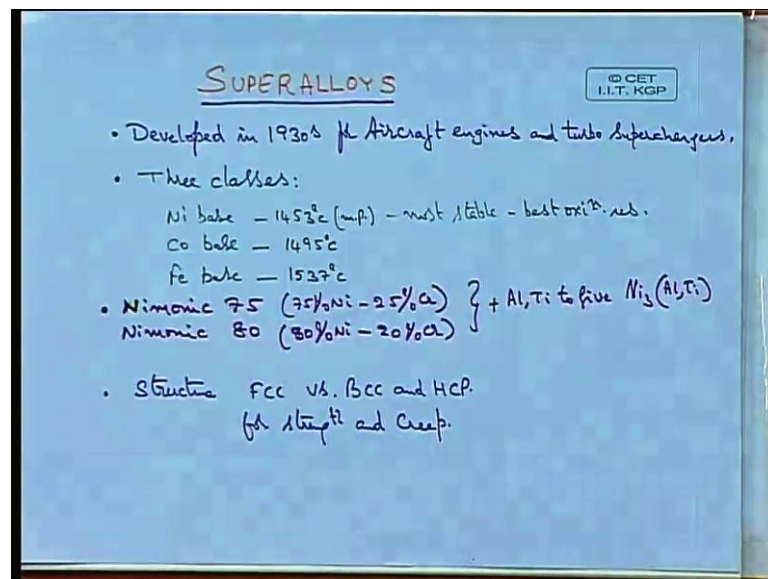


Advanced Materials and Processes
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Lecture - 24
Strengthening Mechanisms Part – I

You can have sufficient time to prepare for the other subjects or for the subject itself. We start as I mentioned in the last class. We have discussed a number of a strengthening mechanisms, which are crucial as for as super alloys are concerned. Super alloys you all are aware are basically high temperature alloys, which have been developed mainly for aircraft engines and turbo superchargers, where people wanted a material to be strong at high temperatures. And we know there are number of mechanisms by now we have already seen a number of strengthening mechanisms, how to make a material stronger at high temperatures.

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So, if you try to look at, how these super alloys have developed? It was basically in 1930s after the First World War. When people realized that the strength basically lies not in just land based fighting, but if somebody has an air supremacy. He would be superior than the other party who is basically strong only on the land.

So, people wanted to develop aircrafts that can go much faster not just a passenger aircrafts. But the aircrafts which are military aircrafts which can go faster and at the same time deliver whatever ammunition you want to drop on some other country. And then come back very fast without being traced by your enemy. So, for that what you need is high speeds when you think of high speeds. The turbine which is basically most of these aircrafts run with the turbines the gas turbines.

And these gas turbines, the moment you want to use high temperature, the gas turbine. You know usually the efficiency of a turbine gas turbine. I think all of you must have gone through Carnot cycle. So, what is how do you define the efficiency of a Carnot cycle?

Student: It is $\frac{t_2 - t_1}{t_2}$.

It is basically $\frac{t_2 - t_1}{t_2}$; that means, the inlet temperature minus the outlet temperature divided by the inlet temperature that is the efficiency of a Carnot cycle.

So, if you think of such a situation. So, if you take what is the inlet temperature of the gas in a turbine, gas turbine and what is the outlet temperature. So, that is why they want to keep the outlet temperature as low as possible. So; that means, it has to be cooled by the time it comes out of the gas turbine. So, that the t_1 is very low and the t_2 has to be as high as possible. So, that is when you can achieve a in principle if you want to achieve 100 percent efficiency t_1 has to be 0.

If t_1 is 0, then $\frac{t_2 - t_1}{t_2}$ will become equivalent 1. So, that is what is the best most efficient Carnot cycle for you, but it is more or less next to impossible to have t_1 as 0. Because thinking of gases which are coming in at very high temperatures of the order of 800 900 degrees centigrade or sometimes even people nowadays use even 1110 degrees centigrade. So, at such high temperatures the gases are coming.

You want to cool them by the time they come out of the engine to room temperature or to 0 degrees is almost next to impossible. So as a result, you lose some thermal energy in terms of the outgoing gases. So, that is how the efficiency of the engine comes down. So, but what is more crucial as a metallurgist for us is not just this part of efficiency, which a mechanical engineer is more worried about. But if you want to achieve this efficiency a

mechanical engineer always wants to think that how do I bring down t_1 and how do I take up the t_2 .

If you want to take up the t_2 , he has no problem he will put more efficient fuels which have high calorific value and then create a higher energy. And then try to inlet those gases at very high energies into the gas turbines. But the problem lies there, because if you are introducing gases at very high energy. The gas turbine material that we are going to use should be able to take up those high temperatures.

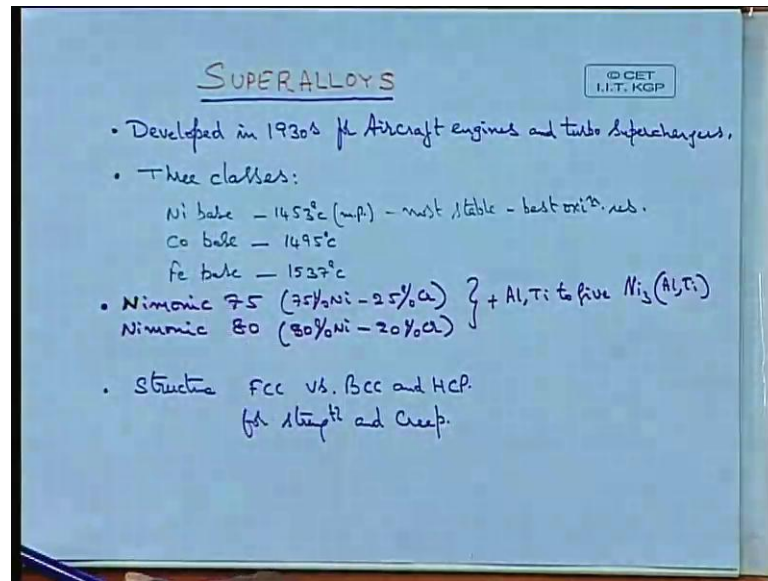
Instead of failing at those temperatures and we all know that metals in general lose their strength as we take to higher and higher temperatures. The yield strength of a material keeps on decreasing as we go to higher and higher temperature. So how do, we really make materials which are metallic steel. We do not want to still use ceramics, we know ceramics can handle much higher temperatures.

