Metal Additive Manufacturing
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Lecture 18
MAM Printed Parts: Mechanical Properties, Strength

Welcome to the lecture series on Metal Additive Manufacturing. We are now seeing what are all the different ways of evaluating the product which is been produced out of additive manufacturing. So, last lecture, we were looking into hardness. Now, we would go into mechanical property evaluation, that is tensile and then we will try to look at service condition exposure which is basically a fatigue testing.

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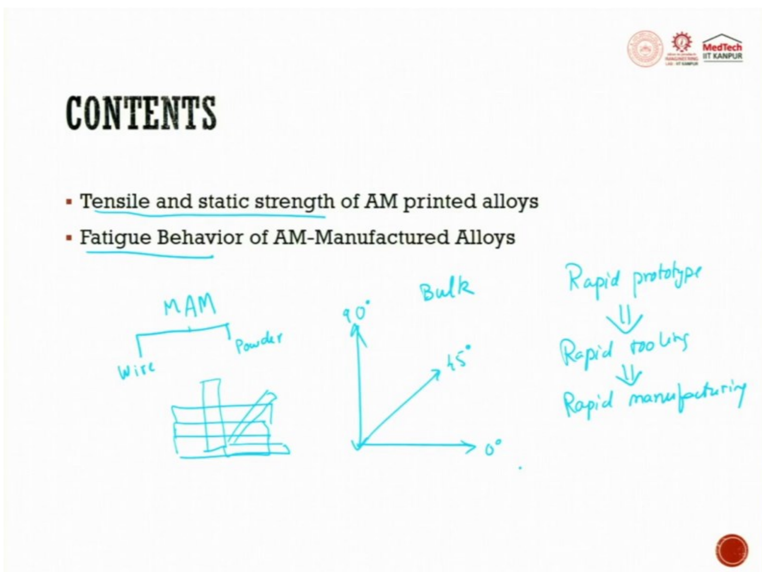

So, we would look at tensile and static strength of additive manufactured printed parts and then we will also look at fatigue behaviour, why are these two very important? Because, if you have a homogeneous material or a bulk material, so, if you do tensile test only in preferably three directions like for example, you do it in the 0 direction, then you do it in 90 direction and then you do around 45 direction, this is 0, maybe this is 0, this is 90 and you have 45^0.

You do tensile test in these three directions that means to say take a sample cut the sample along these three directions, and what you get will be approximately you will try to average out and then you try to report what is the tensile strength. But in additive manufacturing since we are doing layer by layer, the biggest challenge is going to be across this direction and along this direction, and if you cut at this direction, you will get completely get different properties.

And if you do it in metal, and if you start with powder, you will have a different property for the same thing you do it in bulk, you get a different property, this is bulk and this is AM part. So, again in AM, you have two classifications with starting material powder and then starting material wire and we are more focused towards metal.

So, you will get different properties. So, this will try to dictate the efficiency of the component when it is put in real time. Why are we more focusing on this today is what rapid prototyping was thought of till now is now converted into rapid tooling or it is also now thought of rapid manufacturing.

So, when we have to do or get ready for such conditions, then our part or the product what we print should be very good in terms of tensile and static strength and fatigue behaviour apart from your hardness. All these things are destructive testing, there are also non-destructive techniques through which you evaluate the quality of the output. So, tensile and static strength.

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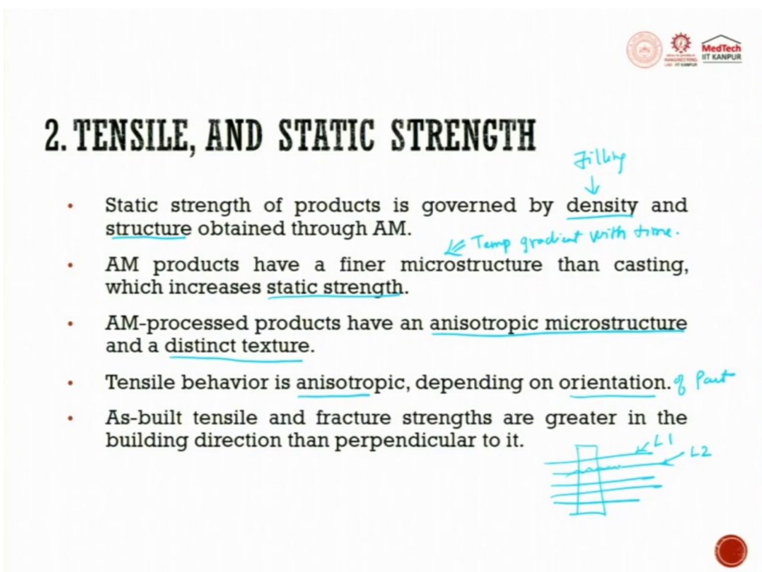

Tensile strength of products is governed by density and structure, density and structure, this density is the filling density which is governed by the structure what we use. Additive manufacturing products have a finer microstructure than casting, which we saw. Why? Because there is a temperature gradient with respect to time.

Which increases the static strength. Additive manufacturing processed products have anisotropic micro structural behaviour or structure and distinct texture anisotropic microstructure and texture, texture and microstructure are two different things. These two play a very important role, when you try to decide the mechanical properties, tensile behaviour is anisotropic depending on the orientation in which the part is built. Anisotropic orientation of the part.

As built, tensile and fracture strength are greater in the building direction than that of the perpendicular direction. So, why in the perpendicular direction? Because in the perpendicular direction you will have layer by layer and this there is a possibility between layer 1 and layer 2 there can be delamination or there can be imperfections which are produced.

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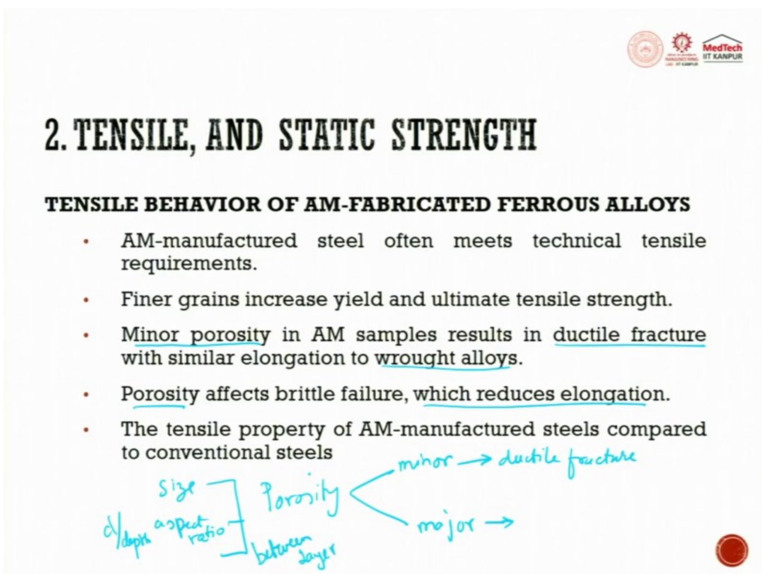

When we look into tensile behaviour of additive manufactured fabricated ferrous alloys. AM manufactured steel often needs technical tensile requirements. Finer grains increase yield and ultimate tensile strength. Minor porosity in additive samples results in ductile fracture with similar elongation to wrought alloys. Note a point in tensile fracture minor porosities will lead to ductile fracture with similar elongation to wrought alloys, porosity affects brittle fracture, which reduces the elongation. So, I am classifying porosity into two which is minor and which is major.

When it is minor it leads to ductile fracture, this is a very important inference which for practicing engineer it will be very much useful and for research scholars, if you have minor porosity, you will get ductile fracture and the elongation will be the equal to or will be approximately equal to the tougher wrought alloy, but when you have a major porosity that means to say the size, aspect ratio, here I will write it down size, aspect ratio.

The aspect ratio can be diameter to depth, because it is a three dimensional one, diameter to depth size or it is running between layers if you try to take if it is running between layers. If it is running, then you will try to have all these responses. The tensile property of additive manufactured steel compares to that of the conventional steel. So, we have come to that level today, whatever is your conventional steel giving, which is we get almost equal to that.

See, when you talk about these conventional steels, it is very difficult for you to compare with that of rolling. We are trying to talk about a part where it is complex, where you have the three dimensional aspect of the part, there we are able to compare or with respect to sheet metal, no, it is with respect to a part and not a metal formed part, keep that in mind. So, manufactured steel is compared to that of conventional steel. So, now, this will give you an eye opener saying that additive manufacturing of steel we can use it for producing parts.

