Metal Additive Manufacturing

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Lecture 19

Common Defects and Post Processing

Welcome to the next lecture in the series of Metal Additive Manufacturing. In this lecture, we will try to see various defects, which arises due to improper choosing of process parameters in metal additive manufacturing. As we saw in the earlier lectures, porosity is one common defect, which happens, we will study about other defects and we will also look at the post processing step which is involved in metal additive manufacturing.

Compared to polymer and ceramic metal additive manufacturing, the post processing step is very, vital, for two reasons, you can try to dictate the grain which in turn dictates the performance of the additive manufactured part. The second one is the surface morphology that means to say roughness, the roughness can also be tampered or tailored to meet the requirement through a post processing step. So, compared to polymer and ceramic metal additive manufacturing, post processing steps plays a very important role. So, that is what we will try to cover in this lecture.

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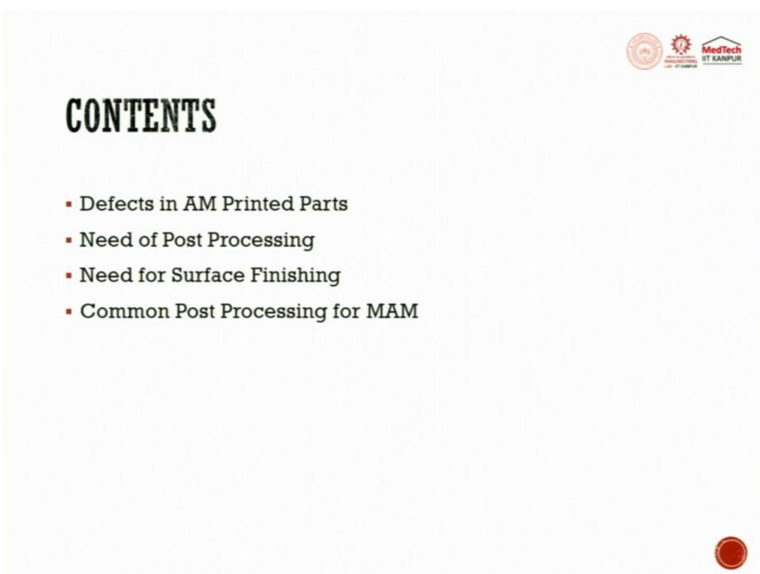

The content of this lecture is defects in additive manufactured printed parts, then, need of post processing, need for surface finishing and some of the common post processing steps involved in metal additive manufacturing. As you know very clearly that using various thermal sources in metal additive manufacturing leads to different performance. So, choosing of the thermal source is also very important.

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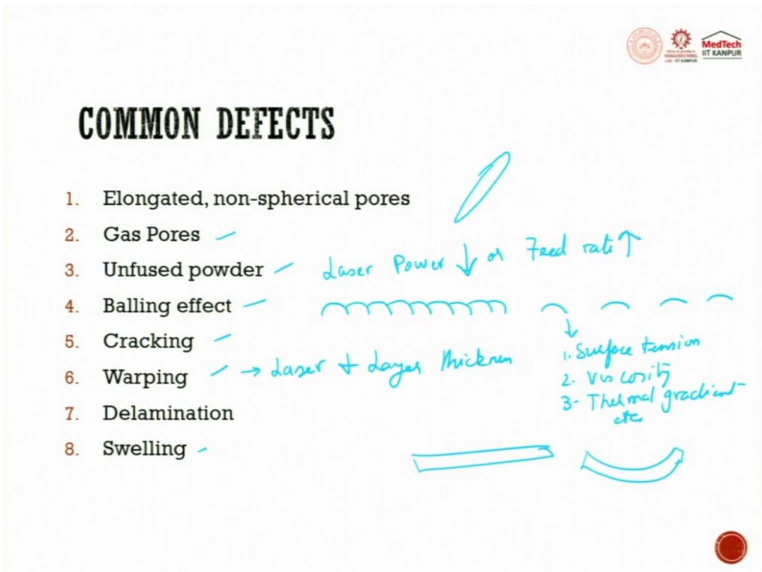

Some of the very common defects which happen in metal additive manufacturing are elongated and non-spherical pores, elongated and non-spherical pores, then gas pores, we saw two pores one is gas the other one is process induced gas pores. The next one is unfused powder, why did the unfused powder come if you choose a laser power lesser or your feed rate and the hatching speed is very high then you get unfused powder.

The next one is balling effect. Balling effect means, when we try to melt powder it should melt and form a one single line. But, if this does not happen, and if it happens something like this, then it is called as balling effect, why is this balling effect? It depends on the surface tension of the molten material, two, viscosity, three, it depends upon the thermal gradient etc. apart from your laser power, laser feed rate etc.

So, balling effect is very important when we do metal additive manufacturing especially laser sintering process balling effect is very common, then we have cracking. So, cracking is because of improper solidification, you will have tensile stresses coming at the top which will pull and it will try to tear it leads to a crack then warping is because of the difference in temperature gradient. So, you have residual stress getting involved and this will try to warp the entire component. If this predominantly depends upon the laser and layer thickness.

If the layer thickness is too less, and if the laser is having too high power, then there is a gradient instead of getting a flat layer, you get a warped layer, then delamination happening between layers and finally, we will try to see swelling also. So, these are the most common eight defects, there are more defects, but normally speaking these are the eight dominant defects, which come in metal additive manufactured parts.

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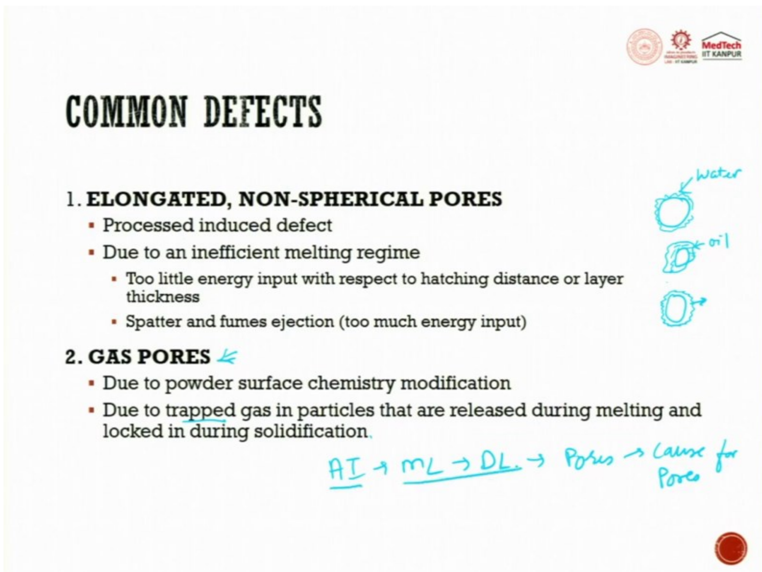

The elongation and non-spherical pores, is because of processed induced defect due to an inefficient melting regime, too little energy input with respect to hatching distance or layer thickness, spatter and fumes injection happening, which leads to elongated or non-spherical pores.

Gas pores are happening because of powder surface chemistry modification or trapped gas in particles that are released during melting and locking during solidification. So, what we are trying to say, if you have a metal powder around the metal powder by chance, if you have some amount of water or you have some amount of oil or you have some amount of some other unwanted elements which are present.

So, this all while reaction it will try to release gas and this gas is getting trapped due to trapped gas in particles that are released during melting and locked in during solidification. So, during melting and solidification these gases get locked and this form gas pores; predominantly gas pores are small and it is also of a regular shape.

You do not get an erratic pour by looking at the port itself you can try to distinguish over a period of time today there are artificial intelligence machine learning and deep learning used DL are used for identifying the pores and coming and telling out what is the cause for this pores. This is done through AI, ML and DL they are using it for additive manufactured parts.

