

Liquid Metal 3D Printing: A Magnetohydrodynamic Approach

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Liquid Metal 3D printing has been of interest in the AM industry since the 1990's because it's dramatically faster and cheaper than powder bed fusion for aluminum additive manufacturing. It is highly scalable to meet the demand for large/high volume AM processes. This paper describes the characteristics of the LM3DP process: drop on demand liquid metal printing using MagnetoJet technology (based on Magnetohydrodynamics and inkjet printing technology). This process feeds commodity wire directly into a heated chamber, where drop size is controlled by both the jetting process and nozzle design. A time varying magnetic field induces eddy currents within the liquefied metal pool generating a Lorentz force which causes the stream to eject as discrete droplets. This technology allows for speeds capable of 1000 droplets/second (yielding 1 lb. or more per hour) and is scalable for production volumes. Proof-of-principle is illustrated with few 3D printed part features. The use of numerical simulations in engineering design for accurately predicting electromagnetic field effects, phase transformation, flow behavior and free surface deformation is also discussed.

Nomenclature

<i>SFF</i>	=	solid freeform fabrication
<i>AM</i>	=	additive manufacturing
<i>LM3DP</i>	=	liquid metal 3D printing
<i>MHD</i>	=	magnetohydrodynamics
<i>DOD</i>	=	drop on demand
<i>LSM</i>	=	level set method

I. Introduction

THIS paper describes the generation and deposition of molten metal droplets from Lorentz Forces for application to the emerging technology of solid freeform fabrication (SFF).

Continuous jetting and Drop on Demand jetting are the two basic jetting methods. If the breakup of the jet stream occurs beyond a certain measurable distance away from the orifice emanating the stream, it is referred to as "Continuous Jet". On the other hand, if the resulting droplets break up at the orifice in a discontinued or periodic manner, it is termed as "Drop on Demand Jet" [1].

Drop on Demand 3D printers are commonly made up of a small size orifice, a reservoir and a print head which is actuated to generate a pressure pulse causing discontinuity in the fluid stream. The source of actuation could be thermal, piezoelectric, or electromagnetic. For the thermal print head, miniature pockets of the liquid printing material are vaporized by means of a heater to produce gas bubbles. Discontinuities arise within the fluid stream due to the collapse and generation of these bubbles thereby resulting in droplet ejection. Piezoelectric models contain electronically controlled actuators. The frequency controlled piezoelectric actuator deforms causing discontinuities

in the stream for the piezoelectric models^[2]. The idea behind the operation of the Vader Magnetojet revolves around magnetohydrodynamics (MHD) which is elaborated in the next section.

