Size

Al_3Zr after 20h

And these are all in the nano crystalline form, one can easily see, very fine crystals of the order of around 10 to 20 nano meters. This is a dark field image in an electron microscope. And you can see, these rings, the sharp rings, clearly indicate that, it is a nano crystalline. So, you can see, that in electron diffraction, always, whenever you get a sharp ring, it means, it is a nano crystalline.

So, from these, one can calculate the lattice parameters on the diameter of the rings and the D spacing first and from D spacing, one can calculate the lattice parameter. And it is also important to note, that the crystallites size of the compound also decreases, with increasing mechanical alloying time. And once, you reach about 20 hours, you have about 50 nano meters or so. So, the crystallite size is again function of the time of milling and it also function of the percentage of zirconium. So, the higher amount of zirconium, you get a lower crystallite size.

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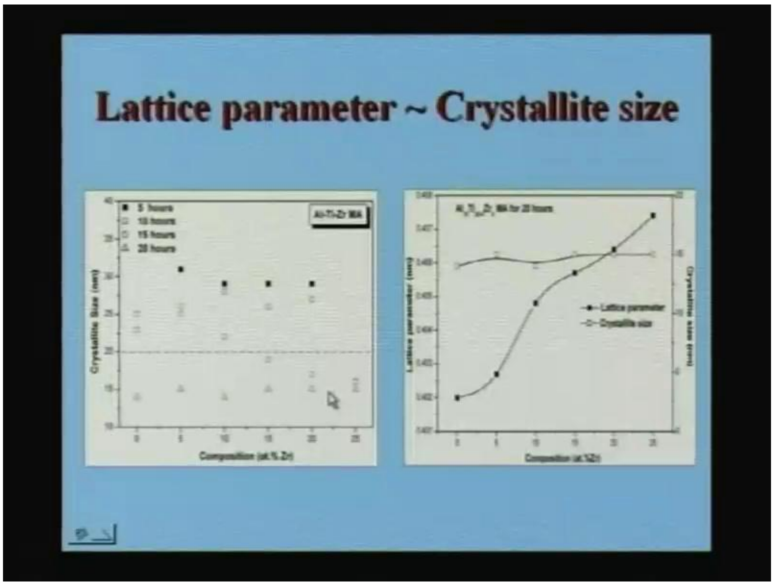

Lattice parameter ~ Crystallite size

And what is also important is that, the formation of these compounds again, occurs below a certain crystallite size. If you plot the crystallite size, as a function of the composition of zirconium, with different amount of zirconium try to look at, what time the inter metallic is forming. And look at the crystallite size at each of those times, this all, for example, different symbols here, show you different crystallite sizes at different ball milling time.

And if you look at that, once you reach below 20 nano meters, that is the time, at which the formation of intermetallics occurs. So, below above a 20 nano meters, the ordered compounds form. So, as you have seen before also, in case of Ni Al also or Al 3, Ni also, we have seen, that below a certain crystallite size, the compounds form. Exactly, similarly here also below a certain crystallite size all the compounds form.

And this is again the lattice parameter and crystallite size. Crystallite size, after 20 hours of milling is more or less constant in all the compositions. You can reach almost about 15 nano meters, you can see on the right side crystallite size is plotted. So, the crystallite size is more or less constant and the lattice parameter keeps on increasing as a function of composition.

And zirconium rich compositions have high lattice parameters; zirconium poor compositions have low lattice parameter. And somewhere in the middle, the lattice parameter is very close to that of the pure aluminium lattice parameter.

