Investigation on Fabricating 3D Structures Using Inkjet Printing Technology

Mustaffa IBRAHIM[1], Takayuki OTSUBO[2], Hiroyuki NARAHARA[3], Hiroshi KORESAWA [4]and Hiroshi SUZUKI[5]
Department of Mechanical Information Science and Technology, Kyushu Institute of Technology

Keywords: Rapid prototyping, Inkjet printing, Piezoelectric, Inkjet device

Abstract

Recently a rapid prototyping method for building parts layer-by-layer has led to interest in fabrication of electrical circuits and optical devices by inkjet printing. In this study a Java program was developed to control a commercial piezoelectric inkjet printer whose nozzles are about 30 µm with experiments focusing on the drop positioning and arrangement required to fabricate three-dimensional structure layer by layer. A single nozzle inkjet device whose nozzles are about 100 µm was also fabricated to study the basic operating parameters affecting the fluid drop formation such as cavity length, viscosity and amplitude voltage.

1. Introduction

An inkjet printer patterns material by ejecting tiny droplets of liquid ink from its printhead nozzles or orifices as it moves in two dimensions approximately 1 mm above a substrate. The prospect of adopting inkjet printing technology in various advanced manufacturing processes is very promising due to its apparent simplicity, the fact that it is data-driven, its high material deposition speed, reduced waste of costly materials and elimination of cross-contamination on surfaces because it is a non-contact process.

With this broader view of the technologies encompassed by the term "inkjet printing", applications in electronics, optics, displays, virtual reality, medical diagnostics, and medical procedures have been developed using inkjet fluid microdispensing as an enabling technology [1]. The characteristic feature of the inkjet process is to print dots, but for printing 3D functional parts, lines and areas with good dot-to-dot conductivity are a necessity, as for example in electrical and thermal conduction applications.

This study intends to utilize Java program to manipulate CAD design data and interface them with a modified commercial 357-nozzle piezoelectric printer with experiments focusing on the drop positioning and arrangement required to fabricate 3D patterns. In order to study the parameters affecting drop formation of a piezoelectric inkjet printer, a single nozzle inkjet device whose nozzle diameter is about 100 µm was also fabricated to study basic parameters affecting fluids drop formation such as voltage amplitude, firing frequency and fluid viscosity.

The printing quality and resolution of an inkjet printhead are closely related to the characteristics of the ejected droplet and therefore it is important to gain insights into how the liquid droplet is formed and ejected in a piezoelectric inkjet printing device. Without a clear knowledge of the operating parameters for the printhead, optimal droplet ejection and printing quality cannot be realized.

2. Experimental Details

In this study, two experimental works were done: deposition experiment using the modified inkjet printer and drop deposition experiment that uses a single nozzle inkjet device.

2.1 Drop deposition using inkjet printer

The focus of the experiments was to study the area covered by ink deposited horizontally and vertically in order to print 3D patterns using the modifed inkjet printer. Although in our previous study, silver nanoparticle ink was successfully printed and can function as a conductive circuit [2], a more thorough understanding of printer capabilities in arranging dots in both the X and Y axis and in patterning 3D patterns needed to be reached.

A Java program was developed to manage CAD data manipulation, control the printer without its software and independently customize the fluid cartridges selection to avoid simultaneous deposition when data was sent and creating problems in fabricating multi-material 3D structure**[s]**. The Java program also synchronizes installed motorized stages with the printing movement so that it was possible to deposit materials selectively layer by layer.

This study used the printer's original ink, with a surface tension of approximately 28.7 mN/m and viscosity at room temperature of approximately 3.59 mPa [3]. The positioning of deposited ink is important because failure to deposit ink in some areas would have a significant effect if functional inks such as conductive or magnetic ink were used. The modified printer horizontal movement is not modified, but the mechanical paper feed mechanism was replaced by motorized stages as depicted in Figure 2.1. In these experiments, micro slide glass was used as the substrate material.