But the ceramics making a gas turbine blades or gas turbine nozzles, particularly they have very low thermal shock resistance. Most of the ceramics have very low thermal shock resistance they are brittle. So, because of which we cannot really form them into a particular shape of interest. And then retain them without breaking because of the thermal shocks that are involved, because the gas comes at high temperature and goes out at low temperature.

So, because of which there are temperature differences that are involved and because of which we do not want to use ceramics. So, if the ceramics are not there; obviously, polymers cannot be used because polymers still have low temperature capabilities. The only thing that is left out for us is metals. So, which kind of metals we should use to be able to be stable at these high temperatures, that is when in 1930's people have come out with what are these called super alloys.

They started calling them as super alloys, because they behave really like a super man at very high temperatures. They were being able to be strong enough without failing without being very ductile and having very high creep resistance. Because, we all know at high temperature the deformation mechanism is creep. So, we want materials which have very high creep resistance that is where three classes of super alloys people have developed.

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If you look at these three classes, one is a nickel base, super alloys cobalt base iron base. If you look at all three of them, the melting points are given here. 1450 approximately for nickel base about 1510 for cobalt base 1495 to be exact. And the iron base we all know iron carbon diagram we are all aware from the beginning. So, it is about 1535 or 1537 approximately around 1535. So, if you look at all these three, they are all high melting when we compare with a typical aluminium base alloys that we have discussed so far.

So definitely, these are high temperature alloys, but at the same time not as high as a tungsten or molybdenum. You may ask me why cannot, we use tungsten or molybdenum. They have much higher melting points, but we are trying to use these low melting. In comparison to tungsten definitely a nickel is much low melting because tungsten what is the melting point 3400 approximately.

He knows it exactly because he works once on that. So, what is it exactly 3420, 3420. You compare 1400 and 50 of nickel which is even less than 0.5 of the melting point of tungsten. But we do not use tungsten as

Student: ((Refer Time: 08:51))

Not that...

Student: ((Refer Time: 08:56))

Creep basically somebody has answered this question. The structure that is crucial when you want to use it for high temperature applications.

So, the common thread between all these three, if you carefully observe. The common thread is all of them have FCC at some temperature. They are not completely FCC at all temperatures, if you carefully observe nickel is definitely FCC at all temperatures. It melts as an FCC phase starting from room temperature up to melting point it has no allotropic transition excepting in that in recent years people who have been working on nano materials.

They start seeing that once you take nickel into nano crystalline state. It changes its structure from FCC to HCP, a number of people have shown. And in addition, if you put high pressures under high pressures there is a possibility of FCC nickel changing into HCP nickel. Because phase diagrams change, once you incorporate pressure into it. Because, we most of the time when we talk of phase diagrams. They are all at atmospheric pressure we do not bring in the third dimension which is the pressure.

So because, we know the free energies is controlled by temperature pressure and composition, whereas, in most of the phase diagrams that we deal with. We take what are called condensed phase diagrams where the pressure is at atmospheric pressure. So, if you increase the pressure, there is a possibility of nickel going to HCP. But, that is not of importance to us because most of our work is related to atmospheric pressure.

So, forgetting that particular special cases, where FCC changes to HCP. Otherwise nickel is FCC. Then come to cobalt, cobalt is what is its structure at room temperature? Cobalt is hexagonal HCP at room temperature and changes to FCC about 450 degrees centigrade. So, it is again FCC at high temperature and melts as an FCC phase. And take again iron about 450, 450 is a transition temperature to be exactly I think it is about 451.

So at high temperature, we have basically again an FCC phase there. Then look at again iron, iron is basically a BCC at room temperature. And we know it transforms to gamma phase FCC at what temperature 910 degrees. And this FCC phase is again stable up to 1400 and at which it again transforms to the BCC. So, there is a range of temperature 910 to 1400, where we know FCC is very stable.

And in addition, we also know that one can add alloying elements which can increase this temperature range of stability of gamma, we call gamma stabilizers. As a metallurgist, who have seen the iron carbon diagram in detail? For all these years you must have gone through all these all gamma stabilizers manganese nickel carbon. So, there are number of such gamma stabilizers.

So which can decrease, what is called the three temperature and increase the A4 temperature which is what defines the temperature range between the A3 and A4. And hence the stability of the austenite, A3 temperature is the temperature where the alpha changes to gamma and A4 temperature is where the gamma changes again to delta. So, that is the temperature range.

So, if we can add a gamma stabilizer it decreases the A3; that means, makes the austenite stable up to lower temperatures and increases the A4; that means, makes the transformation between the austenite to delta more difficult. So as a result, you can have a much wider window for the stability of gamma and that is what we have seen in a number of alloys. So, we know from our metallurgy that one can add alloying element. Similarly in cobalt, if you want FCC phase to be stable even up to room temperature.

One can add alloying elements which stabilize the FCC phase, when we are talking about titanium base alloys also. We have seen that titanium case, we have seen that low temperature phase is HCP high temperature phase is BCC. So, we know the elements which can stabilize the low temperature phase which is called alpha phase and the high temperature phase which is called beta phase. So alpha stabilizer, beta stabilizers are there in titanium base also.

So in any system, wherever there is allotropic transitions involved there are certain elements which can stabilize one of those allotropic forms. So, one can play with the stability range of these phases by just adding elements which are conducive to the stabilization of one of the particular phases. So, this is as per as the stability, but the question is, why do we want FCC, for a high temperature stability.

