Drop-on-Demand 3D Metal Printing

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ABSTRACT

We present a novel method for drop-on-demand (DOD) printing of 3D solid metal structures using liquid metal droplets. This method relies on magnetohydrodynamic (MHD)-based droplet generation. Specifically, a pulsed magnetic field, supplied by an external coil, induces a MHD-based force density within a liquid metal filled ejection chamber, which causes a droplet to be ejected through a nozzle. Three-dimensional (3D) solid metal structures of arbitrary shape can be printed via layer-by-layer patterned deposition of droplets with drop-wise coalescence and solidification. We introduce this prototype MHD printing system along with sample printed structures. We also discuss the underlying physics governing drop generation and introduce computational models for predicting device performance.

Keywords: Magnetohydrodynamic droplet ejection, droplet on demand printing, 3D printing of molten metal, additive manufacturing, thermo-fluidic analysis, molten aluminum.

1 INTRODUCTION

Drop-on-demand inkjet printing is a well-established method for commercial and consumer image reproduction. The same principles that drive this technology can also be applied in the fields of functional printing and additive manufacturing. Conventional inkjet technology has been used to print a variety of functional media, tissues and devices by depositing and patterning materials that range from polymers to living cells [1, 2]. The focus of this work is on the extension of inkjet-based technology to the printing of 3D solid metal structures [3, 4]. Currently, most 3D metal printing applications involve deposited metal powder sintering or melting under the influence of an external directed energy source such as a laser (e.g. Selective Laser Sintering[5] and Direct Laser Metal Sintering[6]) or an electron beam (e.g. Electron Beam Melting[7]) to form solid objects. However, such methods have disadvantages in terms of cost and complexity, e.g. the need to mill the metal in advance of the 3D printing process.

In this work, we introduce a novel approach to additive manufacturing of metal structures that is based on the principles of magnetohydrodynamics. In this method, a spooled solid metal wire is fed continuously into a ceramic heating chamber of an MHD printhead and melted to form a reservoir of liquid metal that feeds an ejection chamber via a capillary force as illustrated in Fig. 1. A coil surrounds the

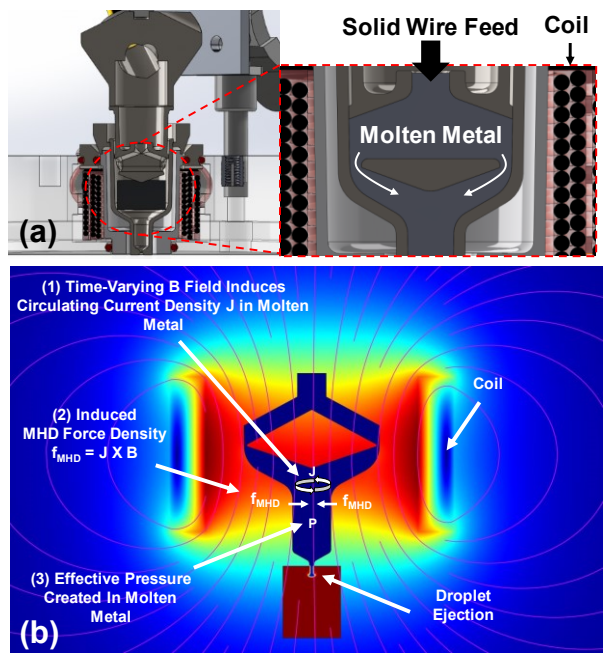

Figure 1: Essential components of the MHD printhead (a) cross-sectional view of printhead showing flow of liquid metal. (b) simulation model showing the magnetic field generated by a pulsed magnetic coil as well as an ejected droplet of liquid aluminum.

ejection chamber and is electrically pulsed to produce a transient magnetic field throughout it, which induces a transient electric field within the liquid metal. The electric field results in an induced circulating current density, which couples to the applied magnetic field and creates a Lorentz force density (f_{MHD}) within the chamber that acts to eject a liquid metal droplet out of the orifice. Ejected droplets travel to a substrate where they coalesce and solidify to form extended solid structures. Three-dimensional structures of

arbitrary shape can be printed layer-by-layer using a moving substrate that enables precise patterned deposition of the incident droplets. This technology has been pioneered and commercialized by Vader Systems (www.vadersystems.com) under the tradename MagnetoJet. The advantages of a MagnetoJet printing process includes the printing of 3D metallic structures of arbitrary shape at relatively high deposition rates and with low material costs. In this work, we discuss the MagnetoJet prototype printing process and demonstrate sample 3D printed structures. We also introduce computational models that enable rational design and prediction of device performance.

