Metal Additive Manufacturing

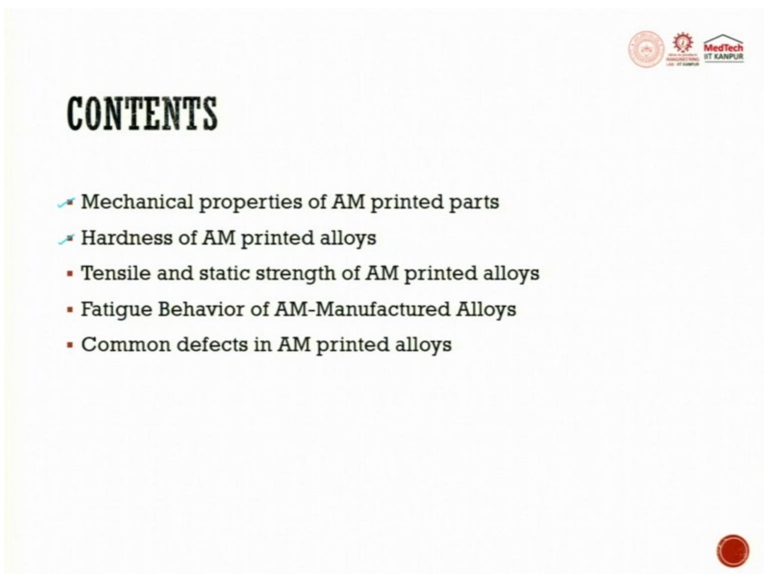
Prof. Janakranjan Ramkumar
Prof. Amandeep Singh Oberoi
Department of Mechanical Engineering and Design
Indian Institute of Technology, Kanpur

Lecture 17

MAM Printed Parts: Mechanical Properties, Hardness

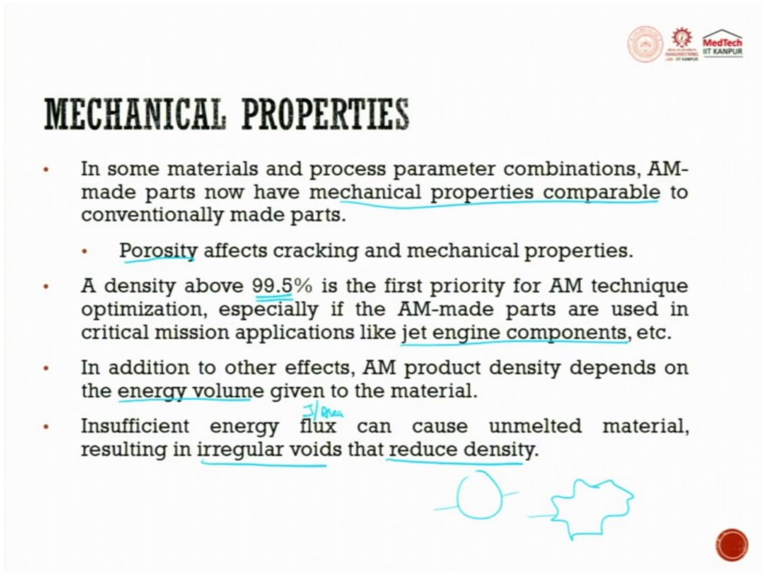
Welcome to the next lecture in the series of Metal Additive Manufacturing. Now, we have made a part, how do we characterize the part we have made? And how do we evaluate the quality of the print will be our prime focus in this lecture. So here we will discuss about mechanical properties.

(Refer Slide Time: 0:42)



So I have split the lecture into two parts. In the first part, I will try to cover mechanical properties of additive manufacturing printed parts, and hardness of additive manufacture printed alloys. I will try to cover the tensile static strength, fatigue behaviour, and common defects in additive manufacturing printed alloys in the next lecture.

(Refer Slide Time: 01:15)



In some materials and process parameter combination, additive manufacture made parts now have mechanical properties, which are comparable to that of conventionally made parts. The mechanical properties are comparable. In the lecture series, we have also seen how microstructure can be tweaked so nicely by using additive manufacturing techniques.

Porosity affects cracking and mechanical property. So this porosity today is avoided in a big fashion. So this porosity could be because of thermomechanical properties of the metal powder, and the laser process parameters. Since the characterization tools have gained, lot of importance and the accuracies have strengthened a lot in this characterization techniques, now porosities can be measured easily through non-destructive testing methods.

Once you establish the process, you evaluate the part through non-destructive testing ways in order to figure out where there are any porosities present or not. These porosities can be on the surface, in between the inner surface and outer surface, it can be in the inner surface also. So porosity affects cracking because porosity is this.

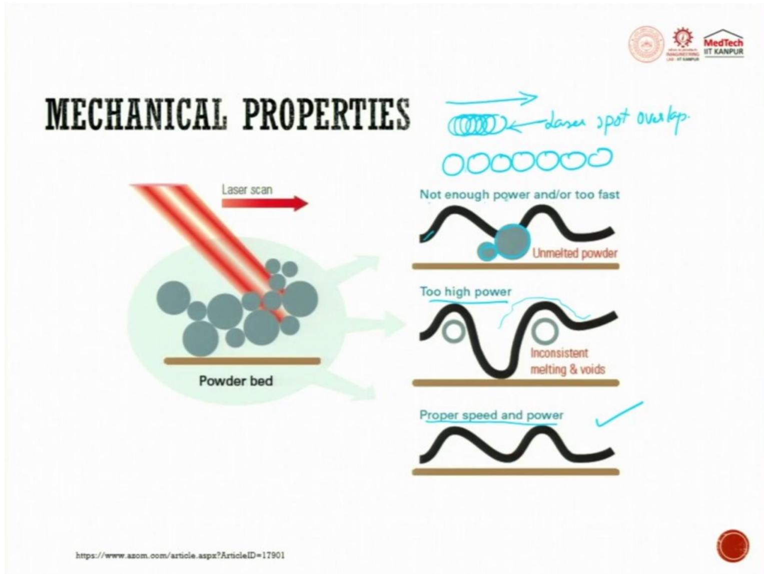
So these porosities affect cracking. And it also tries to reduce the mechanical properties. When we talk about porosities, these porosities are not circular in shape. They are random in shape. And when the crack comes, the energy can be diverted or it can lead for further cracking and chipping off. So porosities are very much thought of, and it is to be avoided.

The density above 99.5% is the first priority for additive manufacturing techniques optimization, 99.5. In the beginning, metal additive manufacturing, people were talking about 60%, then they moved to 80, then they went to 90, 95, 98, then 99. Today we are talking about 99.5% densification, especially if the additive manufactured made parts are used in critical mission applications like jet engine components.