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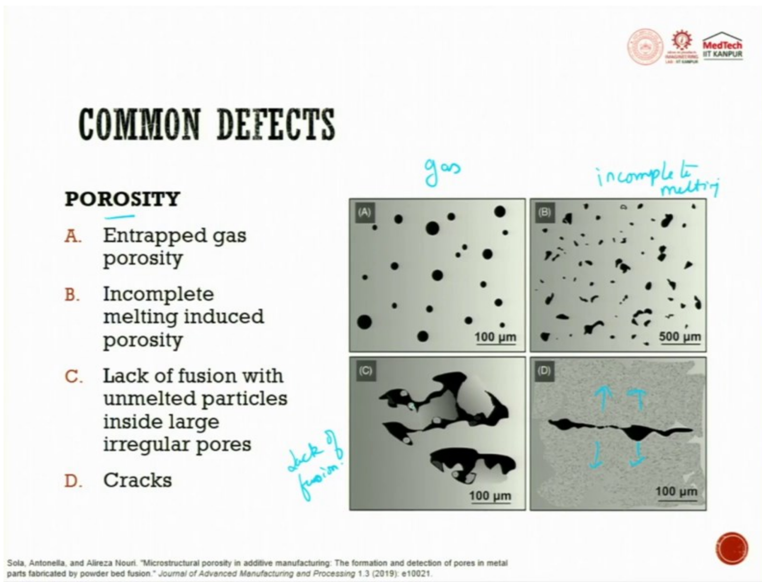

The entrapped gas pores are very nice, you can see circular ones and incomplete melting induced pores these are this incomplete melting induced pores. This can be because of lower power, faster moving rate or surface viscosity change something like that. So, next is lack of fusion with un-melted particles inside large irregular pores.

So, you see here these are powder particles which are getting locked inside the pores and which is not involved when melting and the last one of these are called as cracks. So, the porosity you can have gas porosity and this is incomplete melting. Then lack of fusion and this is crack. This is because of tensile.

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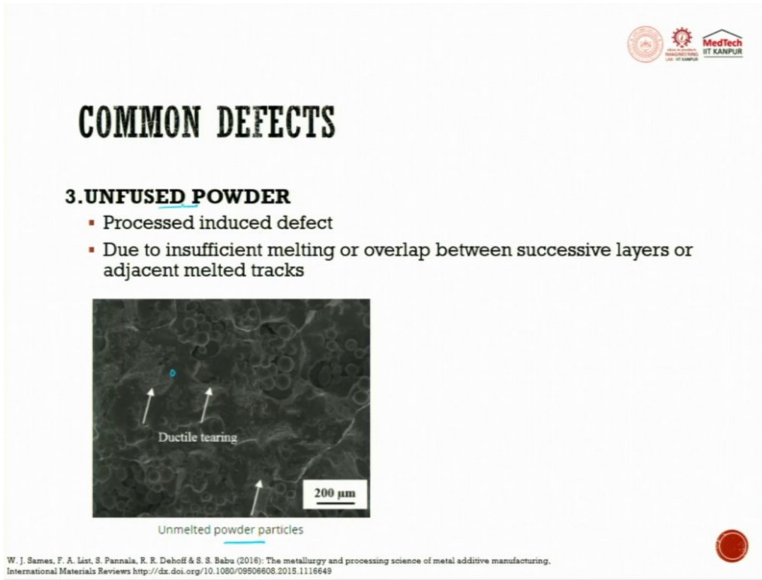

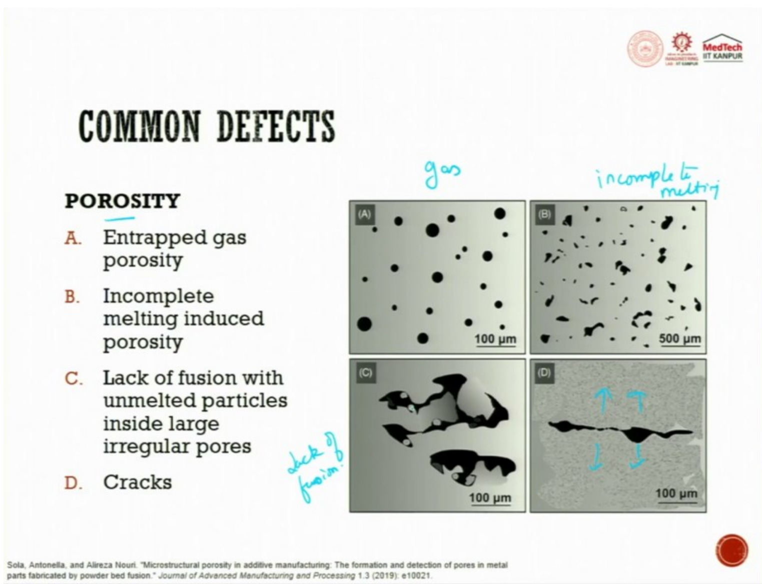

Unfused powders are also seen here. These are all un-melt powders, you also have something called as unfused powders. Processed induced defect, it is a processed induced defect due to insufficient melting or overlap between the successive layers or adjacent melting tracks, you will have unfused powders you can see here these are all un-melt powder particles. So, you can see here these are some of the particles. These are unfused powders.

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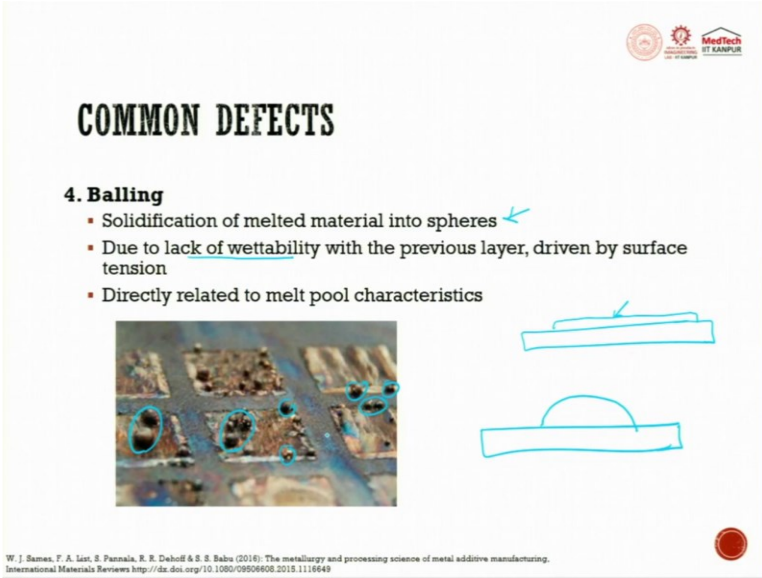

Next, balling you can see these are all balling. Solidification of melted material into spears, this is because of surface tension, viscosity, temperature related phenomena, you create this balling. Due to lack of wettability with the previous layer driven by surface tension. So, it is from one layer to the other layer. If you have a problem with wettability, what is wettability? Wettability means you are trying to take a plate and then you are trying to drop water, if you drop water and the drop water if it stays like this, then it is said as poor wettability.

When you try to drop a water drop on top of a plate, if the water drop spreads itself like this, then it is said to have low wettability. So, low wettability means we can say it has low contact angle this is high contact angle, low contact angle, low contact angle means, the water can spread easily over the surface.

This is very important if it has a surface tension phenomena lack of wetting, it spreads and it stops this leads to balling. So, it is basically landing up to hydrophobic and hydrophilic surfaces for a metal surface with water it is a straightforward phenomena. But for a metal powder melt at very high temperatures, that is a very difficult phenomena to visualize. Directly related to melt pool characteristics you will have this balling effect this is very important, lot of people suffer from this balling effect.

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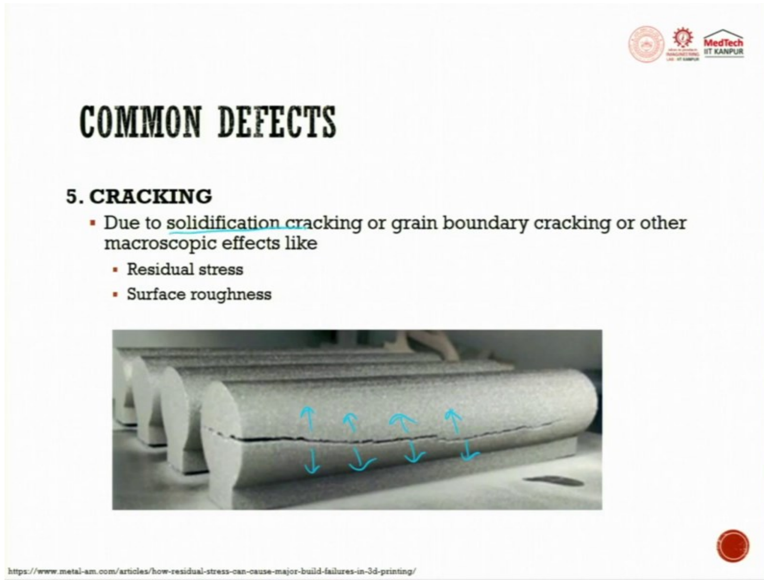

Next is cracking, due to solidification cracking or grain boundaries cracking or other macroscopic effect like residual stresses and surface roughness leads to such cracking. So, these are all tensile stresses. So, these tensile stresses leads to crack and moment there is a crack it is it goes. So, this all these things are happening because of solidification defects, this is called a solidification cracking.

