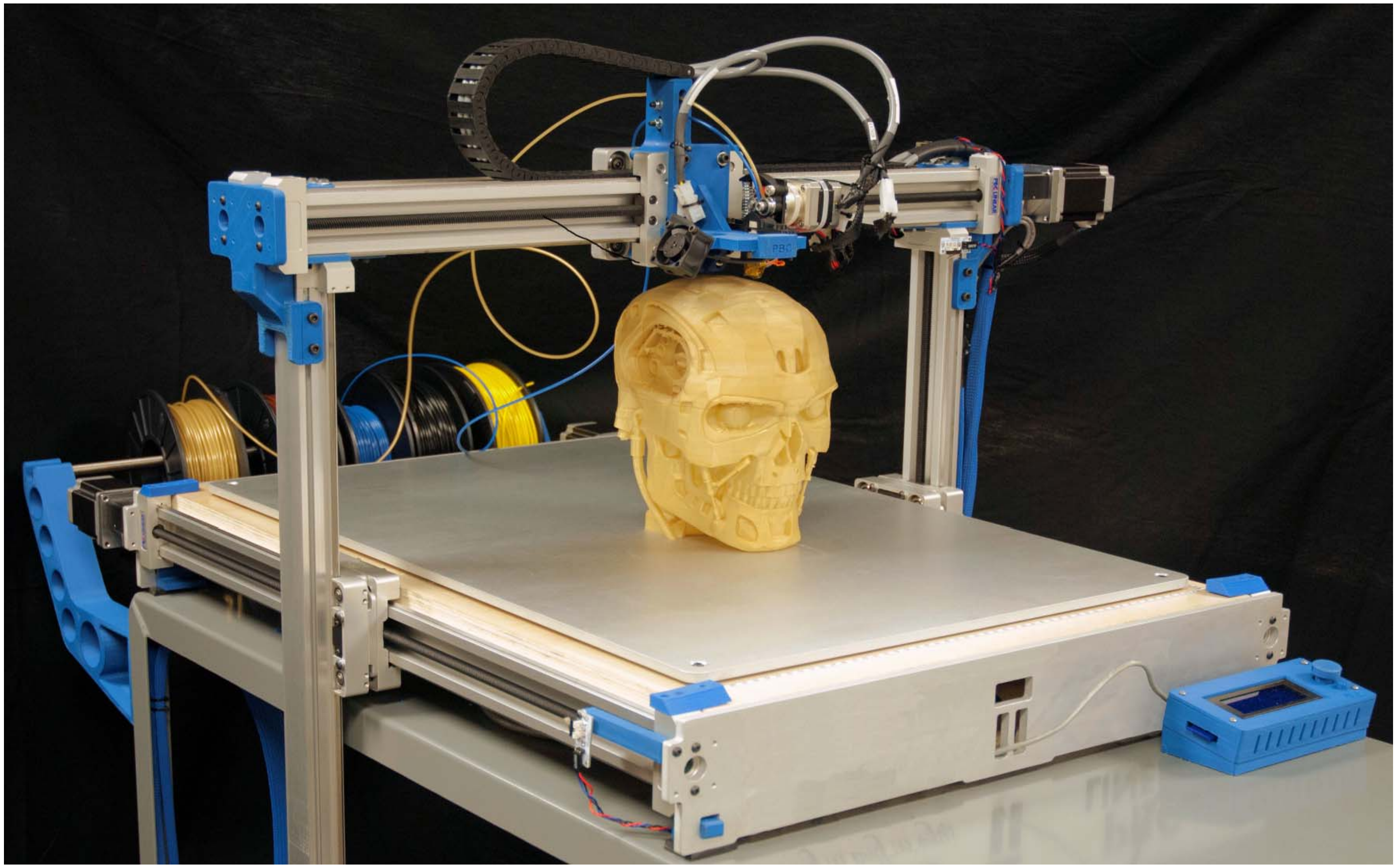
Printing Processes

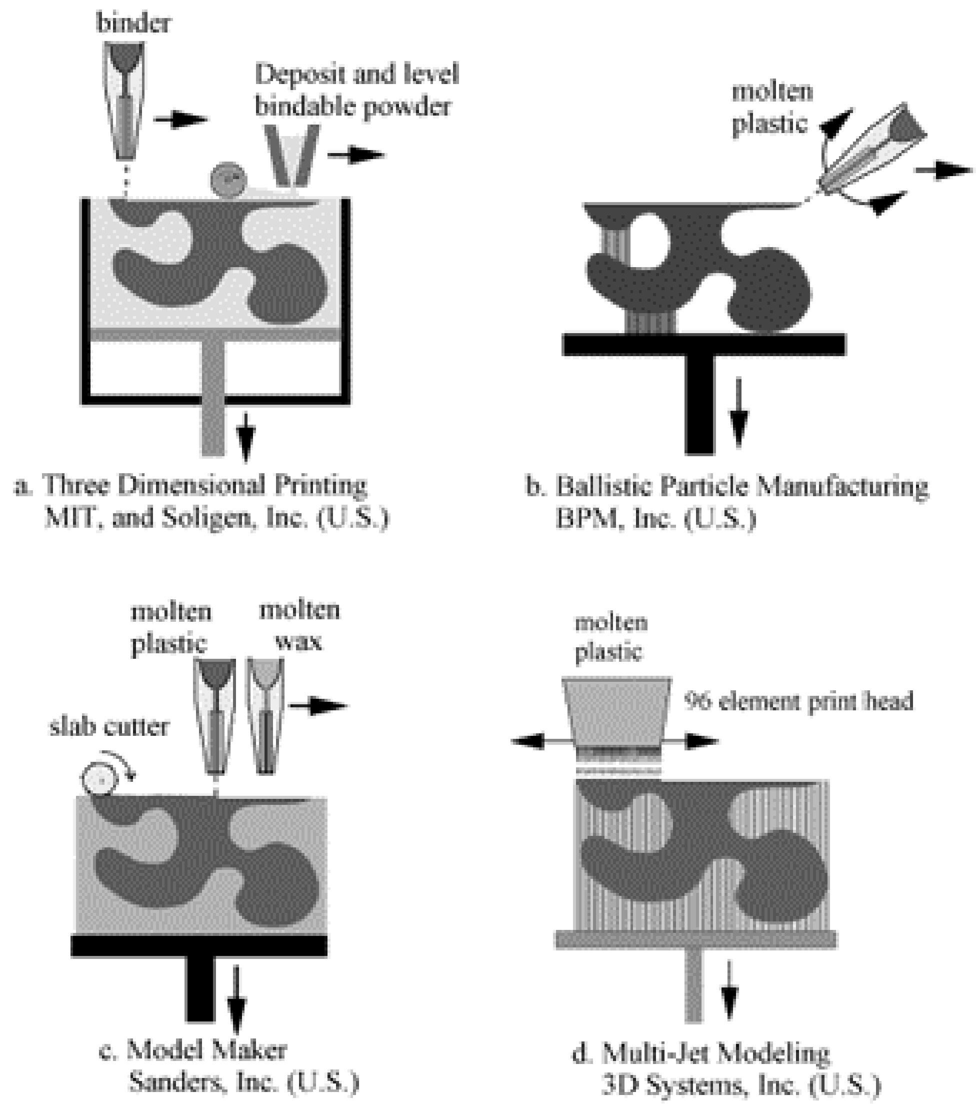
Lecture 21

ME361A



3D Printing (3DP)

