Inkjet Printing Resolution Study for Multi-Material Rapid Prototyping*

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In addition to its application in media printing, inkjet printing is becoming an increasingly attractive option for the distribution and patterning of materials for a wide variety of applications. In this study a commercial inkjet printer was modified to study the resolution of fluid dot placement required to fabricate 3D multi-material patterns layer by layer. A Java-based computer program was developed to convert stereolithography (STL) data layer by layer, control ink cartridges individually and print ink with customized fluid dot placement arrangements. The study found that complement printing between nozzles which are 30 μm in diameter and 144 μm apart is essential to achieve a sufficiently dense 3D pattern. When printed with 36 μm vertical spacing a layer thickness of 1.30 μm is achievable, and when printing layer by layer, the thickness increases almost at a linear rate.

***Key Words*:** Rapid Prototyping, Inkjet Printing, Multi-Material, Resolution, Positioning

1. Introduction

The advancement of manufacturing technologies is being driven by the need for automation, miniaturization, cost reduction and environmentally friendly manufacturing. The prospect of adopting inkjet printing technology in various advanced manufacturing processes is very promising. 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). This study intends to utilize a Java program to manipulate CAD design data and interface them with a modified commercial 357-nozzle piezoelectric printer to produce 3D patterns, as shown in Fig. 1.

1.1 Fabricating 3D structure using inkjet printing

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. The classic definition of rapid prototyping is "a special class of machine technology that quickly produces models and prototype parts from 3D data using an additive approach to form the physical models"(2). The characteristic feature of the inkjet process is to print dots, but for printing multi-material 3D functional parts, lines and areas with good dot-to-dot conductivity are a necessity, as for example in electrical and thermal conduction applications. 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 advantages of inkjet technology are straightforward: 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. The overall size of the particles that can be jetted are limited by the diameter of the nozzle exit ori-

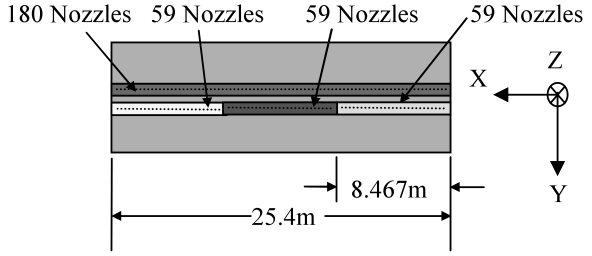

Fig. 1 Piezoelectric printhead configuration

* Received 28th October, 2005 (No. 05-4226)
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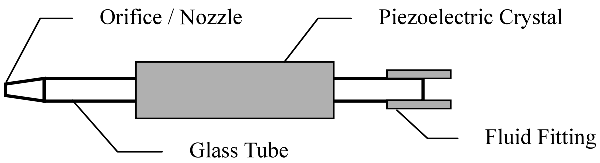


Fig. 2 Single channel drop-on-demand dispensing device configuration

fice diameter, and line width/thickness is determined by the jetted liquid properties and the orifice diameter(3).

1.2 Related studies

Although there is already ongoing research into using inkjet printing to build MEMS, organic displays, and biological arrays(4),(5), most systems use a drop-on-demand platform that has a single-nozzle piezoelectric-actuated device, such as that from MicroFab Technologies Inc.(6), to direct write materials, as denoted in Fig. 2. The Z Corp. rapid prototyping machine, which uses 3D printing technology originally developed at the Massachusetts Institute of Technology, has traditionally used plaster and resin powders onto which an inkjet printer sprays glue to create solid prototypes, and cellulose fiber bound with an adhesive for creating models used for investment and sand castings(7). Objet Geometries Ltd. has successfully inkjet photopolymer to create models, using multiple nozzles to jet layer on layer of photopolymer, with each layer cured immediately by exposure to UV light(8). Even though inkjet printing technology has been used to fabricate 3D structures or models, parts produced by the commercially available rapid prototyping systems are made of a single material. The multi-color 3D printer from Z Corp. only prints colors on surfaces — the material beneath is still the same as the modeling material. In other rapid prototyping systems, various parts are built independently using different colors and then assembled at a later stage. A new system is expected which can produce assemblies composed of parts with more than one color or with more than one material(9). With this capability, some post-processing of rapid prototyping such as assembly, bonding, welding and painting can be eliminated. Drop-on-demand inkjet technology is among the rapid prototyping methods that can be extended to build multi-material assembly by adding more material inkjet nozzles to deposit materials selectively, layer by layer.

