TA 202A

Lecture 10

3D Printing

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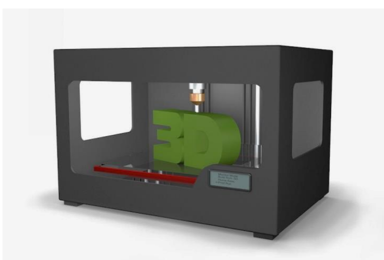
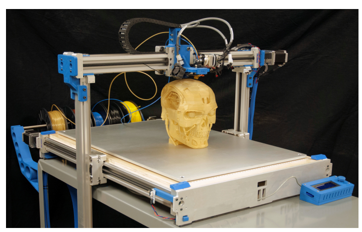
Printing Processes





Development of 3D Printing

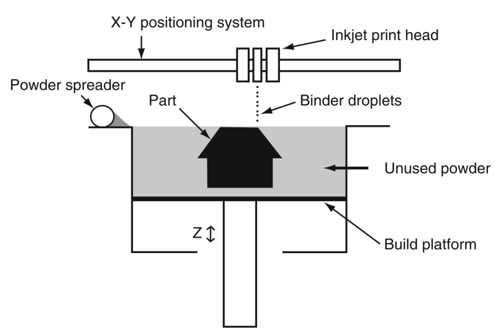
- Printing as a three-dimensional building method.
- Both direct part printing and binder printing technologies are introduced. Direct printing refers to processes where all of the part material is dispensed from a print head, while binder printing refers to a broad class of processes where binder or other additive is printed onto a powder bed which forms the bulk of the part.
- First demonstrated in the 1980s with patents related to the development of Ballistic Particle Manufacturing, which involved simple deposition of “particles” of material onto an article.

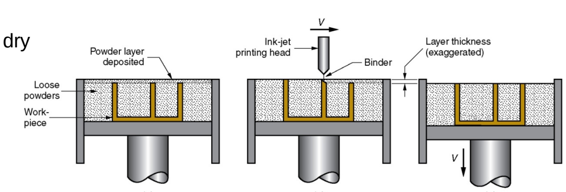
Binder printing methods

- Developed in the early 1990s primarily at MIT.
- They developed the 3D Printing (3DP) process in which a binder is printed onto a powder bed to form part cross sections.
- A recoating system similar to SLS machines then deposits another layer of powder, enabling the machine to print binder to define the next cross section.

3D Printing (3DP)

1. A layer of powder (plaster, ceramic) is spread across the build area
2. Part is built using an ink-jet printer to eject adhesive bonding material onto successive layers of powders
3. Binder is deposited in areas corresponding to the cross sections of part, as determined by slicing the CAD geometric model into layers
4. The binder holds the powders together to form the solid part, while the unbonded powders remain loose to be removed later
5. The platform is lowered and the next layer of dry powder is spread on top of the previous layer
6. Upon extraction from the machine, the dry powder is brushed off and recycled





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3D printing

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

Advantages

- ✓ Low cost
- ✓ High speed using many nozzles
- ✓ Scalability
- ✓ Ease of building parts in multiple materials
- ✓ The capability of printing colors
- ✓ Does not require high energy
- ✓ Does not involve lasers or any toxic materials
- ✓ Simple to operate

Disadvantages

- ✓ Limited functional parts (compared to SLS)
- ✓ Limited materials
- ✓ For direct printing, only waxes and photopolymers are commercially available. For binder printing, some polymer-ceramic composites and metals are available
- ✓ Poor surface finish

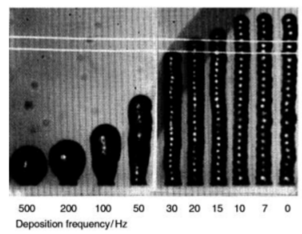
Research Achievements in Printing

- Till now available printing machines use mostly waxy polymers and acrylic photopolymers exclusively.