We have talked about it at some stage do you remember that, why is FCC crucial quite high temperature stability why not we use BCC.

Student: ((Refer Time: 14:52))

Yes, diffusivity that is crucial, high temperature for the creep the most important thing is diffusion. So, if you can have a structure where in which the atomic diffusion is very low which comes from basically from the close packing. So, if a structure is highly close packed then the diffusivities are very low. Hence the creep resistance is very high that is why we want either FCC or HCP type of structure. That is why, when we are talking about titanium base alloys.

I told you that all high temperature titanium based alloys are basically alpha alloys. So, whenever you want to use titanium base alloy for high temperature applications you stabilize alpha phase. Though, we know that alpha phase, there in titanium based alloys is HCP and its formability is poor. But still if you want to use for high temperature applications, you use only alpha based alloys.

And, if you want more formability, then you stabilize beta phase. Because there the beta phase is BCC, BCC has more number of slip systems than the HCP. So, as a result beta phase is more formable than the HCP. So that is, where you can see even in titanium based alloys. We are trying to stabilize the closed pack structure for high temperature applications exactly here the same thing holds good that. Because the FCC is more closed pack it has high temperature strength.

So, that is why most of the efforts have been towards that and that answers our questions which we have put before that why tungsten why not tungsten and molybdenum, why only nickel cobalt and iron. This is basically because of that tungsten molybdenum, vanadium, and niobium. All these elements even for that matter titanium, we do not use titanium based alloys to a temperature level to which we use these super alloys.

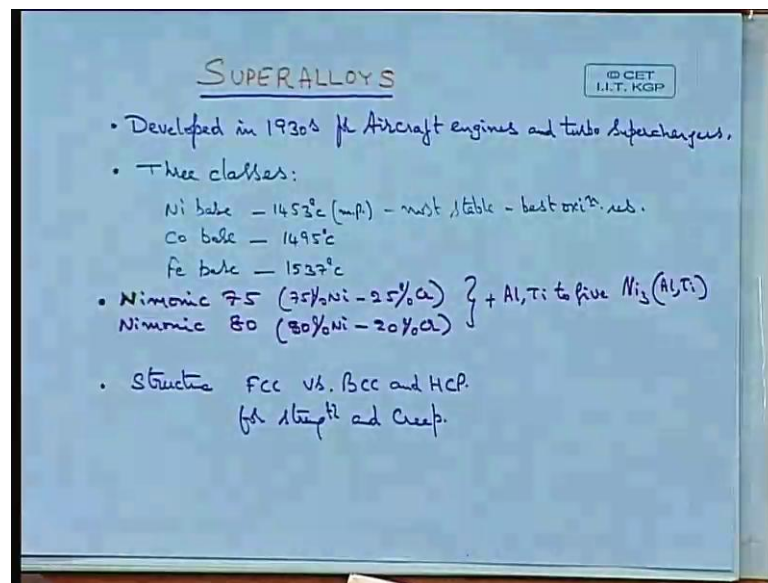
Definitely titanium based alloys are inferior to these three super alloys that we are talking about as far as their high temperature capabilities are concerned. But at the same time you will have if you consider probably the strength versus. The density levels probably titanium based alloys come more or less on par, where density becomes very important. Because, density of titanium is almost half of all these densities, because nickel cobalt iron all of them are in the range of 8 to 8.5 densities.

As we know iron is about 7.8 nickel is about 8.2 cobalt is about 8.3. So, they are all around 8, so they are heavy metals. This is one thing one has to remember. But at the same time, one has to give up something in order to gain something. So, that is what we

are trying to do here. So, titanium even though its density is 4.5 we cannot use titanium at high temperatures. Because, its HCP structure is still not as good as the FCC, FCC is a more or less isotropically close packed.

One has to remember that hexagonal structure if you see basically you have two closed pack planes. And then you have A C axis which separates these two close packed basal planes. So, one has to remember that. We will come to what are called topologically close packed structures a little later which are very similar to this type of structures.

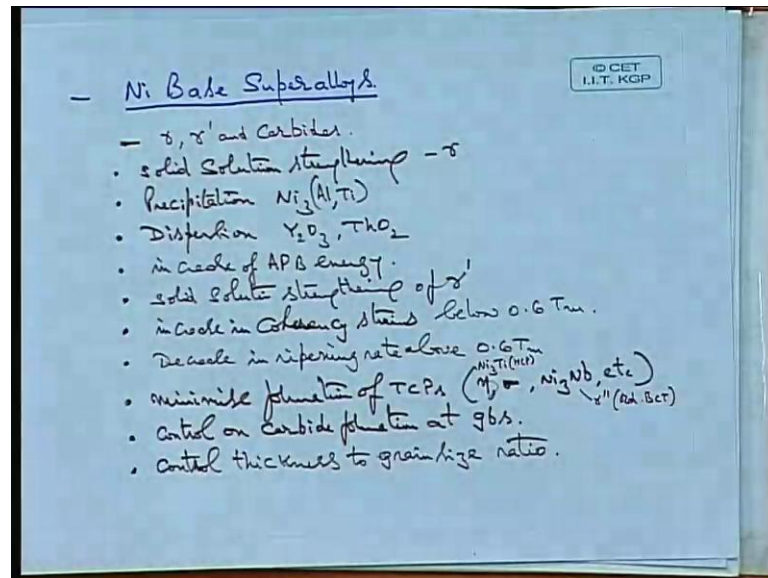
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So, the initial alloys are basically these two which are called mnemonics. Even now people use mnemonics for high temperature elements. In heating elements, this kind of structures, where it is the composition is more or less mnemonics 75 mnemonic 80 where about 75 percent nickel and about 25 percent of chromium and 80 percent nickel and 25 percent of chromium is what constitutes a mnemonic 75 or mnemonic 80 which are what are the standard heating elements which people use it.

