Additive Manufacturing – Module 11

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**History**

1867 Lord Kelvin: Syphon recorder

Continuous inkjet

1951: Chart recorder -- Siemens

Continuous inkjet

1970s: Desktop printer

DOD inkjet

1990s: 3D printer

DOD inkjet
Inkjet Deposition

Commercial Engagement

Credit: Microfluidics - Jens Ducrée
Inkjet Deposition

Applications

b) final device, top view

OLED Active Matrix

Scan Line

Data Line

TFT1

TFT2

Vdd

Cst

OLED

Vss

Light emission

**HP Moore’s Law**

**HP Moore's law**: inkjet printhead performance as printhead drops per second (the number of nozzles times the maximum drop-on-demand frequency) doubles every 18 months for the past 20 years.

Inkjet Deposition

Types of inkjet

The two types of ink-jet technology:

- Types of inkjet
- Inkjet Deposition
- Complexity
- Overview
- Printhead
- Falling
- Deposition
- Drying
Inkjet Deposition

Complexities – Jetting

Inkjet Technology

Continuous

Binary

Multiple

Hertz

μDot

Drop-on-demand

Thermal

Piezo

El.static

Acoustic

Top shooter

Side shooter

Squeeze

Bend

Push

Shear

Inkjet Deposition

Complexities – Drop Formation

Inkjet Deposition

✈ Complexities – Falling

Falling droplets

Streamlines in the vicinity of a bubble. The shape of the bubble is plotted in red.

Streamlines in the vicinity of a drop. The shape of the drop is plotted in red.

Evolution of (a) bubble and (b) drop (gravity reversed) shapes with time.

Inkjet Deposition

Complexities – Droplet deposition

- Deposition of droplets
  - Impingement dynamics of droplets
- Droplets Hardening
  - Single droplet
  - Multiple Droplets
  - Solidification
    - Evaporation of suspension
    - Polymerization
Inkjet Deposition

Complexities

Inkjet Deposition Complexities

Inkjet Deposition

Droplet formation

(a) Rayleigh breakup.
(b) First wind-induced regime.
(c) Second wind-induced regime.
(d) Atomization regime.

Inkjet Deposition

Droplet formation

Inkjet Deposition

❖ Droplet formation

At $t = 91\mu s$

Liquid ink

Nozzle exit

Nozzle entrance

Only pulsed input Pulsed input plus constant flow

Nozzle exit velocity with constant flow
Nozzle exit velocity without constant flow
Nozzle entrance velocity with constant flow

Time (sec)
Emerging from an orifice liquid jet breaks-up into droplets. Because of the surface tension:

- **Droplets have random size**
- **Droplets have random spacing**

\[
\begin{align*}
\alpha_0 &\quad \text{the initial disturbance} \\
\rho &\quad \text{the density of the fluid} \\
\sigma &\quad \text{the surface tension of the fluid} \\
L &\quad \text{break-up length} \\
f_s &\quad \text{the frequency of spontaneous drop formation} \\
\lambda &\quad \text{wave length}
\end{align*}
\]

\[
L = K \ln(d/2\alpha_0) V (\rho d^3/\sigma)^{0.5} \\
\lambda = 4.51d; f_s = V/4.51d
\]
Inkjet Deposition

**Continuous inkjet**

- Can the drop size be controlled?
- Can the spatial spacing of the drops be controlled?
- Can the break-up length be controlled?
- What would be the drop selection method?

Credit: Rafi Bronstein @ HP
**Inkjet Deposition**

긴재트 Deposition

- **Electrostatic Inkjet**

Thermal inkjet

- Uses tiny resistor to rapidly heat a thin layer of liquid ink
- Vaporize a tiny fraction of the ink to form an expanding bubble that ejects a droplet (and any trapped air)
- Nothing moves but the ink – very high frequency attainable
- Use fabrication technology similar to semiconductor manufacturing; nozzles can be integrated at very high densities – provides high throughput and spare nozzles for reliability

Credit: Rafi Bronstein @ HP
Thermal inkjet

- Stack of extremely thin films form the floor of each firing chamber, some are electrically conductive, others are insulators.
- Thin film resistor is located in the center of each firing chamber floor and gets extremely hot when electricity passes through.
- Each resistor is 60um or smaller on each side, but power density on its surface is 1.28 billion watts per square meter – more than on the surface of the Sun!
Inkjet Deposition

Thermal inkjet

A film of ink about 100nm thick is heated to ~340°C
A vapor bubble forms to expel the ink, but it doesn’t “boil”
Inkjet Deposition

Thermal inkjet

- Top-shooter (HP)
- Side-shooter (Canon)

Credit: Rafi Bronstein @ HP
Piezoelectric Inkjet

The elementary cell of PZT: (a) above the Curie temperature; (b) below the Curie temperature. At a high temperature, the electric charges coincide in a cubic structure and there is no piezoelectricity. Below the Curie temperature the electric charges do not coincide anymore. This results in piezoelectric effect.

