Metal Additive Manufacturing
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Lecture 13
Solidification of Parts (Part 1 of 3)

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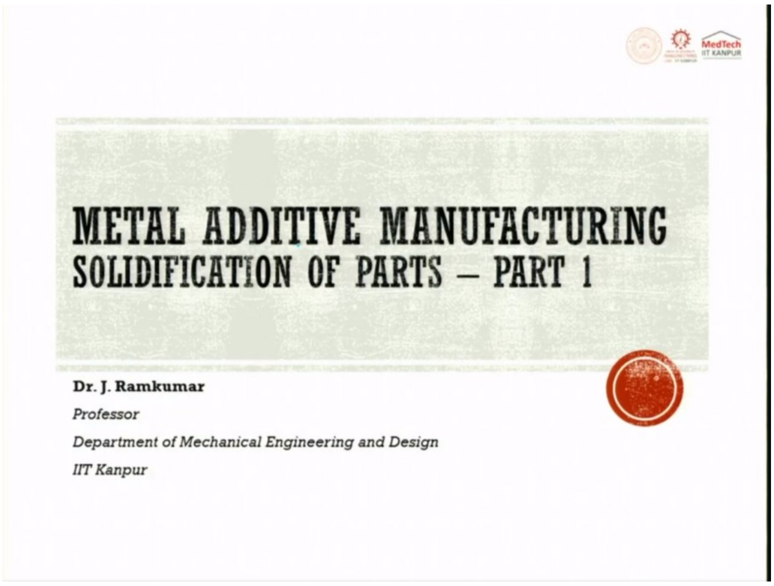

Welcome to the next lecture on Metal Additive Manufacturing. Till now, we have seen metal additive manufacturing basics, we have seen its application, then we moved on to understand powder bed fusion method, then directed energy deposition method, wire additive manufacturing methods. We went on understanding the fundamentals of laser, what are all the important parameters of laser superficially so that when you buy a machine you will be able to understand every specification what they say makes sense.

Then you have also gone through electron beam, fundamentals of electron beam, how is the electron beam getting created? Suppose if somebody comes and says that okay, this cannot be switched off, switched on, why is that? What are the magnetic lenses? What is its role? All these things we saw in electromagnetic.

Then we went on understanding the process parameters and also the subsystems which are involved in metal additive manufacturing processes. Now, moving ahead we will have to study some of these science behind the process which will try to help us in understanding how to produce sound quality output.

So, when that has to be produced, so here we are supposed to understand the process of solidification. Solidification is a major principle which undergoes during metal additive manufacturing. Because of the solidification process, you try to have residual stresses and you also have microstructural changes plus you also have shrinkages.

If you wanted to compensate all these things, you have to better understand solidification process. When you do with stainless steel, you have shrinkage of maybe 3% or 5%. When you do with copper, you might have 8% or 10%. Why is this change coming? And when you do it in casting, there you have surface to volume ratio.

In casting, what happens? You have generally a larger volume and a smaller surface area, very few applications. You try to have surface area large and volume low. Then it is to a large extent easy for you to identify and give the compensation but whereas in metal additive manufacturing it is not so easy.

Why? Because here we try to build in complex parts. So, complex parts and complex geometry are the big USP of metal additive manufacturing. So, in this entire process, solidification plays a very important role.

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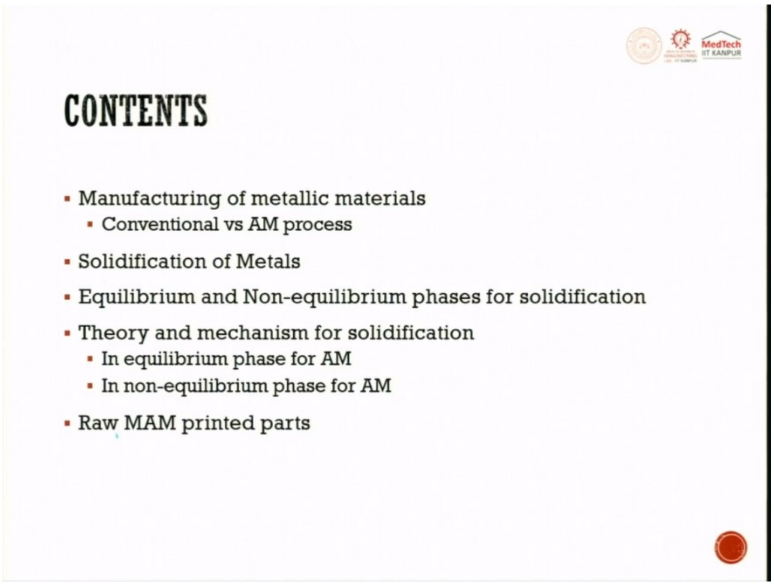

So, in this lecture we have the following content. First, we will try to see manufacturing of metallic material. We will try to compare with conventional casting and additive manufacturing process. Next, we will try to see some basics which is common in casting as well as additive manufacturing, solidification of metals, from there little bit we move forward, understand equilibrium and non-equilibrium phases for solidification.

What are the phases getting formed and what is the role of these phases in terms of product development or the quality of the output? Then theory and mechanism for solidification in equilibrium phase and in non-equilibrium phase for additive manufacturing and the last one we see is raw metal additive manufacturing printed parts.

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When we discuss about manufacturing of metallic materials, we have three sub-divisions which we will cover in the presentation. The first thing is going to be comparing it with conventional and additive manufacturing. Next is various conventional methods and the next one is additive manufacturing methods.

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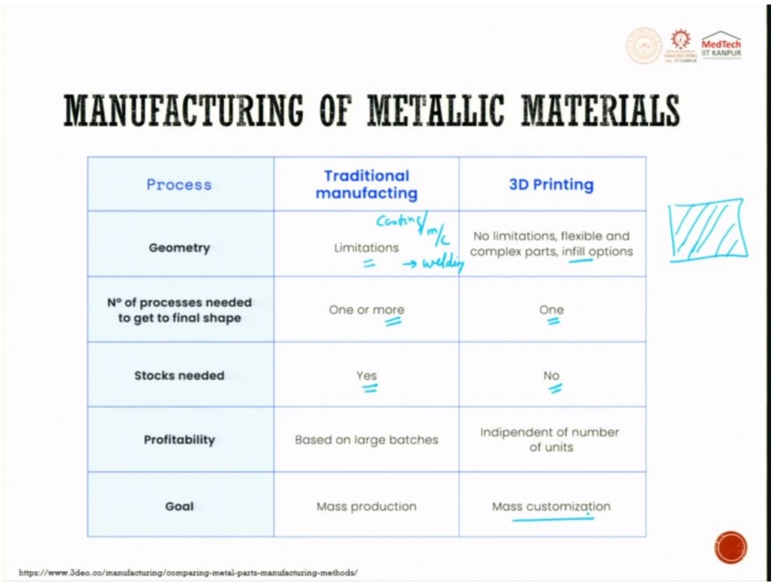

When we try to compare traditional manufacturing process with respect to 3D printing, these are the five major parameters we always try to compare. Geometry, to a large extent there is a limitation. Many a times today we make heavy parts because the geometry which is used in casting will always put a restriction. You will have larger shrinkage or you will not be able to produce a sound quality output.