In jet engine components, there is always a fatigue cycle coming into existence in the service condition. This fatigue cycle can be thermal fatigue, or it can be the mechanical fatigue. In addition to the other effects, additive manufactured product density depends on the energy volume given to the material. We saw what is energy volume while discussing about lasers.

Inefficient energy flux. What is flux? Flux is nothing but joule per area or power per area. Flux can cost unmelted materials. Unmelted materials can happen because the power is too low or the feed rates can be enormously high. It does not give much time for interacting the laser with the metal powder resulting in irregular voids and reducing the density. Many a times, the irregular volume evolves or pushes smoke. This smoke also tries to get trapped in between the molten portion. So that also tries to reduce the density.

(Refer Slide Time: 05:34)



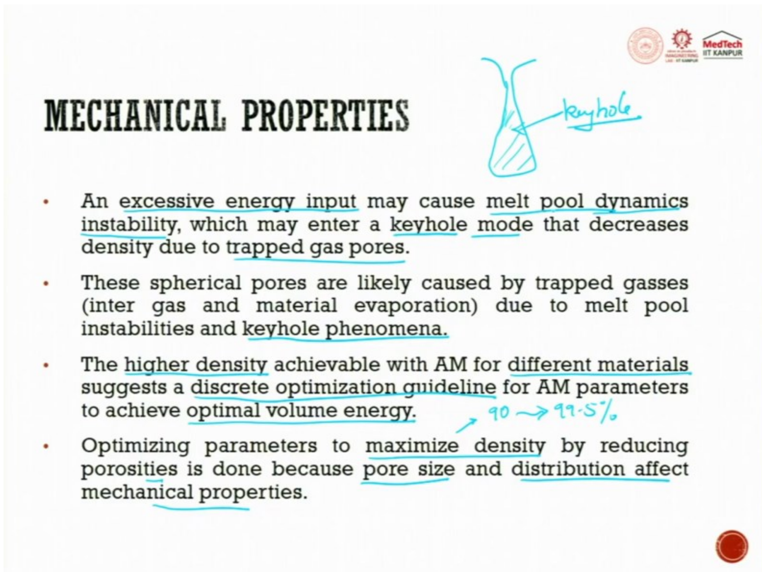
When the laser hits at the powder bed, you can see laser hitting at it, you will have small particles, you will have large particles. So here, you can see not enough power and it is too fast. That is what I said. So if the feed rates are very high, if the feed rates are very slow, you will have overlaps like this. When the feed rates are very slow, so it is moving in this direction and these are nothing but laser spot overlap.

When the laser feed rates are high, you can try to see, this is how the spots will be created. So you will see jumping and in between, you can have layers of metal powders, which are not even molten or which has not even melt. So here, you have not enough power and too fast of movement, you can see unmelted powder particles present.

These unmelted powder particles, when it is done, layer on layer on layer can get trapped and it occupies a space. Sometimes it occupies a space. Sometimes this can be removed while processing, and you have two big voids. The next thing is when you use too high power, you can say that inconsistency of melting happens when you use too heavy a power or too high a power. So you can see here, the melt pool will try to move.

And then what happens? You try very high power. So the liquid flows and it tries to cover up the particles. And this is a problem when you use too high a power. When you use a proper speed and proper power, you will see not any or not many powder particles are present. So we will always choose a proper power and a speed to get very good quality additive manufactured parts. So not enough power, not too high power, these two are used.

(Refer Slide Time: 07:55)



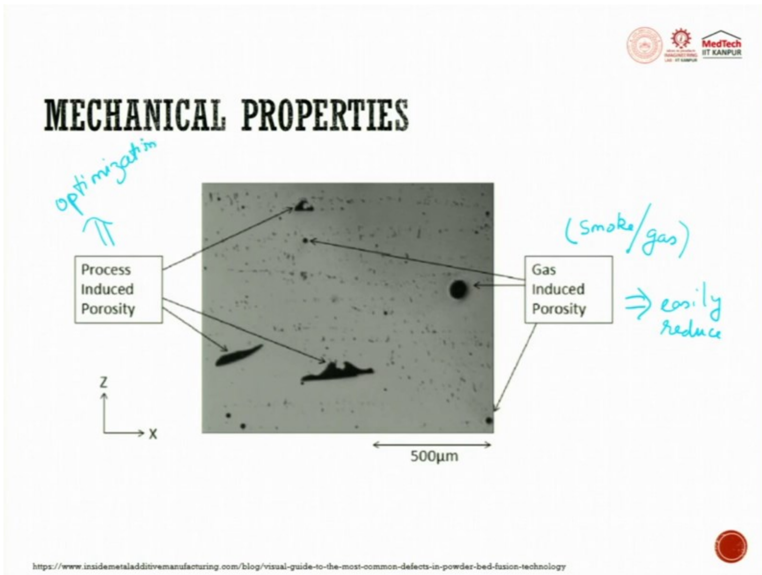
And excessive energy input may cause melt pool dynamics instable or instability in melt pool dynamics will be introduced when we use excess energy power, which may enter a key hole mode that decreases density due to trapped gas pores. Say, for example, keyhole, something like this. You will see, it will try to, and then here, this is a keyhole, so that this is a melt pool. And here, this is keyhole.

So when we use excess power, it tries to introduce melt pool dynamics instability, and it leads to keyhole effect. This keyhole effect leads to gas entrapment in the pores. These spherical pores are likely cost by trapped gases, due to melt pool instability and keyhole phenomena. So like Marangoni effect, you also have something called as keyhole phenomena, which is very common when you do laser matter interaction.

The higher densities achievable with additive manufacturing for different materials suggest a discrete optimization guidelines for additive manufactured parameters to achieve optimum volume energy. In order to achieve higher density, different materials suggest a discrete optimization guidelines. The optimization parameters to maximize density by reducing porosity, so maximization of density.

So from 90, you are moving towards 99.5%. So when you start moving towards that, so what happens is the pores size will go down or number of pores will go down. By reducing the porosity is done because the pore size and the distribution effect, distribution affect the mechanical property. So the keyhole effect is brought in because of the melt pool dynamic instability.