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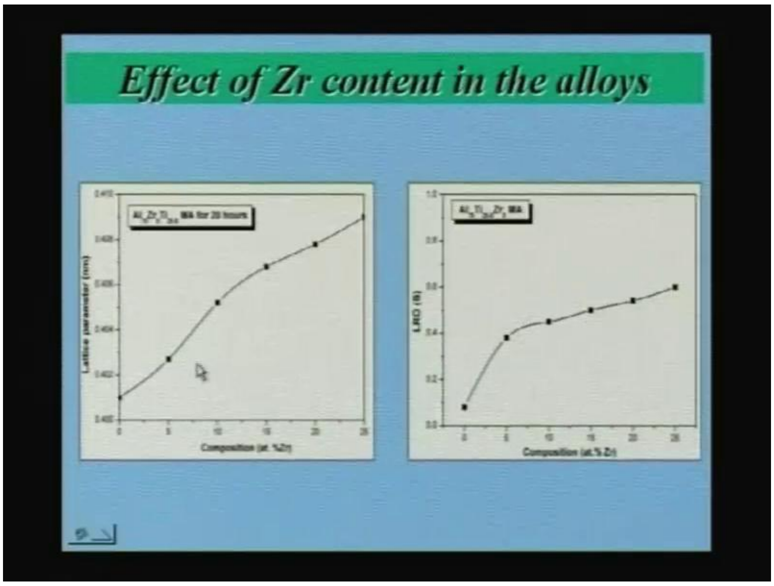

Effect of Zr content in the alloys

And this is again showing the lattice parameter as a function of a composition and L R O, this is another important parameter, what is called long range order parameter. So, how ordered the compound is. So, the order parameter of compound keeps on increasing with amount of zirconium. So, zirconium rich compounds are more ordered than the titanium rich compounds, because titanium Al 3, Ti has a lower ordering energy than Al 3, Z r.

So, as a result, Al 3, Ti can become more easily disordered, when compare to Al 3, Z r. So, Al 3, Z r is at one point, you have to always remember is these are all in the mechanically alloyed condition. When you mechanically alloy, you are always introducing lot of defects into the system. When you are introducing the defects into the system, the order parameter cannot become equal to 1.

Order parameter of 1, means what, it is completely ordered, order parameter of 0 means, it is completely disordered. So, from this, you can see that, even with single phase Al 3, Z r with 25 percent zirconium inte. The ordered parameter is only 0.6; that means, it is only 60 percent order, 40 percent disorder is still there inside it. And where is this 40 percent disorder coming from? It is coming from the defects, that you are putting into the crystal.

Because, of the high intensity ball milling that you are doing putting in and because of that lot of defects are generated. And but, what is important is under the same milling conditions, the Al 3, Ti has much lower order parameter, it is 0.1 or so. Whereas, with Al 3, Z r composition, it is 0.6. So, you can that from that, you all can easily see that Al 3, Ti becomes disordered much more easily than Al 3, Z r. This is again related to thermodynamics, that the ordering energy of Al 3, Ti is much lower than the ordering energy for Al 3, Z r.

And with this, we will stop as per as aluminium alloys are concerned. And now, let us go into the titanium based alloys. Titanium based alloys have been quite popular in recent years. Particularly, as an alternative to aluminium based alloys, why because titanium is also a low density metal, similar to aluminium, not as low density as aluminium. What is the density of titanium, anybody knows, it is 4.5, what is the density of aluminium? 2.7.

So, at least aluminium, you know. So, aluminium is 2.7 and magnesium is much lower. So, magnesium alloys are much more attractive, but there are problems, why?

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Corrosion problem and most important thing is the structure. Look at the structure of magnesium and look at the structure of aluminium. Aluminium is FCC magnesium is…

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HCP, HCP metals are not easily formable like FCC metals. That is why, if you want to use a magnesium base alloy. So, it is formability is much lower than, because the number clip systems are much lower, we all know this. So, as a result, magnesium alloys will not have easy formability. And also, magnesium has a lower melting point than aluminium. So, because it has a lower melting point than aluminium, so it is creep resistance is also lower than aluminium.

So, as a result, you cannot use magnesium alloy to high temperatures, aluminium. Also, we can use, but the temperature capability of magnesium is definitely lower than that of the aluminium, because the melting point itself is lower. So, there are two disadvantages, particularly with magnesium alloys. One is the low melting point, second is structure being HCP and third point, which Ravindra has pointed out, that corrosion problem and it is reactivity.

