Advances in Magnetohydrodynamic Liquid Metal Jet Printing

Scott Vader[1], Zachary Vader[1], Ioannis H. Karampelas[2] and Edward P. Furlani[2, 3]

[1]Vader Systems, Buffalo, NY
[2]Dept. of Chemical and Biological Engineering, [3] Dept. of Electrical Engineering,
University at Buffalo SUNY, NY 14260, Office: (716) 645-1194, Fax: (716) 645-3822, efurlani@buffalo.edu

ABSTRACT

We propose a novel method for drop-on-demand (DOD) printing of molten metal droplets into 3D objects. In this approach, a solid metal wire is melted within the printhead and then subjected to a pulsed magnetic field. The applied field permeates the chamber and induces a magnetohydrodynamic (MHD)-based pressure pulse within the liquid metal that causes a portion of the metal to be moved through the nozzle chamber and, subsequently, ejected. Surface tension forces act on the ejected metal to form a spherical droplet with a velocity in the range of several meters per second, depending on the applied pressure. After a brief flight, the droplet impacts onto a substrate where it cools down to form a solid mass. As a result, 3D solid structures can be printed via patterned deposition and drop-wise solidification. With our current work, we present advances in the development of a prototype MHD printing system along with sample printed structures. We also discuss the underlying physics governing drop generation and introduce new computational models for predicting device performance.

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

1 INTRODUCTION

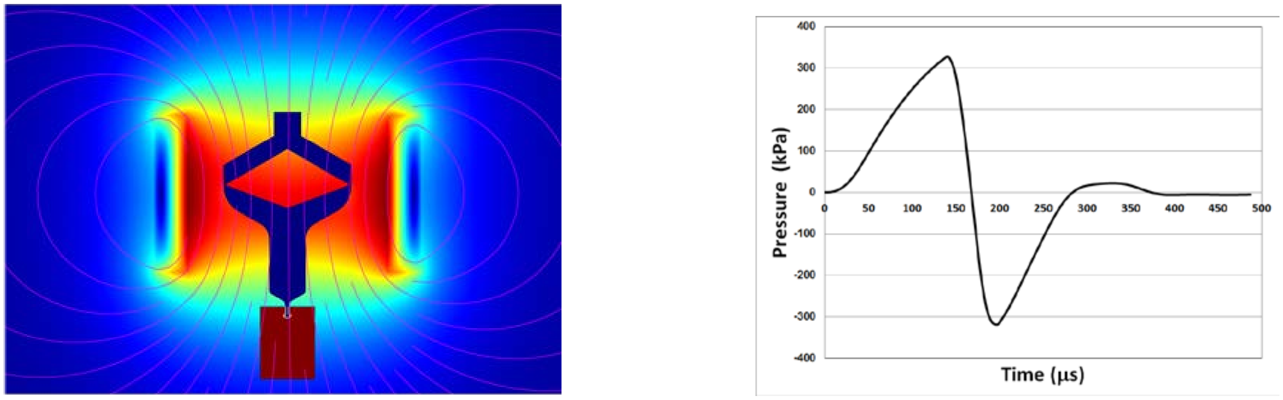
Drop-on-demand inkjet printing is a well-established method for commercial and consumer image reproduction. The same principles that drive this technology can also be applied in the fields of functional printing and additive manufacturing. Conventional inkjet technology has been used to print a variety of functional media, tissues and devices by depositing and patterning materials that range from polymers to living cells. With our current work, an attempt is being made to extend inkjet printing to 3D metallic parts. 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 [1] and Direct Metal Sintering [2]) or an electron beam (e.g. Electron Beam Melting [3]) to form solid objects. However, such methods may pose certain disadvantages in terms of cost and complexity i.e., the need to pulverize the metal in advance of the 3D printing process.