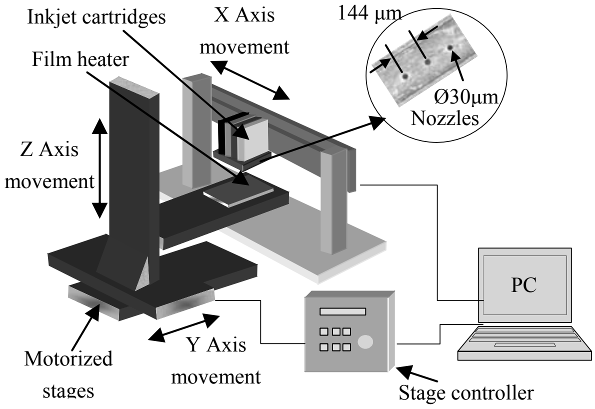


Fig. 2.1. Inkjet printing system

2.1.1 Single drop deposition

An inkjet printer's horizontal resolution is defined by the firing frequency of the printhead and the linear speed of its horizontal movement, while vertical resolution depends on the positioning accuracy of the mechanical paper feed. In this study, however, since the mechanical paper feed was removed and replaced by motorized stages, ink positioning accuracy on the vertical axis was determined by overlaying the ink between the two adjacent nozzles, which were 144 µm apart. In this experiment however, only one nozzle of the printer head was used to deposit inks so that a coverage area and thickness from a single drop could be determined.

The deposited single ink drop shape changed from a circular to an ellipse shape after drying due to solvent evaporation and measures about 90 µm horizontally and about 54 µm vertically as depicted in Figure 2.1.1 (a). The drops were then overlayed in the X and Y direction as seen in Figure 2.1.1 (b) according to a specific distance as denoted in Table 2.1.1. Ra, a parameter for measuring the average roughness of a surface and Ry, the maximum peak to lowest valley vertical distance within a single sample length was measured to study the effect of overlaying distance on the flatness of the deposited drops.

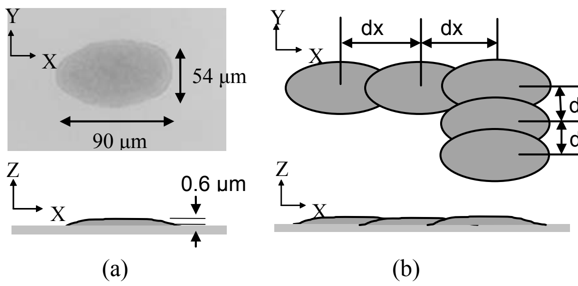


Fig 2.1.1. Description of a. a single drop coverage area; b. the overlaying of drops in the X axis and the Y axis.

Table 2.1.1. Overlaying distance

Distance dx(µm)	92	80	68	56	44

Distance dy(µm)	52	40	28	16

2.1.2 Printing 3D patterns

The ability of inkjet printing technology to arrange dots precisely to create layers of material makes it interesting in layering multiple materials integrated into one part. This experiment however is trying to arrange dots of ink to fabricate 3D patterns based on the distance in the X and Y axis gathered from the previous experiment. Two patterns were fabricated, a rectangular pattern and a pyramid pattern as shown in Figure 2.1.2 (a) and Figure 2.1.2 (b). The patterns was chosen to study the ability of deposited ink drops to be arranged in a flat and inclined shaped so that deposition sequence can be better understood.

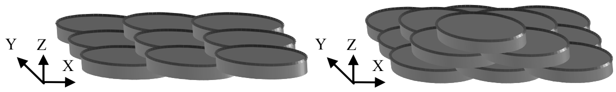


Fig 2.1.2. Description of a a. rectangular pattern; b. pyramid pattern..

2.2 Drop deposition using inkjet device

The objective of this experiment is to investigate drop formation from a drop-on-demand piezoelectric ink jet device and by studying the dependence of several operating characteristics the physical phenomena underlying the operation of such a device can be better understood when fluids with different characteristics compared to normal inkjet inks were used.

The apparatus used in the investigations consists of a squeeze mode piezoelectric disc with external diameter measuring 25.4 mm, inner diameter 6.35 mm and thickness 2.54 mm (APC International, Ltd) which surrounds a glass Pasteur pipette bonded together by epoxy. The bottom end of the Pasteur pipette is closed off by a 0.2 mm thick aluminum plate, which contains a nozzle hole with an aperture dimension typically of 100 µm in diameter, drilled using a microdrill. The piezoelectric assembly forms the cavity length of the apparatus where the upper and lower surfaces of the piezoelectric ring are plated to provide electrodes which rectangular pulses are applied as depicted in Figure 2.2.