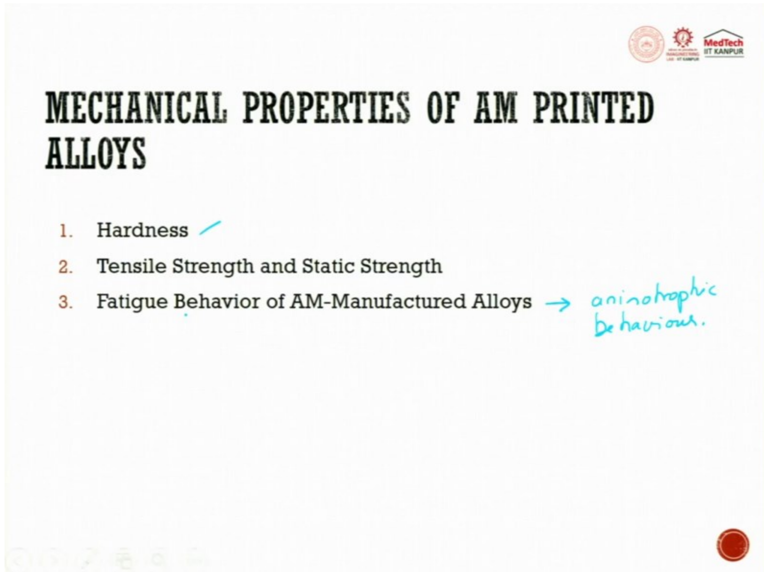
(Refer Slide Time: 10:16)



So a cross section of the metal additive manufactured part, you can see, gas induced to porosity. What is gas induced porosity? It is maybe the smoke, whatever is getting evolved or the gas, whatever is there, which created by the laser movement. So that gas gets trapped completely in the molten pool. So that leads to gas induced porosity. So gas induced porosity, to a large extent, it will be circular. You can get varying size and varying shape, but predominantly it will be circular. When you try to have process induced porosity, they will have different, different shapes and size.

So this is basically process induced porosity. This can happen because of shrinkage and the surface tension viscosity of the liquid, the liquid did not properly flow, and you had something like a keyhole effect, which completely trapped these porosities. So you can have gas induced porosity, you can have process induced porosity. This gas induced porosity can be easily, easily reduced, but this process induced porosity. You have to do a lot of optimization in the process to develop the required output.

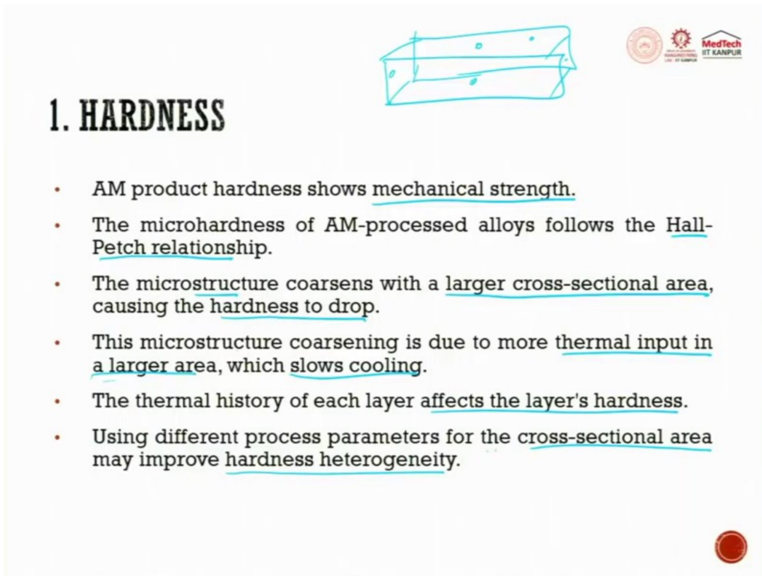
(Refer Slide Time: 11:45)



When we talk about non-destructive way of evaluating the mechanical properties, we generally start with hardness, tensile strength, static strength, and fatigue behaviour of additive manufactured alloy. Why is this important? Because in a metal additive manufacturing, we talk about layer by layer approach. In layer by layer, we try to introduce anisotropic behaviour.

We try to introduce anisotropic behaviour. So this anisotropic behaviour, when you put the component for fatigue behaviour test, it fails miserably. So that is why we try to evaluate the metal, metal additive manufactured parts for hardness, tensile strength, static strength, and fatigue behaviour to evaluate the quality of the output. All these things are part of destructive technique of evaluation.

(Refer Slide Time: 12:50)



Hardness. Additive manufactured product hardness show mechanical strength. Hardness, we directly or indirectly link it up with mechanical strength. The micro hardness of additive manufactured process alloy, follow the Hall-Petch relationship. So as your assignment, you are supposed to figure out what is Hall-Petch relationship, what is its effect with respect to mechanical behaviour. This is an assignment for you.

The micro structural coarsening with a large cross section area causing the hardness to drop. So, when the microstructure becomes large, then there is a drop in hardness. So, if the grain size is large, there is a drop in hardness. This microstructure coarsening is due to more thermal input in large area, which slowly cools or which slows cooling. So more thermal input in a large area, which slows cooling.

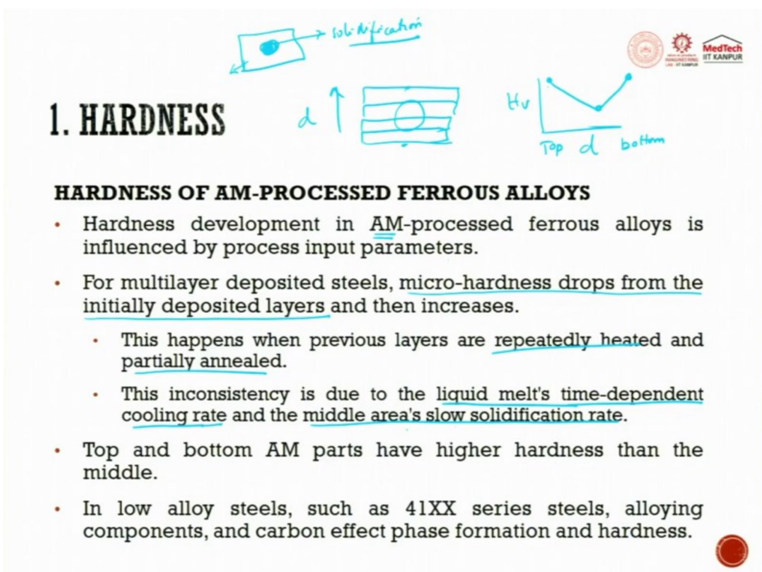
Why? Because you are trying to do, as I said, when you optimize the feed rates, or when you are trying to do one layer and the second layer, between these two layers, if you can, you can have 30 % in the new layer and 60 % in the next layer or 50-50, then this is what is happening. The micro structure coarsening, the grain will start growing, is due to the, is due to more thermal input in a large area.

So the grain has enough energy, so it starts growing. And then, which slows cooling. The thermal history of each layer affects the layer hardness. So from layer to layer to layer, that is a difference in hardness behaviour, which is not a common phenomena in conventional machining. In conventional machining, you measure anywhere in the block, you will try to have the same hardness.

You measure it here, measure it here, here, or here, wherever you measure, or here in the backside, you will try to get the same hardness, but whereas in additive manufactured parts, since you are doing layer by layer, and there is lot of solidification happening on a thin area, you will try to have hardness variation. So that is what is micro structural coarsening also it can happen because of the thermal input.