For high temperature applications, where people add a small amount of aluminium and titanium to give some precipitation of Ni₃AlTi type of precipitates which give you strengthening. So this is, what is basically the originally developed super alloys. Later a number of other super alloys have been developed which can be classified.

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Again, as I told you as three classes we will start with the first class, what is that class that is the nickel based super alloys. Nickel based super alloys as you can see are basically they get their strength, because of three things. One the matrix which is what we call the gamma phase nickel. And, the gamma prime precipitates the precipitation strengthening and in addition some carbides.

And finally, I did not add here, you also have what are called dispersoids. The oxide dispersoids and the basic strengthening in these alloys comes by the control of a number of parameters which I mentioned here. First is solid solution strengthening; that means, we have to strengthen the matrix by adding alloying elements which give you proper strengthening to the gamma phase. So, one has to strengthen the matrix.

As we know pure metal, nickel will not have sufficient strength. So, if you add alloying elements, whose atomic size is different from that of the nickel. We can introduce some strain into the lattice which gives you solid solution strengthening. But at the same time, we also know that each element has different amount of solubility, because the atomic size difference is going to be different.

So, one has to consider what is the solubility that is possible of various elements in to it. And then, add these elements to such an extent that they give you strengthening. And we know, the strengthening that you achieve is directly proportional to...

Student: ((Refer Time: 22:09))

Yes, it is the size difference which is what we call the delta which is called size mismatch, so the strengthening that is going to be achieved.

The incremental strengthening that we are going to achieve is going to be proportional to the size factor. So, the larger the size factor the larger the strengthening. But, at the same time the other factor is also which is important which is what Ravindra has mentioned is that the amount of solute that you are going to add. The size factor is going to decide what, the amount of strengthening that you are going to achieve for 1 percent of addition of the solute.

And, the amount of the solute that we are going to add is also going to increase the strengthening. But, at the same time we also know that the solubility is indirectly proportional to the size factor is not it. So, if the size factor is very large, then the solubility is going to be low. So, one has to play with this. So, as a result if you are going to add an element with high size factor; that means, large atomic size difference with respect to nickel, then its solubility is going to be very low.

So, as a result you cannot add a large amount of that element and if you add more than that solubility limit. You are going to end up in some inter metallic compounds which might be detrimental. For example, we will come to some compounds such as Ni₃ phases which are called topologically close packed phases TCP phases which we will come to it a little later which are going to be detrimental. So, that is why one has to control the amount within what is possible.

Then, the next important thing is precipitation strengthening. The precipitations by adding elements which can go to either the nickel positions or the aluminium positions and then make the bonding between nickel and aluminium going to be stronger. If you think the compound as A₃B type of a compound, Ni₃Al is a A₃B type of a compound it has A positions and B positions, what are the A positions what is the structure of gamma prime.

Student: ((Refer Time: 24:37))

Yes, it is basically gamma prime is a face centred cubic type of a structure.

Ordered face centred cubic type of structure where one of the elements goes to the face centre and the other element goes to the body corners. So, A₃B when I say it is very easy to visualize, because there are three atoms of A and one atom of B. And in a face centred cubic type of structure the face centred positions are three atoms and body corner is one atom. So, it is very easy to understand that A goes to the face centre positions and B automatically goes to the body corners. So, that is what is a A₃B type of a structure.

So, if you add alloying elements some of them will go into the body corners, some of them will go into the face centred positions depending on whether their atomic sizes are similar to the B type of atoms or similar to A type of atoms. Depending on that they will either go to the face centre or go to the body corners. And substitutionally sit in these places; that means, some of the alloying elements which you are going to add can substitute A atoms and some will substitute B atoms.

And so you are going to get additional strengthening of gamma prime we will talk about those things also a little later. So, this is about precipitation strengthening. Then, one can also achieve dispersion strengthening; we have talked about this also, when we are talking about strengthening mechanisms. Eutectic and thoria are the most important compounds and in addition people have also tried Al₂O₃ this is other third strengthening people have tried.

Another possibility is to increase the APB energy of the compound. The gamma prime is an ordered phase we know. So, this ordered compound each ordered compound will have what is called an anti-phase boundary energy which basically is directly proportional to the bond energy or what is called the enthalpy of ordering or the energy of ordering. So, if you can increase the energy of ordering. Then the anti-phase boundary energy increases.

And, if the anti-phase boundary energy increases as I told you before whenever you want to shear the particle. It is this anti-phase boundary energy which is going to decide, what is the increment in the strength? That you are going to achieve during the shearing of the particle the higher the APB energy. The higher will be the strengthening that we can achieve. So, as a result those alloying elements which can increase the APB energy of gamma prime can give you higher strengthening.

And, I have already talked about solid solution strengthening on gamma prime. And, one can also increase the coherency strains add those alloying elements to gamma prime or gamma which can increase the coherency strains. Because, we know that gamma prime is a coherent particle. Gamma prime has it is what is called the lattice mismatch inter planar spacing very close to that of gamma. And that is why mostly the gamma prime precipitates are spherical precipitates.

We will talk to talk about the other morphology that is also possible, but mostly they are spherical precipitates with excellent coherency and which gives you a very low surface energy. So, one can increase the coherency strains by adding alloying elements either to gamma or to gamma prime which can change the inter planar spacing. And, if the inter planar spacing changes the lattice mismatch changes. And, if the lattice mismatch changes that is what is going to decide the coherency strains. The coherency strains are directly proportional to the extent of lattice mismatch is not it.

So, if the coherency strains are going to increase, then the resistance for the dislocation moment is going to increase. So, if you want to achieve additional strengthening we can achieve it by increasing the coherency strains. So, that is going to be achieved by varying the ΔA or the ΔA means what is called lattice parameter. So, lattice parameter difference of the two structures gamma and gamma prime if we can increase this ΔA . The difference between the two lattice parameters we can achieve higher coherency strains.

