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Design of Integrated Ring Extractor for High Resolution Electrohydrodynamic (EHD) 3D Printing

Yiwei Han and Jingyan Dong

Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC
jdong@ncsu.edu

Abstract
This paper presents an integrated ring extractor design in electrohydrodynamic (EHD) printing, which can overcome the standoff height limitation in the EHD printing process, and improve printing capability for 3D structures. Standoff height in EHD printing will affect printing processes and limit the height of the printed structure when the ground electrode is placed under the substrate. In this work, we designed and integrated a ground ring electrode with the printing nozzle to achieve a self-working printer head, which can start and maintain the printing process without the involvement of the substrate. We applied FEA method to model the electrostatic field distribution and strength to direct the ring extractor design, which has the similar printing capability with the system using substrate as the ground electrode. We verified the ring electrode design by experiments, and the results from experiments demonstrated a good match with results in the FEA simulation. We have characterized the printing processes using the integrated ring extractor, and successfully applied newly designed ring extractor to print polycaprolactone (PCL) 3D structures.

Keywords: Ring extractor, Electrohydrodynamic (EHD) printing, Electrostatic field, 3D printing.

1 Introduction

Additive manufacturing (Gibson 2009, Kruth 1998, Melchels 2011, Beaman 1997, Hutmacher 2004) is capable of small volume production and rapid prototyping of parts in many applications, including aerospace, medical device, electrical device and automotive components. Most of the traditional additive manufacturing technologies, such as electron beam melting, selective laser sintering, 3D printing, stereolithography and fused deposition modeling (Gibson 2009, Kruth 1998), have limited resolution (approximately 50μm). The improvement of their resolutions is very difficult, because the limitations of those manufacturing processes are intrinsic. For example, for printing or extrusion based process, the size of printing nozzle is the primary limitation for its printing resolution. When scaling down the nozzle size for better resolution, the extrusion pressure or force will be scaled up to become impractically high for most liquid phase ink. For the electron beam or laser based

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process, many factors have limited its resolution, for example, thermal diffusion, beam spot size and power size.

High-resolution additive manufacturing is critical for many engineering applications. High precision manufacturing requires micron-scale accuracy and high quality surface finishing in order to save significant time and cost in the post-processes. Low part accuracy and surface finish can significantly limit the application of current additive manufacturing processes in the production of high precision industrial parts. In the tissue engineering application, micro-scale structures on scaffolds can provide many advanced functions to regulate cell response to the scaffolds, for examples, cell contact guidance and cell alignment (Tan 2002, Kan 2012). These resolution requirements have driven us to develop a new printing method to achieve high resolution 3d printing for high precision components.

Electrohydrodynamic (EHD) printing (Park 2007, Mishra 2010, Poellmann 2011) is a high resolution printing method, in which liquid phase ink is subject to an electrostatic field to form a Taylor-cone and produce a droplet or fine jet from the apex of the cone. The droplet diameter or jet size are significantly smaller than the nozzle size, indicating that EHD printing can overcome the resolution limitation from the nozzle size. Currently, most of the EHD printing focus on the 2D patterns, and only some initial investigation towards 3D fabrication (Wei 2013, Wei 2014). By using phase change ink, 3D micro-scale structures (Han 2015, Han 2014, Wei 2014) have been successfully fabricated. However, for such 3D structures, their maximum height was limited by the distance between the nozzle tip and the substrate. For most of the existing printing system, the ground electrode was placed under the substrate. As 3D structures are built up layer-by-layer, the nozzle-substrate gap has to be changed accordingly. It is very challenging for process control to keep constant electrical field strength. Moreover, if tall structures need to be printed, the resulting large nozzle-substrate gap may require a voltage that is too large to be provided. On the other hand, the printed structures on the substrate will change the original electrodes configuration, since the dielectric constant of the printing materials is different from that of air.

A few study investigated the integration of ground electrodes into the printing head (Tse 2014, Lee 2012, Kim 2010, Lee 2013, Park 2008). In the Leo Tse's study (Tse 2014), a new double layers ring electrode was designed, which has an insulating layer between two conductive layers. The Upper layer connected with a high voltage supply and the bottom layer is connected with ground. Some other efforts include an electrode plate with a center hole, which was placed between the substrate and printing tip (Lee 2012, Kim 2010, Lee 2013). A cone shape lens around the printing nozzle was also used to concentrate the electrostatic field near nozzle (Park 2008) for EHD printing. Those researches on integrated electrode design reduce the effect from standoff height and improve controllability of printing processes. However these previous studies only focused on the characterization of designed electrode for 2D patterns (droplets or lines). In order to improve EHD printing capabilities for 3D structures, a new ground electrode needs to be designed to satisfy 3D structures printing processes.

In this work, we have designed a new an integrated ring extractor as the ground electrode overcome the standoff height limitation in the EHD printing process. We applied FEA method to model the electrostatic field distribution and strength of the ring extractor design to find feasible design parameters (ring diameter, distance between tip and ring, standoff size) for EHD printing system. We have experimentally verified the designed ring extractor, and the results from experiments have a good agreement with that from FEA analysis, which indicates the ring extractor is capable of replacing the ground electrode under the substrate in traditional configuration and overcoming the limitation of standoff height. We successfully applied EHD printing process for a thermoplastic biodegradable polymer polycaprolactone (PCL) with the designed integrated ring extractor to achieve micro-scale high resolution 3D structures.