

Solder Jet™ - Optics Jet™ - AromaJet™ - Reagent Jet - Tooth Jet and other Applications of Ink-Jet Printing Technology

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Abstract

Over the past twenty years, ink-jet printing technology has not only become a dominant player in the low cost color printer and industrial marking markets, it has become accepted as a precision microdispensing technology. With this broader view of the technologies encompassed by the term *ink-jet*, applications in electronics, optics, displays, virtual reality, medical diagnostics, and medical procedures have been developed using ink-jet fluid microdispensing as an enabling technology.

This paper will survey these nontraditional applications of ink-jet printing technology and focus on solder, optical polymer, aroma, reagent, and optical absorber printing, along with unique requirements and fluid properties associated with these applications. Other applications that will be discussed include genetic diagnostics, protein based drug discovery (proteomics), light emitting polymers, organic semiconductors, and electronic materials. Issues associated with jetting fundamentals versus system requirements will be highlighted.

Introduction

There are several key characteristics of ink-jet printing technology that make it a highly useful fluid microdispensing tool for industrial, medical, and other applications. It requires no tooling (no masks or screens are required); it is non-contact (allowing printing onto non-planar surfaces); and is data-driven (process information can be created directly from CAD information and stored digitally). Being data-driven, it is flexible. As an additive process it is environmentally friendly.

To be able to use ink-jet methods in an industrial process, the working fluid must be low viscosity, nearly Newtonian, and free of particles on the order of the orifice diameter. At first glance, these requirements may appear to be so restrictive as to eliminate the possibility of using of using ink-jet processes in industrial applications. On the other hand, if one looks at the ink used in an offset press, it is hard to imagine how ink-jet printing technology could be possible! By operating at higher or lower temperatures and

by selecting alternate materials and formulations, the number of industrial applications of ink-jet printing can be made surprisingly large.

Solder Jetting

Solder is the most commonly used material for electrical interconnections. It is deposited onto substrates using screen printing, vapor deposition, electroplating, or dipping into a bath of molten solder. Each of these methods has one or more of the following drawbacks: difficulty with small feature size, chemical waste, cost, fixed tooling, and control of the alloy. Being able to deposit micro-droplets of solder using an additive and a digitally controlled process would overcome many of these drawbacks. However, most solders of interest melt at temperatures normally considered too high for piezoelectric materials and molten solder is highly reactive with oxygen.

By using innovative drive waveforms and a design that allows for jetting into a locally inert atmosphere, MicroFab has overcome these difficulties and has demonstrated demand mode jetting of molten metals at temperatures up to 370°C,^{1,2} as is illustrated in Figure 1. Solder Jet™ technology has been used to generate bumps on integrated circuit pads at rates up to 600 per second, as shown in Figure 2. The image and character printed using solder balls shown in Figure 3 illustrates the data-driven nature of Solder Jet™ technology. Applications of Solder Jet™ technology include wafer and die bumping for flip-chip assembly or chip-scale packages (CSPs), 3-D packaging (wafer or die level), and photonics packaging.

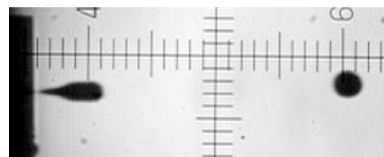


Figure 1. 100µm drops of molten solder being generated at 120 Hz and 200°C using piezoelectric ink-jet. (composite photo)

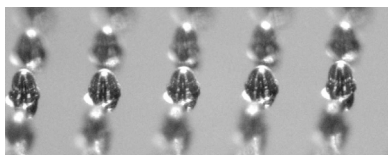


Figure 2. 100 μ m solder bumps ink-jet printed onto 100 μ m pads on 250 μ m centers at 400 per second.

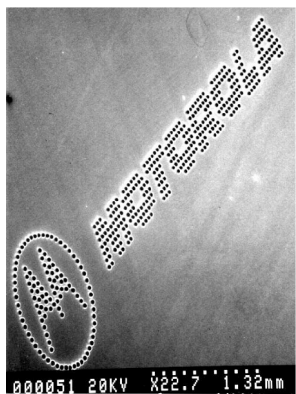


Figure 3. Pattern formed from 80 μ m bumps of solder.