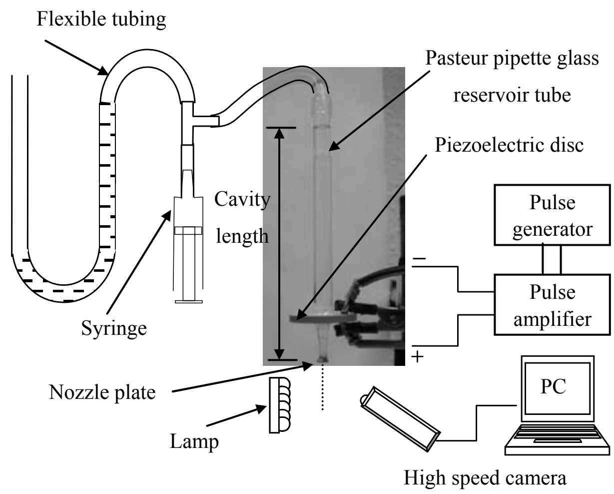


Fig 2.2. The piezoelectric assembly device apparatus

The piezoelectric disc produces fluid ejection by operating in compression, which contracts the volume of the glass fluid reservoir in the region of the hole in the driver disc. This produces a pressure pulse that forces out a fluid jet from the nozzle [4]. The device must be carefully prepared to remove all air from the pipette, since air bubbles absorb the pressure waves produced by the piezoelectric disc preventing a drop from forming. To avoid fluid buildup or leaking at the end of the nozzle when the drop ejector is in static mode, a manometer tube pressure control device was utilized to create a negative pressure to control the volume of air at the rear of the inkjet device reservoir. Too much negative pressure will draw air bubbles inside the device and insufficient negative pressure can cause fluid buildup at the end of the nozzle.

2.2.1 Cavity Length Effect

Experiments were done firstly on the relation of some operation parameters on the different length of fluid cavity. This was done by changing the cavity length while varying the voltage amplitude needed to produce a stable straight jet deposition. The amount of negative pressure required to avoid fluids from dripping was also recorded. De-ionized water was used for the purpose of this experiment. A high speed camera was also used to capture the image of de-ionized water deposited at variable frequency to investigate the frequency effect on drop velocity.

2.2.2 Variable Viscosity Deposition

In order to deposit fluid through the nozzle which diameter is about 100 µm, viscosity and surface tension which are crucial parameters were measured to confirm their capability to be deposited using the inkjet device. Generally, the fluid property requirements for demand-mode inkjet dispensing are as follows, the viscosity should be Newtonian and less than 40 cp, and the surface tensions should be greater than 20 dynes/cm (mN/m) [5]. Among fluids tested were de-ionized water (D.W) and ethylene glycol (E.G) because of their material properties and because they are commonly used as the base fluids for inks in inkjet printing. Their surface tensions are rather similar, but their viscosities are quite different. Inkjet ink was also tested as a comparison. Apart from that, water based low viscosity conductive silver ink was also tested. In this experiment frequency between 3 kHz and 5 kHz was used while maintaining the cavity length.

3. Experiment Results

3.1 Drop deposition using inkjet printer

In these experiments, a film heater was installed under the slide glass at temperature 80°C to evaporate the solvents in the ink and the ink dries in about 10 seconds.

3.1.1 Single drop deposition

Experiments were carried out to establish X and Y axis overlay distance that would give better surface flatness result. Figure 3.1.1 (a) shows the result of Ra and Ry when the dots were overlayed on the X axis and Figure 3.1.1 (b) shows the result of Ra and Ry when the dots were overlayed on the Y axis. The results shows that the best surface flatness can be achieved when overlaying the dots at a distance of 68 µm on the X axis and 40 µm on the Y axis.