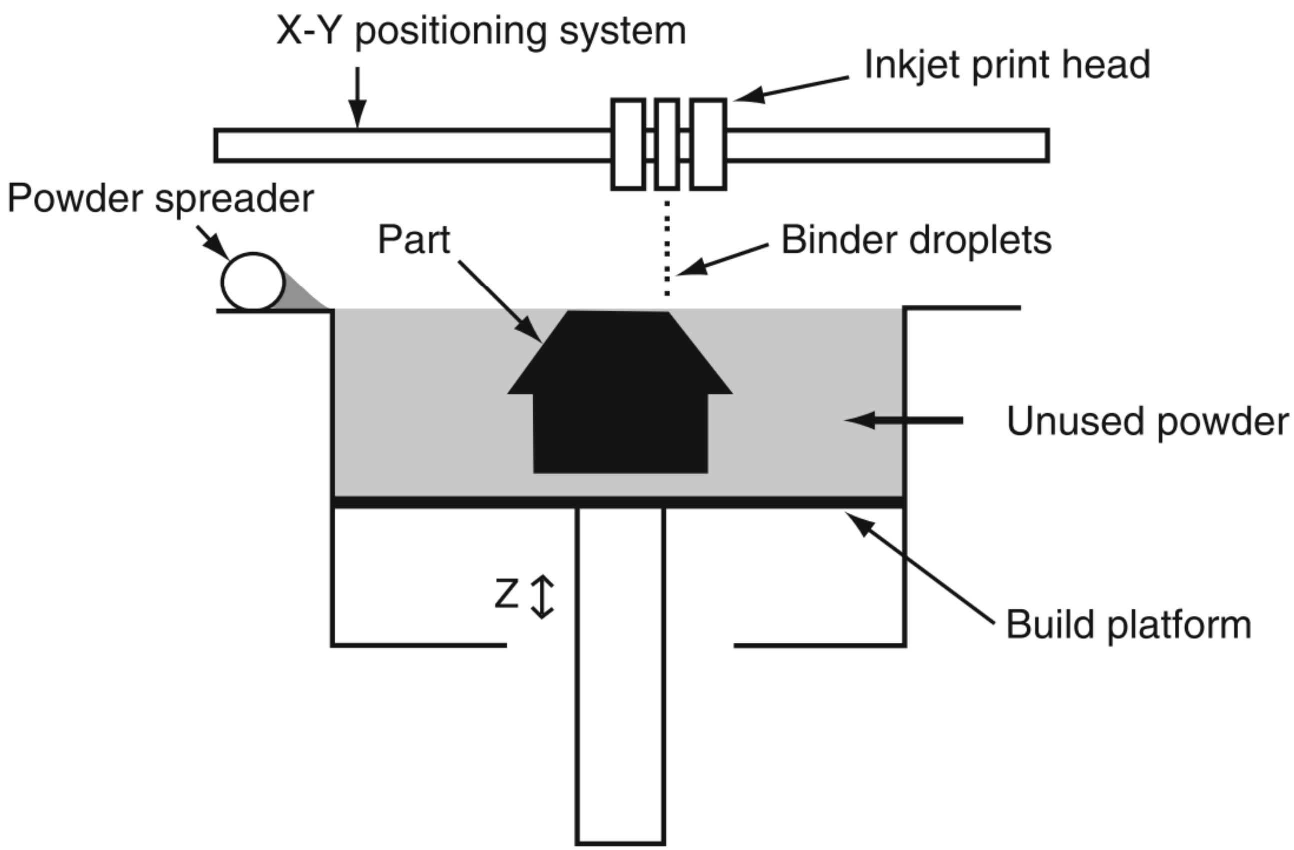
1. A layer of powder (plaster, ceramic) is spread across the build area
2. Inkjet-like printing of binder over the top layer densifies and compacts the powder locally
3. The platform is lowered and the next layer of dry powder is spread on top of the previous layer
4. Upon extraction from the machine, the dry powder is brushed off and recycled



3D printing

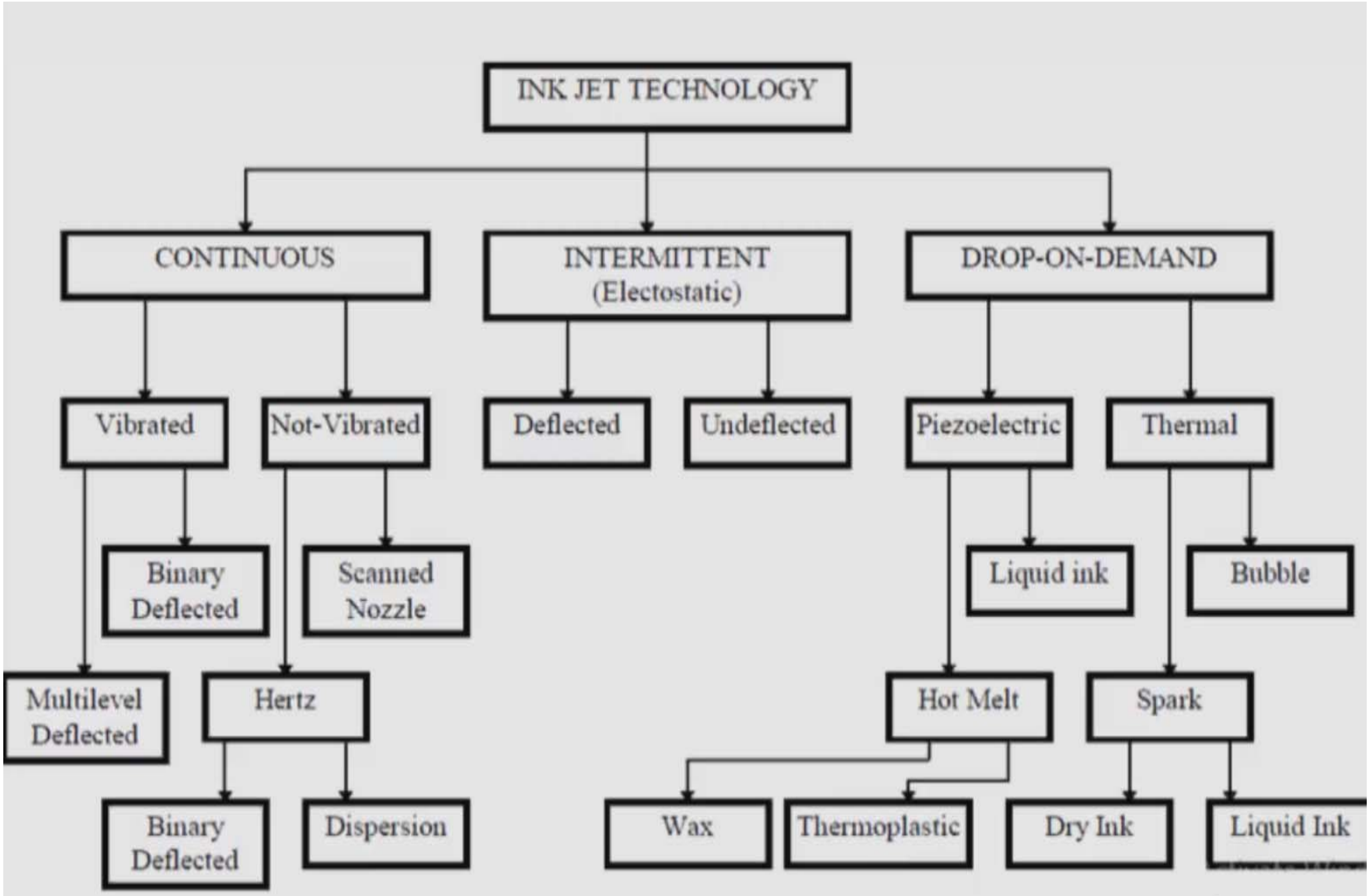
- 3DP prints a binder into a powder bed to fabricate a part. The machine spreads a layer of powder from the feed box to cover the surface of the build piston. The printer then prints binder solution onto the loose powder, forming the first cross-section.
- Hence, in 3DP, only a small portion of the part material is delivered through the print-head.
- Most of the part material is comprised of powder in the powder bed.
- Binder droplets (80 μm in diameter) form spherical agglomerates of binder liquid and powder particles as well as provide bonding to the previously printed layer. The powder is glued together at where the binder is printed. The remaining powder remains loose and supports the layers that will be printed above.
- Once a layer is printed, the powder bed is lowered and a new layer of powder is spread onto it.
- This process (printing binder into bed; recoating bed with new layer of powder) is repeated until the part, or array of parts, is completed.

