Evaluation of Inkjet Technologies for Digital Fabrication & Functional Printing

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Objectives

This report evaluates the dispensing capabilities of available inkjet and related valve jet printheads for providing digital fabrications and functional printing applications against a number of key performance parameters including the ability to flow chemistry at elevated temperatures, pH tolerance, capability to image fine features, ability to deposit required materials at acceptable rates.

Methodology

For this report, we have reviewed available literature and conducted face-to-face, telephone and e-mail interviews with over one hundred technology developers and users.

Introduction

Inkjet technology offers one of the most flexible production methods for building 3D objects, printing electronic circuits and photovoltaic components. Inkjet and related valve jet technology enable the deposition of a range of materials that complements and rivals other digital and analog methods for fabricating objects and functional printing. We are evaluating the success of existing systems with a focus on their printhead performance.

Available Inkjet Digital Fabrication & Functional Printing System

Existing 3D fabrication systems that employ inkjet and valve jet head for material deposition include:

- 3D Systems: ProJet 5000 and 3500 series with modified Xerox M-series PIJ printheads
- Z Corp (3D Systems): ZPrinter 150, 250, 350, 450, 650, 850 with HP TIJ printheads
- Objet (Stratasys): Connex 500, 350, 260 Connex; Eden 500V, 350, 350V, 260V, 250; Objet24; Objet30 Pro with Ricoh Gen3 printheads
- Solidscape (Stratasys): T76Plus, R66Plus, D76Plus

Existing PV fabrication systems that employ inkjet:

- PixDRO: LP50, IP410, IP3000 with selection of Xaar 1001, Fujifilm Dimatix Spectra S-Class SE, SM, SL, (plus hot melt), SE3 and SX3, Konica Minolta KM 204, KM 256, KM 512 (plus hot melt), Trident ITW 256Jet-D.
- Optomec: Solar Lab System with Aerosol Jet

Existing printed electronics and evaluation print systems that employ inkjet include:

- Fujifilm Dimatix: DMP-2800 with DMC 11601 & 11610; DMP-3000 & DMP-5000 with DMC 11601 & 11610, SX3, SE3 & SE-DPN, D-128/1 DPN & D-128/10 DPN; DMP-5005 with DMC 11601 & 11610 and D-128/1 DPN & D-128/10 DPN.
- UniJet: UniJet 100 with Samsung Semjet
- Optomec: Aerosol Jet 300P & 300CE

The preceding lists associate existing inkjet equipment with their respective fabrication and functional printing applications. We have focused on these three application areas, which exhibit some overlap of printheads, but discern groupings reflecting ink volume deposition and minimum feature capabilities and finished. For 3D fabrication, the 3D Systems ProJet 5000 and 3500 printers and the Objet systems use printheads that print ink drop volumes in a range that yields similar thicknesses of layer deposit. These satisfy our standard for smooth contours and sharp edges where appropriate without visible artifact of the print process.

Inkjet Advantages for Digital Fabrication & Functional Printing

Inkjet can produce very small feature sizes and line widths that match or exceed the refinement of production analog print methods, while providing registration that surpasses analog methods for accuracy (see Table 1). As a non-contact print method, inkjet does not stress the print surface resulting in circuit cracks and breaks, to which analog and digital on-contact print methods are prone. It produces a range of thicknesses depending upon the deposition capabilities of the chosen printhead and fluids. It can produce very thin layer deposits that may require post print processing, such as heating, sintering or melting for electronic and electrical applications to insure continuous circuits. It can also print seed circuits with a fine line of silver (Ag) that is then electroplated with a functional layer of less expensive copper (Cu). It can also produce build layers for fabricating 3D objects. The application requirements for 3D builds vary significantly from those for printed electronics. Whereas 3D fabrication typically demands the large drop flow of considerable material to add to layers rapidly, fine printed circuit inkjet printing requires the deposition of small drops. For example, the Objet Polyjet Matrix inkjet 3D prototype printers use Ricoh Gen3-E1 96-nozzle PIJ printheads and generate 30-pl drops. They can build and form layers of 28-µm thick (z-axis) with its six opaque materials. For its transparent clear materials, it builds and forms 16 µm thickness layers. Similarly, 3D Systems use the Xerox M-series 880-nozzle PIJ head for its UV cure inkjet printed acrylic photopolymer systems to yield Z-layers as thin as 16 µm. Both are below 40-µm thick, above which people can discern a stair step between layers, but both deposit a larger flow of chemistry than is desirable for direct printing of electrical circuits. While the Ricoh Gen 3-E1 printhead generates 30 pl drops inkjet and the Xerox M-series fires 15 to 30 pl drops, inkjet printing of highly accurate circuits