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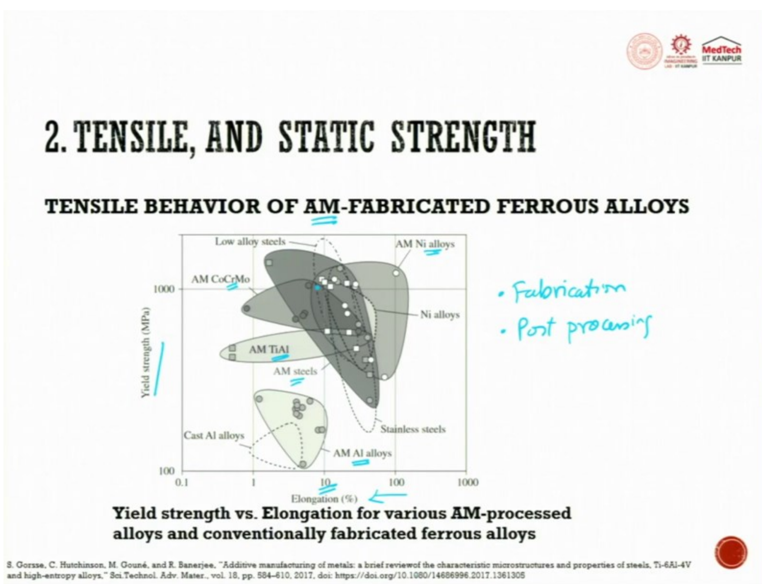

The tensile behaviour of additive fabricated ferrous alloys are listed here. So, this is predominantly called as Ash B curve. So, Ash B is a professor researcher, you can see such types of graphs comparing many different parameters. For example, in x axis here you have yield strength, y axis you have elongation, you can also try to have cost, he has drawn many things so, that you try to have better understanding.

So, here if you see the ferrous low alloy steel is here and this is additive manufactured nickel alloy it is here and the stainless steel is here. For example, tomorrow you decide I want this elongation like 10 % and I want a yield strength of maybe 1000 MPa, if you decided now 10 you just walk it across and then you go down here and then you will try to figure out low alloy steels are performing here, stainless steel is here some compositional change you do and you will try to get an output somewhere here.

So, this tries to talk about the complete range of ferrous alloys, which is used in additive manufacturing. Same way you can see additive manufactured aluminium alloys, titanium aluminium alloys, this is aluminium additive manufacture of steel, cobalt chrome molybdenum alloy, nickel alloys.

So, nickel alloys give elongation 100% and it gives around about 1000. So, today you can tailor make the parts to meet out to this requirement by using additive manufacturing. Additive manufacturing during fabrication and in post process, you can try to dictate whatever you want and get the required output in a very cost economical manner.

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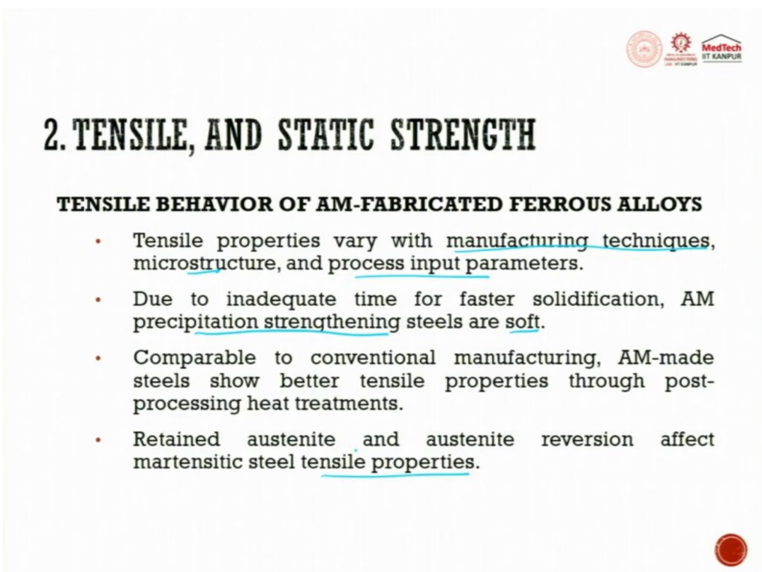

Tensile behaviour of additive manufactured fabricated ferrous alloys tensile properties vary with manufacturing techniques microstructure process input parameters with manufacturing technique, microstructure and process. So, what I am trying to say is, if it is electron beam, it will be a different response, if it is laser, it will be a different response, if it is directed energy deposition wire, different response, powder different response.

It all depends upon the manufacturing technique, microstructure what it generates and the process input parameters. Process input parameters depends on the laser parameters apart from layer height and other things. Due to inadequate time for faster solidification AM precipitation strengthening steel are soft.

Compared to conventional manufacturing, additive manufactured made steel shows better tensile property through post processing heat treatment process. By choosing a proper heat treatment that means to say you are trying to reduce the residual stress grow that make the grains little coarser by doing a heat treatment, you are able to get better performance as compared to that of conventional machines. Retained austenite and austenitic reversion affect the martensitic steel tensile properties. So, you can just play with the different phases, which comes in steel or iron and carbide diagram

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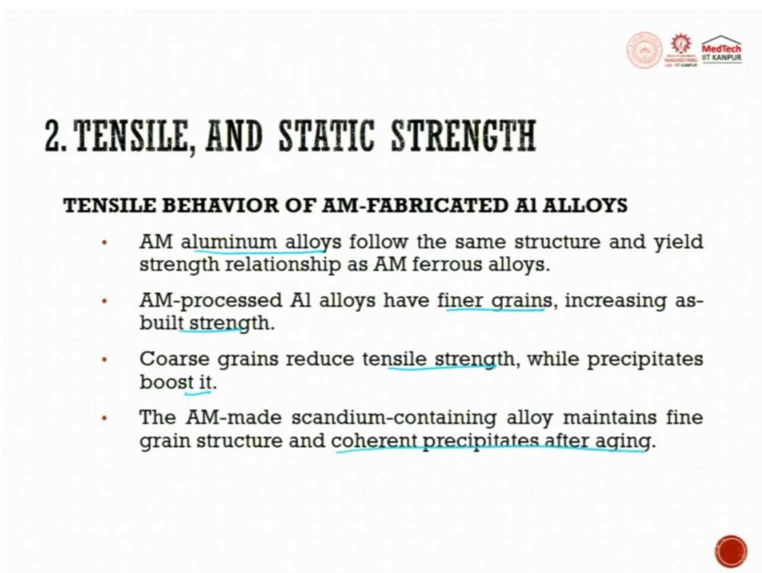

Additive manufacturing. Now, we are trying to talk about aluminium alloys follow the same structure and yield strength relationship as AM ferrous alloys. Almost in the same way whatever response ferrous gives I am not talking about in terms of exact magnitude, but in terms of comparison of ferrous alloy, which is conventional ferrous alloy additive manufacturing the behaviour you will get the same behaviour with respect to aluminium alloy also.

Additive manufacturing processed aluminium alloy have finer grains increasing as build strength. The coarse grains reduces the tensile strength while precipitates boost it. Well this precipitation boosts the reduction of the tensile strength. So, as additive manufacturing scandium containing alloy maintains finer grain structure and coherent precipitates after aging these are all exotic materials.

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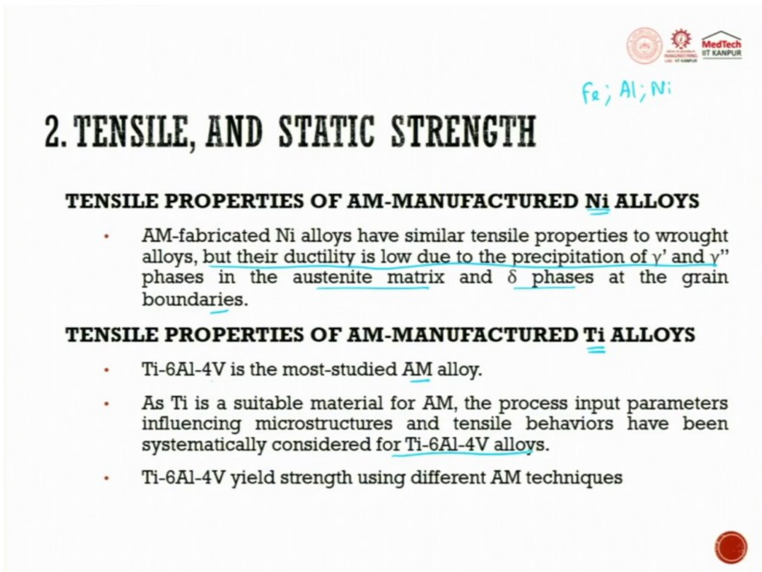

Tensile properties of additive manufactured nickel alloys, we have first talked about ferrous then we went into alloy aluminium and now we are going into nickel. Tensile properties of additive manufactured nickel alloys. AM fabricated nickel alloys have similar tensile properties to wrought alloy. But their ductility is low due to the precipitation of γ' and γ" phases in the austenite matrix and δ phases at the grain boundaries.

Tensile properties are comparable, but the ductility is very low as compared to the tough nickel. Nickel not much research publications have also come and there are a few domains where nickel alloys are exhaustively used. But generally iron and aluminium nowadays magnesium is also people trying to use it.