Process


X-Y positioning system
Inkjet print head
Powder spreader
Part
Binder droplets
Unused powder
Z
Build platform

Features of 3D Printing

- A typical inkjet nozzle delivers approximately 1 cm^3/min of binder; thus a machine with a 100 nozzle printhead could create up to approximately 200 cm^3/min of printed component. Because commercial inkjet printers exist with up to 1,600 nozzles, 3DP could be fast enough to be used as a production process.
- 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.
- 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.
- Binder printing processes can readily print colors onto parts.



INK JET TECHNOLOGY
CONTINUOUS
INTERMITTENT (Electostatic)
DROP-ON-DEMAND
Vibrated
Not-Vibrated
Deflected
Undeflected
Piezoelectric
Thermal
Binary Deflected
Scanned Nozzle
Liquid ink
Bubble
Multilevel Deflected
Hertz
Hot Melt
Spark
Binary Deflected
Dispersion
Wax
Thermoplastic
Dry Ink
Liquid Ink

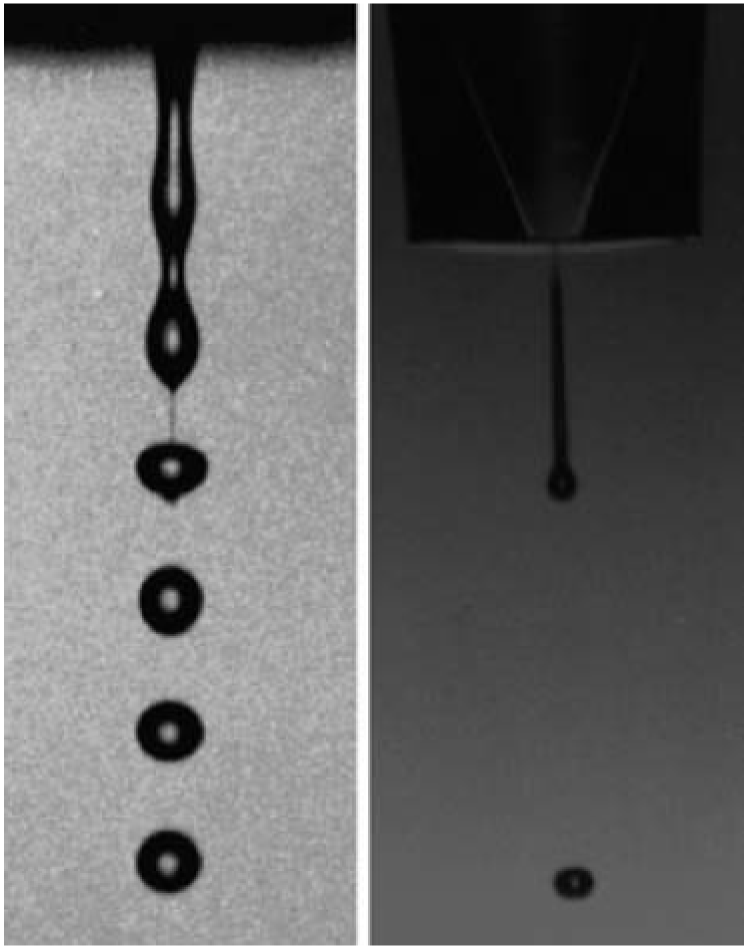
Droplet Formation Technologies

➢ Modes of expulsion:

- Continuous stream (CS)
- 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.

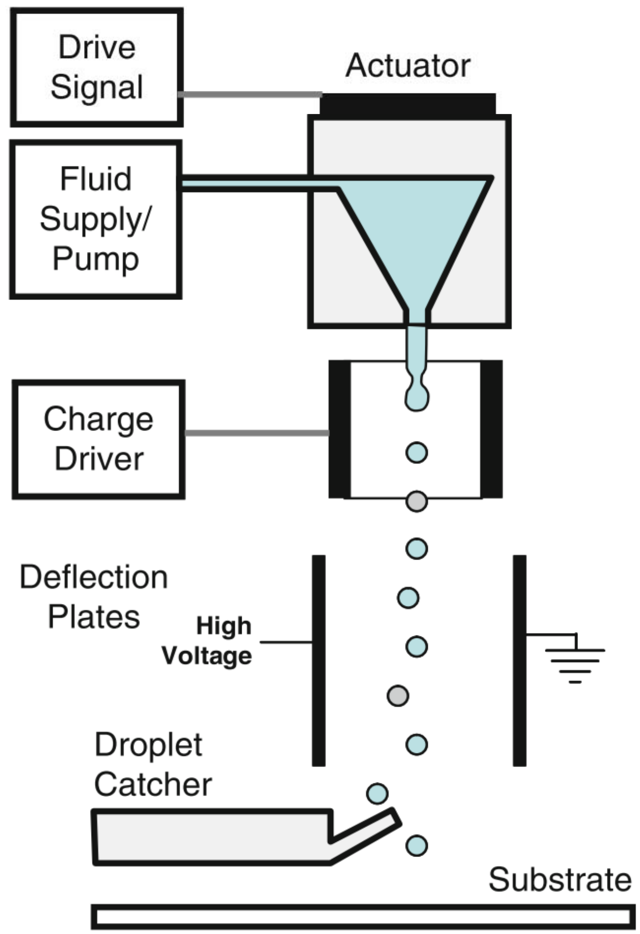
CS DOD



Continuous 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.
- 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