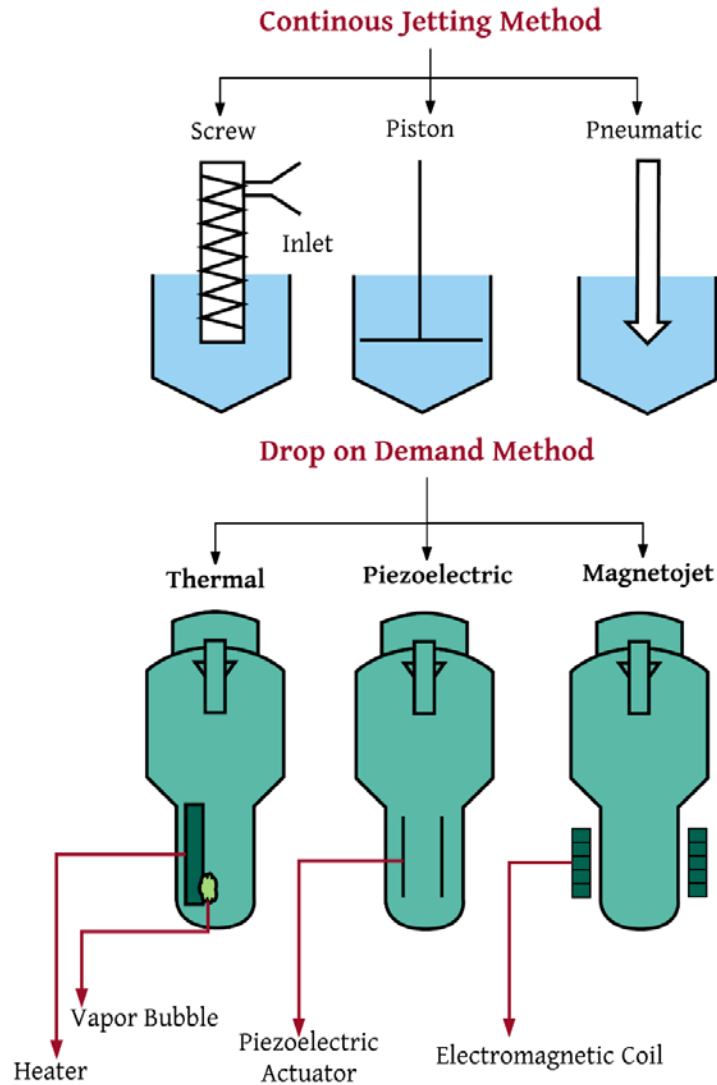


Figure 1: Continuous vs Drop on Demand 3D Printing Approach

Continuous methods utilize robotic dispensing techniques to regulate the pressure system for jetting. Typically utilized pressure systems are categorized based on the viscosity of the fluid and the level of control required in Figure 1.

A. Background of Liquid Metal Jet Printing Systems

Molten metal drop ejectors to Additive manufacturing have been of interest since 1990's. Orme and Muntz at University of California at Irvine employed the technique of electrostatic charging and deflection for droplet creation and fabrication using Aluminium^[3]. Low temperature alloys of Pb-Sn alloys were studied by Tseng^[4], Jiang^[5] and Chao^[6]. US patents for jetting Al, Cu and other high temperature metals have been received by Chun at MIT, Priest, Smith and DuBois at the University of Texas at Arlington and IBM^[7]. One of the recent

advancements include Harkness and Goldsmid's work, having developed a patent allocated to Boeing (U.S) wherein some part features were 3d printed.^[8]

II. Operation Principle

The jetting process of Vader Systems' 3D metal printer involves the concept of magnetohydrodynamics (MHD). As the name suggests, MHD employs the application of electromagnetic forces to conductive fluids. A conceptual schematic of the different system configurations is shown in Figure 2. For the present discussion, only the components involved in the actual jetting process are highlighted.

