Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

Magnetohydrodynamic Drop-on-Demand Liquid Metal 3D Printing

V. Sukhotskiy[1,2], I. H. Karampelas[3], G. Garg [4], A. Verma[4], M. Tong [1,4], S. Vader[2], Z. Vader[2], and E. P. Furlani[1,4]

[1]Department of Electrical Engineering, University at Buffalo SUNY, Buffalo, NY, USA,
[2]Vader Systems, 385 Crosspoint Parkway, Suite 104, Getzville, NY, USA
[3]Flow Science, Inc., 683 Harkle Road, Suite A, Santa Fe, NM, USA
[4]Department of Chemical and Biological Engineering, University at Buffalo SUNY, Buffalo, NY, USA
viktorsu@buffalo.edu

ABSTRACT

We present a novel method for liquid metal drop-on-demand (DOD) additive manufacturing of three-dimensional (3D) solid metal structures. This method relies on magnetohydrodynamic (MHD)-based droplet generation. Specifically, a pulsed magnetic field, supplied by an external coil, induces a Lorentz force density within a liquid metal filled ejection chamber, which causes a droplet to be ejected through a nozzle. Three-dimensional 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: Magnetohydrodynamics, droplet ejection, drop on demand printing, 3D printing, additive manufacturing, thermo-fluidics, 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 process complexity, e.g. the need to use time and energy intensive techniques to create powder in advance of the 3D printing process.

In this work, we introduce a novel approach to additive manufacturing of 3D metal structures that is based on a magnetohydrodynamic droplet ejection method. In this method, a spooled solid metal wire (~1mm diameter) is fed continuously into a ceramic heating chamber of an MHD printhead and resistively melted to form a 3mL reservoir of liquid metal that feeds an ejection chamber via a capillary force as illustrated in Fig. 1. A coil surrounds the ejection chamber and is

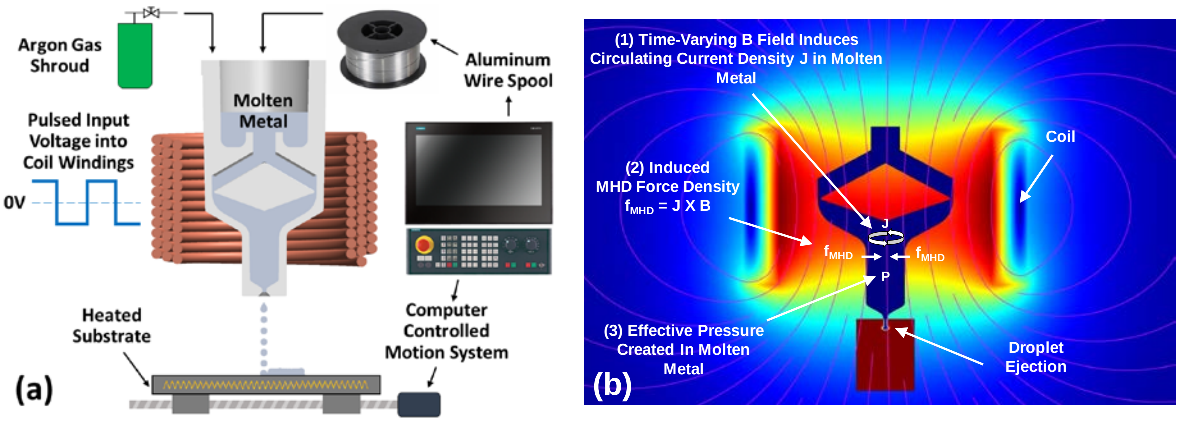

Figure 1: Essential components of the MHD printhead (a) cross-sectional view of printhead and process overview (b) simulation model showing the magnetic field generated by a pulsed magnetic coil as well as the volume fraction of ejected liquid aluminum.

electrically pulsed to produce a transient magnetic **B** field that permeates the liquid metal and induces a closed loop transient electric field **E** within it. The electric field gives rise to a circulating current density **J**, which back-couples to the transient B field and creates a magentohydrodynamic Lorentz force density ($\mathbf{f_{MHD}}$) within the chamber. The radial component of $\mathbf{f_{MHD}}$ creates a pressure **P** 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 [8, 9]. In addition, presence of unique metallic grain structures suggests the ability to print parts with improved mechanical properties [9]. In this work, we discuss the MagnetoJet 3D 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 component of the 3D printing system is a printhead assembly composed of a two-part boron nitride nozzle, and a solenoidal coil. Liquefication at 1146-1246K (850-950°C) occurs in the top part of the nozzle. The lower part contains a submillimeter orifice, which can range from 100µm to 500µm in diameter. The water cooled solenoidal coil surrounds the orifice chamber as shown in Fig. 1a (cooling system not shown). The iterative development of numerous printhead designs has been pursued to explore the effects of ejection chamber geometry on the liquid metal filling behavior as well as droplet ejection dynamics. These prototype systems have successfully printed solid 3D structures made from common aluminum alloys such as 4043, 6061 and 7075 (Fig. 2). Droplets range from 50 µm to 500 µm in diameter depending on the orifice diameter, geometry, ejection frequency and other parameters. Sustained droplet ejection rates from 40-1000 Hz with short bursts up to 5000 Hz have been achieved and stabilized.