So, because of that there is always a limitation in the geometry because of this only we try to make split parts into various numbers and then we start doing assembling. So, we try to do casting or machining and then we do welding and then we get a final part. So, this always puts a restriction on the shape of the geometry whatever you want.

But when we try to do it with 3D printing or metal additive manufacturing there is no limitation. The flexibility and the complex parts can be built in one shot and you can also try to dictate the infill options. In the last class, we saw various hatch patterns, you can have hatch patterns like this and these are hatch lines, between these hatch lines you can vary the spacing and this spacing will try to even reduce the weight.

And once you have made it with lot of hatch patterns, then what you do is you try to diffuse metal inside. When you try to diffuse metal inside, you try to have infill option also given to you. For example, when we try to do biomedical parts, some parts we try to make it porous so that we allow the blood cells or the tissues to grow in it.

So, we make porous structure. So, infill option is also there which is going to be very difficult for you in the traditional methods. The number of processes to get to the finished product here in the traditional way can be one or many. Generally, it will be many, but in 3D printing one shot process, you try to produce the output like a polymer.

You start with pellets, get the final part chair or get a final part spoon. It's one-shot process. Same way in additive manufacturing you get it in one shot. The stock needed is always very high in traditional manufacturing methods and when you talk about 3D printing as and when you require you start buying materials for printing. Profitability based on batch size it goes here but here it is independent of the number of units. Goal, mass production and here it is mass customization producing it more towards customer requirement.

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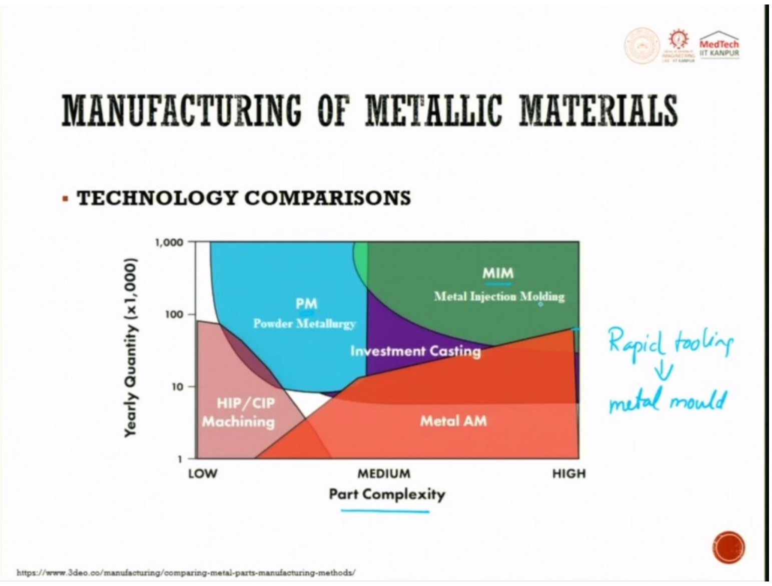

When we try to compare technology, comparison with respect to complexity of the parts you can see here, yearly quantity multiplied by 1000 if you have. So, you can see HIP, CIP and machining. HIP is nothing but hot isostatic pressing. Cold isostatic pressing machining can do up to low complex parts and close to somewhere 100 parts can be made.

So, 100 into 1000, it can be made. So, when we are looking at powder metallurgy parts, it tries to have here, it moves from low to medium complexity of the part. So, you have powder metallurgy parts which are being made. So, you can make it into thousands, thousands multiplied by thousands. So, many parts can be easily made.

When we are looking at metal additive manufacturing, the complexity goes very high. The number of quantity goes little smaller as compared to that of powder metallurgy root. So, here why is that? Because the costing of the powder is very high and many a times sound quality output is not so great. So, now people have understood that metal additive manufacturing can be used for rapid tooling.

So, they try to make a lot of moulds, metal moulds out of metal additive manufacturing and this will be used for mass production. So, metal additive manufacturing is used here. So, somewhere in between the metal additive manufacturing and the powder metallurgy route, you have investment casting.

So, investment casting also plays an important role in developing medium complexity part geometries. Then the extreme high part complexity and large quantity has been done by metal injection moulding method. So, in metal injection moulding method, we try to mix polymer and metal and then inject it. Or we try to inject directly the metal into the mould to produce outputs. So, it is something like your die-casting.

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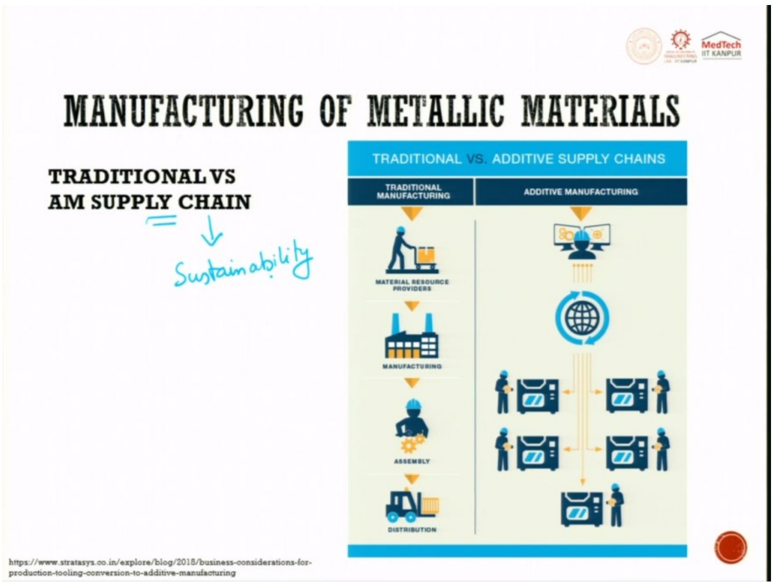

When we look at that traditional versus additive manufacturing supply chain, you see in traditional you have material resource provider. There will be a person, then there will be somebody to manufacture it. After you manufacture it, there will be an assembly section and after the assembly section, there will be somebody to distribute it.