Polymers

As would be expected, if the drops are deposited rapidly (> 50 Hz in this case), the substrate on which they impinge is still at an elevated temperature, reducing the solidification contact angle and resulting in ball-like depositions instead of columns

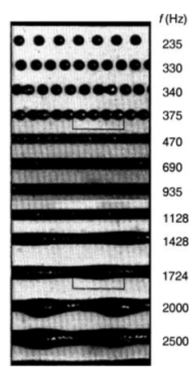
Columnar formation



Polymers

Smooth solid lines will be formed only in a small range of droplet frequencies, dependent upon the sweep speed, droplet size, and solidification contact angle

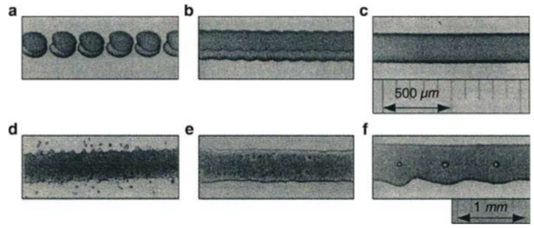
Line formation as functions of droplet impingement frequency



Polymers

Molten Mobilwax paraffin wax deposition.

For low droplet speeds, low sweep speeds created discontinuous deposition and high sweep speeds created continuous lines (Fig. a–c). High droplet impact speed led to splashing at high sweep speeds and line bulges at low sweep speeds (Fig. d–f).

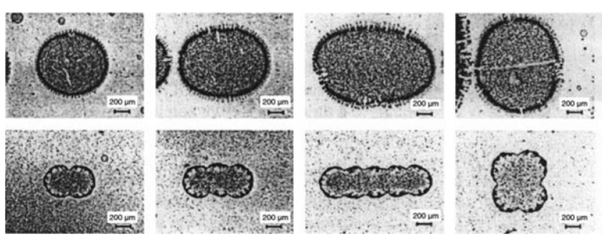


Results of varying sweep and impact speeds

It is clear that process variables, such as print head speed, droplet velocity, and droplet frequency affect the quality of the deposit. These process variables vary depending upon the characteristics of the fluid being printed

Ceramics

It was found that on substrates that permitted substantial spreading of the deposited materials, neighboring drops would merge to form single, larger shapes, whereas on other substrates the individual dots would remain independent (see Fig.).

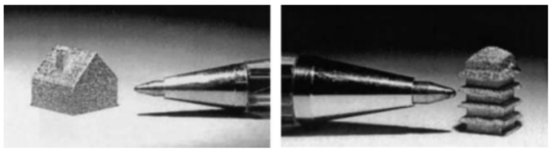


Suspensions of alumina

- Particles are printed via a wax carrier. Suspensions of up to 40% solids loading have been successfully deposited.
- Higher concentrations of the suspended powder have resulted in prohibitively high viscosities.

Metals

- Much of the printing work related to metals has focused upon the use of printing for electronics applications – solder
- One major challenge for depositing metals: the melting point of the material is often high enough to significantly damage components of the printing system.
- More recently, several research groups have demonstrated aluminum deposition



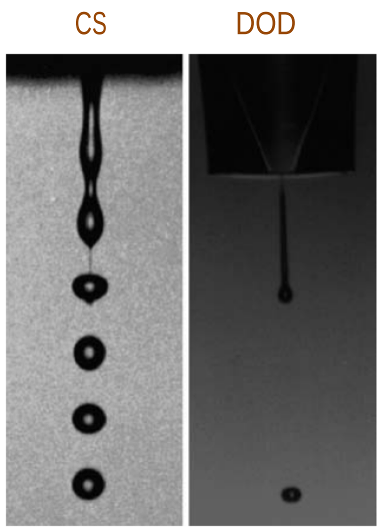
Examples of parts fabricated with metal printing

Droplet Formation Technologies

Modes of expulsion:

- Continuous stream (CS) also called continuous inkjet (CIJ)
- 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.



