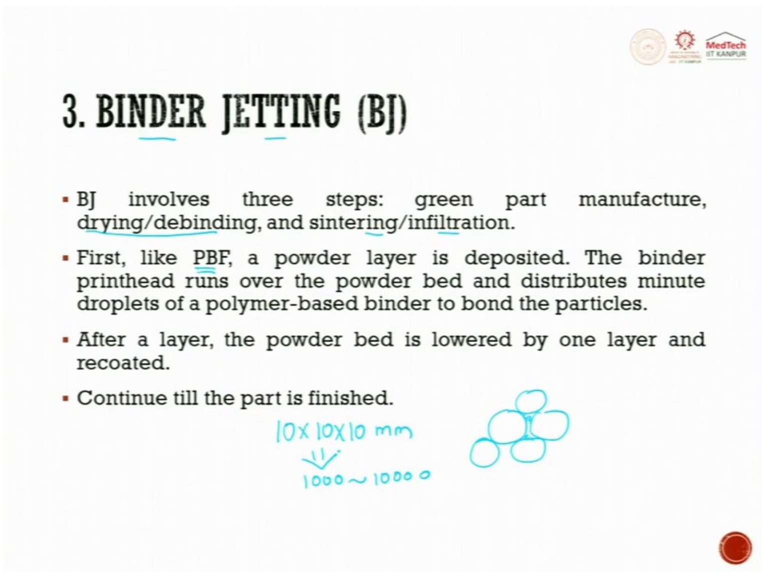
Metal Additive Manufacturing
Prof. Janakranjan Ramkumar
Prof. Amandeep Singh Oberoi
Department of Mechanical Engineering and Design
Indian Institute of Technology, Kanpur
Lecture: 08
Basic Processes

Welcome to the second lecture on the Basic Processes. Last lecture, we covered powder bed fusion process, we also covered directed energy deposition process, we also saw the resolutions, what each process can do and which process is cost effective also we saw. Now, moving further down, we will try to see a next new interesting process, which is binder jetting.

(Refer Slide Time: 00:51)



As the name itself suggests, there is a binder where jetting will be the process through which it is getting deposited, here jetting means it is almost dropping do not think in terms of high-pressure jetting means in droplet form a larger flow rate is created. So, binder jet involves three steps, first we manufacture that green part then we do drying or debinding and then we do either sintering or infiltration. what is infiltration?

Infiltration means, you have set of metal powders which are sitting on each other, but in between you see there is a small gap. Now, you try to infuse metal into this gap or through this gap for several applications maybe for lubrication or maybe for thermal benefits. So, you try to infuse a different kind of material. So, this process is called as infiltration.

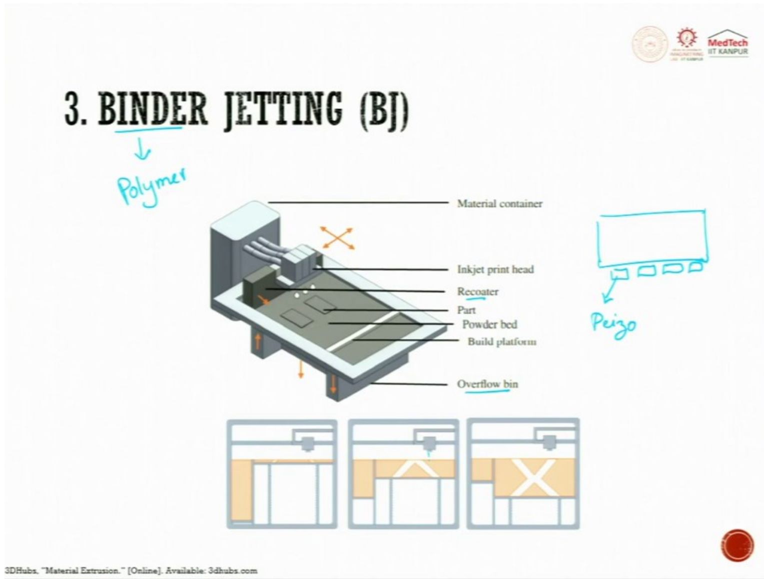
So, your component will be made through green what is green here? You try to take a metal powder or a ceramic powder, you try to add binder to it, so, that all these powder particles gets attached with each other, when you try to take the part out with slight amount of force you can try to break the part.

So, those things are called as green part manufacture, then what we do is, for joining you would have used a binder now, these binders will be removed from their locations and here it will not be in such a way such that the powder gets disintegrated you do that and then what you do is, you do sintering process first, like powder bed fusion, a powder layer is deposited by a recoater.

The binder printhead runs over the powder bed and distributes minute droplets of polymer-based binder to bond the particles it is only to bond and created after a layer the powder bed is lowered by one layer and again it is recoated. This process continues until you get a finished product. Generally, if you are looking for somewhere around, about 10x10x10 mm big object.

It will typically be made the somewhere starting from 1000 layers-10,000 layers, if you do anything less than that, you get a very rough surface since stair case effect dominates. So, what happens is we try to maintain an octave of 1000 layers. So, for binding 1000 layers, it will have to move up and down 1000 times to get the finished part.

(Refer Slide Time: 04:11)



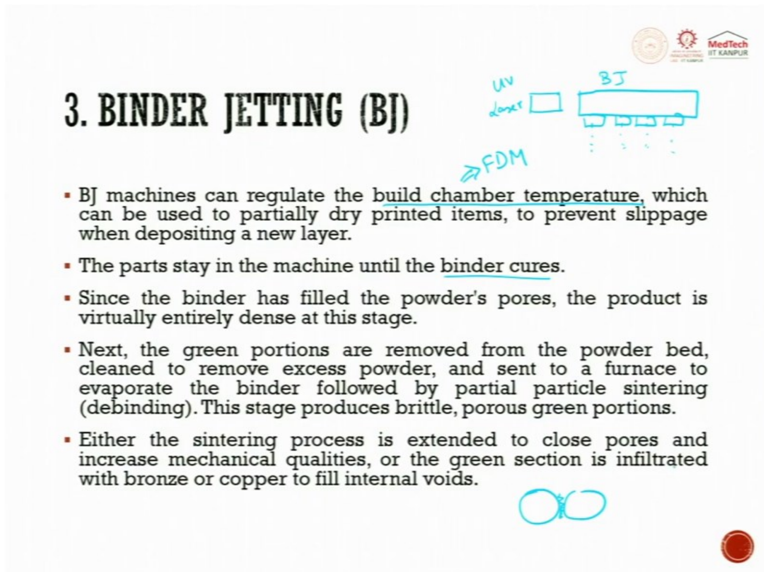
So, this is how the machine will look like. So, you can see this is a top view this is the side view. So, you can see here, this is the table where the powder is fed and you try to develop the part. So, here you can see there will be a drooping which is happening through this nozzle. So, this drooping is nothing but jetting and in this jet what is getting done is a binder.

So, generally we use polymer as a binding element. So, you will look at it if you want to have multiple compositions. Say for example, you wanted to have mixture of three different chemical polymer to generate the best action that also can be done, or if you want to have three different colors, you have basic colors and then by activating it when it droops down it tries to develop and it will try to give the color or the shape whatever it is.

So, binder is a polymer material which is done. Rest all are very clear. Here the material container then you have ink jet printhead. So, you will have your inkjet head. So, here you will have multiple nozzles, these nozzles opening and closing will be done by piezoelectric material or a piezo crystal material. So, it will be very fast.

So, it will try to cut down and it will try to make the droplet size very small. So, then you have a recoater which adds material, the part which is getting built. After the part is made, you suck and remove all the fresh powder for the next operation, then you will have an overflowing, then also it is almost like your powder bed fusion. But rather than a laser, here it is getting developed. So, what is the advantage here, the shrink cages which happens can be reduced to a large extent as compared to that of laser.

(Refer Slide Time: 06:13)



Binder jet machine can regulate the build chamber temperature, which can be used to partially dry printed items. So, we always have a built chamber temperature which is quite common in fused deposition model when you do with polymers. So, there we also have something called as a build chamber temperature, here also you have a build chamber temperature to partially dry the print item to prevent slippage when depositing a next layer.

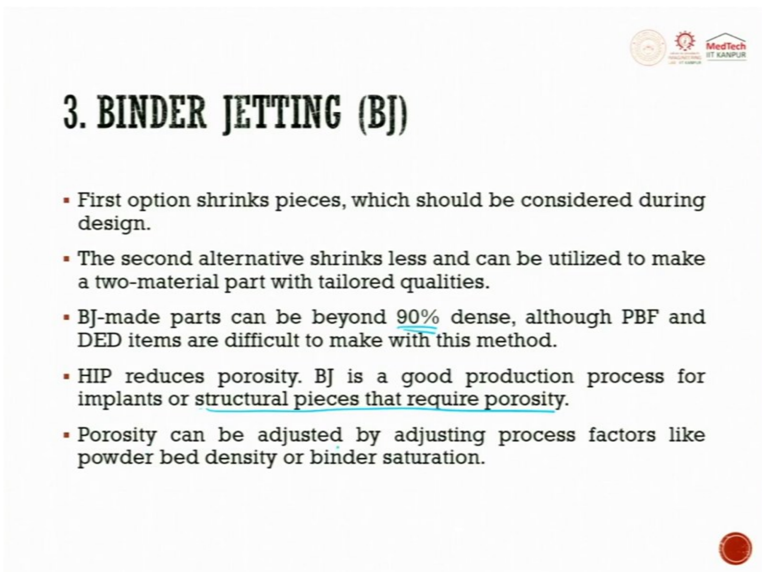
So, the polymer will slightly evaporate, and the part stays in the machine until the binder is cured. So, after the processor nowadays, what they do is along with a binder they also have the nozzles, these are the process. There is a drooping which is happening. Assume that next to the binder jet, you have one more laser this is a UV or a blue laser.