When you look into additive manufacturing, what is happening is this powder is produced. So, first is virtual idea getting generated, then you have various machines which is getting produced and now you do not need to have a factory to produce it. You can have a small room and start producing it. If you look at a supply chain, the supply chain for additive manufacturing completely breaks the conventional thought process.

So, earlier what we were thinking to be produced in a factory, now it can be start producing in a small house. If you have a small room in your house, you can have metal additive manufacturing and start producing 3D complex jobs and you can start supplying just like your Amazon model. Your house can be a warehouse. So, you produce it and keep it there.

And then there will be customers to come and pick it or there will be something like your Zomato model food. Somebody will come and pick the part and deliver it to the customer. So, this supply chain completely killed the conventional thought process. So, additive manufacturing supply chain is more towards sustainability. Sustainable engineering is now talk of the town and sustainability is more and more promising when you do additive manufacturing.

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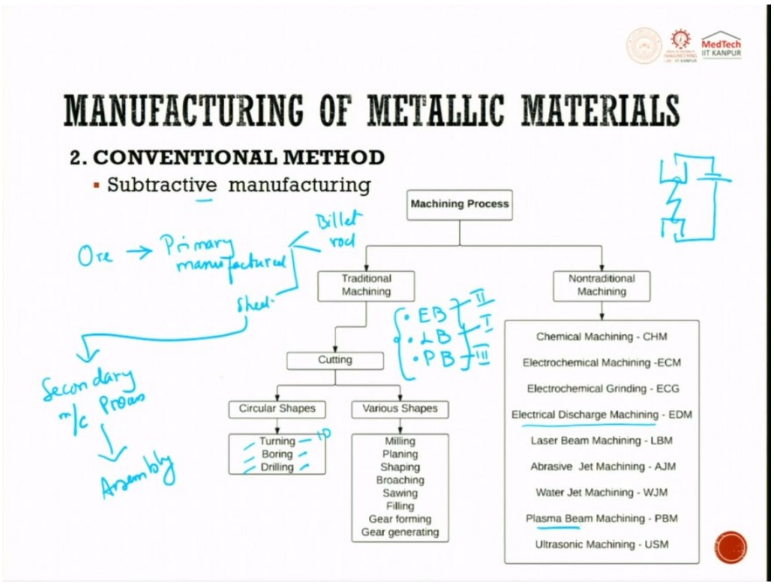

When we look at the conventional subtractive processes, you will have machining process. This machining process is divided into traditional machining process or non-traditional machining process. In non-traditional, it can be called as non-conventional or modern machining process, whatnot. In traditional machining process, you always have a cutting tool which is harder than the workpiece which is used to remove material on contact machining.

So, here you have cutting as the major mechanism of material removal. So, in cutting, shearing action dominates. And here you can try to produce circular parts, you can try to produce non-circular parts or various parts. When you want to produce circular parts, you try to do turning, boring and drilling. Turning is 1D or one cutting edge is there. Boring also, many at times can be one or two cutting edges. When you go for drilling it is two cutting edges.

When you come to other machining process you will have multiple cutting edges. So, in milling you can have horizontal milling or vertical milling. Depending upon your requirement, you choose the process. Planning is also the same. Shaping, you again have a single point tool but you try to generate prismatic parts or something like straight line parts, broaching, sawing, filling and then you have gear forming and gear generation. These are all various shaping processes which fall under cutting to create complex geometry.

So, here the interesting part is you extract ore. Then this ore is primary manufactured into basic shapes like billet, rod, sheets, etc. But then, from here it undergoes secondary machining process. In secondary machining process, you have all the cutting or you will have all the sheet metal operations to produce it.

Many a times after the secondary machining process, it goes for assembly to get the final part. This is a long cycle which it undergoes. Wherever you have a difficulty in cutting, the workpiece can be either soft or it can be hard, it can be brittle. So, what we do is we try to move out from contact machining to non-contact machining processes.

So, in non-contact machining processes we have chemical machining process wherein which it follows the principle of etching which is used for PCB etching and other things. Next, we try to use electrochemical machining which is an accelerated version of chemical machining. We use electrochemical machining, then we have electrochemical grinding, we have electric discharge machining where in which we try to create a spark very similar to that of your laser I said.

You will have an electrode, between these two there will be a spark. You try to apply a high potential. So, this high potential try to release electrons. Thus, avalanche of electrons are created. They try to move along the dry electric field. They try to ionize the path and it creates spark for machining. So, you have this electric discharge machining. So, here you can try to make complex parts.

Then you have laser beam machining, then you have abrasive jet machining, water jet machining, plasma beam machining and ultrasonic machining. So, here also you can see electron beam is used, laser beam is used, plasma beam is used. These are the same things which you also use as thermal source for metal additive manufacturing.

The largest one is this, the second largest one is this and plasma we seldom use it. But whereas when you try to do cutting operations, you see plasma used for cutting thick blocks of metal. Again, you can have non-conducting work pieces also, it can be done by plasma machining process.

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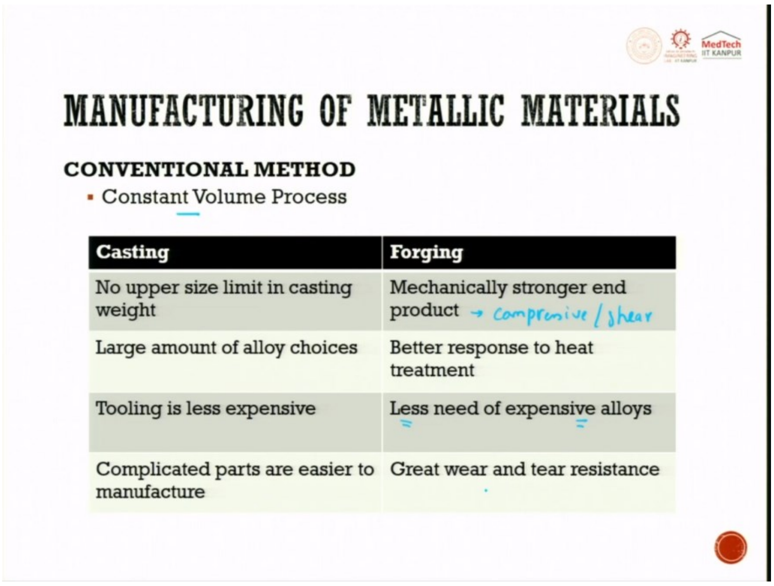

When we look at conventional methods, you have constant volume process. Under constant volume process you have casting and you have forging. In casting, there is no upper size limit in cast of weight. For example, big church bills can be made out of casting. Then large amount of alloy choices can be done by casting.