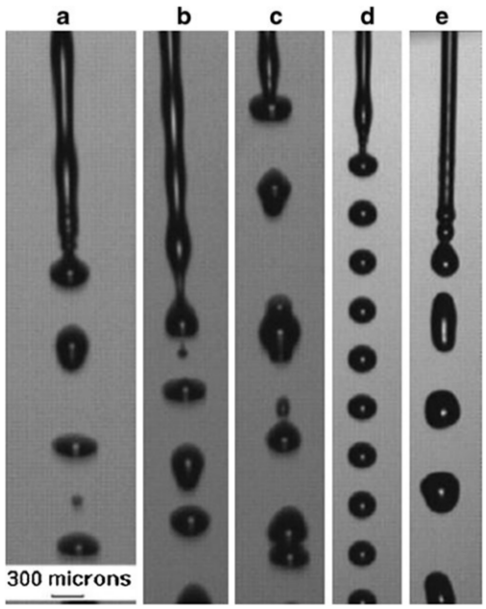


Fig. 10 Captured images of water microdroplet generation using orifice diameter of 150 µm at a gas pressure of 8 kPa—**a** f=0, **b** 1,000, **c** 2,000, **d** 2,842, and **e** 3,500 Hz [109]

Water droplet generation captured by a high-speed CCD camera

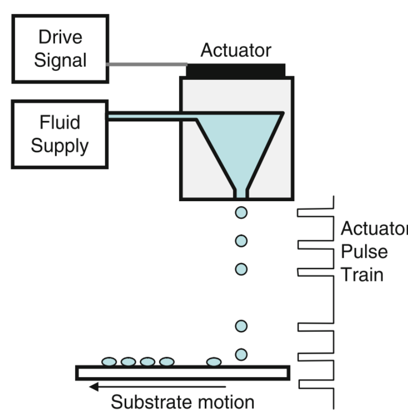
Satellite droplets and the merged droplets cause degradation of the droplet diameter accuracy

When the imposed disturbance frequency is selected properly, the droplets are round with uniform sized and spaced with the same distance

- **Advantage** of CS deposition is the high throughput rate
- **Applications:** such as food and pharmaceutical labeling
- **Droplets Size** are about 150 µm in diameter at a rate of 80–100 kHz.

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

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

Strengths and weaknesses of inkjet Printing

Wide range of materials, ability of multimaterial printing, ability of writing in 3D space, ideal for deposition of biological inks noncontact easy material handling, sensitive process, fair repeatability, and support structure is needed for 3D microparts

Materials

Liquid with viscosity of 2–10 mPas (can contain small particles (CIJ)) and liquid with viscosity of 10–100 mPas (can contain small particles (DOD))

Applications

The ability of inkjet printing technology to produce microparts from various materials , including optical polymers, solders, thermoplastics, light-emitting polymers, organic transistor, biologically active fluids, and precursors for chemical synthesis has been demonstrated.

Theory of Printing Process

- Flow in nozzle:

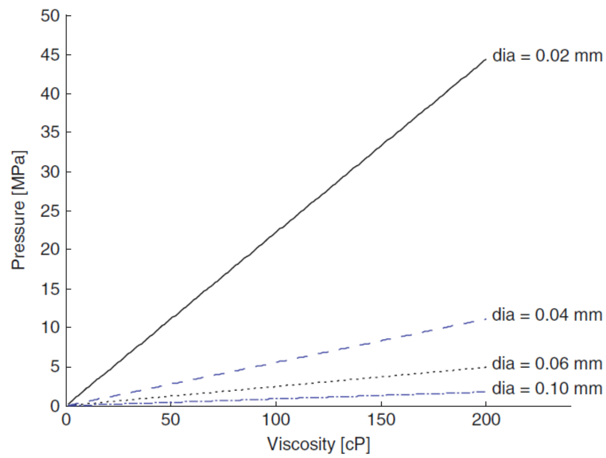
  The flow is fully described by the Navier–Stokes and continuity equations with simplification of steady, incompressible, laminar flow through a straight circular tube of constant cross section.

- 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 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

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

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 and varying viscosities are shown in the following 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

Jettability and droplet formation

- 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.

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

- 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

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

Inverse of printing indicator = Ohnsorge number (*Oh*)

1> Oh > 0.1

Check, diameter is used in the criterion definition, not radius.

For *Oh* > 1, fluid viscous dissipation results in orifice clogging and impedes ejection of drops, and for *Oh* < 0.1 multiple drops is produced instead of a single well-defined drop.

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

Check, diameter is used in the criterion definition, not radius.

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.

We will see in the next section how materials can be modified to make printing feasible.