The other thing is tensile property of titanium is the next exhaustively used alloy. So, here titanium is used for biomedical applications auto and aero applications. As Ti is suitable material for additive manufacturing, the process input parameters influence microstructure and tensile behaviour have been systematically considered for TI-6AL-4Vyields strength different from that of AM techniques.

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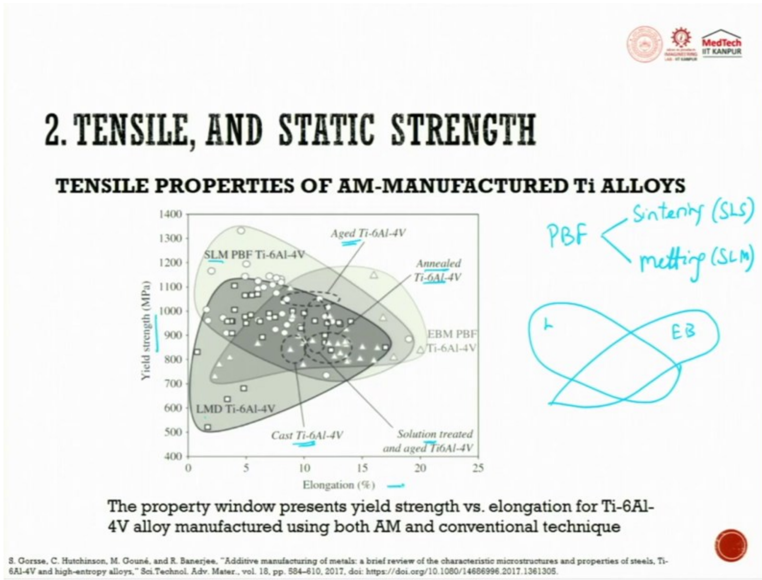

So, this is comparing about different techniques which are used for TI-6AL-4V. You can use selective laser melting technique. So, you have this is powder bed fusion selective laser melting. Powder bed fusion you have two techniques as I discussed earlier one is sintering and the other one is melting.

So, this is called as SLS process selective laser sintering, selective laser melting that is what is here. Selective laser melting powder bed fusion method TI-6AL-4Vyou see the response how it comes. Then you can see here you have cast I am comparing it with that of cast TI-6AL-4Vhow is the response coming.

Then you have aged aging is a process which is used Aged TI-6AL-4V. So you get the response here then you have solution treated you see here and aging, what is the response you are getting. So, these are all samples which are casted, aged on the same sample and solution treated. So, you see the response what you get. And then you can also get tried to get annealed TI-6AL-4V. These are the processes which are used and you get different responses.

Now, when you try to compare with that of additive manufactured part, you see here selective laser melting powder bed fusion method TI-6AL-4V, the response, how do you get? The full response, what do you get? Next is you also have electron beam melting of powder bed fusion, how is the response? You see that is a big response. So, here it is something the response is like this, electron beam the response is like this.

So, this is laser and this is electron beam, you see these for the same raw material, what different response you get. For example, in electron beam you get more elongation as compared to that of laser, then you have LMD process is also there for TI-6AL-4V. So, this is the other response you get. So, all these things variation you try to Taylor make it depending upon the process you choose, you can try to Taylor make elongation and tensile strength behaviour.

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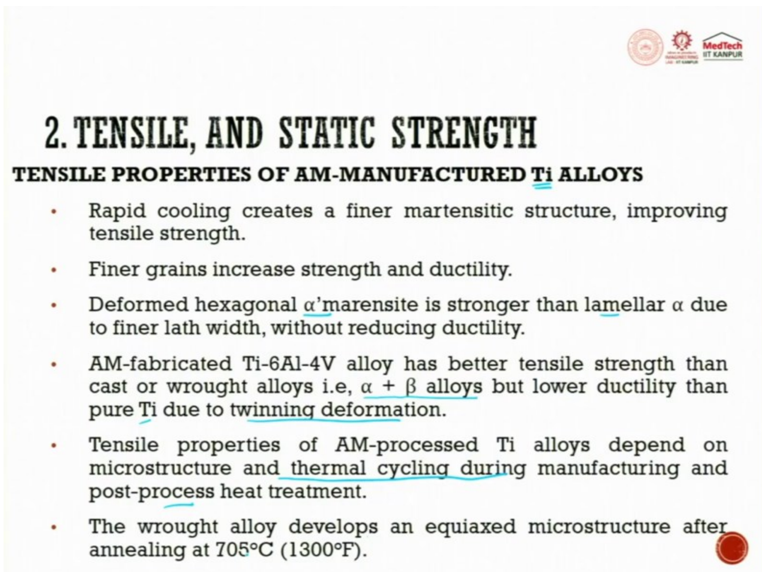

The rapid cooling creates a finer martensitic structure improving the tensile strength as far as Ti-Al alloys are concerned. Finer grains increase the strength and ductility hall petch effect. Deform the hexagonal alpha prime martensite is stronger than lamellar alpha due to finer lath width without reducing the ductility.

So, now, all these things you will understand when you try to look into the phase diagram of TI-6AL-4V. So, you will try to get the hexagonal alpha prime martensite lamellar alpha also you will try to get. Additive manufactured fabricated TI-6AL-4Valloy has better tensile strength than cast or wrought alloys that is α + β alloys. But lower ductility than pure titanium due to a twinning deformation.

So, why is that change in response coming also we can try to see the microstructure and the texture, what comes and then you can try to talk about it. The tensile properties of additive manufacturing process Ti alloys depend on the microstructure and thermal cycling during the process. And after this also you can do a post process to get to the requirements. The wrought alloy develops an equiaxed microstructure after annealing at 700^{0}C approximately 705^{0}C.

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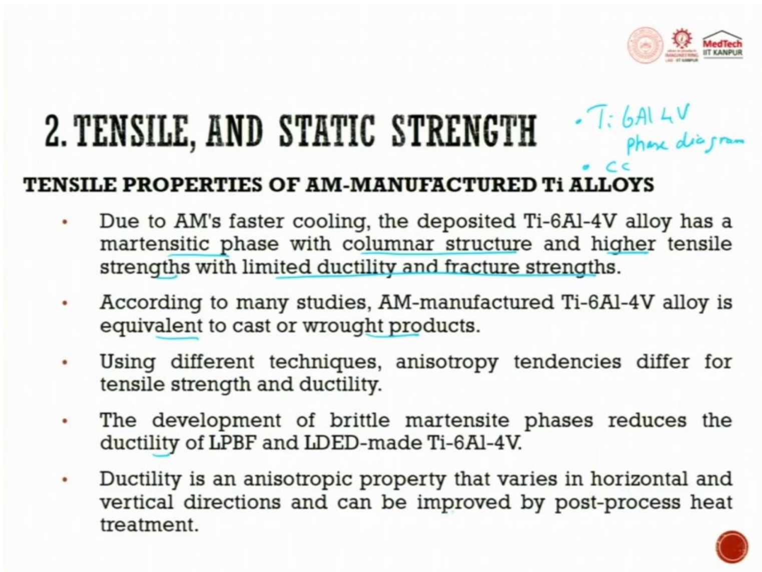

Due to AM's fast cooling the deposited TI-6AL-4V has a martensitic phase with columnar structure and higher tensile strength with limited ductility and fracture strength. All these lecture slides are being extracted from various research papers. So, that is why you see some of the things are abstract, but all these things you will be able to appreciate when you parallelly go through the TI-6AL-4Vphase diagram.

And you can see the cooling curve response for this alloy. So, with this you will try to able to understand all these things. According to many studies AM manufacturer TI-6AL-4Valloy is equivalent to cast or wrought products using different techniques anisotropic tendency differ for tensile strength and ductility. The development of brittle martensitic phase reduces the ductility and the ductility is an anisotropic property that varies in horizontal and vertical direction and can be improved by post processing.

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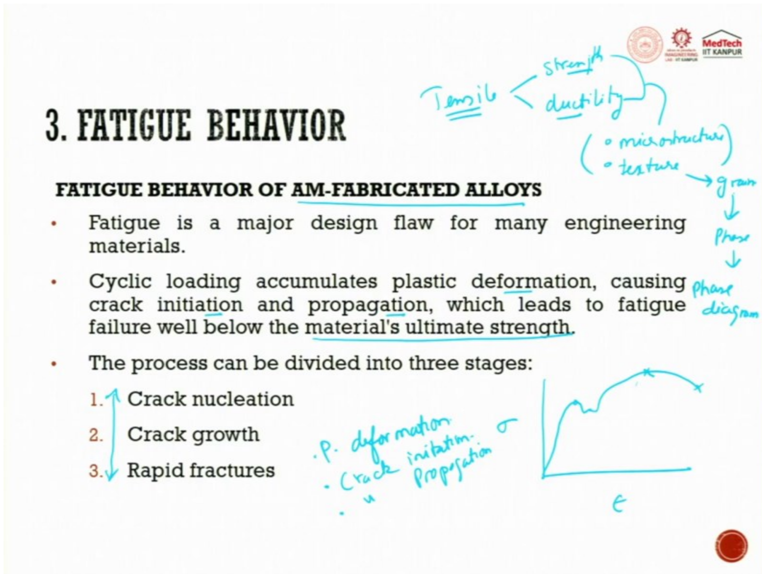

So, these are all for tensile behaviour. Predominantly if you see tensile property you have strength and ductility. Now, these two how do you tailor-make in with respect to microstructure and texture. So, with this, what we do is? We try to play with the strength and ductility of tensile. So, here all these things depend predominantly on grain.