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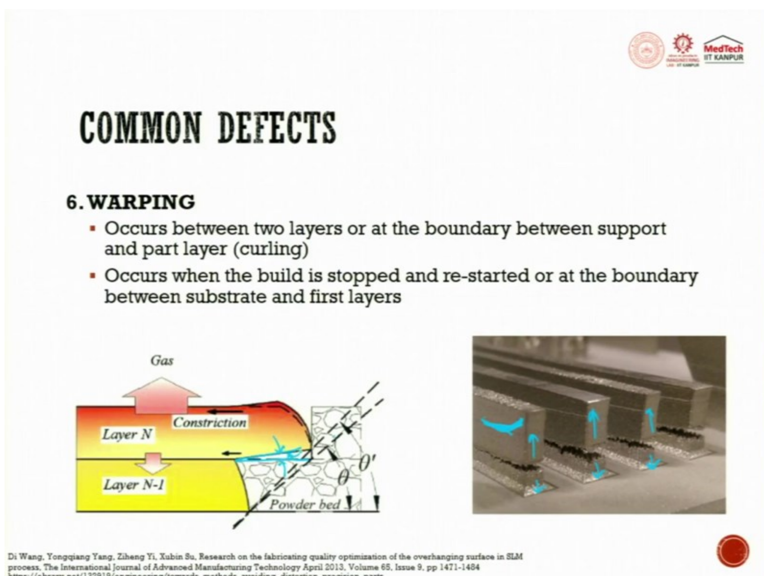

Warping, warping is as I told you, because of the thermal gradient. So, here what will happen between the layers, there is here delamination which is happening which tries to break. So, now, this sample which are supposed to be flat is now warped like this. So, occurs due to between two layers or at the boundary between support and the part layer. So, you can see curling, occurs when the build is stopped and the restart or at the boundaries between the substrate and the first layer.

So, you can see here layer 1, layer N-1, these are the constructions happening, the pulling happening. So, because of the pulling, you see here there is a delamination. So, this is the powder bed and you have a delamination happening. So, this is nothing but warping defect, this is warped, θ.

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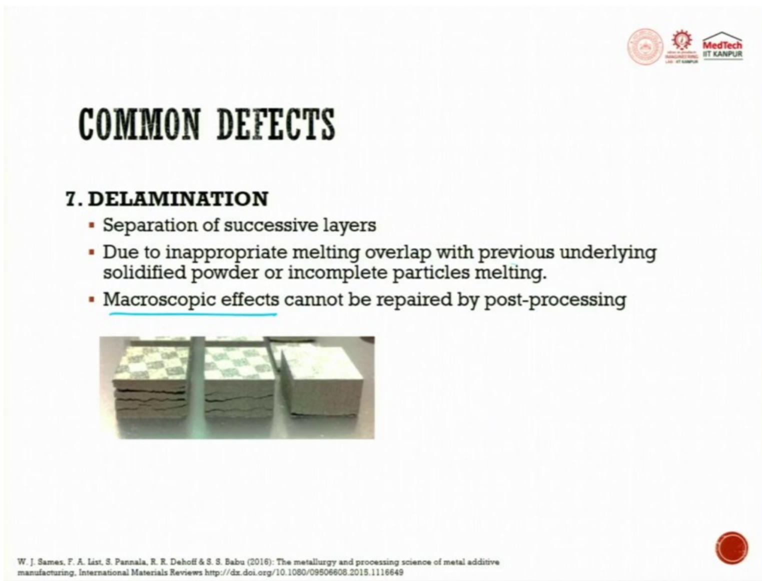
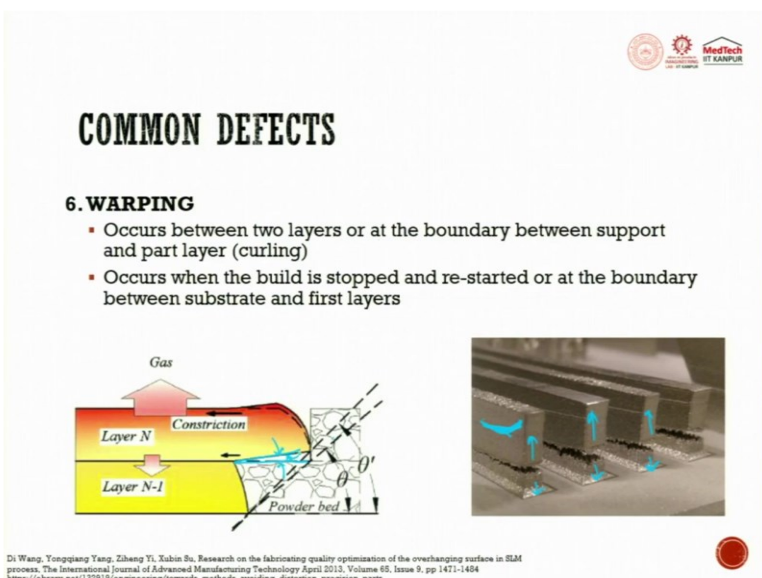
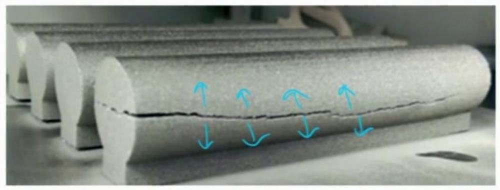




COMMON DEFECTS

5. CRACKING

- Due to solidification cracking or grain boundary cracking or other macroscopic effects like
  - Residual stress
  - Surface roughness

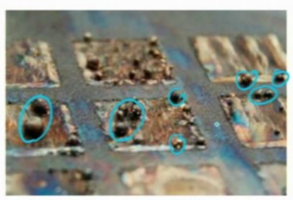


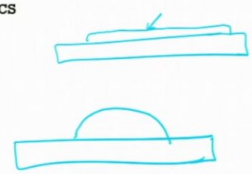
https://www.metal-am.com/articles/how-residual-stress-can-cause-major-build-failures-in-3d-printing/

COMMON DEFECTS

4. Balling

- Solidification of melted material into spheres
- Due to lack of wettability with the previous layer, driven by surface tension
- Directly related to melt pool characteristics



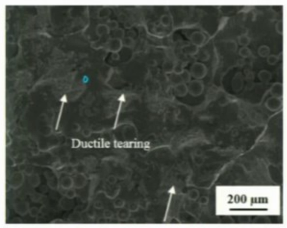


W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff & S. S. Babu (2016): The metallurgy and processing science of metal additive manufacturing, International Materials Reviews http://dx.doi.org/10.1080/09506608.2015.1116649

COMMON DEFECTS

3. UNFUSED POWDER

- Processed induced defect
- Due to insufficient melting or overlap between successive layers or adjacent melted tracks



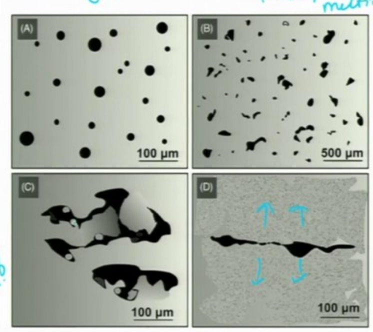
Unmelted powder particles

W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff & S. S. Babu (2016): The metallurgy and processing science of metal additive manufacturing, International Materials Reviews http://dx.doi.org/10.1080/09506608.2015.1116649