In this presentation we propose a fundamentally different approach of metal additive manufacturing 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. Once 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, describe advances in device development and demonstrate sample printed structures. We also describe the mechanism of drop generation-ejection and present a series of new computational models for predicting printing 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 liquefaction 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

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



(a) **(b)**

Figure 2. Computational model of magnetohydrodynamic-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 liquefied metal (blue) causing drop ejection, (b) the equivalent pressure pulse in the ejection chamber caused by the Lorentz force density.

capable of programmable motion where the droplets coalesce to form an extended 3D object. **Figure 1** shows an early stage prototype 3D printing system. The prototype development has proceeded through several major design changes and a plethora of minor iterations alongside computational modeling and experimentation. Aluminum 6061 droplets between 250µm and 1000µm in diameter have been created. Sustained pulse rates from 50 to 1000Hz with short burst rates of up to 5000Hz have been demonstrated. It was discovered that molten aluminum droplets could be printed directly onto a variety of substrates including steel, glass and thermoplastic substrates. In addition to aluminum, 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

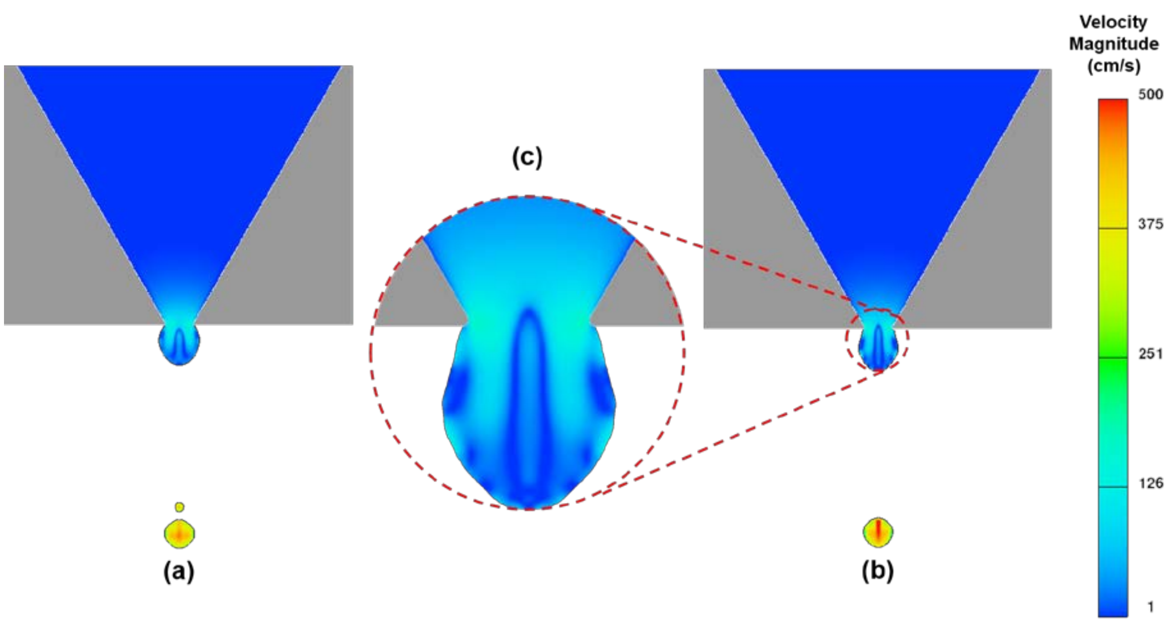


Figure 3. CFD analysis of droplet generation showing fluid velocity magnitude (cm/s): (a) droplet ejection in vacuum, (b) droplet ejection in atmospheric conditions, (c) inset showing fluid deformation after the applied pressure pulse and the geometrical details of the nozzle.