Now, grain and inside a grain what are all the phase. So, all these things are just in a nutshell I have put these points. So, here you will get alpha phase, beta phase, austenite phase, bainitic phase, martensitic phase all these things you will get depending upon the, so, for all these things, what you are supposed to do is, you are supposed to go through the phases you are going to go through phase diagram.

And once you do an additive manufactured part, then you start looking into the phase diagram to identify all the phases which is there. So, what you are intended to make and what you achieve there will be a drastic difference, then what you do is you try to do post processing like annealing or something like that to get to the phase whatever you want. So, this will in turn dictate the strength and ductility that is all nothing more. So, this is the important nutshell of whatever we have discussed till now.

Now, let us move to fatigue behaviour. Fatigue behaviour is a very important thing because if you have a moving part, then the next thing comes is fatigue cycle. So, in fatigue cycle you can have tensile in one round and compressive in the other round or whatever it is you can have further classifications also.

Fatigue behaviour of additive manufactured alloy is also a hot topic for discussion, fatigue is a major design flaw for many engineered materials. Cyclic loading accumulates plastic deformation causing crack initiation and propagation which leads to fatigue failure well below the material ultimate strength.

So, when you try to do a tensile strength, you will see a higher ultimate strength, but when you put the component into fatigue cycle, even before the failure, it will die. For example, if you try to talk about steel, mild steel, you will have some response like this.

So, before even reaching to this point, it might fail somewhere here itself. So, why is that happening or even before reaching this point, it might fail here itself, why is that? Because it is undergoing a cyclic loading, which accumulates plastic deformation, crack initiation and propagation. So, deformation, of course, it is plastic, then the next point is crack initiation and next one is crack propagation.

So, these three are the steps which are involved in fatigue. So, the process can be divided into three stages, crack, nucleation starting, then crack growing, then the last one is rapid fracture. Crack initiation is very difficult moment you initiate a crack, then depending upon the cyclic load, the crack can grow very fast. Moment it starts growing then it is going to have a rapid fracture and you will try to have it into two pieces. So, these are the very important steps which are involved in fatigue behaviour of any given sample.

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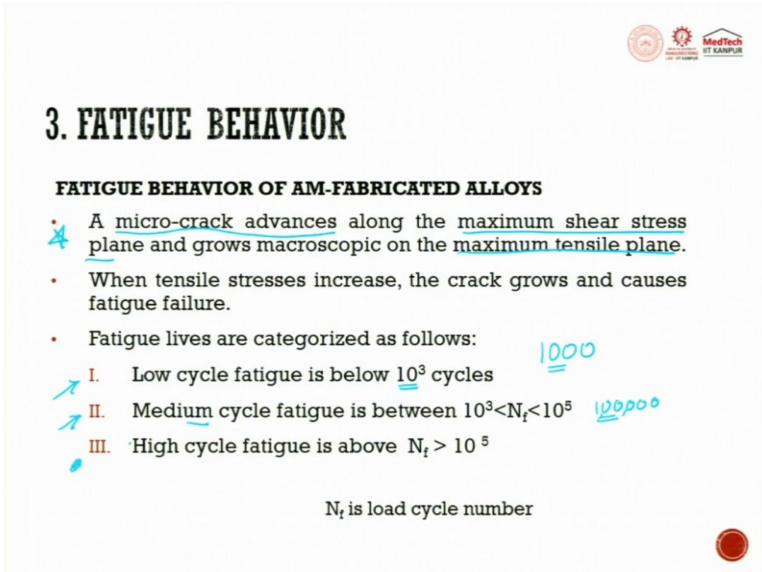

A micro-crack advances along the maximum shear stress plane this is very important micro-crack advances along a maximum shear stress plane and grows macroscopic on a maximum tensile plane very important point to note, micro-cracks advance along maximum shear strength plane shear stress plane and grows macroscopic on the maximum tensile plane. When tensile stresses increase the crack grows and causes fatigue failure.

The fatigue life are categorized into three, low cycle, medium cycle and high cycle fatigue. Low cycle fatigue is below 10^3 cycles, 10^3 is one two three 1000 cycles. Below 1000 cycles it is called as low cycle fatigue. So, for example, if you are trying to talk about bullet firing like Arjun tank bullet firing 1000 rounds is pretty huge. You use it for only 100, 200, 300 and maybe it has to come for refurbishment and other things it will happen rework all these things will happen.

So, here we use for low cycle fatigue is 1000, medium is somewhere between 1000 to 100000 cycle. So, here what we do is we look at all the bearings which comes under this category medium cycle. So, bearings are this cycle 100000 cycles and then low cycle 1000 then anything higher than 100000 cycle is called as high cycle fatigue.

So, we will try to develop our components additive manufactured components trying to hit at this portion, but we are very successful here and to this zone to a partial success we have received on final part fatigue testing. Apart from doing it on your coupons on the final part testing here these two row zones success is made, but here we are still struggling to get this success.

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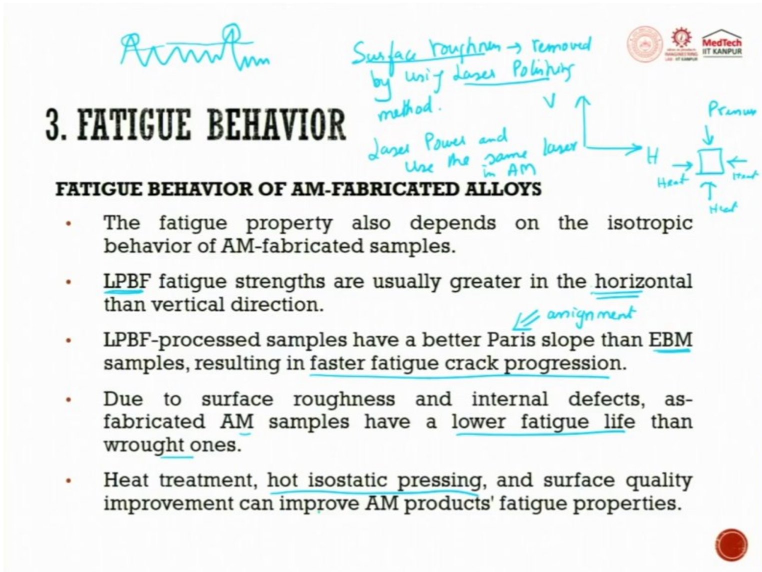

The fatigue property also depends on the isotropic behaviour of additive manufactured samples, laser powder bed fusion fatigue strength are usually greater in horizontal than vertical direction, horizontal is this, vertical is this. So, laser powder bed fusion technique, fatigue strengths are greater in horizontal as compared to the tough vertical. The laser powder bed fusion processed samples have a better Paris slope than electron beam machining or electron beam powder bed fusion samples resulting in faster fatigue crack progression.

This Paris slope I leave it to you as an assignment. So, please check in the fatigue behaviour of samples you will see this Paris slope you try to understand what this Paris slope and then you can try to interpret this statement. Laser powder bed fusion processed samples have a better Paris slope than electron beam machining. Resulting in faster fatigue crack progression. Due to surface roughness and internal defects, fabricated additive manufactured samples have a lower fatigue lifecycle than wrought ones.

So, this surface roughness and internal defects can be nullified by using post processing. For example, today we are trying to talk about surface roughness in metal samples to be removed by using laser polishing method. So, here the idea of laser polishing is to try to reduce the laser power and use the same laser in AM.

So, in the same machine, first you will try to use the laser power for making an additive manufactured part, next you use the same laser, you try to reduce the power or you try to go to the defocused zone, energy reduces and then try to melt the surface sothat it can slowly start flowing.

So, here the surface roughness, why it is supposed to have peaks like this. So, here you need the surface area is too small and it is almost a point. So, laser when it is exposed, even at a lower temperature it softens and it starts so, that it can do the polishing operation and you get a better surface finish.

Due to surface roughness and internal defects as fabricated AM samples have a lower fatigue life than wrought ones. So, what we do is we try to do heat treatment and we try to do surface roughness polishing methods. So, heat treatment- hot isostatic pressing means, you place the component and you apply pressure and you also apply heat.