Magnesium is much more reactive. In fact, melting and casting of magnesium alloys is much more difficult than aluminium. Aluminium can be easily melted and casted. Because, magnesium caches fire very easily, so you cannot melt and cast. So, easily for example, Muthu is struggling to make magnesium base alloys. So, you know that, magnesium based alloys are not very easy.

So, that is why, people started looking for other alternatives to aluminium. And definitely, it is very difficult to find out metals, which are much lower density than magnesium aluminium. So, people started looking for slightly higher density. At the same time, strong alloys and useful alloys, that is where titanium comes into picture. Titanium has density of about 4.5 and so obliviously, it is almost somewhere in the middle between aluminium alloys and steels.

Steels, what is a approximate density, 7.8 is for iron, so most of the steels depending on alloying elements changes of course. So, around 7.5 to 8, let say is the density of steels, one can take it and so, this is a titanium is somewhere in the middle. So, density wise it has an advantage. It has good corrosion resistance; it is melting point is very high. What is a melting point of titanium, it is 1670, 1668 to be exact.

So, 1668 is much higher than even iron, iron is 1535. So, it is have a higher melting point than iron. So, definitely it is very attractive and more important thing is that, it has an allotropic transition.

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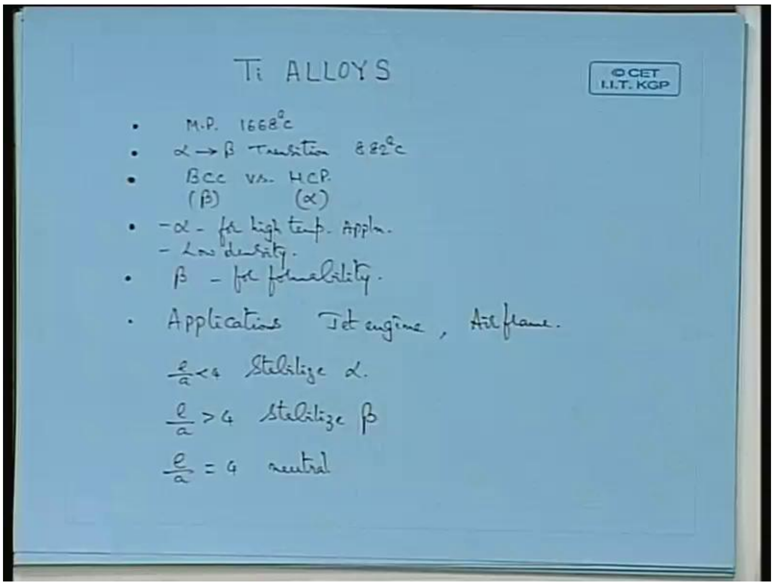

Ti ALLOYS

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- M.P. 1668°C
- $\alpha \rightarrow \beta$ Transition 882°C
- BCC vs. HCP
  (β) (α)
- $-\alpha$ - for high temp. Appln.
  - Low density.
- β - for formability.
- Applications Jet engine, Air frame.

$\frac{e}{a} < 4$ Stabilize α.

$\frac{e}{a} > 4$ Stabilize β

$\frac{e}{a} = 4$ neutral

If you look at here, titanium has an allotropic transition from alpha to beta at about 882 degree centigrade. The low temperature form is called alpha, what is the structure of that, it is HCP, alpha is HCP. So, titanium at room temperature is HCP and titanium at high temperature, beyond 882 is BCC beta. So, once you have an allotropic transition, there is a lot of advantage and that is a basic advantage of steels.

Why steels have become so popular, among all the alloys, is just because of this allotropic transition. The moment you have an allotropic transition, you can heat treat it. If you do not have an allotropic transition, aluminium, pure aluminium, pure copper, you cannot do any heat treatment. So, strengthening is limited in metals without any allotropic transition.