Binary deflection continuous printing

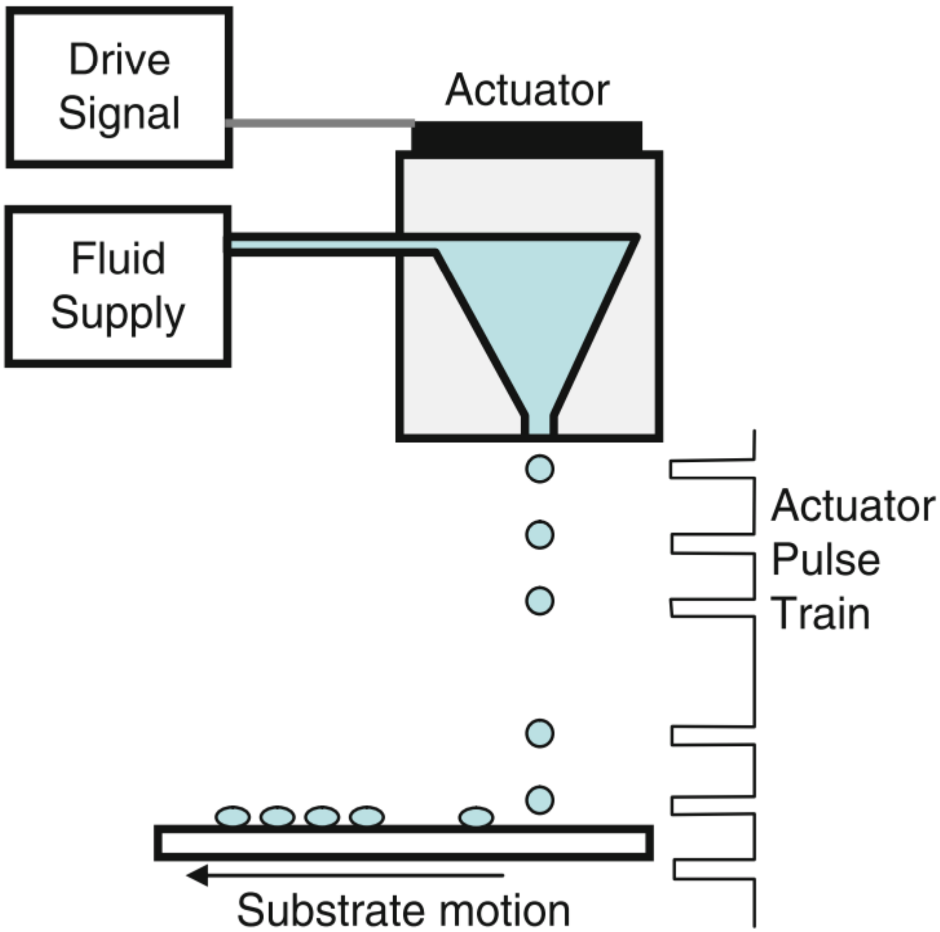


Drop-on-Demand Mode

- 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 (bubble-jet)
- Electrostatic
- Piezoelectric
- Acoustic
- Other actuators

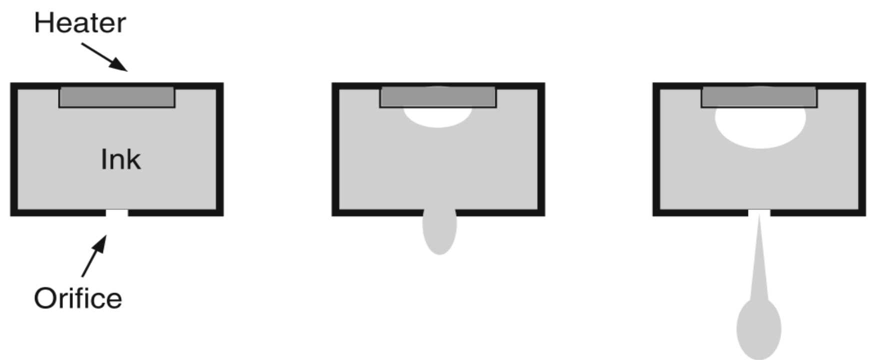
In the current DOD printing industry, thermal (bubble-jet) and piezoelectric actuator technologies dominate

Schematic of DOD printing system

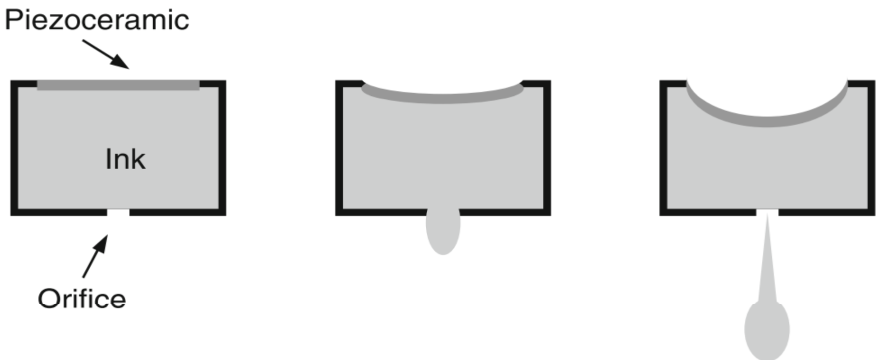


- Deposit droplets of 25–120 μm at a rate of 0–2000 drops per second.
- Thermal actuators rely on a resistor to heat the liquid within a reservoir until a bubble expands in it, forcing a droplet out of the nozzle. Piezoelectric actuators rely upon the deformation of a piezoelectric element to reduce the volume of the liquid reservoir, which causes a droplet to be ejected.

Thermal DOD ejection



Piezoelectric DOD ejection



Advantages of DOD :

DOD is preferred method due to its smaller drop size (often of diameter similar to the orifice) and higher placement accuracy in comparison to CS methods

Piezoelectric DOD is more widely applicable than thermal because it does not rely on the formation of a vapor bubble or on heating that can damage sensitive materials.

At present, all commercial AM printing machines use DOD print heads

Technical Challenges of Printing

Challenges is formulation of the liquid material:

- 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. The addition of tiny particles can dramatically change its droplet forming behavior.

Technical Challenges of Printing..contd

- 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.

- Parameter that affect the trajectory:
  - location of the droplets' arrival
  - Droplet velocity
  - Size will also affect the deposition characteristics.

These can be measured and controlled via nozzle design and operation.

Technical Challenges of Printing..contd

- 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.
- 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 time and place of this conversion will also affect the droplet’s interaction with the substrate and the final deposition created.

Technical Challenges of Printing..contd

- In direct printing, an additional challenge arises: 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.

- Nozzles are so small, they often clog, preventing droplets from exiting. Solution for Nozzle clog through purge and cleaning cycles during their builds to keep as many nozzles open as possible; they may also wipe the nozzles periodically.

Printing Process Modeling

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
  - kinetic energy
- The fluid flow 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 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.
- This energy conservation can be summarized as

$$E_{\text{imparted}} = E_{\text{loss}} + E_{\text{surface}} + E_{\text{kinetic}}$$

- The conservation law can be considered in the form of actual energy calculations or in the form of pressure, or energy per unit volume, calculations.
- Sweet used the following approximation for the gauge pressure required in the reservoir of a continuous jetting system

$$\Delta p = 32\mu d_{\mathrm{j}}^{2} v_{\mathrm{j}} \int_{l_1}^{l_2} \frac{dl}{d_n^4} + \frac{2\sigma}{d_{\mathrm{j}}} + \frac{\rho v_{\mathrm{j}}^2}{2}$$

