3D Printing Processes

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3D printing
- introduction

- Printing technology has been extensively investigated, with the majority of that investigation historically based upon applications to the two-dimensional printing industry.

- Recently, it has spread to numerous new application areas, including electronics packaging, optics, and additive manufacturing. Some of these applications, in fact, have literally taken the technology into a new dimension.

- The employment of printing technologies in the creation of three-dimensional products has quickly become an extremely promising manufacturing practice, both widely studied and increasingly widely used.

3D printing
- introduction

- 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 technologies are introduced.

- Direct printing refers to processes where all of the part material is dispensed from a print head, while binder printing refers to a broad class of processes where binder or other additive is printed onto a powder bed which forms the bulk of the part.

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.

well established process
mass produced → economical

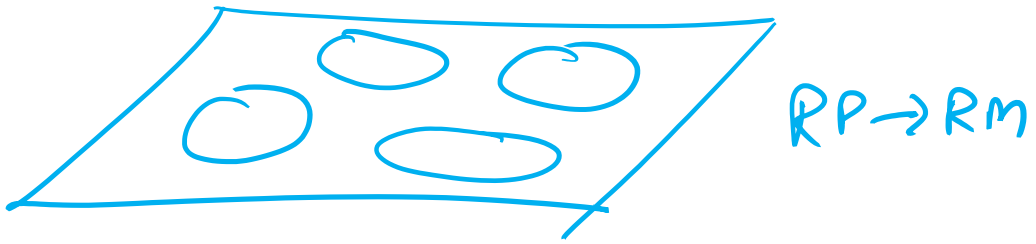
- From the topic of pure printing technologies, we move to the three-dimensional binder printing process, where binder is printed into a powder bed to form a part.

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.

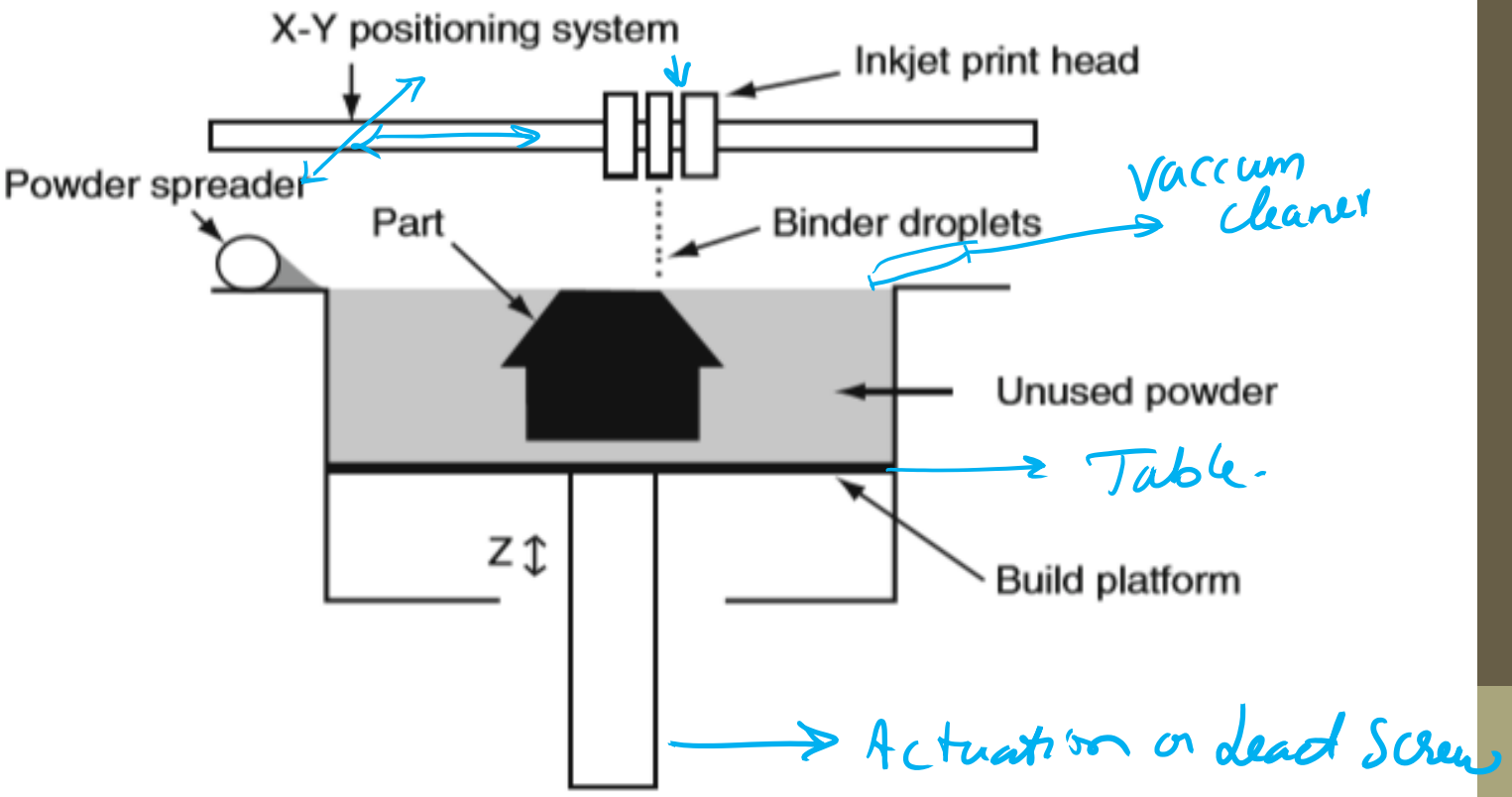
- This process (printing binder into bed; recoating bed with new layer of powder) is repeated until the part, or array of parts, is completed.