Material Modification Methods

- The maximum printable viscosity threshold is reported by a number of sources to be in the range of 20–40 cP at the printing temperature
- While other factors such as liquid density or surface tension and print head or nozzle design may affect the results, this limitation on viscosity quickly becomes the most problematic aspect for droplet formation of functional polymers and most other materials desirable for use in three-dimensional printing settings.
- The current method of addressing this issue is to lower the viscosity of the material to be printed. The most common practices of using heat, solvents, or lower viscosity components

  ✓ Hot Melt Deposition
  ✓ Solution- and Dispersion-Based Deposition

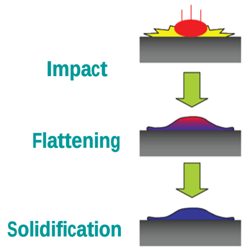
Hot Melt Deposition

- Heat the material until its viscosity drops to an acceptable point.
- Much of the deposition of metals and ceramics as well, is based upon this hot melt practice. e.g., melted wax as the carrier for their ceramic particles.

Solution- and Dispersion-Based Deposition

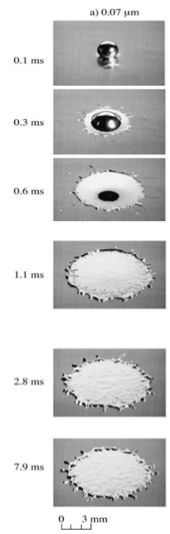
- As hot-melt deposition has very specific requirements for the material properties of what is printed, many current applications have turned to solution- or dispersion-based deposition.
- This allows the delivery of solids or high-molecular weight polymers in a carrier liquid of viscosity low enough to be successfully printed.
- In deposition of ceramics, too, the use of a low-viscosity carrier is a popular approach.

Modelling Droplet based AM Processes

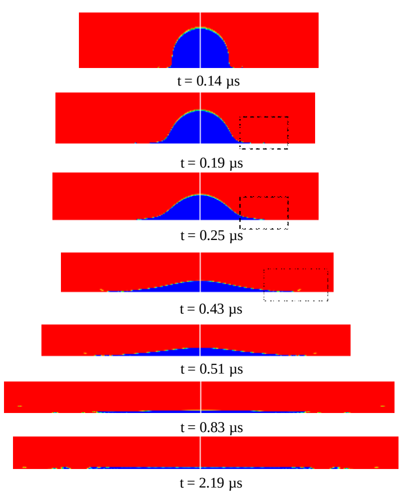


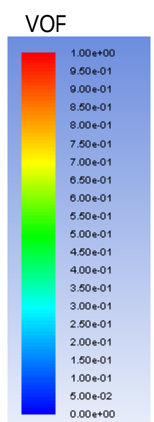
Physical phenomena

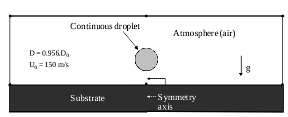
- Flattening
- Dynamic wetting
- Substrate melting
- Splashing
- Rapid solidification



Splashing



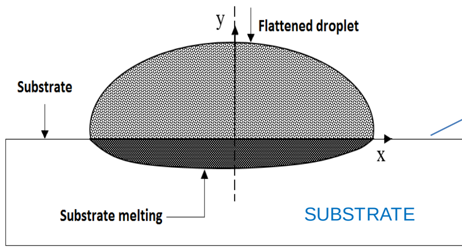




Spreading pattern of continuous droplet during the impact process (shown by contour of VOF for liquid phase)

Final solidified splat

Substrate melting during droplet impact



Droplet substrate contact line

No mixing of melted substrate and molten droplet, i.e., droplet do not penetrate the melted substrate