Using different process parameters for the cross-section area may improve hardness heterogeneity. Using different process parameter for the cross-section area, so maybe the outer layer is done with a different speed, feed rate and internal hatching will be done in a different speed rate and power. So that is what it says, using different process parameters for the cross-section area may improve the hardness heterogeneity.

(Refer Slide Time: 15:46)



Hardness developed in additive manufactured processed ferrous alloy is influenced by process input parameters of additive manufacturing. For multilayered deposited steel, for example, dye steel or duplex steel, micro-hardness drops from the initial deposited layer, and then increases. The micro hardness drops from the initially deposited layer, and then increases.

So initially deposited layer, micro-hardness drops, so this is distance. So if you try to talk distance with respect to d, it says, the micro hardness drops from the initial deposited layer, drops from the initial deposited layer, and then slowly increases. This happens when previous layer are repeatedly heated and partially annealed. Very important parameter.

Repeated heating and partial annealing happens when we do in the additive manufacturing. This inconsistency is due to the liquid melt's time-dependent cooling rate, and the middle area slow solidification rate, two important phenomenas. One is liquid metal time-dependent cooling rate, the other one is middle layer, slow solidification rate.

What are we trying to say? If you have this layer, so here in the centre, it will be slowly cooling. That is what it says. Middle area slow solidification rate and liquid metal time-dependent cooling rate. So here it, is cooling rate, and here it is solidification rate. So both things try to dictate the output. That output is nothing but the hardness.

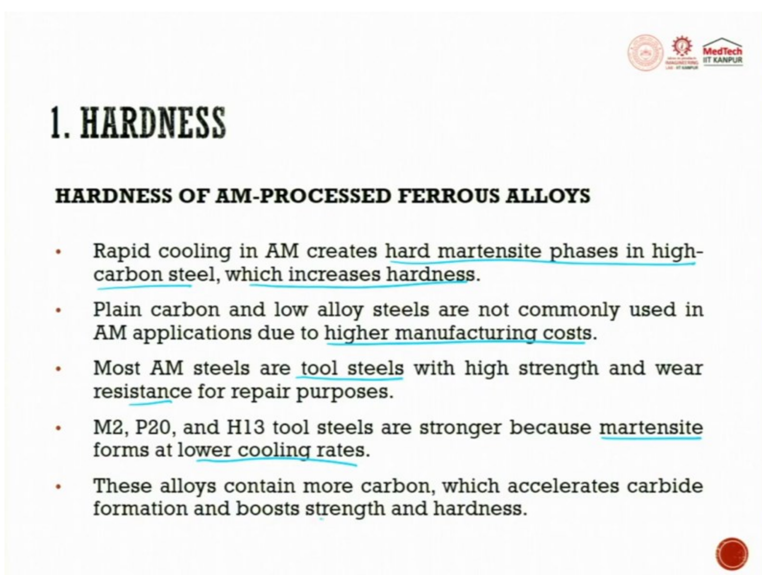
Top and bottom additive manufactured parts have higher hardness. Top portion and the bottom portion have higher hardness than the middle portion. So here you will have lesser hardness. So you will have lesser hardness. If I change this graph and I say, this is top, this is middle, and this is bottom.

So this is top and this is bottom, and you have, this is the d. So it will decrease. So the top and bottom additive manufacture parts have higher hardness than the middle. In low alloy steels, such as 41XX series steel, steel, alloying components and carbon effect phase formation and hardness generally happen.

(Refer Slide Time: 18:41)

So if you look at low alloyed steel for additive manufacturing, this is AM designed by Porsche, so you can see here, here, you can have 20MnCr5, low alloyed steel. So it has a very high strength and ductility. The gear has very high or very excellent wear assistance. It has inherent toughness in it. It has very easy for machineability and it has no nickel in it. So it gives a better performance.

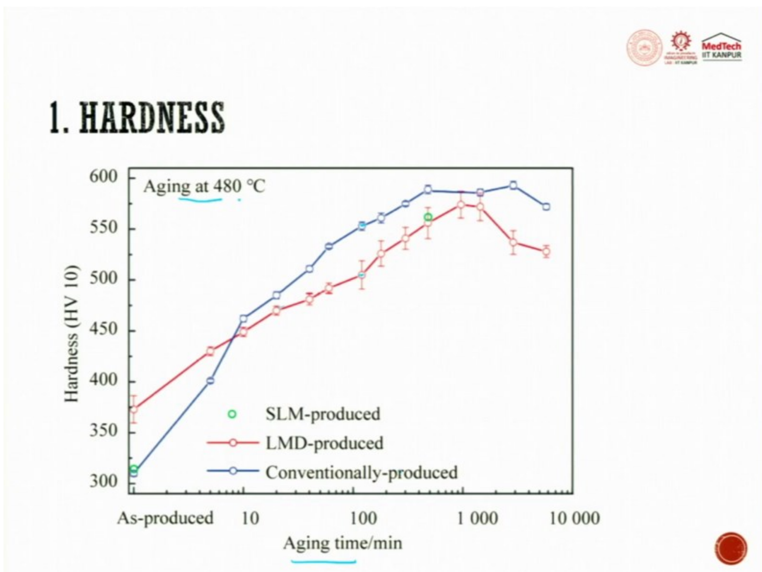
(Refer Slide Time: 19:08)



So when we try to talk about hardness of additive manufactured or processed ferrous alloys, rapid cooling in additive manufacturing creates hard martensitic phase in high carbon steel, which increases the strength. Rapid cooling, when you do rapid cooling, the C, carbon, whatever is there, rather than getting dispersed in iron, it tries to, it tries to segregate, or it tries to go, stay and forms hard martensite.

The plain carbon and the low alloy steel are not commonly used in additive manufacturing application due to higher manufacturing cost. Most additive manufactured steels are tool steel with high strength and wear assistance. M2, P20, H132 steels are stronger because martensite forms at a lower cooling rate. Martensite, so Martensite is nothing but a hard phase. These alloys contain more carbon, which accelerates carbide formation and boosts strength and hardness.

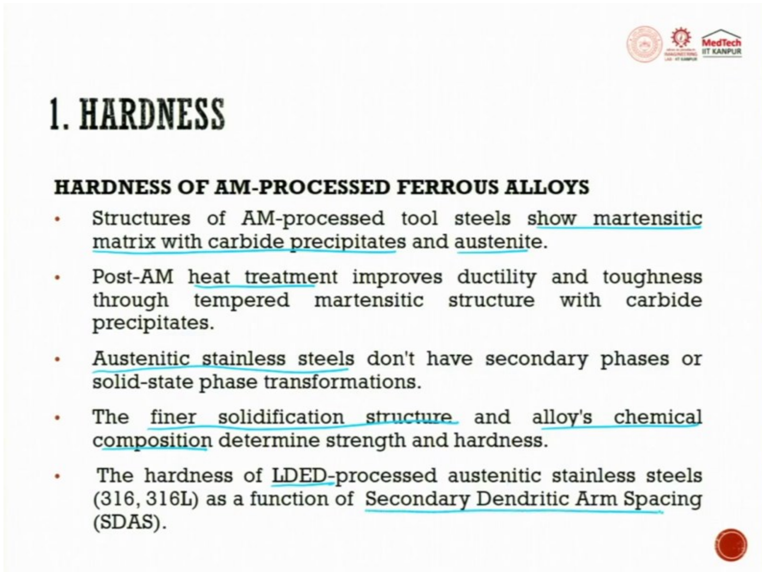
(Refer Slide Time: 20:17)



So if you see there, we can compare process. Selective laser melting produced is green one. Then LMD produced laser melt deposition produced is red one. And you can see conventional produced is blue one. At the aging of 480^0C, you see there with respect to time almost, a very close behaviour is there.