So basically, when you start melting it, you start dumping all your ingredients to it and in a crucible it tries to get melted and the alloys get formed. You have to follow some principles such that these alloys get diffused one into each other to get into a liquid state. Then the tooling cost is extremely low. You either make a mould or you make a collapsible mould and try to produce it.

So, tooling is not so expensive and the complicated parts are easily manufactured by doing casting. But when we are saying this, if you want to make mass production of the same thing, we try to avoid casting because every time collapsing and making it becomes a challenge. But predominantly, it is used for complex shapes, large parts casting comes up in a big way when we go to forging.

So, here we use mechanical force. Either we use compressive force or we use shear force to remove material or cut material to give a shape what we want. So, we can try to use mechanical forces in developing the product. These products have a better performance as compared to that of your casting.

Better response to heat treatment comes from forging less need of expensive alloys because here tooling, when you try to see here it is less. But here once you make it one tool, you can use it for multiple things. Less need of expensive alloys, then greater wear and tear resistance build parts can be made through forging process.

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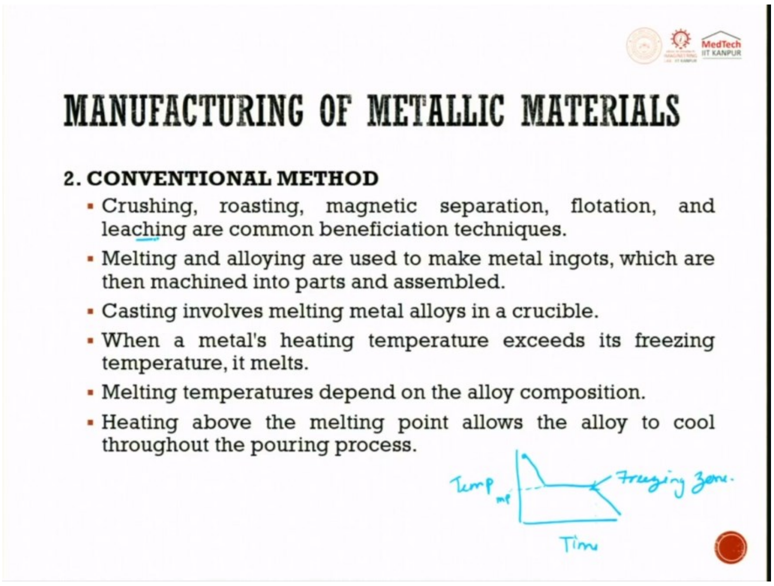

So, when we talk about the conventional methods, crushing, roasting, magnetic separation, floating, leaching are some of the common beneficiary techniques. Melting and alloying are used to make the metal ingots which are then machined into parts and assemblies. Casting involves melting of metal alloys in a crucible. When a metal heating temperature exceeds its freezing temperature, it melts.

Melting temperature depends on the alloy composition. So, heating above the melting point allows the alloy to cool throughout the pouring process. So, what we are trying to talk about is you have temperature versus time plot. So, you have something like melt, freeze and solidify. So, you have this above the melting point of any given alloy.

So, here you try to take the temperature of the alloy to this point for casting so that what happens is the flowability of the material is very good. So as and when the time exceeds slowly, the temperature drops down and once it reaches a freezing zone, you can try it slowly start solidifying and once it reaches a limit, then it starts solidifying to the room temperature.

So, when a metal's heating temperature exceeds its freezing point, it melts. Melting temperature depends on the alloy composition. Heating above the melting point allows the alloy to cool throughout the pouring process. So, here leaching. Leaching means you are trying to add some chemical and etch or remove the material.

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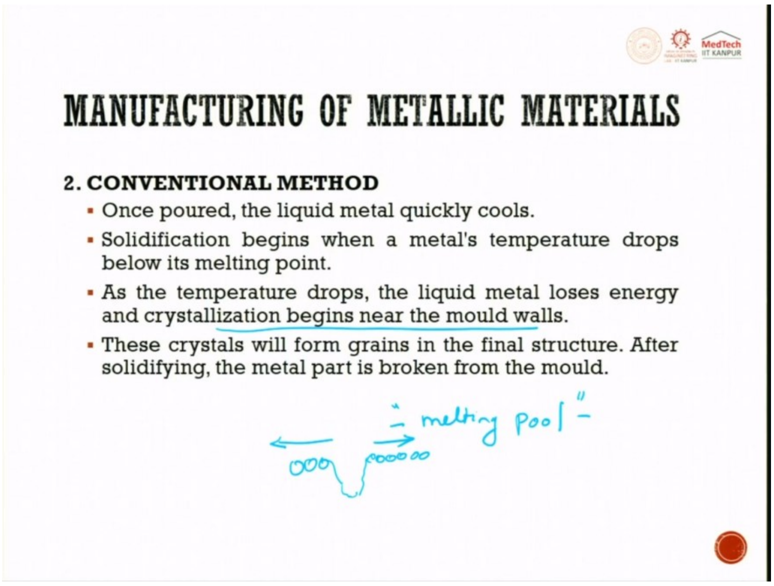

So, the conventional method is once poured, the liquid metal quickly cools. That is what I said in the previous part, temperature versus time. Solidification begins when the metal temperature drops below the melting point, solidification I told you. Then, as the temperature drops, the liquid metal loses energy and crystallization begins near the mould walls.

Generally, from the mould wall, it starts going towards the center and these crystals will form grains in the final structure. After solidifying, the metal part is broken from the mould. So, if you look into it, these are typically the set of sequence in a casting process. Take it above, bring it to solidifying, allow it in the freezing temperature zone for some time and then it gets into the solidifying zone and the material solidifies and then you try to get the final part.

All these things have to be done in additive manufacturing also but here it is getting done in a very small fashion. So, that is why every time in additive manufacturing we keep discussing about melt pool. This melt pool analogy, you should try to take everything from casting and bring it here. Melt pool is an area where the metal melts and then it forms a pool.

So, this one is very important. When you move the laser in this direction, the melt pool also does it. You can have a backward trend or you can also have a forward trend. The laser moves ahead and the melt pool is created. So, you can create in any direction depending upon your requirement. Once the melt pool is done, the material undergoes higher melting temperature.

Once the melting happens, then the next process is solidification. So, it goes to freezing limits and then it solidifies. As the temperature drops, the liquid metal loses energy. So, now the laser is away from the spot and crystallization begins near the mould. So, crystallization happens. So, here there is no mould.

