

Towards Scalable 3D Microfabrication: Multi-Nozzle Electrohydrodynamic Printing of Ceramic Inks

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Short abstract

The fabrication of micro- and nano-scale structures is increasingly important for applications such as printed electronics, sensors, biomedical devices, optical components, and functional surfaces, where device performance strongly depends on feature size and spatial accuracy. Electrohydrodynamic (EHD) printing has emerged as a promising high-resolution additive manufacturing technique that employs electric fields to drive ink ejection, enabling droplet and jet sizes significantly smaller than the nozzle diameter while retaining the flexibility and material compatibility of printing-based processes. In this work, EHD printing is extended toward high-aspect-ratio three-dimensional microfabrication using multi-nozzle printheads to improve productivity. For this feasibility study, a submicron particle-based ceramic ink was used. By tuning the waveform with the EHD printhead driver, a stable droplet ejection was achieved at applied voltages between 1000 and 1200 V. Printing experiments were conducted on a printer from Notion Systems equipped with Scriona Gen 3-8 multi-nozzle printheads. The printed structures were deposited on indium tin oxide (ITO) coated glass substrates and characterized using optical microscopy and confocal surface topography measurements. Three-dimensional patterned structures were successfully fabricated via layer-by-layer deposition, achieving a feature size (resolution) of 10 μm and heights of up to 6 mm. The use of multi-nozzle printing significantly reduced fabrication time while maintaining stable jetting behaviour and high printing quality, demonstrating the potential of multi-nozzle EHD printing as a scalable approach for high-resolution three-dimensional microfabrication.

Keywords: electrohydrodynamic printing, microfabrication, nanoparticle inks, multi-nozzle printing, additive manufacturing

1. Introduction and background

The fabrication of micro- and nano-scale structures plays an increasingly important role in modern printing and manufacturing technologies, including printed electronics, sensors, biomedical devices, optical components, and functional surfaces. At these length scales, device performance is strongly influenced by feature size, geometry, and spatial accuracy, driving the demand for printing processes capable of delivering high resolution while maintaining flexibility and material diversity.

Conventional high-resolution fabrication techniques, such as optical lithography, can produce sub-micrometre features with excellent precision. However, these methods are inherently costly, rely on masks, and are largely restricted to planar substrates and a limited range of compatible materials. Subtractive micro- and nano-machining processes, including laser micromachining, offer greater geometric freedom but operate by material removal, which complicates multi-material integration and limits their applicability to a narrow set of machinable materials.

Additive manufacturing and printing-based technologies provide an attractive alternative by enabling maskless, digitally driven fabrication with direct material deposition. Among these methods, inkjet printing has become the most widely adopted micro-scale printing technology in industrial and research environments due to its low cost, ease of operation, and compatibility with a broad range of functional inks. Nevertheless, inkjet printing is fundamentally constrained in

resolution by nozzle diameter and pressure-driven droplet generation, typically limiting achievable feature sizes to approximately 30 μm . Further reduction in feature size is impeded by increased pressure requirements, ink viscosity limitations, and nozzle clogging, highlighting a fundamental resolution limit of pressure-based printing processes.

Electrohydrodynamic (EHD) printing has emerged as a promising high-resolution printing technology that bridges the gap between conventional inkjet printing and lithographic processes (Schneider et al. 2016). By employing electric fields rather than pressure to drive ink ejection, EHD printing enables the generation of droplets and jets with dimensions significantly smaller than the nozzle diameter, allowing micro- and nano-scale feature fabrication (Ferraresi et al. 2024). In addition, for inkjet, ink is pushed out of the nozzles by a pressure wave, while with EHD, ink is pulled out of the nozzles by the external electric field, which is much more energy effective, as all the energy put into the system is purely for drop ejection.

Besides, inkjet printing is typically limited to low-viscosity inks (4–20 cP), whereas EHD printing can accommodate a much broader viscosity range, from approximately 1 to 10^5 cP (Esa et al. 2022). Inks with higher particle loading are particularly attractive for three-dimensional material printing.

In a typical EHD printing setup, a high electric potential is applied between a conductive nozzle and a substrate, resulting in electrostatic forces that deform the ink meniscus into a Taylor cone and induce material ejection in the form of discrete droplets or continuous jets. Depending on process parameters and ink properties, EHD printing can operate in microdripping or cone-jet modes, supporting both drop-on-demand deposition and continuous direct writing. These capabilities make EHD printing particularly attractive for functional printing applications requiring fine conductive lines, patterned functional materials, and high spatial control.

