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Material Jetting 3D Printing Process by Thermal Ink Jet Head

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Abstract

A new type of 3D printing process is introduced. The printing mechanism is based on material jetting process by inkjet-printing head to eject and deposit a photopolymer ink as the 3D object building material. The existing material jetting 3D printer adopted multi nozzle piezo-electrical print head. The piezo ink jet head requires complicated head structure, ink supply and maintenance system. The printing area should be large because of wide area of printing head and it causes that the 3D printing machine should be large and expensive for a commercial purpose only. In this study, Thermal ink jet head is applied to the print head for 3D printing process. The thermal head has low cost and compact printing mechanism but it is hard to apply photo polymer ink of material jetting process for jetting fluid because the thermal ink jet head fires the ink droplet by boiling mechanism. The specific building material for jetting in thermal head is applied and a 3D printing process is investigated for stable ejection and deposition on the substrate for building 3D object. The droplet volume of print head is under 20 pico-litters and ejection frequency is 2 kHz and the thickness of single layer deposited for building object is more than 10 micro-meters. The 3D printing system is fabricated and the hollow cylindrical object with high aspect ratio is successfully built and printing process is verified.

Introduction

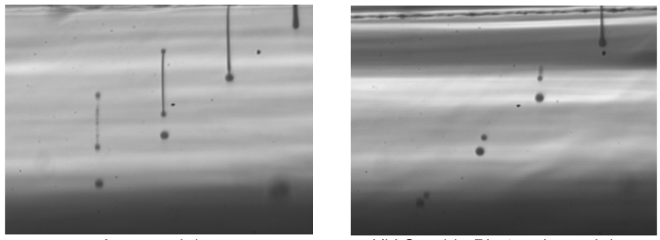
Material jetting process is based on inkjet printing by firing droplets of liquid photopolymer to build 3D Object. The photopolymer consists of oligomer, monomer and photo-initiator is ejected from print head and spread on the substrate and solidified by UV light. The photo-initiator is radicalized by UV ray and polymerizes oligomer and monomer. The monomer decreases the viscosity of photo-polymer and makes it possible to eject the droplet from print head. A piezo ink jet print head was used for jetting photopolymer because of high viscosity of liquid polymer. The piezo ink jet head is able to eject the ink droplet from the head by deformation of membrane in the print head and pushing the liquid into the nozzle.

In case of thermal ink jet print head, aqueous ink is heated and vaporized on the heater and bubble is grown and pushes ink through the nozzle into the paper. However it is impossible to boil the liquid polymer because of high boiling temperature of monomer. Also it is easy to deposit the solidified polymer on the heater and prevent the heat transfer from the heater to liquid.

Trueba and Buskirk [1] proposed a curable ink fluid composition for a thermal fluid ejection device where in the printing fluid comprises a curable liquid-phase monomer, a volatile driver fluid capable of being vaporized by a thermal fluid ejection print head. The driver fluid which has low boiling point enable the thermal ink jet head to eject the photopolymer. The ink formulation is considered for preventing material deposition on the heater during ink droplet firing. The material jetting 3D printing process is based on this type of ink and a layer by layer deposition process is suggested for building 3D object in this study.

Ink Droplet Ejection Performance

A commercialized HP45 ink jet print head is adopted for 3D printing head because it has spring bag type ink cartridge so as to replace aqueous ink with liquid photopolymer easily. A droplet volume of liquid photopolymer is 20 pl (Pico Litter) and droplet velocity is 5 m/s. The volume and velocity of ejected droplet are smaller than the ones of aqueous ink; 25 pl and 14m/s because the maximum bubble size is smaller than the aqueous ink due to the low heat capacity of photo polymer. The small bubble generates small drop volume and causes to the low drop velocity. Figure 1 show that drop ejection behaviors of aqueous ink and polymer ink are different from each other. The satellite and tail of photopolymer ink drop is smaller than the one of aqueous ink due to the low drop velocity. While Ink is boiling for jetting, high surface temperature can leads to a residue on heater and bubble generation is prevented from low heat conduction to ink. The adopted photopolymer ink has maintained initial drop volume of 20 pl throughout drop ejection test as shown in Figure 2. The residue is not observed on the heater after the photopolymer ink jetting test.



