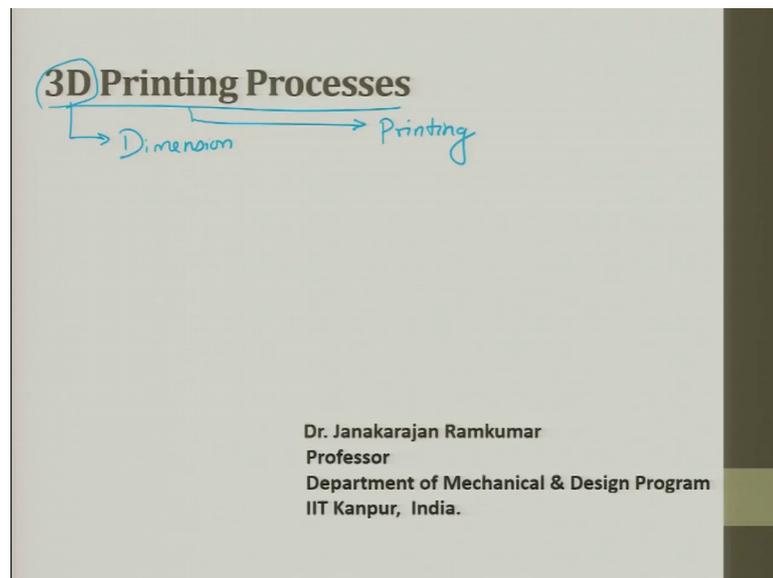


Rapid Manufacturing
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Lecture – 26
3D Printing processes

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Welcome to the next lecture on 3D Printing Processes. So, 3D it talks about the dimension of the object which we are going to do and we are going to use the technology what we use in printing. Printing currently you almost every house has a desktop printer where in which what we print is 2D laminate information in one sheet paper. So, we are going to use that technique and we are going to develop 3 dimensional objects.

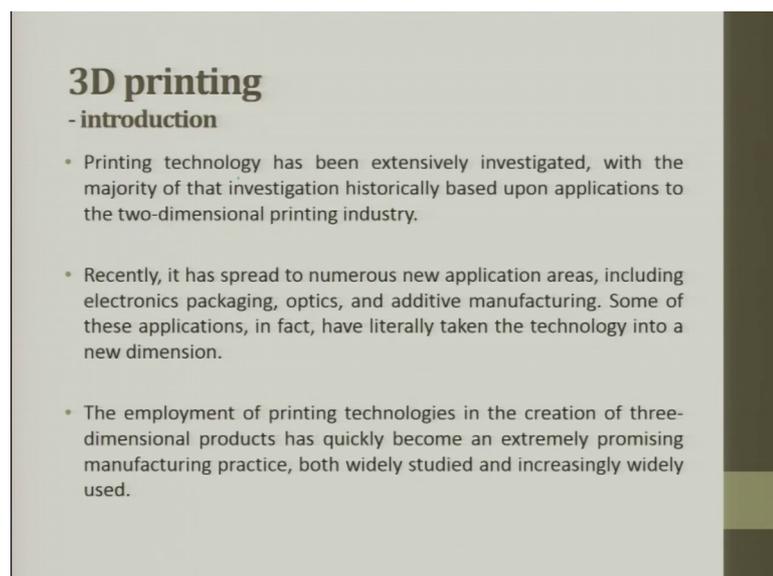
So, that is what is discussed in this process 3D printing processes and by the way I reiterate all these things are focused towards rapid manufacturing today. We are not talking about prototyping, this technique whatever gets developed or the product which is get developed this can be used for make used as a mold or it can be used to make a dye from which you can get a product. So, all these techniques are used only for that.

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In this lecture, we will try to cover 3D printing. In 3D printing technology, advantages and technical challenges which are available today. Then there is another technique which is called as droplet formation technologies where in which there is a continuous mode drop on demand mode. Other droplet formation methods, then we have printing processes modeling, then material modification, binder printing and last we will see fused deposition modeling.

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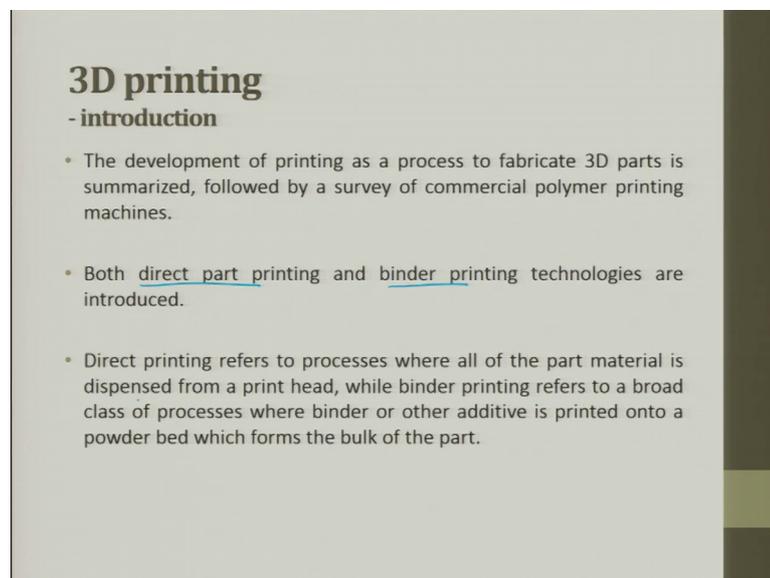


Introduction; printing technology has been extensively investigated, with the majority of the investigation historically based upon applications to the two-dimensional printing industry; two dimensional printing industry. Recently, it has spread to numerous new application areas including electronic packaging, optics, additive manufacturing printing technology. Today we have started printing electronic circuits on shirts.

Printing images which can change color; printing technology has got so advanced. Some of these application in facts have literally taken the technology into a new dimension that is true. Today we have flexible electronics where in which printing technology is exhaustively used.

Now, started making printing optics and then additive manufacturing is one big area where printing technologies exhaustively used. The employment of printing technologies in the creation of three-dimensional products have quickly become an extremely promising manufacturing practice both widely studied and increasingly widely used; it is not in research, it has already come to the application.

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The development of printing as a process to fabricate 3D parts is summarized, followed by a survey of commercial polymer printing machines. Both direct part printing and binder printing technology; direct part printing and binding technology are introduced. Direct part means whatever you get will be the direct product. Here, we will try to bind the building materials and use that as a technology to develop a 3D product. Direct

printing refers to processes where all the part material is dispensed from a printing head while binder printing refers to a broad class of process where binder or other additive is printed.

So, here where all the part material is dispensed through a printing head in the direct part printing. When we talk about binder part, the building block is not dispensed, but the binder is dispensed through which we try to develop your 3D part.

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3D printing
- introduction

- Some of the technical challenges of printing are introduced; material development for printing polymers, metals, and ceramics is investigated in some detail.
- From the topic of pure printing technologies, we move to the three-dimensional binder printing process, where binder is printed into a powder bed to form a part.

well established process
→ mass produced → economical

Some of the technical challenges of printing are introduced; material development for printing polymer, metals, ceramics is investigated in some details. From the topic of pure printing technologies, we move to three dimensional binder printing process where binder is printed into a powder bed for me a part. See why printing technology is very well talked about is because it is a well established process; well established process and it can be mass produced and so it is economical. So, that is why printing technologies are exhaustively used and printing.

Technologies over a period of time has got so much of nascent knowledge which can be taken to the other fields and which can be used. Today we use bio printing. Today we talk about printing of cloth where in which that in that cloth wherever you print you print metal and these metals are functionalized and those functionalized metal printing on cloth is used as a sensor. So, printing technology is fabulously going high in their level.

So, through optical fibers we have now started weaving shirts and through this optical fiber when light is passed through it generates different different colors.

So, printing technology has been evolving over a period of time. Today we talk about tissue printing and we have talking about organ printing. So, printing technology has gone to such a high level. And here so, once the when I say technology, it is not the machinery alone the raw material the quality check and the consistency in the product all these things have got enhanced. So, that is why printing technology is now adapted in additive manufacturing or rapid manufacturing.

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3D printing
- technology

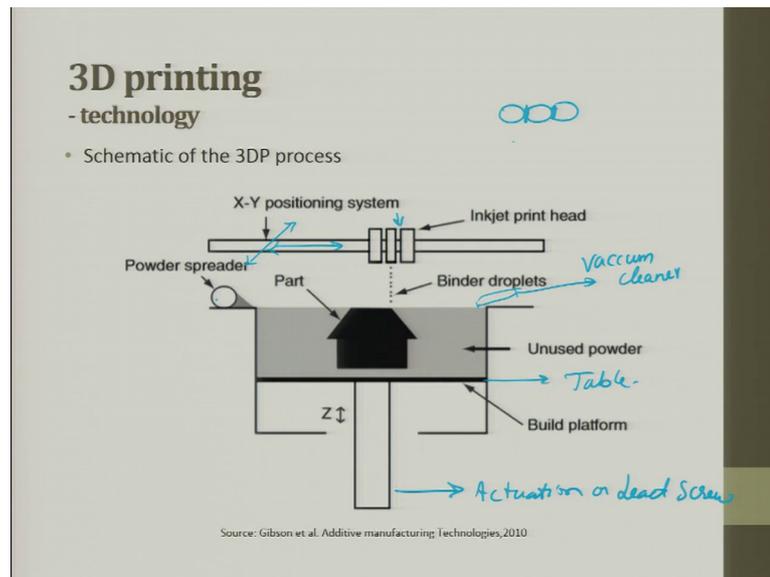
- Once a layer is printed, the powder bed is lowered and a new layer of powder is spread onto it (typically via a counter-rotating rolling mechanism), very similar to the recoating methods used in powder bed fusion processes.
- This process (printing binder into bed; recoating bed with new layer of powder) is repeated until the part, or array of parts, is completed.
- Because the printer head contains several ejection nozzles, 3DP features several parallel one-dimensional avenues for patterning.



Once the layer is printed, the powder bed is lower it is just like your SLS process and a new layer of powder is spread on it; very similar to a recoating method used in powder bed fusion process. The process is repeated until the part or the array of parts is completed. Till now I did not talk about this array of parts. So, in a single bed; in a single bed, you can make multiple parts growing simultaneously.

So, this is where we are now talking about rapid prototyping to rapid manufacturing. So, you have optimized the space and you have placed the part what is to be printed in such a manner such that you can get 4 or 6 or 10 in one shot ok. An array of parts is completed because the printing head contains several ejection nozzles, 3D printing features several parallel one dimension have been used for patterning.