Micro-Optical Elements

Micromirror arrays, vertical cavity lasers, optical switches, and fiber-optic interconnects can all take advantage of microlenses and other micro-optical structures to improve performance, lower cost, and/or increase ease of integration. Optical materials that can be patterned photolithographically have poor mechanical and thermal properties (i.e., they scratch easily and reflow at low temperatures). Individual lenses can be fabricated and mechanically placed, but this is a slow, expensive process.

A jettable optical material is constrained by the jetting requirements (viscosity <20cp), optical performance, and durability over time. Solvents cannot be used because the surface curvature of the printed optical element determines the optical performance, and solvent evaporation causes surface defects. Thermoplastics can be heated until they are low viscosity liquids and, when printed onto a substrate, freeze into the correct shape, but they have low durability and can cold-flow.

Using a UV thermoset epoxy, a wide variety of optical elements have been printed using Optics-Jet™ technology,^{3,4} as illustrated in Figure 4. Hemispherical microlens printing accuracies and reproducibilities are 1- 2% for diameter and focal length. Hemi-elliptical lenses are useful for edge-emitter lasers that have significantly different divergence angles in the two planes. Square lenses can have increased packing efficiency for light collection applications. Waveguides, in conjunction with printed active optical elements, could be used to produce photonic circuits. Ink-jet printing of active optical materials,⁵ such as the phosphors and light-emitting polymers, shown in Figure 5, is being pursued or studied by almost every display manufacturer world-wide.

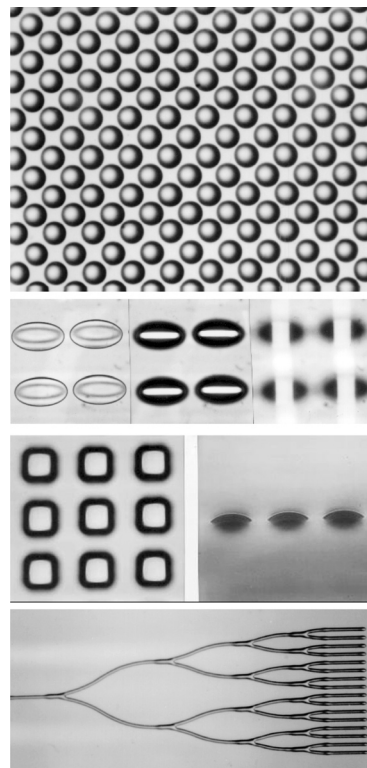


Figure 4. Micro-optical elements printed using ink-jet technology. Top, portion of 19,000 element array of 300 μ m lenslets; center-top, hemielliptical microlenses 284 μ m long, shown in substrate, fast-focal and slow-focal planes; center-bottom, 300 μ m square microlenses shown in focal plane and in profile; bottom, 100 μ m 1:16 branching waveguide.

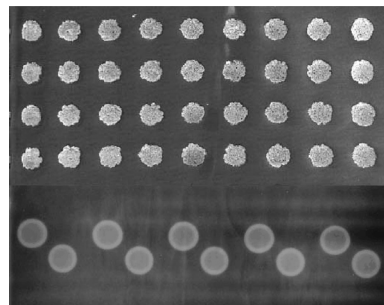


Figure 5. 90 μ m spots of phosphor particles (1 μ m, spherical) and 200 μ m spots of light-emitting polymer, printed using ink-jet technology.

Aroma Generation

Advances in computer and display technology have lead to great advances in visual simulation for applications ranging from military training to video games. Audio and motion simulation achieved acceptable capabilities decades ago. Smell, known to be very closely associated with memory and thus critical to realistic training, is simulated with almost stone age primitiveness by comparison. State-of-the-art in aroma generation is scratch and sniff, peal-and-sniff,

and large (i.e., slow response time) pneumatic systems. The first two methods can only be automated through the use of mechanical “fingers,” making them poorly suited for simulation.

Creating and projecting an aroma is a much simpler than turning off the aroma. However, the method used to create the aroma determines how easy it is to turn it off. Rapid turn-on is required for rapid turn-off. Use of ink-jet technology allows one to dispense, effectively instantaneously, a minute quantity of an odorant onto a heater element, vaporizing the odorant, again effectively instantaneously. If the heater is in a moving airstream, this aroma event can be directed towards the subject with no perceptible time lag. Because so little odorant is used to generate the aroma event, it dissipates rapidly and does not create a background in the room that interferes with subsequent aroma events.