Despite its demonstrated advantages, most EHD printing studies to date have focused on two-dimensional patterning or structures with limited vertical extension, typically on the order of a few micrometers (Miskovic et al. 2022). In addition, practical implementation remains constrained by low throughput associated with single-nozzle operation. Addressing these limitations is essential for advancing EHD printing from a high-resolution laboratory technique toward an industrially relevant additive manufacturing process.

In this work, EHD printing is extended toward the fabrication of high-aspect-ratio three-dimensional structures with heights of up to 6 mm. In addition, the scalability of the process is addressed through the use of Scrona Gen 3-8 multi-nozzle EHD printheads integrated into a single MEMS-based printhead architecture. Unlike conventional multi-nozzle arrangements based on parallel assembly of individual nozzle systems, the integrated MEMS design enables nozzle spacings as small as 150 μm while minimizing electrical and fluidic crosstalk between adjacent nozzles. This architecture enables highly parallelized printing and substantially improves fabrication throughput while maintaining stable jetting behaviour and high spatial resolution. By combining three-dimensional EHD printing with parallel nozzle operation, this study demonstrates the potential of EHD printing as a scalable manufacturing approach for advanced functional microfabrication.

2. Materials and methods

2.1 EHD printing

The printing system used in this study is a Notion Systems platform equipped with Scrona's printhead driver and Gen 3-8 multi-nozzle printheads. The ink was loaded under a pressure of approximately 160 mbar to establish a stable meniscus at the nozzle. A voltage in the range of 1000–1200 V was applied to generate a sufficiently high electric field for stable droplet jetting. The working distance between the nozzle and the substrate was approximately 0.8 mm.

The droplets were deposited onto indium tin oxide (ITO) coated glass substrates with dimensions of 50 × 50 mm and a thickness of 0.55 mm. The ITO layer had a sheet resistance of 40–60 Ω/sq and an approximate thickness of 35 nm.

2.2 Microstructural characterization

The printed structures were examined using a Keyence VHX-PFA H16 digital microscope. Surface topography and height measurements of the printed structures were further characterized using the confocal mode of a Sensofar microscope.

3. Results and discussion

Figure 1 shows the printed patterns (the “Scrona” logo) characterized using the Keyence VHX-PFA H16 microscope. Figure 1(a) presents the top view of the printed structure. The total length of the pattern is approximately 3.7 mm, while the width is below 1 mm. Figure 1(b) shows a tilted view of the printed pattern with the camera positioned at an angle of 30°, allowing visualization of the vertical structure and the layer-by-layer build-up of the printed features. Figure 1(c) presents an enlarged image at higher magnification of the framed region in Figure 1(b).

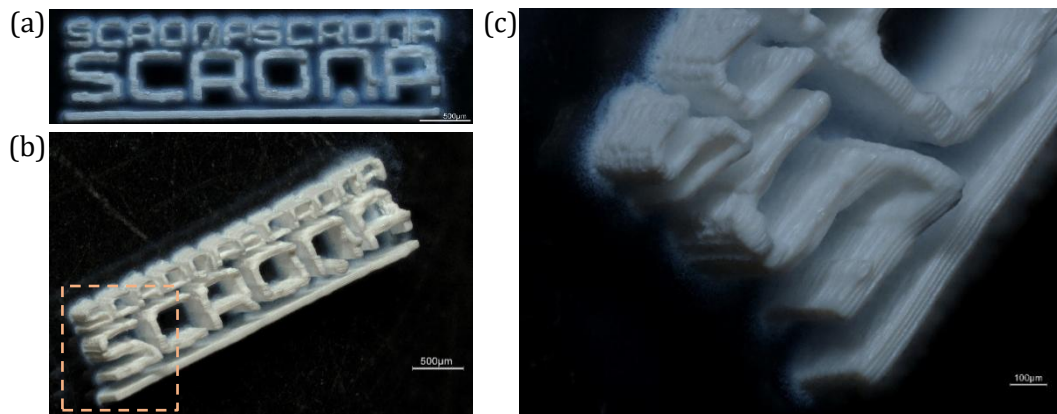


Figure 1: Printed patterns (“Scrona” logo) characterized by Keyence VHX-PFA H16. (a) Top view. (b) Tilted view at 30°. (c) Enlarged view of the framed region in (b).

The printed structures demonstrate well-defined pattern fidelity and stable material deposition during the printing process. The formation of continuous and uniform lines indicates that stable droplet jetting was achieved under the applied electric field conditions. The multi-nozzle EHD system enabled simultaneous deposition while maintaining consistent feature quality across the printed pattern.