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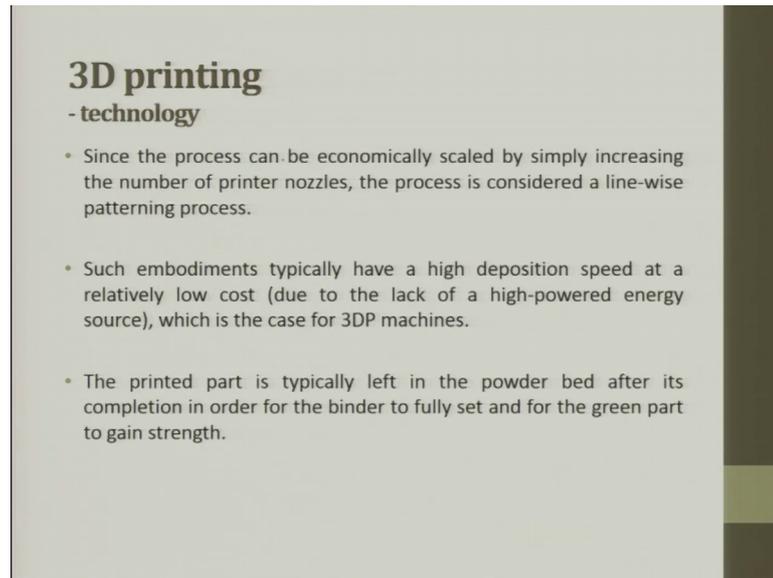


So, this is how a typical schematic diagram looks like you have a powder, spreader. So, that spreads on top of the table. So, the table will have a tank. So, this is the table, this is the actuation or your lead screw which moves back and forth up and down. And so, here the powder when it is spread on top of it so, one layer thickness is maintained and then we use the inkjet printing head which is attached to a frame which can move in X and Y direction and the inkjet drops; the inkjet drops the binder on top of the powder. So, now, the powder gets agglomerated. So, between this you have a binder which falls.

So, it need not be exactly. So, the binder can fall on top of it and also connect the powder parts which is a building block. So, the powder is spread on top of the table one layer thickness is done. So, now, the inkjet head which can move in X and Y direction moves and then the binder is dropped at exact locations where the part has to be build now the part is getting build and finally, the part is called as a green part because the binder might not have very high strength.

After this, the part can be immersed inside another polymer varnish or something like that so that the outer core layer is stiffened ok. So, here the part need not have very high strength, it is only to give you a form shape by this process ok. After this, you can use this as a more as a pattern for making a mold; mold to your component etcetera, etcetera.

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3D printing - technology

- Since the process can be economically scaled by simply increasing the number of printer nozzles, the process is considered a line-wise patterning process.
- Such embodiments typically have a high deposition speed at a relatively low cost (due to the lack of a high-powered energy source), which is the case for 3DP machines.
- The printed part is typically left in the powder bed after its completion in order for the binder to fully set and for the green part to gain strength.

Since the process can be economically scaled by simply increasing the number of print losses, the process is considered a line-wise patterning process. Such embodiments typically have a high deposition speed at a relatively low cost because the technology is already known, which is the case for 3D machines. The printed part is typically left in the powder bed after its completion in order for the binder to fully set and for the green part to gain strength.

So, after this you remove the part, you can put it for cross processing, you can put it for an annealing temperature. This annealing temperature will have to be related with respect to that of the binder which is used. So, do not think of very high temperatures very low temperatures, it will be kept for annealing. So, that the binder all properly joins melts and adhered with the powder.

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3D printing
- technology

colour + binder => colour object
Powder -> white colour.

- Post-processing involves removing the part from the powder bed, removing unbound powder via pressurized air, and infiltrating the part with an infiltrant to make it stronger and possibly to impart other mechanical properties.
- The 3DP process shares many of the same advantages of powder bed processes. Parts are self-supporting in the powder bed so that support structures are not needed.
- Similarly to other processes, parts can be arrayed in one layer and stacked in the powder bed to greatly increase the number of parts that can be built at one time. Finally, assemblies of parts and kinematic joints can be fabricated since loose powder can be removed between the parts.

The post-processing involves removing the part from the powder bed, removing unbounded powder via pressurized air. So, whatever powder was available so, now you put a vacuum suck; this is a vacuum cleaner vacuum or vacuum cleaner. So, this just cleans and sucks all the loose powders and it is taken back. Now that is reused and fed into the tank of the powder spreader. Pressurized air and infiltrating the part with the infiltrant to make it stronger and possibly to impart other mechanical properties.

The 3D process shares many of the same advantages of powder bed processes parts are self supporting in the powder bed so, that the supporting structure are not needed. And interestingly if you want to add color to your binder color plus binder, you might get a colorful object. The building block can be the powder can be white in color when you try to mix color to the binder.

So, again this concept you can always visualize with respect to 3D printing inkjet printing. So, you have three colors the three cartridges are filled with different different colors and what you get a printout is multicolored printout. So, like that you can control the color added to the binder and the binder when it drops on top of a powder which is white and color, you get different different colors. For example, if you want to give a three dimensional topological mapping of your hill region. So, you can always very clearly say where are the land, where is green, where is a patch, where is water running

everything can be taken a printout used using this 3D printing. So, it is very good ok. So, the 3D printing process shares many of the same advantages of powder bed processors.

Parts are self supporting in the powder bed so that the supporting structures are not needed. Similar to other processes part can be arrayed in one layer and stacked in the powder bed to greatly increase the number of parts that can be built at one time. Finally, assemblies of the parts and the kinematic joints can be fabricated since loose powder can be removed between the parts ok. So, this is very important.

So, what we are trying to say is suppose you want to make a big part so, then the big part because of the size restriction of the table you are not able to make. So, then the other easiest way of making it is, you make them into several small pieces and at every piece you try to have a female and a male part. So, that once the part is made you remove the part and attach it and attach male and female together so that you get the require output that is what we are trying to say. The other way around, you can make multiple array of parts in one shot and start printing it. So, this is what is discussed in this point.

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3D printing
- advantages

Each RM process has its advantages and disadvantages.

- The primary advantages of printing, both direct and binder printing, as an RM process include low cost, high speed, scalability, ease of building parts in multiple materials, and the capability of printing colors.
- Printing machines are much lower in cost than other RM machines, particularly the ones that use lasers.
- In general, printing machines can be assembled from standard components (drives, stages, print heads), while other machines have many more machine-specific components.

driven < Belt Lead screw

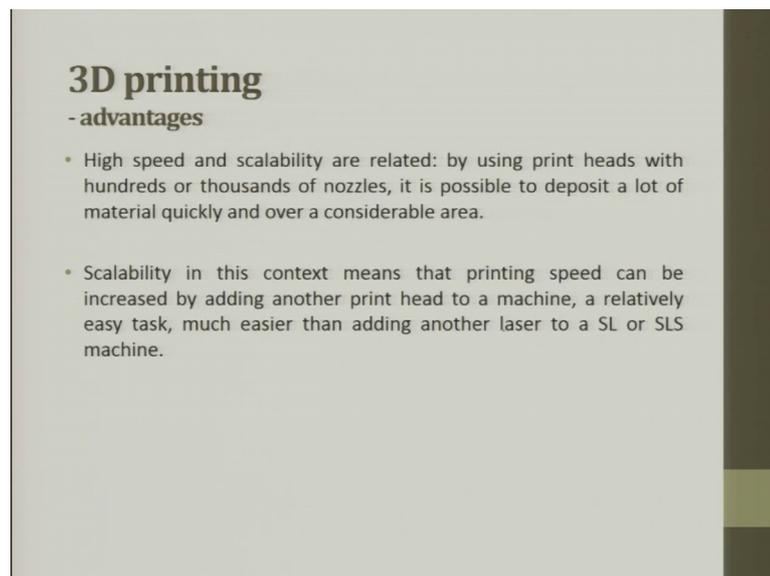
So, each rapid manufacturing process has its advantage and disadvantage. The primary advantage of printing both direct and binder printing as an RM process includes low cost, high speed; scalability is for building parts in multiple materials and the capability of printing color. So, all these things are possible in 3D printing which gives it a major edge

over the others. When you use laser, you can generate this color; but here you can easily generate the color because you are mixing it with a binder.

The printing machines are much lower in cost than the other RM process particularly the ones that laser use in general printing machines can be assembled from standard components driver. So, there are drivers when you talk about drivers. There are 2 drivers as I told you earlier; it is belt the another one is lead screw. Then stages then you have printing heads. So, these are some of the building components which are already available commercially in the market.

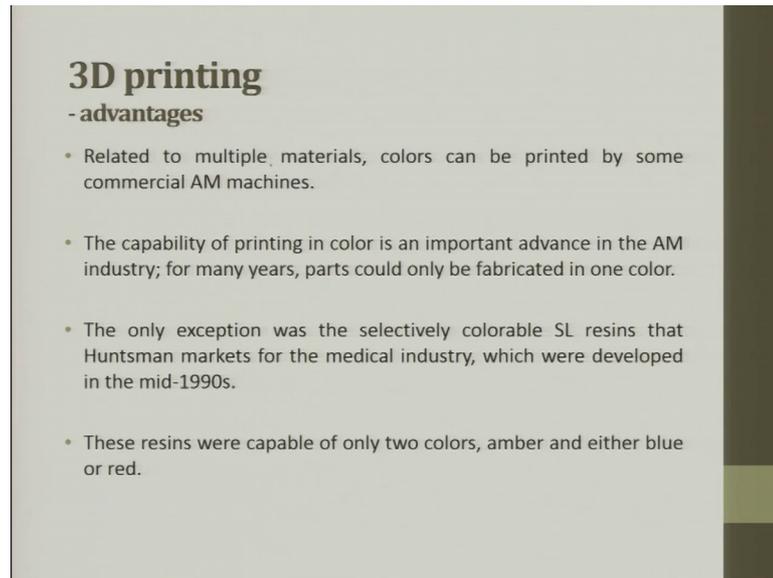
So, all you have to do is you do your shopping pick it up online shopping, pick up all those things to your requirement and then start customizing to get the required specification in your 3D printing while other machines have more machine specific components.

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High speed and scalability are related: by using printing head with hundreds or thousands of nozzles it is possible whereas, when you do a extrusion process it is only one nozzle. So, here you can have hundreds of nozzles. It is possible to deposit you a lot of material quickly and over a considerable area. Scalability in this context means that printing speed can be increased by adding another printing head to the machine. Here relatively easy task much easier than adding another laser in a SL process or SLS process machines.

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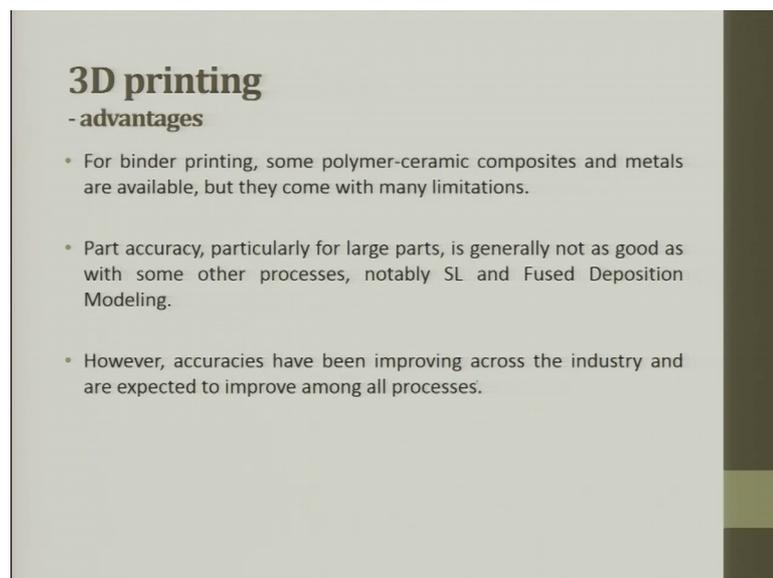


3D printing
- advantages

- Related to multiple materials, colors can be printed by some commercial AM machines.
- The capability of printing in color is an important advance in the AM industry; for many years, parts could only be fabricated in one color.
- The only exception was the selectively colorable SL resins that Huntsman markets for the medical industry, which were developed in the mid-1990s.
- These resins were capable of only two colors, amber and either blue or red.

