Metal Additive Manufacturing
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Lecture 15
Solidification of Parts (Part 3 of 3)

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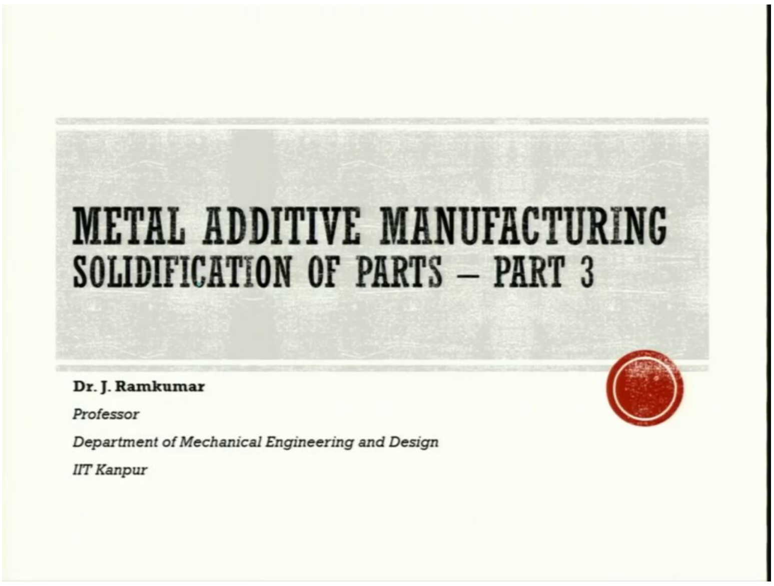

Welcome to the course on Metal Additive Manufacturing, we will now discuss in this small lecture exclusively on various phase diagrams, I repeat, it is a small lecture, maybe for 20 minutes or 15 minutes, this exclusively covers like the different phases, which can happen in alloys.

This diagram or this information is very much required because if you are going to talk about all these α phase, β phase, γ phase, martensite, austenite in the microstructure, all these things can be derived from these diagrams. And this diagram will dictate the microstructure, which in turn describes or defines the service condition of the part in real time.

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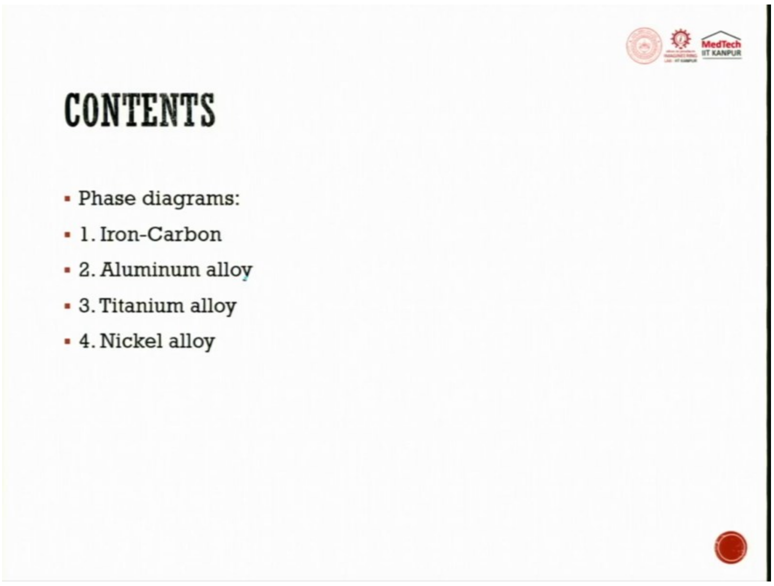

In this lecture, we will try to cover the phase diagram of Iron-Carbide diagram, Aluminium alloy, titanium alloy and nickel alloy whatever 4 we are trying to cover, we have picked up the alloy composition, which is exhaustively used in metal additive manufacturing.