Aroma Jet™ technology has been demonstrated in desktop computer peripheral devices (eight aromas), kiosks (16 aromas), and in diagnostic instruments (two aromas), as shown in Figure 6. Multiple aromas can be used as independent aromas (burning tire, coffee, lemon, pig sty, etc.), or as constituents in synthesizing a single aroma, such as a customized perfume. In synthesis mode, a simple computer interface can be used to control the formulation of the compound aroma to be generated. Remote synthesis has demonstrated over the internet by “sending” aroma formulations from Sydney, Australia to Plano, Texas.

Medical Instruments

Neurodegenerative Disease Diagnostics

In addition to virtual reality applications, Aroma Jet™ technology has been used in medical diagnostics. In the brain, the olfactory lobe is located near the hippocampus, a center of advanced cognitive function that deteriorates in many neurodegenerative diseases, such as Alzheimer's. Because of the colocation of these two area in the brain, degradation of the sense of smell can be used to detect onset of neurodegenerative diseases, hopefully at an early stage when treatment may be effective. The diagnostic instrument shown in Figure 6 has been used to measure the detection thresholds of over 200 people in a clinical setting. This information will be used to formulate the strategy for an early onset diagnostic test.

Laser Surgery

Ink-jet technology has been used to augment laser ablation of tissue. Although laser surgical tools have been in widespread use for decades, there are no approved hard tissue (i.e., tooth and bone) procedures. One of the drivers for using lasers in dentistry is that no anesthesia is required.

An inherent problem with laser ablation, whether of tissue or other materials, is its dependence on the absorption coefficient of the material being ablated. For lasers that a dentist can afford, tooth enamel has a high reflectance, a low absorbance, and a transmittance that is high enough to induce thermal nerve damage.



Figure 6. Implementations of Aroma Jet™ technology: top left, 8 aroma desktop computer peripheral; top right, 16 aroma kiosk; bottom, 2 aroma diagnostic instrument.

A solution to this problem is to use a thin layer of an absorbance enhancer on the surface to be ablated. The enhancer must be thin to minimize the thermal mass and resistance, thus its extinction coefficient must be very high.

For a single laser pulse, the enhancer can be painted onto the surface and allowed to dry. For most practical applications, multiple laser pulse must be used, so small amounts of enhancer must be applied at laser firing rates of 10-60 Hz. This is well within the temporal resolution of ink-jet technology. Figure 7 and Figure 8 show typical results for Tooth Jet technology.⁶ Laser power to produce removal of tissue is lowered by an order of magnitude. In Figure 7, if the enhancer is not jetted onto the tooth, almost all the energy is reflected and no ablation occurs.

Although the plasma shown in Figure 7 does not heat the tooth significantly, it does help transport material away from the surface and toward the jetting device. Thus one unique requirement for the jetting system for this application is that it be insensitive to the ejecta of the ablation process. In addition, the materials used in the ink must not only be safe when in contact with human tissue, but the ablation products formed from the ink of the ink must also be safe.

Glucose Testing

The same method used to ablate hard tissue can be applied to making small holes in the skin and without pain using a very inexpensive, low power laser. Frequent monitoring of glucose in diabetics is critical to their long term prognosis, but the pain associated with finger stick methods inhibits testing. Measurement of glucose in interstitial fluid is being pursued by a number of diagnostics companies, and pain-free laser based microporation is one approach being pursued.

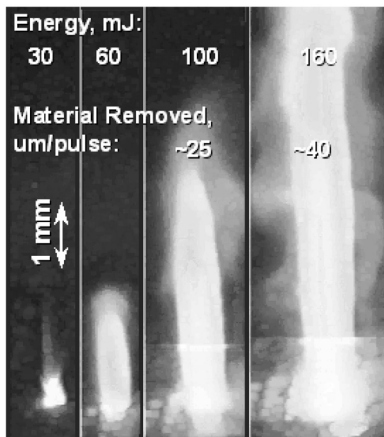


Figure 7. Dye microdrop (1nl) assisted laser ablation of a tooth. Despite instantaneous temperatures high enough to create a plasma, the increase in tooth temperature is $< 1^{\circ}\text{C}$.

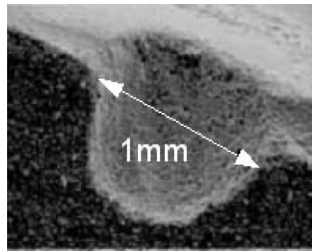


Figure 8. Hole drilled in human enamel using dye assisted laser ablation: Tooth Jet.