In our previous study, silver nanoparticle ink which contains silver, plated gold, tetradecane as solvent and has a particle size between 3 and 7 nm was successfully printed using inkjet printing technology to directly write an electronic circuit as depicted in Fig. 3. The results also show that the environment and ink curing temperature have a strong effect on the silver ink viscosity and volume resistivity as shown in Figs. 4 and 5. Due to these differences, it is not easy to get the same printing results as with the original ink. Conductive lines measuring 100 μm in width were printed with the printer, and after curing the solvent evaporates, causing the silver ink to lose about 20% of its volume, leaving the silver ink with a width of 80 μm(10).

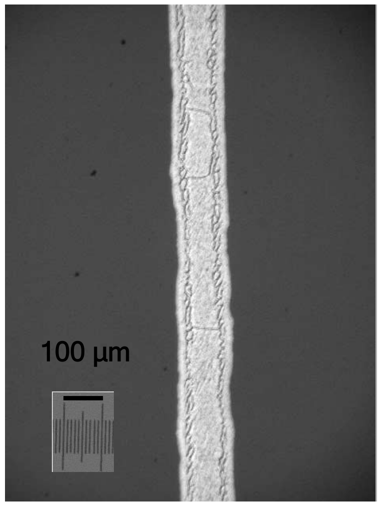


Fig. 3 Printed silver ink

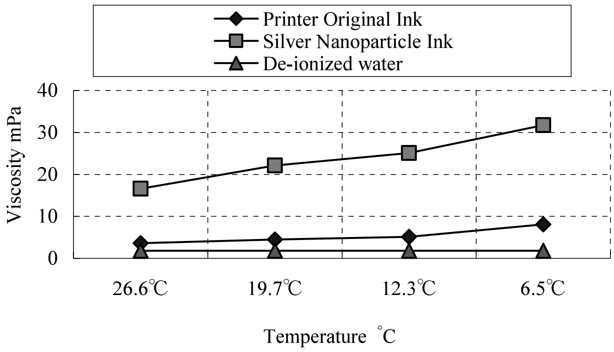


Fig. 4 Temperature effect on viscosity

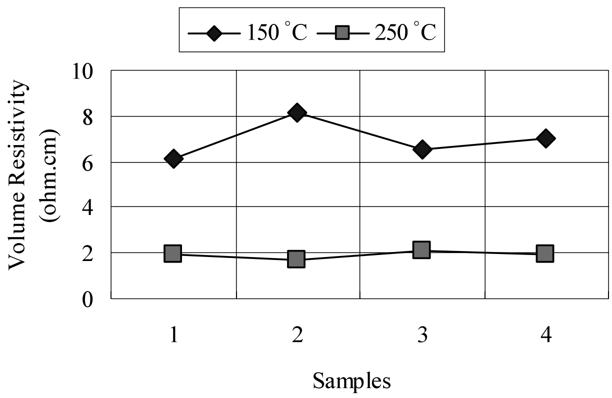


Fig. 5 Temperature effect on volume resistivity

2. Materials and Methods

The focus of the experiments was to study the area covered by deposited ink horizontally and vertically in order to print 3D patterns. Although in our previous study, silver nanoparticle ink was successfully printed and can