If you try to compare, it is around about 500, 500, and this is around about 525, 530. So that is a small variation, which is there. So when you try to do conventional, you see the error bar is very less, when you are trying to do LMD parts or a SLM parts, you can see that the error bar is slightly higher. So we are doing aging at 480^0C to get this response.

(Refer Slide Time: 21:15)

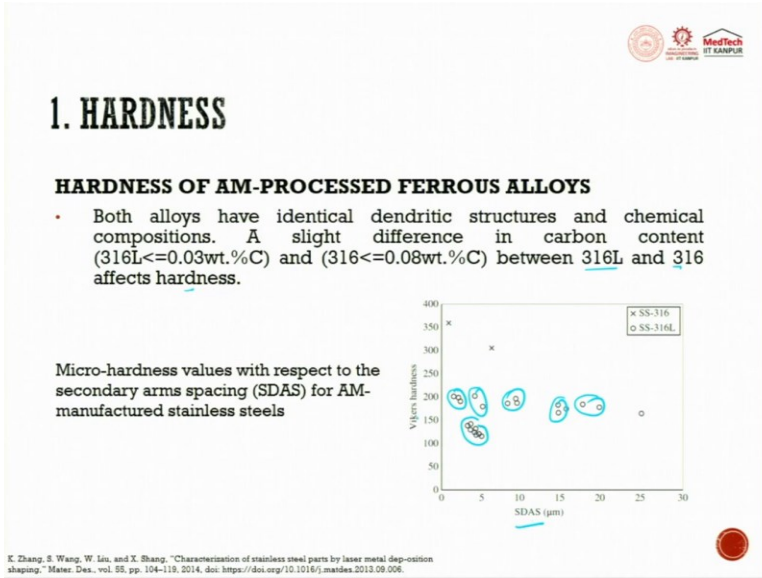


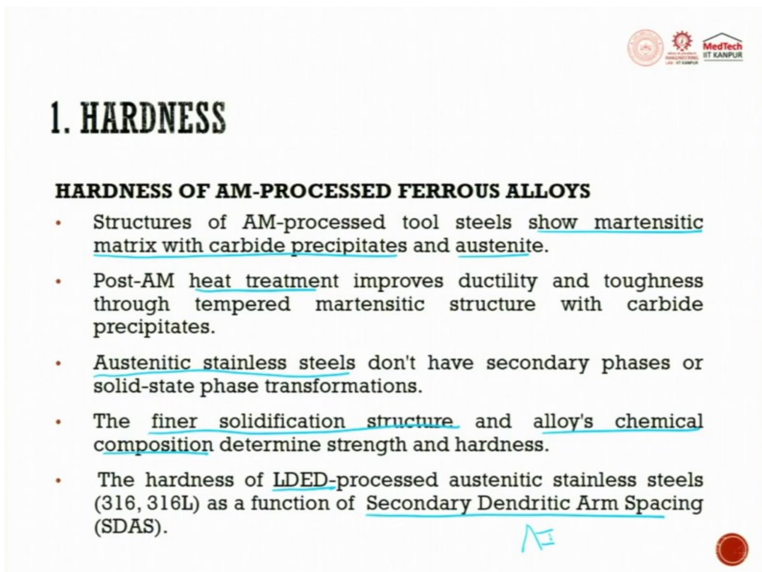
The structure of AM-processed tool steels show martensitic matrix with carbide precipitates and austenite. So this is very important. Martensite matrix with carbon precipitates and austenite is there. Post additive manufacturing heat treatment improves ductility.

So the heat treatment, so it is, you are doing annealing, so improves ductility and toughness through tempered martensite structures with carbide precipitates. So, post additive manufacture heat treatment improves duct ductility and toughness through tempered martensitic structure with carbide precipitation.

Austenitic stainless steel does not have secondary phase or solid state phase transformation. The finer solidification structure and alloy's chemical composition determines strength and hardness. The hardness of LDED-processed austenitic stainless steel as a function of Secondary Dendritic Arm Spacing were seen very nicely. The hardness of L, laser directed energy deposition-processed austenitic stainless steel as a function of Secondary Dendritic Arm Spacing.

(Refer Slide Time: 22:49)

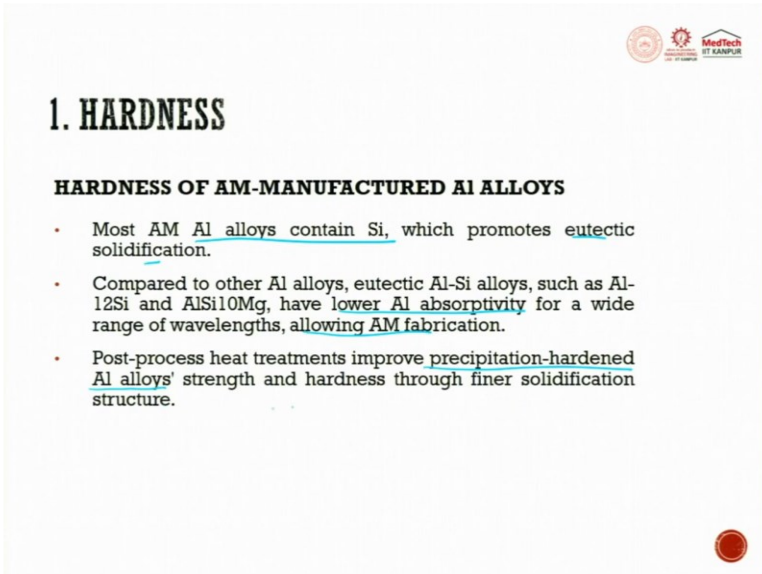




So if you try to see, the additive manufactured parts, so with respect to Viker hardness, and SDAS, what is SDAS? SDAS is Secondary Dendritic Arm Spacing, which is in microns with respect to viker hardness, you can see the plots which are there.