Related to multiple material color can be printed by the same AM material. The capability of printing in color is an important advantage in the am industry using 3D printing. The only exception for was the selectively colorable SL resin that Huntsman machine marketed for the medical industry which were developed in the mid-1990s. These resins were capable of only two colors, amber and either blue or red. So, these are the colors it is which it could do. But here you could have any number of colors you want.

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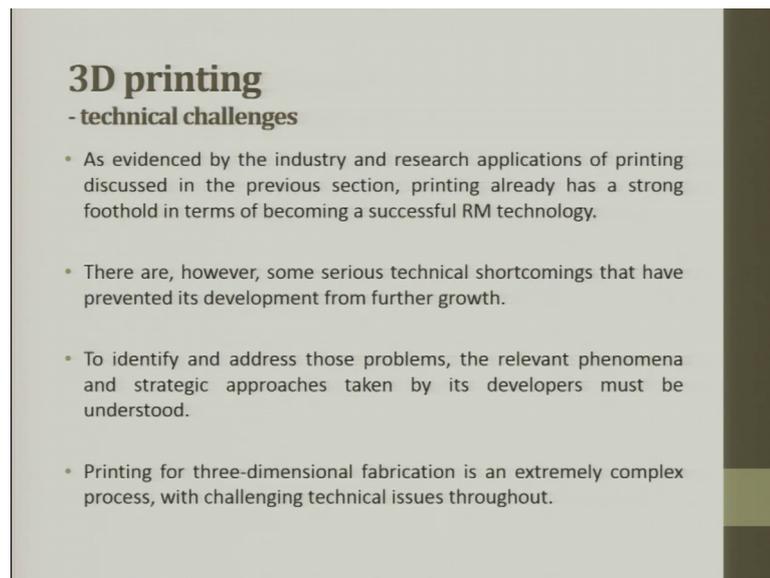


3D printing
- advantages

- For binder printing, some polymer-ceramic composites and metals are available, but they come with many limitations.
- Part accuracy, particularly for large parts, is generally not as good as with some other processes, notably SL and Fused Deposition Modeling.
- However, accuracies have been improving across the industry and are expected to improve among all processes.

For binder printing, some polymer ceramic composites and metals are available, but they come with many limitations. Part accuracy, particularly for large parts is generally not as good as with some other processes, notably SL or fused deposition modeling. This is one of the disadvantage. However, accuracies have been improved across the industries and are expected to improve among all other processes.

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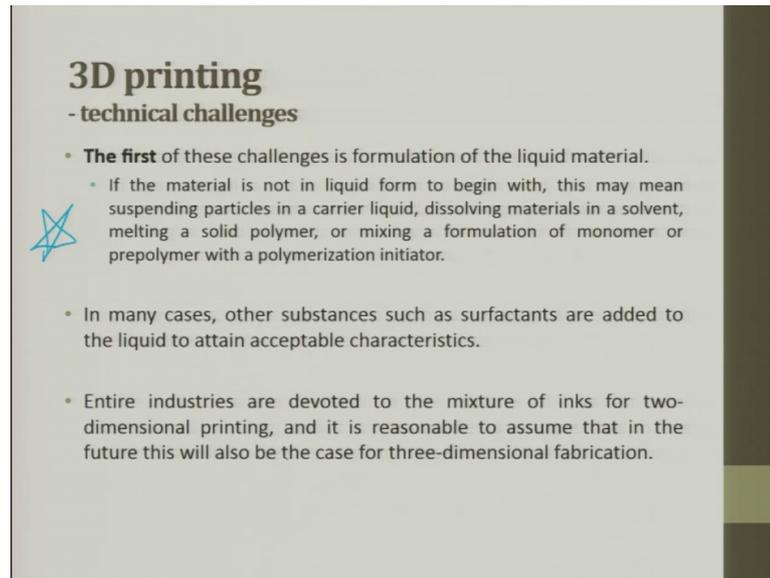


3D printing
- technical challenges

- As evidenced by the industry and research applications of printing discussed in the previous section, printing already has a strong foothold in terms of becoming a successful RM technology.
- There are, however, some serious technical shortcomings that have prevented its development from further growth.
- To identify and address those problems, the relevant phenomena and strategic approaches taken by its developers must be understood.
- Printing for three-dimensional fabrication is an extremely complex process, with challenging technical issues throughout.

What are the big technical challenges? So, as evidenced by the industry and research application of printing discussed in the various in the previous section, printing already has a strong foothold in terms of becoming a successful RM technology. There are however, some serious technical shortcomings that have prevented its development for further growth. To identify and address those problems, the relevant phenomena and strategic approach taken by its developers must be understood. Printing for three dimensional fabrication is an extremely complex process with challenging technical issues throughout.

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3D printing
- technical challenges

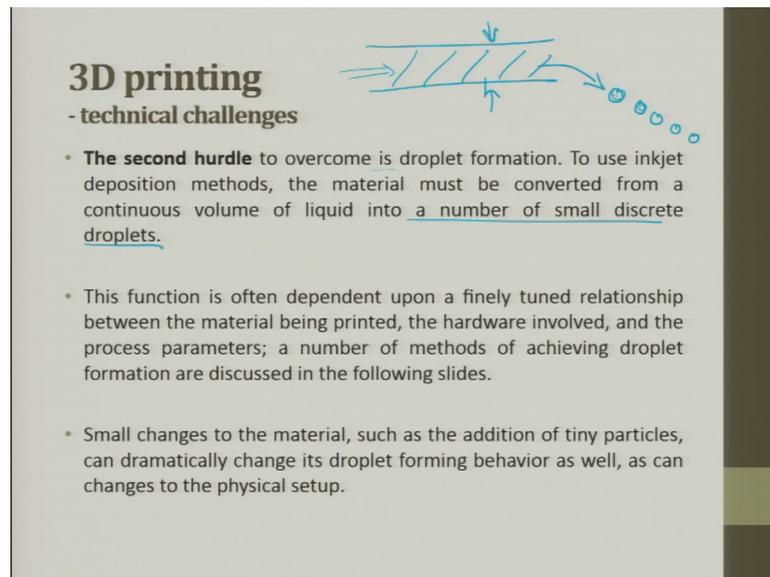
- **The first** of these challenges is formulation of the liquid material.
 - If the material is not in liquid form to begin with, this may mean suspending particles in a carrier liquid, dissolving materials in a solvent, melting a solid polymer, or mixing a formulation of monomer or prepolymer with a polymerization initiator.
- In many cases, other substances such as surfactants are added to the liquid to attain acceptable characteristics.
- Entire industries are devoted to the mixture of inks for two-dimensional printing, and it is reasonable to assume that in the future this will also be the case for three-dimensional fabrication.

The first challenges if the material is not in liquid form to begin with, this may mean suspending particles in a courier fluid, dissolving materials in a solvent, melting a solid powder or mixing a formulation of monomer or pre polymer with a polymerization initiator formation is a big challenge in printing.

So, the binder becomes a big challenge. If the material is not in liquid form, then you have a big challenge binder material. In many cases other substances, such as surfactants are added to the liquid to attain acceptable characteristics. Now you see a surfactant is there, liquid metal is there, then you have a building material. So, all the three will have different different wetting properties. They will have different temperatures required for adhering.

So, all those things bring us it makes multi physics interaction for understanding the process needs multi physics approach. The entire industry are devoted to the mixing of ink for two dimensional printing and it is reasonable to assume that in the future, this will also be the case for three dimensional fabrication.

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3D printing
- technical challenges

The diagram shows a nozzle on the left with a blue arrow pointing right into a channel. Inside the channel, there are several blue diagonal lines representing the material being pushed. On the right side of the channel, there are blue arrows pointing outwards, and a series of blue circles representing droplets being dispensed from the nozzle.

- **The second hurdle** to overcome is droplet formation. To use inkjet deposition methods, the material must be converted from a continuous volume of liquid into a number of small discrete droplets.
- This function is often dependent upon a finely tuned relationship between the material being printed, the hardware involved, and the process parameters; a number of methods of achieving droplet formation are discussed in the following slides.
- Small changes to the material, such as the addition of tiny particles, can dramatically change its droplet forming behavior as well, as can changes to the physical setup.

The second hurdle to overcome this droplet formation to use inkjet deposition method. The material must be converted from a continuous volume of liquid into number of small discreet droplet us. This is also a big challenge. You have your flow of liquid; there is a flow of liquid. So, this flow of liquid has to be now converted into droplet which is a huge challenge. So, you have to reduce the flow. When you reduce the flow there will be lot of surface dominated friction. So, this will not allow the liquid to flow so easily.

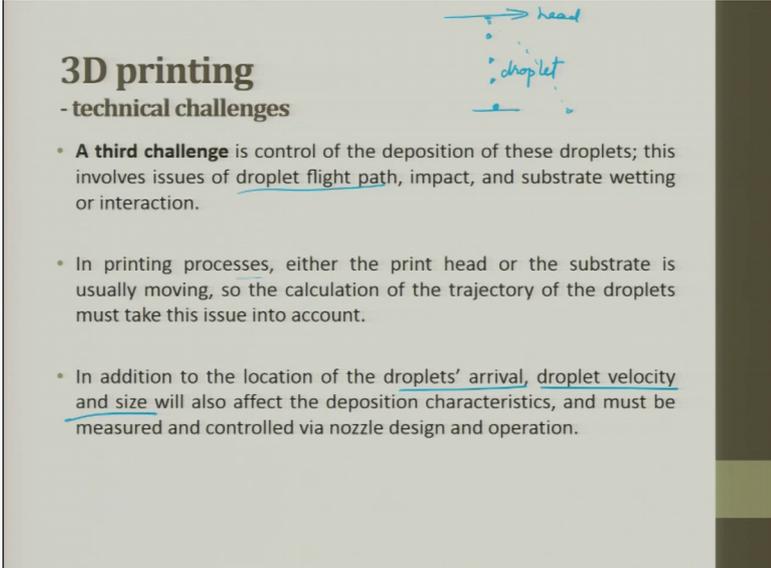
So, you have to pressurize it and then take it out. When you take it out again the droplet size should be uniform and this droplet should not get joined to each other. So, one should joint; when it is getting dispensed, it will not be uniform and when we are trying to move this binder head on top of the powder bed you there is air bubble which is getting stuck while flowing, then that portion there will be a defect which is getting created. And when you burn it or keep the post processing process when you anneal it, there starts here defect from that process.

So, here this is a big challenge. You have to understand the fluid flow through micro channel and getting dispersed into small small droplets. The droplet size plays a very very important role if the droplet size is large, then unnecessarily lot of binder will be used. If the droplet size is small, it has to be synchronized with the feed rate; if that is not, then it is prone for defects ok. This function is often dependent on your finely tuned the relationship between the material being printed, the hardware involved and the

process parameter. Your number of methods of achieving droplet formation are discussed in the forthcoming slides. Small change of the material such as the addition of tiny particles may drastically change its droplet formation behavior as well as can change to the physical setup.

So, in this droplet if you have nano particles dispersed, then this becomes a different ballgame completely to operate.

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The slide is titled "3D printing" with a subtitle "- technical challenges". It contains three bullet points. To the right of the text is a diagram showing a blue arrow labeled "head" pointing right, with a blue dot labeled "droplet" falling from it. The slide has a light green background and a dark green vertical bar on the right side.

