High-Resolution Direct printing of Molten-Metal using Electrohydrodynamic Jet Plotting

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Abstract

In this paper, a high-resolution direct printing process was developed for molten metal using Electrohydrodynamic (EHD) printing technology. The effect of the critical printing conditions, such as voltage and printing speed, on the printing process was characterized. Compared with direct extrusion using pneumatic pressure, the EHD printing can effectively reduce the dimension of the printed filament down to less than 50 μ m with better quality of the printed features. We successfully applied EHD printing to print high-resolution 2D patterns and some high aspect-to-ratio 3D structures, which demonstrated the potential capabilities of EHD printing process in producing fine metal structures.

Keywords: Electrohydrodynamic (EHD), electrostatic field, metal printing, 3D printing

1 Introduction

Additive manufacturing [1-5] has a capability of rapid prototyping and small volume production of parts for many different industries (e.g. medical device, aerospace, automotive, etc.). The resolution of tradition additive manufacturing, such as 3D printing, stereolithography, fused deposition modeling (FDM) and selective laser sintering [1-2], is approximately no better than 50 μ m, and the improvement of the resolution from these processes is very difficult. For extrusion based printing processes, the nozzle size is the primary limitation for achieving high printing resolution. Adopting the nozzle with too small size will result in impractically high extrusion pressure, because the extrusion pressure scales up much faster when the nozzle size is scaled down.

High-resolution metal printing is vital for many engineering areas, ranging from additive manufacturing to electronics fabrication [6-7], since high precision manufacturing of metal patterns enables the production of complex structures with reduced cost and time. A few research groups studied drop-on-demand metal printing [7-12]. The common methods for the generation of the droplet are the pneumatic-driven, piezoelectric-driven, electromagnetism-driven and laser-driven printing processes. Pneumatic driven printing uses pneumatic pressure to generate droplets [8]. Piezoelectric-driven printing

uses a volumetric change in fluid created by the piezoelectric actuator to generate a pressure or velocity transient to print molten droplets [7,10]. The electromagnetism driven printing uses a piston that is accelerated by the magnet force to create droplets [11]. Laser-driven printing uses laser to melt thin metal layer to produce droplets [12]. Most of the current metal printing methods [7-14] are limited in resolution and the setup of the printing system is relatively complicated and expensive. New printing technology needs to be developed for high-resolution metal printing.

Electrohydrodynamic (EHD) printing [15-17] is a high-resolution printing approach, which liquid ink is subject to the electric field to form a Taylor cone and eject a droplet or jet. The size of the droplet or jet is much smaller than the size of the nozzle, which can effectively overcome the resolution limitation from the nozzle size. Currently, to the best of our knowledge, EHD printing processes were applied to polymers, metal nanoparticle inks, and biologic material [18-22], but no results has been reported on direct molten metal EHD printing.

In this work, we have successfully applied EHD printing for low melting point metal (Field's alloy) for micro-scale fabrication of metal features. High-resolution metal filaments with the smallest diameter about 50 μm were successfully printed. High aspect-of-ratio 3D metal structures and metal bridges were also fabricated that have great potentials in electronics as the conductive interconnects. Compared with direct extrusion with pneumatic pressure, EHD printing significantly improves the printing resolution down to less than 50 μm and provides much better quality of the printed features.

2 Electrohydrodynamic printing system

The EHD printing system includes four subsystems, which are a high voltage supply, a pneumatic dispensing system, a heating system and a precision three-axis motion system. The high voltage is connected to the printing nozzle, and the ground is connected to the ground electrode placed under the substrate. The pneumatic dispensing syringe is used to provide pressure for liquid flow from the printing nozzle. The syringe is heated by a heating rope with the temperature measured from a thermal couple. A PID temperature controller is used to control the syringe temperature at the desired level. The precision motion system is used to control the displacement between the printing head and the substrate in XYZ axis with an accuracy and repeatability of 100nm. A camera with a resolution of 0.5 μm is used to monitor the printing process. The material used in this study is

Figure 1: Schematic of EHD printing system

Field's Metal (32.5% Bismuth, 51% Indium, 16.5% Tin), which is a eutectic alloy with a melting point of 60 °C and an electrical resistivity of $0.522\mu\Omega\cdot\text{m}$.