Aluminium can be strengthening only by putting some precipitation to it. You can do some, what is called solid solution strengthening, you can do, what is called strain hardening, nothing beyond that. And the amount of strengthening that you can achieve by both solid solution strengthening and strain hardening is not very high. And precipitation hardening, that is why one of the rules people use.

So, if you one can heat treat the alloy and produce different morphologies of the second phase, one can have much higher strengthening possibilities. So, that is where, the titanium alloys are similar to aluminium alloys. That is why people a similar to iron base alloys. That is why people call titanium as the iron of non ferrous metals, because it is almost like iron.

That, whatever, you can do for example, you can have paralite in titanium base alloys, and you can have binary type of structures. You can have a martensite take the high temperature BCC alloy, quench it, you have a martensite. And take the martensite, start tempering it, you can have all kind of tempered structures, whatever you generate in steels.

So, similarly, you can have the second phase with different sizes. The one can vary the size of the precipitates sizes by controlling the cooling rate, annealing, normalizing, all kinds of things that can do with steels, exactly you can do with titanium base alloys. So, that is why, titanium base alloys has become very popular. But, there are limitations with both alpha and beta, what are the limitations of alpha. Formability is the limitation, because it is hexagonal structure.

So, as a result, one cannot use it for highly formable type of structures. If you want to use titanium base alloys, what are the basic applications of these titanium base alloys? One is jet engines; people want to use them, by high temperature jet engines. Second is for the frame, air frame. So, if you want to use it for air frame and jet engines, the requirements are different. For jet engine, what you need is high temperature strength, for air frame, what you need is a good formability, because you have to make them into sheets.

So, definitely, one has to think of which one to be used, where. So, the alpha is a structure, which is hexagonal. So, hexagonal structure, diffusivity is much more difficult than a BCC structure, BCC is a more open structure. So, diffusion can occur more easily. So, definitely, we cannot use BCC structures for high temperature application. That is why, all super alloys, look at all super alloys, nickel base super alloy, iron base super alloys, iron base super alloys.

Nobody, will use an alpha iron for a super alloy, people will always use a gamma iron, because that is a FCC structure. Similarly, the cobalt also, for cobalt base super alloys, when we come to super alloys, we will talk about those things. Cobalt also has a phase transition.

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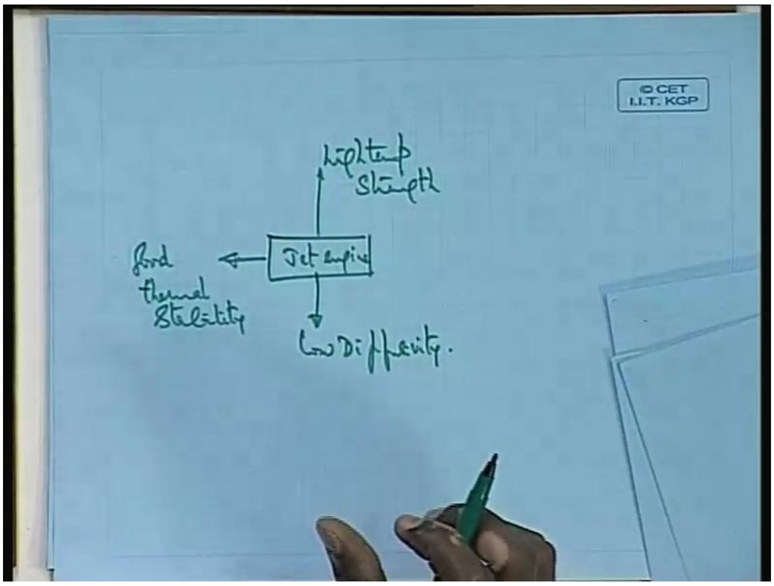

So, we use all those structure most which are more close pack structure for high temperature application. So, alphas is one, such as example, if you look at a jet engine and look at the requirements of a jet engine, if you put it as a jet engine, what are the requirements? A requirement is high temperature strength. Second is, low diffusivity. Third is good thermal stability.