$D$ is the electric displacement field (or the charge density), $S$ is strain, $E$ is the applied electrical field, $T$ is stress, $d$ and $d^T$ are matrices for the piezoelectric effects.

Caused by lack of symmetry, and therefore inherently anisotropic.

s is compliance matrix, characterize mechanical behavior;
\( \varepsilon \) is permittivity matrix, characterize electrical behavior;
\( d \) is the piezoelectric matrix, characterize the coupling effects.
\[ \Delta y = d_{33}V, \quad d_{33} \approx 0.4 \text{nm/V} \] for most piezo materials;
For 25 pl droplet with a channel of 10 mm length and a width of 250 mm, the displacement of the piezo element should be 20 nm. This requires a driving voltage of 80 V.

Inkjet Deposition

Piezoelectric Inkjet
**Inkjet Deposition**

**Piezoelectric Inkjet**

- **Actuation efficiency**
  - Piezo (electrical to mechanical): \(~15\% \text{ to } 25\%~
  - Piezo deformation to channel deformation: \(~13\%~
  - Channel deformation to acoustic pressure wave: \(~20\%~
  - Acoustic pressure to droplet (for low viscosity): \(~10\%~
  - Total efficiency: \(~0.07\%~
  - For a 32pL droplet with a ejection velocity of 7m/s, the surface energy and kinetic energy of the droplet is \(~0.85 \text{ nJ}~. \text{ As a result, the required input of electric energy is } 1200 \text{ nJ.}~
  - For an operation frequency of 100 kHz (10\text{us}), the required power is then 0.12W. For a voltage of 40V, current 3mA.

Inkjet Deposition

Piezoelectric Inkjet

Inkjet Deposition

Droplet falling in the air

\[ \vec{F}_g - \vec{F}_v - \vec{F}_d = 0 \]

\[ \vec{F}_d = -b \vec{v} \]  \hspace{1cm} \text{Low speed}

\[ \vec{F}_d = -\frac{1}{2} \rho \vec{v}^2 AC_d \]  \hspace{1cm} \text{High speed}
### Inkjet Deposition

#### Droplet falling in the air

<table>
<thead>
<tr>
<th>Drop size</th>
<th>Characteristic shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14 mm</td>
<td><img src="image1.png" alt="Spherical shape" /></td>
</tr>
<tr>
<td>0.50 mm</td>
<td><img src="image2.png" alt="Oblate spheroid" /></td>
</tr>
<tr>
<td>1.4 mm</td>
<td><img src="image3.png" alt="Base flattening" /></td>
</tr>
<tr>
<td>2 mm</td>
<td><img src="image4.png" alt="Concavity begins" /></td>
</tr>
<tr>
<td>5 mm</td>
<td><img src="image5.png" alt="Drop breakup" /></td>
</tr>
</tbody>
</table>

- Surface-tension forces are able to maintain the spherical shape against external forces.
- A very slight shortening of the vertical axis and the drop is an "oblate spheroid". The vertical axis is about 98% of the horizontal axis.
- Flattening of bases begins.
- Concavity of the flattened base begins.
- At 5 mm the force of the air through which the drop is falling causes the drop to break up.
Inkjet Deposition

*Droplet deposition*

Pictures Courtesy Dr. Alberto Aliseda at University of Washington

- spreading
- rebounding
- splashing
Inkjet Deposition

★ Droplet deposition

★ Wetting on a solid surface

Reason for Surface tension

Total wetting  Partial wetting  Partial non-wetting  Non-wetting
Inkjet Deposition

Droplet deposition – different wetting

- Hydrophilic
- Hydrophobic
- Partial Wetting
- Ultra-hydrophobic
Inkjet Deposition

• Droplet deposition

• Droplet spreading dynamics

Schematic representation of the spread factor with time
Inkjet Deposition

Droplet deposition

Physics of droplet spreading dynamics

Kinetic Energy

\[ F_p = \rho U^2 D^2 \]

Inertial Force
Favor uniform film

Viscous Dissipation

\[ F_{\text{vis}} = \eta UD \]

Surface Tension
Favor sphere cap

\[ F_\sigma = \sigma D \]