3D printing

- technical challenges

- A **third challenge** is control of the deposition of these droplets; this involves issues of droplet flight path, impact, and substrate wetting or interaction.
- In printing processes, either the print head or the substrate is usually moving, so the calculation of the trajectory of the droplets must take this issue into account.
- In addition to the location of the droplets' arrival, droplet velocity and size will also affect the deposition characteristics, and must be measured and controlled via nozzle design and operation.

The third challenge is controlled to the deposition of this droplet. This involves issues of droplet flight path, impact and substrate wetting or interaction. When the droplet falls from a certain height, how does it fall and how does it interact? In printing process, either the printing head or the substrate is usually moving. So, the calculation of the trajectory of the droplet us must take this issue into account because the droplet is falling it is like your plane dropping a bomb. So, a droplet is forming and parallely this head is moving head droplet ok; droplet falling down, head the moving. So, what will happen is there will be a flight path. So, this will instead of falling like this, it might take your path like this.

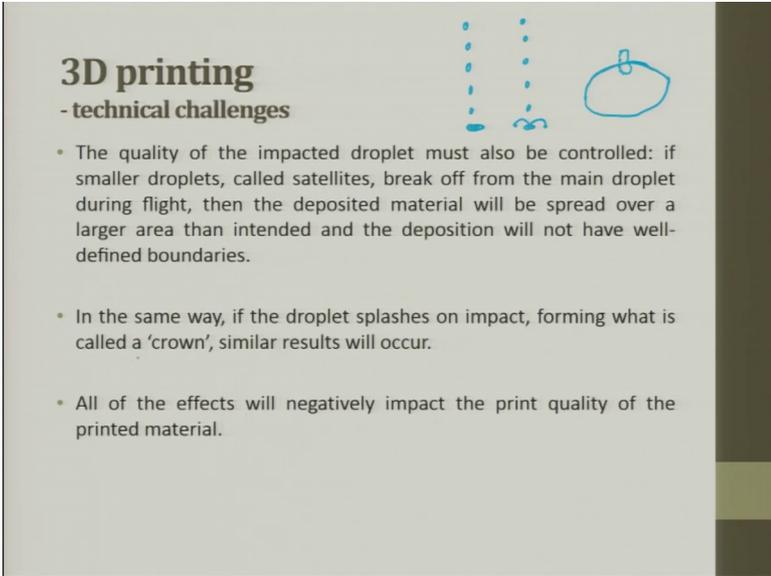
So, we have to be careful. In printing process, either the printing head or the substrate is usually moving. So, the calculation of the trajectory of the droplet must take this issue into account. Otherwise, what will happen? You will keep moving and the droplet will not fall, it will jump and you will not get additions. In addition to the location of the

droplet arrival, droplet velocity and size the droplet size is very important and the droplet velocity is also important. It is very very complicated issue when you start modeling it. And once you do not model, you will not be able to do experiments and find out the range with which it is done.

Otherwise, you will keep doing experiments humpty number of times. So, you should have a ballpark field such that you can try to convert your liquid flow into droplet us and droplet size control. How do they control the droplet size? They have at the exit; they have a piece of crystal the opening on the piece of crystal happens. So, fast and the droplet us are formed and it is allowed to drop and if the droplet which is formed is too small and in the flights movement when the binder head is moving, this droplet will just ooze out and it will fly in air. So, you have to be very careful.

So, this is a huge challenge, binder formation of the binder; if it is not a liquid huge challenge. Second thing is if it is liquid. how to convert it into droplet us is a challenge. Third thing dropping, these liquids is also a challenge. So, we have three big challenges in front of us when we talk about this 3D printing.

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3D printing
- technical challenges

- The quality of the impacted droplet must also be controlled: if smaller droplets, called satellites, break off from the main droplet during flight, then the deposited material will be spread over a larger area than intended and the deposition will not have well-defined boundaries.
- In the same way, if the droplet splashes on impact, forming what is called a 'crown', similar results will occur.
- All of the effects will negatively impact the print quality of the printed material.

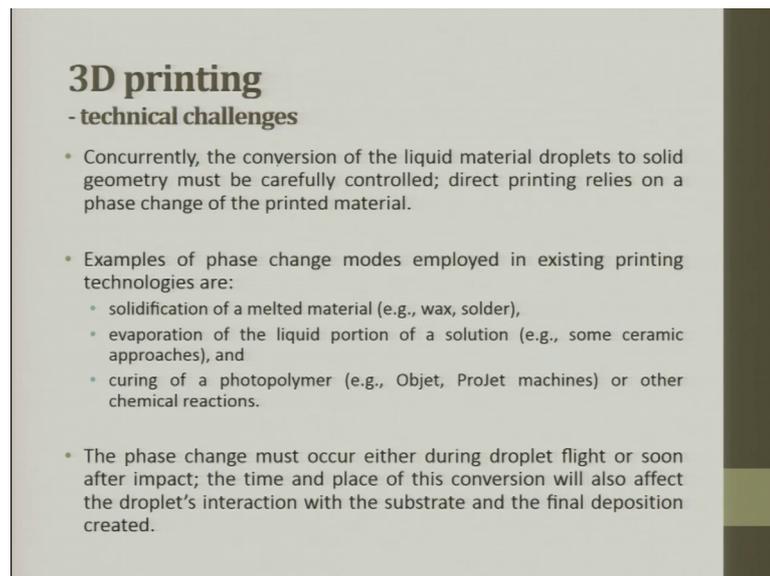
The diagram on the right shows two vertical dashed lines representing droplet paths. The left path ends in a single solid blue droplet. The right path ends in a solid blue droplet with a smaller satellite droplet breaking off from its side. To the right of these paths is a hand-drawn blue circle representing a droplet with a crown-like splash on top.

The quality of impact droplet must also be controlled. If the small droplet are called satellite breaks off from the main droplet during flight, then the deposition material will be spread over a large area than intended area and the deposition will not have a well defined boundary; very interesting. So, when it falls down suppose if it stays here, it is

good. When it falls down and if it does not stay, it jumps because of weight or because of the volume of the material, it just drops and it shatters. When it shatters, it shatters in the other area; suppose if the path is like this it shatters here, it shatters here. So, this is the boundary condition of the information in one layer.

So, if it shatters, now this layer also will get stuck to it. Now you see instead of getting a precise external boundary condition, you will have a large thicker boundary condition. This is challenged to be controlled. In the same way, if the droplet splashes on impact forming what is called the crown similarly results will occur. All of the effects will negatively impact the printing quality of the printed material. This three challenges puts a major restriction of using this technique for printing feature size which is very small and having very high resolutions. So, there is lot of work going on to improvise to pair with the viscosity of the binder and then the droplet formation dispersion and all those things.

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3D printing
- technical challenges

- Concurrently, the conversion of the liquid material droplets to solid geometry must be carefully controlled; direct printing relies on a phase change of the printed material.
- Examples of phase change modes employed in existing printing technologies are:
 - solidification of a melted material (e.g., wax, solder),
 - evaporation of the liquid portion of a solution (e.g., some ceramic approaches), and
 - curing of a photopolymer (e.g., Objet, ProJet machines) or other chemical reactions.
- The phase change must occur either during droplet flight or soon after impact; the time and place of this conversion will also affect the droplet's interaction with the substrate and the final deposition created.

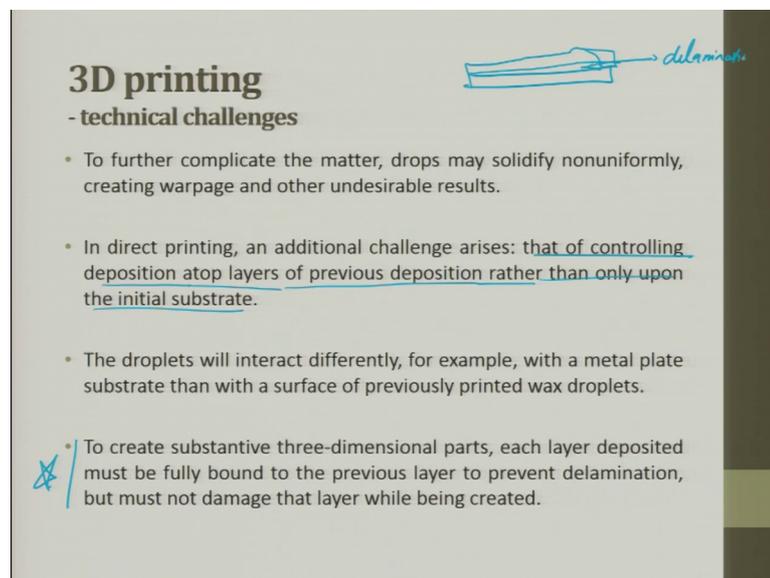
Concurrently, the conversion of a liquid material droplet to a solid geometry must be carefully controlled; direct printing realized on a phase change of printed material. Example of phase change mode employed in existing printing technologies are solidification of a melted material. For example, they would like to drop wax and go they would like to drop solder paste and go so, solidification happens.

Evaporation of liquid portion of your solution so, what happens? There is a ceramic there is a liquid when it is exposed to the atmosphere, it evaporates volatile material. So,

evaporation of liquid portion of yourself of your solution happens. Then curing a photo polymer or other chemical reactions can also happen. So, these objet and projet machines follow this curing of a photopolymer by chemical reactions.

The phase change must occur either during droplet formation or some soon after impact phase change either exiting out of the tube and falling on top of the bed, there have before that there has to be a phase change or once it falls down, it has to have a phase change. The time and place of this conversion will also affect the droplet interaction with the substrate and final deposition creation. So, this is the major challenge in front of 3D printing.

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3D printing
- technical challenges

- To further complicate the matter, drops may solidify nonuniformly, creating warpage and other undesirable results.
- In direct printing, an additional challenge arises: that of controlling deposition atop layers of previous deposition rather than only upon the initial substrate.
- The droplets will interact differently, for example, with a metal plate substrate than with a surface of previously printed wax droplets.
- To create substantive three-dimensional parts, each layer deposited must be fully bound to the previous layer to prevent delamination, but must not damage that layer while being created.

To further complicate the matter drops may solidify non-uniformly creating warpage and other undesirable results. In direct printing and additional challenge arises that the controlling deposition a top layer of previous deposition rather than only upon the initial substrate. The droplet will interact differently for example, with a metal plate substrate than with surface of previously printed wax droplet.

To create substantive three dimensional parts, each layer deposited must be fully bound to the previous layer to prevent delamination, but must not damage the layer while being created. So, this is also a major challenge while creating a 3D part, each layer deposit must be fully bonded to the previous layer to prevent delamination. So, as we told, this is delamination

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3D printing

- technical challenges

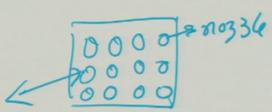
- Commercially available machines tend to approach this problem by employing devices that plane or otherwise smooth the surface periodically.
- Operational considerations also pose a challenge in process planning for printing.
- For example, because nozzles are so small, they often clog, preventing droplets from exiting.
- Much attention has been given to monitoring and maintaining nozzle performance during operation.

Commercially available machine tend to approach this problem by employing devices that clean or otherwise smooth the surface periodically. So, you have a knife or a sharp objects to smoothen the surface. Operational consideration also pose a challenge in process planning of printing. For example, because nozzles are so small, they often clog, preventing droplet to exit. Much attention has been given to monitor and maintain nozzle performance during the operation.