So, this laser tries to interact with a polymer and try to quickly cure it. So, that is done by binder curing. So, a laser is getting attached with a binder jet to produce the output whatever you want. So, here the binding chamber temperature will be regulated to some extent, since the binder has filled that powder pores. So, once you do sintering, you still have 95-96 % density 3-4% will be having pores.

So, that is where we tried to do infiltration. So, here the part may be in the machine until the binder cures. So, you can use laser for it, the new machines are coming with this add on feature. Since the binder has filled the powder pores, the product is virtually entirely dense at this stage, it is called green you can break it when you apply force.

But when it goes to sintering it becomes hard, next the green portion are removed from the powder bed, cleaned and remove excess powder and sent to the furnace to evaporate the binder followed by partial particle sintering. This stage produces brittle porous green portion. Either the sintering process is extended to close the pores and increase the mechanical quantities or the green section is infiltrated with bronze or copper to avoid or to fill internal voids.

(Refer Slide Time: 09:12)



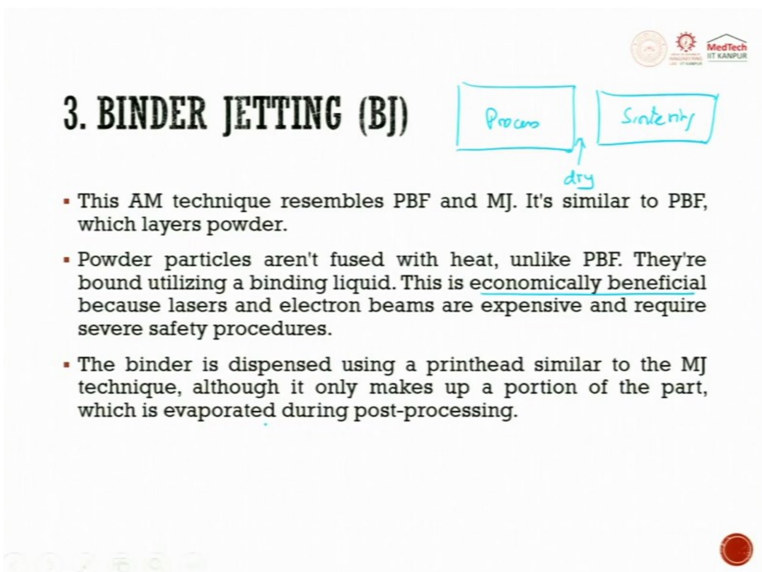
So, I have clearly said the distinction between sintering and infiltration which happens depending upon your requirement. And when the copper is fed in, the copper's viscosity or the bronze viscosity is very important such that it can try to have a capillary action into it, and having capillary action is also very tough, because the pore size are small and it is metal.

So, you need to have a negative pressure which is very high. Generally, it does not happen so easily. So, if you are still not able to visualize or understand, assume that you have a sponge which is used for cleaning the table. As soon as you immerse the sponge inside water, you see the water getting sucked into the pores. So, that is infiltration. So, if it happens by free atmosphere, it is easy if not what you do is you try to suck it.

So, these things are done. The first option shrinks piece, which should be considered during the design itself, because, after this you are going for sintering, a shrinkage or a shrinkage element has to be given. The second alternative shrinks less and can be utilized to make two material parts with tailor quantities.

Binder jet made parts can be beyond 90% densification although powder bed fusion and DED are difficult to make with this method. HIP reduces the pore size or the porosity. Binder jet is a good production process for implants or structural pieces that require porosity. So, wherever you intentionally needed, we also try to induce this by this binder jet. Porosity can be used for advantage as well as for disadvantage. So, you tune the pores there for your benefit. Porosity can be adjusted by adjusting process factors like powder bed density or binder saturation.

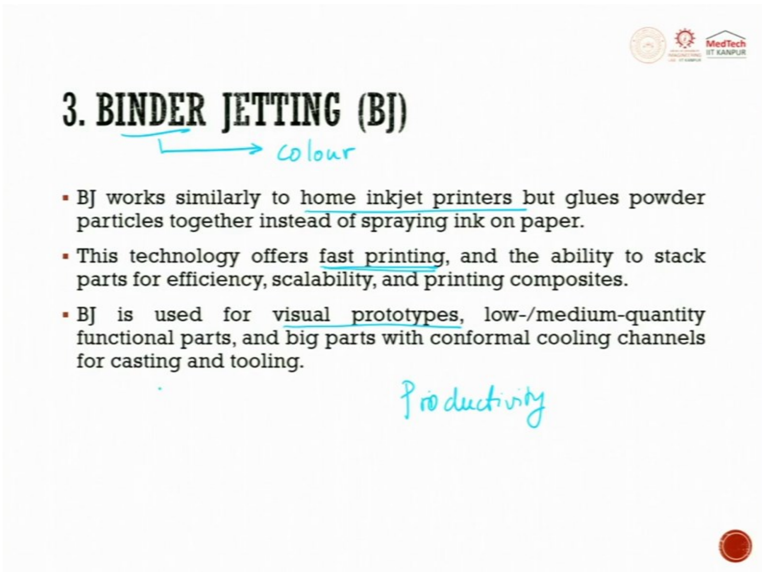
(Refer Slide Time: 11:22)



This AM technique resembles powder bed fusion and metal jetting; we will see what is metal jetting later. It is similar to powder bed fusion with layer powder. Powder particles are infused with heat, unlike powder bed fusion, they are bound at utilizing a binding liquid. This is economically beneficial because laser and electron beam are expensive and requires severe safety procedures. So, if you are looking for economical way of producing metal additive manufacturing part, binder jetting is one alternative because you will try to have the process which is done in one place and then you will have to go to a sintering station.

Next that is all so, in between you can try to have a drying station. So, this tool does not try to take lot of shrinkage, but here there might be shrinkage. So, all these things have to be calculated upfront before doing the process. The binder is dispensed using a printhead similar to that of metal jetting technique, although it only makes up a portion of the part which is evaporated during post processing.

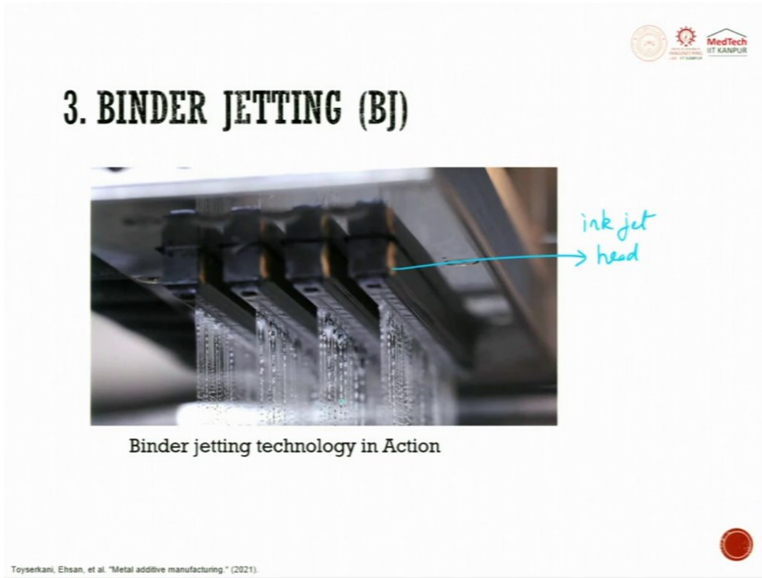
(Refer Slide Time: 12:48)



Binder jet works very similar to that of your home inkjet printer, there are cartridges, in that cartridges there are binders. So, these binders will do whatever function you want, but glues powder particles together instead of spraying ink on a paper this technology offers fast printing.

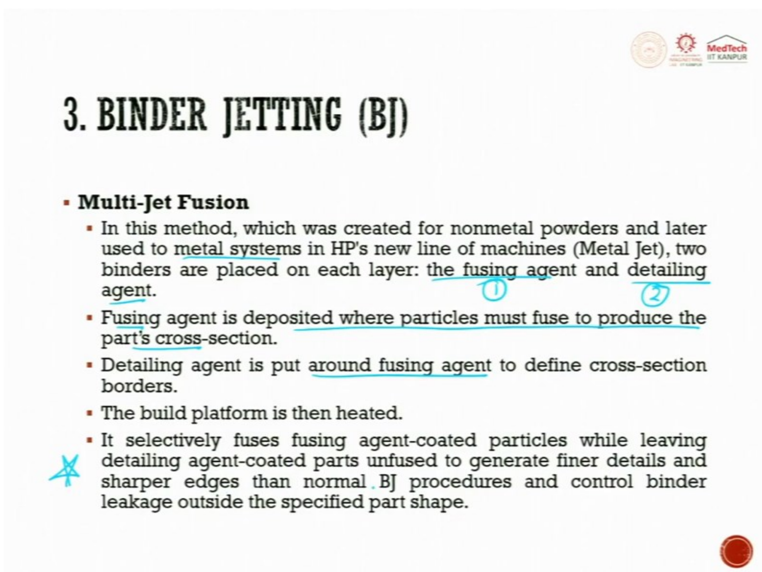
So, it is very fast today in additive manufacturing especially in metal, we always look for productivity. So, this process is helping to have higher productivity, the ability to stack parts for efficiency scalability and print composition. Binder jet is used for visual prototype also. Suppose in this ink whatever we are trying to talk about this binder, you can add color also for visualization, when you do sintering it will go off. But sometimes, the color also gets written but in green stage if you want you can use it for visual prototype, low medium quantity functional parts and big parts with conformal cooling channels for casting and tooling can be made out of binder jetting process.