Δp = total gauge pressure required

ρ = liquid's density

μ = dynamic viscosity of the liquid

σ = liquid's surface tension

d_{j} = diameter of the resultant jet

d_n = inner diameter of the nozzle

v_{j} = velocity of the resultant jet

l = length of the nozzle or supply tubing

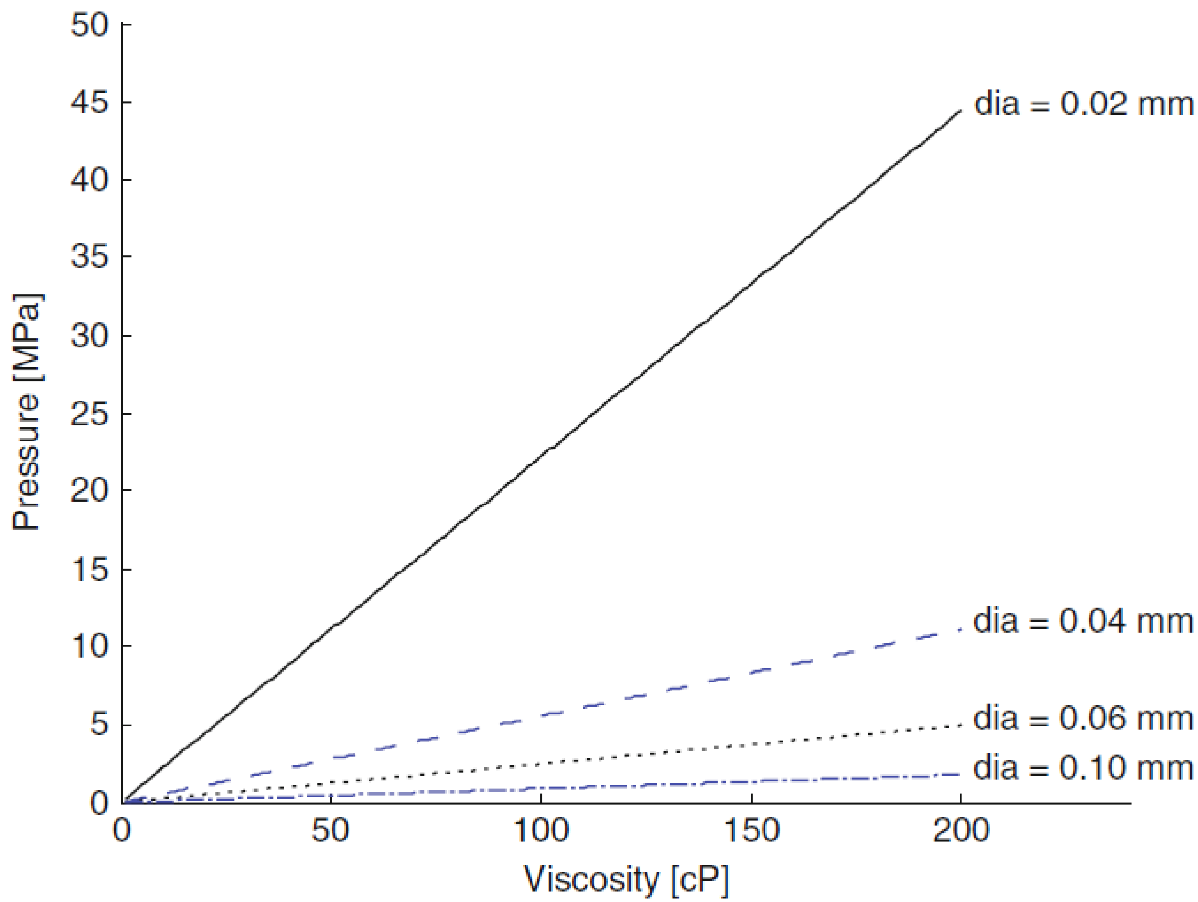
- First term on the right of is an approximation of the pressure loss due to viscous friction within the nozzle and supply tubing.
- Second term is the internal pressure of the jet due to surface tension
- Third term is the pressure required to provide the kinetic energy of the droplet or jet.

- Before the fluid leaves the nozzle, the positive effect of the driving pressure gradient accelerates it, but energy losses due to viscous flow decelerate it.
- The kinetic energy with which it leaves the nozzle must be enough to cover the kinetic energy of the traveling fluid as well as the surface energy of the new free surface.
- The flow is fully described by the Navier–Stokes and continuity equations with simplification of steady, incompressible, laminar flow through a straight circular tube of constant cross section.
- The solution is the Hagen– Poiseuille law, which reflects the viscous losses due to wall effects:

$$\Delta p = \frac{8Q\mu l}{\pi r^4 \sigma}$$

where Q is the flow rate and r is the tube radius. Note that this expression is most applicable when the nozzle is a long, narrow glass tube. However, it can also apply when the fluid is viscous.

Pressure required to overcome wall friction for printing through nozzles of different diameters vs. Viscosity



Another assumption made by using the Hagen–Poiseuille equation is that the flow within the nozzle is fully developed. For the case of laminar flow in a cylindrical pipe, the length of the entry region l_e where flow is not yet fully developed is defined as 0.06 times the diameter of the pipe, multiplied by the Reynolds number

$$l_e = 0.06d\mathrm{Re} = \frac{0.06\rho\bar{v}d^2}{\mu}$$

Consider printing with a 20 µm nozzle in a plate that is 0.1 mm thick, where the droplet ejection speed is 10 m/s. The entry lengths for a fluid with the density of water = 1000 kg/m^3 and varying viscosities are shown in Table

Viscosity (cP)	Density (kg/m^3)	Entry length (µm)
1	1,000	240
	1,250	300
10	1,000	24
	1,250	30
40	1,000	6
	1,250	7.5
100	1,000	2.4
	1,250	3
200	1,000	1.2
	1,250	1.5

Flows are fully developed through most of a nozzle for fluids that are at the higher end of the range of printable viscosities

- Fluid flows for printing preferred is almost always laminar; i.e., the Reynolds number is less than 2,100.
- Weber number, which describes the relative importance of a fluid's inertia compared with its surface tension.

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

It will be *d* and not *r*

- 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 .
- 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

$$1 \leq \frac{\mathrm{Re}}{\mathrm{We}^{1/2}} = \frac{\sqrt{\rho r \gamma}}{\mu} \leq 10$$

It will be *d* and not *r*

The inverse of the printing indicator is another dimensionless number called the Ohnsorge number, that relates viscous and surface tension forces. Note that values of this ratio that are low indicate that flows are viscosity limited, while large values indicate flows that are dominated by surface tension.

Some examples of Reynolds numbers and printing indicators are given in Table. For these results, the surface tension is 0.072 N/m and the density is 1,000 kg/m^3 (same as water at room temperature). v = 1 m/s

Nozzle diameter [mm]	Viscosity [cP]	Reynolds no.	Printing indicator
0.02	1	20	26.8
	10	2	2.68
	40	0.5	0.67
	100	0.2	0.27
0.05	1	50	42.4
	10	5	4.24
	40	1.25	1.06
	100	0.5	0.42
0.1	1	100	60
	10	10	6
	40	2.5	1.5
	100	1	0.6

Water is usually easy to print through most print-heads, regardless of the nozzle size. But the printing indicator predicts that water (with a viscosity of 1 cP) should not be ejectable since its surface tension is too high.

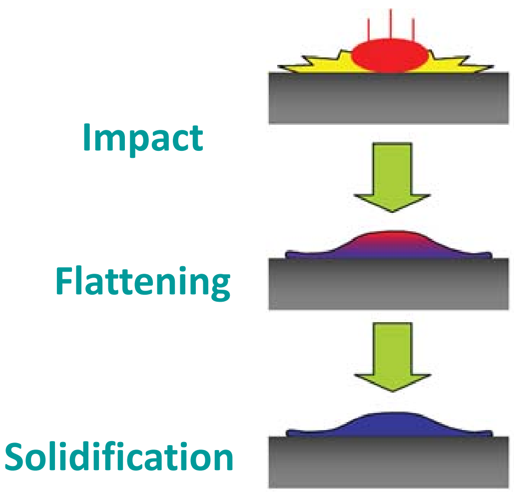
It will be *d* and not *r*, so values in the last column will change

While the general challenges of direct printing for three-dimensional fabrication are identified, there are many aspects that are not well or fully understood. Open research questions abound in almost all stages of the printing process – droplet formation, deposition control, and multilayer accumulation.

For the case of functional polymer printing, the most appropriate limitation to address is that of droplet formation.