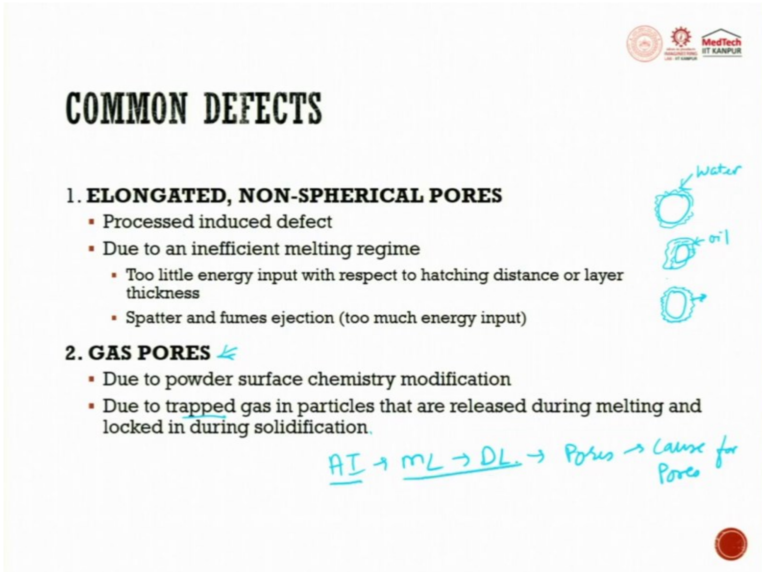
COMMON DEFECTS

POROSITY

A. Entrapped gas porosity
B. Incomplete melting induced porosity
C. Lack of fusion with unmelted particles inside large irregular pores
D. Cracks



Sola, Antonella, and Alireza Nouri. "Microstructural porosity in additive manufacturing: The formation and detection of pores in metal parts fabricated by powder bed fusion." *Journal of Advanced Manufacturing and Processing* 1.3 (2019): e10021.



Then delamination, warping is different delamination is different, but you can link all those things this warping leads to delamination. So, delamination is separation of successive layers due to inappropriate melting overlap with previous underlying solidified powder or incomplete particles melt leads to delamination, macroscopic effect cannot be repaired by post processing.

So, keep in mind this cannot be removed, all these defects cannot be removed. So, delamination cannot be removed by post processing, warping cannot be done, crack to some extent it can be done, balling cannot be done, unfused powder it cannot be done, porosity there can be some amount of closure happening little bit and elongation of nano-pores closure to some extent. So, these are some one, two can be done by post processing, fused, balling, cracking, warping and delamination cannot be done by post processing step. You cannot peel it, it cannot be repaired through the post processing step.

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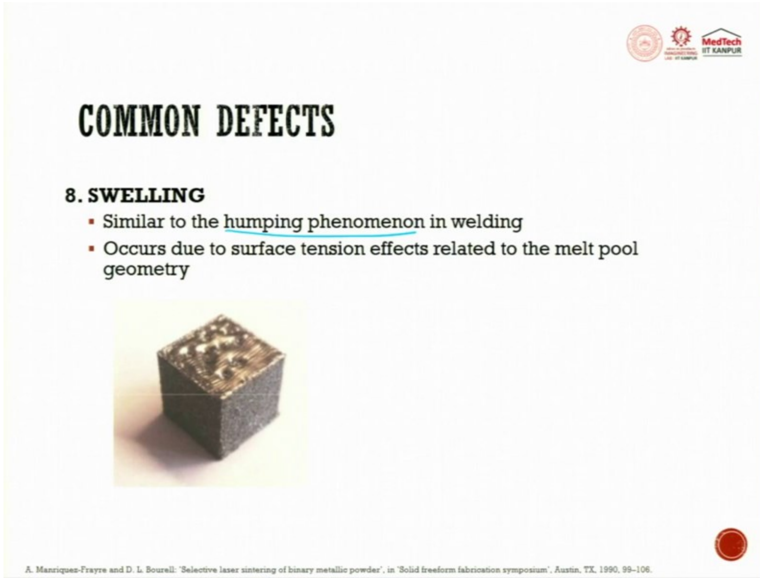

Swelling similar to humping phenomena in welding. So, occurs due to surface tension effect related to the melt pool geometry. So, there is a swelling which is happening around it there is a humping effect. So, this is common in welding. So, the same thing is here because in welding also you melt and pour material it solidifies.

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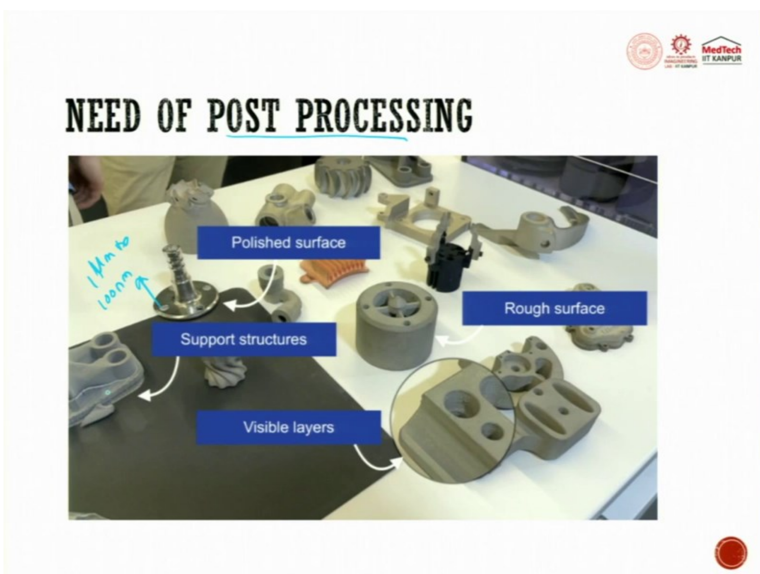

So, these defects are very common. So, now, you have understood those defects, you have to now work towards process optimization in getting a good quality output. Moving to the next topic of discussion, where we are trying to talk about post processing. So, if you are trying to see the post processing, the most important thing is heat treatment, the other one is roughness removing.

So, you have a rough surface here, you have this rough surface is polished and you get a very, smooth or very low Ra you can also get going from 1 µm to 100 nm, Ra you can try to get. So, these Ra tries to increase the fatigue response of the component. So, you can and have supporting structures, these supporting structures should be chiselled and removed. So, all these things are done by post processing.

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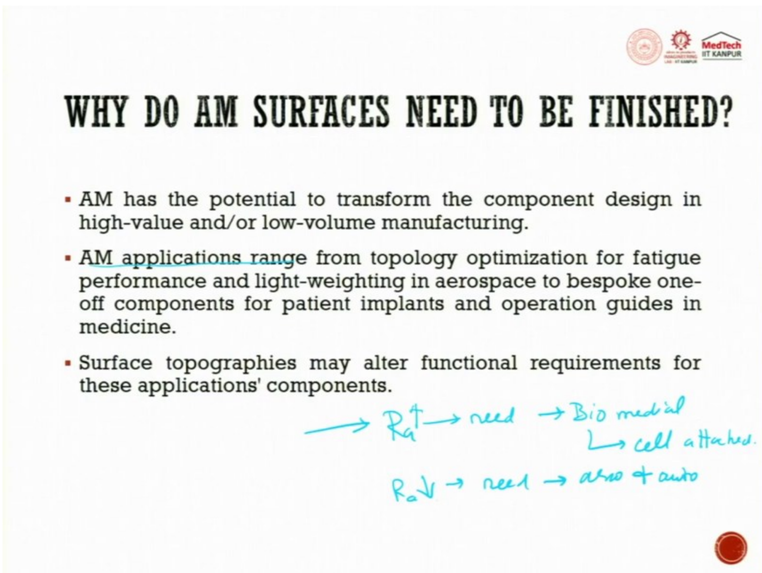

So, why do additive manufactured surfaces need to be finished? Additive manufactured has the potential to transform the component design in high value or low volume manufacturing. Additive manufacturing application range from topology optimization for fatigue performance and light weighting in aerospace to be spoke, one of component for patient implant and operation guides in medicine. All these things are the range in which the additive manufacturer use. Surface topologies may alter functional requirements for these surfaces. So, what I am trying to say is, there are certain places where you need Ra.

For example, for biomedical applications, you will need to have a rough surface so, that the cell gets attached, this is for a rough surface Ra very high. Ra very low is needed for aero and auto applications, automobile applications. Why you would like to have a smooth surface? Because of the smooth surface you can try to reduce the drag or when you put it for fatigue cycle, the crack propagation does not happen so easily. So, you depending upon your functional requirements, you go ahead tweaking the surface topography.