Schematic of substrate melting phenomenon

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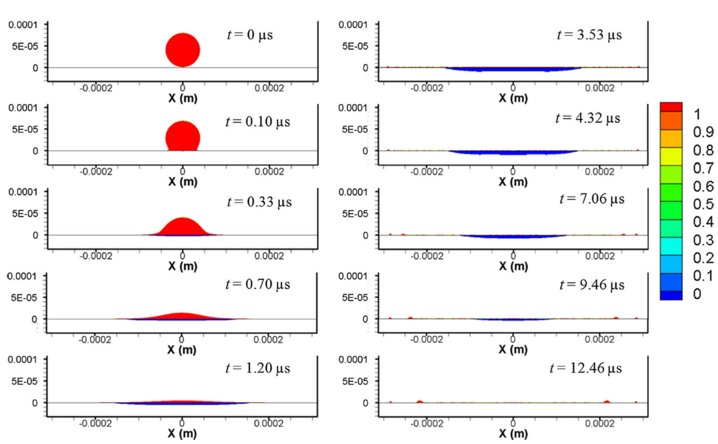
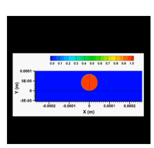
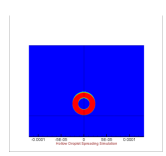
Droplet shape and substrate melting front vs time







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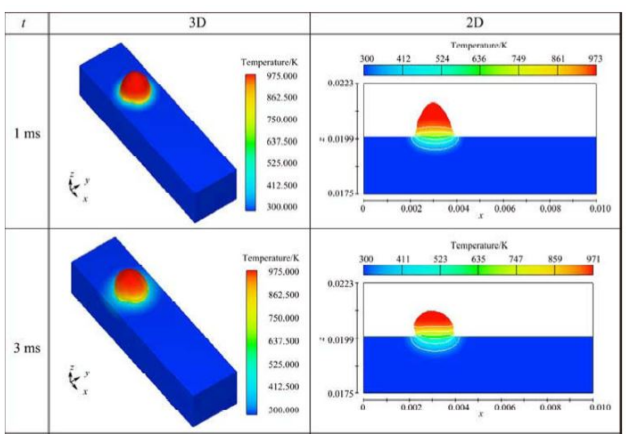
Deposition 7075 Al alloy droplets in 3D printing technology

7075 Al alloy droplets in 3D printing

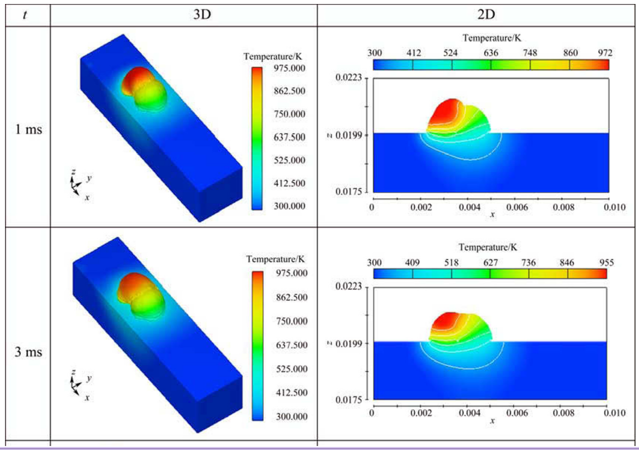
Deposition of single droplet

Impact conditions: 1.5 mm diameter droplet, velocity of 0.8 m/s, 975 K impact onto a horizontally moving substrate (10 mm×2.6 mm×0.95 mm) with a velocity of 0.055 mm/s.



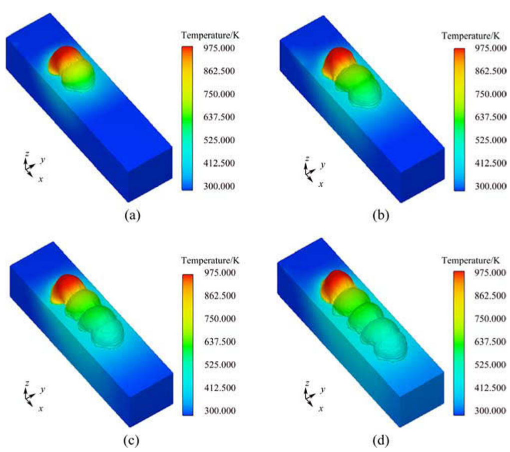
Temperature distribution

Deposition of multiple droplets

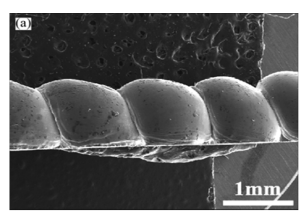


Temperature distribution

- After impact, the second droplet landed on the edge of the solidified droplet and then spread.
- The heat transferred from the high temperature droplet made part of the solidified droplet in the contact area to re-melt, which is beneficial to metallurgical bonding between droplets.