Stability of the phases, what I mean is; that means the phase, which has a high temperature strength should be stable up to high temperatures. Why, this is very important, here is because there phase transition. That is possible here; alpha goes to beta at high temperatures 882 for pure titanium. So, if alpha transforms to beta, during the services.

Then, definitely you lose whatever advantage that you have as high temperature strength. So, because beta has a low has a high diffusivity, so low cri persistent, then alpha. So, if alpha transform beta during services, do not want to that happen. So, that is why, you want the transition temperature from alpha to beta to be as the higher as possible. That can be achieved by adding some alloying elements. Like, in steels we add what are called first stabilizers and gamma. Similarly here, one can add, what are called alpha stabilizers and beta stabilizers.

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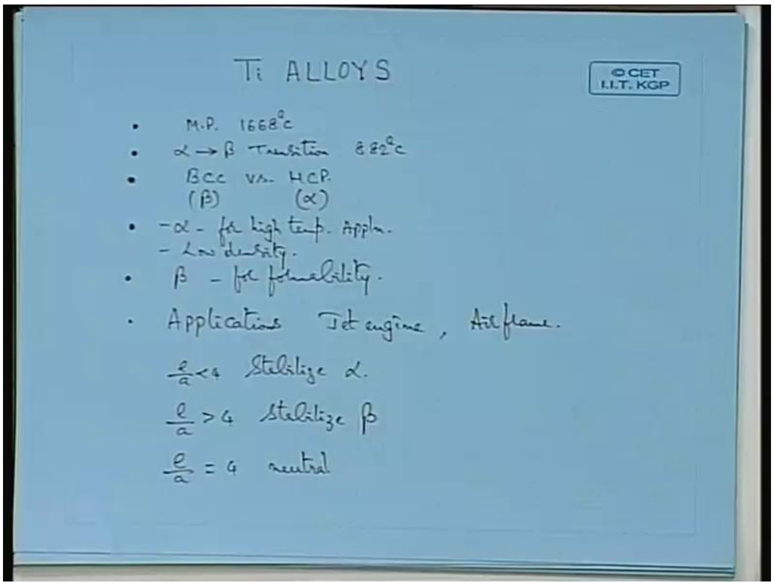

Ti ALLOYS

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- M.P. 1668°C
- $\alpha \rightarrow \beta$ Transition 882°C
- BCC vs. HCP
  (β) (α)
- $-\alpha$ - for high temp. Appln.
  - Low density.
- β - for formability.
- Applications Jet engine, Air frame.

$\frac{e}{a} < 4$ Stabilize α.

$\frac{e}{a} > 4$ Stabilize β

$\frac{e}{a} = 4$ neutral

And people have generally observed that, e by a ratio is less than 4 for any element. All those elements stabilize alpha. If the e by a, is more than 4, the stabilize beta and if it is equal to 4, they are more or less neutral. So, if you want to have alpha, so you add all those elements, which have a low e by a ratio. That means, if you want to use titanium base alloy for engines, you add all those elements, which have a lower e by a ratio. So, that you stable alpha.

And once, you stabilized alpha, then beta transmission to from alpha to beta transmission does not occur. So, is easily, so the transmission temperature can be raised. For example, you see in steels, when you add carbon to the iron, the higher the carbon; that you add, a 3 goes down and a four goes up. That means, austenite stability range increases, why, because of carbon stabilizer is austenite. So, whenever you add an element, which stabilizers a particular structure, it is phase field, enhances in that phase diagram.

If you look at carefully iron carbon diagram, with increasing carbon, that from 910, a 3 temperature keeps on coming down to 723 at 0.83, 0.8 degrees, 0.8 percent, carbon. Similarly, a 4 temperature goes up. A 4 temperature is the temperature, where the gamma transforms to delta that temperature also goes up. So, you can have a much wider phase field. So, exactly, similarly, people have added various elements.