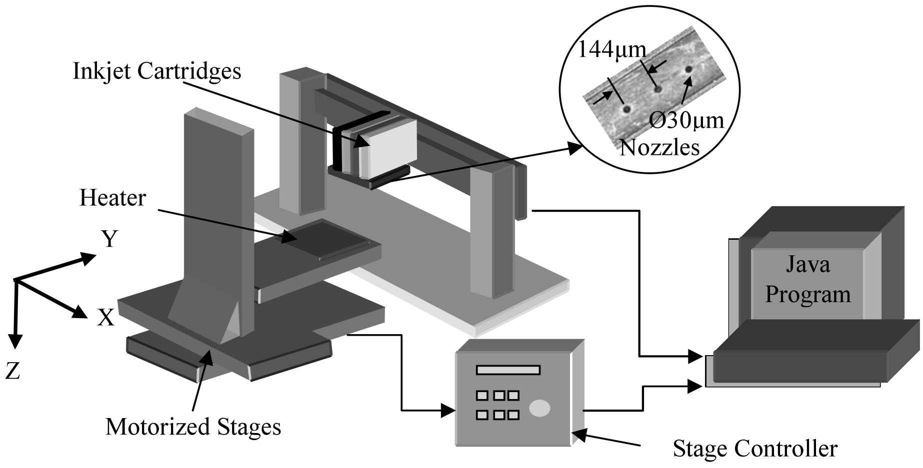


Fig. 6 Inkjet printing system

function as a conductive circuit, 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 because of limitations in using the window based printer driver software. Among the printer software limitations are:

- Several nozzles will be depositing simultaneously when image data was sent and this will create problem in fabricating multi-material 3D structure.
- The paper feeding mechanism distance movement cannot be customized when complement printing is required.
- Synchronization between printing and motorized stages cannot be done due to different operating window.

The Java program developed in this study is capable to:

- convert from CAD data to pixel image data
- direct control the printer bypassing the printer software
- independently control the fluid cartridges selection
- synchronize motorized stages and printing movement

The present study used the printer's original pigment ink, with a surface tension of approximately 28.7 mN/m and viscosity at room temperature of approximately 3.59 mPa(11). The ink cartridges were mounted on a commercially available desktop printer that was modified to be capable of fabricating 3D patterns layer by layer. 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 to be used.

2.1 Drop-on-demand inkjet systems

Among the numerous types of inkjet technology, the most common are drop-on-demand systems such as thermal and piezoelectric, which have dominated the lower-end printer market. In thermal inkjet technology, the drop is initiated by heating the ink to create a bubble until pressure forces it to burst and hit the paper. However, the high temperatures may trigger problems or incompatibilities with certain functional ink formulations. The other inkjet technology used in this study is from Epson, and utilizes a piezoelectric crystal positioned at the rear of the inkjet reservoir. When actuated, the piezoelectric crystal flexes and forces a drop of ink out of the nozzle(12).

2.2 Experimental setup

This study used a Java program to slice rapid prototyping STL data and translate them to bitmap data layer by layer. The layer image was then sent to the printer, which was also controlled by the Java program, so that it was feasible to choose the inkjet cartridge individually for color selection and to avoid the color mixing process which the printer software would initiate under normal operation. The modified printer was equipped with motorized stages and a heater in order to fabricate 3D patterns. The inkjet printing system's horizontal movement is not modified, but the mechanical paper feed mechanism was replaced by motorized stages as depicted in Fig. 6. The Java program synchronizes movement of the motorized stages with the printer in order to fabricate 3D patterns identical to the rapid prototyping concept. A film heater was placed on top of the stage to dry the deposited fluids and maintain their shape rather than allowing them to spread out on the surface, which would cause dots to interact with one another. The printer's printhead nozzle is about 30 μm in diameter and the distance between nozzles is 144 μm. A summary of the conditions under which the experiments were carried out is given in Table 1.

2.3 Ink drying and spreading

First, the ink drying temperature had to be determined, because partial drying would cause the ink to appear dry on the surface while trapping solvent underneath. A film heater was used, and the voltage supplying it was varied to ascertain the time and temperature required to dry the ink. To make sure heat was evenly distributed, a