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3D printing

- technical challenges

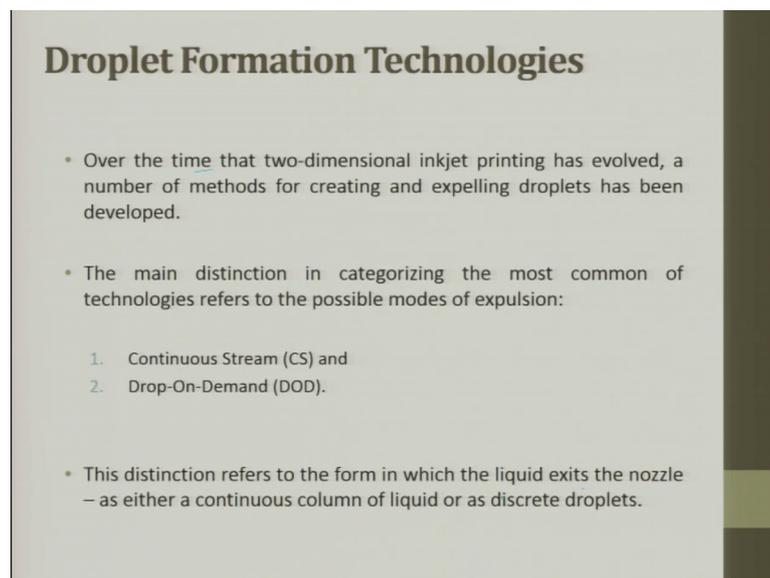


- Most machines currently in use go through purge and cleaning cycles during their builds to keep as many nozzles open as possible; they may also wipe the nozzles periodically.
- Some machines may also employ complex sensing systems to identify and compensate for malfunctioning or inconsistent nozzles.
- In addition, many machines, including all commercial RM machines, have replaceable nozzles in case of permanent blockage.
- Finally, to achieve the best print resolution, it is advantageous to produce many small droplets very close together.

Most machines which are currently in use go through a purge and cleaning cycle during the building to keep as many nozzles open as possible; they may also wipe the nozzle periodically. So, what they do is they stop they have something like a dressing cycle. They will have a cleaning cycle to have a purging cycle. While the component is made the head will move out of the table completely. It will try to purge, it will try to clean after 10 minutes of are 100 layers and then it will come back and start doing it.

So, this is becoming an inbuilt feature in this machines. Some machines may also employ complex sensing systems to identify and compensate for malfunctioning. In addition, many machines include all commercial RM machines have replaceable nozzles in case of permanent blockage. So, suppose if there are array of nozzles; now the system is built in such a manner that you can replace every nozzle every nozzle as and when it is done. Finally, to achieve the best printing resolution, it is advantageous to produce many small droplet us very close to the dimensions.

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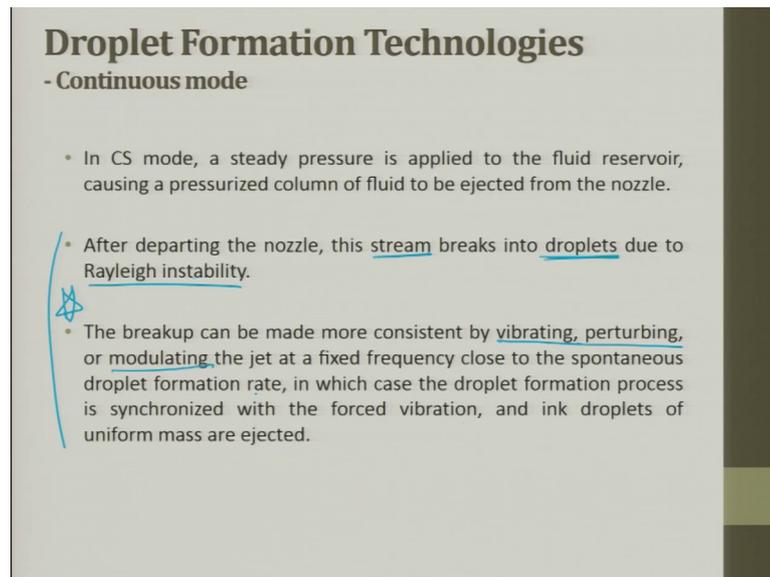


Droplet Formation Technologies

- Over the time that two-dimensional inkjet printing has evolved, a number of methods for creating and expelling droplets has been developed.
- The main distinction in categorizing the most common of technologies refers to the possible modes of expulsion:
 1. Continuous Stream (CS) and
 2. Drop-On-Demand (DOD).
- This distinction refers to the form in which the liquid exits the nozzle – as either a continuous column of liquid or as discrete droplets.

Droplet formation technology: over the time that two dimensional inkjet printing has evolved, a number of methods for creating and expelling droplet us have been developed. The main distinction in categorizing the most common of technologies refer to the possible mode of expulsion. One is continuous stream, another one is Drop On Demand DOD. This distinction refers to the form in which the liquid exit the nozzle - as either a continuous column of liquid or a discrete droplet.

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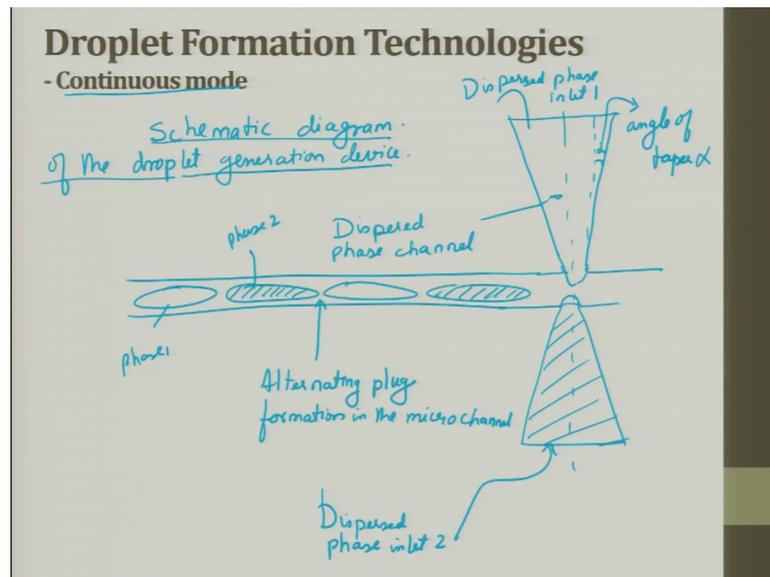
Droplet Formation Technologies
- Continuous mode

- In CS mode, a steady pressure is applied to the fluid reservoir, causing a pressurized column of fluid to be ejected from the nozzle.
- After departing the nozzle, this stream breaks into droplets due to Rayleigh instability.
- The breakup can be made more consistent by vibrating, perturbing, or modulating the jet at a fixed frequency close to the spontaneous droplet formation rate, in which case the droplet formation process is synchronized with the forced vibration, and ink droplets of uniform mass are ejected.

Continuous mode: there are two modes; drop on demand continuous mode. We are seen continuous mode. The continuous mode a steady pressure is applied to the fluid reservoir, causing a pressurized volume of the fluid to be ejected from the nozzle. After departing the nozzle, the stream breaks into droplet us because due to Rayleigh instability. Stream breaks into droplet us because of Rayleigh instability.

The breakup can be made more consistent by vibrating perturbing or modulating the jet at a fixed frequency close to the spontaneous droplet formation rate, in which case the droplet formation process is synchronized with the forced vibration and ink droplet us of uniform mass are ejected. Very very important point and lot of research is going in this area; very important point. So, a stream breaks into droplet us due to Rayleigh instability; then you can also vibrate, perturbate and modulate the jet at a fixed frequency close to the spontaneous droplet formation.

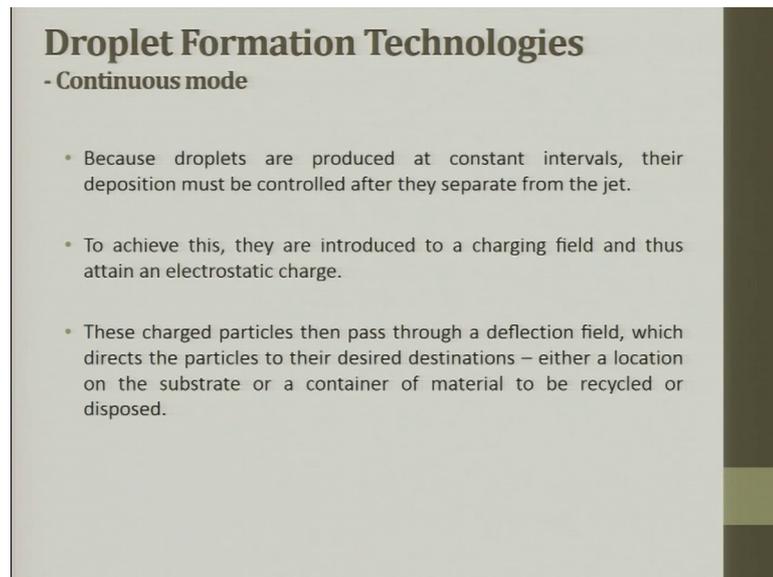
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So, let me draw a small schematic diagram of continuous mode. So, schematic diagram who have alternative layers. So, you will have here ok. So, this is the dispersed phase channel; this is alternating plug formation in the micro channel. This will be dispersed phase inlet 2; this will be dispersed phase inlet 1. And if I try to draw a line, this angle theta is the angle of taper alpha. This is a schematic diagram of the droplet generation device. This is a schematic diagram of the droplet generating device.

So, it you have a dispersing phase inlet 1 and you have a dispersing phase inlet 2 right. So, these two phases, they try to eject. So, you can see alternative of the dispersion phase. So, this is phase 1 and this is inlet phase 1 and this is phase 2. So, you see how it is the continuous droplet phase. So, this the continuous phase inlet and the two phase dispersion inlet us are shown here ok. The angle of taper is denoted by alpha.

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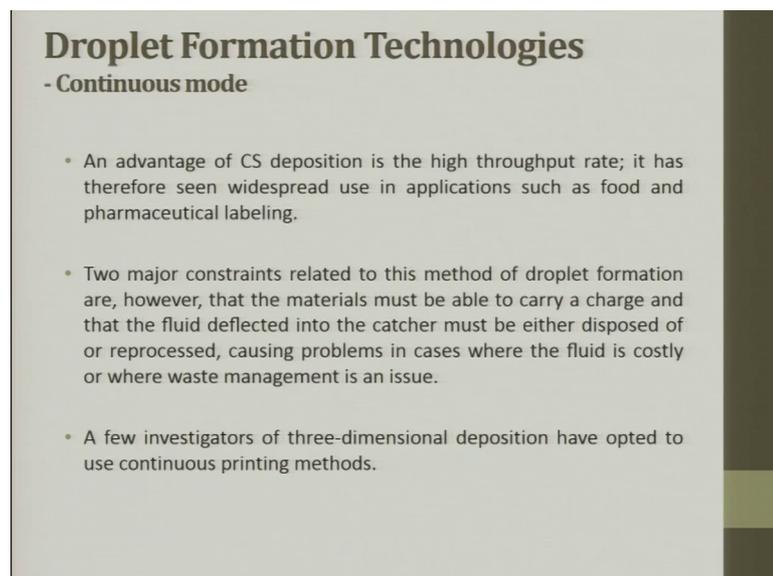


Droplet Formation Technologies
- Continuous mode

- Because droplets are produced at constant intervals, their deposition must be controlled after they separate from the jet.
- To achieve this, they are introduced to a charging field and thus attain an electrostatic charge.
- These charged particles then pass through a deflection field, which directs the particles to their desired destinations – either a location on the substrate or a container of material to be recycled or disposed.