So, what happens next is immediate to the melt zone, there would have been melt solidified part or a fresh part. So, that will try to take the heat and then it tries to form crystallization. These crystals will form grains in the final structure. So, now you can try to orient these grains and try to get the maximum strength or maximum property out of the additive manufactured part.

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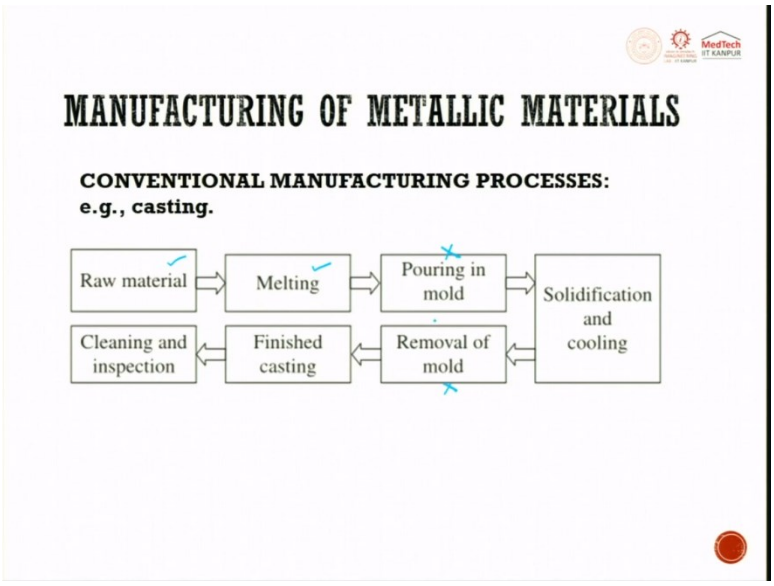

So, raw material, melting, pouring it into the mould, solidification and cooling, removal of the mould, finishing of the casting, cleaning and checking, all the sequence is now completely changed into one shot process. Raw material which is a metal powder, it melts, you do not pour it, it solidifies. So, this step is not there in additive manufacturing.

Melt, solidification and cooling happens and then it jumps to the finish and then you do cleaning and inspection. So, creating mould is now out. Removing from the mould is out. This reduces a lot of time while doing manufacturing.

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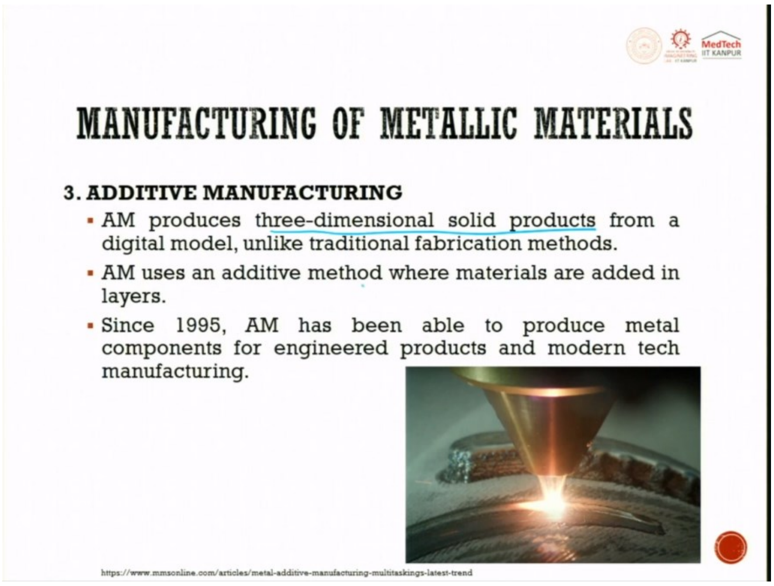

When you go to additive manufacturing, additive manufacturing produces three dimensional solid products from the digital mould unlike traditional manufacturing process, whatever is given in the drawing, you would convert it into STL file to slicing files.

From slicing files, it is directly moved to a machine and in the machine, you take all the topology data plus the machining process data, mix it and then start feeding it into additive manufacturing machine and it tries to produce a part. Additive manufacturing uses additive methods where material is added in layers. It has been able to produce metal components for engineered products and modern technique manufacturing.

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So, additive manufacturing metal powder manufacturing involves only three steps. So, look at the comparison from so many steps you have brought in three steps. At each step you will always try to have a defect and that defect to nullify. You have to keep start working until you establish the process it is a tedious job.

Moment you establish the process, then continuously the production will start. So, today when we are trying to talk about product lifecycle reduction, here additive manufacturing plays a very important role. And second thing, additive manufacturing is more focused towards mass customization.

When we talk about mass customization, it is wonderful. So, it tries to customize to meet out to customer requirements. So, here you have in additive manufacturing, mining, extraction of wood to fabricate pure metal and alloy powders and then powder production by either water atomization, plasma atomization, plasma rotate electrode process.

Then you have rotate electrode process, you have gas atomization, electrode induction, melt inert gas atomization, all these things are there. But we saw only four prominently used atomization techniques in which metal powders can be produced in a consistent fashion. So then once the powder is produced, it is sorted out, classified and validated.

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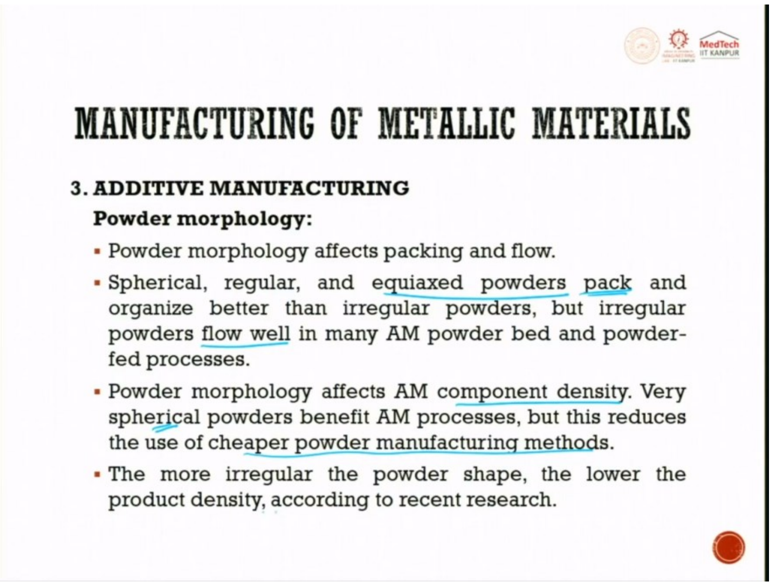

When we talk about powder morphology, powder morphology affects packing and flowing. So, if you have all cylinder, it is all spherical. The packing factor is low. So, if you have a mixed bag of spherical and non-spherical, yes, you can have a huge packing factor and the flow also can be made easily spherical.