Table 1 Experimental conditions

Experiments	Conditions	Measurement
Ink Drying Time and Temperature	From 50°C to 80°C	Tape pull test (Customized Jig)
Ink Spreading	Stainless steel plate, glass, inkjet film	Spreading area (Keyence digital microscope VK8550)
Complement printing	1 complement - 11 complements in between 144µm	Regions covered in between dots (Keyence digital microscope VK8550)
Surface Roughness	1 complement - 11 complements in between 144µm	Surface Roughness parameter (Ra) (Keyence digital microscope VK8550)
Layer Thickness	1 printing layer – 3, 5, 7, 9 printing layers	Thickness measurement (Keyence digital microscope VK8550)

copper plate was placed on top of the heater. A tape pull test was then performed to make sure that the ink was adhering well to the substrate. The spreading of deposited ink was studied by printing the ink on different substrate materials: stainless steel plate, slide glass, and inkjet film. Although the nozzle size was known to be about 30 µm, the actual size of the printed dot needed to be determined. The spreading of the ink is important when trying to get a precise deposition pattern in inkjet printing. This experiment was carried out to study the ink-spreading area on different materials when the same volume of ink was deposited, so that spacing for complement printing distance

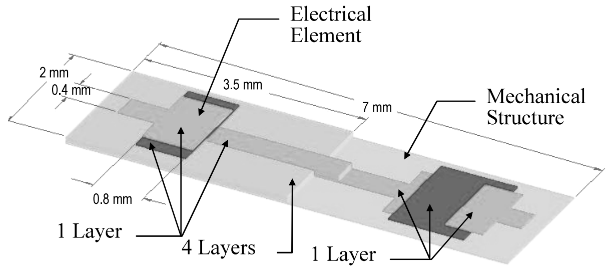


Fig. 7 Integration of mechanical and electrical elements in a part

can be established. The printed line width and its average roughness (Ra) were measured and recorded.

2.4 Printing resolution

Resolution is a basic term used to classify printers and is most commonly expressed in dots per inch (dpi), denoting the number of clearly resolved points a printhead can theoretically print in a one-inch interval. 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 complement printing, or overlaying the ink between the two adjacent nozzles, which were 144 µm apart. Ra, a parameter for measuring the average roughness of a surface, was measured from 1 complement printing up to 11 complement printings.

2.5 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. By printing layer by layer on top of one another, thicknesses of 1, 3, 5, 7 and 9 layers were recorded. In this study, experiments were also carried out to fabricate a part consisting of a mechanical structure and electrical elements, such as printing a schematic of a capacitor pattern on a surface of different heights using pigment ink for positional verification, as shown in Fig. 7.

3. Experimental Results

3.1 Ink drying and spreading

From this simple experiment, the results show that increasing drying temperature reduces drying time, and at 80°C the ink dries in about 10 seconds, as depicted in Fig. 8. Although we can use higher temperatures to shorten drying time, care must also be taken concerning the effect of heat on nozzle surfaces, to prevent ink drying and clogging the printhead nozzles. Heat should be just high enough to evaporate the solvents in the ink. The results shown in Fig. 9 indicate that ink printed on three different materials, stainless steel plate, slide glass and inkjet film, gave different spreading areas. The width of the line