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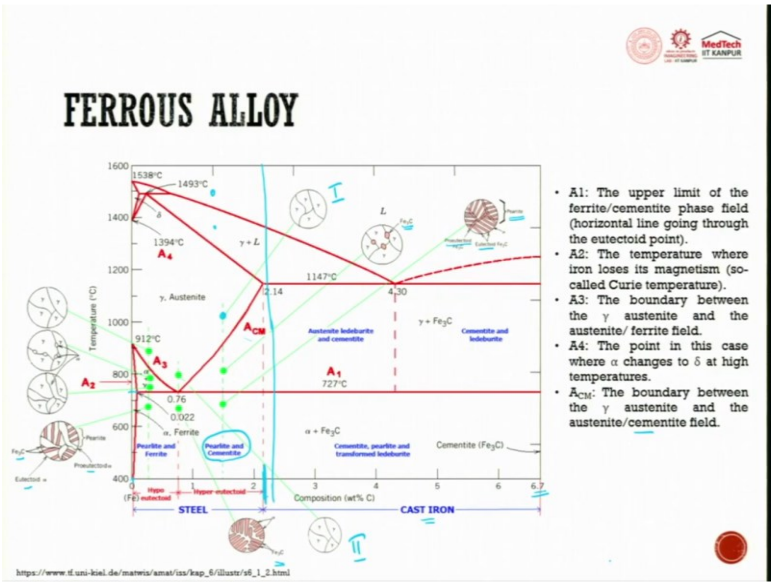

First, we will look into Iron and Carbide diagram, which is very famous and very common, people when they teach in your basic material science course, they try to go through this phase diagram. So, this phase diagram is all about taking 2 metals, 1 is ferrous the other one is carbon, these 2 are getting mixed to each other, when they mix at varying compositions and at varying temperature, what will be the microstructure, this will be our prime focus.

So, if you try to look into it, you have here 0, carbon and maximum carbon in cast iron can happen when C gets diffused into iron, we can go up to 6.7%. Anything above 6.7 does not form a proper alloy, and does not have engineering properties. So, we will always look forward for iron and carbide diagram where the carbon content is maximum up to 6.7.

But, when we are looking at the additive manufacturing, we always work in a composition close to 2, 2.1 or 2.2. This is where in the domain we will keep start working and cast iron is predominantly used for casting, and for bulk material formation or bulk part formation we use cast iron. So, let us focus only in this zone where it is talking about 2.1 or 2. So, in this zone you can get hypo eutectoid condition.

If I tried to take the composition of mixing of iron and carbon and take it to very high temperature up to 1400, 1500 which is very common, when you are trying to use in additive manufacturing, when you are exposing it with respect to laser or with electron beam the temperatures can go very high easily it can go up to 1000 and if you slightly push it further it can go up to 1500, 1600.

So, you are almost in this zone. So, when you are at this zone you see it is completely liquid. Now, from here, if I slowly start cooling it down, you see here I get into γ plus liquid phase, then when I push it further down I get into austenitic phase. So, what is austenitic phase? You see, this is what is the microstructure. It looks like you will have grain boundary and then you will have γ which is quite common.

Now, I further allow it down to go to this temperature, you can see small precipitations of carbon, which are getting trapped or formed along the grain boundary. So, these trapped ones are called as Iron-Carbide, and you can see the γ there, when I further go down with this ferrous carbide, Fe_3C which got precipitated or formed along the grain boundary, it will try to get spread all around and you try to get a Pearlitic phase.

So, you just brought down the temperature you see how many different phases are coming. Now, in all these phases suppose, let us assume I pause the temperature and then I quench it down, then in my quenched sample predominantly I will be able to get the microstructure from where I paused and I quenched. So, when I do with iron-carbide diagram and with laser as a source for heating, these micro structures are very common to make.

So, when I go further down, you get this pearlitic structure, you can see here eutectoid solution and peri eutectoid thing forming in the microstructure. So, now, here I have a combination of pearlite and cementite. So, maybe perlite and cementite might give a good mechanical properties, maybe I am just giving you an example maybe or it can give you a good toughness.

So, now, what do I do, I try to get this microstructure and I freeze it anything less than 600, 700^0C or somewhere close to 700^0C, whatever you get is frozen up to room temperature. Now, you try to quench it and get it from the above, you try to quench it and you get the desired microstructure in the workpiece. In the same way, when I try to do it somewhere around about here, you can see here in the austenitic phase, you have this γ phase which is there.

So, here it is the same only difference between this and this is the compositional difference of C which is getting pushed inside the iron or in the microstructure, then I move it to the next phase. So, this phase you have got Fe_3C and here whatever is getting here done, it will be almost the same.

When I further push it down, I tried to get this structure all around the material, when I go further closer that means to say I reduce carbon to a large extent and I drop it down. From 900 degrees I go down, I get a γ phase, then I get the precipitation. Here you said α+γ, what is γ? This is γ, what is α? It is a phase which is predominantly seen here, which is nothing but a ferrite phase.