Regular uniaxial powders pack and organize better than the irregular powders. But irregular powder flow well in many additive manufacturing powder bed and powder fed processes. See package wise equi-axial powder with organizers. It gives you a huge packing factor but if you have irregular, it flows well in additive manufacturing, the powder morphology affects additive manufacturing component density.

Very spherical powders benefit additive manufacturing process but this reduces the use of cheaper powder manufacturing methods. If you want to have all spherical, then your powder production process becomes expensive. More irregular the powder shape, lower is the product density according to the recent research.

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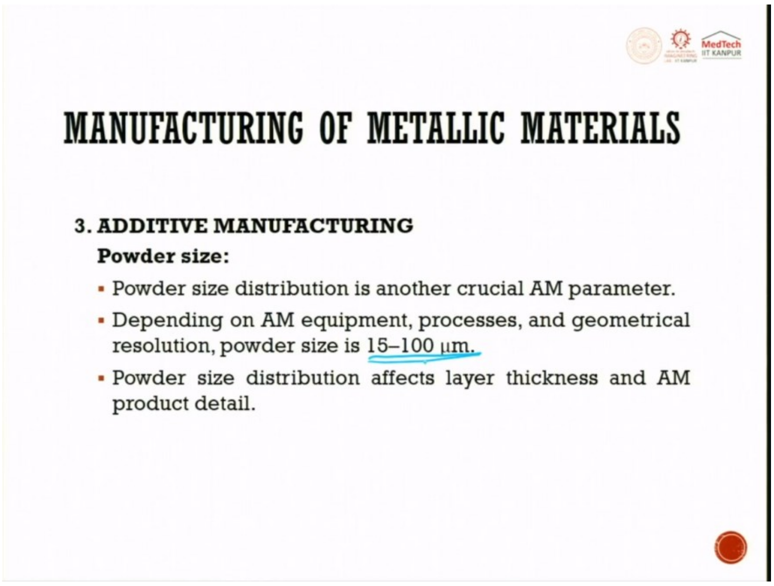

The powder size distribution is another crucial additive manufacturing parameter. It generally varies from 15- 100 µ. Okay, the process and the geometric resolution depends upon the powder size. Powder size distribution affects layer thickness and also product detailing in additive manufacturing.

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These are some of the additive manufactured parts. You can see here the smallest feature size which we are talking about has round about 50 µ, people have achieved this feature size. That is the smallest feature, 50 µ and if you want to go for wire and all, it goes to 200 µ. Sometimes it goes to even millimeters. This is the smallest feature you can make. So, this is the smallest component.

From here you can see how large they have gone. So, this is just to give an idea, a coin of country and then you see a match stick. So, this will try to give you a feel about the length of the component. So, this tail stock, whatever is made, is almost half or quarter of a match stick. Now, this gives you the freedom in additive manufacturing. You can make very complex parts.

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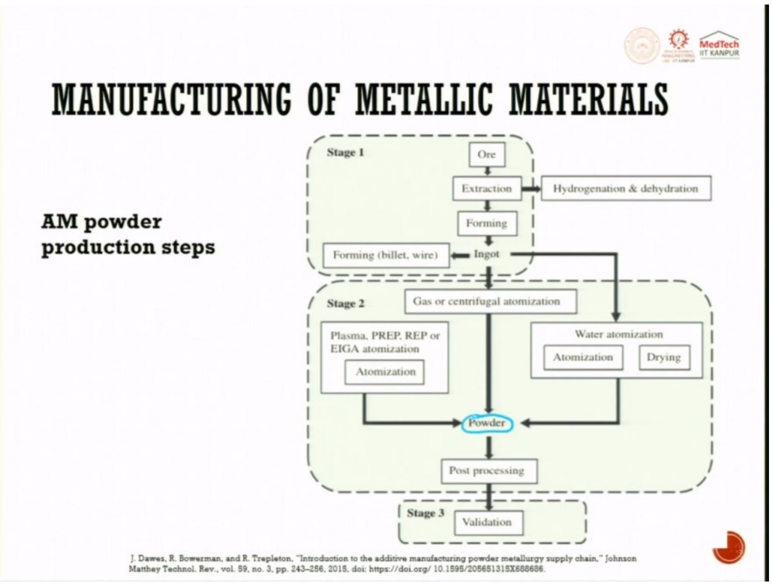

In additive manufacturing, powder production steps. We have seen the ore extraction forming ingot. Then we have the second thing- gasification. Then from there, powders are made by post processing of powders. And it is validated when we talk about it, water atomization and then drying. So, you have all the other processes which helps in making a powder.

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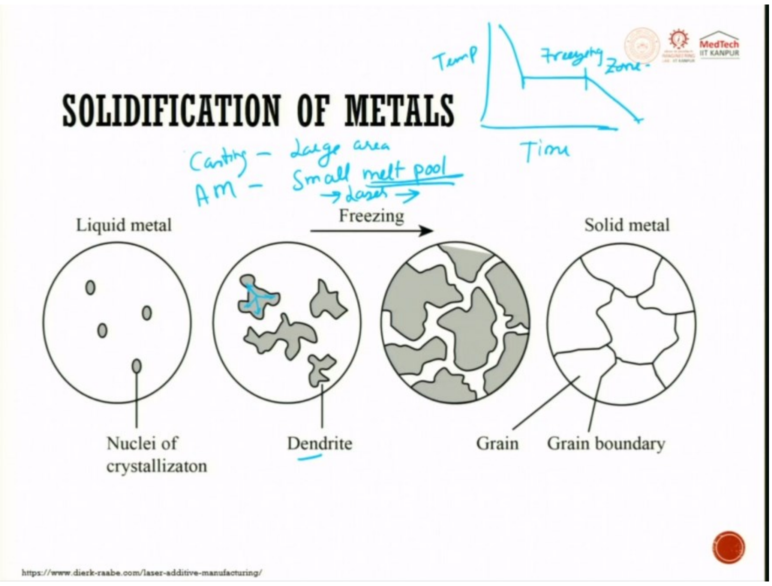

So, let us get into solidification of metal. So, when you have a liquid metal, it has the cross section, which schematically looks like this. You will have some of the nuclei which are just getting generated. And, these nuclei is not that it seeds there and it starts growing from there to reach an equilibrium. When it reaches an equilibrium, it starts growing otherwise this nucleus will get destroyed.