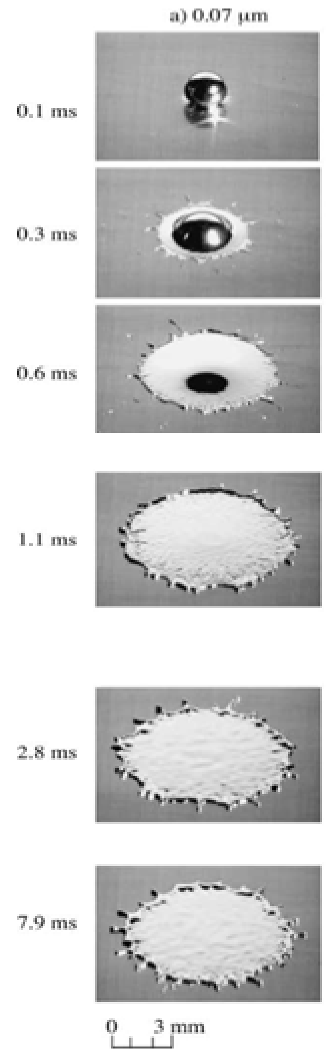
Modelling
Droplet based 3D Printing Processes

Droplet based 3D printing

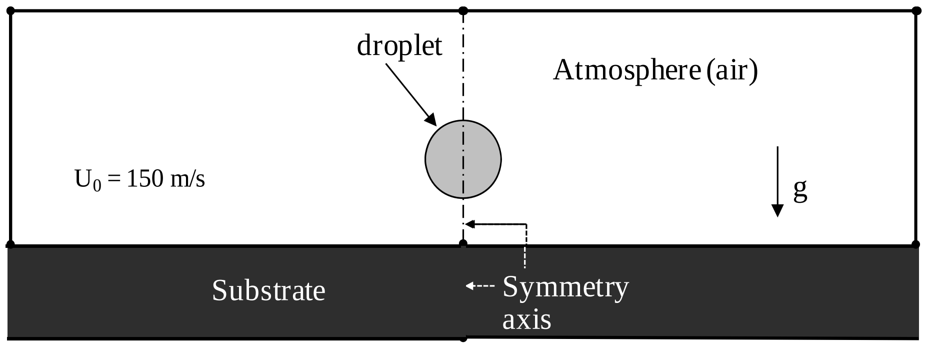


Physical phenomena

- Flattening
- Dynamic wetting
- Substrate melting
- Splashing
- Solidification



1. Droplet impact and flattening on a substrate



Axis-symmetric model

Governing equations

Free surface modelling: The volume of fraction function *F* is advected using the continuum mixture velocity field

$$\frac{\partial F}{\partial t} + \nabla \cdot \vec{u}F = 0$$

$0 < F < 1$ represents air- molten droplet interface
$F = 0$ indicates that the cell contains only air
$F = 1$ corresponds to a cell full of droplet material

A cell of droplet material may consists both liquid and solid phase (mushy state). Continuum definitions are:

$$g_l + g_s = 1, \quad f_l + f_s = 1, \quad f_l = \frac{g_l \rho_l}{\rho_d}, \quad \rho_d = g_l \rho_l + (1 - g_l)\rho_s$$

$$\rho = F\rho_d + (1 - F)\rho_{air} \quad \text{with} \quad \rho_d = g_l \rho_l + (1 - g_l)\rho_s$$

$$k_{eff} = F\, k_d + (1 - F)\; k_{air} \quad \text{with} \quad k_d = g_l k_l + (1 - g_l) k_s$$

$$c_{eff} = F\, c_d + (1 - F)\; c_{air} \qquad \mu = F\, \mu_d + (1 - F)\; \mu_{air}$$

Fluid flow, heat transport and solidification modelling:
Newtonian, incompressible and laminar flow

Continuity:

$$\frac{\partial}{\partial t}(\rho)+\nabla\cdot(\rho\vec{u})=0$$

Momentum conservation:

$$\frac{\partial}{\partial t}(\rho\vec{u})+\nabla\cdot(\rho\vec{u}\,\vec{u})=-\nabla p+\nabla\cdot\left[\mu(\nabla\vec{u}+\nabla\vec{u}^{T})\right]+\rho\vec{g}+F_{vol}-S\vec{u}$$

$$S\vec{u}=\begin{cases}\left[C\dfrac{(1-g_l)^2}{g_l^3}\right]\vec{u} & F=1\\ 0 & F<1\end{cases}$$

Sink term to account for damping of flow during solidification

F_{vol} = continuum surface tension force calculated by a standard method of Brackbill et al.

Energy conservation:

$$\frac{\partial}{\partial t}(\rho c_{eff}T)+\nabla\cdot(\rho\vec{u}\,c_{eff}T)=\nabla\cdot(k_{eff}\nabla T)+S_h$$

$$S_h=\begin{cases}-L\left[\dfrac{\partial}{\partial t}(\rho f_l)+\nabla.(\rho\vec{u}\,f_l)\right] & F=1\\ 0 & F<1\end{cases}$$

$$\begin{aligned} f_l &= 1 \quad if\ \ T\ge T_{liquidus}\\ &= 0 \quad if\ \ T\le T_{solidus}\\ &= \frac{T-T_{solidus}}{T_{liquidus}-T_{solidus}} \quad if\ \ T_{solidus}<T<T_{liquidus}\end{aligned}$$

Coupling relation of solidification with fluid flow and VOF

In the substrate only conduction heat transfer

$$\frac{\partial}{\partial t}(\rho_w c_w T)=\nabla\cdot(k_w\nabla T)$$

A value of $1.8\times10^{-6}\ m^2\,K\,W^{-1}$ for the thermal contact resistance is applied = stainless steel substrate roughness of 0.06 µm