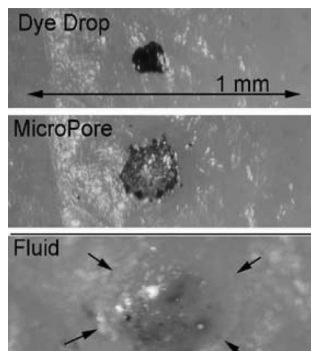


Figure 9. Poration of skin, using very low laser power, for pain free glucose measurement.

Medical Diagnostics

Antibody and Enzyme Based Diagnostics

Manufacturing of devices for biomedical diagnostics (both human and nonhuman) using ink-jet technology dates to the 1980's. Early research explored fabrication of glucose

sensors⁷ and antibody based assays.⁸ An example of these efforts is shown in the blood typing assay in Figure 10. Abbott laboratories has used similar methods to produce over a billion dollars worth of their TestPack™ product line, principally pregnancy tests, as shown in Figure 11. Although it was not brought to market, Boehringer-Roche developed a pilot production facility to manufacture small disposable diagnostic assays (MicroSpot™) that had up to 100 individual tests inkjetted into an area the size of your thumbnail, as shown in Figure 12.⁹



Figure 10. Four antibody test printed using ink-jet technology.



Figure 11. Two-antibody diagnostic assay printed using ink-jet technology.



Figure 12. Disposable diagnostic test that contains up to 100 tests printed using ink-jet technology.

Printing proteins using ink-jet technology usually requires special considerations in the materials used for the wetted surfaces. Proteins adhere to most surfaces and can lose their functionality (denature) thus controlling the wetted surface area and use of inert materials is usually required. Since many proteins are surface active, they can easily form a "skin" at the meniscus at the orifice of the ink-

jet device, preventing operation until it is rehydrated. Finally, almost all proteins of interest are rare and/or expensive, thus wastage and system dead volume are important design considerations.

DNA Diagnostics

More recent developments in medical diagnostics have focused on genetic applications. Screening for genetic information has employed DNA microarrays¹⁰ which use large (over 200,000) or small (less than 100) sets of known DNA sequences to interrogate a sample with unknown sequences. Where the sequences in the sample are identical to the known sequences, they bind and are detected optically, or by other means. A simulated DNA microarray is shown in Figure 13. Ink-jet printing methods have been used by a number of organizations in the fabrication of DNA microarrays by deposition of oligonucleotides that have been synthesized and verified off-line.^{11,12}

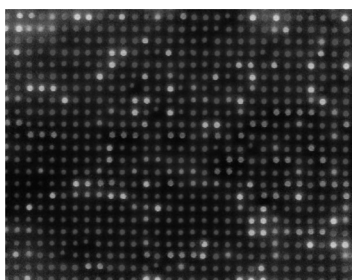


Figure 13. Simulated DNA array printed with ink-jet technology: 75 μ m spots on 200 μ m centers.

The chief difficulty in deposition of oligonucleotides is the number of fluids to be dispensed. In situ synthesis of DNA arrays using ink-jet technology greatly decreases the number of different fluids required. Only the precursor solutions of the four constituent bases (A, G, C, T) of DNA, plus an activator, are jetted.¹³ The chemical synthesis must take place in an anhydrous environment. Unfortunately, acetonitrile, the most common solvent for the bases, has a low viscosity and surface tension, causing difficulties both with jetting and with controlling the spreading on a nonporous surface. One solution to these problems is the use of a different solvent (i.e. reformulation of the "ink"). Another solution is the use of substrates with wetting and non-wetting regions (analogous to using special "paper").

Proteomics

One of the most prominent area of biomedical research currently is Proteomics. Where genetic information is the "blueprint" for biological activity, the detailed structure of proteins is the means by which most biological activity actual takes place.

Proteome Systems, Ltd. is using ink-jet methods to deconstruct proteins into their constituent peptides for analysis by mass spectroscopy.¹⁴ As illustrated in Figure 14, ink-jetting is used in a Chemical Printer to perform

microchemistry on proteins that have been separated by 2-D electrophoresis. Regions of < 1mm diameter can be analyzed in this way. Complex chemistries, such as those used to determine the nature of functional groups added to the peptide backbone (i.e., sugar and phosphate groups), can be performed on the microvolume scale. Even microarrays of antibodies or antigens can be printed onto selected proteins, resulting in a microarray being printed onto a macroarray.