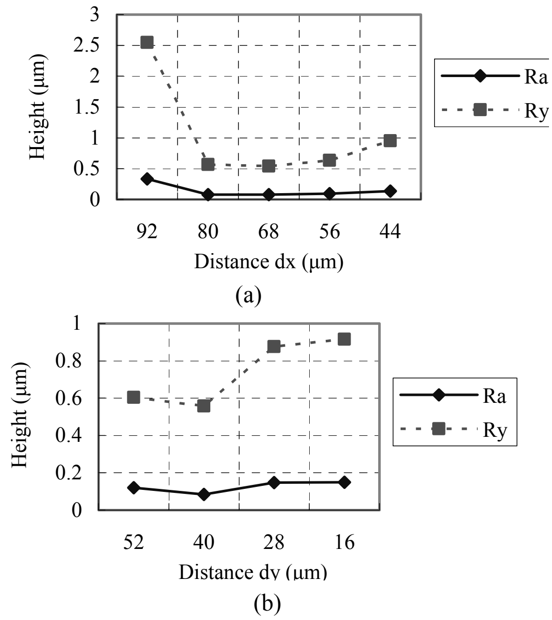


Fig. 3.1.1. Surface flatness on a. X axis; b. Y axis

3.1.2 Printing 3D patterns

Experiment result on printing a rectangular pattern shows that the ink seems to sink at the intersection area of dots as described in profile 1 and profile 2 shown in Figure 3.1.2 (a). Experiment done in arranging the dots to fabricate a pyramid pattern also show that there is a sinking setback with the deposited pattern as can be seen in profile 1 and profile 2 shown in Figure 3.1.2 (b).

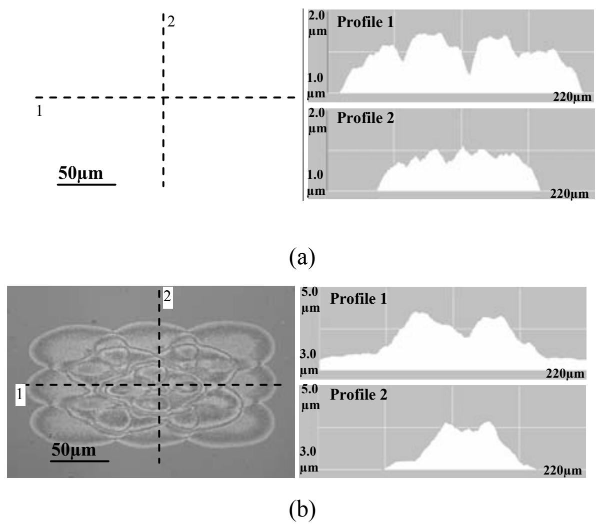


Fig. 3.1.2. Surface profile of the a. rectangular pattern; pyramid pattern

3.2 Drop deposition using inkjet device

As it is difficult to verify the droplets coming out of the nozzle with naked eyes, droplets formation were monitored using the Phantom v5.0 high speed digital imaging system.

3.2.1 Cavity Length Effect

From experiments done to study the relation of some operation parameters on the different length of fluid cavity, observation showed that the voltage pulse amplitude needed to eject drops increased when cavity length of the inkjet device is reduced almost at a constant rate while the negative pressure hold the fluid from dripping reduced as shown in Figure 3.2.1. This means that if a fixed voltage amplitude wished to be used, a fluid filling mechanism have to be installed to maintain the fluid level for a stable drop formation. Experiments to investigate the frequency effect on drop velocity shows that as frequency increased the distance between drops and drop velocity reduced as shown in Table 3.21 and Figure 3.2.1.1. The relationship between the frequency, distance between drops and drop velocity is very important if the inkjet device system was to be used to direct write functional materials using.

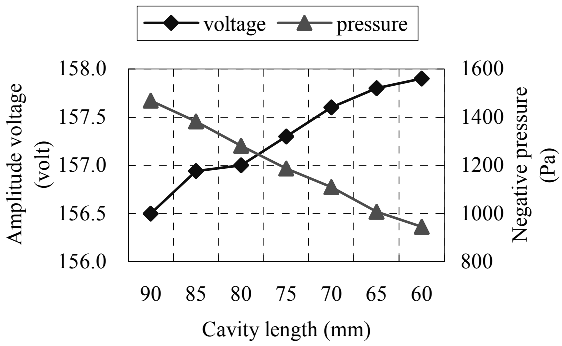
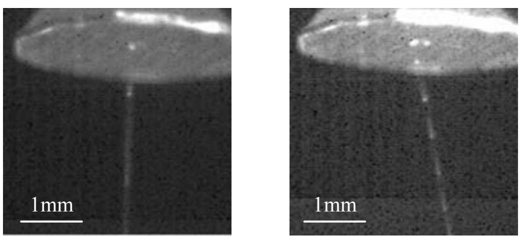