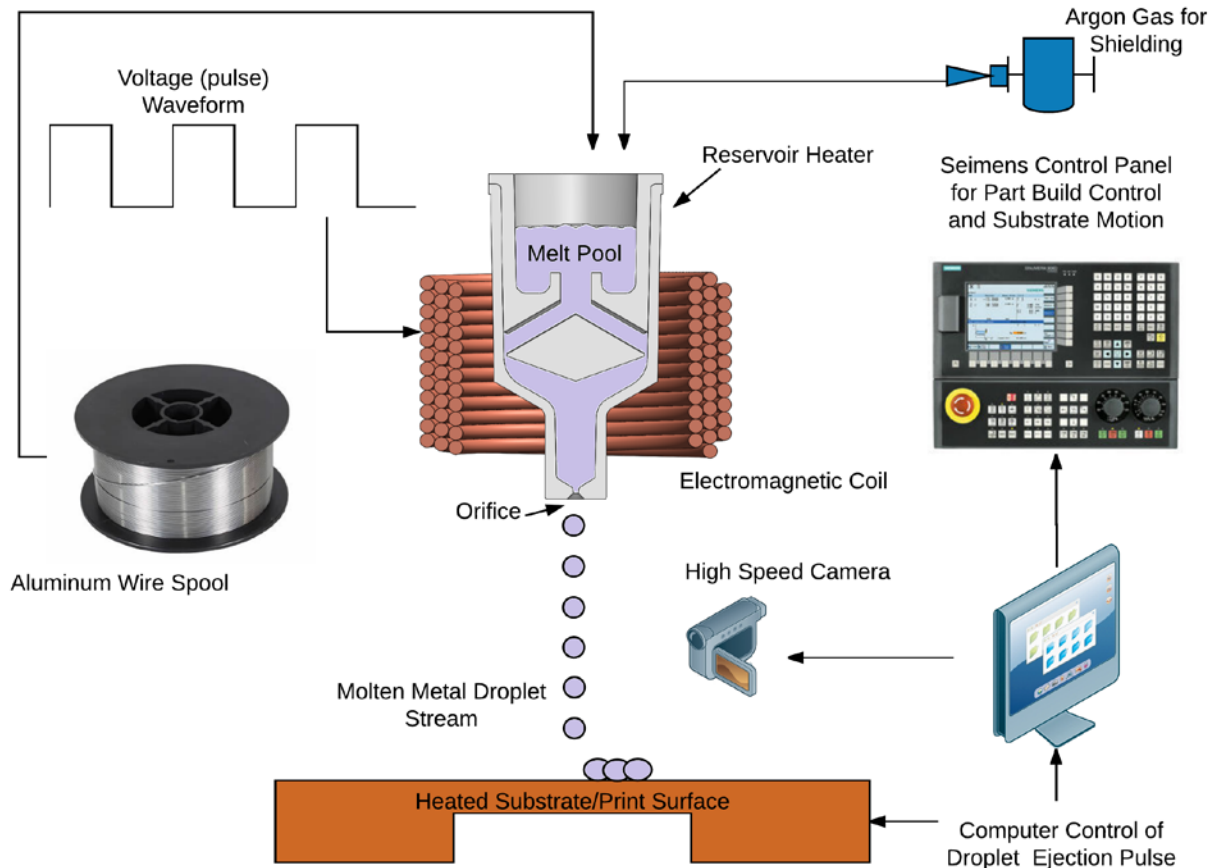


Figure 2: Schematic view of the molten metal droplet deposition facility

Aluminum wire enters the tube from the open end on the top from a wire feeder system consisting of a wire spool, feed rollers and a servo motor connected via a gearbox. Next, the tip of the metallic wire is resistively heated. The molten metal is held in the reservoir and the nozzle. A voltage is applied to the electromagnetic coil creating an electric current which creates a pulsed magnetic field. The time varying magnetic field induces eddy currents within the liquefied metal. The coupling between the magnetic field and the electric current results in a Lorentz force which provides a pseudo-pressure for jetting the molten metal onto a build platform. The motion of the substrate coordinated with the ejecting droplets facilitates building of 3D structures with feed rates up to 1 lb/hr, Figure 2. The process makes use of a conventional cad file in STL format with a slicing technique compatible with standard G-codes.

The electrical power to the kanthal wire is auto adjusted so as to maintain a constant temperature at the nozzle surface. The argon cylinder is used to provide a shielded environment in order to reduce oxidation, ensure angular

stability of the stream and the pressure is regulated by a solenoid valve. An edgetronic High-Speed camera is used to capture the dripping or jetting process. It has an exposure time set to 50 μ s and can capture 10,000 frames per second.

The simplicity of the process arises from the fact that in this operation, there are no moving parts in direct contact with the ejected metal droplets. If the crucible can be refilled amid operation, larger size parts and arbitrary structures can be printed despite having a smaller initial fill volume. Hence, the system employs a feedback loop to sense the molten metal level in the reservoir using a level sensor and to control the motorized wire feed mechanism.

III. Numerical Methods

The technology uses drop on demand technique where individual droplets are ejected directly from the nozzle as a discontinuous jet with a periodic exciting mechanism. Drop wise solidification offers potential advantages in spatial resolution, accurate drop placement, drop size and velocity control, regulating solidification process and temperature profiles. The combined effects of Lorentz force, gravity and surface tension causes the molten metal to eject through the nozzle.

