Magnetohydrodynamic Liquid Metal Jet Printing

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ABSTRACT

We introduce a novel method for drop-on-demand (DOD) printing of molten metal droplets into 3D objects. In this approach, solid metal is pre-heated within a printhead to form a reservoir of liquid metal that feeds a nozzle chamber. Once the chamber is filled, a pulsed magnetic field is applied that permeates the chamber and induces a magnetohydrodynamic (MHD)-based pressure pulse within the liquid metal that causes a portion of the metal to be ejected through the nozzle. The ejected metal forms into a droplet with a velocity in the range of several meters per second, depending on the applied pressure. The droplet is projected onto a substrate where it cools to form a solid mass. 3D solid structures can be printed via patterned deposition and drop-wise solidification. In this presentation, we demonstrate a prototype MHD printing system along with sample printed structures. We discuss the underlying physics governing drop generation and present computational models for predicting device performance.

Keywords: Magnetohydrodynamic droplet ejection, DOD printing of molten metal, 3D printing of molten metal, additive manufacturing.

1 INTRODUCTION

Drop-on-demand inkjet printing is a mature technology for commercial and consumer image reproduction. However, it represents an emerging technology for 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. Recently, there has been a growing interest in extending inkjet printing to 3D metallic parts. At present, 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 (SLS) [1] and Direct Metal Sintering (DMLS) [2]) or an electron beam (e.g. Electron Beam Melting (EBM) [3]) to form solid objects. Potential disadvantages of such methods are cost and complexity, e.g. the need to powderize the metal in advance of fabrication.

In this presentation we introduce a fundamentally different approach to printing metallic structures that is based on the principles of magnetohydrodynamics. This method involves a spooled solid metal wire being fed into a print head and pre-heated upstream from the nozzle to form a reservoir of liquid metal that feeds the nozzle chamber. When the chamber is filled, a pulsed magnetic field is applied that induces a transient current within the liquid metal. The induced current couples to the applied field and creates a Lorentz force density, providing a pseudo-pressure within the chamber that acts to eject a molten metal droplet whose velocity depends on the applied pressure The droplet is projected onto a substrate where it cools to form a solid mass. 3D solid structures can be printed by patterning the deposition of the droplets and allowing for drop wise solidification. This promising new technology could have a broad impact in additive manufacturing applications due to its low material cost, high build rate and attractive material properties. With our current work, we introduce a novel 3d printing system and demonstrate sample printed structures. We also describe the mechanism of drop generation-ejection and present a series of computational models for predicting device performance.

2 PROTOTYPE DEVICE DEVELOPMENT

A single nozzle prototype printhead system has been fabricated and partially characterized. This system consists of a refractory reservoir where metal liquification occurs, a specially designed nozzle chamber with an orifice, a power source, a custom drive coil that encloses the nozzle chamber and provides the magneto-hydrodynamic force and a substrate capable of programmable motion where the droplets coalesce to form an extended 3D object. **Figure 1** shows an early stage prototype printhead system. The prototype development has proceeded through 12 major design changes and 100's of minor iterations alongside computational modeling and

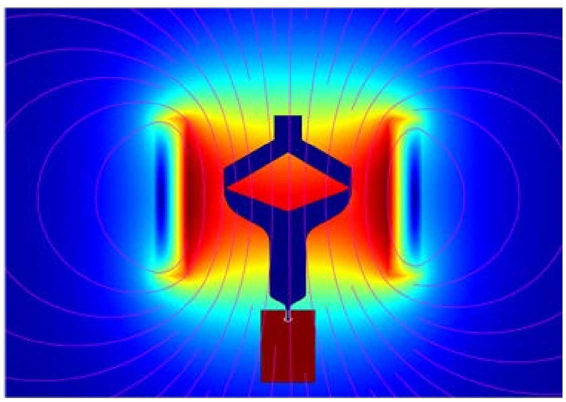
Figure 1. Early stage prototype of a single nozzle printhead.

experimentation. Aluminum 6061 droplets between 500 μm and 1000 μm in size have been created. Sustained pulse rates from 0 to 300 Hz with short burst rates to 5000 Hz have been demonstrated. It was discovered that molten aluminum droplets could be printed directly onto thermoplastic substrates. Coordinated pulse deposition and motion control have been used to create initial experimental 2D and 3D test structures using gallium.