(Refer Slide Time: 14:04)



So, this is how the jetting technology is, while doing it action will happen. So, you will have multiple heads. So, these are all inkjet heads. So, you will have so many binders drooping down and then they will try to fall on it and the parts will be done. So, it is very fast process.

(Refer Slide Time: 14:29)

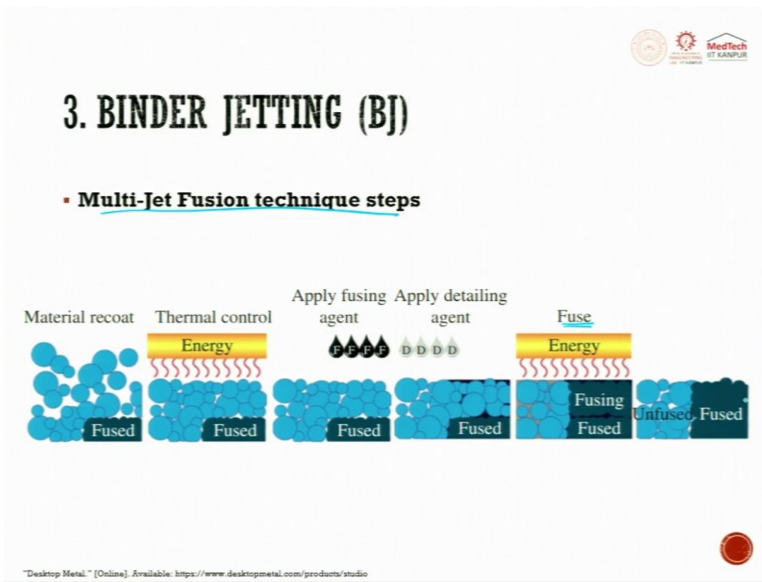


You also have Multi Jet Fusion process. So, this method was created for non-metal powders, and later used to metal systems, by HP new line of machines, metal jet, two binders are placed on each layer, the fusing agent and the detailing agent. Two different agents are present. One is called as fusing agent, the other one is called as detailing agent.

So, fusing agent is deposited when or where particles must fuse to produce the parts cross section that is fusing, detailing agent is put around the fusing agent to define cross section borders. So, two things are important one is fusing agent the other one is detailing agent.

The building platform is then heated it selectively fuses fusing agent coated particles while leaving the detailing agent coated parts unfused to generate finer details and sharper edges than normal binder jet procedure and control binder leverage outside the specified part shape. This is a very important point you should understand when you do Multi Jet Fusion or metal jetting. The selective fusing agent coated particles while leaving detailing agent coated parts unfuse to generate finer feature details and sharper edges than normal binder jet procedure.

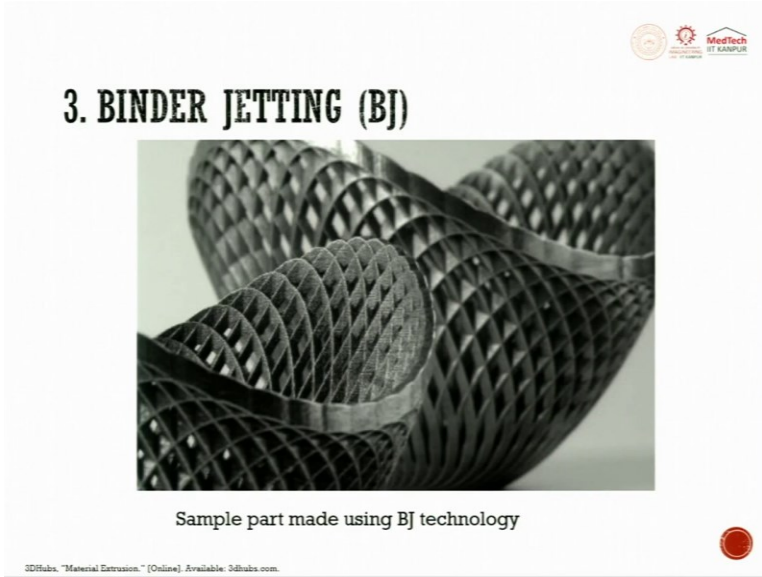
(Refer Slide Time: 16:27)



So, this is a schematic diagram for Multi Jet Fusion techniques steps. First it is material recoated then you will have thermal control energy which is applied, then you will try to have applying fusing agents. These are fusing agents, these are detailing agent, so, then you will try to expose it to once again temperature. So, fusing is getting done. So, this is fuse and then you try to put the fusing agent, as I told you will be done through this piece of electric inkjet nozzle.

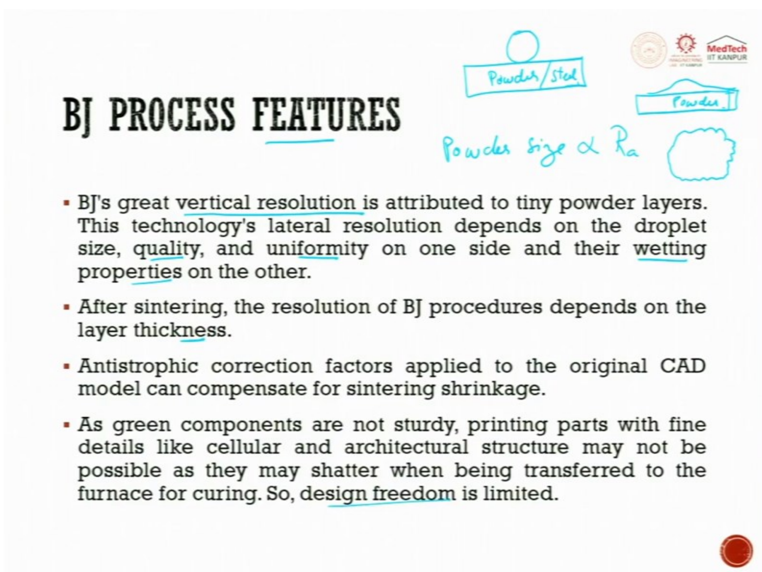
So, you will have several of these fuses coming down then you will have details. So, the difference between these two polymers are also there. So, fusing happens here and the other side you do not have any detailing. So, this detailing will try to give you sharp edges unfused and then fused is a very interesting technique, now, it is gaining speed.

(Refer Slide Time: 17:35)



So, such wonderful details can be done by binder jetting method, sample part by using binder jetting technology wonderful feature and hollow wires everything can be created.

(Refer Slide Time: 17:50)



So, now, let us see the process feature is great vertical resolution attributed to tiny powder layers. So, this vertical resolution is extremely good get to tiny powder. So, powder size is to some extent proportional to the roughness, because later when you fuse it and all these things wear but to some extent.

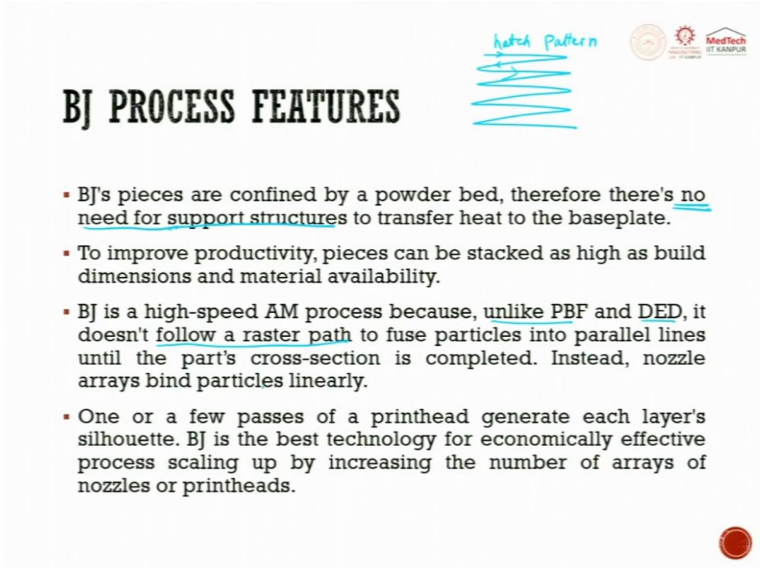
So, in this technique, it is almost proportional this technology, later resolution depends on the droplet size, quality and uniformity on one side and that wetting properties on the other. What is wetting properties? Let us make a set of powder or RS steel sheet.