But, this is crucial only at low temperatures. Obviously at high temperatures the strain gets relaxed very easily. We have lattice expansions taking place and because of which the strain gets recovered very easily. So at high temperatures, the coherency strains do not really give us the strengthening. Because, at high temperatures even precipitate coarsening also occurs because of which the coherency strains are lost. So, the coherent precipitate becomes a semi coherent precipitate and then tries to become even an incoherent precipitate.

If the mismatch is very large, unfortunately and fortunately for as (Refer Slide Time: 19:52) I should fortunately the game frame the strain mismatch never goes to such a level that you get in coherent precipitates. So, will you never achieve in coherent states

in case of gamma, gamma friend kind of combination. So, always you are either coherent or semi coherent. So, will not really loose the strengthening to much this is one accept.

So, and then other aspect as a told you high temperatures is how to decrease the coarsening rate, this is crucial. And, we have talked about this earlier how to decrease the coarsening rate, we will also come to it a little later. So, this is another crucial design aspect. And then finally, one more aspect which is crucial is how to minimise the unwanted phases which are called topologically closed pack structures.

These topologically closed pack structures are structures which have closed packed planes atomic planes separated by large atoms. So, you have like a hexagonal kind of structure with two basal planes separated by each other by a large distance. And, such structures are such as theta phase which are Ni₃Ti sigma phase and Ni₃Nb which is called gamma double prime phase which is ordered BCC structure.

All these phases are structure, which are not like the gamma prime. Gamma prime is basically what we call geometrically closed pack it is closed pack in all directions. Gamma prime is basically an FCC type of a structure, any direction you look at it is closed pack whereas, hexagonal closed pack direction structures are not closed pack in the C axis. So, these are what are called topologically closed pack. They have certain closed packing in certain planes, but not in the direction perpendicular to the plane they do not have closed packing.

And, such structures are not really wanted structure at high temperature. So, that is why we want to avoid this. So, do not add high amounts of elements which can form this kind of phases. So, for example, if add large amount of titanium or niobium. We are going to end up in Ni₃Ti and Ni₃Nb which is not going to be useful for us or end the. In fact, they are going to be brittle and they are going to reduce your strengthening of your alloy.

So, another thing is the formation of carbides people also achieve strengthening because of carbides. But, one aspect one has to take control is how to control carbides at the grain boundaries. Because usually, the tendency of the carbides used to form at the grain boundaries, because grain boundaries are regions where carbon can easily segregate.

And, the carbides form very easily at the grain boundaries and making the grain boundaries brittle and that is why the people also add what we will come to them also add what are called elements which can segregate to the grain boundaries and increase the strengthening that we can achieve which is called increasing the cohesion at the grain boundaries. We will talk about those elements which go to the grain boundaries.

Then, finally controlling the thickness versus grain size ratio, if we are talking of a turbine blade having a certain thickness the thickness versus grain size ratio is very crucial, why we want for high temperature applications materials which have higher grain size. We do not want materials with very fine grain size. So, you should have a certain thickness versus grain size ratio which should be as low as possible. In fact, ideally we want the whole thickness to be one grain.

In fact, people are trying to make super alloys single crystal super alloys. People have also made single crystal gamma prime. For example, we know that there are some super alloys where the gamma prime amount of gamma prime is of the order of almost 70 percent volume fraction of the gamma prime then people thought why not make single phase gamma prime alloys. People have made single crystals of gamma prime people have also made single crystal of super alloys.

And when we when people try to make them, they have realised that particularly in case of the gamma prime. They have realised that there is some problem as far as the strengthening at the grain boundary. So, particularly when we have the gamma prime single phase gamma prime, people were unable to achieve some formability in that in them. So, because of which they try to add boron, boron goes to a grain boundary of this gamma prime.

And then, improves the cohesion at the grain boundary because the boron very small atom. So, very small atoms can easily go to the grain boundary segregate to the grain boundary and give you some strengthening at the grain boundary. We will talk about that also this are basically the design criteria as for as nickel based super alloys.

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CET
I.I.T. KGP

Stabilisers:

γ - Group V, VI, VII elements Co, Cr, Mo, W, Fe ($\delta = 2-13\%$)

γ' - Group III, IV, V elements Al, Ti, Nb, Ta, Hf ($\delta = 6-18\%$)

Carbides - Cr, Mo, W, Nb, Ta, Ti (C - 0.05-0.2%)

S.b. - B, C, N ($\delta = 21-27\%$)

10-20% Cr, 5-10% Al, Ti, 5-10% Co.

SSS

Co	Fe	Cr	V	Al	Ti	Mo	W
0.09	0.56	0.8	2.3	3.3	4.0	4.2	4.5

$\Delta\sigma$ in Kg/mm^2 Per 1%.

γ' A_3B A: Ni, Co, Fe ($(\text{Ni, Co})_3(\text{Al, Ti})$)
 B: Al, Ti, Nb
 $\delta = 0-0.2\%$ Sphers
 $0.5-1.0\%$ Cubes
 $> 1.25\%$ Plates
 $> 0.6\text{TM} \delta$ Crankshaft.

Then look at the individual accepts of the nickel based super alloys, if you look at the various phases gamma. We talked about gamma stabilisers which are the gamma stabilisers are basically the groups V group VI group VII type of elements which are cobalt chromium molybdenum tungsten iron type of elements. These are all gamma stabilisers. They go in to the gamma and stabilise the gamma and give you strengthening and the strengthening we can achieve is give here the increment in the strength.

For every 1 percent of the alloying element, that you add increases in this order cobalt is very small. Because nickel and cobalt, if you look at it they are next to each other more or less in the periodic table. So, as a result strengthening that you can achieve is not going to be very large. Because, atomic size difference is very small as I told you the strengthening solid solution strengthening basically depends on the atomic size difference. So, as the atomic size difference increases in the same order your strengthening also will increase.

So, this is what you can see tungsten gives you much more strengthening than these. But, at this same time we do not want to add large amount of tungsten, because tungsten with nickel will give you. Other type of TCP phases when you add large amount of them like Ni_3Nb Ni_3W kind of phases will come into picture when you add large amount of tungsten. So, we do not want to add. So, there is a limit to which we can add just because is giving you high strengthening we cannot add large amount of strengthening.