- Because the printer head contains several ejection nozzles, 3DP features several parallel one-dimensional avenues for patterning.



3D printing
- technology

- Schematic of the 3DP process



Source: Gibson et al. Additive manufacturing Technologies,2010

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.

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.

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.

drives < Belt
Lead screw

3D printing
- advantages

- High speed and scalability are related: by using print heads with hundreds or thousands of nozzles, it is possible to deposit a lot of material quickly and over a considerable area.

- Scalability in this context means that printing speed can be increased by adding another print head to a machine, a relatively easy task, much easier than adding another laser to a SL or SLS machine.

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.

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.

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.

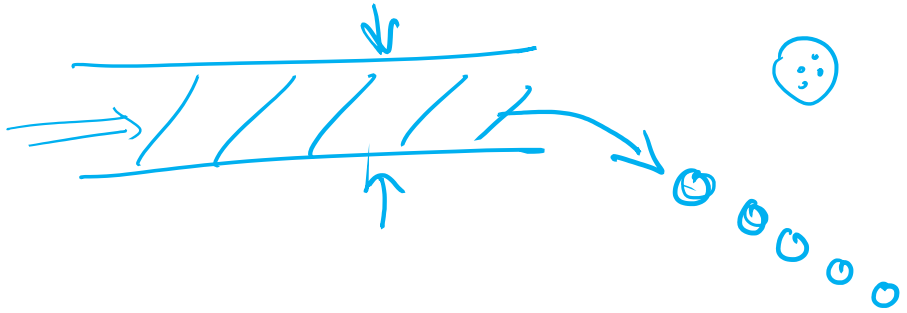
3D printing
- technical challenges

- **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.

3D printing
- technical challenges

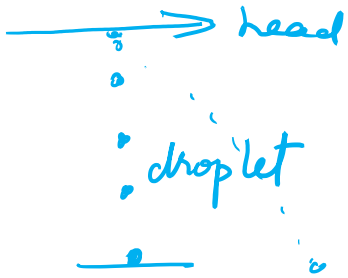


- **The second hurdle** to overcome is droplet formation. To use inkjet deposition methods, the material must be converted from a continuous volume of liquid into a number of small discrete droplets.

- 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.

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.

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.

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.

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.