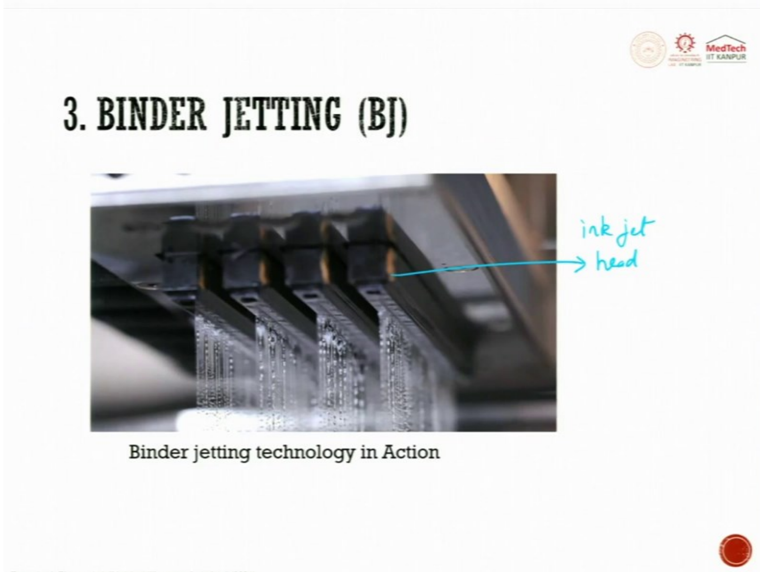
If it is there, when a droplet falls on top of it, now, the characteristics of the droplet can be to stay there rolling or it can go down completely wetting. So, this is for the powder. What about the sheets? So, now here it is just spreading it outside when the wettability is good, so that you will try to have maximum contact when you look at powder also, microscopically if you see, it will have surfaces like this.

So, when you have surfaces like this and if a droplet has done so through these small ridges, the polymer or the binder will be having a capillary action and it can spread. So, that is what we are trying to talk about. It tries to talk about the quality and the uniformity and their wetting properties on each other. If you have a rough powder and then the viscosity of the binder is also low so then it can have a capillary action spread easily. After sintering so, this is green and after sintering the resolution of binder jet procedures depend on the layer thickness and isotropic correction factor applied to the original CAD model, that can compensate for the sintering shrinkages.

As green component are not sturdy, printed parts with fine detailing like cellular and architectural structure may not be possible as they may shatter when being transferred to the furnace for curing. So, design freedom is limited when we are trying to look at this process.

(Refer Slide Time: 20:43)



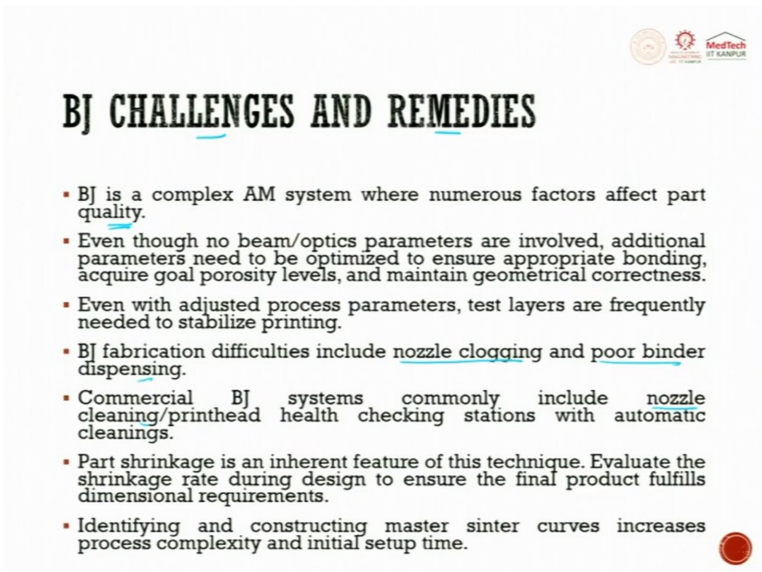


The printer jet pieces are confined by the powder bed therefore, there is no need to have a support structure, big relief when we do optimization, we also try to do today support structure optimization with takes lot of time and many a times when you try to break the support structure, the component also breaks.

So, here you do not need that at all, there is no need for support structure to transfer heat to the base plate. To improve productivity pieces can be stacked as high as build dimensions and material availability. Binder jet is a high-speed AM process because unlike PBF and DED it does not follow a rastering path because laser or electron beam will follow a rastering path.

So, this is the hatch pattern. So, in this hatch pattern, it will follow rastering path into parallel lines until the parts cross section is complete. Instead, nozzle array bind particles linearly that is what you saw here, when you saw this. You saw how the inkjet heads are lined and the nozzles. How does it downpour the binder jet? So, one or a few passes of printer head generates each layers. Binder jet is the best technology for economically effective process scaling up by increasing the number of array of nozzles or the print heads.

(Refer Slide Time: 22:23)



So, still what are all the big challenges though, it is very economical, very fast, but still there are lot of challenges and remedies which are there. It is a complex AM system where numerous factors affect the quality, viscosity, powder, all these things. Eventhough, no beam optical parameters are involved.

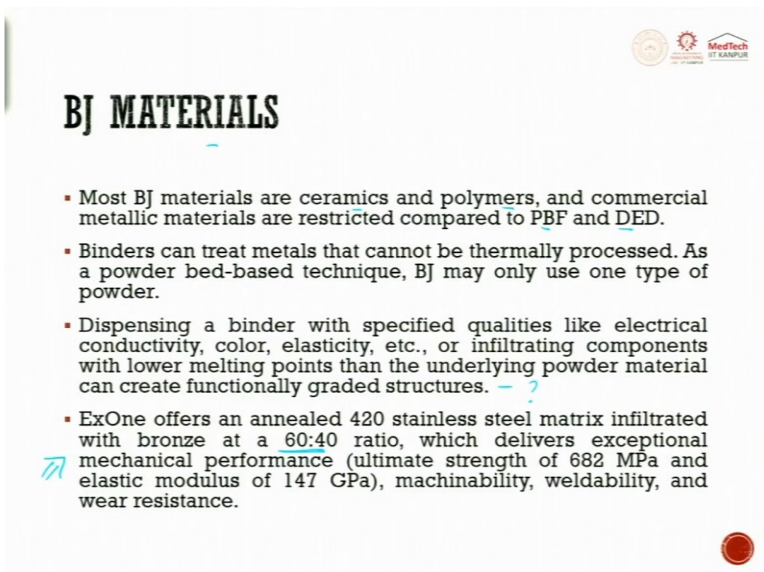
Additional parameters need to be optimized to ensure appropriate bonding to acquire goal, porosity level and maintain geometrical correctness. Even with adjusted process parameters, test layers are frequently needed to stabilize the printing. The fabrication difficulty includes nozzle clogging, and poor binder dispensing nozzle clogging is a very big feature.

So, while printing itself, if the nozzle gets clogged, then all your printer fails in FDM process also if you do improper selection of material or the process parameter, then there is always a nozzle clog. Moment there is a nozzle clog, further printing will not happen the entire part will get damaged.

So, binder jet fabrication difficulties include nozzle clogging and poor binder dispensing. Commercial binder jet system commonly includes nozzle cleaning, printhead health checking stations with automatic cleanings. So, in the system itself they have a station, after printing it goes there and then they try to apply heat, they try to see whether all the nozzles are getting clogged. If so, then it tries to raise an alarm.

So, that is what we have here. Nozzle cleaning station is there automatically inside the machine. Parts shrinkage is an inherent feature of this technique, evaluate the shrinkage rate during design to ensure the final product fulfillment. The identifying and the constructing master center curve increases the process complexity and the setup time.

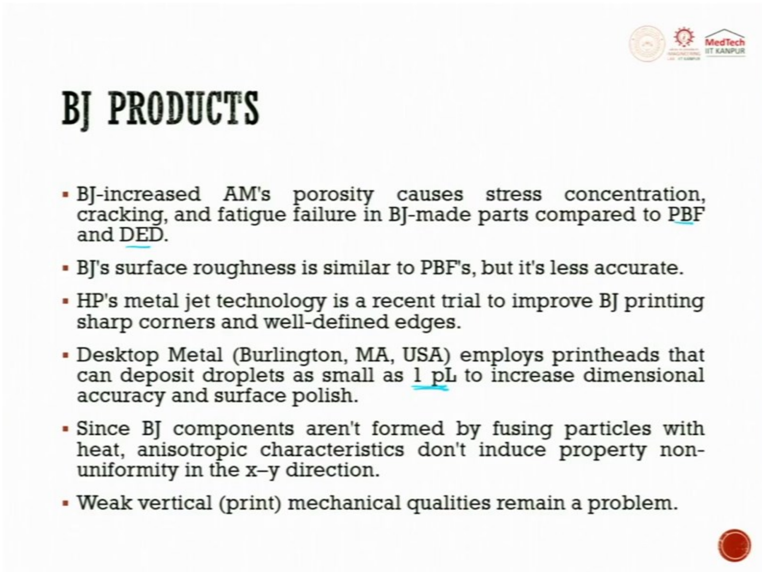
(Refer Slide Time: 24:25)



So, what are all the materials predominantly? The binder jet materials are ceramics. And the polymers and commercially metallic material are restricted compared to PBF and DED. the binder can treat metals that cannot be thermally processed as the powder bed-based technique BJ may only use one type of powder. Alloying cannot be done here, it uses only one.

Dispensing a binder with specific quantities like electrical conductivity, color elasticity etc. or infiltering components with lower melting point than the underlying powder material can create functionally graded material. This is a challenge, but people have started doing it. ExOne offers an annealing 420 stainless steel matrix infiltrated with bronze at a ratio of 60:40 which delivers exceptional mechanical performance, machinability weldability and wear resistance. So, why I have given you this is you can understand that there are original parts being made for real time application.