2 PROTOTYPE DEVICE DEVELOPMENT

Prototype printing systems with a single ejection orifice have been developed and characterized by Vader Systems. A key element of the 3D printing system is a printhead composed of a reservoir where metal liquefaction occurs, and a lower ejection chamber with a submillimeter orifice, both made from refractory materials, and a water cooled solenoidal coil that surrounds the orifice chamber as shown in Fig. 1a. Numerous printhead designs have been iterated to explore the effects of ejection chamber geometry on the filling behavior as well as droplet ejection dynamics. The prototype systems have successfully printed solid 3D structures made from common aluminum alloys as shown in Fig. 2, with droplets that range from 50 µm to 500 µm in diameter depending on the orifice diameter and geometry. Sustained droplet ejection rates from 40-1000 Hz with short bursts up to 5000 Hz have been achieved.

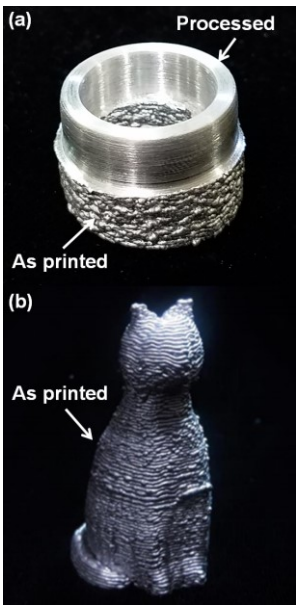

Figure 2: Printed 3D structures: (a) ring showing as printed base and processed upper portion, and (b) cat.

2.1 Computational Models

As part of the prototype device development, computational simulations were performed in advance of specific prototype fabrication to screen design concepts for performance, i.e. droplet ejection dynamics, droplet-air and droplet-substrate interactions. In order to simplify the analysis, two different complimentary models were developed that utilized computational electrodynamic (CE) as well as computational fluid dynamic (CFD) analysis. In the first model, a coupled CE and CFD analysis was used to study MHD-based droplet ejection behavior and effective pressure generation. In the second model, thermo-fluidic CFD analysis was employed to study the patterning, coalescence and solidification of droplets on the substrate.

We developed a coupled CE and CFD model using the COMSOL Multiphysics 5.2a software package (www.comsol.com) to study MHD-based droplet ejection. Specifically, COMSOL's AC/DC and laminar two-phase flow physics modules were coupled to solve the underlying MHD equations. Initial prototype designs were screened using a 2D axisymmetric model as shown in Fig. 1b**.** The magnetic field distribution generated by the electromagnetic coil as well as the volume fractions of liquid aluminum and air are shown in the same figure. The volume fraction of the molten metal is denoted by a dark blue region and the inert atmosphere is denoted by dark red region directly below the orifice. Several prototype printheads were fabricated based on simulation results, which identified viable drive voltage waveforms, ejection orifice dimensions etc. A droplet ejection rate of 1 kHz was achieved using early stage prototypes, which produced an equivalent material deposition rate of approximately 540 g/h.

Following the magnetohydrodynamic analysis, the equivalent pressure profile was extracted from the first model and used as input to a second CFD-based analysis that was designed to explore the transient dynamics of droplet ejection as well as droplet-substrate interactions. The Multiphysics CFD program FLOW3D (www.flow3d.com) was used for this analysis. Simulations were performed to understand the effects of wetting in and around the nozzle on droplet ejection. By varying the fluid initialization level, both inside and outside the orifice and allowing for a time period between pulses as determined by the pulsing frequency, we were able to identify differences in the characteristics of the ejected droplets including size and velocity.