Then, the next important is gamma prime in the gamma prime the stabilisers are basically group III group IV and group V type of elements which are aluminium, titanium niobium, tantalum and hafnium, whose size factors is in the range of around 6 to 18 percent. This is the size factor for these alloy elements with respect to nickel. And if you look at gamma prime, as a told it is A 3 B type of structure.

And all elements which occupy A positions are basically nickel cobalt iron nickel cobalt iron they all occupy A type of positions. And aluminium, titanium, niobium, they occupy the B type of position. So, that is why when we add the elements we should try to see the stoichiometry is something like this is like an Ni 3 Co 3 Ni Co 3 Al Ti or if you want to add niobium also there so whatever elements. So, even for example, hafnium also goes to the B position.

So, like that if you look at tantalum goes to the B position. Aluminium, titanium, niobium, tantalum, hafnium, these all go to the B position. Nickel, cobalt, iron they are all go to the A position. And here, again the morphology of the phase that comes out depends on basically what is called the size mismatch. If the lattice parameter mismatch is very small, if it is 0 to 0.2 percent then you end up in spears.

We talked about this morphology business at some point of time earlier. We saw that if you have spherical precipitates the surface area to volume ratio is very small. So, every precipitate wants to be spherical. But at the same time if you have spherical precipitates then the strain is much larger lattice strain, because the lattice has to maintain coherency. So, maintaining coherency is very difficult if you have a spherical particle. So, if you have a flat type of particle like cube like a plate, you will have much better coherency.

So, if the size factor or what is called the lattice mismatch is very small then the precipitate would prefer to be spherical. So, that it can reduce the overall surface energy. If the size factory is large, if it still wants to be spherical you are going to have problem, because the strain is going to be very large. So, the precipitate would change its morphology from spherical to cubic type of structure. And, if the size factor is more than 1.25 percent then you end up in plates and so this one has to be remember.

So, it is not the always gamma prime is spherical, gamma prime is spherical only when you add and how does this change this changes by the alloying elements that you are putting in here. I told you there are elements which can which stabilise gamma prime.

We have talked about them aluminium, titanium, niobium, tantalum, hafnium, these all alloying elements which stabilise gamma prime. Whenever you are adding these elements into it each element changes the lattice parameter of gamma prime.

Whenever, I add an alloying element into gamma prime the lattice parameter changes, because each alloying elements has a different atomic size. So, lattice parameter changes if the lattice parameter of gamma changes and if the lattice parameter of gamma is not changing, then the difference between the two is changing. So, this difference between the two lattice parameters is what is going to decide here.

So, the alloying elements the going to add are what are going to decide the size mismatch and finally, going to decide the shape of the precipitates. So, that has to be remembered and one also has to remember that it is usually gamma prime coarsens at high temperatures. And one more interesting feature of gamma prime is that which is not common with all inter metallic's is that its strength increases with increase in temperature at least up to 650 degree centigrade. This is one very interesting phenomena with ordered some of the ordered components.

Particularly, Ni₃Al is one such compound where the flow stress or the stress required for the deformation of the compound increases with increase in temperature. For a long time, people had lot of controversy with it. Because, it is kind of is against our general understanding we all know that any metal the strength decreases with increase in temperature whereas, this particular phase behaves in exactly 180 degree out of phase. So, people have realised that particularly at high temperatures.

Some of the slip systems do not operate that well and because of which the strengthening increases with increasing temperature. So, as the result some of the low dense slip systems come into operation at these high temperature. Because, of this the stress required for the slip to occur increases with increase in temperature. So, this is one of the reason why this special phenomena that you observe in gamma prime. So, that is why gamma prime is again very important.

And, there are other strengtheners that are strengthening of because of carbides which can be done by addition of a number of carbide forming element such as chromium, molybdenum, tungsten, niobium, tantalum, titanium. And we know there are number of carbides that are feasible such as M₃C type of carbides; that means, A₃B type of carbides,

tantalum carbides TaC TiC niobium carbides. These are all MC type of carbides there are also M₆C type of carbides chromium carbides. There are also M₂₃C₆ type of carbides as again chromium and molybdenum type of carbides.

So, various types of carbides are possible and carbon is typically added in the range of 0.05 to 0.2 percent to give you carbides strengthening. But, at the same time carbon people want to keep it very low, because the tendency of the carbon is to form carbides of the grain boundaries which is what people do not want. And that brings down the hot corrosion property of the super alloy also. See the more important thing is not only is strength.

But, also the corrosion resistance at those high temperatures, because high temperature the gases are passing through the sample. So, as a result high temperature corrosion and stress corrosion all these have to be considered. So, that is why a design of a particular component is not done always keeping only one parameter in mind. Strength is not the always the only parameter. You have to consider many things such as oxidation resistance, corrosion resistance at high temperature stress corrosion resistance, all these factors are very important.

And, fatigue resistance this is also very important, because high temperature gases are coming and then they are cooled again high temperature gas are coming. So, because of which there are thermal fluctuations not only thermal fluctuations. The turbine keeps on rotating, because of which you have fatigue on that. So, fatigue strength also will be very crucial not just the normal tensile strength. So, all these have to be considered.

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CET
I.I.T. KGP

Stabilizers:

δ - Group V, VI, VII elements Co, Cr, Mo, W, Fe ($\delta = 2-13\%$)

δ' - Group III, IV, V elements Al, Ti, Nb, Ta, Hf ($\delta = 6-18\%$)

Carbides - Cr, Mo, W, Nb, Ta, Ti (C - 0.05-0.2%)

S.b. - B, C, Zr ($\delta = 21-27\%$)

10-20% Cr, 5-10% Al, Ti, 5-10% Co.