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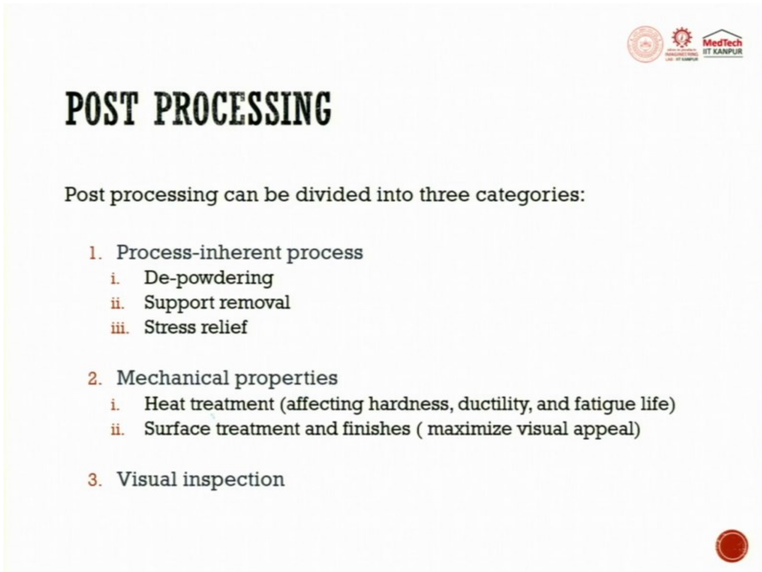

The post processing can be divided into three categories- process inherent process, then mechanical properties, then visual inspection. The post processing process inherent process are De-powdering, support removal, and stress relief. Mechanical properties, heat treatment and surface treatment finishing. So, these are some of the few post processing steps.

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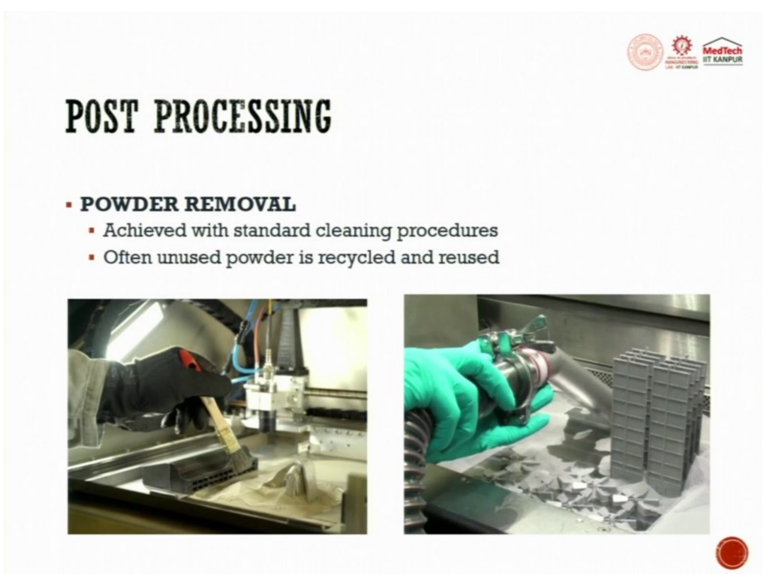

The powder removal achieved with standard cleaning procedure and often unused powder is recycled and it is reused. So, once the process is made, then what we do is we try to suck through vacuum sucking we try to suck all the free powders where it has not been sintered or melted by laser or electron beam. All those powders are taken back and these powders will be recycled and reused for the next printing. So, achieved with standard cleaning procedure, often unused powders are recycled and reused.

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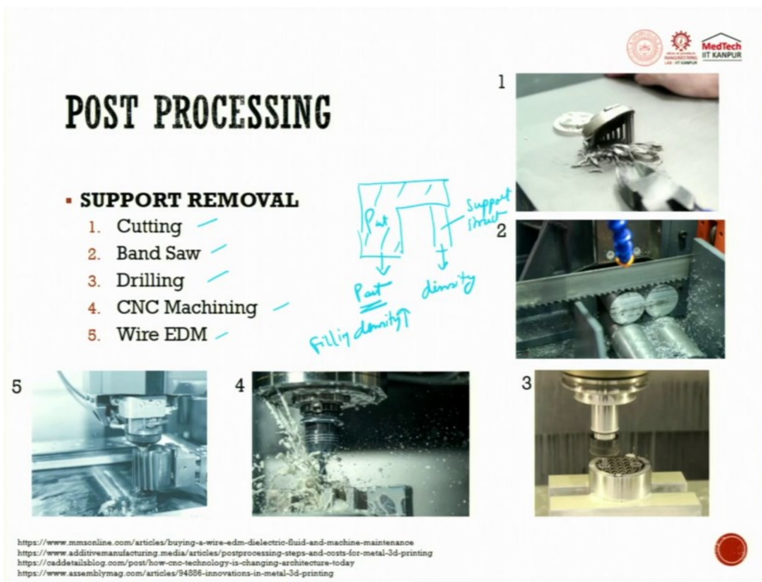

The support removal is another important thing we use some time cutting, band saw, drilling, CNC machining and wire EDM for removing the supporting structures. So, these are band sawing we do. So, what is, why do we have supporting structures? So, these are part and this is free handing. So, here I tried to have a support structure.

So, we can cut, you can do band sawing, you can do drilling, you can do CNC milling, and you can do wire EDM to remove those support materials which were used while development. You can use the same material or you can use a different material, generally we use the same material and here the density of filling will be completely different to that of the part. Part will have higher density, filling density I am talking about. Filling density will be higher, here it will be lower so, that it can be chipped off or removed very easily.

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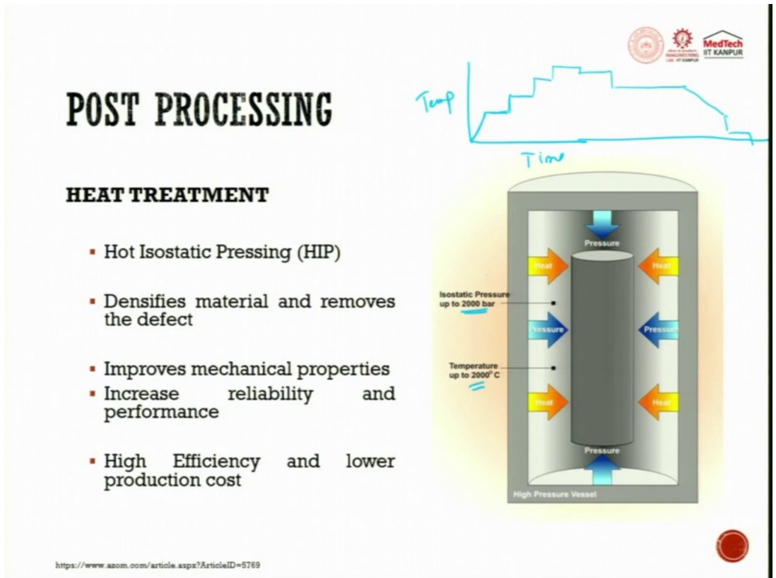

Heat treatment these are some of the heat treatment process which predominantly is used hot isostatic pressing. In hot isostatic pressing, you try to have pressure and then you also try to have temperature. So, the isostatic pressure up to 2000 bar is used here and the temperature also goes up to 2000^0C.

So, with this what they do is the component is compressed and when it is compressed, there is a possibility that the cracks pores can be closed, but it is a very expensive process. People also use cold rather than applying heat that is also possible the difference between cold and hot is, hot you have to the pressures applied are slightly lower than that of the cold.

Densifies material and removes the defect improves mechanical property increases reliability and performance and high efficiency and lower production cost. So, heat treatment is done for this if I do not apply pressure, then I just apply the heat treatment when I do the heat treatment also temperature versus time you have a cycle so, it goes through the cycle. So, this is the loading cycle, and then it maintains for a longer time, then it comes like this and then you try to get the output. So, this is the temperature time profile, which is logged into the furnace and it will try to do it.