Isostatic means uniformly you are applying heat as well as pressure so, that the sample small porosities and other internal defects cracks it can be compressed and it will try to remove small wires which are there on the on just below the surface also it cannot remove, but it will try to compress and it will try to re-spread the material. Hot isostatic pressing and the surface quality improvement can improve additive manufactured products fatigue property.

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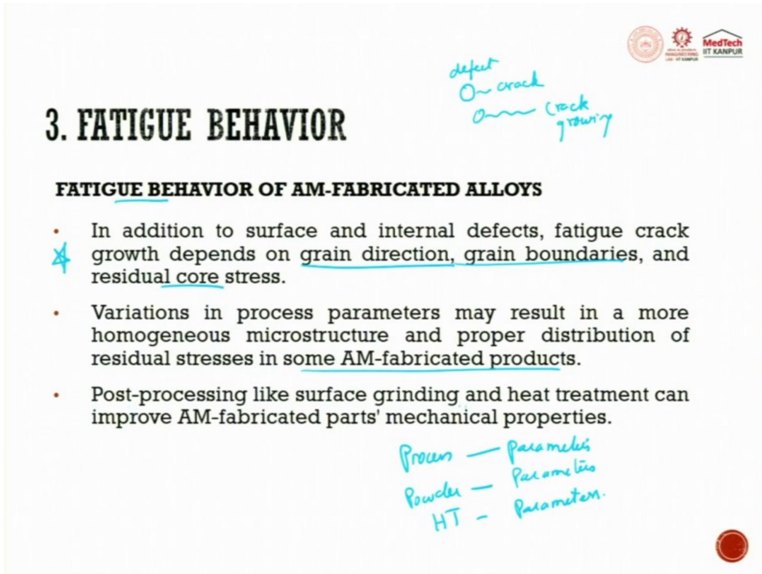

In addition to the surface and internal defects fatigue crack growth depending on the grain direction grain boundary and residual core stress, very important point it is not only because of the defect, crack and crack growing. It is also because of grain direction, grain boundaries and residual core stresses. These things also influences the crack propagation and reduces the fatigue behaviour of additive manufactured samples.

Variation in process parameters may result in a more homogeneous microstructure and proper distribution of residual stresses in some additive manufactured products. So, finally, it looks like process. In process you have parameters, you have powder, parameters and you have heat treatment. Again it is process parameters which all has to be optimized such that you can produce a good quality output of additive manufactured part. Post processing like surface grinding and heat treatment can improve the additive manufactured parts mechanical properties.

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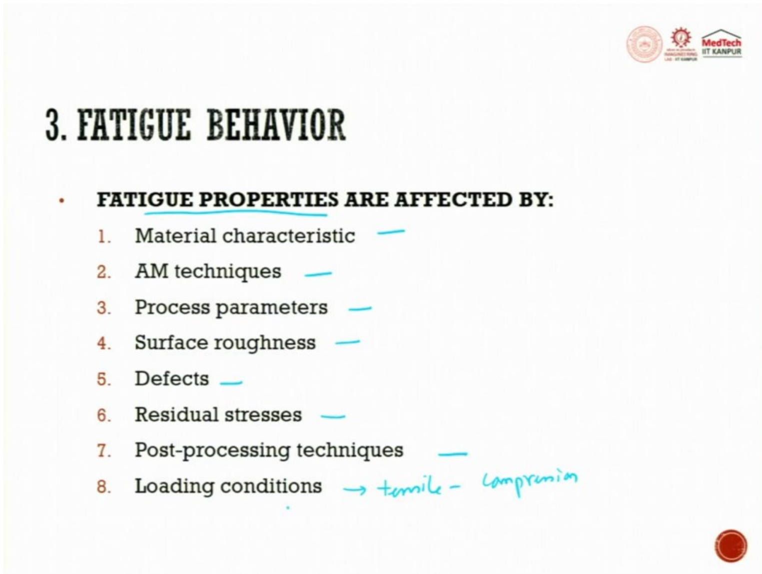

The fatigue properties are affected by material characteristics, AM technique, process parameters, surface roughness, defects, residual stresses, post processing techniques and the loading conditions. All these things have a direct influence on the fatigue properties of your additive manufactured sample technique material characteristics, process parameters which we discussed, roughness which is an output which gets, defects again it is an output which comes, residual stresses are again an output parameter depending upon the process parameter technique and material characteristics.

Then you go into post process treatment again here you can do, aging, you can do annealing, normalizing, quenching whatever it is, you try to do so to get output and finally, the loading condition place. Loading condition is tensile, compression then you can have same loads, varying loads, tensile tensile, tensile compression, compression compression, all these things are loading conditions which come at the part.

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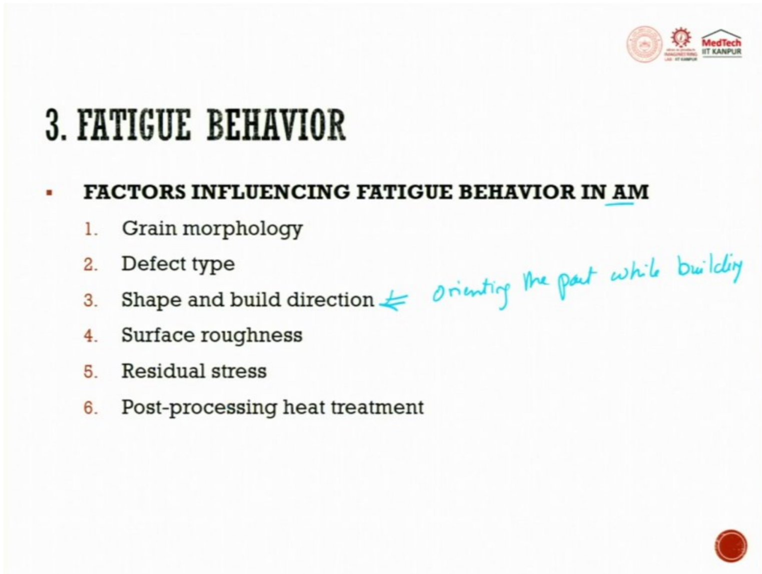

The factors affecting the fatigue behaviour in AM is grain morphology, defect type, then you have shape and build direction, which is very important orienting the part while building this is very important, shape and building direction is orienting the part while building then surface roughness, residual stresses, post processing heat treatment. All these things play a very important role. Grain morphology, defects types, shape and build direction, surface roughness, residual stress and post processing heat treatment all these things influence the fatigue behaviour of additive manufactured part.

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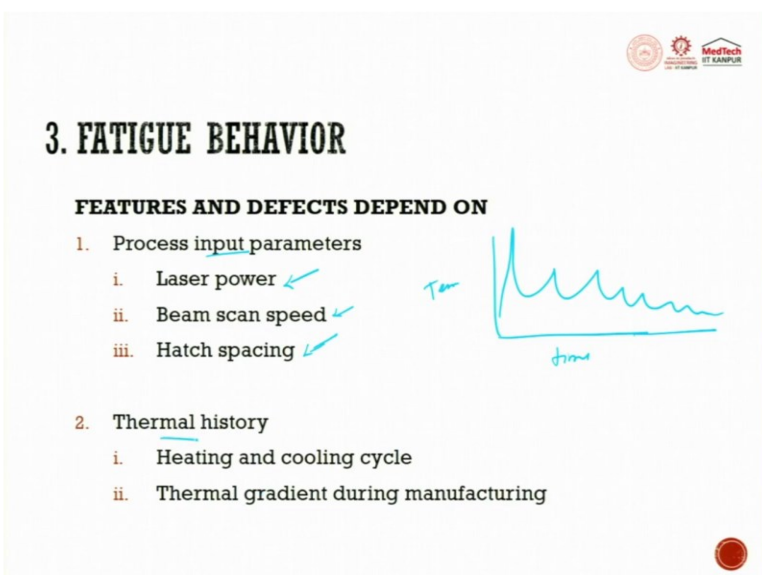

When we talk about the process input parameters, laser power, beam scan speed and hatch spacing all these things play an important role as far as input parameters are concerned. The thermal history heating and cooling cycle plays a very important role that is what we saw in the last class, temperature versus time. So, this is the heating and cooling cycle which is happening when you start printing it layer by layer by layer then thermal gradient during the manufacturing is the ambience and at the point of doing. So, this is thermal history.