So, here there is a struggle for the nucleus to form and then start growing. So, here is a place where there is back and forth movement and nucleus is getting formed there and peripherally you will have very high temperature. This struggle is over. Nucleation starts. So, nuclear crystallization starts.

The moment the crystallization of the nucleus starts and the stability is achieved, then there is an organic growth or there is a growth. So, nuclei forms this slowly, there is a growth of dendrites. These dendrites can have uniaxial growth or it can be equally distributed or you can have exactly circular one to form it. So, now it grows in multiple directions.

First, it keeps expanding and then you see it grows to this level. In between you will have some amount of liquid which is present there. This liquid over a period of time is getting solidified and finally, it tries to form a grain boundary. So, if I try to plot it with respect to time, temperature with respect to time, in times of solidification, from here to here is the freezing zone.

So, in the freezing zone you will have these two phenomena- dendrite forming phenomena and the dendrite which are formed will try to grow once the solidification starts. Then you get into this portion where it gets solid metal slowly getting formed and then finally you get a final microstructure output.

So, here if you see the same phenomenon is common in casting, the same phenomenon is also common in additive manufacturing. The only difference between casting and additive manufacturing is that the casting will have a larger area but here it will have additive manufacturing.

You will have a very small melt spool and this melt pool will be created by laser and it instantly solidifies and comes to room temperature as and when the laser moves. This is why in the process parameter we were discussing about the ambience which is created around the powder bed fusion. So, this ambience will try to prevent it from getting oxidized and it also will allow you to slowly form the grains and then it starts growing.

So, liquid metal will have nucleus of crystallization. Then you have dendrite formation. Then you will try to have solidified part where grain and grain boundary exist. Grain boundary is a place where there is lot of energy which is available there. So, you can try to do that ambient you can try to reheat.

First round you try to melt and next round you try to heat or during heat treatment after the process is done through additive manufacturing you can slightly play with the grain size, grain orientation and the grain boundaries. You can do it. So, this is the basic understanding you should have even in melt pool, whatever we are talking about all these phenomena happen. So at least in casting, you can try to control the temperature gradient.

Here it is not so easy to control the temperature gradient. That is why an electron beam, it is very fast. Sometimes you get a very good quality output when you use electron beam powder bed fusion method.

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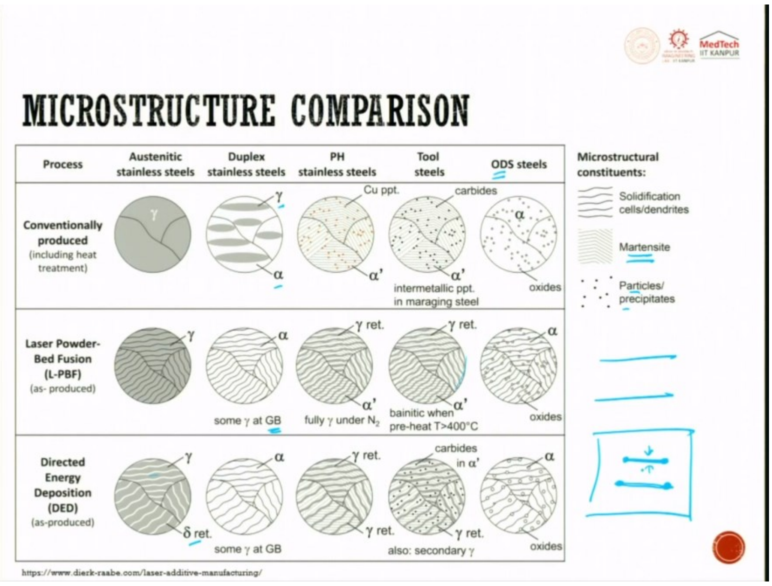

So, I have just compared three different processes for your understanding and visualization. So, you take a process which is conventional. If you have Austenitic stainless steel today, Austenitic stainless steel whatever part you make or a cast you make, you also can make it through additive manufacturing. You see the Austenitic stainless steel, the gamma face which is getting formed and the grain boundary.

So, when you try to do laser powder bed fusion method, you can see there is something like your finger impression. You will have a gamma face which is in between the finger face. So, it means to say fingerprints. So, this is called as fingerprints and in between you have a gamma face. And then you can see in direct energy deposition, you can try to see how these gamma faces are formed and how the finger impressions are made.

And this is what is delta, which is a residue which is there or this is called as delta which is retained. So, this is including heat treatment and this is as produced and this is also as produced. You can see how wonderfully you are doing grain engineering to get the required sound quality output from the product. So, this is for same austenitic stainless steel, how does the microstructure look like?

And you can have for the directed energy deposition. So, when we try to take Duplex stainless steel, you can see Duplex's α phase and γ phase. You will have two phases which is there and here you can see how is it after heat treatment. And here, how does it create some gamma at grain boundaries?

These two are almost similar. But here you see a big difference. So, that is why today in additive manufacturing, grain engineering is a big area which people are trying to do. So, they try to do various process parameters, measure the mechanical properties, look into the microstructural properties, give a cross correlation how the mechanical property and grains are related.

So, once you know this, then onwards it becomes very easy if you have these microstructures, when you get these microstructures, immediately you can ascertain and say this will be the mechanical property. So, when we try to talk about stainless steel, you can have copper precipitation happening, then you have α′.

So, when we try to do the same thing with the stainless steel, you can see here, γ retain is there and α′ is there. And you can see how these things are, that it is along the grain boundary and it is also between the grain. You have this relation so these things will try to dictate the mechanical properties.

Next is tool steel. You can see that carbides are present everywhere and then you can see α′. So, intermetallic precipitates in managing steel can happen when we try to do in tool steel. So, here it is binitc with preheating temperature which is greater than 400^0C. As you can try to get here and here you would have carbides in α′ so it is γ retain is there and these are all secondary γ which is present.

So, when we try to see the microstructure, these are all solidification dendrites, these are all martensitic dendrites, small lines which you see here, these are all martensitic and these are all small particles called precipitates which are there when you try to see about ODS steel. So, you can see here the oxides are getting dispersed. So, this is α. So, you try to get α phase here and then you will try to have this martensitic phase is also in between in α of the laser powder bed fusion method and directed.

So, now this clearly tells you that whatever you want to get in the final product, grain boundary or grain performance or grain structure or the phases you can try to get that easily by doing metal additive manufacturing. This is a very important thing which you have to understand and appreciate.

In casting or in any other process you do, you have to undergo a heat treatment and then after heat treatment also what you get will be completely different to that of this and here you can also use in laser powder bed fusion, you can also have selectively reinforcement for example in a powder bed in one layer suppose let us assume these are the points or these are the tracks where you will try to have maximum wear resistance compared to rest of the part.