So, this talks about increase in temperature with respect to time, then you hold it your holding or soaking time you do, hold it for some time and then you rapidly increase you do it. So, rapidly increase, and you slowly reduce the temperature with respect to time. So, this is the temperature heat treatment cycle, which is logged and followed depending upon this the grain structure, precipitation, hardening all these things can happen.

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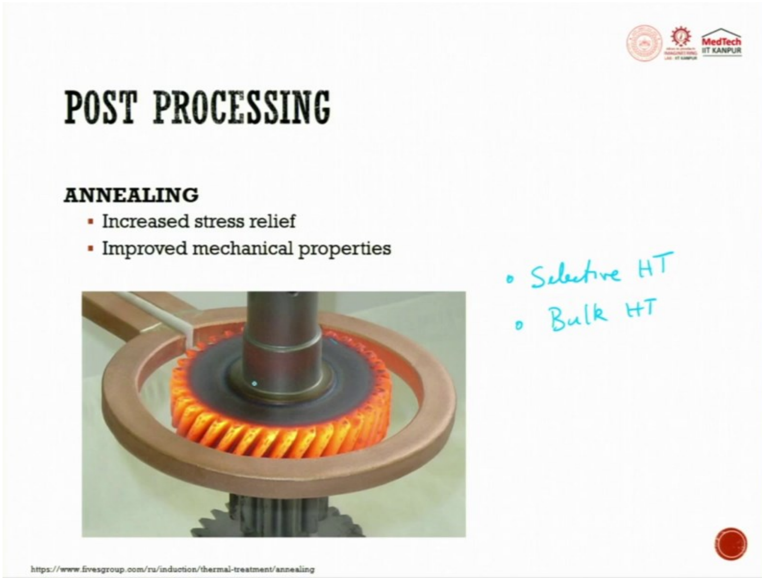

You can also do annealing. Selective annealing can be done only at few parts of the entire build additive manufactured part. Annealing increases stress relief and improves the mechanical property such that the fatigue cycle goes high and it can be used for a longer time. You can do selective heat treatment or you can do whole bulk heat treatment. Both you can do. So, when I say heat treatment annealing, normalizing, aging everything comes into that. So, annealing you can do it selectively at only the gear teeth and rest all you do not have to do the annealing. So, you can try to get the better performance.

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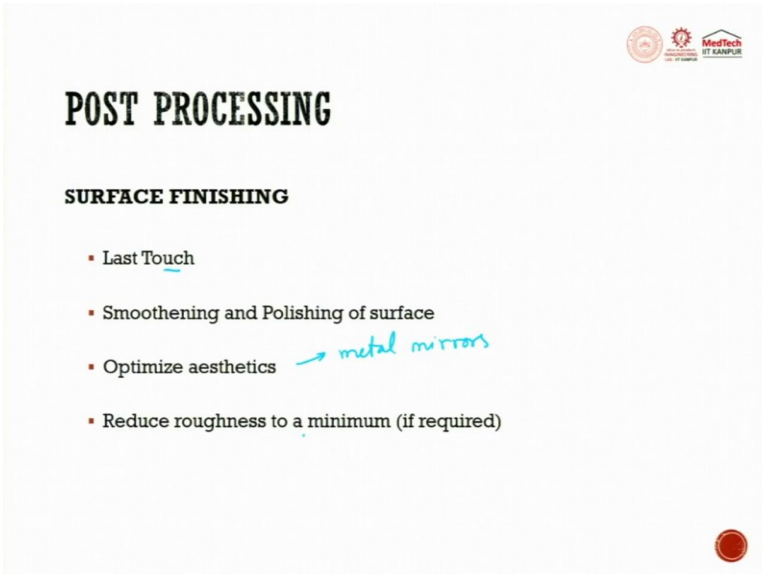

Surface finishing it has given for the last touch. So, smoothing and polishing of surfaces can happen, it optimizes the aesthetic look. See, if you look today we talk about metal mirrors. The substrate is metal and it is buffed or polished to such an extent it looks as though like a mirror.

So, for certain applications, we use additive manufactured part buff it or polish it to such an extent and use it as a metal mirror, because, these mirrors are also not flat or simple in geometry, they are very complex. And for this complex geometry, if you are looking for heat extraction and backward supporting for heat management system, then additive manufacturing comes in a big way. So, here it reduces roughness to a minimum.

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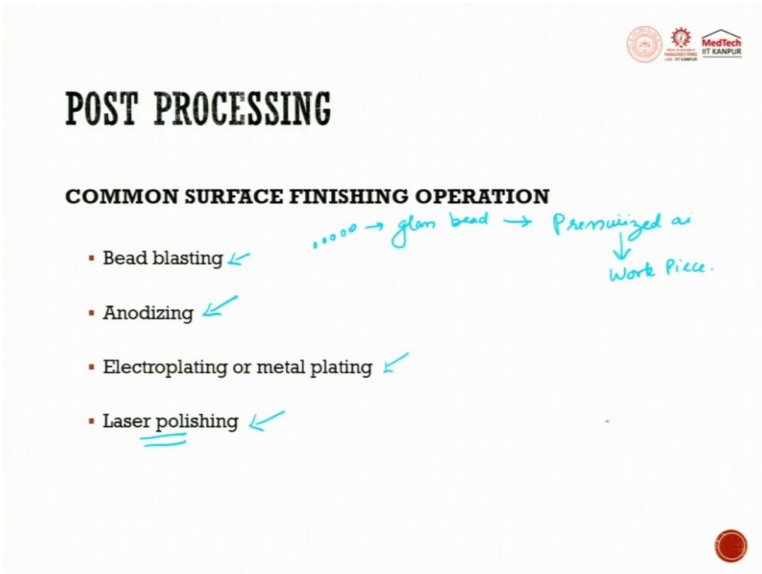

Some of the common surface finishing operations are bead blasting, bead blasting means you use small beads, these beads are glass beads, very small, it is like a powder glass beads, and this glass bead is passed through a pressurized air it is focused on the workpiece. So, that you can try to remove the staircase effect to a large extent. So, bead blasting like shot blasting, you also use bead blasting, you use anodising for giving a metal coating on top of it.

Anodising, you can also do metal plating on top of it. You can do dip coating, electroplating and you can also try doing laser polishing. The latest trend is to use the same laser which is used for building, and use it for polishing. Basically, you try to melt the surface you do not melt it you try to melt and then it flows easily if the flowing happens because of capillary action. So, it is a process which is coming up in a big way now.

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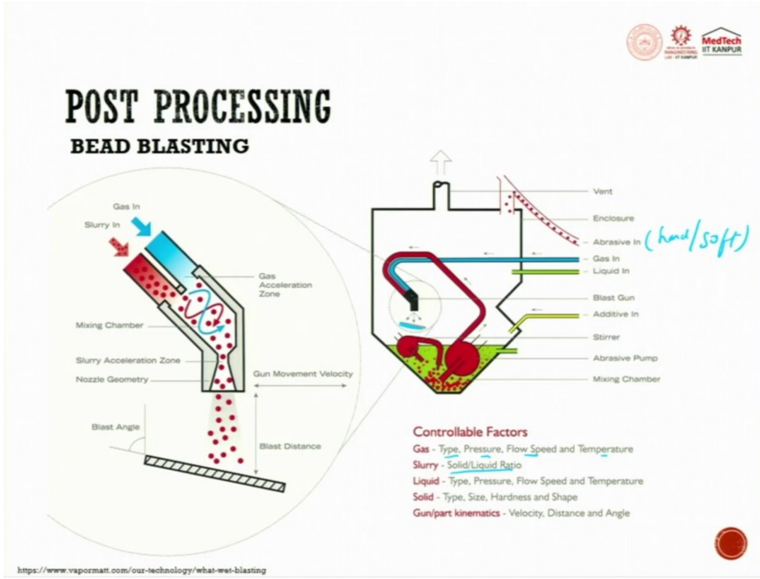

So, this is a bead blasting you see our gas in the slurry is given. So, there is a mixing which is happening and then the slurry mixed with air is allowed to hit on the surface which is additively manufactured. So, you have a mixing chamber just like our waterjet cutting mixing chamber, you have a slurry acceleration zone, then you have a nozzle geometry, you place the workpiece. This is the blast angle and then you try to maintain the stand-off distance, the gun movement can happen and the gas acceleration nozzle is here.

