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High-Resolution Electrohydrodynamic (EHD) Direct Printing of Molten Metal

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Abstract

In this paper, we developed a high-resolution direct printing process for molten metal using Elctrohydrodynamic (EHD) printing technology. We characterized and verified the effect of the electric field on the printing process, which can continuously print fine molten metal filament from the nozzle without requiring any pneumatic pressure. By comparing direct extrusion with pneumatic pressure and EHD printing with a voltage, we found that the EHD printing can effectively reduce the printed filament dimension down to less than 50μm and achieve better quality (uniformity and shape) of the printed features. We successfully applied EHD printing to print high-resolution 2D patterns and some high aspect-ratio 3D structures, which demonstrated the potential capabilities of EHD printing process in producing fine metal structures and microelectronic fabrication.

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

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1. Introduction

Additive manufacturing [1-5] has a capability of rapid prototyping or small volume production of parts for many different industries (e.g. medical device, aerospace, automotive, etc.). The resolution of traditional additive manufacturing such as 3D printing, stereolithography, fused deposition modeling (FDM), electron beam melting(EBM) and selective laser sintering [1-2] is approximately no better than 50μm, and the improvement of the resolution of these processes is very difficult. For extrusion based printing processes, the nozzle size of the print head 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

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size is scaled down. For EBM or laser based process, many factors will limit the resolution (e.g. beam spot size, thermal diffusion, etc.) and usually it is very difficult to have improvements on those factors.

High-resolution metal additive manufacturing is vital for many engineering areas, including electronics industries [7], since high precision manufacturing of metal patterns enables the production of complex integrated circuits with reduced fabrication cost, time and post processes at the same 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 a simple mechanism (i.e. pneumatic pressure) to generate droplets. This method has very limited resolution on the printed droplet, as the size of the droplet is usually several times larger than the nozzle size [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]. In Zenou's group, a laser-induced forward transfer (LIFT) method is used to melt thin metal layer to produce droplets [12]. Lei's group have created a new technology that injects molten liquid with a certain speed into another immiscible fluid to create 1 mm diameter droplets [13]. A few groups studied continuous droplet printing using high-frequency mechanical vibration [7]. Typically, the diameter of the droplets is no better than 50um. Hsieh's group is using FDM method to extrude molten metal line, and the resolution of extruded line is about 500µm [14]. All of the current metal printing methods do not have a high 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, in which the liquid ink is subject to electric field and forms a Taylor cone and ejects a droplet or jet. The size of the droplet or jet is much smaller than the size of the nozzle. Therefore EHD printing method 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 [18-20], but no results have 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 size about 50 µm were successfully printed. High aspect-ratio 3D metal structures and metal bridges have also been fabricated that have great potentials to be used in microelectronic manufacturing as the conducting connectors. Compared with direct extrusion with pneumatic pressure, EHD printing effectively improves the resolution of the printed filament down to less than 50µm 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 schematic of the EHD printing system setup is shown in Figure 1. For the voltage supply, the high voltage is connected to the printing nozzle, and the ground is connected to the ground electrode that is made of an aluminium-coated silicon wafer placed under the substrate. The pneumatic dispensing syringe is used to provide pressure for liquid flow from the printing nozzle, which is controlled by an air pressure regulator. A heating rope is wrapped around the syringe, which can heat the material up to 385°F. With the temperature feedback from a thermal couple, a PID temperature controller is used to control the syringe temperature at the desired level. The precision motion system is located on an optical table to reduce the environmental vibration, and is used to control the printing head and stage movement 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

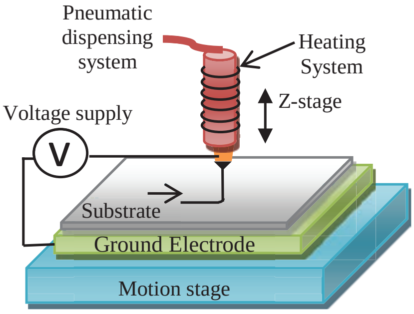

Fig. 1. Schematic of EHD printing system