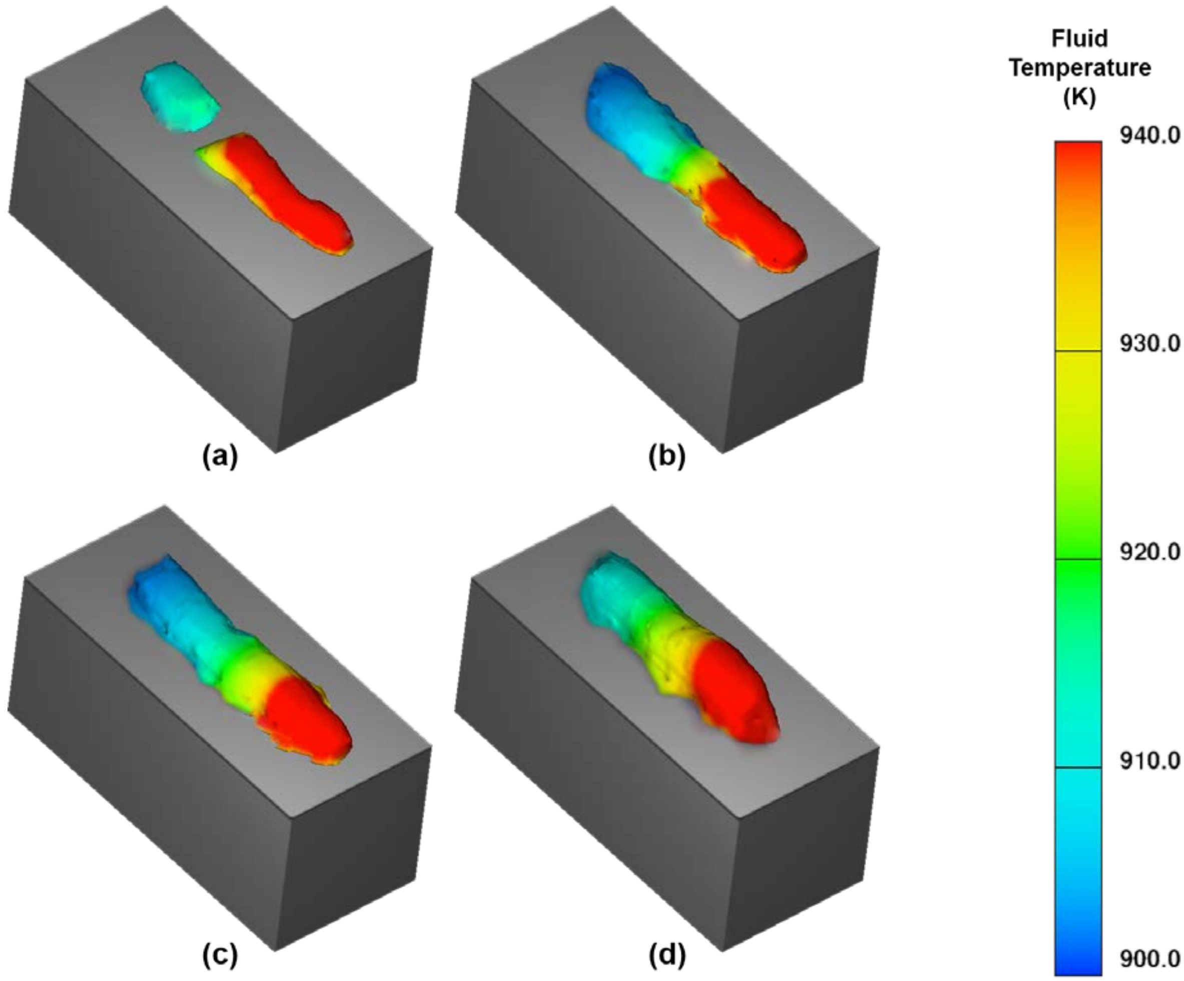


Figure 4. Parametric CFD analysis of the effects of ejected droplet (R=250μm) separation distance (center to center) on the creation of a 4mm 3D printed line showing fluid temperature (K): (a) droplet spacing of 650μm, (b) droplet spacing of 500μm, (c) droplet spacing of 300μm, (d) droplet spacing of 200μm.