- Aqueous Ink- *-UV Curable Photopolymer Ink*

Figure 1 Droplet Ejection UV Curable and Aqueous Liquid

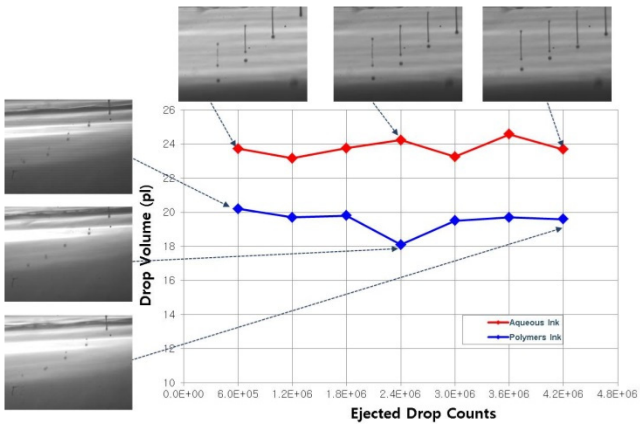


Figure 2 Drop Ejection performance of the Ink jet print Head

Analysis of Droplet Spreading On the Substrate

The droplet of liquid polymer ejected from print head can be analyzed by energy conservation. Kim and Chun[2] have proposed mathematical model for the recoiling of liquid droplet upon collision with solid surfaces as bellow.

$$\int_{t_1}^{t_2} (\delta T^* - \delta V^* + \delta W_f^*) dt^* = 0 \qquad (1)$$

where T* is kinetic energy and V* is potential energy; sum of surface energy and gravitational energy and W_f* is frictional work. The droplet behavior on the substrate was calculated and described as the height of droplet. It is important for the droplet to deposit on the substrate as semi-spherical shape not to splash and scatter. Mundo et al [3] suggested experimental formula whether deposition or splashing.

$$K = Oh \cdot Re^{1.25},\ Oh = \frac{\mu}{\sqrt{\rho D \sigma}} \quad (2)$$

where Oh and Re are the Ohnesorge number and the Reynolds number, respectively. A value of K exceeding 57.7 leads to incipient splashing, whereas K less than 57.7 leads to complete deposition of the liquid.

The viscosity of aqueous ink is between 2 cP(Centipoise) and 3 cP, droplet velocity is more than 14 m/s. The case I of calculation table shows that decision parameter of K value is 61.5 more than 57.7 and droplet can splash and scatter on the substrate. In case of the photopolymer ink of the thermal ink jet head, the drop velocity is decreased because low heat capacity of the photopolymer causes to minimize bubble size on the heater. Case III is based on the experimental result of photopolymer ink test: the droplet volume is 20 pl (Picoliters) and droplet velocity is 5 m/s. The viscosity of adopted ink in the study is about 3.5 cP and lower than conventional photopolymer ink of piezo ink jet head. The calculated Ohnesorge number is 0.11 and Reynolds number is 48.1. The calculated K value is 14.0 and smaller than 57.7 means to stable deposition. High viscosity increased drag force on the substrate and low drop velocity of ink decreased inertial force of droplet. These effects result in the stable deposition on the substrate and photopolymer ink is more favorable than aqueous ink in the thermal ink jet head. In case of low viscosity same as aqueous ink and a little higher drop velocity than photopolymer ink, stable deposition condition is accomplished as shown in Case II. Conventional piezo ink jet head has stable deposition condition because of high viscosity and low drop velocity as shown in Case IV, V.

The Result of Calculation for Drop Spreading on the Substrate

Head Type	Thermal			Piezo	
Case No.	I	II	III	IV	V
Viscosity (centipoise)	2	2	3.5	15	15
Drop Volume (picolitters)	25	20	20	30	80
Drop Velocity (m/s)	14	10	5	8	8
Surface Tension (dyne/cm)	28	28	28	30	30
K Value	61.5	38.2	13.9	19.3	24.7