The overall concept of the governing phenomenon is overlooked by the experimental techniques restricted to imaging and post solidification analysis. The objective of the simulations is to find numerical models that accurately predict phase transformation, flow behavior and free surface deformation in order to develop a comprehensive understanding and optimization of the system parameters. System studies suggest that surface tension modelling, free surface tracking, heat transfer driven by convection and non-isothermal solidification is to be modeled. Comsol Multiphysics® offers advanced interactive features for coupling the above mentioned physics.

The physical properties of Molten Aluminum at 800°C used in the study are highlighted in Table 1.^[10]

Density (kg/m ³)	Viscosity (Pa.s)	Surface Tension Co-efficient with Argon (N/m ²)	Electrical Conductivity (S/m)	Thermal Conductivity [W/(m*K)]
2380	0.0012	0.9	3.9e6	100

The multiphase flow is analyzed using the Level Set Method (LSM) application mode in Comsol Multiphysics®. The 0.5 contour of the smeared Heaviside level set function (Φ) represents the interface between the fluids, namely molten aluminum and argon. Φ equates to 1 in molten aluminum and 0 in argon with a smooth transition across the interface. The convection of the level set function is given by

$$\frac{\partial \Phi}{\partial t} + \mathbf{u} \cdot \nabla \Phi = \gamma \cdot \nabla (-\Phi(1 - \Phi)) \frac{\nabla \Phi}{|\nabla \Phi|} + \varepsilon \nabla \Phi$$

Where γ is the re-initialization parameter, \mathbf{u} is the velocity, t is time, ε is the interface thickness

The velocity flow field is determined by the Navier Stokes equations, namely conservation of mass and momentum.

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \nabla \cdot \mathbf{u} \right) = \nabla [-p\mathbf{I} + \mu \nabla \mathbf{u} + (\nabla \mathbf{u}^T)] + \rho \mathbf{g} + F_{ST} + F$$

F_{ST} is the surface tension force, P is the pressure, \mathbf{I} is the identity matrix and \mathbf{g} is the gravitational acceleration^[9].

The interface normal (\mathbf{n}) and delta function (δ) is computed by

$$\mathbf{n} = \frac{\nabla \Phi}{|\nabla \Phi|}$$

$$\delta = 6|\phi(1 - \phi)||\nabla\phi|$$

The smoothing of the pressure and viscosity gradients across the interface and the surface tension is given by

$$F_{ST} = \nabla \cdot [(\sigma(I - nn^T))\delta]$$

$$\rho = \rho_1 + (\rho_2 - \rho_1)\phi$$

$$\mu = \mu_1 + (\mu_2 - \mu_1)\phi$$

Where σ is the surface tension, μ is the dynamic viscosity, ρ is the density and the subscripts 1 and 2 represent the two phases for argon and molten aluminum respectively.

Magnetic Field interface (mf) is added as a separate module in the same setting for a periodic square pulse of 300V between 30-40 μs optimized for each study. Sequentially, Lorentz force contribution defined in the magnetics study is coupled to the volume force in the fluidics study as

$$F = \frac{1}{2} R_s (J \times B)$$

Where F Lorentz force, R_s is the Reynolds number, B is the amplitude of the magnetic field density and J is the current density^[11]. The jetting profile is illustrated in Figure 3.