Because the droplets are produced at constant intervals, their deposition must be controlled after they separate from the jet. To achieve this, they are introduced to a charging field at the exit of the jet where there is a charging field and thus attain an electrostatic charge. These charged particles then pass through a deflection field which directs the particles to their desired destination either your location on the substrate or a container of material to be recycled or deposited. So, that is how you break a continuous one into discrete parts and discrete droplets and then this discrete droplet is allowed to fall.

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Droplet Formation Technologies
- Continuous mode

- An advantage of CS deposition is the high throughput rate; it has therefore seen widespread use in applications such as food and pharmaceutical labeling.
- Two major constraints related to this method of droplet formation are, however, that the materials must be able to carry a charge and that the fluid deflected into the catcher must be either disposed of or reprocessed, causing problems in cases where the fluid is costly or where waste management is an issue.
- A few investigators of three-dimensional deposition have opted to use continuous printing methods.

An advantage of CS deposition is the high throughput rate; it has therefore, seen widespread use in applications such as food and pharmaceutical labeling. There we use this CS deposition. Two major constraints later to this method of droplet formation are; however, that the material must be able to carry a charge and that the fluid deflected into the catcher must be either disposed of or reprocessed, causing problem in cases where the fluid is costly or where waste management is an issue.

So, these are the two major constraints related to the droplet formation to carry a charge and that the fluid deflection into the catcher must be either disposed or reprocessed. Few investigators of three dimensional deposition have opted to use continuous printing method.

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Droplet Formation Technologies
- Drop-On-Demand mode

- In DOD mode, in contrast, individual droplets are produced directly from the nozzle.
- Droplets are formed only when individual pressure pulses in the nozzle cause the fluid to be expelled; these pressure pulses are created at specific times by thermal, electrostatic, piezoelectric, acoustic, or other actuators.
- In the current DOD printing industry, thermal (bubble-jet) and piezoelectric actuator technologies dominate; these are shown in Figure below.
- Thermal actuators rely on a resistor to heat the liquid within a reservoir until a bubble expands in it, forcing a droplet out of the nozzle.

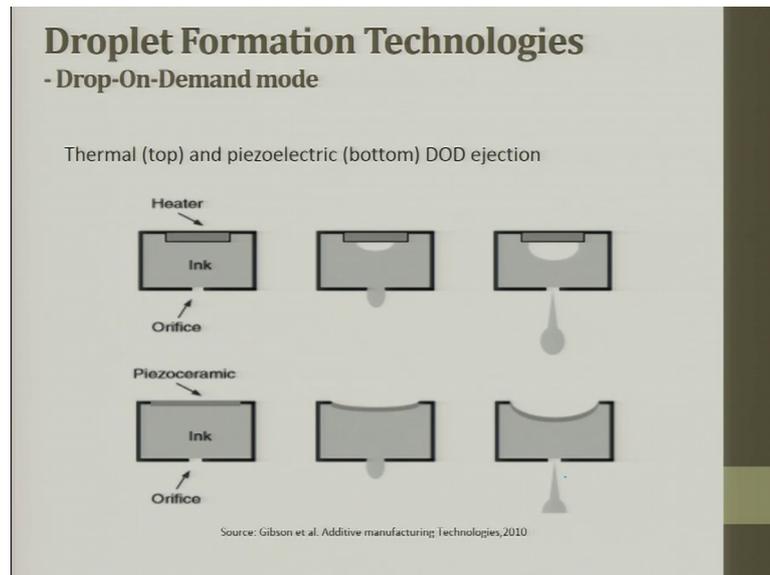
I²Rt

Drop-On-Demand mode; in drop on demand mode in contrast, individual droplet us are produced directly from the nozzle. Droplet us are formed only when individual pressure pulses in the nozzle causes the fluid to expel. In the previous one it was not so, it was a fluid coming you are you applied a electrical charge field as a droplet came. But here you will pressurize such that individual pulses get expelled out. These pressure pulses are created at specific time by thermal, electrostatic, piezoelectric, acoustic or other actuators.

Generally in our printers, we use piezoelectric. This is well established and well controllable so, we go for piezoelectric. In the current DOD, printing industry thermal

and piezoelectric actuator technologies dominate. These are shown in the next slides. The thermal actuators rely on the resistor of heating. Heating is $I^2 R t$ Joule heating effect rate. The liquid within your reservoir until your bubble expands in it, forcing a droplet out of the nozzle.

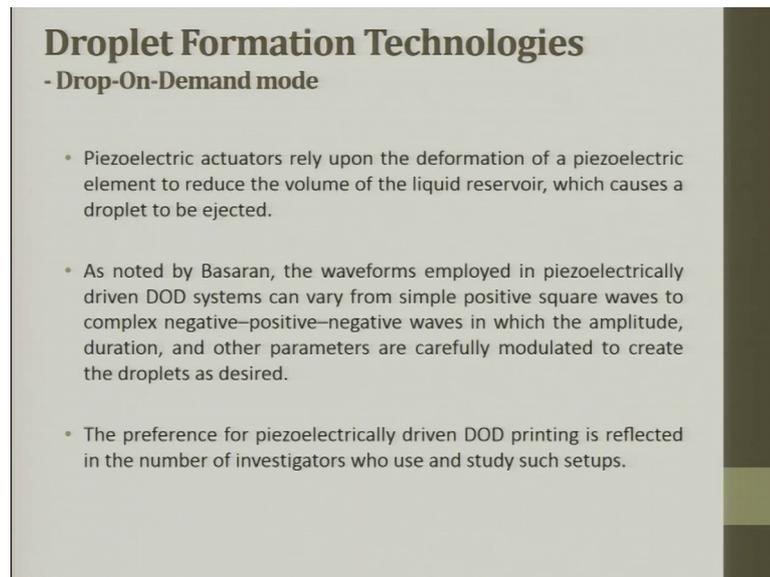
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So, you can see here thermal and the piezo; these are piezo crystal is there. So, heater is applied there is a ink. So, there is an orifice when it is heated, this gets heated up and this pushes the ink through the orifice. And when the weight is more when the weight or the droplet size is whatever equal or slightly more than the orifice diameter, it tries to droop off from the tank. Till that time heating is used. The other way around, we try to use a piezocrystal; piezoceramic.

So, piezoceramic is you activated, you apply a voltage, it has a displacement this displacement pushes the ink. So, this ink pushes. So, the orifice you have a droplet which is coming out. When there is more amount of displacement given the droplet falls down and you get fine droplet. So, this is on demand wherever there is a need this is done. In the earlier one, it is continuously flown and then you have a droplet which is getting formed.

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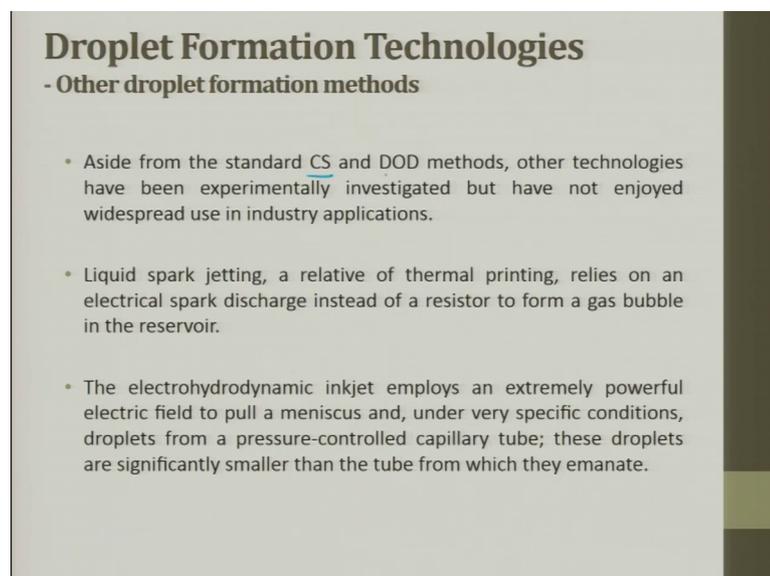


Droplet Formation Technologies
- Drop-On-Demand mode

- Piezoelectric actuators rely upon the deformation of a piezoelectric element to reduce the volume of the liquid reservoir, which causes a droplet to be ejected.
- As noted by Basaran, the waveforms employed in piezoelectrically driven DOD systems can vary from simple positive square waves to complex negative–positive–negative waves in which the amplitude, duration, and other parameters are carefully modulated to create the droplets as desired.
- The preference for piezoelectrically driven DOD printing is reflected in the number of investigators who use and study such setups.

So, two different technologies are used. Piezoelectric actuators rely upon the deformation of a piezocrystal element to reduce the volume of the liquid reservoir, which causes a droplet to be ejected. As noted by bus run, the wave form employed in piezoelectrically driven DOD system can vary from simple positive square wave to complex negative-positive-negative wave in which the amplitude, duration and the other parameters are carefully modulated to create the droplet as desired. The preference for piezoelectrically driven DOD printing is reflected in the number of investigators who use and study such steps.

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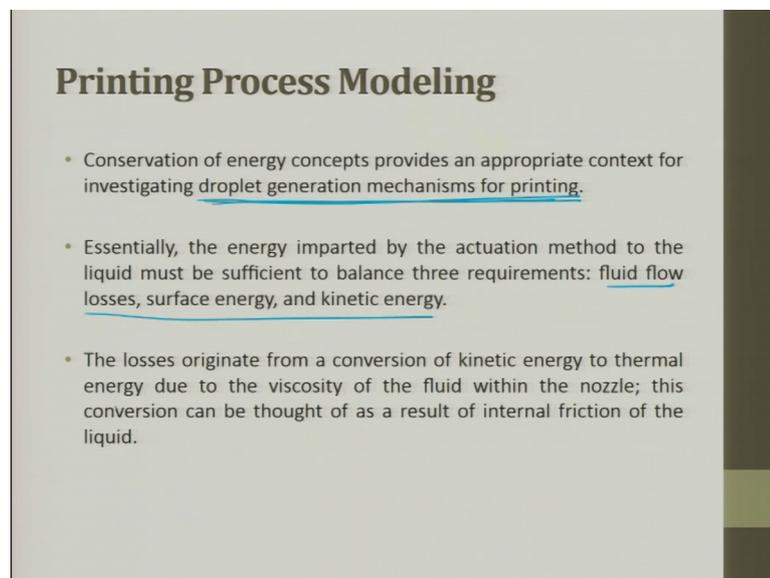
Droplet Formation Technologies
- Other droplet formation methods

- Aside from the standard CS and DOD methods, other technologies have been experimentally investigated but have not enjoyed widespread use in industry applications.
- Liquid spark jetting, a relative of thermal printing, relies on an electrical spark discharge instead of a resistor to form a gas bubble in the reservoir.
- The electrohydrodynamic inkjet employs an extremely powerful electric field to pull a meniscus and, under very specific conditions, droplets from a pressure-controlled capillary tube; these droplets are significantly smaller than the tube from which they emanate.

Aside from the standard continuous mode and the drop on demand method, other technologies have been experimentally investigated but have not enjoyed widespread use in the industries. There are other techniques, it is not only these two; liquids spark jetting, a relative of thermal printing. They realize on an electrical spark discharge instead of resistor to form your gas bubble in the reservoir.