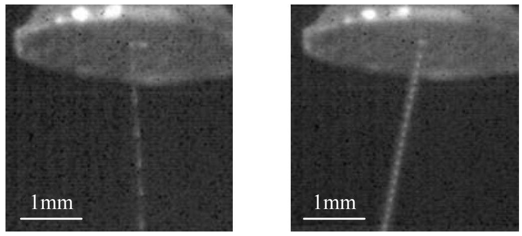
Fig. 3.2.1. Inkjet printing system

Table 3.2.1. Frequency effect on drop velocity

Frequency (kHz)	2.5	2.6	2.7	3.0
Distance between drops (mm)	1.74	0.84	0.58	0.19
Drop velocity (m/s)	2.24	1.08	0.75	0.43



(a) (b)



(c) (d)

Fig 3.2.1.1. Drop deposition at frequency a. 2.5 kHz; b.2.6 kHz; c. 2.7 kHz; d.3.0 kHz..

3.2.2 Variable Viscosity Deposition

The results of viscosity and surface tension measurement of the fluid materials were shown in Table 3.2.2. From the experiments done on depositing the materials, it seems that more voltage pulse amplitude is needed to eject fluid material with higher viscosity as shown in Figure 3.2.2. Fluids with different material characteristic require different parameter setting. In this experiment, the same cavity length was used to test all the fluid materials due to its effect on the voltage amplitude. Fluids filtering will also help reduce**[ ]** the possibility of the nozzle being clogged due to foreign particles.

Table 3.2.2. Fluid material properties

Fluid Material	Viscosity (mPa.s)	SurfaceTension (mN/m)
D.W	1.14	55.2
E.G 25% D.W 75%	1.79	62.6
E.G 50% D.W 50%	3.44	56.7
Printer Ink	3.59	32.2
Silver Ink	1.81	53.9

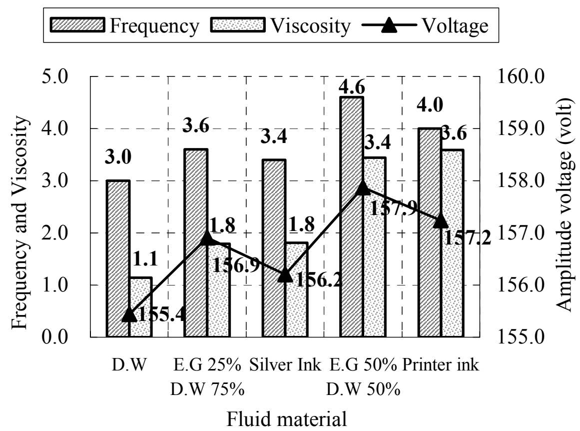


Fig 3.2.2. Variable viscosity deposition

4. Discussion

The ability to convert CAD design data and control an inkjet printing machine within a Java program provides the flexibility to harmonize different equipment in the same environment. Although there are still many improvements to be made in terms of hardware and software, the capability of the inkjet printing technology in depositing material layer by layer to build 3D structures is promising. Fabricating multi-material 3D structures using inkjet printing technology require arrangement and overlaying the deposited dots in a manner that will create a dense and flat layer pattern. In order to direct write patterns with the deposited fluid, the movement of the additional axes must be synchronized with the ink deposition rate. A study of inkjet printing resolution using normal printing ink was necessary prior to printing with functional inks because fluids such as metal-filled conductive inks or polymer inks are not cheap and extra care must be taken in handling these materials.