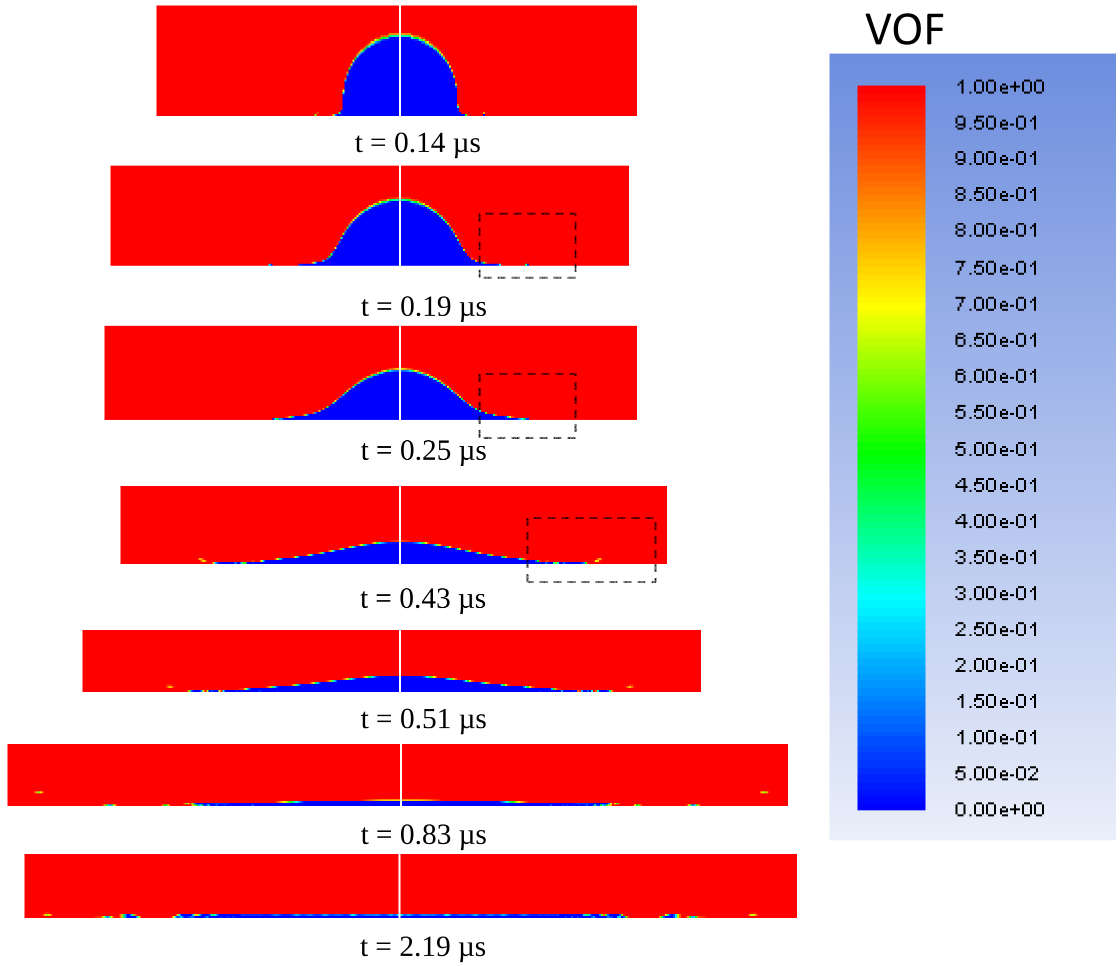
Initial conditions at t = 0

droplet temperature (void and shell) T_d = 2970 K

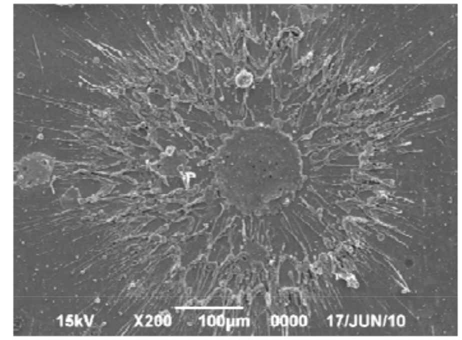
F = 1 in the droplet shell, F = 0 in the droplet void

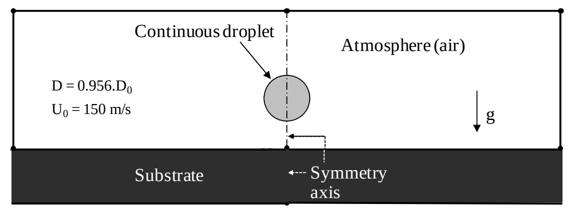
droplet velocity = 150 m/s; u = v = F = 0, T = 300K everywhere else in the domain

Droplet impact and flattening

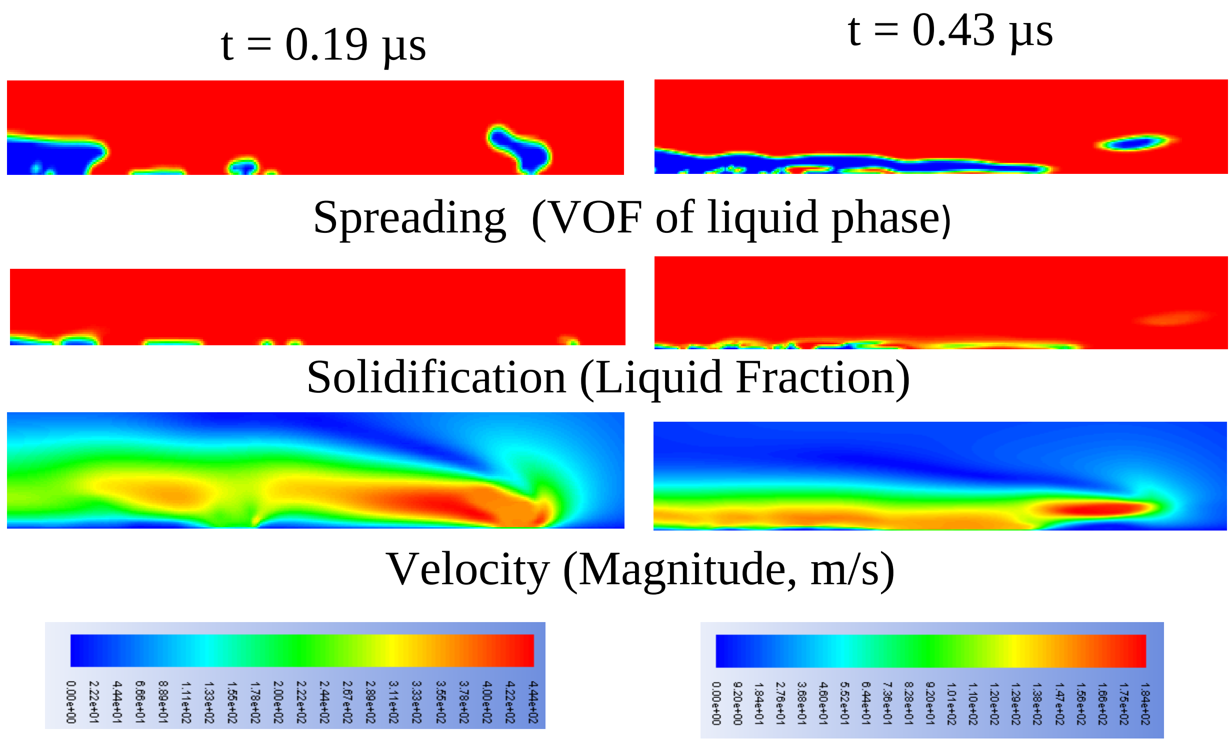


Spreading pattern of continuous droplet during the impact process (shown by contour of VOF for liquid phase)





Final solidified splat



- Initial droplet spreading occurs with very high velocity (450 m/s) which creates instability at the advancing edge
- A thin discontinuous solidified layer forms at the substrate
- Subsequent flattening of droplet occurs over this layer
- Droplet material during further spreading topples over this layer and creates fattening splashing

➢Deposition of multiple droplets

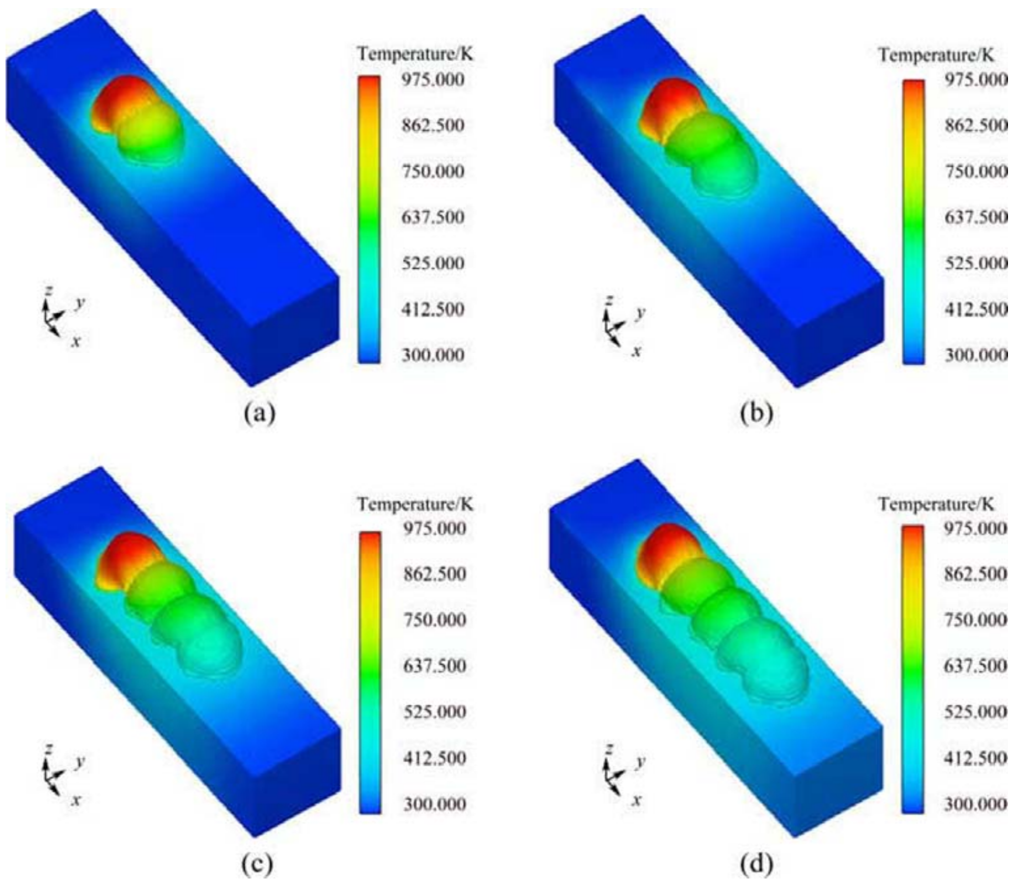


Fig. 5 Computed images of droplets after impact at 1 ms: (a) The second droplet; (b) The third droplet; (c) The fourth droplet; (d) The firth droplet