So, you can see here α+γ, then further I moved down you see there this γ. Whatever is there, it is getting spread along the grain boundary nicely I get it about somewhere around about 800^0C or somewhere around about 723^0C, I get this.

So, now, I further move down you see here there is a pearlitic phase, there is Fe_3C there is a eutectoid α and then it is protectoid α you get. So, all these things are getting. So, now, these things try to dictate the microstructure and the ductility of the component. A1 the upper limit of ferrite cementite phase field. So, you can see A1 is here.

So, you can get a field here A_1, then A_2 is somewhere here, the temperature where iron loses its magnetism property. So, a Curie point can happen at A_2. At A_3, you try to have the boundaries between γ austenite and the austenite ferrite field, you try to get A_4 you get the point in this case, where α changes to δ you get here.

Then, we have A_{CM} critical is a point here, which the boundaries between the γ austenite and the austenite cementite field, you can try to get this. So, from this diagram, you can try to see how carbon and iron gets influenced with each other and you get varying microstructures at varying temperatures. So, you can see this and then you can see this in turn will be affected by your residual stress, which is getting introduced in the additive manufacturing.

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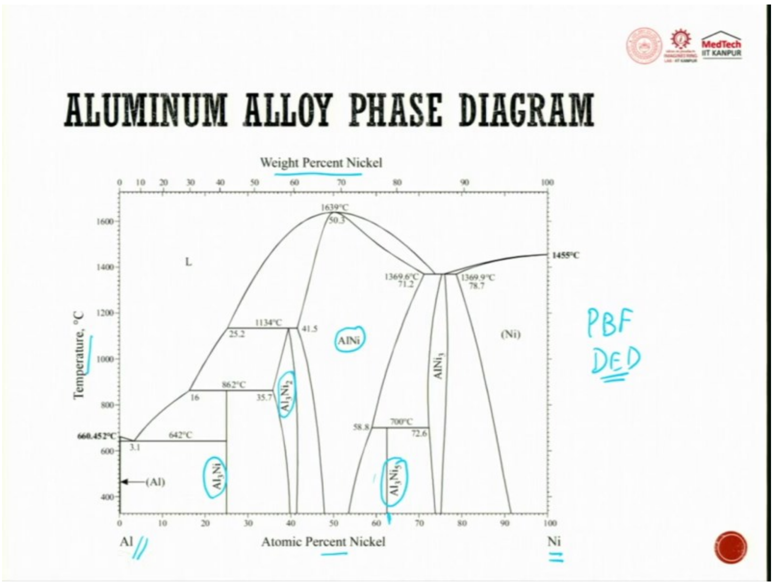

Next when we move into aluminium alloy phase, you can see weight of Nickel percentage is given here. So, you have temperature, you have atomic percentage of Nickel. So, this is used for aluminium and nickel getting fixed. So, this side is nickel and this side is aluminium, I have just taken an example of one particular alloy.

So, here you can see it is liquid phase and as and when I start going down, you can see here what are all the different compounds which are getting formed. Al_3Ni is getting formed, Al_3 Ni_2 is getting formed and AlNi is getting formed. So, you can see all these things, each one has its influence on the output.

Depending upon the composition, what you have mixed it in the powder bed fusion or in directed energy deposition, you try to mix that alloy in the starting material itself. When we expose it to laser, you see it undergoes to various temperatures and depending upon the temperatures various phases gets formed.

So, if you are able to maintain at around about 65% of nickel at around about 700^0C, you try to get these compounds getting formed. So, just by changing the compensation, you can get multiple micro structures in one component.