So, this is just like our plasma spraying, shot blasting the same way you use bead blasting. The other way around is you can also have something like this. So, here you have a vent and then you have abrasive in. Abrasives can be hard, it can be soft, so to depending upon your requirements you can use. So, these abrasives are allowed to hit on top of a surface.

So, you have a gas in and then you have a liquid in also there. So, liquid and gas are there, then you have a blast gun. So, then you have something called as a stirrer. So, there is an additive pump abrasive pump and then you have a mixing chamber. So, this is where the blast happens and then it comes here. So, all these things what comes out is getting accumulated and then you try to pump it. So, gas type, pressure, flow speed, temperature, all these things are important.

Next is slurry, solid liquid ratio, liquid type pressurized flow speed and temperature, this liquid is only to accumulate the abrasives and then take it for recycling. Solid is type, size, hardness and shape it is important. Then you have velocity, distance and angle.

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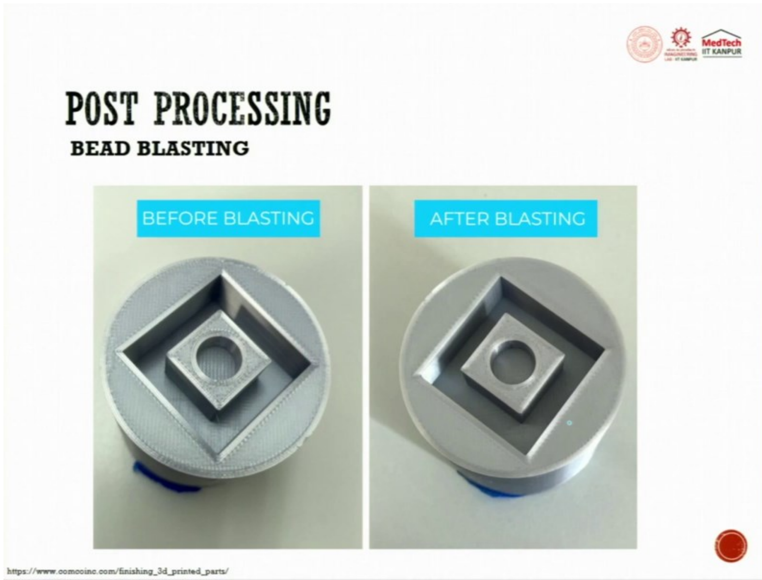

So, this is a part which is done before blasting and this is a part which is achieved after blasting.

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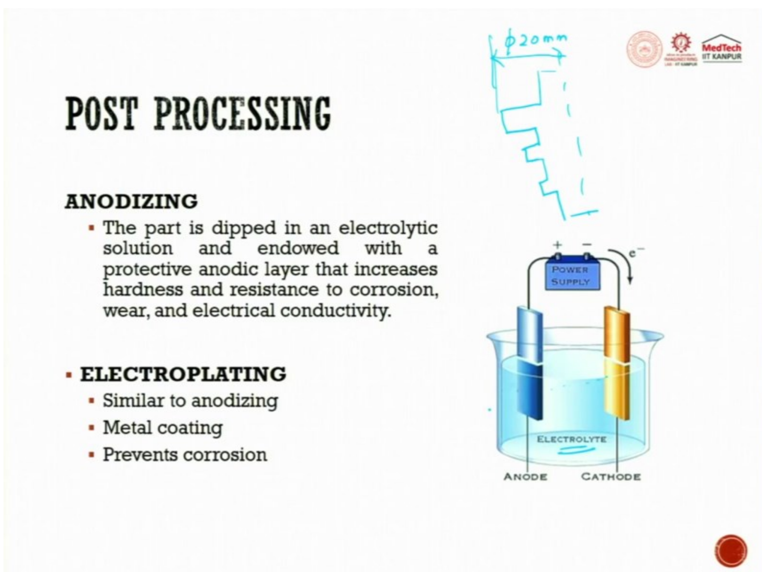

So, anodizing part is dipped in the electrolytic solution and endowed with a protective anodic layer that increases the hardness. So, this is an anode. So, you attach it to a power supply, you keep it inside an electrolyte whatever solution you want to get deposited, you do it.

The part is dipped into electrolytic solution and endowed with a protective anodic layer that increases the hardness and resistance to corrosion where the electrical conductivity we use it. Today we are trying to make additive manufactured parts for batteries which is used in Evehicles. So, when we do that, we also tried to have that as wear resistance, thermal cycle fatigue resistance.

So, what we do is we try to see such type of anodic coatings can be done. So, today we are trying to talk of battery something like this. So, this dimension is dia 20 mm, which is printed and they are trying to play with the surface area, they are trying to do coating, there are lot of things people are doing.

Then the next one is electroplating similar to anodizing, metal coating happens, it prevents corrosion. So, these two anodic coating you can take or electroplating you can do. Electroplating means, you try to do it, there is an ion which moves from the negative towards the positive and you try to get the output.

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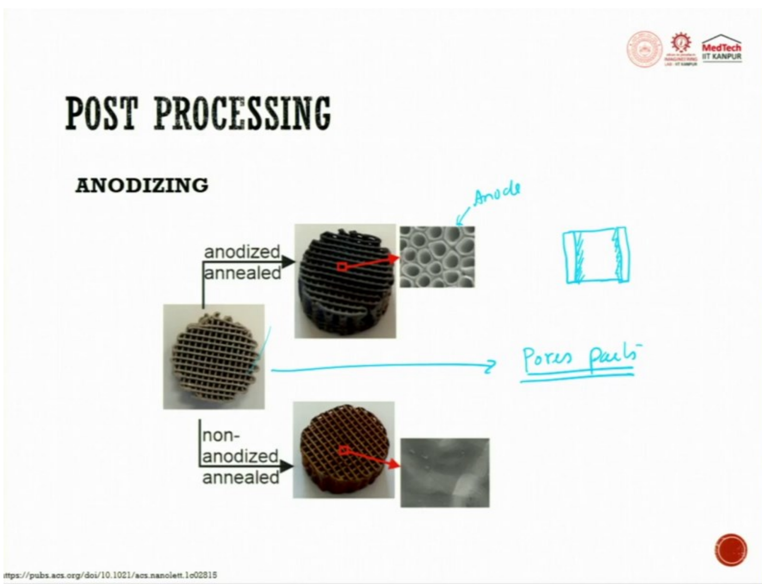

So, these are anodized. So, you can see these are a part anodizing you try to do this and then you try to get it so, you can see here on the square whatever it is, you have now coated with anode. So, suppose you have a metal, let us assume like this you have a metal cell one cell and inside the metal cell you have done this anodizing, very interesting. If you are looking for acoustic metamaterial properties, such structures will be huge breakthrough for various acoustic metamaterial properties, which a lot of companies are trying to work on.

When you try to do with a non-anodized annealing you try to see the entire cell is getting distorted. So, here, when we see at this part, all these things we were trying to make only solid parts now, these are all porous parts which are built such that it can be used for some application. So, anodizing is also part of it.

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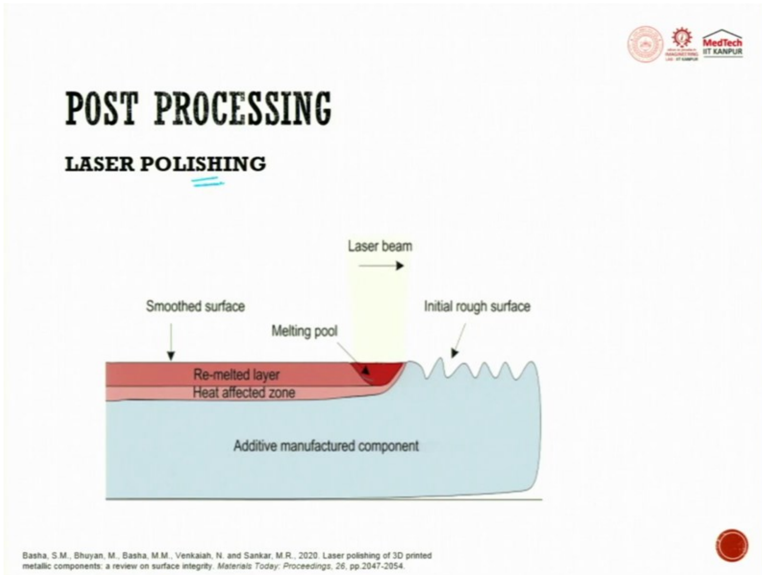

The next one is laser polishing. So, laser polishing as I told you, you try to de-focus the laser with a smaller amount of energy, it tries to re-melt the layer, when it tries to re-melt the layer there is a conduction. So, you will have a heat affected zone. So, you make sure that the heat affected zone does not affect the geometry, make sure that is there. And then you have a small melting which is happening.