3D printing
- technical challenges

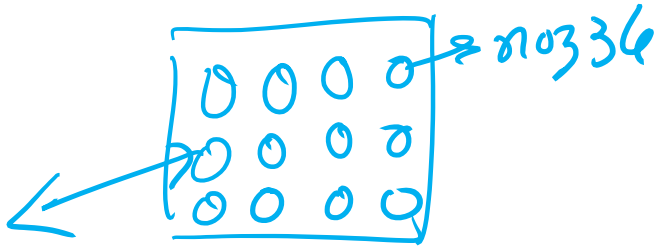
- Commercially available machines tend to approach this problem by employing devices that plane or otherwise smooth the surface periodically.

- 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.

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.

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 Technologies
- Continuous mode

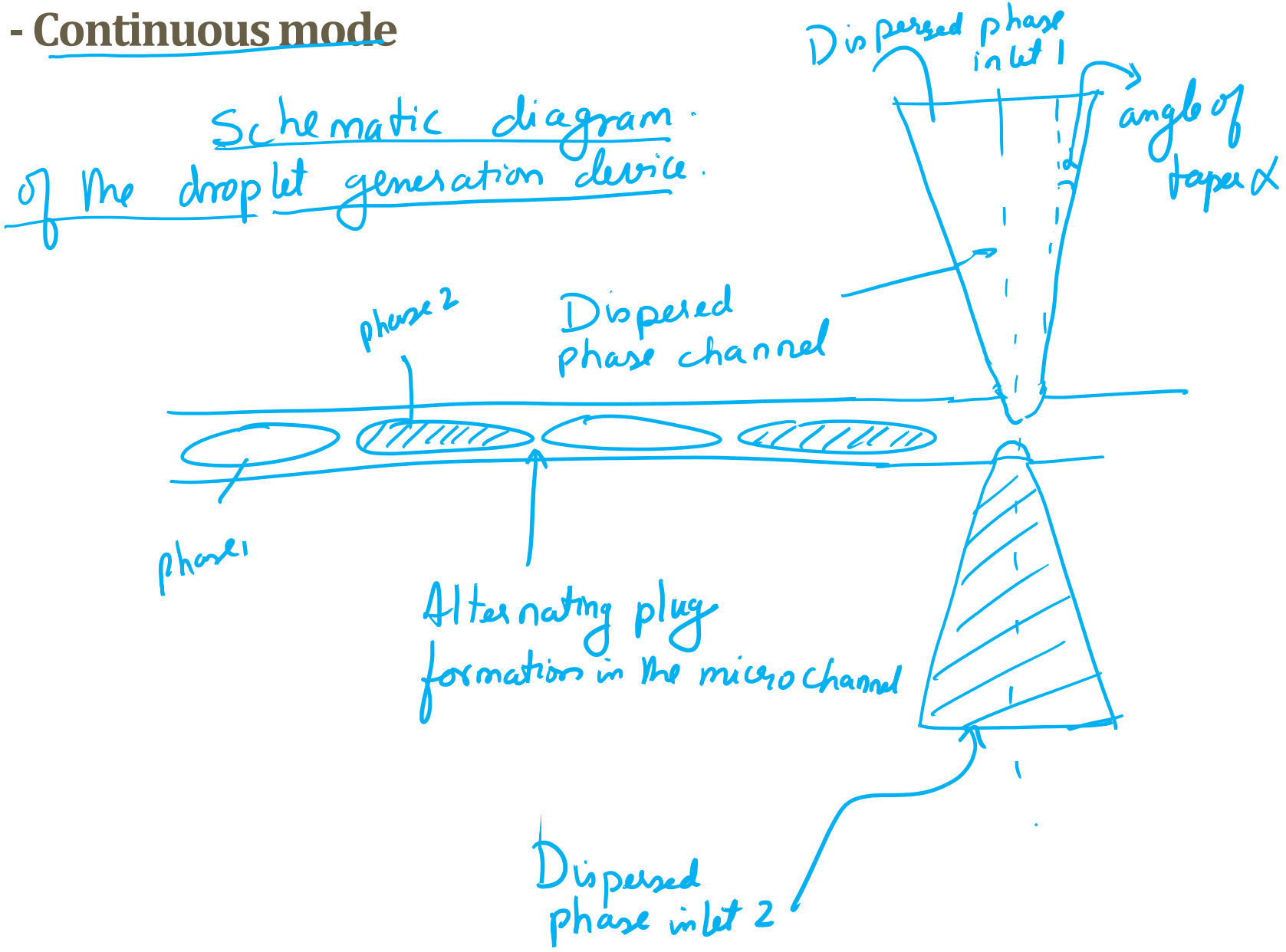
- In CS mode, a steady pressure is applied to the fluid reservoir, causing a pressurized column of fluid to be ejected from the nozzle.