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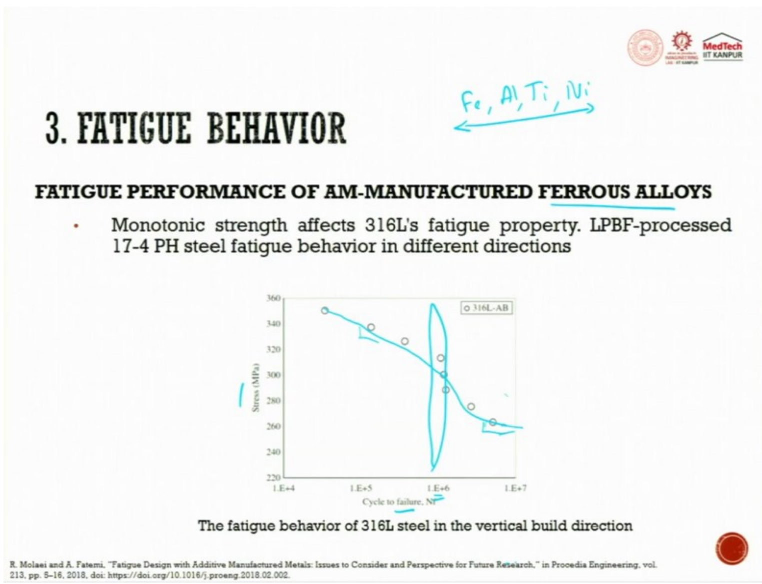

When we look at the fatigue performance of ferrous alloys like last time, I will compare your ferrous, aluminium and titanium, nickel also. So, these are the four common alloys which we are focusing and if you want you can start looking into these four phase diagrams. And in this phase diagram also you have certain combinations, you can look into those combinations and find out all the different phases.

So, monotonics strength affects 316L fatigue property, laser powder bed processed 17-4 PH steel fatigue behaviour is in different conditions are shown here. So, this is TI6L which is a part stainless steel which is made and then you have this cycle of fatigue and stress, you can see it slowly fall down.

So, here this is the limiting one. So, 10^6. So, now 10^6 you see there are almost three samples and then onwards you see there is a strong declination. So, the slope over here, the slope over here will be completely different, it can be very high here, the slope will be very low here, the gradation change will be very low in terms of stress.

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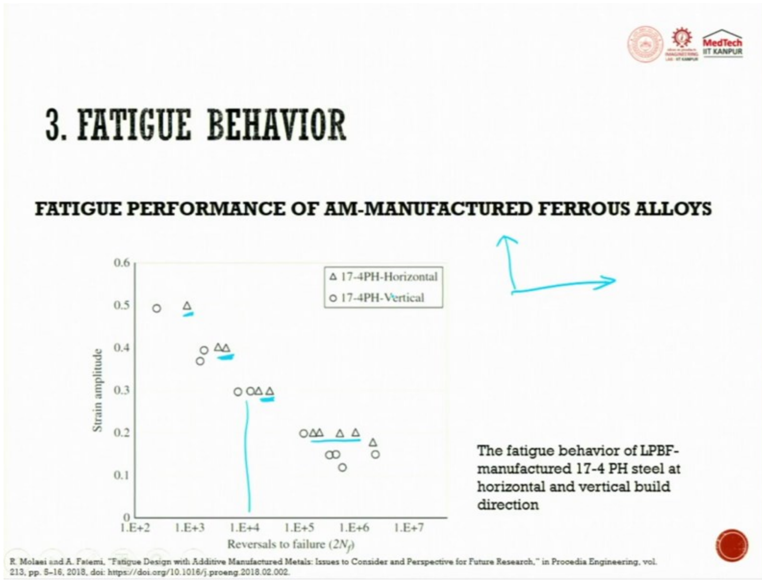

So, when we try to look into the strain amplitude with respect to the reversal of failure, which is $2N_f$ you can see here, this is 17-4PH horizontal direction. This is horizontal and these are vertical. So horizontal along the horizontal along the vertical, they have accumulated the strain amplitudes. In the experiment they strike to see what is the strain it can do it and then you get the output. So, if you see that up to 10^4 it is almost same and afterwards you can see that vertical direction there is a reduction but whereas, in horizontal direction there is a slow reduction.

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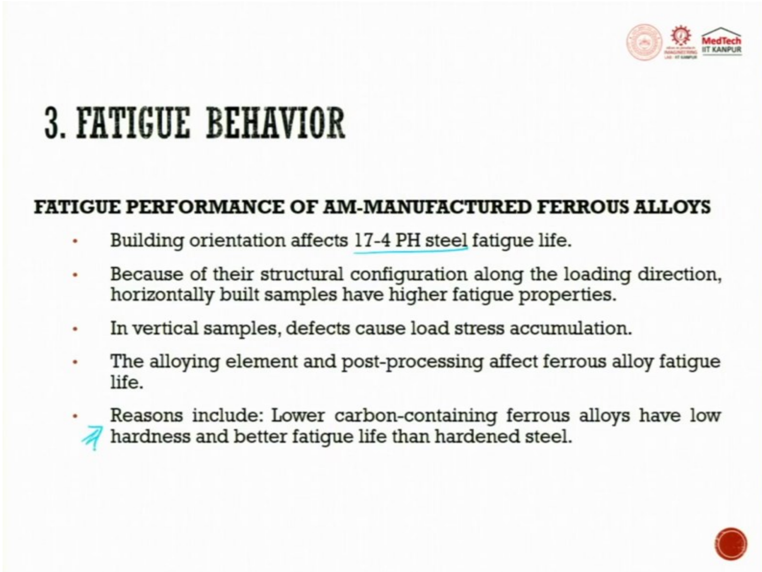

The fatigue performance of AM manufactured ferrous alloys are building orientation affects the 17-4 PH steel, this is a type of PH steel. You have to only worry about steel 17-4 PH steel fatigue life, because of their structural configuration along the loading direction, horizontal build samples have higher fatigue properties. In vertical samples that defects cause low stress accumulation.

So, the properties are low in the vertical direction. The alloying element and post processing affects the ferrous alloy fatigue life the reasons include low carbon containing ferrous alloys have low hardness and better fatigue life than hardened steel. This is the major reason for it. Fatigue life response with respect to AM part.

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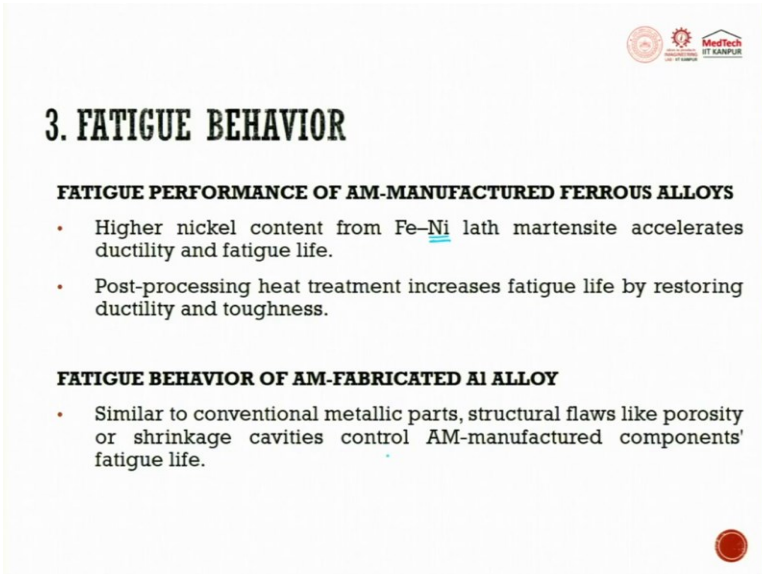

Next, higher nickel content from Fe-Ni lath martensite accelerated ductility and fatigue life, this is nickel because of nickel. The post processing heat treatment increases fatigue life by restoring ductility and toughness, post heat treatment post processing. The fatigue life of AM of aluminium alloy you can see similar to the conventional metallic part structural flaw like porosity or shrinkage cavity controls the additive manufactured part.

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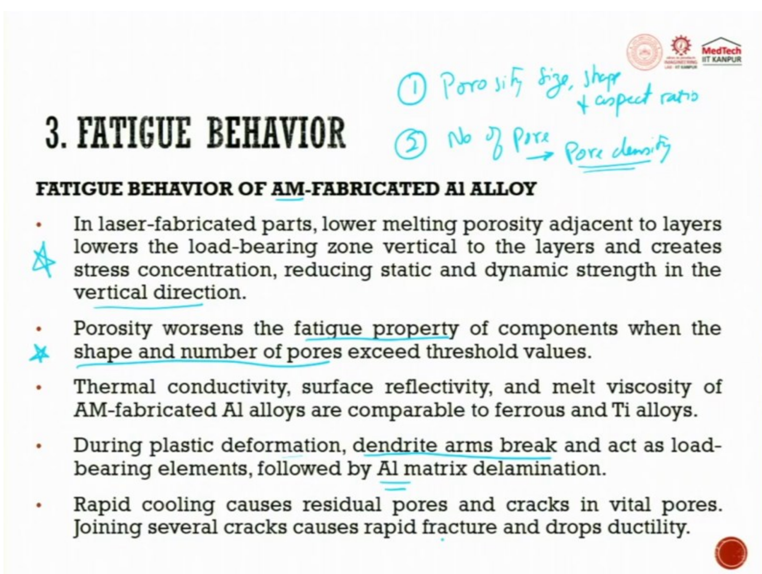

The laser fabricated part lowering melting porosity adjacent to layer lowers the load bearing zone vertical to the layer and creates a stress concentration reducing static and dynamic strength in the vertical direction. Why is it reducing in the vertical direction? This is also an important inference which you have to look into in laser fabricated parts lower melting porosity adjacent to layer lowers the load bearing zone, lower melting porosity adjacent to a layer next to a layer. Lowers the load bearing zone vertically to the layer and creates stress concentration reducing static and dynamic strength in vertical direction. The porosity worsens the fatigue property of the component when the shape and number of pores exceeds the threshold value.