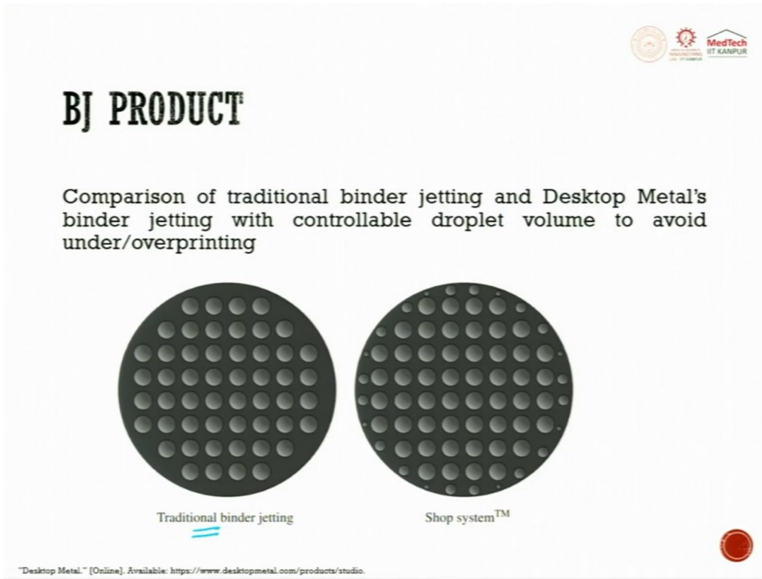
(Refer Slide Time: 25:35)



So, these are some of the products. BJ increases AM porosity, causes stress concentration, cracking and fatigue failure in BM made parts compared to the DED and PBF binder jetting. Surface roughness is similar to the tough powder bed fusion. HP's metal jet technology is recent trial to improve BJ printed sharp corners and well-defined edges history has already done.

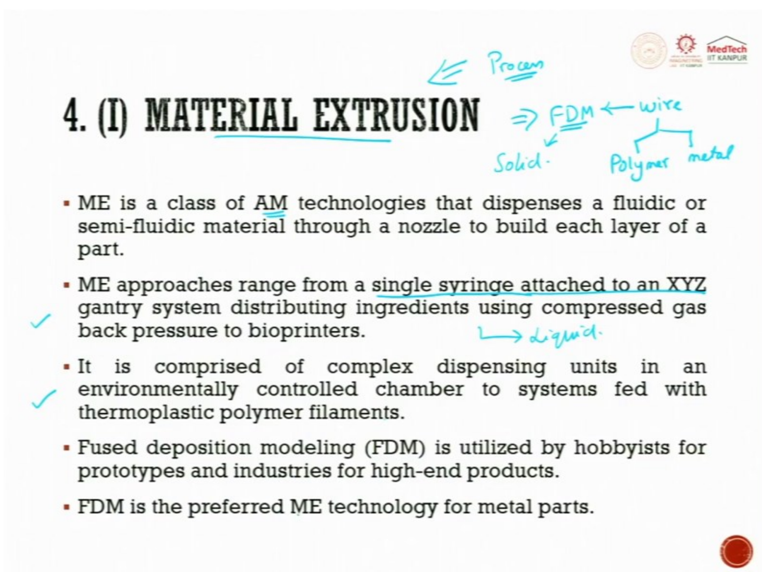
Desk top metal employs printer head that can deposit droplets as small 1 pL to increase dimensional accuracy and surface polishing. Since BJ components are not formed by fusing particles with heat, anisotropic characteristics does not induce property non-uniformity in the x-y direction. Weak vertical mechanical quantities remain a problem even today.

(Refer Slide Time: 26:41)



Comparison, of traditional binder jetting and desktop metal binder jetting with controlled droplet volume to avoid under and over printing. So, this is traditional binder jetting and this is the shop system. So, it is capable of printing little more and it also tries to give you a better performance. So, traditional binder jetting and desktop metal binder jetting with controlled droplet volume to avoid, under and over printing.

(Refer Slide Time: 27:18)



So, the next process is material extrusion, the process itself clearly says the extrusion will be the principal or the process, which is involved in this type of process. So, here, we will try to extrude material through a nozzle and print it to develop the output. It looks very similar to that of FDM, fused deposition method in polymers, almost the same thing here we try to do with respect to metals, a wire is used, this wire is made out of polymer and metal.

So, we mix polymer and metal and then we extrude it and make it into a wire. So, this extruded wire passes through a nozzle and then it gets printed on top of a table like your FDM process. Once the print is done, so, like last time what you did pre heating here, there are machines, which has come up with the washing station.

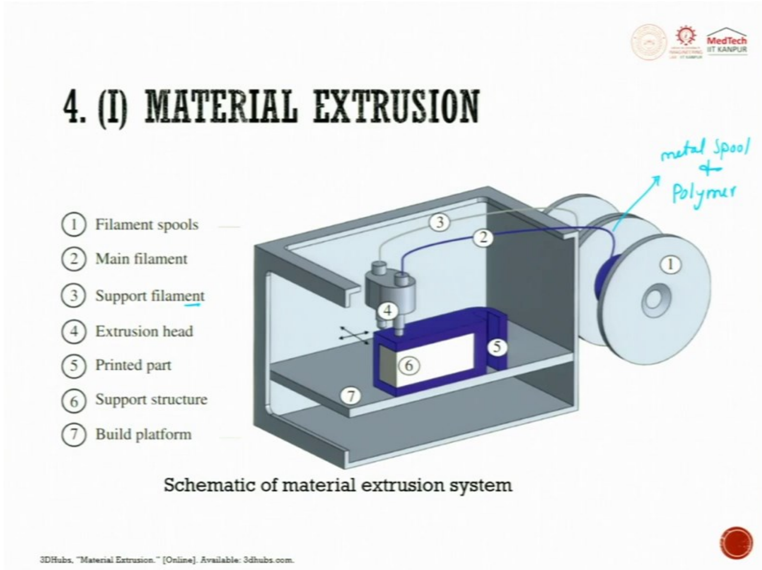
So, in the washing station, what we do is we remove all the polymers and then try to have a green part. This green part further will be placed inside a sintering furnace to produce the final required output. So, the first part what we used is a binder jet and then metal part edition. Here we mix the polymer and the metal part extruded through a nozzle and get the required output.

So, ME material extrusion is a class of AM technologies, this is very much used today, because here there is not much of heat induced metal sintering or metal melting. So, the thermal induced stresses will not be dominating in these two processes. Because once you finish the process, then you go for sintering. In sintering you can do a controlled sintering so you do not induce lot of heat damages, but when you use laser you induce lot of heat damages.

So, material extrusion is a class of AM technologies that dispenses. You have fluidic or semi fluidic material through your nozzle to build each layer on the part. Any approaches range from a single syringe attached to your xyz gantry system distributed ingredients using a compressed gas back pressure to bio printer, which is comprised of complex dispensing unit in an environmental controlled chamber to system fed with thermoplastic polymer filament.

So, you can use this one or you can use this one. ME approaches a range from a single syringe attached to here. So, what you are trying to do is metal powder is getting mixed to liquid and then it is pushed through the liquid here when I talked about the FDM process, here it is a solid here you can also have it as a liquid. So, liquid you dispense for example, nano copper powder is dispensed in a polymer. So, it is pushed through it and is allowed to deposit. So, the fused deposition modeling is utilized by hobbyists for prototyping and industry for high-end products. FDM is the preferred ME technology for metal parts.

(Refer Slide Time: 31:08)

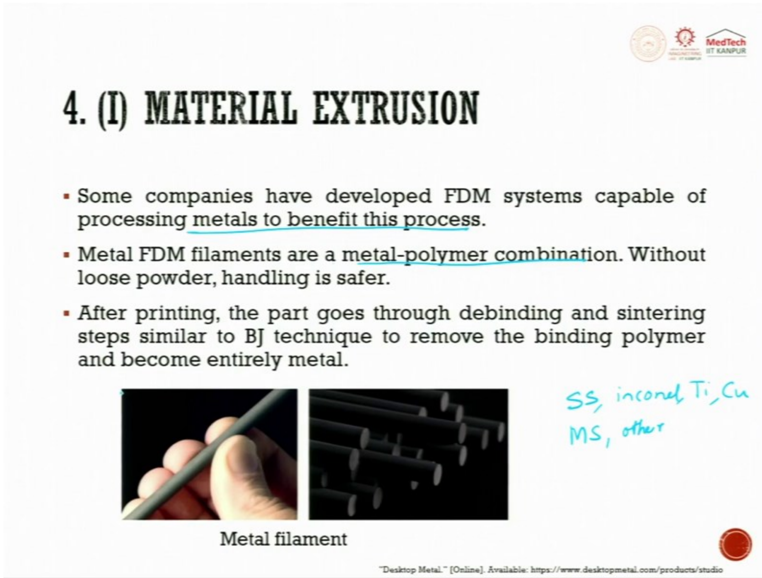


So, it is almost the same, you have a filament spool one. Then you have a main filament, supporting you will have the same in like your FDM. Here also there is the spool whatever we are talking about, this is a metal spool where polymer is mixed. It is a IP process in extruding this wire it is not so easy, the cost of it will be a few 1,000 dollars/kg or it will be 1,500 dollars/kg.

So, where is the USP, the USP here is generating the metal spool, there will be a spool there will be a supporting one. So, like your FDM wherever there is a free hanging structure, the support comes in and the support will be washed in the washing station and whatever polymer is here that to some extent will be washed, but rest will be degassed when you do a sintering process.