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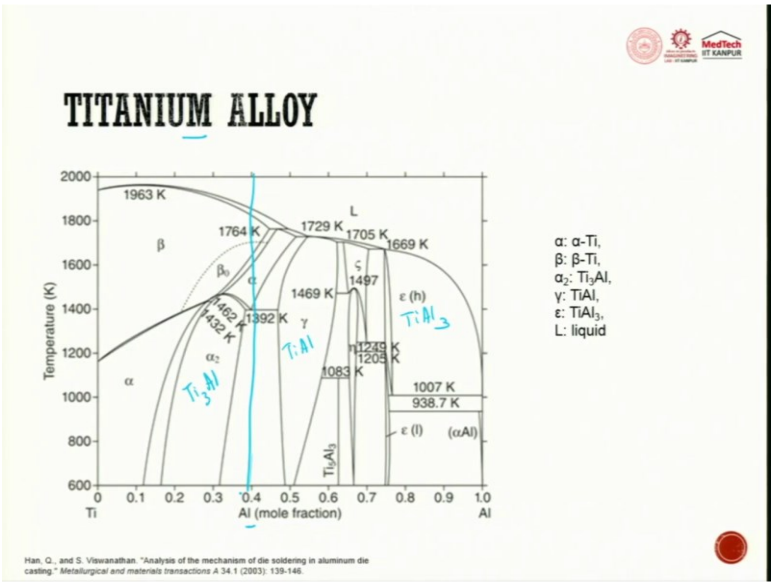

When you are looking at titanium alloy, it is titanium alloy you can see Ti 6Al V4 is the most common one which is used. So, you can see here when we are trying to change the aluminium composition with respect to titanium, let us assume it is dropping down somewhere here.

So, you will see here first it is at a liquid phase then from here it enters into a β phase, β_0 is nothing but β_T, titanium alloy then it moves into α, where α titanium is there, from there you can try to get α titanium 12.4. When you slightly shift this gets into α_2 which is nothing but Ti_3Al.

So, when I get into this portion, when I try to take γ, this is TiAl; when I try to take ε, it is $TiAl_3$. So, you get different compositions at proportions whatever you mix and make an alloy and then you try to see their phase diagram, to find out the multiple phases which are getting formed.

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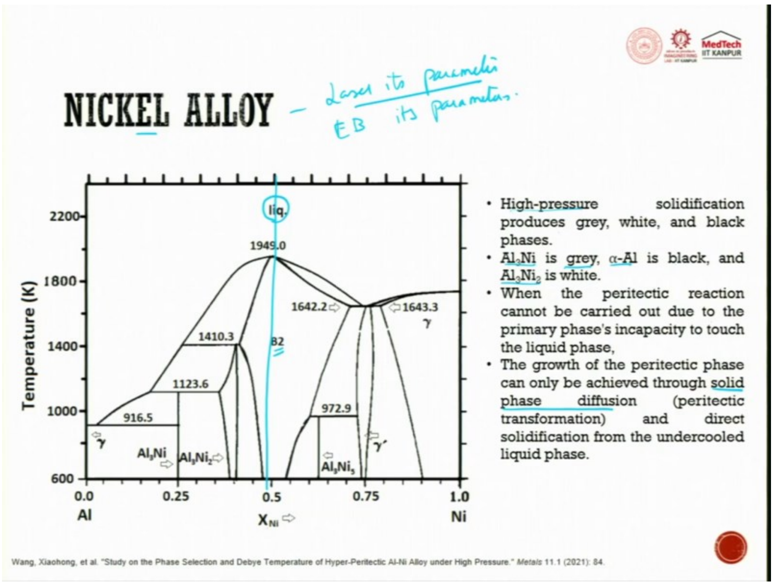

When we talk about nickel alloy, nickel alloy is pretty interesting. It is nowadays used in aerospace application you see at around about 2200 K, you find it as a liquid dropped down. So, you can see here at one phase it is Nickel, so, I dropped out and then I get into β phase. So, this β phase is different as compared to that of your γ, γ′.

So, they are different. So, here you will get this Ti_3Ni which is forming here and you have Al_3Ni, $Al_3Ni_3Ni_5$, will be formed here and at this point you get γ′. So, high pressure solidification process produces gray, white and black faces, but here we do not use high pressure, but without doing high pressure, high temperature and instant cooling you can get multiple combinations, Ai_3Ni is gray, α-Al is black and Al_3Ni_2 is white.

So, depending upon the microstructure, you can easily find out by looking at the microstructure, if it is gray, it is Al_3Ni, if it is black, it is α-Al, and if it is white, it is Al_3Ni_2. So, when the Peritectic reactions cannot be carried out due to primary phase incapability to touch the liquid phase, the growth of the Peritectic phase can only be achieved through solid phase diffusion.

So, what is the mechanism it undergoes? That is a separate course itself, but we are only trying to understand the influence of laser, its parameters with respect to forming of these phases in the same way electron beam its parameters.

So, what undergoes the growth of the Peritectic phase can only be achieved through solid phase diffusion and direct solidification. From the undercooled liquid phase it can happen. So, in nickel you try to get all these combinations to meet out to the requirements.