Table 1: Comparison of Analog and Inkjet Capabilities

Print Method	Viscosity (Pa-s)	Layer Thickness (μm)	Feature Size (μm)	Registration Accuracy (μm)	Throughput (m^2/s)
Gravure	0.01-0.2	0.02-12	75	> 10	3-60
Flexography	0.01-0.05	0.04-8	80	20-200	3-60
Offset Lithography	5-100	0.5-2	10-50	> 10	3-30
Rotary Screen	1-700	1-100	20-100	> 25	2-3
Inkjet	0.001-0.03	0.01-0.5	10-50	< 10	0.01-0.5

Source: H. Kopola, VTT

typically use printheads capable of jetting fine drops in the 1 to 6 picoliter range.

Inkjet's advantages for printed electronics and photovoltaics are its capability to produce small feature sizes and thin etching and conductive deposition lines, and to position chemistry precisely without the deposition device contacting and stressing the print surface. These factors are particularly useful in producing for high efficiency solar cells and printed circuits.

Inkjet for fabrication and functional printing has suffered, however, from very slow print throughput, which has restricted its application for prototypes, samples, one of a kind items and very short-run production. While advances in inkjet printhead technology, however, promise to increase the throughput of both inkjet 3D fabrication and functional printing, it currently accounts for less than 2% of printed circuit production, while screen printing produces over 80%.

Applications for Digital Fabrication & Functional Printing

The applications for automated fabrication and functional printing are expanding in both number and size. Medical, Dental, Automotive, Aerospace, Design, Architecture, Prototyping Jewelry, Electronics, Photovoltaics, Lighting, Displays, Machine Tool, Electronic Product Identification, Packaging, and Construction Industries have adopted digital manufacturing and functional printing. While subtractive CNC digital fabrication methods have been manufacturing machine tool and parts for over sixty years, additive methods are providing parts for automotive, transportation and aerospace products. Digital fabrication has begun to expand beyond prototype and sample production to agile manufacturing and toward mass production. Align Technology Inc. produces over 60,000 digitally fabricated customized braces each day and counts over 1.7 million treated patients. Digital fabrication methods are producing replacement joints. Inkjet and inkjet like technologies are helping to manufacture LCD spacers & materials, OLEDs, color filters, back lighting, electrophoretic media, RFID tags and short-run electronic circuits and photovoltaics. Production jewelers have adopted inkjet modeling for generating casting models. Dentists are using inkjet and other digital fabrication technologies to create molds for crowns and replacement teeth. Advances in digital printing of organic and polymeric light emitting diodes hold the promise of lower energy and longer lasting lighting and video displays.

Inkjet printhead developers are increasing the performance and capabilities of inkjet printheads. Inkjet's throughput production print speeds have improved rapidly. Industrial fabricators are beginning to use rapid single-pass inkjet printing in addition to its slower scanning head cousin. The Xaar 1001 printhead has found application for single-pass label and ceramic printing. The recently announced Dimatix StarFire 1024 PIJ printhead offers droplet generation of 35 kHz for drop volumes of 26 pl in a robust head with ceramic and textile printing capabilities. Konica Minolta introduced three new heads, including the KM-1800i that prints 3.5 pl drops at a remarkably rapid 84 kHz rate with all nozzles firing at the same time. This 1776-nozzle head or its KM-1024i cousin with independent firing ink channels and 13pl primary drop that could serve to print RFID tags for commercial print and packaging applications.

Inkjet Chemistry and Materials for Digital Fabrication & Functional Printing

The functions of the chemistries for inkjet 3D fabrication and functional printing are:

- Conductive
- Dielectric
- Structural
- Protective
- Surface modification

We have identified five general categories of material that can be considered for jetting:

1. Melters
2. Thermoplastic polymer
3. Radiation cured formulations
4. Thermoset polymers
5. Inks

Substances with sharp melting points usually produce low viscosity fluids. Jetting requires merely operating the supply and head at a temperature where solidification will not happen, the material will not noticeably decompose and viscosity is consistent. Natural and synthetic waxes were in widespread use with solid ink printheads, so they have been readily imported to 3D technologies. There are thousands of organic and inorganic substances that could be processed by inkjet for 3D production, if there is a reason. There will be applications for molten metals – they have challenges not just from their high melting points, but also because of their very high surface tensions (tin's in air at 232°C is 660 dyne/cm). Controlling the atmosphere to avoid oxidation or hydrolysis will often be needed.