2.1 Computational Models

As part of the prototype device development, computational simulations were performed in advance of 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 electromagnetic (CE) as well as computational fluid dynamic (CFD) analysis. In the first model, a two-step 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 two-step CE and CFD model using the COMSOL Multiphysics software (version 5.3, 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 and calculate an equivalent pressure pulse. The pressure pulse was then entered into the Multiphysics CFD program FLOW3D (www.flow3d.com) as an input condition. Initial prototype designs were screened using a 2D axisymmetric COMSOL model as shown in Fig. 1b**.** The magnetic field distribution generated by the electromagnetic coil is shown in the background, 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, pulse duration times, 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.

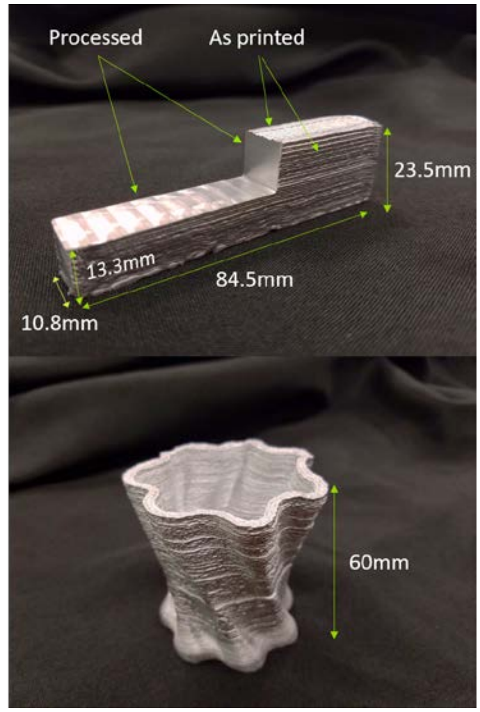

Figure 2: 4043 Aluminum printed 3D structures: (a) rectangular prism test bar showing unprocessed section and cut portion and (b) twisted helix vase.

Following the magnetohydrodynamic analysis in COMSOL, an 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. FLOW3D (www.flow3d.com) was used for this analysis. Simulations were performed to understand the effects of wetting in and around the orifice 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 depending on the voltage pulse parameters, 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 droplet placement for patterning is achieved using a high resolution 3D motion base. However, controlling solidification to create well-formed 3D structures with low porosity and without undesired layering artifacts is a 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, (c) the droplet ejection frequency and (d) thermal diffusion from the already formed 3D object. 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 (intralayer) and between layers (interlayer). 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 melting temperature. This reduces the temperature gradient between the droplet and its surroundings, which slows the diffusion of heat from them 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.

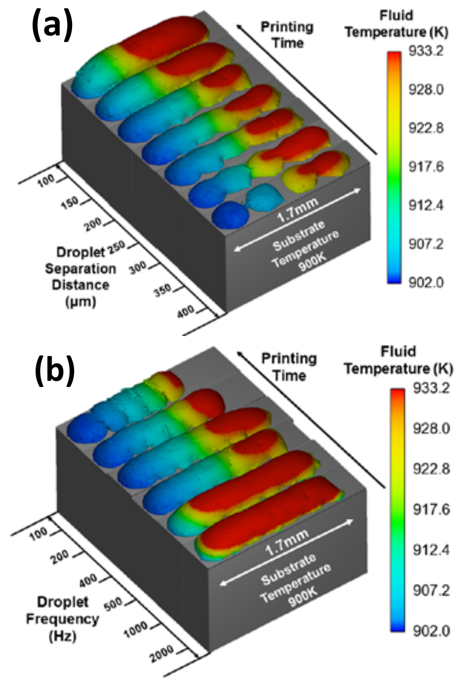

Figure 3. (a) Droplet coalescence vs. center-to-center separation. (b) Droplet coalescence vs. ejection frequency.

We investigated intralayer 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. Figure 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, they show undesirable artifacts such as lack of strong coalescence between subsequent layers of deposited metal (intralayer coalescence). 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. This can even be done dynamically to adjust for the higher thermal diffusion as the part becomes larger during printing.