They have used that the electro hydrodynamic inkjet employs and the extremely powerful electric field to pull a meniscus and under very specific condition, droplet from a pressure controlled capillary tube. These droplet us are significantly smaller than the tubes from which they ma.

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Printing Process Modeling

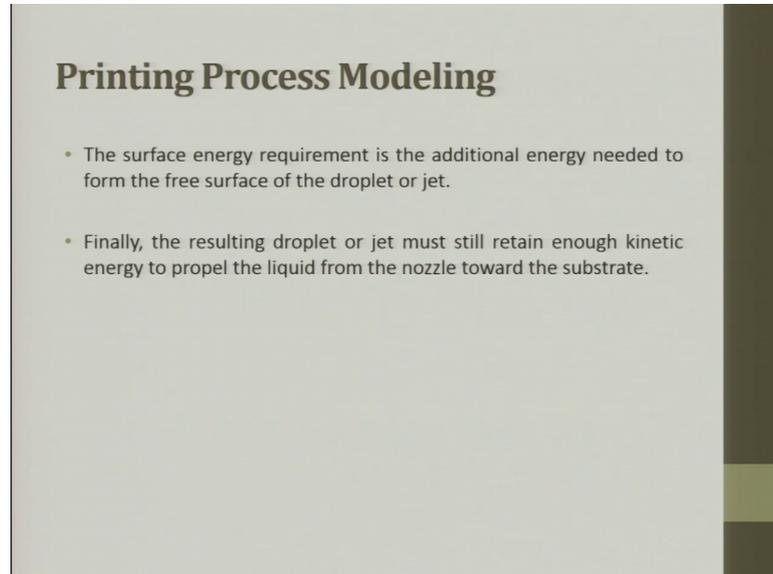
- Conservation of energy concepts provides an appropriate context for investigating droplet generation mechanisms for printing.
- Essentially, the energy imparted by the actuation method to the liquid must be sufficient to balance three requirements: fluid flow losses, surface energy, and kinetic energy.
- The losses originate from a conversion of kinetic energy to thermal energy due to the viscosity of the fluid within the nozzle; this conversion can be thought of as a result of internal friction of the liquid.

The conservation of energy concept provides you an appropriate content for investigate and droplet generation mechanism for printing. So, this is the important point droplet generation. Essentially the energy imparted by the activation method to the liquid must be sufficient to balance three requirements; fluid flow loss, surface energy, kinetic energy. Again this point is very important. The energy balance will be done between fluid flow loss, surface energy and kinetic energy.

The losses originate from your conservation of kinetic energy to thermal energy due to the viscosity of the fluid within the nozzle. This conversion can be thought of as a result in internal friction of the liquid. So, these are all techniques, but in the entire 3D printing

technique you should understand the of the binder which comes out that getting it into a droplet size is a big challenge.

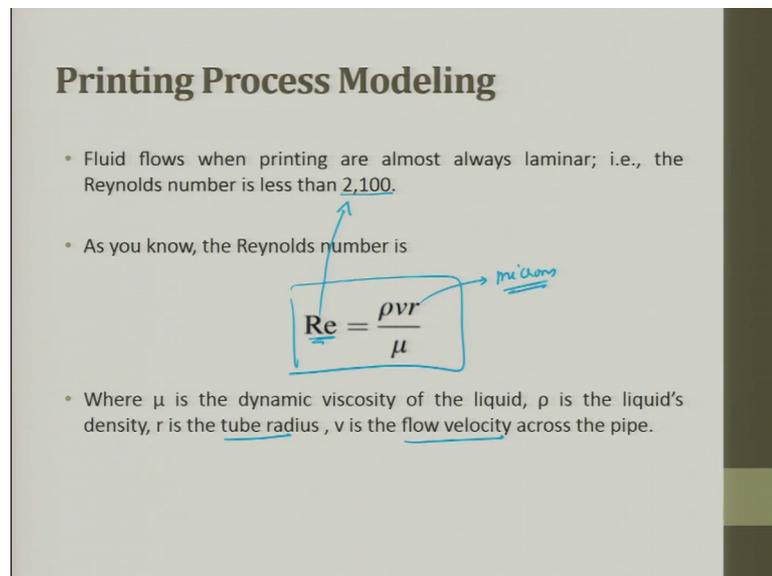
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Printing Process Modeling

- The surface energy requirement is the additional energy needed to form the free surface of the droplet or jet.
- Finally, the resulting droplet or jet must still retain enough kinetic energy to propel the liquid from the nozzle toward the substrate.

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Printing Process Modeling

- Fluid flows when printing are almost always laminar; i.e., the Reynolds number is less than 2,100.
- As you know, the Reynolds number is

$$\text{Re} = \frac{\rho v r}{\mu}$$

Where μ is the dynamic viscosity of the liquid, ρ is the liquid's density, r is the tube radius, v is the flow velocity across the pipe.

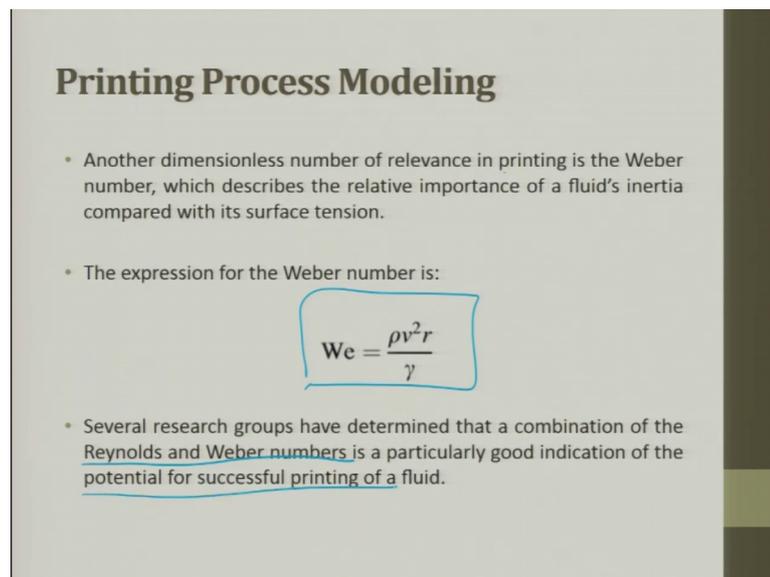
Handwritten annotations: A blue box surrounds the formula. An arrow points from the text 'As you know, the Reynolds number is' to the 'Re' in the formula. Another arrow points from the text 'mu is the dynamic viscosity' to the denominator 'mu' in the formula. The word 'microns' is written in blue next to the formula.

So, the fluid flow when printing are almost always lamellar that is Reynolds number is less than 2,100. As you know Reynolds number Re depends on ρ v r and μ ; μ is the dynamic viscosity of the liquid, ρ is the liquid density, r is the tube radius; v is the flow velocity across the pipe. With this we calculate the Reynolds number. The Reynolds

number if it is less than 2,100 it is called as a laminar flow. The fluid flow will always be maintained at lobular because when you go to turbulent flow, it becomes a challenge.

And the other thing you should understand when we talk about all these Reynolds number, we talk about the radius of the tube. Say the radius of the tube, this all holds good. When the tube is in millimeters, when you have a micro channel and through which the liquid has to flow and get dispersed; this will all be in microns.

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Printing Process Modeling

- Another dimensionless number of relevance in printing is the Weber number, which describes the relative importance of a fluid's inertia compared with its surface tension.
- The expression for the Weber number is:
$$We = \frac{\rho v^2 r}{\gamma}$$
- Several research groups have determined that a combination of the Reynolds and Weber numbers is a particularly good indication of the potential for successful printing of a fluid.

So, this is a big challenge. Another dimensionless number of relevance in printing is the Weber number, which describes the relative importance of a fluids inertia compared with the surface tension. So, Weber number is the other thing. Again Weber number, We is given by rho v square r by gamma. Several research groups have determined that the combination of Reynolds number and the Weber number is a particularly good indicator of the potential for successful printing of fluids.

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Printing Process Modeling

- Specifically, if the ratio of the Reynolds number to the square root of the Weber number has a value between 1 and 10, then it is likely that ejection of the fluid will be successful.
- This condition will be called the “printing indicator” and is

$$1 < \frac{Re}{\sqrt{We}} = \frac{\sqrt{\rho r \gamma}}{\mu} \leq 10$$

So, the condition which is called as printing indicator is this. So, you will have one which is less than or equal to Reynolds number Weber number 2 the root of Weber number which is equal to rho root of rho R gamma by mu which is again 1 less than or equal to Re; Reynolds number Weber number to the root that is greater to the root half is root of Weber number is equal to root of rho r strained by mu which is again lesser than or equal to 10.

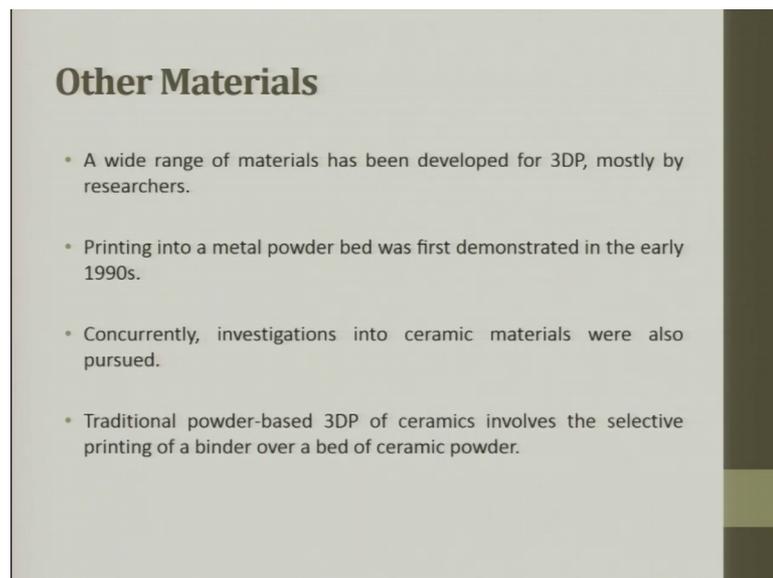
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Material Modification

- The earliest and most often used solution to the problem of high viscosity is to heat the material until its viscosity drops to an acceptable point.
- As hot-melt deposition has very specific requirements for the material properties of what is printed, many current applications have turned to solution- or dispersion-based deposition.
- The most recent development in addressing the issues of viscosity is the use of prepolymers in the fabrication of polymer parts.

The earliest and the most often used solution to the problem of high viscosity is to heat the material until its viscosity drops to the acceptable point. Your hot melt deposition has very specific requirement for the material property of what is printed, many current application have tuned to solution or dispersion based deposition. The most recent the past development in addressing the issue of viscosity is to use a pre polymer in the fabrication of polymer parts.

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Other Materials

- A wide range of materials has been developed for 3DP, mostly by researchers.
- Printing into a metal powder bed was first demonstrated in the early 1990s.
- Concurrently, investigations into ceramic materials were also pursued.
- Traditional powder-based 3DP of ceramics involves the selective printing of a binder over a bed of ceramic powder.

A wide range of materials have been developed for 3D printing. Printing into a metal powder bed was first demonstrated in early 1990. Currently investigation with ceramic materials are going on the traditionally powder based 3D printing of ceramics involves the selective printing of a binder over the bed of ceramic powder.

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Other Materials

- Fabrication of ceramic parts follows a very similar process compared with metal parts.
- Green parts created by this process are subjected to a thermal decomposition prior to sintering to remove the polymer binder.
- After binder burn-off, the furnace temperature is increased until the ceramic's sintering temperature is reached.
- Sometimes an infiltrant is used that reacts to form a ceramic binder.
- Another possibility is to infiltrate with a metal to form a ceramic-metal composite.