From the experiments done using print head nozzle 30 µm in diameter, 144 µm apart and printed at a horizontal resolution of 360 dpi, the smallest dot can be printed is about 90 µm horizontally and about 54 µm vertically. Overlaying the ink in a controlled environment provides the flexibility in programming the drops deposition both on the X and Y axis. The drops positioning however must be improved to get smooth surface 3D patterns. The ability of the program to control fluid deposition with different sizes will inevitably improve the print resolution because circular dots tend to leave void areas at their corners, making it difficult to fabricate sharp edges.

The drop deposition experiment using the inkjet device shows that depositing fluids with precise control trajectory requires control of its operating parameters such as amplitude voltage, pulse frequency and cavity length. These parameters have big influence on the capability of fluids to be deposited, their velocity, distance between drops and some of these parameters are related to each other. The information is very useful in fabricating multi-material 3D structure using the inkjet printing system. The imaging system however must to be improve so that deposited drop size could be measured. The inkjet device fabricated is also capable to deposit fluids without having in contact with the piezoelectric material and this makes it possible to test fluids that require special consideration.

5. Conclusion

The ability to build multiple-material prototypes or models from a rapid prototyping machine will inevitably bring manufacturing technology to another dimension. The inkjet printing machine that was built shows flexibility in depositing fluid of multiple materials generating one ink cartridge (tool) path file for every different material. From the experiments done to explore ink deposition resolution using a commercial piezoelectric printer, a few conclusions can be made:

- ♦ The minimum dot size achievable which is from a single drop is about 90 µm in the X axis and about 54 µm in the Y axis.
- ♦ The overlaying distance to arrange the drops that gives a more flat pattern is about 68 µm in the X axis and 40 µm in the Y axis.

The inkjet device also gives valuable information on deposition of drops using a piezoelectric device. Among the conclusions that can be made are:

- ♦ The cavity length or the fluid volume in the reservoir will give a significant effect on the drop deposition. Fluid cavity of 90 cm required frequency of 3.7 kHz and amplitude voltage of 156.5 volt while fluid cavity of 60 cm required frequency of 4.7 kHz and amplitude voltage of 157.9 volt to be deposited.
- ♦ The cavity length or the fluid volume in the reservoir will also give a significant effect on the negative pressure needed to hold the fluid from dripping. Fluid cavity of 90 cm will require a negative pressure of 1468 Pa while fluid cavity of 60 cm will require a negative pressure of 945 Pa.
- ♦ Frequency will give significant effect on the drops characteristic. A frequency of 2.5 kHz will deposit drops with velocity of 2.24 m/s and distance between drops of about 1.74 mm while a frequency of 3 kHz will deposit drops with velocity of 0.43 m/s and distance between drops of about 0.19 mm.
- ♦ Fluids with different material characteristic require different parameter setting. To deposit inkjet ink with viscosity of 3.59 mPa.s require frequency of 4.0 kHz and amplitude voltage of 157.24 volt while conductive silver ink with viscosity of 1.81 mPa.s require frequency of 3.4 kHz and amplitude voltage of 156.2 volt.

6. References

[1] Wallace D.B. and Hayes D.J. (2002), “Solder Jet™ - Optics Jet™ - AromaJet™ - Reagent Jet - Tooth Jet and other Applications of Ink-Jet Printing Technology”, in Proceedings, NIP18: International Conference on Digital Printing Technologies, San Diego, CA.

[2] Mustaffa B.I., Narahara H. and Suzuki H. (2004), “Electronic Circuit Fabrication Using Inkjet Printed Silver Nanoparticles For SFF”, in Proc. of Japan Society for Precision Engineering National Conference, pp. 83-84, Tokyo

[3] Mustaffa B.I., Narahara H., Koresawa H. and Suzuki H. (2004), “Integration of Silver Nanoparticle Inkjet Printing and Layered Manufacturing Technology”, Proc The 7th. Intl. Conf. Quality in Research (QIR) 2004 (Mech. Engineering), ME-DM-04-1-4, Jakarta, Indonesia, August.

[4] Eric R. Lee (2003), Microdrop Generation, CRC Press, pp. 166.

[5] Wallace D.B., Cox W.R., and Hayes D.J. (2002), “Direct Write for Ink-Jet Techniques”, in A. Pique and D.B. Chrisey, eds, Direct Write Technologies for Rapid Prototyping Applications- Sensors, Electronics, and Integrated Power Sources, Academic Press, New York.