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



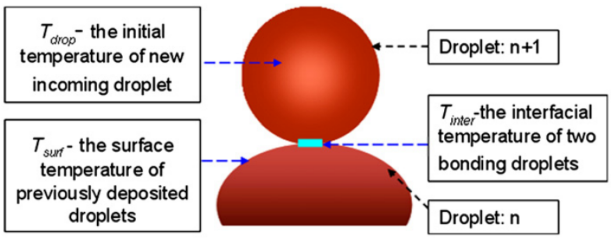
SEM images

The predicated droplets shapes, especially the last four droplets, well agree with SEM images

Remelting and bonding of deposited droplets in metal droplet deposition

Analysis of remelting temperature condition

- 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.



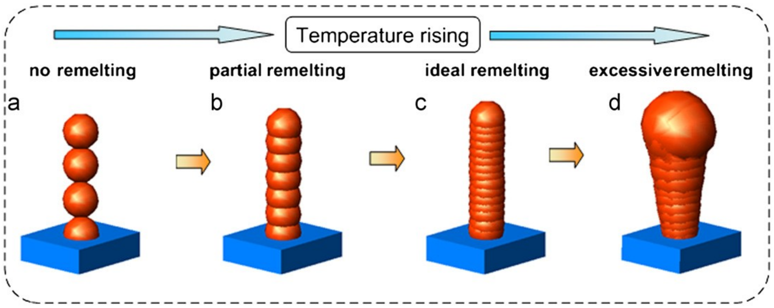
Fusion principle of two droplets

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

c = specific heat of droplet material
λ = thermal conductivity

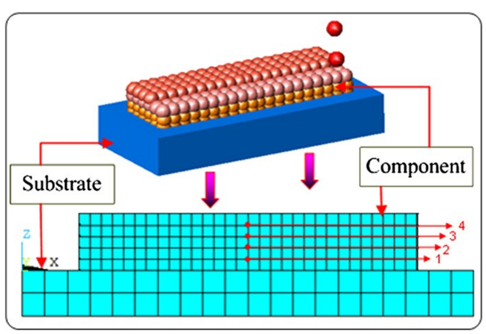
$(\sqrt{c \times \lambda})_{\text{surf}}$ is relate to the previously deposited droplet,

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

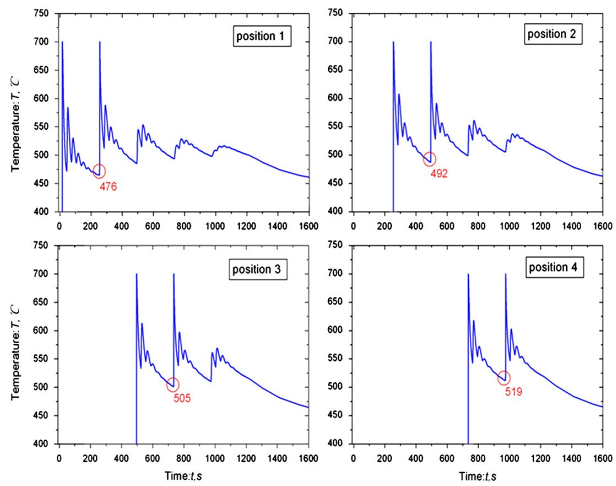


Remelting and bonding states under different temperature conditions

3D finite element simulation



3D finite element meshed model of droplet deposition manufacture



Thermal cycle curves of position 1, 2, 3 and 4 at different deposition times

- The results show that every thermal cycle curve includes several temperature peaks and valleys, and experiences a concussion cycle with temperature increasing, decreasing and stabilization.
- Furthermore, the thermal cycle curves of every position have two temperature peaks reaching 700 ºC. Showing remelting phenomenon.

Recap of This Lecture

- 3D printing
- Theory of printing
- Modelling of droplet based printing

Next Lecture

CNC Machining