In order to verify the calculation, numerical analysis was performed by ANSYS-CFX. Park [4] has analyzed ink drop spreading behavior ejected by piezoelectric head on the substrate. The liquid droplet ejected from thermal ink jet head spreads on the substrate at various contact angles as shown in Figure 3. The drop volume is 20 pl, the drop velocity is 10m/s and the viscosity is 3.5 cP. The droplet is spread and forms a thin layer on the hydrophilic surface with 20° of low contact angle and the layer thickness enough to build 3D Object cannot be achieved. In case of high contact angle more than 90 °, the droplet forms sphere shape on the hydrophobic surface and easily slips on the substrate and hard to form a layer. The optimum contact angle is near 70°. Due to the low viscosity of photopolymer ink in the thermal head, ink drop is evacuated at the center of spreading droplet after 10 μs and the excluded ink is merged again and forms a deformed semi spherical shape.

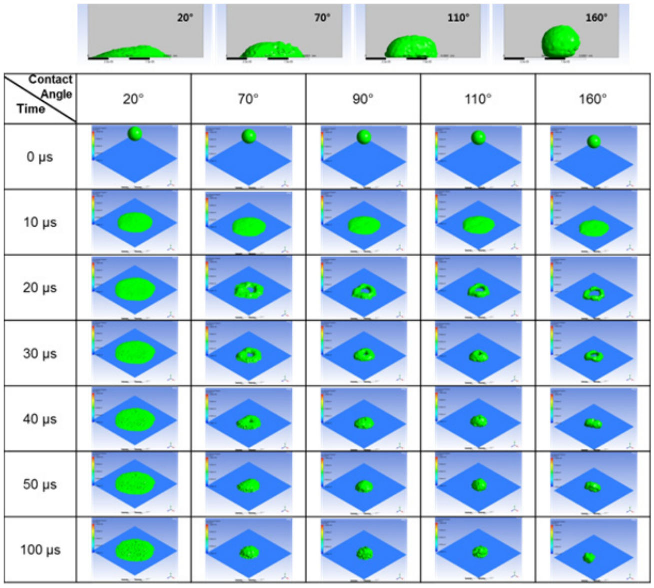


Figure 3 Spreading Behavior of Single Droplet

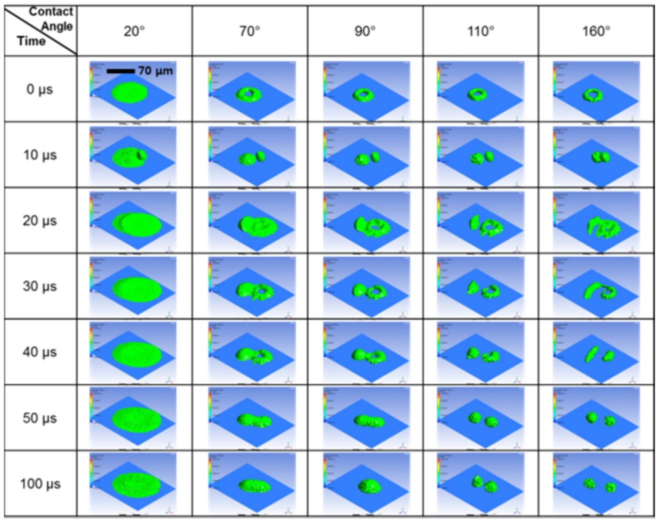


Figure 4 Spreading Behavior of consecutive Dual Droplets

A behavior of consecutive dual Ink drop spreading is analyzed at the various contact angles as shown in Figure 4. The second drop is placed at the distance of 42 μm (600dpi) near the first drop. The first and the second drops are not merged in case the contact angel is more than 110°. As the theoretical model predicted, splashing of ink drop on the substrate is not observed in the simulation result.