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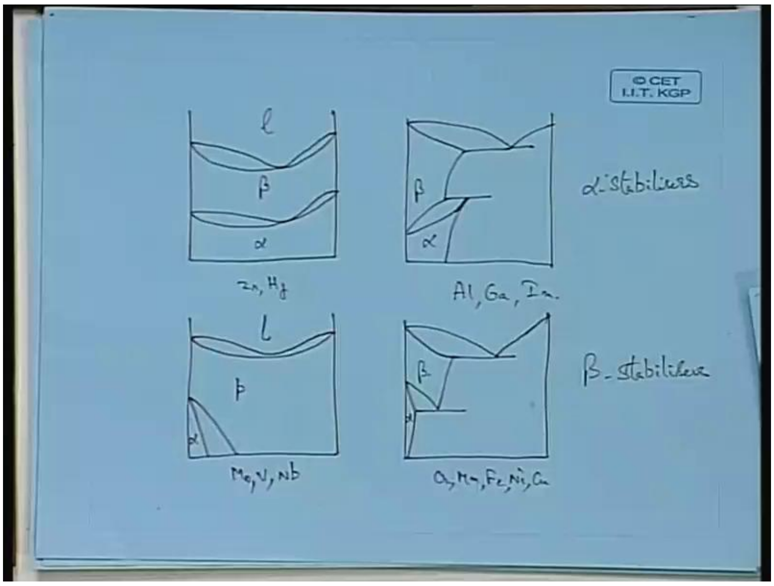

And when you add various elements, you get a various types of phase diagrams. These are the some phase diagrams that you get. When you add alpha stabilizers, one possible type of phase diagram is this. You have an isomorphous, liquid transforms to beta and again betas transforms to alpha. And you have a single phase alpha, for the whole composition range from one end to the other end.

And that you get a add elements, such as zirconium and hafnium, zirconium and hafnium are isomorphous with the titanium, where there crystal structure are exactly similar. And there the atomic sizes are similar, this satisfies all those Hume Rothery rules, so you get isomorphous phase diagrams. And if you add other elements, such as aluminium, gallium, indium, this kind of elements and also, what are called the interstitial elements. Such as, oxygen, carbon, nitrogen, this kind of interstitial elements, they also stabilized alpha.

And when, you add this kind of elements, you get a different type of phase diagram, where an alpha is stabilized. How do you know alpha is stabilized from this phase diagram, we can see that alpha to betas transition temperature, which is given by this line is going up with increasing amount of the stabilizer. And this temperature is also going up. That means, the alpha transforms to beta at a higher temperature, when you add an element which stabilizes an alpha.

And so, one has to look at this two temperature, which are called alpha beta trances temperature. And at when, you do at add any element this is equal to 882, for pure titanium. And when you add an element, it increases beyond and that is what is alpha stabilizer. And what are beta stabilizers, you can come here beta stabilizers some of them are like this, molybdenum, vanadium, niobium, have you seen any phase diagram like this is in a iron base alloys, steels.

Exactly, similar phase diagram, there is one or two elements, which gives you like that. When you add an element to iron, you get exactly similar phase diagram, what is that? Manganese, nickel, which are austenite stabilizers. There the high temperatures phases not beta, it is gamma. So, if you add some amount of, in fact, if you add more than 8 percent, that is what is austenitic stainless steel, when you add more than 8 percent of a nickel, you have single phase, gamma at room temperature. That is why; austenitic stainless steel is austenite, even at room temperature. You are bringing down the temperature of a 3 up to room temperature. This is nothing but, a 3 temperature for you in the steels. So, you are bringing down a 3 temperature to room temperature by just adding 8 percent of nickel. And similarly, some amount of manganese, nickel and manganese are gamma stabilizer there.