Thermoplastic polymers are highly desired as they are so frequently used for injection-molded items, and are the mainstay of FTM. Only those that with low melt viscosities and very low extensional viscosity so that the droplets will separate from the nozzle will prove valuable. Hot melt adhesives fit this model better. High-pressure jetting methods (e.g., valve jet) have more latitude.

Radiation cured inks are widely used for thin layer depositions (printing). 3D objects have different requirements. Totally new formulations have been needed to get the structural properties of solids when all the material is deposited by jetting, and the arsenal is rapidly expanding for both pure and pigmented polymer formulations, as well as systems of compatible mixtures that can be applied from different print heads in different ratios, or one on top of the next. Formulating is easier when the fluid is being used to bond a layer of particles spread by coating. Acrylic cross-linking is common, but the side groups are disparate.

Thermoset polymer formulations are not easily adapted – premature reaction is the end of life for the nozzle assembly, and maintaining the correct temperature differential between the nozzles and the object is tricky. However, polymers from 2 or 3-part formulations can be formed from deposition as separate layers or by jetting from separate nozzles.

Inks with fugitive carrier fluids permit the deposition of very thin layers for filling, changing surface characteristics or bonding particulate structures when the product should have porosity. In these cases drying becomes a process requirement. Forming conductive linkages from flash fusing silver inks should be obvious.

Summary

The report determined that the dispensing requirements for digital fabrication and functional printing applications vary widely. Inkjet printing for 3D fabrication requires the deposition of layers that are less than 40 µm along the build Z-axis. Deposit of 30-µm layers for opaque photo polymeric materials and 16-µm layers for transparent polymeric materials have demonstrated that evidence of the layering process is not discernable to the naked eye. The modified Xerox M-series PIJ bend mode head, which has 880 nozzles and ejects drops of 15 or 30 pl, produced even layers and smooth contours without evidence of process artifacts. Similarly, Objet printers using Ricoh Gen3PIJ piston mode printheads produce similarly smooth results, but the production process may require some layer shaving to yield the desired layer thickness. These dimensional targets will satisfy most visual, functional and radiation curing requirements for 3D fabrication applications. The ZPrinters, which use HP TIJ heads to fire polymer into tri-calcium phosphate powder coating, produce Z-layers over 100 µm thick. These typically require some post print curing and finishing.

The reports from inkjet printers of electronics indicate that drop volumes of direct printing with metallic nano-particle silver require drops in the range of 1 to 10 pl depending on the refinement of the circuits lines. The Fujifilm Dimatix DMP inkjet print systems have become standard equipment in almost 700 research and development facilities for testing and producing printed circuits. Dimatix offer its 16-nozzle MEMS cartridge printheads in both 1 and 10 pl versions. Other companies have developed similar systems.

PixDRO has developed production inkjet systems for fabricating solar cells using a variety of printheads to match process requirements. The Company offers Xaar 1001, Fujifilm Dimatix Spectra S-Class SE, SM, SL, (plus hot melt), SE3 and SX3, Konica Minolta KM 204, KM 256, KM 512 (plus hot melt), Trident ITW 256Jet-D.

Acid etching and caustics deposit for some circuit printing approaches requires deposition devices with a wide pH tolerance range. We determined that heads that were stainless steel could provide the greatest pH range. The Trident ITW 256Jet-D head offers tolerances in the pH range of 2 to 13, and the ability for a trained end user to dissemble the head for maintenance.

The chemical composition of inkjet printheads must have a surface energy that permits the flow of the print fluid with its surface tension through the head. The fluid must also have a surface tension that permits its adhesion with adjacent build layers. More viscose thermoplastic polymers will typically require heating to lower their viscosity to optimal levels for industrial inkjet printing. Heaters and thermistors are available for most industrial head. In addition to providing consistent temperature for jetting fluids, they can also provide hot melt capability. While Dimatix rates its DMC, D-series and most S-series heads at 70^{o}C it also offers heads with ratings to 135^{o}C. Xerox rates its M-series head as capable of handling fluid to 140^{o}C. The MicroFab MJ-SF piezo dispenser and the Geiger SMLD 300G valve jet are rated to handle fluids up to 250^{o}C. Canon Océ has applied for a patent for an inkjet type device that can tolerate fluid temperatures in excess of 1500^{o}C. The ability to dispense liquids at high temperatures greatly extends the range of what is possible with inkjet fabrication and functional printing.