So, this is very important point you should note there are two things we are talking about, one is the porosity size, shape and aspect ratio. The second thing what we are trying to say is number of pores. So, this is called as pore density. If the porosity or number of pores, if it is more than naturally it will try to worsen the fatigue behaviour.

So, this pore density or porosity density is another important parameter they measure when we do additive manufactured samples, in a bulk or in a normal conventional way such porosities do not occur to a large extent or if you are very well established these pores can be avoided. But in additive manufacturing because of the process dynamics and thermo mechanical behaviour of the material, you will try to have pores, shrinkage happens because there is a melt pool in melt pool we have a keyhole effect. So, this will lead to pores formation.

The thermal conductivity, surface reflectivity and melt viscosity of additive manufactured fabricated aluminium alloys are comparable to ferrous and titanium alloys. During plastic deformation, dendritic arms breaks and act as a load bearing element followed by aluminium matrix delamination. So, this is how the failure happens in aluminium.

The dendritic arm breaks and acts as a load bearing element followed by aluminium matrix delamination. Rapid cooling causes residual pores and cracks in vital pores. Joining several cracks causes rapid fracture and drops the ductility which we saw in the beginning. So, crack formation, crack growth and rapid fracture three steps are there.

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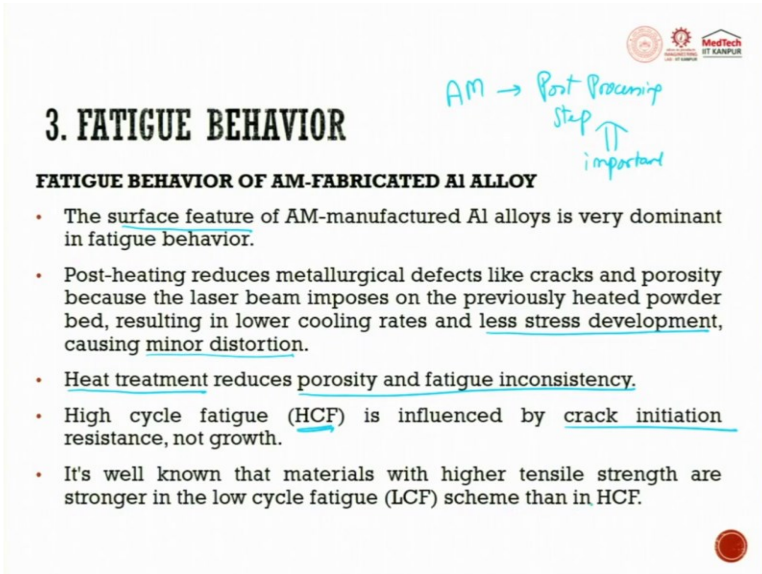

The surface feature of additive manufactured aluminium alloy is very dominating in fatigue behaviour surface feature. The post heating reduces the metallurgical defects like cracks and porosity, because the laser beam imposes on the previously heated powder bed resulting in lower cooling rates and less stress development causing minor distortion, less stress development. Heat treatment reduces porosity and fatigue inconsistency.

So, what is important is in AM the post processing step plays a very very important role because it changes the grain structure and it also texture the high cycle fatigue is influenced by crack initiation resistance not growth, high cycle fatigue is initiation only. It is well known that the material with higher tensile strength are stronger in low cycle fatigue scheme than the high cycle fatigue.

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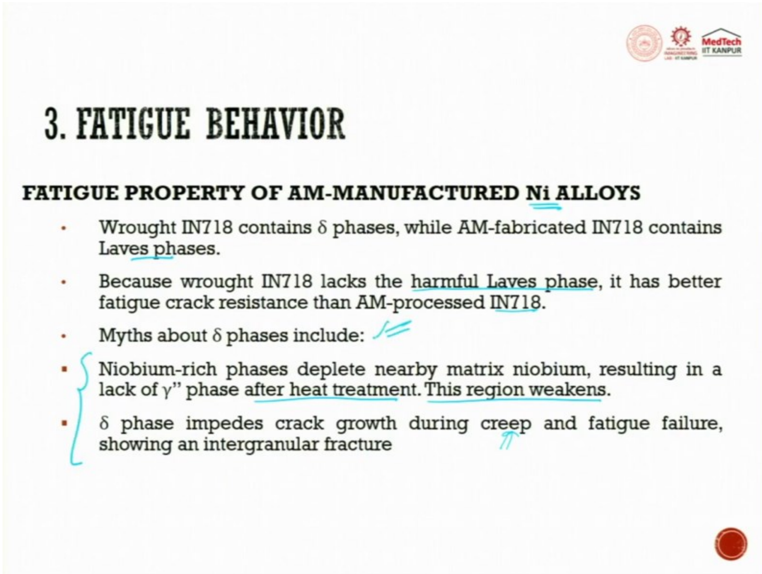

When we talk about nickel alloys as I told you ferrous aluminium then we will go to nickel and last we will see titanium. Wrought Inconel 718 contains γ phase while AM fabricated Inconel 718 contains laves phase. It produces a different phase itself because wrought Inconel 718 lacks the harmful laves phase.

It has better fatigue crack resistance than AM processed Inconel 718 with about γ phase includes niobium rich phase deplete nearby matrix niobium resulting in a lack of γ" phase after heat treatment, this region weakens. The δ phase impedes crack growth during creep and fatigue, creep is time verses load fatigue failure showing an inter granular failure. So, these two points are very important, this is the myth which generally people try to think.

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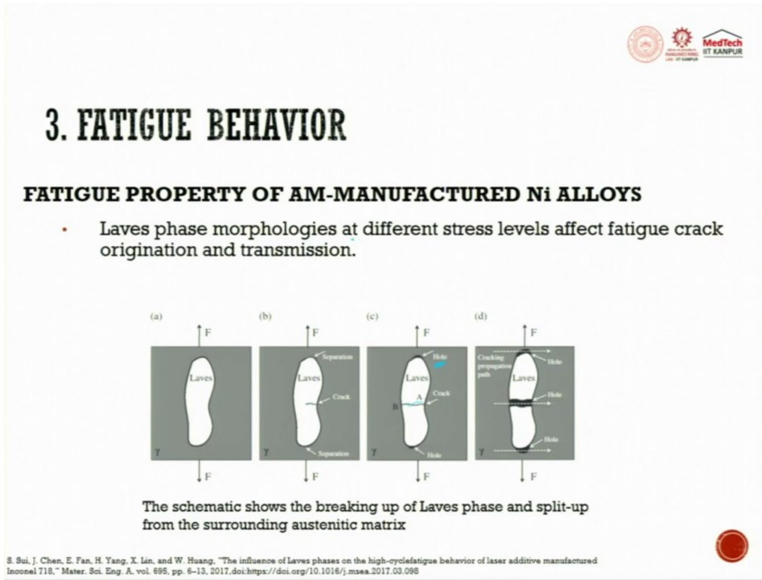

So, laves phase morphologies at different stress levels affect fatigue cycle, orientation and transmission. This is laves you have force. So, you see a crack which is happening then there is a separation. Then there is a hole which is getting created there is a crack which is getting formed. Now, there is a hole at the top and then there is a hole at the bottom. So, here there is a breaking of laves top bottom. So, the laves phase morphologies at different stress levels affects the fatigue crack orientation and transmission.

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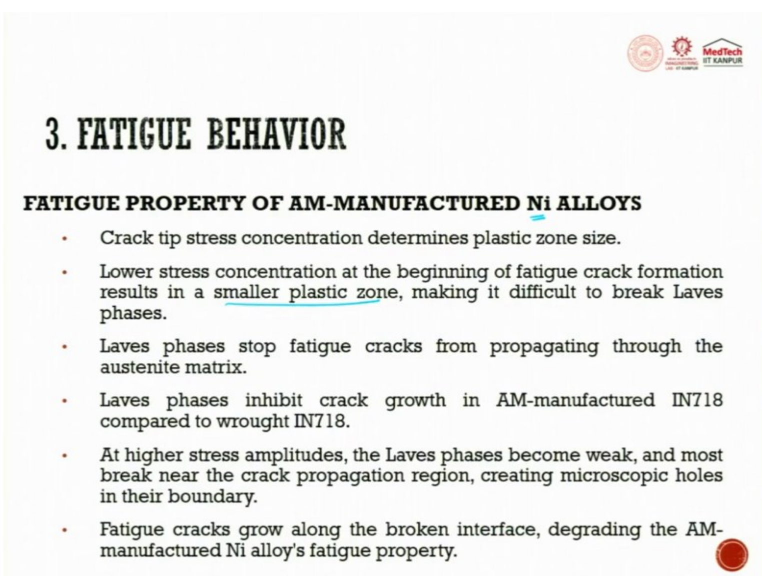

The fatigue behaviour of Ni alloys, the crack tip stress concentration determines the plastic zone size. Low stress concentration at the beginning of the fatigue cycle, fatigue crack formation results in smaller plastic zones making it difficult to break laves phase. Laves phase stop fatigue crack from propagating through the austenitic matrix.