X is SS316, SS316L is this. So both alloys have identical dendritic structures and chemical composition, a slight difference in carbon content between SL1, 316L and 316 affect the hardness. You can see the variation, it forms cluster, it beautifully forms cluster, you see. It all forms cluster. So all these things are SS 316L, where the secondary dendritic structure variation you have with respect to Vikers hardness.

(Refer Slide Time: 23:55)

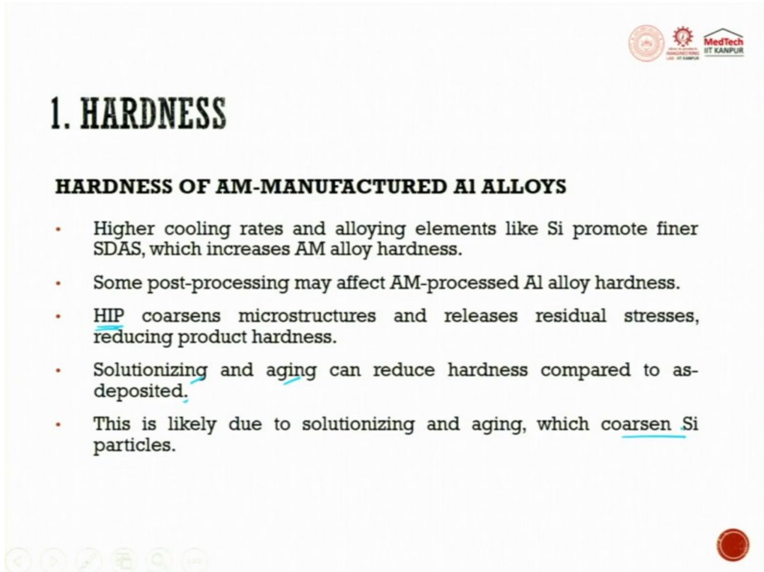


Most additive manufacturing aluminium alloys contains silicon. So this, it is basically added to the atomized powder, which promotes eutectic solidification. So this is all eutectic, eutectoid, peritectic, peritectoid, these all come in the binary phase diagram. So a basic knowledge about that is important to understand this. Most AM aluminium allows contain silicon.

Why is the silicon? This silicon helps in solidification or silicon helps in flowability, something like that. It has to have some role. So which promotes eutectic solidification. Compared to other aluminium alloys, eutectic aluminium silicon alloys such as Al12Si, and AlSi10Mg have lower Al absorptivity for a wider range of wavelength, allowing AM manufacturing. Lower Al absorptivity.

The post process heat treatment improves precipitation-hardened aluminium strength and hardness through finer solidification structures. On post-processing heat treatment improves precipitation-hardened aluminium alloys, strength and hardness through finer solidification. So finer structure, the hardness goes higher.

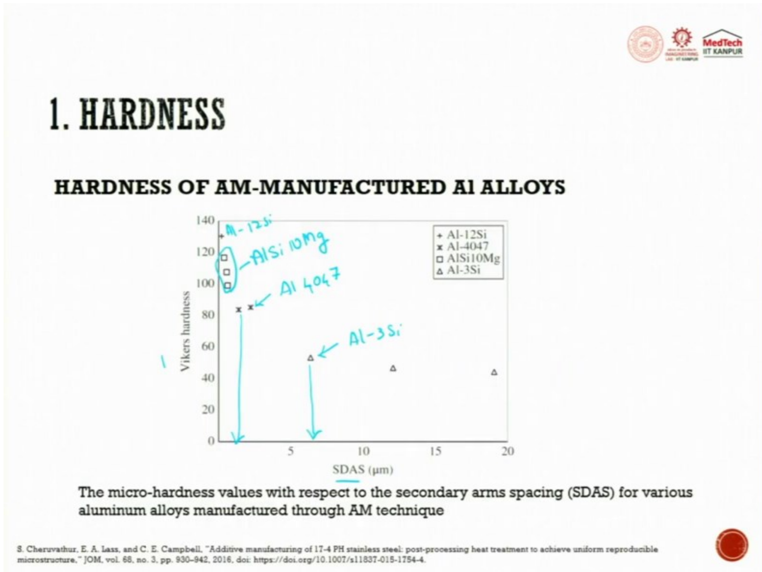
(Refer Slide Time: 25:10)



Higher cooling rate and alloying elements like silicon promotes finer SDAD, Secondary Dendritic Structure, which increases aluminium, which increases additive manufacturing, alloy hardness. Some post processing may affect additive manufacture-processed aluminium alloy hardness.

HIP, hot isostatic pressing coarsens microstructure and releases the residual stress reducing product hardness. So HIP, when you do, it tries to coarsen the microstructure and releases residual stresses, reducing product hardness. This solutionizing and aging can reduce hardness compared to that of as-deposited. Solutionizing and aging, these two are very important. Solutionizing and aging can reduce hardness compared to as-deposited. This is likely due to solutionizing and aging, which coarsen silicon particles.

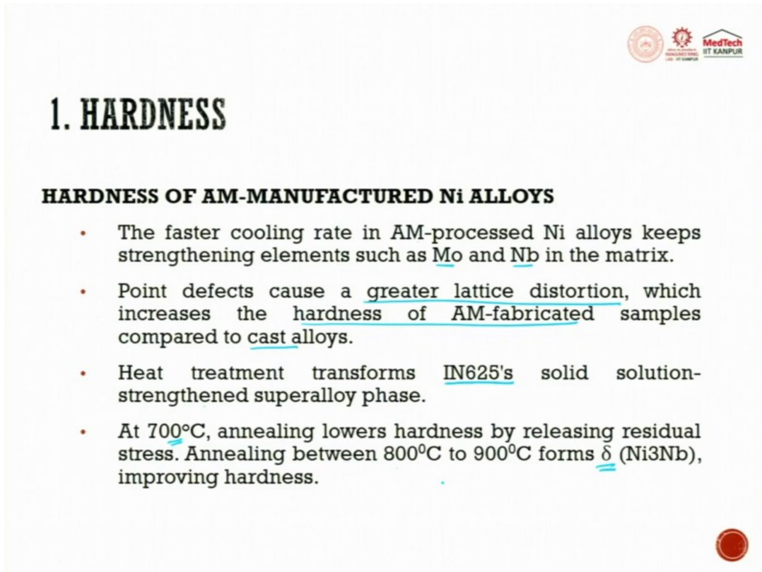
(Refer Slide Time: 26:14)



So hardness of additive manufactured part of aluminium alloy, you can see this is SDAS, and this is Viker hardness. So you have all the stars are Al, this is all Al4047, and you have, the triangles are Al3Si. Box are all, this are all AlSi10Mg, and there is only one, this is Al12Si. So Al12Si, so SDAD, these are the Viker hardness. Then it is AlSi10Mg, these are the things. And then you have Al4047, which is here.