SSS

Co	Fe	Cr	V	Al	Ti	Mo	W
0.09	0.56	0.8	2.2	3.3	4.0	4.2	4.5

$\Delta\sigma$ in Kg/mm^2 Per 1%.

δ' A_3B A: Ni, Co, Fe ($(Ni, Co)_3$)
 B: Al, Ti, Nb ($(Al, Ti)_3$)

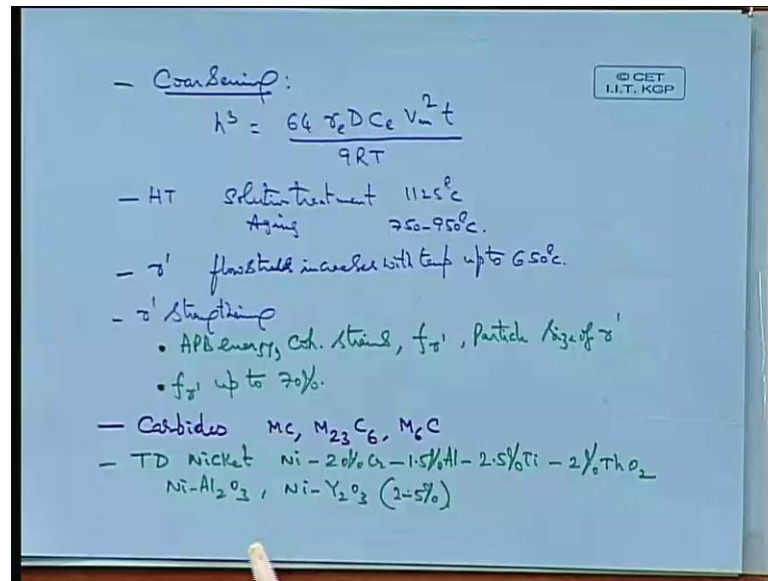
$\delta = 0-0.2\%$ Spheres
 $0.5-1.0\%$ Cubes
 $> 1.25\%$ Plates

$> 0.6\mu m$ & Coarsens.

And then, the grain boundary strengtheners such as boron carbon zirconium, where the size factor is much larger, for example, zirconium is much larger atom, boron and carbon atom much smaller atom with respect to nickel. So, these either small atoms or very big atoms they go to the grain boundaries. Because, grain boundaries is more open structure at was to the go to the grain boundaries.

They gate locked of there and then give you some cohesion at the grain boundary. So, that grain boundary are not very weak, usually grain boundary are very weak and then is give you what is called interregal cracking. And, when you add these elements the interregal cracking comes down. And then, the usual amounts of the elements that are added are about 10 to 20 percent chromium about 5 to 10 percent of aluminium and titanium and cobalt about 5 to 10 percent. And another crucial aspect is coarsening; we have talked about it to some extent earlier. The coarsening is related to basically four parameter. As I told you before, one is a interfacial energy.

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You can see here, the particle size to the power 3 is given here h cube which is taken as particle height. One can also talk in terms of particle diameter, why the question of particle height comes into picture is; when we are talking of disk shape particles or cuboids type of particles. We do not talk in terms diameter comes into picture when you are talking at spherical particles and gamma prime is not always spherical. So, that is why people talk in terms of height, the thickness. Instead of the particularly even for a plate what is crucial is thickness.

So, if you are talking of thickness, how does it change as a function of various parameters? You can see this formula it is $64 \gamma_e D c_e V_m^2 t$ by $9 R T$ where γ_e is the interfacial energy D is a diffusivity, c_e is the equilibrium solubility of the solute in the solvent and V_m is nothing but the molar volume of the gamma prime, small t is the time. Obviously the growth also depends on the time because growth is always a time depended phenomena and then the temperature.

If you see here, the temperature is coming in the denominator, why is that.

Student: ((Refer Time: 48:47))

Happening, do not you think that coarsening should increase with increasing temperature.

Student: ((Refer Time: 49:03))

If you carefully observe this, there is no anomaly. You know that D , there is a temperature which is exponential this is basically this formula is basically equivalent to the growth is always can be written as in terms of some pre exponential term into exponential minus cube by $R T$. So, this t comes from that. And the Q which is the activation barrier that consists of all these terms we can see.

So, if you look at D , D we can write as D equal to D_0 into exponential minus Q by $R T$. So, temperature comes in the exponential term in a denominator. So, as the temperature increases, then the exponential term decreases, then the diffusivity tremendously increases. So here, one has to remember this aspect and as we increase the temperature D increases. And so D is very crucial and γ_e and c_e are also very crucial, we have talked about it in the last class, when we are talking about coarsening of the particles.

And usually, for the formation of gamma prime, we do two stages heat treatment, the alloy is solution treated at high temperatures where all the alloying elements get dissolve. And then, it is aged in the range of 750 to 950 centigrade for the precipitate of the gamma prime. And, gamma prime can be strengthened by either increasing the APB energy or increasing the coherency strains or increasing the volume fraction of the gamma prime or decreasing the particle size of the gamma prime.

There are four parameters which can give you strengthening the as gamma prime is concerned. Because, gamma prime is crucial strengthen in nickel based super alloys. We always consider how to get strengthening. Because of gamma prime and these are the four parameters which control the strengthening that is obtained by gamma prime. One is the APB energy increase, the APB energy; that means, add those alloying elements which can increase the APB energy. Second increase the coherency strains so; that means, again add those alloying elements which can increase the coherency strains.

Then increase the volume fraction or decrease the particle size. If you increase the volume fraction, what you are going to achieve, is you are going to decrease what is called lambda. We have talked about it in the last class, the inter particle distance lambda is what decides the strengthening in case of the particle strengthening. So, if the lambda is smaller, then you have higher strengthening.