Temperature Control of Ink Jet Head and Printing Performance

Temperature control of thermal ink jet head is a key parameter for obtaining stable ejection performance. The viscosity of aqueous ink is sensitive to the temperature of head and the variation of viscosity causes to the variation of ink drop volume. Because the heat capacity of photopolymer applied for thermal ink jet head is lower than the aqueous Ink, the temperature of head is more sensitive to the head ejection condition. In case of Ink drop visualization test, tens of nozzles are fired and measured ejection frequency is up to 5 kHz. Ejection frequency of head is decreased in full nozzle firing for printing. Figure 5 shows the result of measured temperature of ink jet head during full coverage printing on A4 paper. The printing swath of head is 1/2 inch and 20 paths were printed. The printing resolution is 600 dpi (2 kHz) and 1200 dpi (4 kHz). The result shows that temperature of ink jet head rises up to 70℃ at 2kHz, 85℃ at 4kHz and even higher than the aqueous ink in same condition. The low heat capacity of polymer ink causes to fast ink heating and low cooling of head. It leads to the higher temperature of head at the same driving condition than aqueous ink. Temperature range of head should be maintained under the 65℃ for common 2D ink jet document printer because of stable firing condition and prevention aeration. Consequently, the firing frequency of head for photo polymer ink is limited under 2 kHz in case of full nozzle firing.

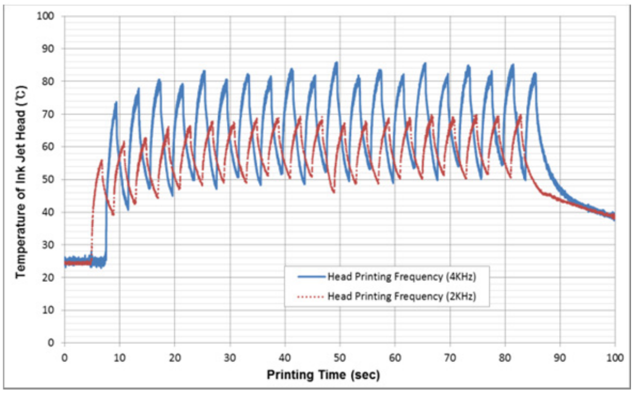


Figure 5 Temperature of Ink Jet Head during Full Coverage Pattern Printing

In this study, the target configuration of 3D object is determined a hallow wall cylinder because of verification for high aspect ratio object building capability by proposed thermal ink jet 3D printing. In order to build 3D object, printing path should be designed. Printing frequency is 2 kHz due to the result of full nozzle printing test. Figure 6 shows the designed printing paths. In order to minimize the difference between the printed swaths, Ink jet carriage is fed vertically by 1/3 of swath and printing swaths are overlapped. The 16 paths is printed for single cross section, three layers are deposited during single printing process. The outer diameter of cylindrical cross section is 21.2 mm and wall thickness is 3.39mm. The bidirectional printing is applied to increase the speed and the uniformity of drop volume during the printing.

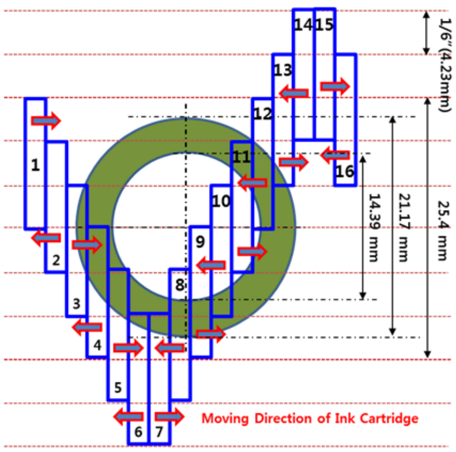


Figure 6 Printing Paths for Hallow Wall Cylindrical Cross Section

Figure 7 shows the temperature profile during the proposed printing process. The upper graph represents the temperature distribution for the first layer printing. The Ink Jet head is heated from ambient temperature to 50℃ during the first layer printing. The carriage moving speed is 3.3 inch per second. The rising and falling of temperature depends on the printing image. However, peak temperature is saturated to 50℃ during the first layer printing. The lower graph is temperature distribution for the second layer printing. The temperature rises little higher than the first layer but saturates to 54℃. The temperature range is from 46℃ to 54℃ and smaller than the first page. The designed printing path for target object cross section is verified for stable temperature control.