And you can see 4047, they will have somewhere SDAS of 2 microns. Then you have Al3Si which is 6, 7 microns. You can have variation. So solutionizing and aging can reduce the hardness compared to that of as-deposited. This is likely due to solutionizing and aging, which coarsens silicon particles. So you can do solutionizing and aging on this additive manufactured part.

(Refer Slide Time: 27:33)

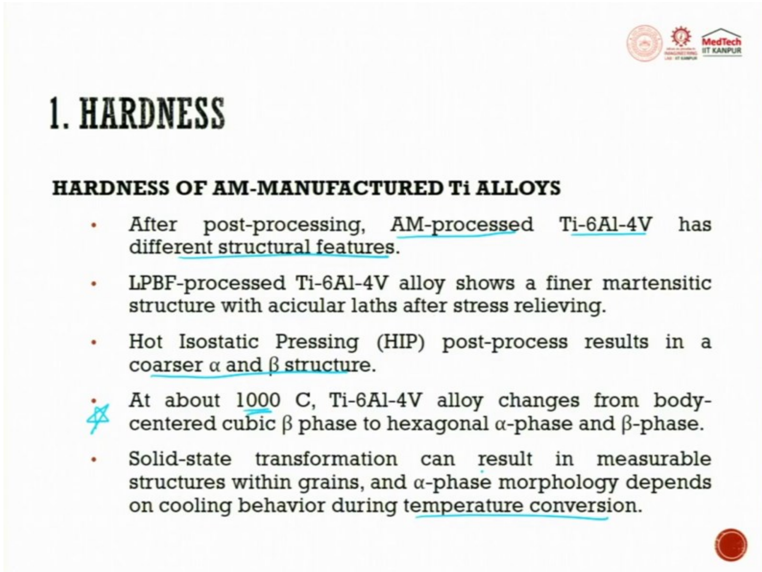


The faster cooling rates in additive manufacturing processed-nickel alloys keeps strengthening elements, such as molybdenum and niobium in the matrix. Faster cooling rate, almost like quenching, the faster cooling rate in additive manufacture processed-nickel alloys keeps strengthening elements, such as molybdenum and niobium in the matrix.

Point defect cause a great lattice distortion. The point defects, there are point defects, line defects, area defects, volume defects, all these things. The point defects causes a greater lattice distortion, which increases the hardness of AM-fabricated samples as compared to that of your cast alloys.

Heat treatment transforms IN625's solid solutions-strengthened superalloy phases. Heat treatment transforms IN625's solid solutions-strengthening superalloy phases. At 700^0C, annealing lowers hardness by increasing residual stresses. Annealing between 700 to 900 forms delta, which improves the strength. So at 700, you do, your hardness reduces and your residual stresses releases. When you do annealing at 800 to 900, it forms del and then you get the improved version.

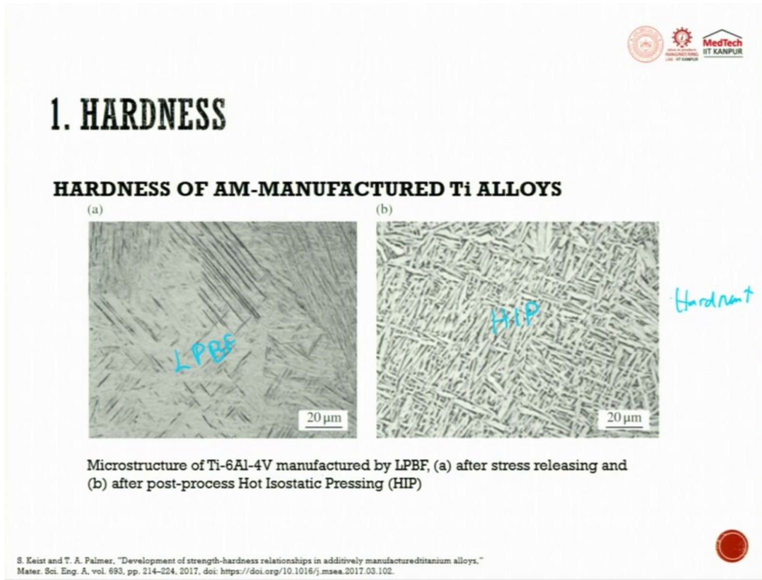
(Refer Slide Time: 28:59)



After post processing AM-processed Ti-6Al-4V has different structural features. Completely, there is a change in the structural features. The laser powder bed fusion process, a processed Ti-6Al-4V alloy shows a finer martensitic structure with acicular laths stress relieving. Isostatic pressing, post-processing results in coarse alpha and beta structure.

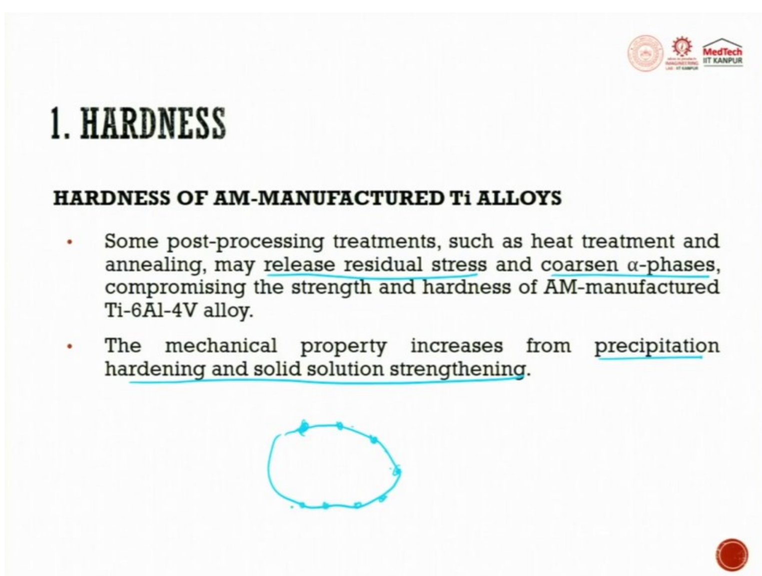
At about $10,000^0$C, Ti-6Al-4V alloy changes from BCC beta phase to hexagonal alpha phase and beta phase. So you see there is a complete change in phase itself when you do annealing or a post processing process. The solid state transformation can result in measurable structures within grain and alpha phase morphology depends on cooling behaviour depending temperature conversions. The solid state transformation can result in measurable structures within grain and alpha phase morphology depending upon the cooling behaviour.

(Refer Slide Time: 30:26)



So if you look at it, these are the two things. One is Ti-6Al-4V manufactured by LPBF. And after stress annealing, you get this. And then this is post annealing by HIP. So you can see here, so how the change in the microstructure there, and this microstructure increases the hardness value. Hardness value increases just by changing the microstructure. And this is what we studied in our time, temperature-dependent, phenomena, cooling curve, all these things.