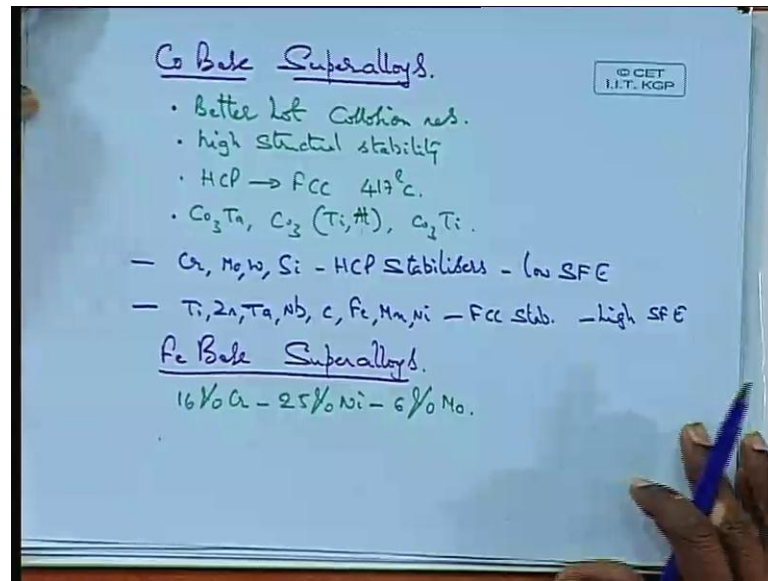
And in fact, we also talked about a Hall-Petch type of relation with the lambda. Sigma strength is equal to $\sigma_0 + k \lambda^{-1/2}$, we have talked about it in the last class. So, if you are increasing the volume fraction of the precipitates by keeping the size constant then what we are basically increasing is at within a given volume the number of particles, you are increasing. If you are increasing number of particles within a given volume, what you are doing basically is a decreasing the delta. So, if you are decreasing the delta, then not delta the lambda then; obviously, you are increasing the strengthening.

So, that is one and in some cases the volume fraction can be of the order of 70 percent. And, we are talked about the carbides and then the dispersion strengthening. Dispersion strengthening, the first dispersion strengthened alloy is what is called the nickel thoria dispersed nickel. In fact, I told you mechanical alloying also started with this. Because, they wanted to disperse the thoria in the nickel based super alloys and wanted to have a uniform dispersion of thoria.

And saw that the wet ability is very poor and to improve the wet ability. They wanted to code the nickel and that is how the mechanical alloying technique has come. So, this thoria dispersed nickel is basically a nickel based alloy with about 20 percent chromium about 1.0, percent aluminium and 2.0 percent titanium. This gives you the Ni₃AlTi precipitates. And, this thoria gives you the strengthening, because of the dispersion strengthening.

And there are also strengthening because of Al₂O₃ and Y₂O₃ which people have used at a later stage. Because of thoria has problems, because we know thorium is a radioactive element. So, nobody was to use that to a largest end. So, people have replace thoria with Eritrea and alumina and recent airs and usually volume fraction that we use is about 2 to 5 percent. So, this is all about nickel base.

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Then we will see the cobalt and the iron based this is not much of work as far as iron base is concerned. Because the iron base, you cannot really go to very high temperatures. The temperature capability is limited in iron base and so basically iron base alloys are nothing but extension of what is called stainless steels. Stainless steel, we are already know that, we add alloying element to be stabilise one of those elements.

Austenite stainless steel, for example is that where gamma is stabilise. So, for super alloys we need a gamma. So basically, what we are talking about is an austenite stainless steel? So, in austenitic stainless steel you add certain elements which can also give you solid solution strengthening and also add some elements such as aluminium and titanium which can give you gamma prime type of precipitates or other type of precipitates that gives you the strengthening.

That is why iron based super alloys are use. But, iron super alloys have low stability when compared to nickel based super alloys. Among all the three alloys thermal stability is maximum with the nickel base. And if you look at hot corrosion resistance it is best with cobalt base. So, cobalt based alloys are still a competitors for nickel base super alloys. But whenever the temperature is not very high and cost becomes a factor, then iron based super alloys are used, when compared to nickel base to super alloys.

When you want use it at higher temperature; obviously, nobody wants to for iron base, then you go for nickel base. And, the cobalt base alloy also have good structural stability.

And because, this temperature of transmission to a HCP to FCC is very low 417 degrees. And, this temperature being very low, beyond this temperature it is all gammas. And when we want to use a super alloys, we want use it at temperature such as 700 800 900 degree centigrade. So, at that temperature it is any way gamma.

So, the cobalt base super alloys are really stable, where as if you look at iron base super alloys the transformation temperature of BCC to gamma is very high, that is a negative point as far as the iron base super alloys are concerned. So, you need to add large amount of alloying elements to bring down that transmission temperature to very low temperature, if you want to use iron base super alloys.

Then the strengtheners, in cobalt base super alloys are basically Co₃Ta Co₃Ti Al and Co₃Ti, these are type of compounds. And, we use for HCP stabilising chromium molybdenum tungsten silicon. If you want to stabilise the HCP phase of the cobalt, because the HCP phase is also equally closed pack we say though as I told you know it is not geometrically closed packed.

But at the same time, this one advantage of all these alloying elements which stabilise it HCP that their stacking fault energy is very low. They decrease the stacking fault energy, where as all FCC stabilisers to cobalt base alloys such as titanium, zirconium, tantalum, niobium, carbon, iron, manganese, nickel. They have a tendency to increase the stacking fault energy. So, we know the stacking fault energy is very crucial at high temperature applications.

Crossly particularly occurs more easily, if the stacking fault energy is high. Because, if the stacking faults energy is high, then the width of the stacking fault is low. Then, the cross loop if we use very high very easy. So, we want the cross loop to be more difficult if you want creep resistance. So, as a result it is better to add alloying elements which can stabilise the HCP phase. So, one has to play with it.

So, definitely as for as diffusivity is concerned the FCC is better structure than these, but unfortunately those elements which are stabilising the FCC phase are also increasing. So, one wants to add a combination of these elements. So, that we can have better options as for as both are concerned. So, this is what is the story about super alloys, we will stop at this moment.