2.2 Droplet Deposition

In the MagnetoJet printing process, droplets are ejected with a velocity that typically ranges from 1-10 m/s and cool slightly during flight before impacting the substrate. The ability to control the patterning and solidification of droplets on the substrate is critical to the formation of precise 3D solid structures. Accurate patterning is achieved using a high resolution 3D motion base. However, controlling solidification to create well-formed 3D structures without undesired layering artifacts or voids is a complex challenge as it involves the control of (a) thermal diffusion from the droplet to the surrounding materials as it cools, (b) the size of the ejected droplet, and (c) the droplet ejection frequency, among other parameters. By optimizing these parameters, the droplets will be small enough to provide high spatial resolution of printed features, and they will retain sufficient thermal energy to facilitate smoother coalescence with the

neighboring droplets. One way to confront the thermal management challenge is to maintain a heated substrate at a temperature that is below, but relatively close to the solidification temperature. This reduces the temperature gradient, which slows the diffusion of heat from the droplets thereby promoting coalescence and solidification to form a smooth solid 3D mass. A parametric CFD analysis was performed to explore the viability of this approach. As noted, the FLOW-3D CFD program (www.flow3d.com) was used for the analysis.

We investigated droplet coalescence and solidification on a heated substrate as a function of the center-to-center spacing between droplets as well as the droplet ejection frequency. In this analysis, spherical droplets of liquid aluminum impact a heated stainless steel substrate from a height of 3 mm. The droplets have an initial temperature of 973 K and the substrate is held at 900 K, slightly below the solidification temperature of 943 K. Fig. 3 shows droplet coalescence and solidification during the printing of a solid line when the droplet separation distance is varied from 100 µm to 400 µm in steps of 50 µm, with the ejection frequency held constant at 500 Hz. It is worth noticing that when the droplet separation exceeds 250 µm, solidified segments with cusps appear along the line. At a separation distance of 350 µm or greater, the segments become discrete and the line has unfilled gaps, which is undesired for the formation of smooth solid structures. We performed a similar analysis for substrates held at lower temperatures, e.g. 600 K , 700 K etc. It was observed that while 3D structures can be printed on cooler substrates, there are more artifacts such as lack of strong coalescence between subsequent layers of deposited metal. This is due to the increased rate of loss of thermal energy in the deposited droplets. Thus, the ultimate choice of substrate temperature can be determined based on an acceptable print quality of an object for a given application.

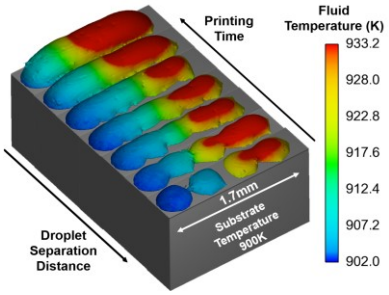

Figure 3: Droplet coalescence vs. center-to-center separation: formation of a 2mm line for droplet spacing of 100µm to 400µm in steps of 50µm.

3 CONCLUSIONS

Prototype MHD-based liquid metal DOD printheads have been developed that are capable of printing 3D solid metal structures of arbitrary shape. Three-dimensional aluminum alloy structures have been successfully printed using layer-by-layer patterned deposition of submillimeter droplets that are ejected by an MHD force at up to kHz frequencies. Material deposition rates of hundreds of grams per hour are achievable with one orifice. The commercialization of this technology is well underway but many challenges remain in realizing optimum printing performance in terms of throughput, efficiency, resolution and quality. Computational models have been developed to address these challenges and evaluate design concepts. These models have guided the experimental work in advance of fabrication. The ability to print 3D metal structures on demand holds potential for transformative advances across a broad range of industries such as automotive and aerospace. The modeling approach presented herein enables the rational design of MHD printing systems and should be of considerable use in the development of novel related applications.

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