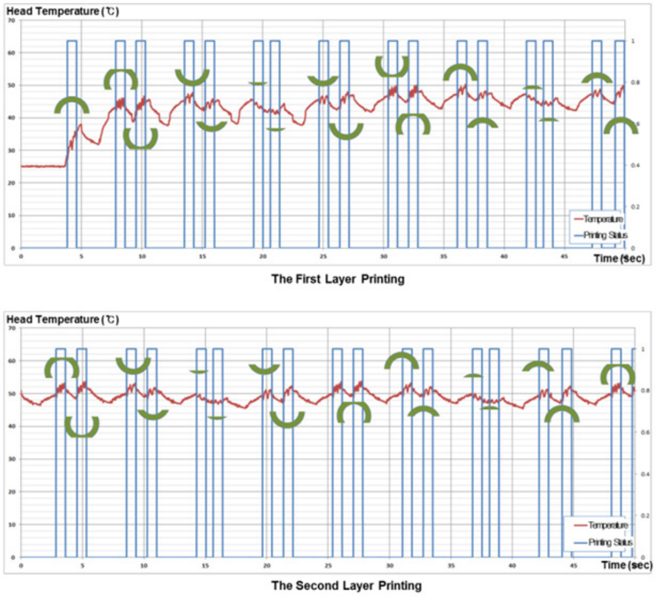


Figure 7 Ink Jet Head Temperature Profile during Printing Process

Printing System Fabrication and 3D Object Building

In order to verify the 3D printing process of material jetting by thermal ink jet print head, a 3D printing machine has been fabricated as shown in Figure 8. A precision 3-axis stage is assembled for building 3D object. For UV curing process, 395 nm LED type UV light source is adopted. The power and the size of curing apparatus is smaller than the lamp type UV light source applied to the conventional piezo head material jetting 3D Printer. A carriage including 2 print head and LED UV light source was attached to 3 axis stage. The first head is prepared for building material and the second head is for support material. The ink jet printing process for support material is not included in this study.

The UV ray reflects on the printed material and substrate and then illuminates the nozzles of the head because UV light source is located near the ink cartridge as shown in Figure 8. The reflected UV lay cure the ink in the nozzles and block the nozzle opening. The UV reflection blocking structure is applied to the carriage between the cartridge and the UV light source.

The capping and wiping mechanisms are installed for nozzle recovery during the printing process. The optimum maintenance algorithm will be determined in future study.

The single layer thickness of printed material is 14μm and resolution of printed image is 600 x 600 dpi. If the cross section of 3D Object is square with 100mm x 100 mm, single layer could be printed with 8 swaths and a printing time is 23.4 seconds. The building speed for the cube structure is about 2 mm/hour in case maintenance time is supposed to 100 seconds for an hour.

The designed printing path is applied and repeated layer by layer for building a hollow cylindrical object. Figure 8 shows a printed target object by the fabricated 3D printing system and height of the object is more than 30mm. A thin walled cylindrical object with high aspect ratio is obtained by the proposed thermal ink jet head.

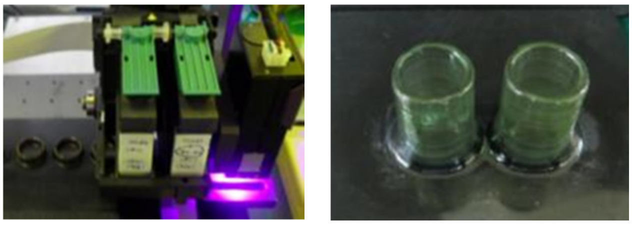


Figure 8 Printing System & Build Object

Conclusion

Material jetting based 3D printing process by using thermal ink jet print head is introduced and proved to be 3D printing system and capable of building 3D object. The proposed 3D printing process is accomplished by specific photopolymer composite ink and design of printing process considering physical behavior of liquid photo polymer in print head and on printing the substrate.

The drop volume and drop velocity is smaller than the aqueous ink and the temperature of head during printing is heated higher due to the low heat capacity of photopolymer ink. The vertical building speed of 3D printing is more than 2 mm/hr. The proposed printing process can be applied for personal 3D printer because of low cost thermal print head and LED UV source.

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Author Biography

Oh Hyun Baek received the B.S. and M.S. degrees in mechanical engineering from Korea University, Seoul, Korea, in 1991 and 1993,, respectively. He joined Samsung Electronics Co, Ltd. Seoul Korea, and he worked on research and study of ink jet and Laser Beam printing process at the Digital Media Communication R&D Center. His recent research topic is focused on the 3D Printing process.