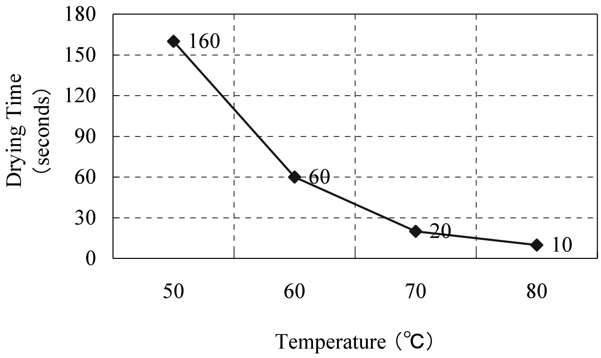


Fig. 8 Drying time

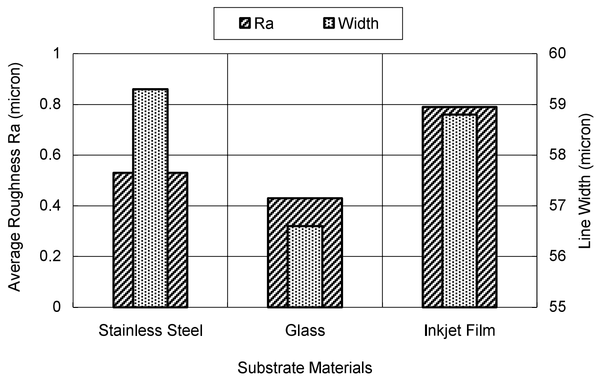


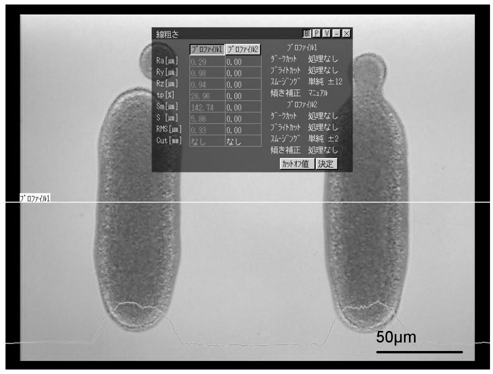
Fig. 9 Ink spreading

printed on glass is less than that of ink printed on stainless steel plate and inkjet film. This shows that the ink spread less on glass because its contact angle, which determines its wetting, is greater than ink printed on the other substrates. The average roughness value of ink printed on glass is also lower than the other materials.

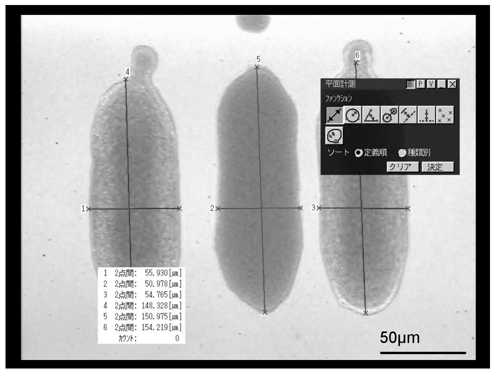
3.2 Printing resolution

Experiments were carried out to establish a fully dense deposition pattern by means of complement printing. Figure 10 (a) shows the result of printing without complement, with a gap of about 90 μm between the two adjacent nozzles. After one complement printing, the gap was still not fully covered by the ink, because the width of a dot is only about 55 μm, as shown in Fig. 10 (b). In order to fully fill the gap between the two adjacent nozzles a minimum of two complement printings 48 μm apart are necessary, as shown in Fig. 10 (c). With nozzle size 30 μm in diameter, nozzles 144 μm apart, and printed at a horizontal resolution of 360 dpi, the smallest a dot can be printed is about 55 μm horizontally and 150 μm vertically, which is from one pixel square image, as depicted in Fig. 11. Overlay printing until there are 11 complements between the two nozzles shows that the roughness of the surface increases as more lines were printed with smaller print spacing, as shown in Fig. 12.

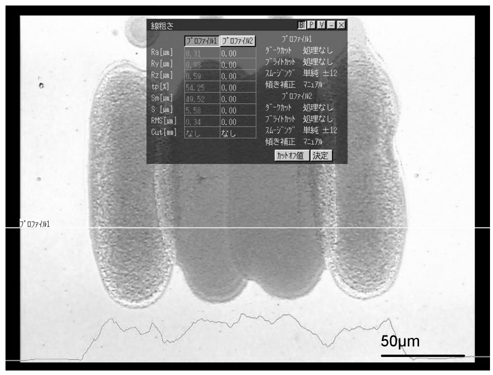
For the layer thickness experiment, a 36 μm print spacing was used to print a square pattern, and differ-