Figure 4 shows a cup structure printed on a heated substrate. During the printing process, the temperature of the heated substrate was increased gradually from 733K (430°C) to 833K (580°C) in real time based on the instantaneous height of the printed part. This was done to overcome the increase of local thermal diffusion as the object surface area increases. The high thermal conductivity of aluminum makes this especially difficult, since any adjustment to the local thermal gradient has to be made quickly, otherwise the temperature will decrease quickly and degrade the intralayer coalescence.

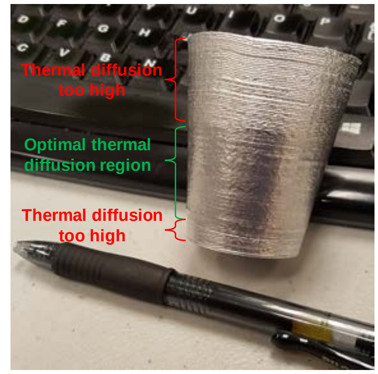

Figure 4: Differences in droplet coalescence in a printed cup structure. The lower part of the 57mm tall cup has smooth coalescence, whereas the top shows visible layering.

The cup object was printed using 450μm droplets in an argon gas shroud, with an ejection rate of 500Hz. The semi-inert environment minimized the buildup of Al_2O_3. A lack of intralayer disruptions in Fig. 4 shows that the part contains excellent horizontal intralayer droplet-droplet coalescence throughout the entire printing process. This suggests that each incoming droplet, as well as the previously deposited droplet have enough thermal energy to effectively coalesce. Vertical interlayer coalescence is depicted in Fig. 4 by noticing two distinct coalescence modes, a self-smoothing mode and a non-smoothing mode shown by the green and red regions respectively. An appropriate combination of the abovementioned thermal parameters such as previous layer temperature as well as incoming droplet temperature allowed for the self-smoothing mode. Both temperatures were dictated by the local thermal gradient, and it is clear that there is a narrow parameter window for this self-smoothing to occur. Further work will include measurements of the local temperature plus local thermal gradient and identification of the parameters that allow for the self-smoothing mode.

CONCLUSIONS

Prototype MHD-based liquid metal DOD printheads have been developed by Vader Systems that are capable of printing 3D solid metal structures of arbitrary shape. Three-dimensional 4043, 6061 and 7075 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 over 540 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 material selection. Further experimental and modelling work is planned to quantify transient thermal effects during the printing process as well as dynamic meniscus behavior. Scaling the MagnetoJet process to multi-nozzle printing will lead to unprecedented mass deposition rates. Improvement of the overall thermal capacity of the system will allow for printing using metals with higher melting points (e.g. copper, gold, steel, titanium). Computational models have been developed to address some of these challenges and evaluate design concepts. The ability to print 3D metal structures on demand without the use of specially prepared powders 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.

REFERENCES

[1] Roth, E.A., Xu, T., Das, M., Gregory, C., Hickman, J.J. and Boland, T., “Inkjet printing for high-throughput cell patterning,” *Biomaterials* 25(17), 3707-3715 (2004).

[2] Sirringhaus, H., Kawase, T., Friend, R.H., Shimoda, T., Inbasekaran, M., Wu, W. and Woo, E.P., “High-resolution inkjet printing of all-polymer transistor circuits,” *Science* 290(5499), 2123-2126 (2000).

[3] Tseng, A.A., Lee, M.H. and Zhao, B., “Design and operation of a droplet deposition system for freeform fabrication of metal parts,” *Transactions-American Society of Mechanical Engineers Journal of Engineering Materials and Technology* 123(1), 74-84 (2001).

[4] Suter, M., Weingärtner, E. and Wegener, K., “MHD printhead for additive manufacturing of metals,” *Procedia CIRP* 2, 102-106 (2012).

[5] Loh, L.E., Chua, C.K., Yeong, W.Y., Song, J., Mapar, M., Sing, S.L., Liu, Z.H. and Zhang, D.Q., “Numerical investigation and an effective modelling on the Selective Laser Melting (SLM) process with aluminium alloy 6061,” *International Journal of Heat and Mass Transfer* 80, 288-300 (2015).

[6] Simchi, A., “Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features,” *Materials Science and Engineering*: A 428(1), 148-158 (2006).

[7] Murr, L.E., Gaytan, S.M., Ramirez, D.A., Martinez, E., Hernandez, J., Amato, K.N., Shindo, P.W., Medina, F.R. and Wicker, R.B., “Metal fabrication by additive manufacturing using laser and electron beam melting technologies,” *Journal of Materials Science & Technology*, 28(1), 1-14 (2012).

[8] J. Jang and S. S. Lee, "Theoretical and experimental study of MHD (magnetohydrodynamic) micropump," *Sensors & Actuators: A. Physical*, 80(1), 84-89 (2000).

[9] M. Orme and R. F. Smith, "Enhanced aluminum properties by means of precise droplet deposition," *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, 122(3), 484-493, (2000)