- 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.

Droplet Formation Technologies

- Continuous mode



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.

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.

Droplet Formation Technologies
- Drop-On-Demand mode

- In DOD mode, in contrast, individual droplets are produced directly from the nozzle.

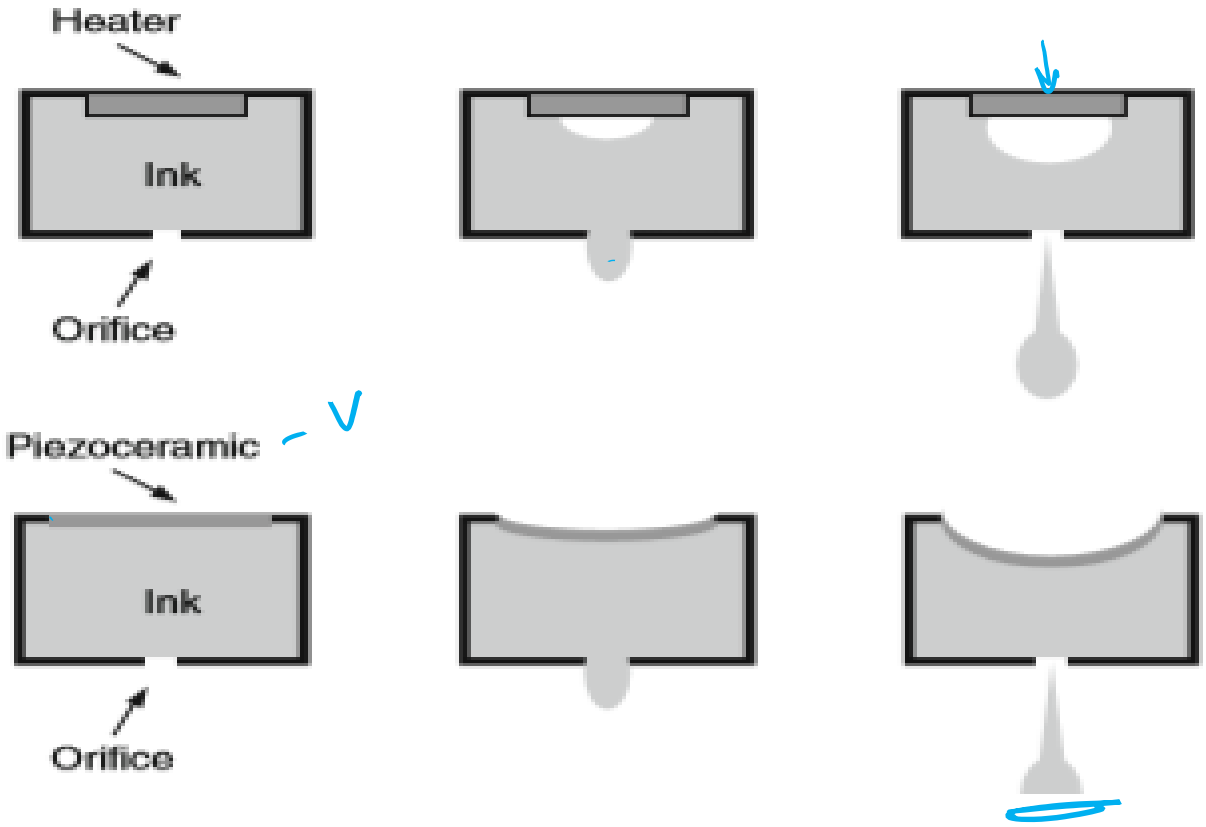
- Droplets are formed only when individual pressure pulses in the nozzle cause the fluid to be expelled; these pressure pulses are created at specific times by thermal, electrostatic, piezoelectric, acoustic, or other actuators.

- 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.