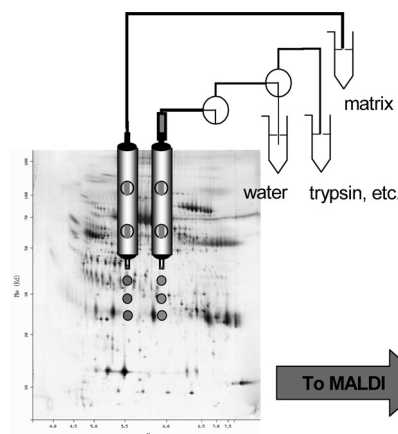


Figure 14. Schematic of a Chemical Printer for analysis of proteins. Dark areas are individual proteins displayed by 2-D electrophoresis.

Other Applications

Electronics Materials

Resistive polymer solutions (aqueous and organic solvent based) have been dispensed to form embedded resistors on the inner layers of multilayer circuit boards. Figure 15 shows a portion of a test vehicle on a 18"x12" core sheet. Resistors ranging from 100 Ω to several M Ω have been created using materials with resistivities as low as 200 Ω /sq. Printed resistors can be much smaller than discrete resistors.

Other electronic materials that have been dispensed using ink-jet technology include polyimide, organometallics, dielectrics, solder mask, and photoresistors.

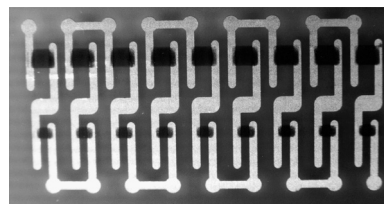


Figure 15. Conductive polymer resistors printed using ink-jet technology, <200 Ω /sq, ~1mm long.

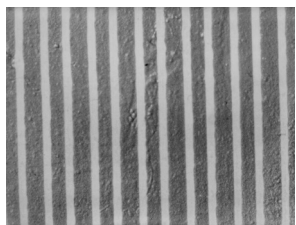


Figure 16. 250 μ m silver nanoparticle lines on a ferrite nanoparticle layer, both ink-jet printed, forming an antenna structure.

The use of nanostructured materials has the potential to increase the number of jettable electronic materials significantly, in particular for conductors, capacitors, resistors, and conductors, as illustrated in Figure 16. In addition to enabling rapid prototyping of electronic circuits, these developments could result in significant cost reductions in solar cell manufacturing¹⁵ and enable low cost organic electronics for applications such as RF identification tags.

Tissue Engineering

The ability to “write” biopolymers, cells, and growth factors (stimulants and inhibitors) with picoliter volume precision opens the possibility of digitally constructing engineered tissue using ink-jet printing technology. Bioresorbable polymers (e.g., PLGA) can be printed as a three dimensional structure, using methods currently employed in free-form fabrication, to form scaffolds in the desired tissue shape. Cells seeded into this scaffold would grow into this shape and gradually dissolve the polymer structure after it has been implanted, leaving only the tissue and no “foreign” materials for the body to reject. Figure 17 shows initial results obtained at MicroFab in creating small features of biosorbable polymers using ink-jet technology. Figure 18 shows human liver cells being dispensed using an ink-jet device. Viability testing of the cells after they had been dispensed indicated no immediate effect as the result of the dispensing process.

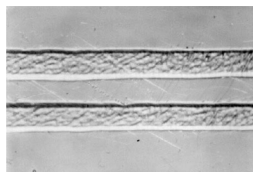


Figure 17. PLGA lines, 275 μ m wide, printed using ink-jet technology.

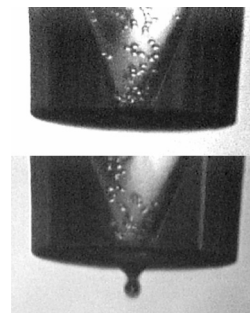


Figure 18. Human liver cells being dispensed using an ink-jet device.

Drug Delivery

The same family of bioresorbable polymers used in creating structures for tissue growth can be loaded with small molecules, steroids, proteins, peptides, genetic material, etc. to be used as therapeutic agents (i.e., drugs). Embedding these materials in the polymer allows for controlled release, with the polymer formulation and the geometry controlling the release profile. The simplest shape useful for drug delivery is spheres, which can be controlled to a very uniform diameter, or generated in a specific diameter distribution. Figure 19 shows effectively monodispersed 100 μ m spheres loaded with Taxol, an anti-cancer drug. Materials other than polymers, such as cholesterol, can also be used as the delivery vehicle.