Laves phase inbuilt crack growth in additive manufactured Inconel 718 compared to that of wrought 718 as at high stress amplitudes at higher stress amplitudes the laves phase become weak and most break near the crack propagation region creating microscopic holes in the boundaries. The fatigue crack grow along the broken interface degrading the additive manufactured nickel alloy fatigue property.

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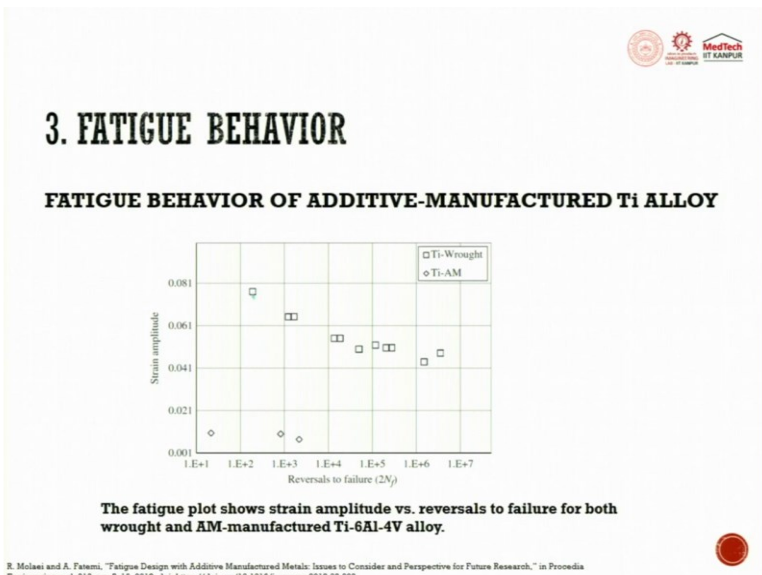

The fatigue behaviour of additive manufacture is shown here. So, you have strain accumulation and reversal or to failure you can see for titanium wrought it is here and for titanium additive manufacturing it is here.

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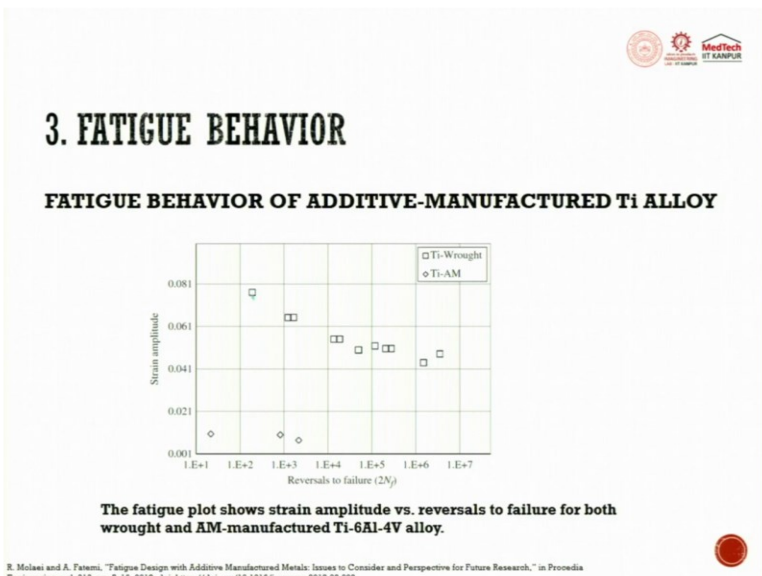

So, now for titanium alloys additive manufactured alloys have shorter fatigue life than wrought alloys. Internal defects which acts as micro notches and causes and cause stress accumulation greatly affect the AM alloy fatigue property. The post processing treatment removes or shrinks pores preventing them from fatigue failure.

AM manufacturer alloy show less cyclic softening than wrought alloys. This behaviour is due to poor ductility of additive manufactured alloy and shorter fatigue life. So, in titanium still we have a long way to go as compared to the tough Ti wrought and Ti AM. So, titanium still lot of work going on and heat treatment cycles are thought of to play a very important role.

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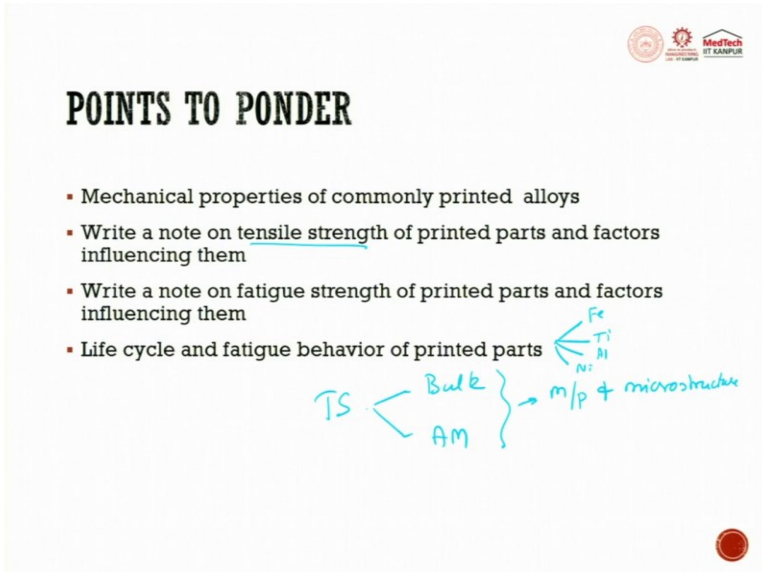

So, in this lecture, what did we see was, we saw mechanical properties of commonly printed alloys. We also write a note on tensile strength of printed part and factor influencing them, I have given you two, three assignments in between, so, which you will use it for yourself learning and you also make a note on tensile behaviour. So, tensile strength TS for a bulk and for AM part, try to do it. Look and discuss in terms of mechanical property and microstructure, make a note of it.

So, this will try to give you or more insight about it. Then, write a note on fatigue strength of printed parts and factors influencing them, we have listed all the factors lifecycle we talked about three types, low cycle, medium cycle, high cycle. Life cycle and fatigue behaviour of the printed parts was also discussed for four different alloys, one is Fe, the other one is Ti, Al and nickel.

So, all these things were discussed in detail. So, you please study them properly in the examination you can have cross correlation questions where in which you have to take the phase and then try to see what will be the response in tensile strength as well as in fatigue behaviour.

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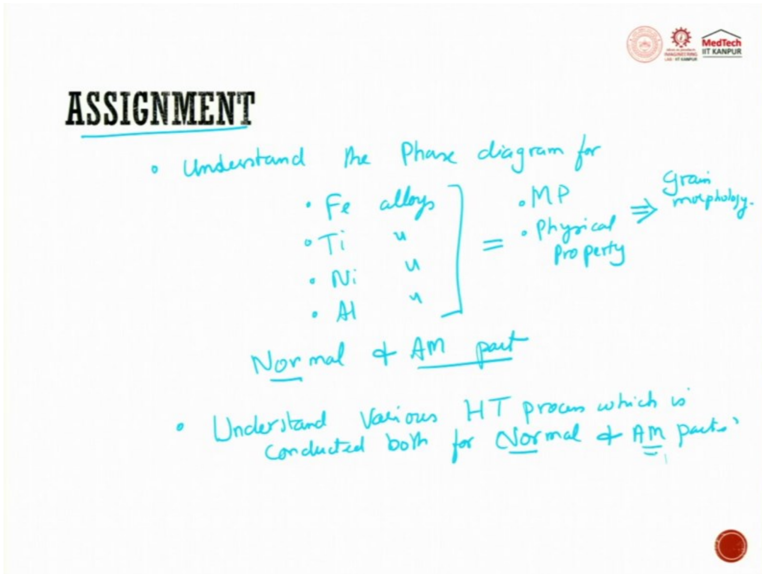

The assignment I have already given understand the phase diagram for iron alloys, next is titanium alloys, next is nickel alloys and the last one is aluminium alloys. You have to focus in the mechanical property and physical property and this in turn has to be related to grain morphology. So, this is for normal and AM part.

The next one is try to understand various heat treatment process which is conducted both for normal and AM parts. For example, normal you can say annealing, normalizing, aging, then you can also think of carburizing all these things, you write it down understand the process and then you try to see in AM what all can be done such that their performance can be enhanced. Thank you very much.