So, supporting filament is there, then we try to extrude it through the head, this is the extrusion head then it is printed. So, the supporting structures for all free hanging structures, we have supporting structures, the entire thing is built on a platform this is just like FDM process, but the only difference here is you will have a material which is a metal spool as compared to that of an exclusive polymer. So, you can also do the same process having your syringe or a liquid container or a hopper and you use a pneumatic pressure to force the liquid metal to come through the nozzle and get deposited. So, there will be a lot of binder here there is a solid binder.

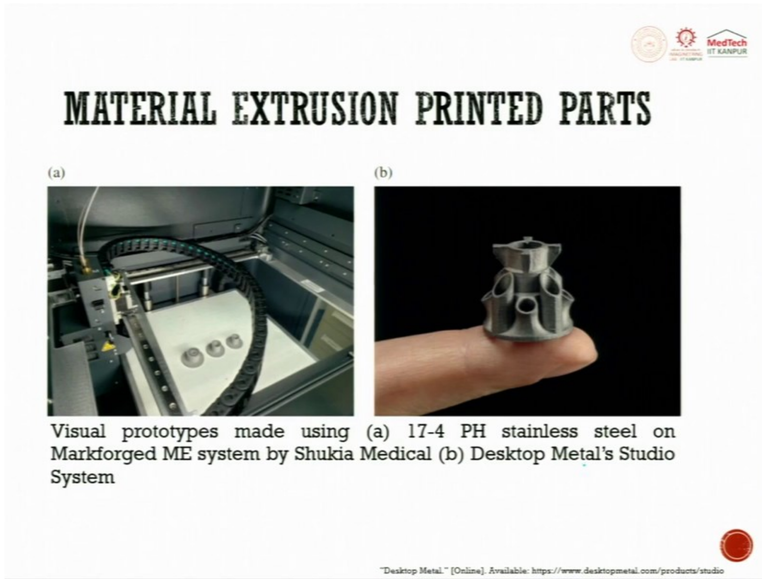
(Refer Slide Time: 33:01)



So, you can see here this is the metal wire which is made. So, some companies have developed FDM systems capable of processing metal to benefit this process. So, today, we have stainless steel Inconel, Titanium, Copper, you have mild steel and other materials also we have and here these machines are expensive, because the wires they are already iterated for the process parameter and this process parameter is set on the machine to use this for printing.

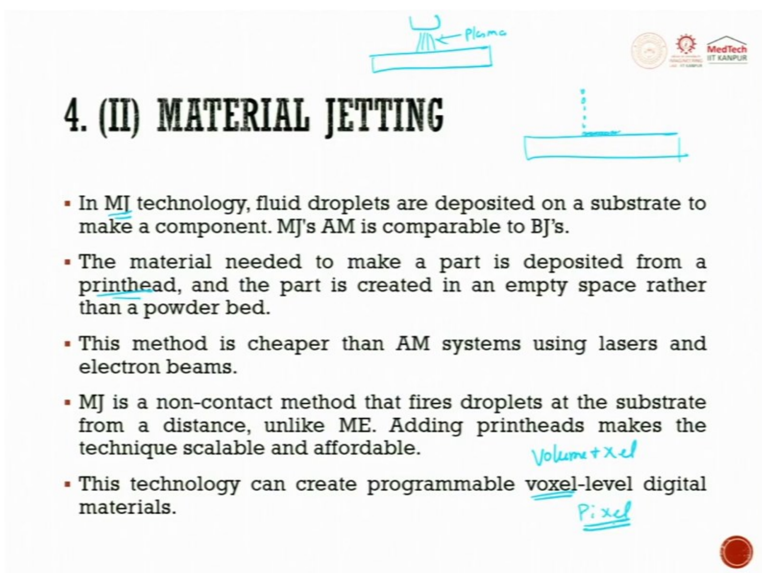
So, it is almost an IP process and the process parameter selection also is inbuilt. So, the machine as of today is pretty expensive. The metal FDM filaments are a metal polymer combination without losing powder handling is very safe here. After printing, the part goes through debinding and sintering steps similar to the top binder jet technique to remove the binding polymer and become entirely metal.

(Refer Slide Time: 34:17)



So, you can see such small parts can be printed. So, this is a desktop metal studio system used and they try to print it and here you can see how does the material extrusion printer head looks like? So, these are the three parts which are printed.

(Refer Slide Time: 34:38)



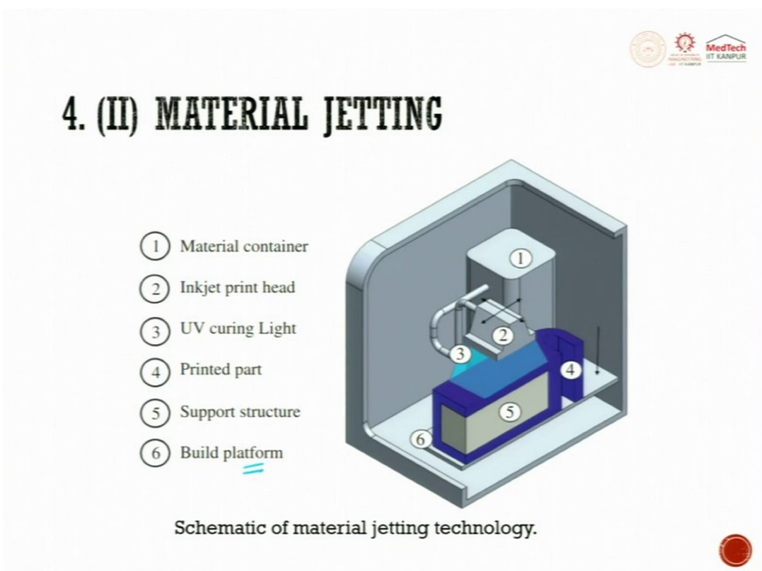
So, the other one is material jetting. In material jetting technology, fluid droplets are deposited on a substrate to make your component. For example, look, think of it and welding. So, what we do is we pass a welding rod there, we pass a very high current between the welding rod and the workpiece. So, the welding electrode melts and it gets deposited.

So, in the similar way we try to do material jetting. So, in material jetting technology, the fluid droplets are deposited on your substrate to make the component. So, Multi Jet additive manufacturing is compared to that of binder jet. The material needed to make a part is deposited from a printhead. So, polymer printhead is easy.

So, here you should have a metal which is liquid and passing through it and viscoelastic behavior you have to control and the part is created in an empty space rather than in a powder bed. It is just like a bed and then droplets of the metal comes and does and you try to control the layer shape whatever is getting done. This method is cheaper than additive manufacturing system using laser and electron beam.

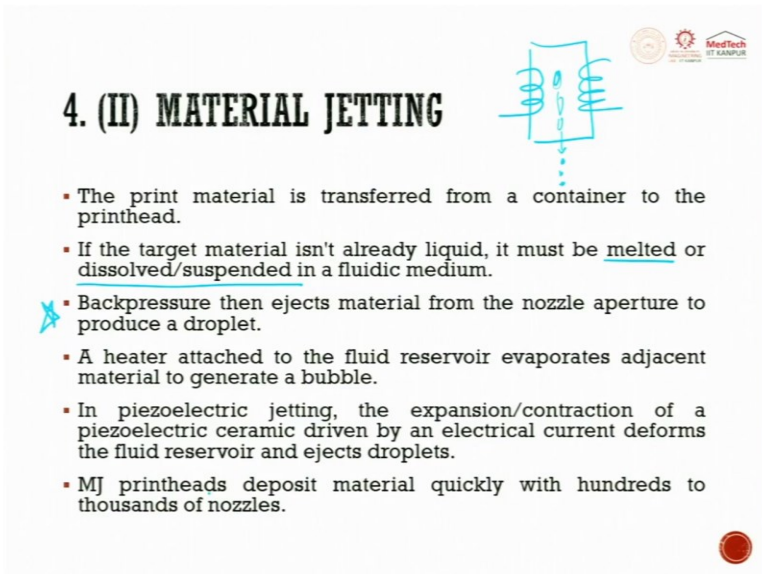
The metal jet is a non-contact method that fires droplets at the substrate from a distance unlike ME, so, if you look at it something like plasma spring, there will be a substrate, there will be a nozzle, there will be a plasma which is used to melt the material and then deposit. So, adding printed head makes the techniques scalable and affordable. This technology can create programmable volume work cell. So, this is volume cell. So, when we say pixel it is picture xel. So, it is 2-D, this is volume xel, voxel digital material.

(Refer Slide Time: 36:56)



So, the setup looks like this. This is a material container and then you have ink jet printing head, then we have a UV curing light, then you get the printed part, then we have a supporting part, we have a binding part. So, here this is another technique, which is exhaustively used for metal jetting or material jetting.