As and when the laser keeps moving you see a melt pool which is getting formed and this is the roughness which is there on the surface. So, this one when it moves completely you will see the re-melt portion will make it completely flat and you get a very good polishing which is done on the surface.

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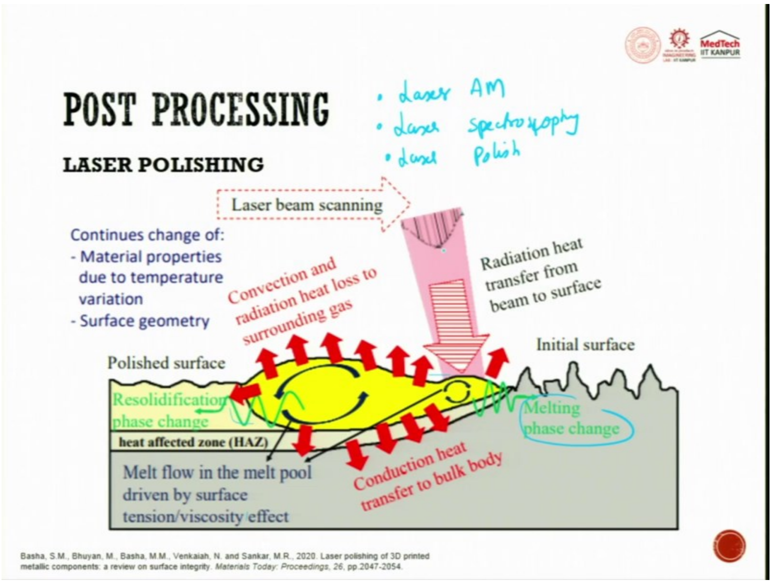

So, little bit of understanding what I talked about keyhole effect, Marangoni effect all these phenomena has happened in laser polishing also. Laser beam scanning which is happening. So, this is the laser radiant which is hitting. You have a Gaussian distribution which is there in the heat profile, the radiation heat transfers from the beam to the workpiece, initial surface is very rough.

So, because of the laser moving, there is a melting phase change which happens, there is a hot layer on the top, there is a cold layer on the bottom. So, that is a Marangoni convection which is happening. So, here if you see the melt flow in the melt pool driven by surface tension viscosity effect, it keeps going.

So, this is a convection so, you also have this is radiation. So, you have convection and radiation heat loss from the gas which happens on the surface. And here you will try to have re-solidification phase happening at this end. So, melting phase happens at this end, re-solidification happens at this end, all this rough surface is now converted into a smooth surface on the top.

So, this is a very important phenomena, which is used today for post processing of finishing of additive manufactured part. So, we use continuously change of material property happens due to the temperature variation and surface geometry of the part is also very important. So, this is a very promising technique, now, lot of companies are using it.

So, now, the laser is used for additive manufacture, laser is used for spectroscopy, it is used for reverse engineering and then the same laser is used for polishing. So, all are done by the same laser just by tweaking the power and the interaction time; all these things are done in one machine today.

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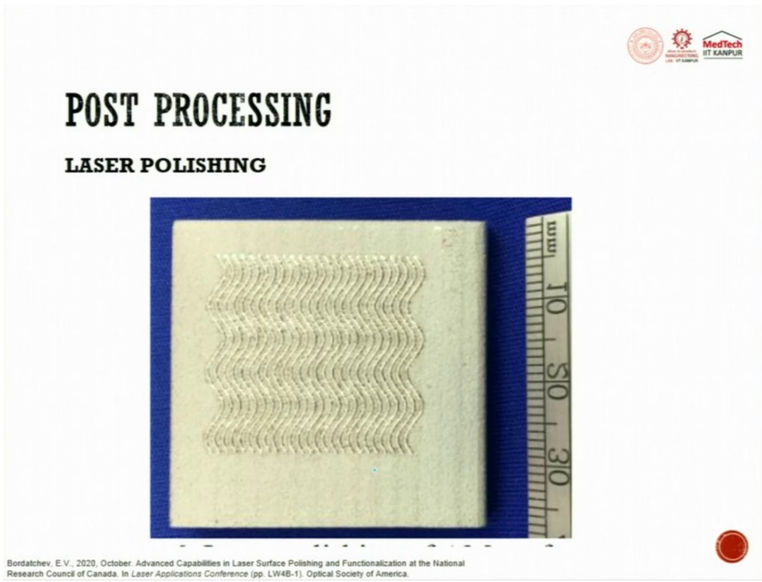

So, this is the laser polishing process wherein which all these things are whirls are created and you have a polished surface here.

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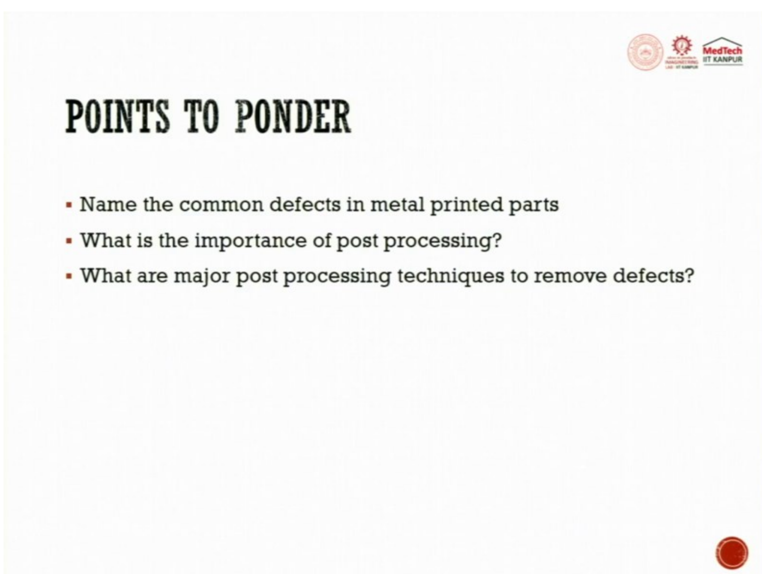

Points to Ponder in this lecture, what all did we cover, we looked into some of the common defects in metal printing parts. We saw some of the importance of post processing and in post processing the major post processing techniques were discussed to remove the defects.

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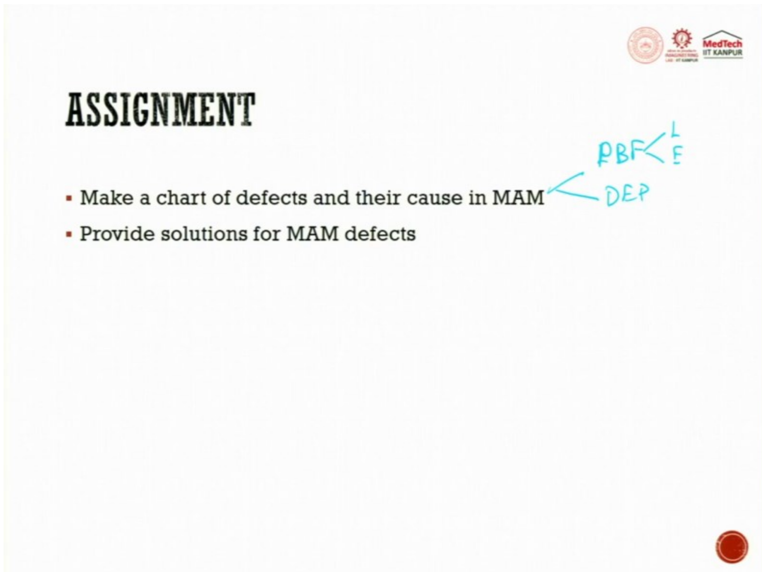

So, make a chart of defects and their costs in metal additive manufacturing, both in terms of powder bed fusion method and DED, and here again laser and E you can see provide solution for metal additive manufacturing defects which has happened while processing. Thank you very much.