3 Characterization of EHD metal printing process

To characterize the effect of EHD printing and compare it with pneumatic extrusion-based printing, we performed printing experiments using a nozzle with an inner diameter of $160\mu\text{m}$ and an outer diameter of $250\mu\text{m}$ and keeping syringe temperature at 193 °C to achieve a good ink flowability. A standoff distance between the nozzle and the substrate is selected to be $100\mu\text{m}$ to reduce the impact of the ink stream and ink spreading on the substrate

When only applying pneumatic pressure to the syringe, for a molten metal, a large pressure is required for ink extrusion, due to the large viscous force from the molten metal. When gradually increasing the pressure, the molten metal becomes to be ejected from the nozzle and forms a droplet at the nozzle tip because of the large surface tension force and viscous force of the molten metal. The size of the droplet continues to grow when the pressure is gradually increased, and detaches from nozzle to form a bulk drop. As can be observed from Figure 2 (a), the printed droplets are at the scale of millimeters, which is much large than the nozzle dimension. After further increasing the pressure to a threshold level, which is 10 psi in our experiment, continuous jet will form and be printed from the nozzle. The jetting speed of the molten Field's alloy is very fast. The stage speed needs to match the jet speed to achieve the uniform line and avoid the distortion (breaking line, wave line, etc.). The extruded metal lines have diameters of a few millimeters, as shown in Figure 2(b, c). Overall, the direct pneumatic extrusion cannot provide high printing resolution, and the feature uniformity is not satisfactory.

Figure 2:(a) Pneumatically extruded droplet under pressure of 5psi. (b) Printed metal lines at a pressure of 10psi and speed of 20mm/s. (c) Printed metal line with a pressure of 10psi and speed of 40mm/s.

Figure 3: (a) Cone shape during the EHD printing process. (b) and (c) Printed metal line at printing voltage of 1000v and 2000v with a fixed printing speed of 1mm/s. (d) and (e) Printed metal line at printing speed of 2mm/s and 6mm/s with a fixed printing voltage of 2000v

To achieve better printing resolution, EHD printing is applied for the fabrication of the molten Field's Metal. Applying a voltage to the ink produces an electrostatic force, which pulls the ink out from nozzle to form a cone shape (i.e. Taylor Cone) and ejects a filament from the Taylor cone at the high enough voltage, as shown in Figure 3(a). When the applied voltage is large enough, even without the pneumatic pressure, the electrostatic force can overcome the surface tension and viscous force of the molten metal and eject the ink onto the substrate. The experiments were performed to characterize the EHD printing process and find the working voltage for the stable EHD printing. When the applied voltage (i.e. 1000V in this setup) is not large enough, a discontinuous metal line is printed on the substrate (Figure 3b), which comes from small ink flow rate due to inadequate electrostatic force. After further increasing the voltage to 2000v, a fine straight line with a small diameter of less than 50 μm is achieved (Figure 3c). Printing speed is the other critical factor that will affect the printing results. When keeping a constant voltage (2000v in this experiment), low printing speed will result in material accumulation at the nozzle tip and large line width of printed feature, as shown in Figure 3(d). Too high printing speed will cause line necking and discontinuity of the printed features (Figure 3e)).

4 High resolution EHD printing of metal structures

Using EHD printing process, we successfully fabricated high resolution 2D and 3D metal features. For 3D printing, the temperature of the molten metal needs to be selected carefully, so that the printed metal ink solidifies quickly without re-melting the previously printed structures. Figure 4(a) shows a directly printed 2D metal pattern, which has very uniform line width, about 80-90 μm . The overall resistance of this 2D pattern is about 20 ohms, which gives a resistivity of 0.6 $\mu\Omega\text{m}$ and has good potentials to be used in the direct fabrication of interconnects in electronics. Figure 4 (b) shows a two-layer scaffold structure by EHD metal printing. By printing along the vertical direction, high aspect of ratio pillar was directed printed onto the substrate. Figure 4(c) shows a printed vertical metal pillar with the diameter about 90 μm , and the height about 10mm, which give an aspect-to-ratio as high as 100. With

proper overlap of filaments and repeating the printing sequences layer by layer, 3D structures can be printed directly with good resolution.

Figure 4(d) demonstrate the printed thin wall structure with the wall thickness of 100 μm and wall height of about 3mm. Moreover, direct EHD metal printing can create bridging metal structures, as shown in Figure 5(e), which has potential applications in wire bonding and high quality interconnects in chipboard manufacturing and electronics manufacturing. Compared with the the best feature resolution (X/Y resolution of 0.012- 0.016 inch or 305-406 μm)

Figure 4: (a) Metal wire (b) Microscope image of two layer scaffold structure (c) Vertical metal wire (d) Thin wall (e) Microscope image of two adjacent layer of thin wall (f) metal bridge structure

from the start-of-art 3D metal printing machines, such as Stratasys Direct, Inc., the EHD metal printing offer much better resolution capabilities.

5 Conclusions

In this study, a direct molten metal EHD printing process was developed. The effect of the critical printing conditions, such as electrostatic field and printing speed, on the printing process was characterized, and the representative results were demonstrated. In EHD printing, the resulting electrostatic force can continuously print the molten metal even without using any pneumatic pressure. Compared with direct extrusion using pneumatic pressure, the EHD printing can effectively improve the printing resolution to better than 50 μm and achieve better quality of the printed features. We successfully applied EHD printing to print high-resolution 2D patterns and high aspect-to-ratio 3D structures, which demonstrated its potential capabilities in producing fine metal structures.

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