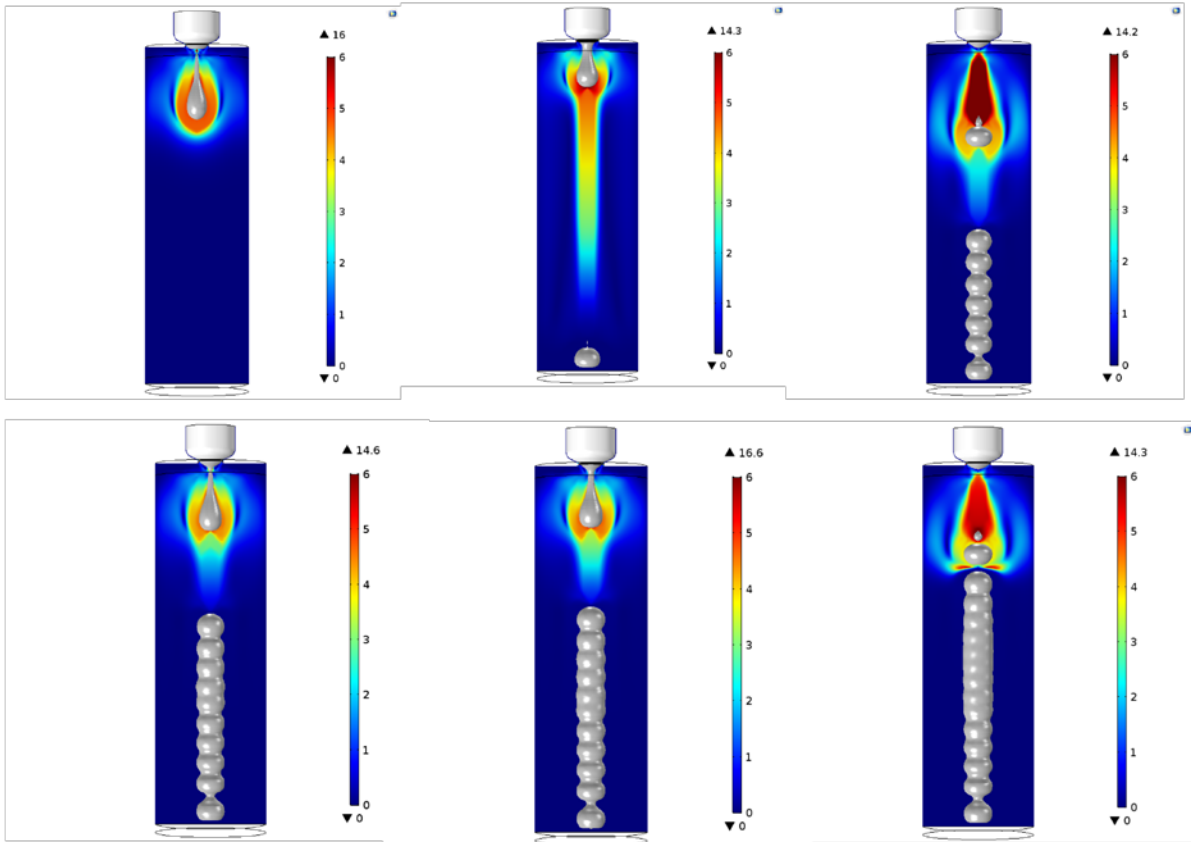


Figure 3 Velocity(m/s) and Volume Fraction rendering for sequence of metal drop ejections

Moreover, the process of phase change for successive remelting of the previous layer, splat formation, droplet break up at impact is to be examined in order to develop an understanding in the metallurgical bonding between the ejected droplets, Figure 4. The goal of these simulations was to ensure that the oncoming metal drop successfully remelts the previous layer. The printhead is held at constant temperatures of around 750-850 °C.