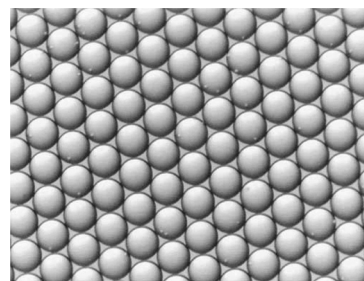


Figure 19. 100 μ m spheres of drug loaded (Taxol), biosorbable polymer.

MEMS Devices: Fabrication & Packaging

It is usually desirable to integrate a variety of functions into MEMS devices and their packages. A single device may contain a variety of technologies: optics, electronics, motion, chemistry, biology, etc. One application of the Solder JetTM, Optics JetTM, Reagent Jet, and other methods discussed above is to MEMS device fabrication and packaging. Other ink-jet based processes that could be used in MEMS device fabrication and packaging are discussed below.

Adhesives for sealing and bonding can be ink-jet printed. Simple line (Figure 20) and dot patterns can be applied. In addition, complex patterns that vary both the spatial and volume distribution of adhesive can be printed, as shown in Figure 21.

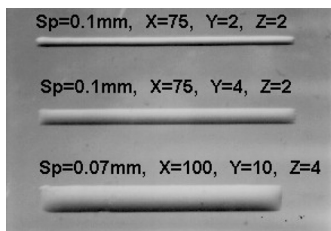


Figure 20. Printed thermoset epoxy lines (top is 300µm wide).

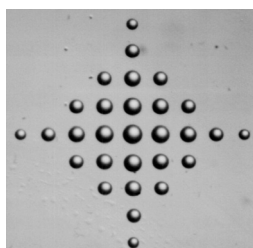


Figure 21. Variable volume printed adhesive spots, >80 :m.

Chemical sensor materials can be ink-jet printed onto MEMS devices for use in clinical diagnosis,¹⁶ manufacturing process control, environmental monitoring, etc. UV-curing optical epoxies used can be modified to be porous and doped with chemical indicators. These can then be printed as sensor array elements onto detection surfaces, such as the tips of imaging fiber bundles, providing a sensor configuration as exemplified by Figure 22.

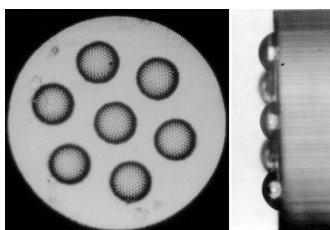


Figure 22. Array of 80µm sensor elements printed onto 480µm fiber-optic bundle.

Materials can be printed using ink-jet technology to modify the surface of a substrate to create an attachment or synthesis sites for bioactive molecules; to locally control of wetting or reactivity; or to create a time release flow obstructions. Jetting solid phase materials such as nitrocellulose (Figure 23), methyl cellulose, sol gels, and biotinylated PLGA have been demonstrated. Chromic acid has been used to modify polypropylene and acetone to modify polystyrene. Finally, cleavable linkers such as succinate, amide have been dispensed.

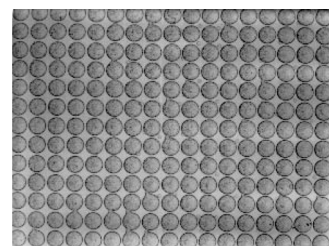


Figure 23. 120 µm spots of nitrocellulose printed on glass using ink-jet printing.

Conclusion

The capability of ink-jet printing systems to controllably dispense a wide range of materials for a diverse set of applications has been demonstrated. Materials dispensed include optical polymers, adhesives, solders, thermoplastics, light-emitting polymers, biologically active fluids, and precursors for chemical synthesis. In addition to the wide range of suitable materials, the inherently data-driven nature of ink-jet printing technology makes it highly suited for both prototyping and flexible manufacturing.

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Biography

David B. Wallace is currently a Vice President for MicroFab Technologies, Inc. He has a B.S.E. and M.S.M.E. from Southern Methodist, and a Ph.D. in Aerospace Engineering from the University of Texas at Arlington. He has over 25 years experience in complex fluid flow and has over 70 reports, papers, and presentations covering this work, plus 26 patents. He is an Adjunct Faculty member of the Biomedical Engineering Program, UTSw/UTA and ad hoc reviewer for ACS, ASME, and MRS.