So, similarly here, beta stabilizers can be added. Where, the beta to alphas transition temperature can be brought down. Here, in case of alpha stabilizer the transition temperature is increasing. In the case of beta stabilizer, the transition temperature is decreasing and you get an element such as molybdenum, vanadium and niobium, give you this kind of phase diagram.

Where you have completely beta beyond a certain amount of molybdenum vanadium niobium and you can see all these are BCC elements. We always know that, when you add a BCC elements, BCC’s face get stabilize. This is a typical understanding of all of us. So, that is molybdenum, vanadium, niobium they all stabilize that. And coming to other type of elements, other transition metals, they do not give this much stability.

But, definitely, they give you a stable resume; again you can see transition temperature here decreases. Here also, the transition temperature is decreasing and you get tick toyed type of phase diagram. And in fact, this type of phase diagrams are more useful then this type of phase diagram. If you have this type of phase diagram, beyond certain amount, you cannot do any heat treatment. These are all non heat treatable alloys, only below this, you can do heat treatment.

And there also, you can have beta to alpha transition, nothing more than that. Whereas, as if you have eutectoid transformation, then one can have beta giving you alpha plus some other second phase. And one can control the morphology of this, one can have lamellar, one can have whatever type of a possibility like paralite, binite. All kind of micro structures possible, whenever you have a eutectoid type phase diagram, that is why all these elements are very use full to give you eutectoid transformation. But, there is certain limitations, as per as the addition of these elements are concerned. Because to have two much of element, some inter metallic comes in to picture, one such thing is with alpha stabilizers.

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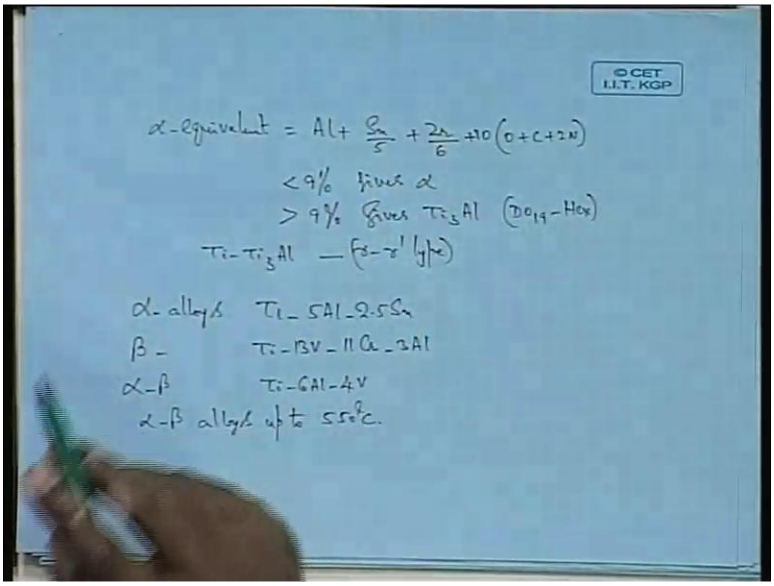

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α-equivalent $= Al + \frac{Sn}{5} + \frac{Zr}{6} + 10(O + C + 2N)$

$< 9\%$ gives α

$> 9\%$ gives Ti_3Al (DO_{19}-Hex)

$Ti-Ti_3Al$ — ($\gamma-\gamma'$ type)

α-alloys Ti-5Al-2.5Sn

β- Ti-13V-11Cr-3Al

$\alpha-\beta$ Ti-6Al-4V

$\alpha-\beta$ alloys up to 550°C.

When you add two much of alpha stabilizers, for examples, there is something called alpha equivalent. If you remember a similar equivalent, we here in iron carbon alloys, carbon equivalent, in case of cast iron. When you have a carbon equivalent more than some amount, you get a gray cast iron. If the carbon equivalent is less, you get white cast iron, because carbon is a graphite stabilizer there.