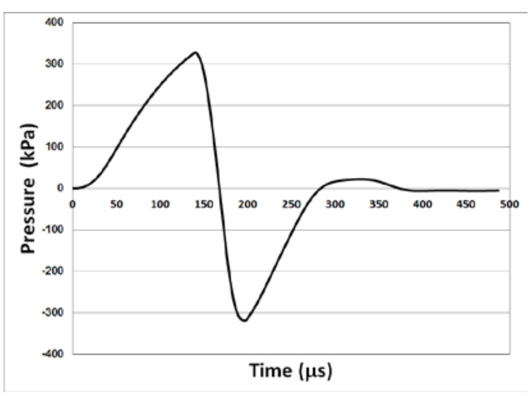
2.1 Device Modeling

As part of the prototype device development, a series of simulations were performed in advance of fabrication to evaluate design performance in terms of droplet generation, ejection and flight as well as droplet-media interactions (i.e. droplet impact and solidification on the printing substrate). A combination of computational electromagnetics and thermo-fluidic CFD analysis was used to predict device performance. An initial evaluation of a prototype design was performed using 2D axisymmetric models as shown in **Figs. 2** and **3**. **Figure 2a** illustrates the magnetic field generated by the electromagnetic drive coil surrounding the ejection chamber (not shown). The dark blue region in the center of the figure represents the molten metal and the maroon region, towards the bottom of the computational domain, represents the region outside the nozzle where the droplet forms. **Figure 2b** shows an effective pressure pulse within the ejection chamber caused by the Lorentz force density generated by the time-varying magnetic field. The pressure takes on positive and negative values that correspond to the ejection and refill processes, respectively. The oscillations of the magnetic field can also be used to regulate the pulsing frequency and, consequently, the printing speed. The modeling indicates that a droplet ejection rate of 1 kHz can be achieved in early stage prototypes, which corresponds to an equivalent material deposition rate of approximately 200 mL/h.

Following the magnetohydrodynamic analysis, the equivalent pressure profile was used as input to CFD simulations which were designed to explore the details of droplet ejection and droplet-substrate interactions. Simulations were performed in order to understand the effects of oscillations, caused by fluid forces (from viscous forces and surface tension), on the behavior of the ejected droplet. 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 drops including shape, size and velocity. The sample simulation shown in **Fig. 3**, illustrates the location of the fluid at equilibrium before ejection (**Fig. 3a**) and the post-pulse droplet formation (**Fig. 3b**).

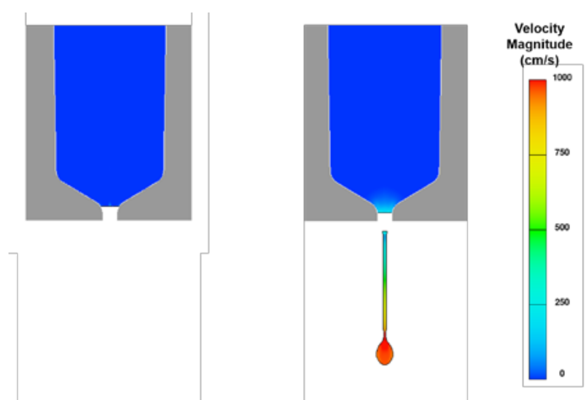


(a)



(b)

Figure 2. Computational model of magnetohydro-dynamic-based drop generation (printhead reservoir and ejection chamber not shown): (a) the magnetic field generated by a pulsed coil is shown. This creates a Lorentz force density within the liquified metal (blue) causing drop ejection, (b) the equivalent pressure pulse in the ejection chamber caused by the Lorentz force density.



(a) (b)

Figure 3. CFD analysis of droplet generation showing fluid velocity magnitude (cm/s): (a) fluid is at rest in the ejection chamber before the onset of the ejection pressure, (b) droplet ejection due to the applied pressure pulse of Fig. 2b.