Droplet Formation Technologies
- Drop-On-Demand mode

Thermal (top) and piezoelectric (bottom) DOD ejection



Source: Gibson et al. Additive manufacturing Technologies,2010

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.

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.

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

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

- 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.

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:

$$\mathrm{We} = \frac{\rho v^2 r}{\gamma}$$

- 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.

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

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

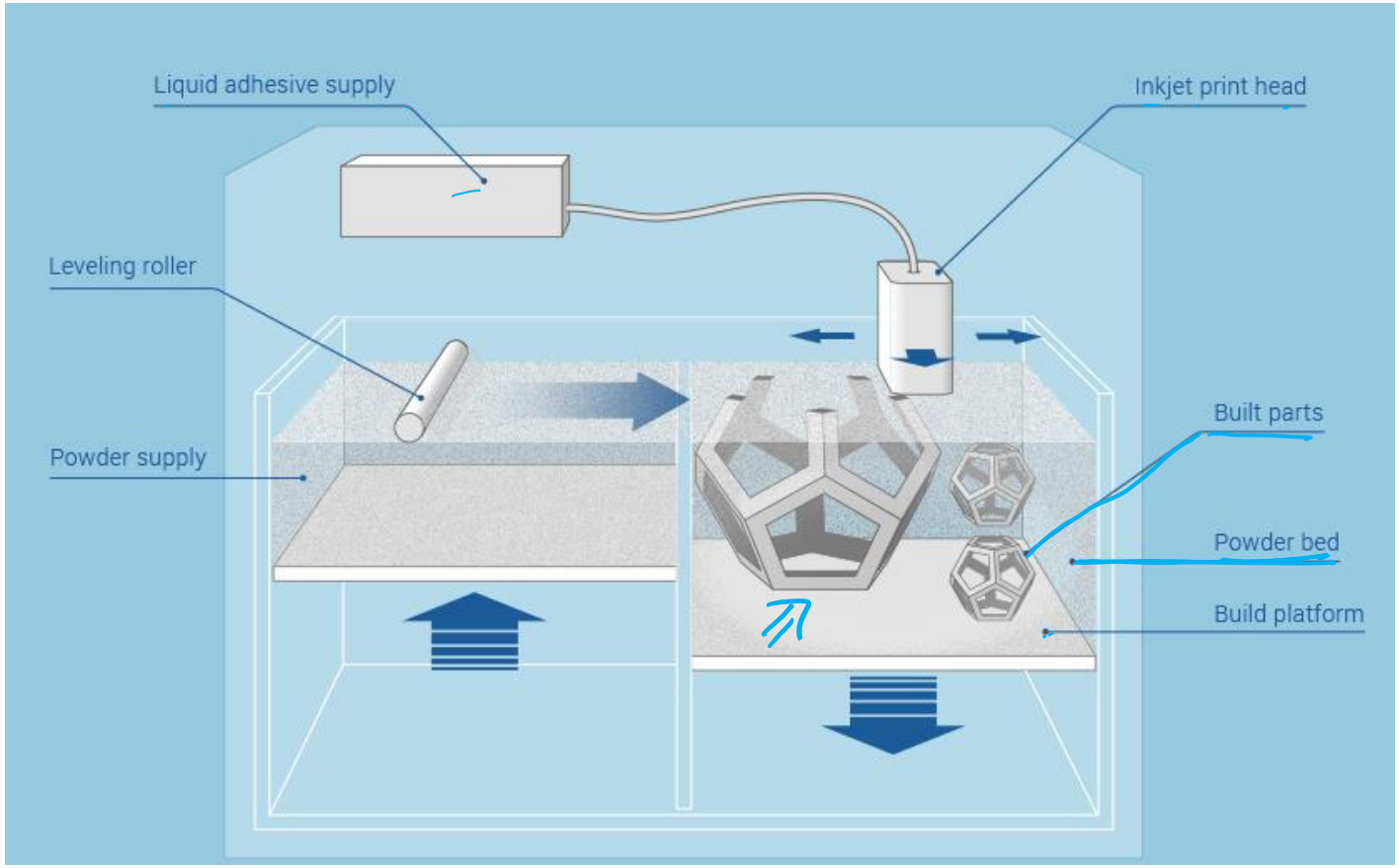
Other Materials

- 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.