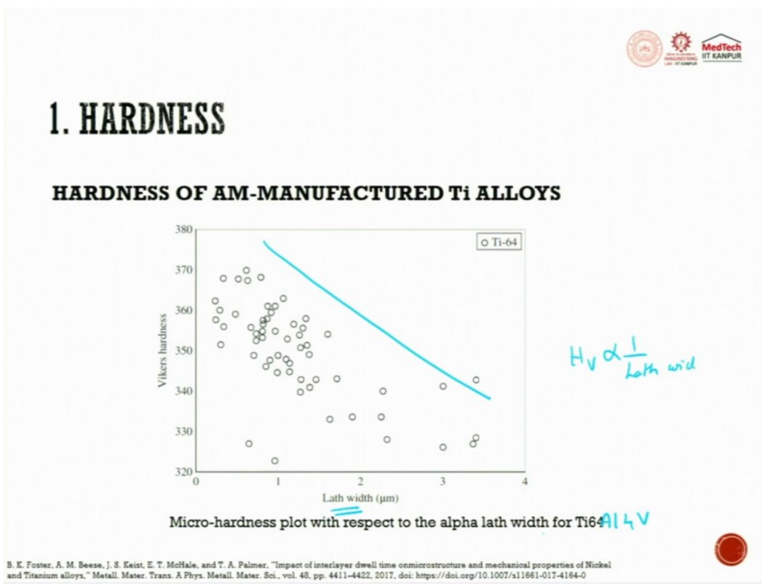
(Refer Slide Time: 31:06)



Some of the post processing treatments, such as heat treatment and annealing, may release residual stresses and coarsen the alpha phase. Moment the alpha phase coarsens, the hardness decreases compromising the strength and hardness of the additive manufactured part. The mechanical property increases from precipitation hardening and solid solution strengthening.

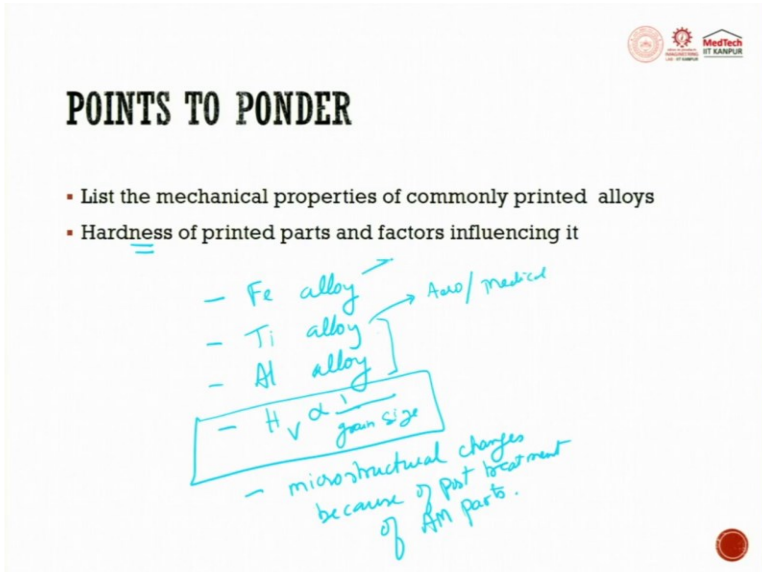
These two are mechanical property enhancing techniques. Precipitation hardening, so in the precipitation hardening, you get precipitates of carbon, which are getting fixed all around the boundary. And the next one is, solid solution strengthening is also another way where you can try to increase or decrease the mechanical properties.

(Refer Slide Time: 31:50)



So when we try to have micro hardness plot with respect to the alpha lath width for Ti-6Al-4V, you can see here, this is a spread you get. So as the lath width increases, you can see Vikers hardness falling down. Smaller or shorter the width, higher the hardness. So finally, you get a response, something like this. The hardness is decreasing with respect to lath width. So the hardness is inversely proportion to lath width.

(Refer Slide Time: 32:27)

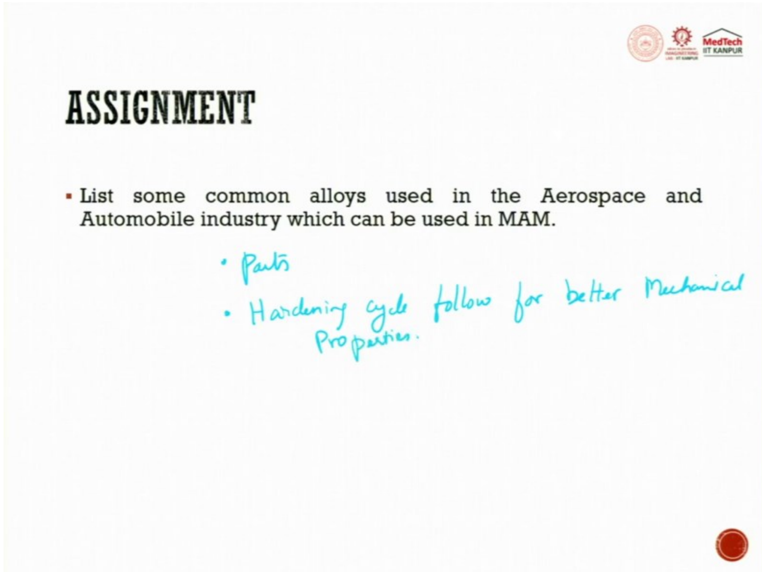


So points to ponder. Here, in this lecture, we looked into list of all mechanical properties of commonly printed alloys. So what are the commonly printed alloys? You can take iron alloys, you can take titanium alloys and you can take aluminium alloys. So here, what we do is we compared it with the conventional strength and with additive manufacture strength.

Here, nowadays, we are trying to get a better mechanical properties as compared to the tough conventional strength. There are several parameters. One such parameter we have used till now was hardness. Hardness, H V is directly proportional to the grain size. As the grain size increases, the hardness decreases, inversely proportional. Grain size, if increases, hardness decreases. So it is inverse proportion.

We studied about it, and we also studied what are all the micro structural changes, which happened because of post treatment of AM parts. So we saw this in this lecture. This is very important. You can try to see for iron, titanium and aluminium alloys because titanium and aluminium alloys are exhaustively used in automobile industry, titanium is used exhaustively in aerospace industry and in medical industry, it is used, and iron alloys are generally used for heavy engineering applications and for rapid tooling.

(Refer Slide Time: 34:15)



So assignments. List some common alloys used in aerospace and automotive industry, which can be used in metal additive manufacturing. Try to list down the parts and then try to list down if at all, there is any hardening cycle, hardening cycle followed for better mechanical properties.

Start making these assignments. These assignments need not be submitted to us. It is only for your understanding and learning. Once you start doing all these assignments, you will start appreciating what are all the big changes this additive manufacturing is trying to bring in the community. With that, thank you so much.