2.2 Device Characterization

The early stage prototype device shown in **Fig.1** was systematically characterized to quantify the viability of the printing method. The experimental work was guided by the modeling. For example, the coil design and pulsing strategy were based on magnetohydrodynamic analysis, as shown in **Fig. 2**. Drop generation (volume and velocity) were evaluated as a function of the magnitude of the drive voltage and the pulse profile as well as firing frequency. **Figure 4** shows a variety of experimental results: **Figure 4a** is a still-frame image of a droplet in flight, moving at a few m/s towards the substrate where other droplets have solidified. **Figure 4b** is a close-up image of a single solidified droplet on a plastic substrate. **Figure 4c** shows a printed 3D ring structure which is formed by the coalescence of multiple droplets. **Figure 4d** is an image of a spiral pattern of droplets formed by printing a continuous stream of droplets while moving the substrate using a translations stage. Finally, **Figure 4e** shows a printed aluminum pillar that was formed from coalesced droplets.

Thermo-fluidic CFD analysis was performed to model the coalescence and solidification of molten metal droplets. This analysis was performed using the FLOW 3D software (www.flow3d.com), which takes into account heat transfer within the droplet during cooling and the transition to solid matter pointwise within the droplet. **Figure 5** shows the results of a simulation of molten metal droplets impacting a substrate maintained at an ambient temperature of 300K. The simulated group of falling droplets was either initialized in a perfect line or randomized slightly to account for potential external influences. The figure shows the initial formation of a solid pillar structure, similar to that shown in **Fig. 4e**.

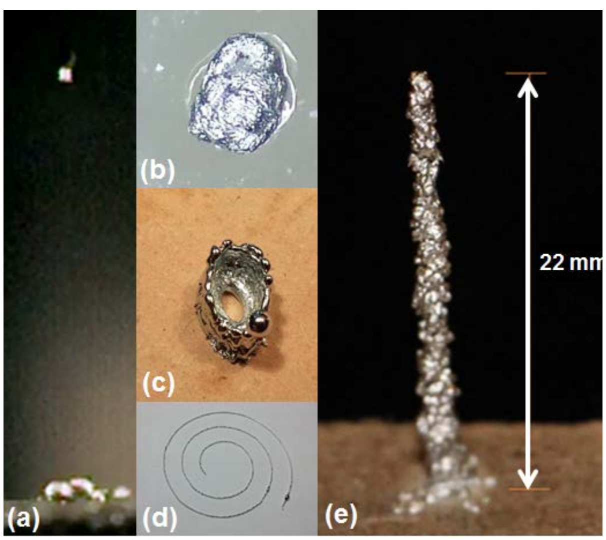


Figure 4. Droplet generation and droplet-media interactions: (a) jetted aluminum droplet in flight, (b) aluminum droplet solidified on a plastic substrate, (c) solidified printed ring structure, (d) spiral pattern of printed droplets after solidification, (e) printed pillar of coalesced aluminum droplets.

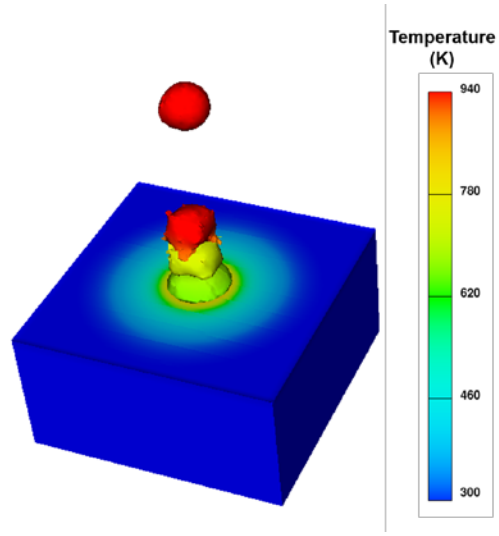


Figure 5. CFD simulation illustrating the initial formation of a solid metal pillar by the coalescence and solidification of sequential molten droplets.

3 CONCLUSIONS

A novel magnetohydrodnamic-based method has been introduced for enabling DOD printing of molten metal droplets into 3D solid objects. A prototype device has been described and its ability to print extended 3D structures has been demonstrated. A series of computational models that advance understanding of the printing process and enable the rational design of prototype systems have also been presented.

REFERENCES

[1] Loh, LE et al. (2015), International Journal of Heat and Mass Transfer **80**: 288-300

[2] Simchi, A. (2006), Materials Science and Engineering A-Structural Material Properties Microstructure and Processing **428**(1-2): 148-158

[3] James, WJ et al. (2014) Journal of Materials Research **29**(17): 1920-1930