(Refer Slide Time: 37:29)

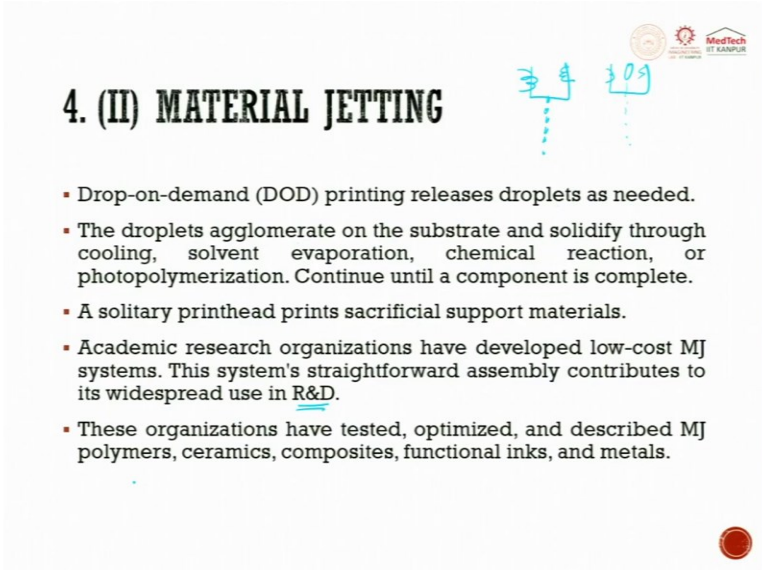


The print material is transferred from the container to the printhead if the target material is not already a liquid, it must be melted or dissolved or suspended. It is interesting heat or you dissolve and suspend into a fluidic media. So, then it can be dropped. Backpressure then injects material from the nozzle aperture to produce a droplet.

This is an important point which you should record. So, back pressure, then eject the material from the nozzle aperture to produce a droplet. A heater attached to the fluid reservoir evaporates the adjacent material to generate a bubble. So, to generate heat, a heater is attached to the fluid reservoir say for example, this is the reservoir here is a heater, heater attached to the fluid reservoir evaporates adjacent material to generate.

So, when you heat it there is a bubble. So, this bubble will try to push and then you try to get droplets. In piezoelectric jetting, the expansion/contraction of a piezoelectric ceramic driven by an electrical current deforms the fluid reservoir and ejects the droplet. So, you have a bubble. So, when you heat it, the bubble expands and when the bubble expands it tries to push it down. Metal jetting printer head deposit material quickly with 100s or 1000s of nozzles to do it.

(Refer Slide Time: 39:18)

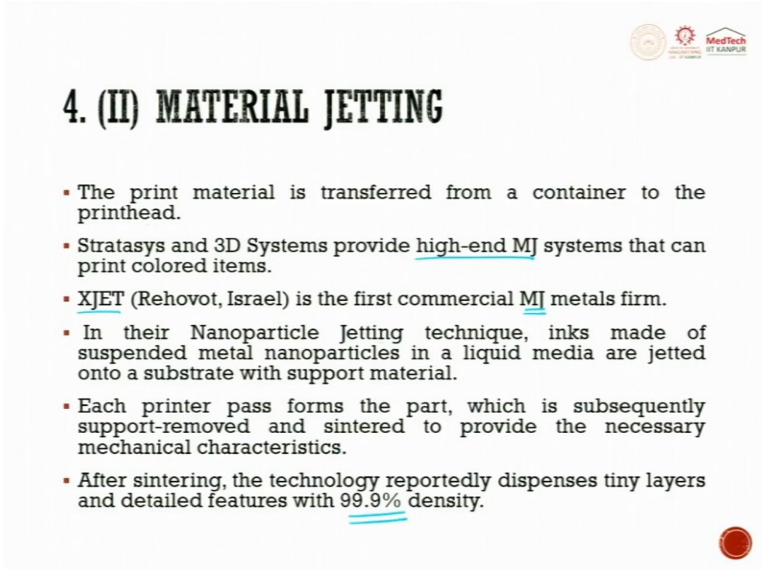


Drop-on-demand, printing releases the droplet as needed. The droplet agglomerates on the substrate and solidifies through cooling. So, droplet on demand is, wherever you want the droplet is done. So, you heat it or you have here your bubble which expands and pushes the material down. So, droplet on demand printing releases droplet as needed.

The droplet agglomerates generally, the droplet in whatever forms agglomerates on the substrate and solidified through a cooling solvent evaporation chemical reaction or photo polymerization continue until the component is complete. A solidarity print head prints sacrificial support material.

Academic research organization have developed low cost MJ system. These systems straightforward assembly contributes to its widespread use in R and D organization. These organizations have tests. So, it is predominantly used in our tested optimized and described MJ polymer ceramic composite functional inks and metals.

(Refer Slide Time: 40:35)



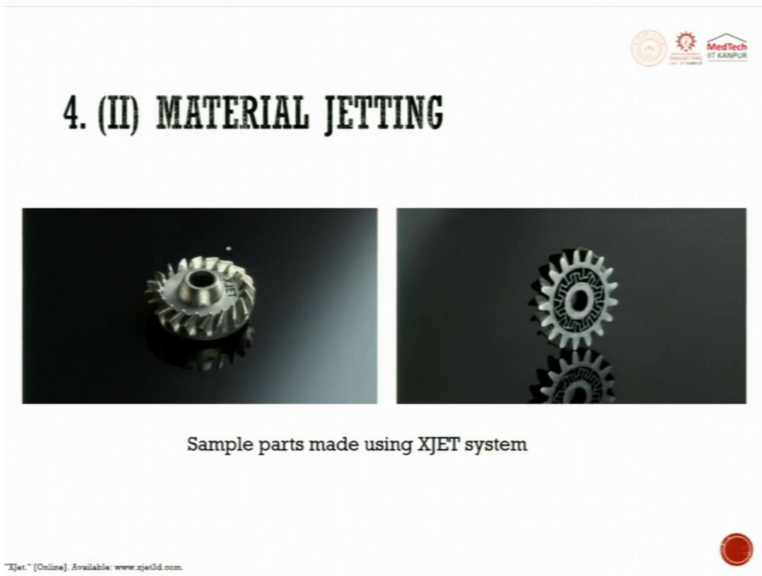
Printed material is transferred from a container to a printhead. The two big companies- Stratasys and 3-D systems have provided high end MJ systems. The XJET is the first commercial metal jet printer firm. All these things are still in the research for not only in the lab, but there are machines, there are companies who are using it, there are parts which are produced and they are put into action.

So, the next era of additive manufacturing is going to be only metal based additive manufacturing. In their nanoparticle jetting technique, inks made of suspended metal nanoparticles in liquid media are jetted on to the substrate with supporting material. So, the jetting comes and here suppose these nanoparticles are used for giving biomedical applications, it is also used for conducting applications.

So, on top of a polymer, you just eject this and then you try to get it. So, each printer passes through the part, which is subsequently supported, removed and sintered to provide the necessary mechanical characteristics. After sintering 99.9% densification can be achieved in this process.

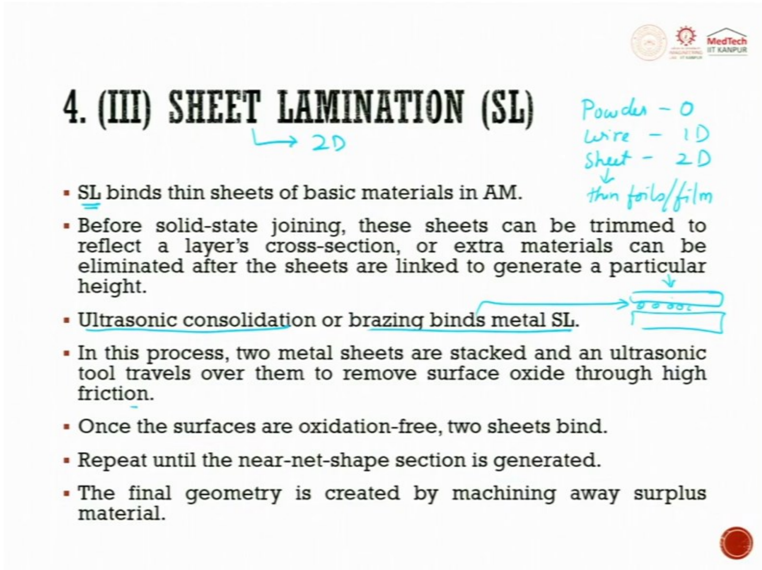
(Refer Slide Time: 42:02)

(Refer Slide Time: 41:58)



So, this is how it looks like. The jetting technique is one of those for emerging metals. So, you can see these are metal, these are all polymer this gets deposited, so that you get the required output. So, these are some of the gears which are made by material jetting process. So, you can see here the spur gears are made, then surface gears are made.

(Refer Slide Time: 42:27)



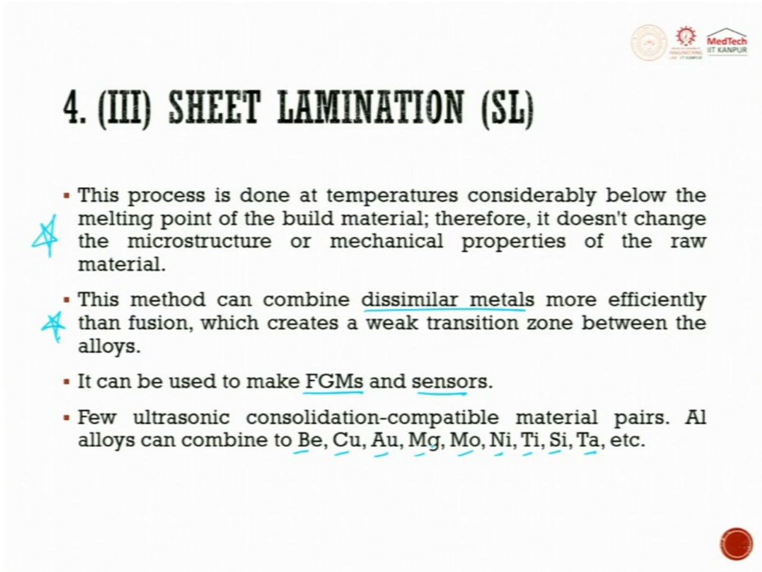
The last process for discussion is going to be sheet lamination. So, as I said sheet means it is 2-D. So, powder, you can call it as 0-D, wire you can call it as 1-D, sheet you call it as 2-D. So, naturally when you use powder, you will get high resolution as compared to that of wire and 2-D. So, 2-D is basically a sheet.