The fabrication of ceramic parts follows a very similar process compared with the metal part. The green parts created by this process are subjected to a thermal decomposition prior to sintering to remove the polymer binding. After the binder burns out the furnace temperature is increased until the ceramic sintering happens. Sometimes an ill infiltrant is used that the reactant to form a ceramic binder. Another possibility is to infiltrate with metal to form a ceramic metal composites.

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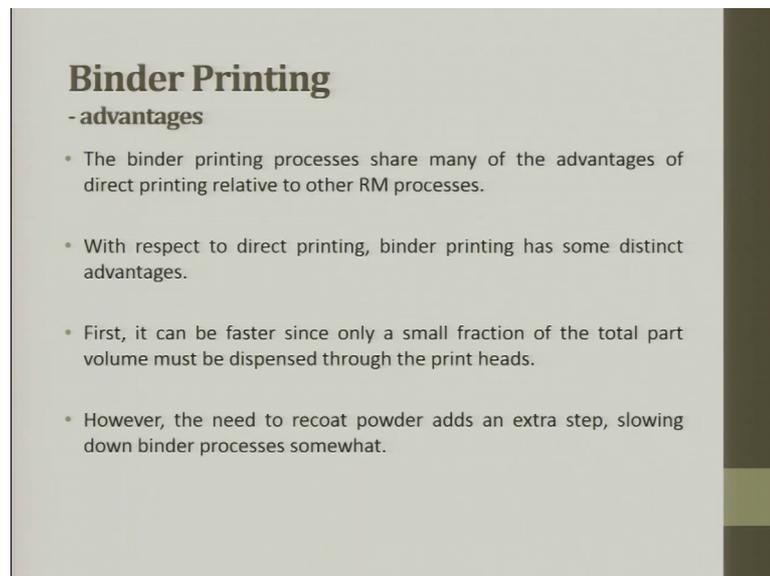
Binder Printing (or Binder Jetting)

The diagram illustrates the binder printing process. It shows a liquid adhesive supply connected to an inkjet print head. The print head is positioned above a powder bed. A leveling roller is used to spread the powder. The build platform moves vertically to deposit layers of powder and binder. The final built parts are shown on the right.

<https://www.additively.com/en/learn-about/binder-jetting>

So, this is a process of binder jetting. So, we have a liquid adhesive and supply. This is a liquid printing head which is there. So, this is a powder bed; we have a powder bed this is a building platform, this is a powder bed and this is a build part ok. The same like your SLS process, you will have a supply which comes air and then here you will have a liquid adhesive and fall supplying and then inkjet printing head. So, liquid adhesive from here supplies to here and then this fellow moves in xyz direction and you can start developing it.

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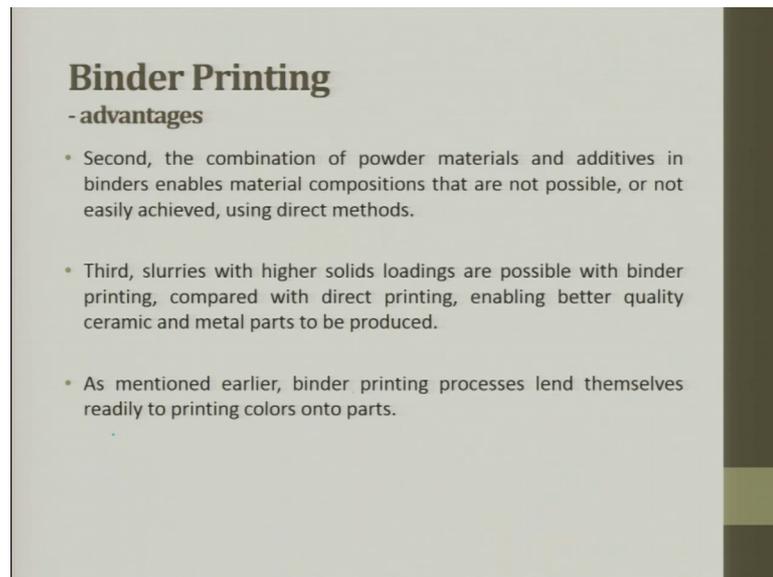


Binder Printing
- advantages

- The binder printing processes share many of the advantages of direct printing relative to other RM processes.
- With respect to direct printing, binder printing has some distinct advantages.
- First, it can be faster since only a small fraction of the total part volume must be dispensed through the print heads.
- However, the need to recoat powder adds an extra step, slowing down binder processes somewhat.

So, advantage of binder printing process shares many of the advantage of direct printing relative to the other RM process. With respect to the direct printing, binder printing has some distinct advantages. First it can be faster since only a small fraction of the total part volume must be dispensed through the printing head. However, the need to recoat powder adds an extra step to the process.

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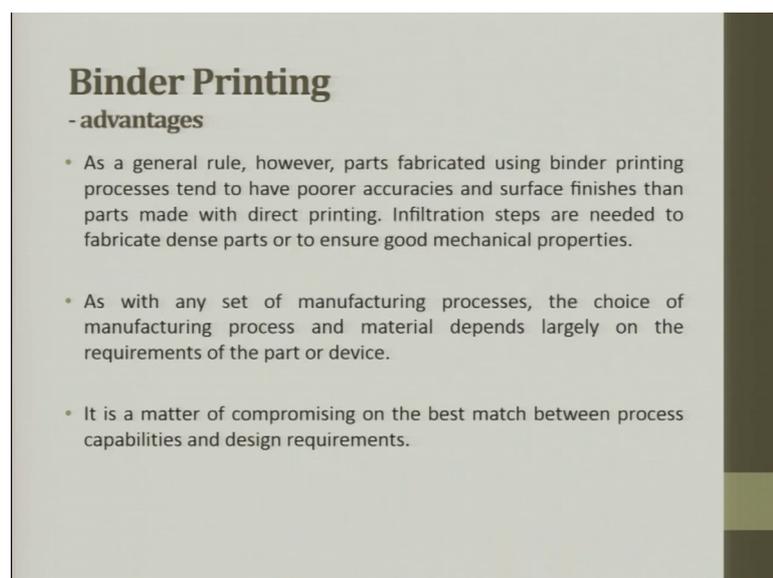


Binder Printing
- advantages

- Second, the combination of powder materials and additives in binders enables material compositions that are not possible, or not easily achieved, using direct methods.
- Third, slurries with higher solids loadings are possible with binder printing, compared with direct printing, enabling better quality ceramic and metal parts to be produced.
- As mentioned earlier, binder printing processes lend themselves readily to printing colors onto parts.

Second, the combination of powder material and additives in binder enables material composition that are not possible and not easily achievable with direct method. Third, slurries with higher solid loads are possible with binder printing, compared with the direct printing, enabling better quality ceramics and metal powders as mentioned earlier binder printing process lend themselves readily to printing colors on top of parts.

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Binder Printing
- advantages

- As a general rule, however, parts fabricated using binder printing processes tend to have poorer accuracies and surface finishes than parts made with direct printing. Infiltration steps are needed to fabricate dense parts or to ensure good mechanical properties.
- As with any set of manufacturing processes, the choice of manufacturing process and material depends largely on the requirements of the part or device.
- It is a matter of compromising on the best match between process capabilities and design requirements.

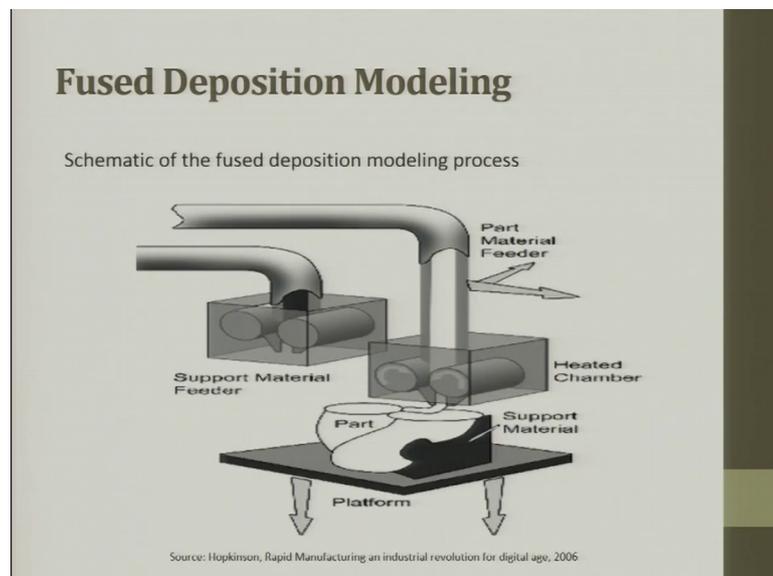
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Fused Deposition Modeling

- This process was first commercialised by Stratasys in 1991 with patents awarded to Scott Crump, the company founder in 1992.
- Stratasys now have more machines installed than any other RP supplier (over 3000 globally) and in 2003 surpassed all previous annual unit sales, shipping 691 machines, although it should be stressed that many of these machines are at the cheaper end of the market than many other processes.
- The fused deposition modeling (FDM) process creates parts by extruding material (normally a thermoplastic polymer) through a nozzle that traverses in X and Y to create each two-dimensional layer.

The last process of discussion is going to be fused to deposition method.

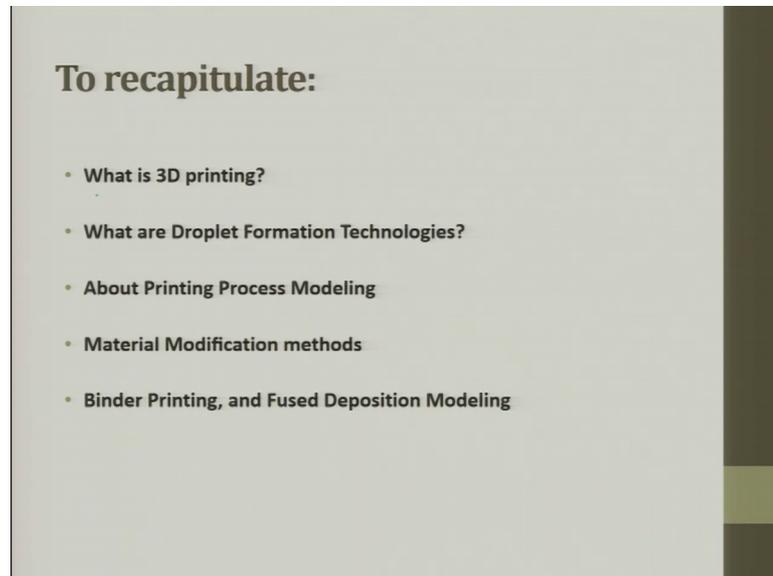
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So, it is this process almost overlaps with that of your extrusion based process. So, here we need to have a supporting material. So, the supporting material is separately fed, the building material is separately fed the tension in the extrusion process is maintained by these two spools or two rollers. They try to maintain the tension and the filament comes from the spool, passes through your nozzle where it is heated and then it is allowed to

deposit on top of a table or a platform; the platform sinks down. So, layer by layer information is built and then you start getting the required output.

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So, in this chapter, what we saw was 3D printing what was droplet formation technology, about printing process modeling we saw, material modification methods we saw and binder printing and fused deposition models we saw.

Thank you.