So, you can try to play with the hatch pattern, you can try to play with the laser movement, you can try to play with densification and make these two lines or two small thicker lines. You can try to make where there is very high wear resistance which is not possible in conventional techniques.

In conventional techniques, when you do heat treatment also or when you do selective carburization, it is very difficult. So, this introduces more and more processes to come into existence to make the required output. Whereas in additive manufacturing you directly get this printed on the material in the green state or in the final state.

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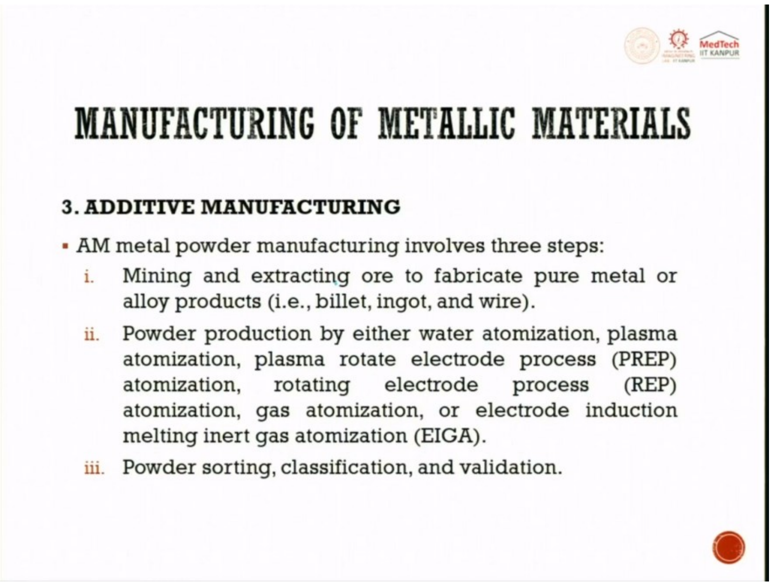

So, additive manufacturing, the metal powder manufacturing involves three steps. We have seen it in detail- mining and extraction, powder forming and powder sort classification and validation.

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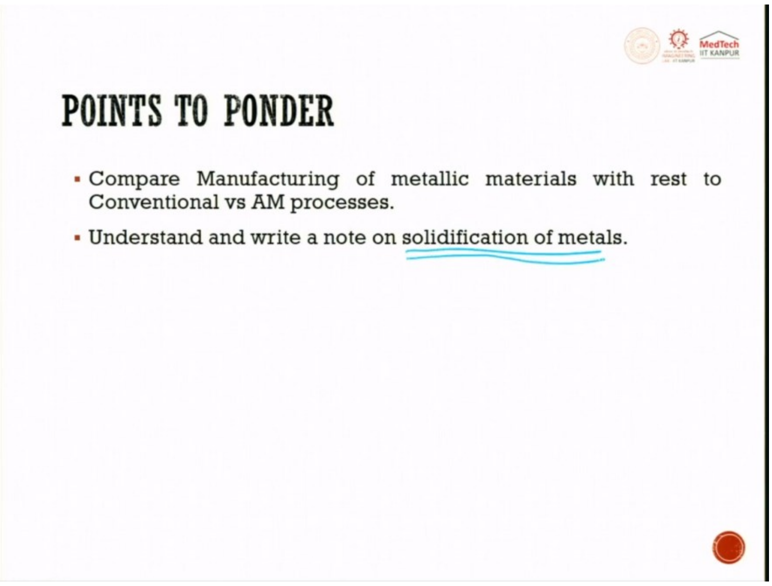

So, in this lecture, what did we do is we tried to compare conventional processes with additive manufacturing processes. So, we tried to say in conventional processes, even for generating and raw material for the constant volume process, you have to undergo several steps and in the process also, you have to undergo several steps to get the final desired output.

But whereas in additive manufacturing it is all one shot process. Start with a metal powder and you get the final part, whatever you want. We have also compared between these two processes what is the microstructural change, or microstructural impact, there in additive manufactured part as compared to that of your conventional part.

So, we have compared various manufacturing processes, metal manufacturing processes with additive manufacturing processes. We have also understood in a very small detail what is solidification of metal and during solidification of metal you will have a melt zone and then you will have a freezing zone then you will have a solidification zone.

In additive manufacturing, how does it happen? Which in comparison with casting, we also saw that. So, this lecture would have been an eye opener for you to appreciate that additive manufacturing helps in grain boundary engineering or grain engineering to produce sound quality output.

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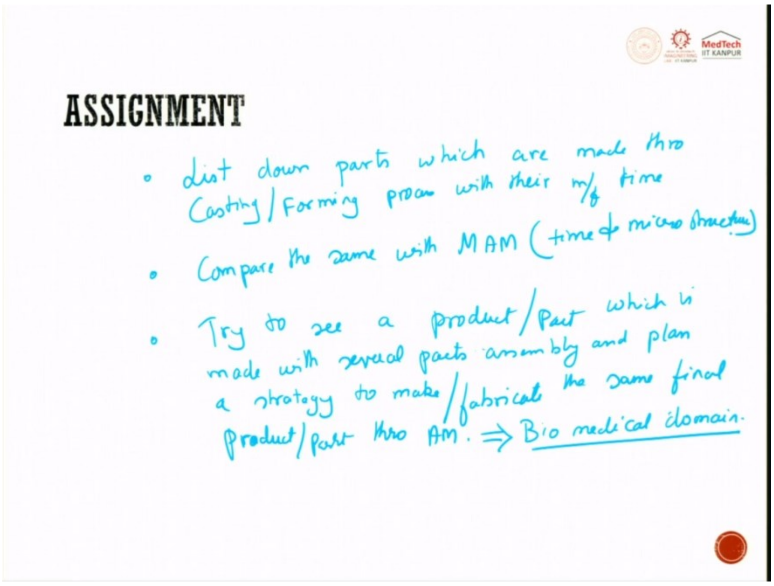

The assignment here is try to list down parts which are made through casting/forming process with their manufacturing time and compare the same with metal additive manufactured part. You also try to see a product/part which is made with several parts assembly and plan a strategy to make or fabricate the same final part product or part through AM process. So, here what I am trying to say do not try to go for GE.

I have already shown you that example. Try to look for some biomedical domain. So, look into this and then see. So, here in this last question, you will try to compare how is the time reduction done? And then the top two questions are linked. So, you will try to see in casting, forging how much time does it take?

And directly doing by metal additive manufacturing, how much time does it take? Okay. So, comparison you can do it with respect to microstructure. So, I will say compare in terms of time and microstructure.

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Thank you very much.