(a) Without complements



(b) One complement



(c) Two complements

Fig. 10 Complement printing results

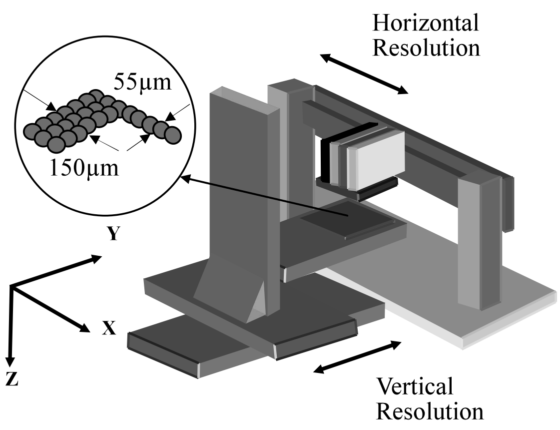


Fig. 11 Printing resolution

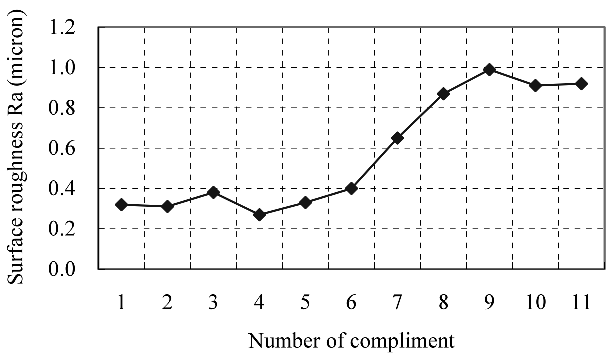


Fig. 12 Complements printing surface roughness

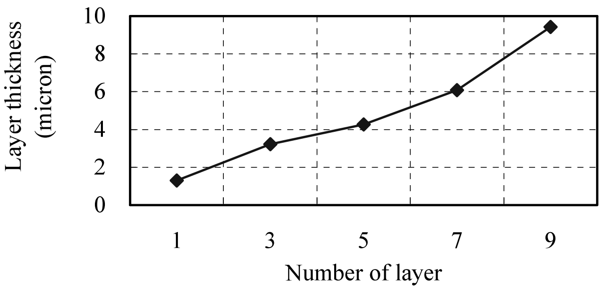


Fig. 13 Layer thickness

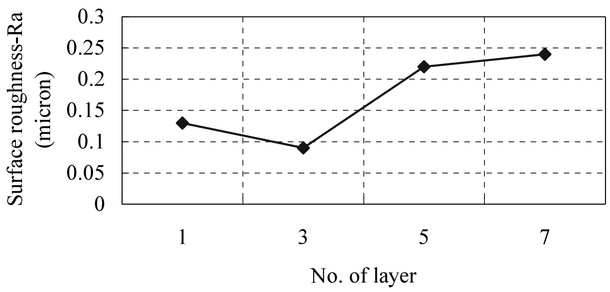
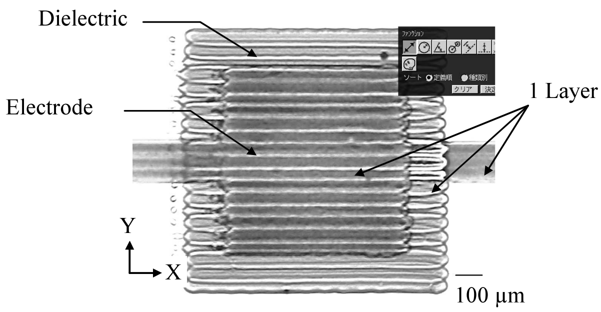


Fig. 14 Layer surface roughness

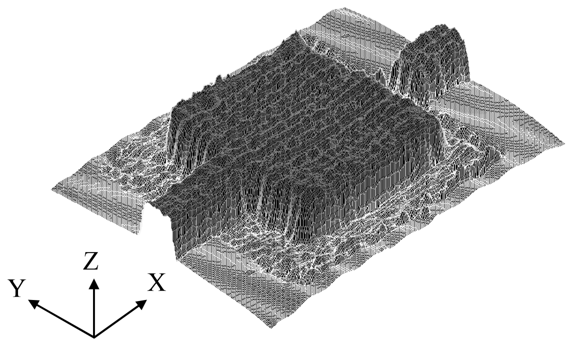
ences in thickness were measured. The results indicate that when the first layer was printed on the slide glass, the edge of the ink tended to spread on the glass surface. As the number of layers increased there was almost a linear increase in the average thickness of the pattern, as shown in Fig. 13. The surface roughness on different number of layers was also presented as shown in Fig. 14.