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, a series of CFD simulations was performed in order to explore the details of droplet ejection and droplet-substrate interactions. Simulations were designed to better understand the effects of printing chamber ambient pressure on droplet generation dynamics while also taking into account the effects of oscillations caused by viscous forces and surface tension. By varying the initial pressure, both inside and outside the orifice, allowing for a time period, determined by the pulsing frequency, for the fluid to oscillate and, subsequently, applying the prescribed pressure pulse, we were able to identify differences in the characteristics of the ejected fluid, including shape, size and velocity. More specifically, as demonstrated in the simulation excerpt shown in **Fig. 3a**, drop ejection in vacuum causes the generation of a satellite droplet and lower drop velocity compared to droplet generation in atmospheric conditions (**Fig 3b**). In both cases, a very fine mesh was used in order to account for the minor geometrical details of the ejection chamber i.e., the nozzle curvature seen in **Fig 3c**.

In order to provide rational design guidelines in substrate programming and movement, a parametric CFD thermo-fluidic analysis of droplet spacing was implemented. This analysis was performed using the Flow3D software

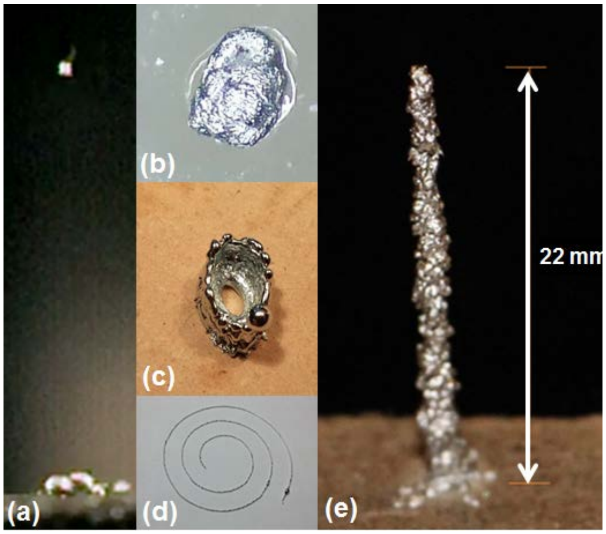


Figure 5. Droplet generation and droplet-media interactions: (a) jetted aluminum droplet in flight, (b) aluminum droplet solidified on a plastic substrate, (c) solidified printed ring structure, (d) spiral pattern of printed droplets after solidification, (e) printed pillar of coalesced aluminum droplets.

(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 4** shows the results of simulations of molten aluminum droplets, with a radius of 250μm, impacting a substrate maintained at temperature of 900K. The simulated group of falling droplets was initialized at a temperature of 970K and programmed to form a straight 4mm line. For this study, droplet generation frequency was maintained at 100Hz. This parametric analysis demonstrates the effects of droplet spacing on the creation of the 3d printed layer and provides rational design insight for the development of the programmable substrate. As such, it appears to indicate that a center-to-center droplet spacing of 500μm to 250μm is optimal for the creation of the first layer of a 3d printed object.

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. The thermo-fluidic analysis, as shown in **Figs. 3** and **4**, was used as a basis for the development of the substrate moving algorithm. **Figure 5** shows a variety of experimental results: **Figure 5a** 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 5b** is a close-up image of a single solidified droplet on a plastic substrate. **Figure 5c** shows a printed 3D ring structure which is formed by the coalescence of multiple droplets. **Figure 5d** 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 5e** shows a printed aluminum pillar that was formed from coalesced 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. These computational models include a magnetohydrodynamic analysis, which guides the pulsing strategy and a thermofluidic analysis that describes the behavior of the ejected fluid after it leaves the nozzle of the printhead, thus providing insight for the development of a more effective 3d printing algorithm.

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