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.

Binder Printing (or Binder Jetting)



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

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.

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.

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.

Fused Deposition Modeling

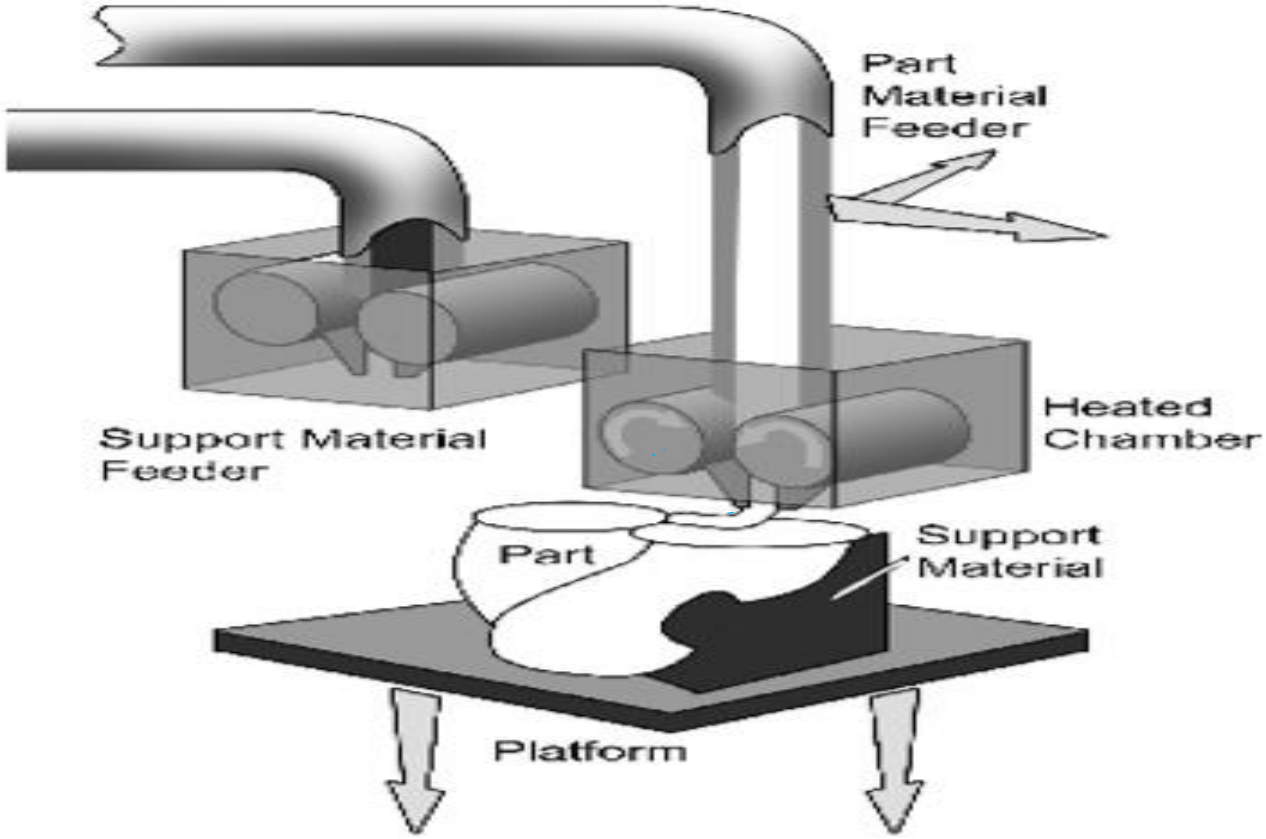
- This process was first commercialised by Stratasys in 1991 with patents awarded to Scott Crump, the company founder in 1992.

- 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.

Fused Deposition Modeling

Schematic of the fused deposition modeling process



Source: Hopkinson, Rapid Manufacturing an industrial revolution for digital age, 2006

To recapitulate:

- What is 3D printing?
- What are Droplet Formation Technologies?
- About Printing Process Modeling
- Material Modification methods
- Binder Printing, and Fused Deposition Modeling

Thank You