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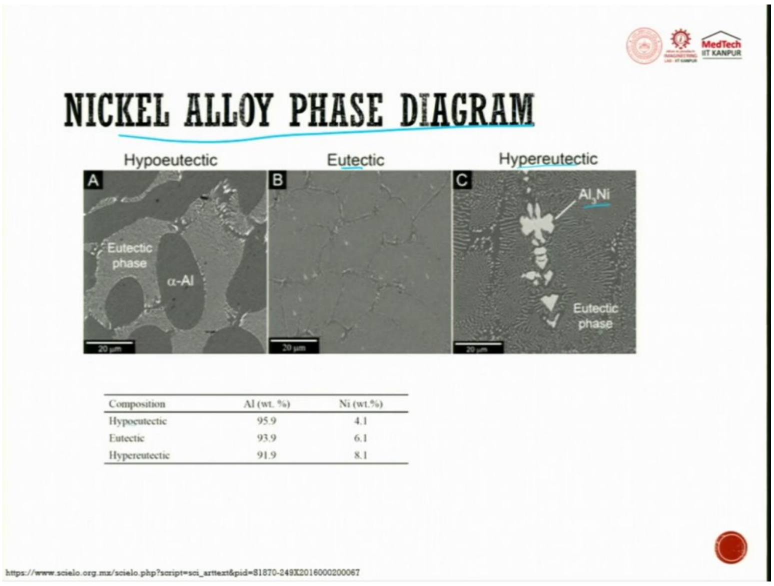

When you look at nickel alloy phase diagram, you can see hypoeutectic. So, this is eutectic phase in which Al is there. So, here hypoeutectic the aluminium composition is close to 96% and the nickel is 4; in eutectic Al is 94, Ni is 6%; and hypereutectic Al is 91 and Ni is ~8%. So, if you see hypereutectic, this is how the microstructure looks like, when you look at eutectic it is looking like this and like this when you look at hypereutectic. These are Al_3Ni white phases which are present and it is eutectic face.

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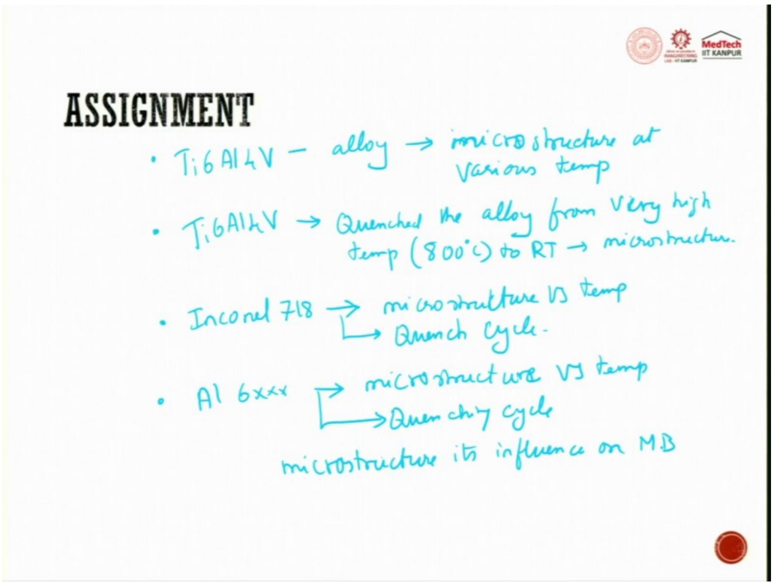

So, in this lecture I have few assignments for you. One is try to look for Ti 6Al 4V. So, try to look at this alloy and try to get its micro structure at various temperatures. Next try to see some literature on Ti 6Al 4V, where they have quenched the alloy from very high temperature, we are talking about 800^0C to RT, room temperature. See the alloy microstructure.

Next one, you try to look at Inconel 718 which is exhaustively use for aerospace application. So, what is microstructure, varying microstructure at varying temperatures versus temperature, then you try to see here a quench cycle. Then the third one is going to be Ti_6, then it is going to be Aluminium 6xxx series try to do the same, microstructure versus temperature and then it’s quenching cycle.

So, when you try to look into all those things, it will try to give you a wider perspective and you will see varying microstructures are getting formed. So, that will try to give you an understanding of the microstructure and its influence on mechanical behavior. Thank you very much.