Favor uniform film > Viscous force > Favor sphere cap
**Inkjet Deposition**

- **Droplet deposition**

- **Regimes of droplet spreading dynamics**

![Diagram showing regimes of droplet spreading dynamics](image)

- **Impact Driven**
  - Almost Inviscid, resisted by inertia
  - \( We = Oh^2 \)  
  - IV

- **Capillarity Driven**
  - Highly viscous, resisted by viscosity

- **Impacts Regime**
  - I
  - II
  - III

- **Inkjet**
- **Overview**
- **Complexity**
- **Printhead**
- **Falling**
- **Deposition**
- **Drying**
Inkjet Deposition

🌟 Droplet deposition

🔹 Splash
 🔹 Corona splash
 🔹 Prompt splash

Caused by surrounding gas
Caused by rough surface
Inkjet Deposition

Droplet deposition

Contact angle hysteresis

Advancing contact angle

Receding contact angle
Inkjet Deposition

♦ Droplet deposition

♦ Simulations of droplet impingement dynamics

Most previous research: single droplet impact due to prohibitive computational complexity and cost

Make it more relevant to manufacturing, we need to study multiple droplet interaction
Inkjet Deposition

Droplet deposition

Simulations of droplet impingement dynamics – Lattice Boltzmann method

Re: 238.26
We: 12.88

Fluid: Water
Droplet size: 48.8um
Density: 1e3 kg/m³
Impact velocity: 4.36m/s
Viscosity: 8.93e−4Pa*s
Surface tension: 0.072N/m

COMSOL on a cluster
CPU: 16-core
Memory: Over 100GB
Time: Over a month

Our LBM on a Laptop
CPU: single thread
Memory: ~ 1GB
Time: Less than 20 hrs
Inkjet Deposition

Droplet deposition

Simulations of droplet impingement dynamics – Lattice Boltzmann method – validation

Contact Angle 107°

Time (µs)

D* or H*
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

LBM D*
LBM H*
Experiment D*
Experiment H*
COMSOL D*
COMSOL H*
**Inkjet Deposition**

**Droplet deposition**

- **Multiple droplet interaction**

Droplet spacing = 0.3*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity
Droplet deposition

Multiple droplet interaction

Droplet spacing = 0.6*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity
Inkjet Deposition

Droplet deposition

Multiple droplet interaction

Droplet spacing = 0.8*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity
Droplet spacing = 1.0*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity
Inkjet Deposition

Droplet deposition

Suspension droplet drying

(a)

Heat Flux

(b)

Critical Heat Flux

Minimum Heat Flux

T_{ONB} T_{max} T_{Leid} T_w

mass transfer

free water
wet core
solid particles
receding evaporation interface

heat transfer

mass transfer

wet core
dry crust
solid particles
receding evaporation interface
crust pores full of air-water vapor mixture
# Inkjet Deposition

## Droplet deposition

### Suspension droplet drying

<table>
<thead>
<tr>
<th>Zone</th>
<th>Regime</th>
<th>Superheat</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1    | Film evaporation     | Low       | - When $T_w < T_{ONB}$, the droplet spreads and evaporates slowly  
                        - Total contact of the droplet with the surface  
                        - Conduction is the dominant mechanism inside the droplet |
| 2    | Nucleate boiling     | Intermediate | - When $T_{ONB} \leq T_w \leq T_{max}$, vapor bubbles arise in the droplet  
                        - Increase in momentum transport around the droplet causes increase of heat transfer  
                        - Partial and intermittent contact of the droplets and solid surface |
| 3    | Transition boiling   | Intermediate | - When $T_{max} < T_w \leq T_{Leid}$, the frequency of contact of the droplet and solid surface decreases, causing a decrease in heat transfer  
                        - Formation of an unstable vapor film between droplet and solid surface |
| 4    | Film boiling         | High      | - When $T_w > T_{Leid}$, a thin and stable vapor film is present  
                        - No contact between the liquid and solid surface |
Inkjet Deposition

Droplet deposition

Suspension droplet drying – coffee ring effect

Cracks in the printed line – not conductive

Coffee ring effect: evaporation flow

Contact line pinned – form a ring

Contact line moving – no ring

8x faster
Inkjet Deposition

Droplet deposition

- Suspension droplet drying – skinning effect

Water on substrate

NovaCentrix ink on substrate

Possible solutions

- Nanoparticle skin
  - Form a skin on top of the surface, prevent further drying

- Porous substrate:
  - change evaporation flow

- Larger particle size and high viscosity:
  - reduce particle motion
Inkjet
Overview
Complexity
Printhead
Falling
Deposition
Drying

THANK YOU!