So, whenever you add high amount of carbon, silicon is also a graphite stabilizer. So, because of that silicon also comes in to the carbon equivalent as a positive quantity. But, other elements, which take out carbon and form, inter metallics, such as chromium, molybdenum, vanadium. All those things go as negative values into the carbon equivalent, if you remember your cast irons part.

So, similarly here, there are, what are called alpha equivalents. So, aluminium is an alpha stabilizer, tin is a alpha stabilizer, zirconium is an alpha stabilizer. All these alpha stabilizer plus the interstitial elements, such as, oxygen carbon nitrogen. All of them come into this. And if this carbon equivalent alpha equivalent, sorry, I should not call carbon equivalent. So, if the alpha equivalent is less than 9 percent, you can get alpha.

If it is more, then you end up in a compound called Ti 3 Al and Ti 3 Al is an ordered compound with a D O 19 type of structure, which is basically a hexagonal type of structure and a high melting compound. So, but the only problem is, it is formability is poor. So, if you want more formability into your alloy, do not add large quantities of these alloying elements to end up in this Ti 3 Al.

But, at the same time an inter metallic with a high melting point and an ordered structure, if it is present in a matrix of metal, you will definitely get much higher strength. So, that is why, you can think of an alpha matrix, with particles of Ti 3 Al to get you much higher strength. And this situation is exactly similar to our nickel base super alloys, where you have gamma, gamma prime, we say where you have an FCC matrix, which is nickel base solid solution and what is the precipitate there, Ni 3 Al, Ni 3 Al is an ordered FCC, L 12 structure. And that gives you much higher strength and similar micro structure, we have seen in aluminium base alloys, what is that, exactly similar structure. We have seen in aluminium alloys, I have taught you in the last 2, 3 classes, aluminium Al 3, Li alloy.

You have a aluminium matrix Al 3, Li, which is again an ordered FCC structure. So, you have an FCC matrix and ordered FCC particles in a matrix. And that is also gives you a good formability and at same time, good ductility. Another possibility is what I told you is the another alloy, which is again a similar situation with an FCC matrix. And ordered FCC particles, what is that, again aluminium base Al 3, Ti, ordered Al 3, Ti, which is a L 12 structure.

If we can convert the D O 22 structure or D o 21 structure of Al 3, Ti and Al 3, Z r into an L 12 structure from the tetragonal to cubic structure, which we have shown examples of it. Again, you have an ordered structure of a cubic structure ordered particles in a disordered cubic matrix. So, all these are examples, which are similar to the gamma, gamma prime type of nickel base super alloys and you can get much higher strength.

Only thing is here, because the hexagonal matrix is there and ordered hexagonal particles the formability here is not very high. One has to remember that, but one can use this. And when we think of the alloys that are possible, there are alpha alloys, which are basically stabilized by alpha stabilizers aluminium and tin. 5 percent aluminium, 2.5 percent tin is a typical example of an alpha alloy.

And beta alloys, which give or stabilized by beta stabilizing elements, such as, vanadium, chromium and you also add a small amount of aluminium, why do we add this, is because most of the beta stabilizers. Interestingly, if you look at it, they are all having high densities. So, because of which beta alloys are heavier alloys, when compared to alpha alloys.

Alpha is stabilized by aluminium interstitial elements tin this kind of elements. Because, of which the alpha alloys are low dense alloys. So, because you are all adding elements which have a lower density, so the overall alloys, having a low density. So, that is why, these are the alloys which are for high temperature applications and at the same time less density, whereas the beta alloys, because you are adding elements which have high densities.

So, because of which the overall alloy becomes dense. Then, we can have alpha beta alloys, where you can have a combination of alpha stabilizer and a beta stabilizer. The most popular alloy is titanium 6, aluminium 4, vanadium. But, there are limitations again the alpha beta alloys cannot be used for high temperature applications. One has to control that. And in this alpha, beta alloys, one can control the properties by controlling the micro structure. We will talk about this in the next class, how to control the micro structure to control the properties in these alloys.