It can be observed that the first printed layer exhibits relatively coarse resolution due to the higher wettability of the ink on the ITO glass surface. At the initial stage of printing, the ink spreads more easily upon contact with the substrate, resulting in broader line features. As additional layers are deposited, the printed features become more defined and the resolution improves. This improvement can be attributed to the change in surface interaction during the layer-by-layer build-up: subsequent droplets increasingly contact the previously deposited ceramic material rather than the ITO substrate. The ceramic surface exhibits lower wettability for the ink compared to the ITO glass, which limits lateral spreading of the droplets and promotes more confined material deposition. As a result, the structures become progressively better defined as the height increases.

Figure 2 shows the surface topography of the printed patterns measured using the Sensofar microscope in confocal mode. Figure 2(a) presents the topography map of the printed structures, where the colour scale represents variations in surface height. Figure 2(b) shows an enlarged image of the first two letters ("s" and "c"), allowing for clearer observation of the vertical morphology of the printed features. The confocal measurements reveal that the printed structures reach an average height of approximately 400 μm , with a maximum height of about 530 μm .

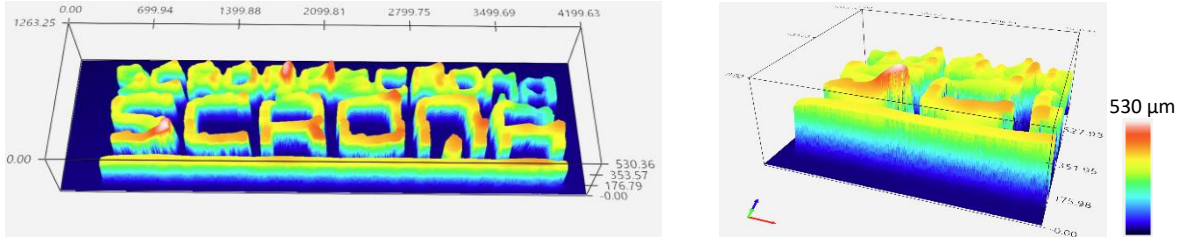


Figure 2: Printed patterns ("Scrona" logo) characterized by Sensofar microscopy. (a) Topography view. (b) Enlarged view of the letters "s" and "c".

Figure 3 demonstrates the fabrication of a rectangular pillar with a height of approximately 6 mm. The results confirm the capability of EHD printing to produce high-aspect-ratio structures through layer-by-layer deposition, with good structural stability and no significant collapse.

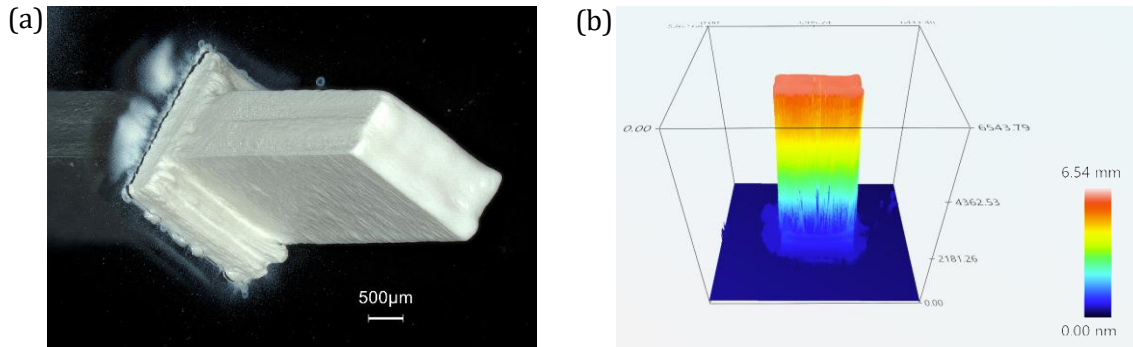


Figure 3: Printed rectangular pillar characterized by (a) Keyence optical microscopy (30° tilted view) and (b) Sensofar confocal microscopy for surface topography analysis.

4. Conclusions

This study demonstrates that EHD printing can be used to fabricate high-resolution three-dimensional microstructures through layer-by-layer deposition. The applied electric field, combined with proper working distances, enables stable droplet jetting without compromising printing quality. The process shows potential for building structures with even greater heights.

Furthermore, the use of multi-nozzle printheads significantly accelerates the printing process. The total fabrication time for the "Scrona" logo was below 30 minutes, highlighting the potential of multi-nozzle EHD printing for improved productivity and future industrial implementation.

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