3.3 Printing 3D patterns

For the experiment to print a capacitor pattern, described in Fig. 15 (a), two types of ink were used: cyan, representing conductive ink for the electrodes, and magenta, representing dielectric ink. The bottom electrode, dielectric and top electrode layers were laid down successively. Both the area and thickness of the dielectric could be varied to select the value of the capacitance. The 3D profile of the pattern was shown in Fig. 15 (b). For the second 3D pattern, the capacitor was printed on the surface of the mechanical structure, represented by the yellow ink. A structure with varying surface heights was fabricated



(a) Inkjet printing of capacitor model



(b) 3D profile of capacitor model

Fig. 15 Capacitor patterns printing result

by printing different numbers of layers, with each layer roughly 1 μm thick. The images described in Fig. 16 show the use of inkjet printing to fabricate multiple material 3D patterns with reference to Rapid Prototyping technology, which fabricates 3D objects layer by layer.

4. Discussion

The ability to convert CAD design data and control an inkjet printing machine within a Java program gives us the flexibility to harmonize different equipment in the same environment. A commercial inkjet printer was modified and transformed into a machine that can fabricate 3D structures. 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. The movement of the additional axes must be synchronized with the ink deposition rate so that we can direct write patterns with the deposited fluid.

From our experiment with nozzle size of 30 μm in diameter, 144 μm apart and printed at a horizontal resolution of 360 dpi, the smallest dot can be printed is about 55 μm horizontally and about 150 μm vertically which is from one pixel square image. The pixel image data need to be modified so that variable dot size can be chosen based on the size of the region that needs to be printed. The abil-

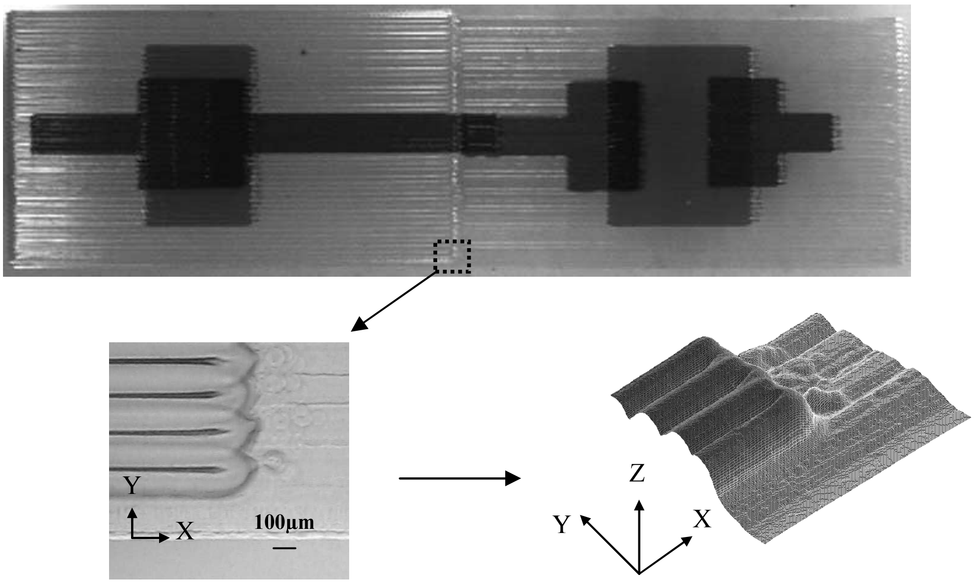


Fig. 16 Inkjet printing of part with capacitor model

ity 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 nozzles must also be taken care of because heat interaction on fluid can clog nozzle openings. If particles clog parts of a nozzle, both horizontal and vertical resolution can be affected, and a deviation of 1 degree can cause dot misplacement of a few microns. This will also cause "satellite drops", unwanted drops of ink that break off from the main droplets. 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.

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 we built shows flexibility in depositing fluid of multiple materials and in the number of complement printings needed to build 3D structures layer by layer using the Java program. The program can also be used to generate one ink cartridge (tool) path file for every different material to be deposited onto using inkjet printing technology. From the experiments done to explore ink deposition resolution using a commercial piezoelectric printer, a few conclusions can be made:

- When printing at a horizontal resolution of 360 dpi, the minimum width achievable is 55 μm in the X axis and about 150 μm in the Y axis.
- The minimum complement printing distance necessary to connect dots in the Y axis is about 48 μm, which is 2 complement printings between nozzles 144 μm apart.

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