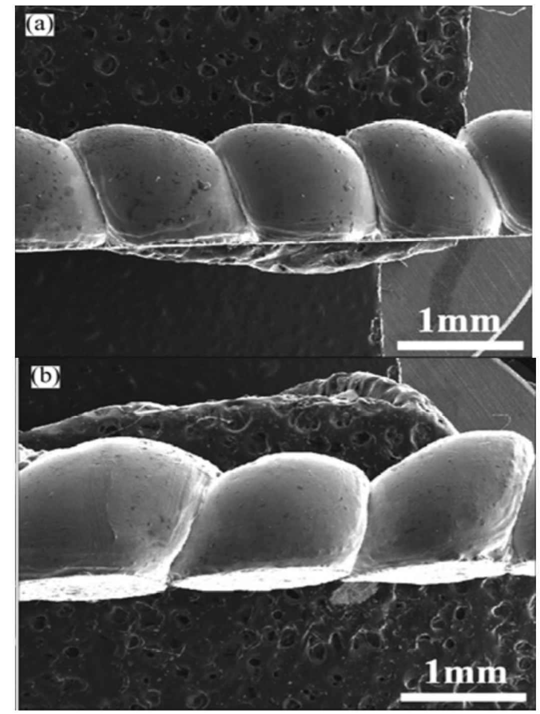


Fig. 6 SEM images of 1.5 mm diameter 7075 Al alloy droplets after solidification at different deposition stages: (a) Stable stage; (b) Initial stage with velocity of 0.8 m/s at initial temperature of 975 K

2. Remelting and bonding of deposited aluminum alloy droplets in metal droplet deposition

Analysis of remelting temperature condition

- Fig.1 shows the schematic diagram of fusion principle of two droplets. T_{inter} is interfacial temperature of two bonding droplets, T_{drop} is initial temperature of new-incoming droplet, and T_{surf} is surface temperature of previously-deposited droplets.
- When a new-incoming droplet (n+1) impacting on the surface of previously-deposited droplet (n) to fuse together, T_{inter} decides the remelting and bonding of droplets.
- If T_{inter} is much lower than the melting points of droplets, the droplets may fail to fuse together.
- If T_{inter} is too high than the melting points of droplets, the new- incoming droplets may flow away from the deposited point before solidification under the surface tension.

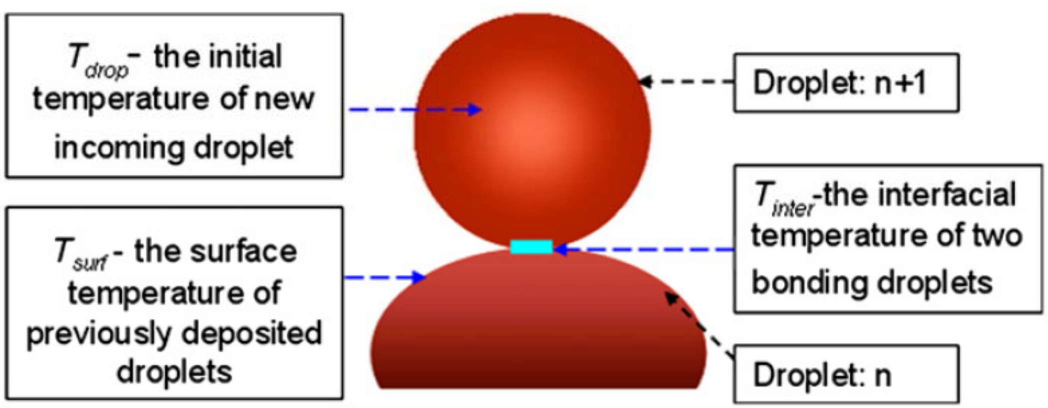


Fig.1 Schematic diagram of fusion principle of two droplets.

- Based on above analysis, the deposited droplets will have four kinds remelting and bonding states with the increase of temperatures: no remelting, partial remelting, ideal remelting and excessive remelting. Fig. 2 shows these four states under different temperature conditions.
- So, it is necessary to determine an appropriate remelting temperature condition in which deposited metal droplets could obtain ideal remelting to fuse with the incoming droplets and form metal component.
- The new incoming single droplet and the previously deposited droplet can be assumed as semi-infinite bodies during an infinitesimal time. The calculation model of interfacial temperature (T_{inter}) by the following equation (note that interfacial thermal resistance of droplets was neglected).

$$T_{inter} = \frac{T_{surf}(\sqrt{c \times \lambda})_{surf} + T_{drop}(\sqrt{c \times \lambda})_{drop}}{(\sqrt{c \times \lambda})_{surf} + (\sqrt{c \times \lambda})_{drop}}$$

where c and λ are the specific heat and thermal conductivity of droplet material

$(\sqrt{c \times \lambda})_{surf}$ is relate to the previously deposited droplet,

$(\sqrt{c \times \lambda})_{drop}$ is relate to the new incoming droplet.

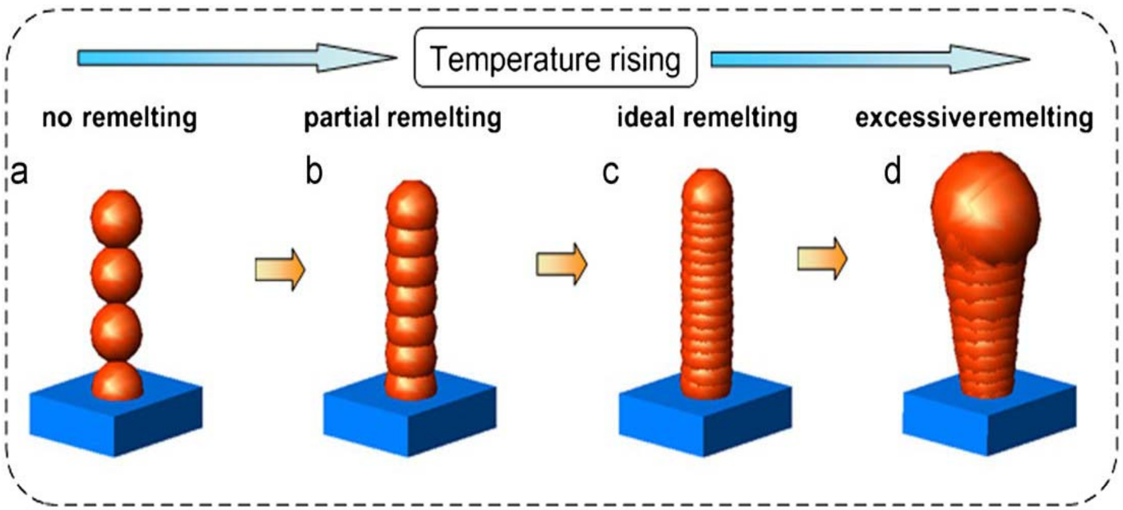


Fig. 2. Remelting and bonding states under different temperature conditions.