So, sheet lamination is a cell which is used for metals. So, here when we talk about sheets, these are all thin foils or fillings. Do not think, plates will be used. Before solid state joining, these sheets can be trimmed to reflect a layer cross section or extra material can be eliminated after the sheets are linked to generate a particular height.

Then we try to use an ultrasonicator too or a brazing binder metal. This is the binder, and this will be ultrasonically vibrated, so that it spreads and attaches or you try to use ultrasonic so that by heat it tries to join. Heat means these heats are very less predominantly ultrasonic, what it does is it cleans the oxidation layer, nascent to material comes in contact.

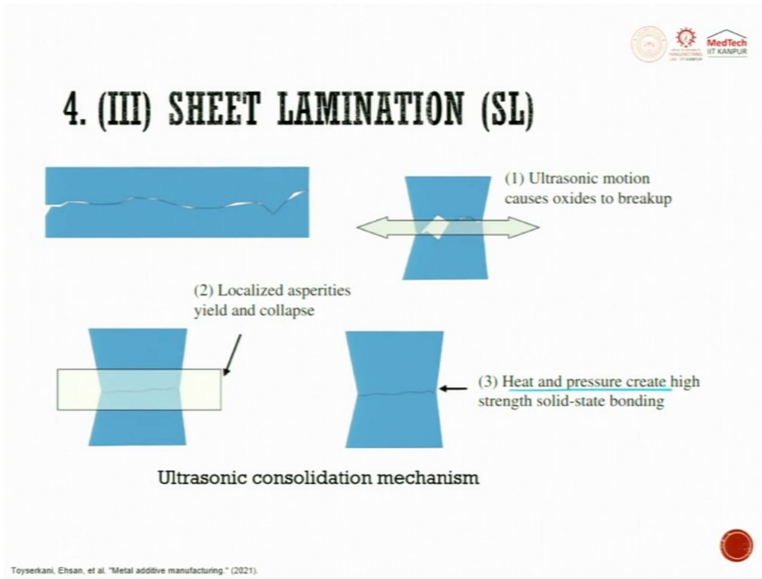
So, it tries to join. In this process two metal sheets are stacked and an ultrasonic tool travels over them to remove the surface of oxidation through high friction. Once the surface or the oxide oxidation free layer is there, then the two sheets bind because you have two nascent layers which binds. Repeated until the near net shape is generated and the final geometry is created and machining will be done to get the required output.

(Refer Slide Time: 44:29)



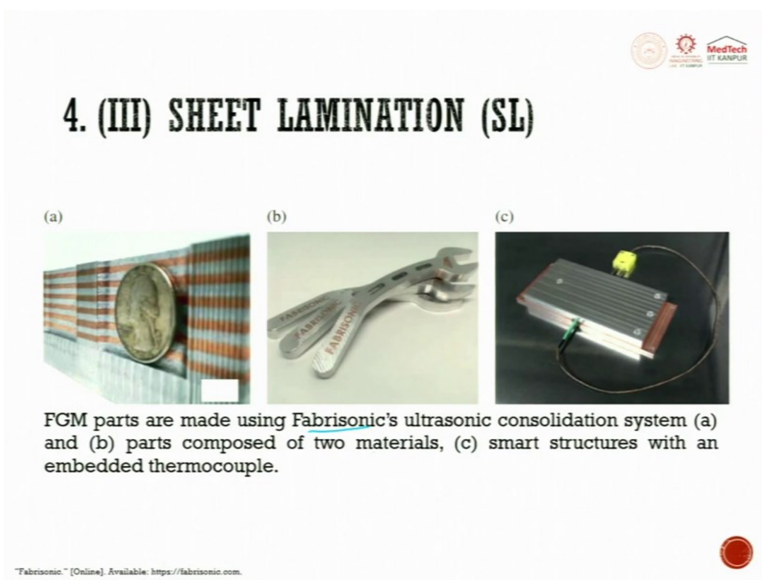
This process is done at temperatures considerably below the melting point of the built material. Therefore, it does not change the microstructure or the mechanical property important point is, this method can combine dissimilar metal, fusion can be done to meet out the requirements, it can be used for functionally graded materials or for building sensors. Few consolidate ultrasonic consolidation compatible material pairs or aluminum alloys can be compared with be copper, gold, magnesium, molybdenum, nickel, tin, silicon, tantalum, etc. Aluminum can be mixed with all these things.

(Refer Slide Time: 45:15)



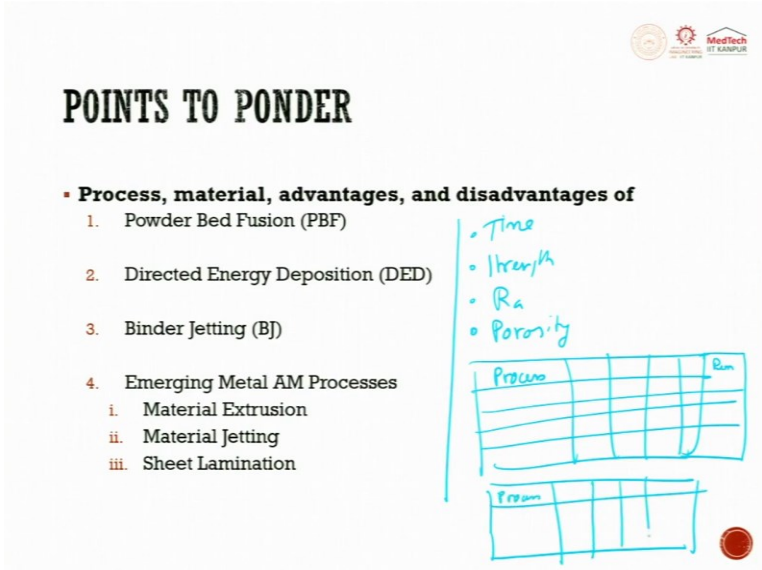
So, this is how a test is? So, first you put the ultrasonic motion causing the oxide layer to break, then localized asperities yield, so, that it tries to join and the heat and pressure is attached to it so, that you try to get the joining done between the layers.

(Refer Slide Time: 45:32)



So, these are some of the examples where it is been made. FGM parts are made using fabrisonic's ultrasonic consolidation system, a part composed of two materials, smart structures with an embedded thermocouple by using this sheet lamination process.

(Refer Slide Time: 45:56)

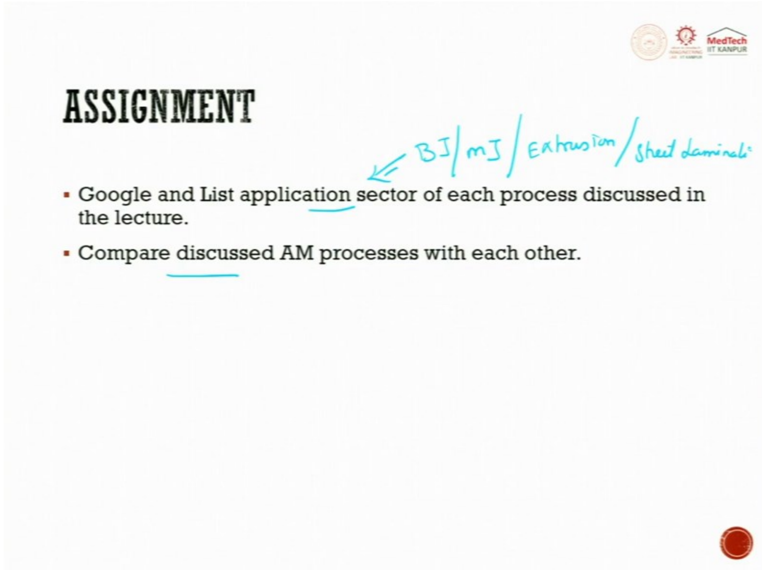


So, points to ponder. Till now, we have studied the most significant or the most used processes in metal additive manufacturing. First one is powder bed fusion where in which you use laser or electron beam, sometimes we also use plasma. Next, we saw directed energy deposition, then we saw binder jetting, then we saw material jetting, then we saw material extrusion and finally, we saw sheet laminate, metal additive manufacturing process.

The process material, advantages and disadvantages of all these processes, you are supposed to note it down and write it using any reading or open source available material. Try to write down time, strength, roughness and porosity. Keep those parameters as the evaluating criteria and write the process then you also write a remarks column for each of these processes.

So, if you prepare this table, then you will try to understand different types of processes and their capabilities. Now, once you finish this, then you will build one more table where in which you try to write down the process and different types of materials which can be used for building the output.

(Refer Slide Time: 47:51)



So, assignment I have already given. So, one is compare and discuss these additives, then list down various application sectors where we use binder jetting, metal jetting and extrusion application sheet metal. So, please try to go through the open source available and try to write it down, prepare a table so that it will be a helpful for you for the examination. Thank you very much.