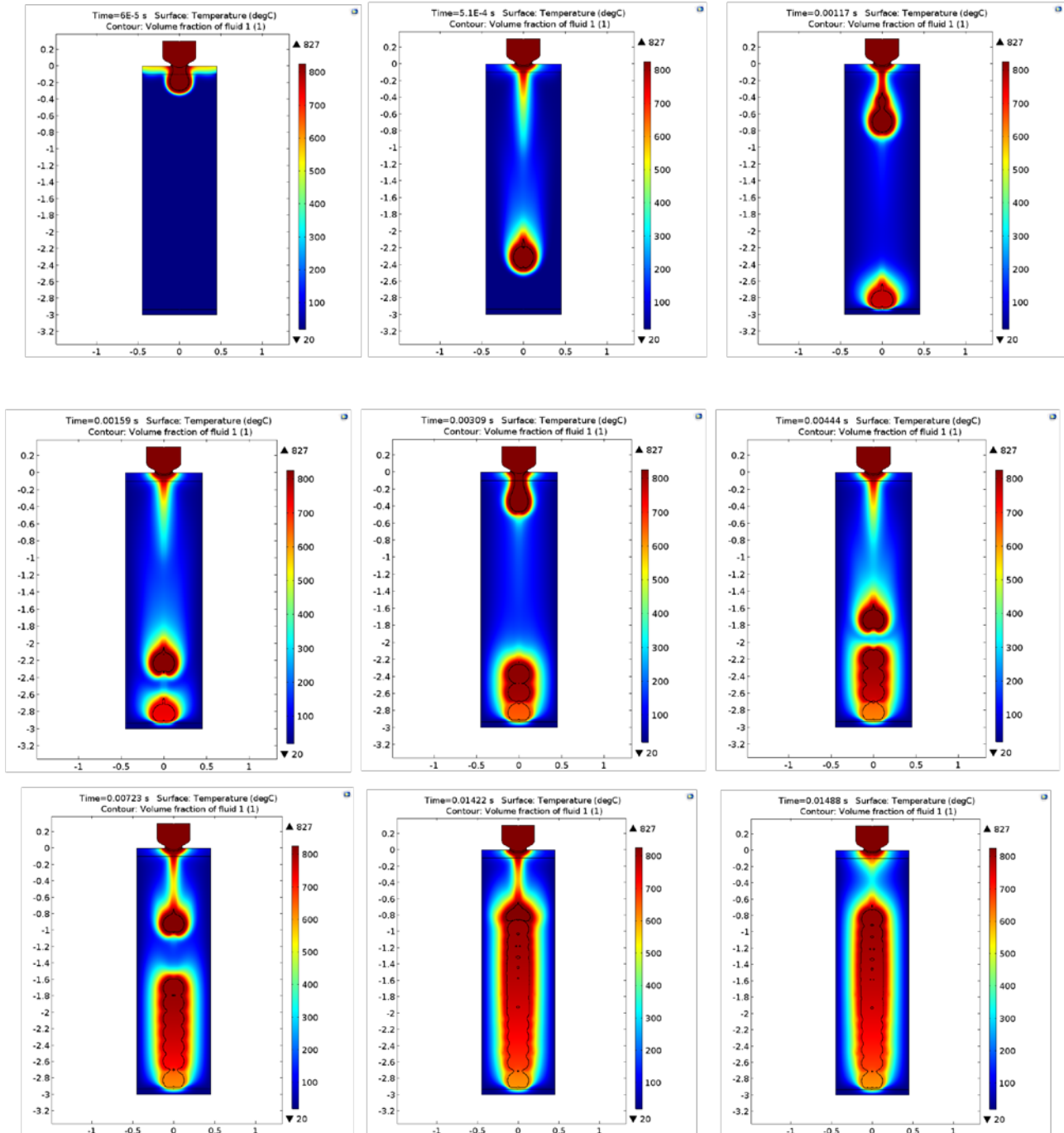


Figure 4 : Temperature profile (°C) for successive drop impingement

For the process of drop formation, even small changes in nozzle geometry, driving frequency, and Volatges can have a great effect on the outcome. For this reason, it is essential to identify proper system parameters for a desired

behavior. Beyond a certain value of droplet firing time (us) and Voltage(V), the dripping transforms to jetting or continuous mode. Controlling this transition has an important impact on the build resolution and volume. Figure depicts the velocity of the droplet as a function of voltage and droplet firing time. These results were rendered with Comsol Multiphysics®. The results were compared with experiments at 300 V and different firing times. The maximum error margin was found to be 9%. At higher on pulses like 50 us, the increase in droplet velocity does increase the throughput but accompanies a larger droplet volume and satellite drops. This is detrimental to the part resolution. Droplet velocities below 6 m/s have been found to eject single droplets more consistently and repeatedly, Figure 5.

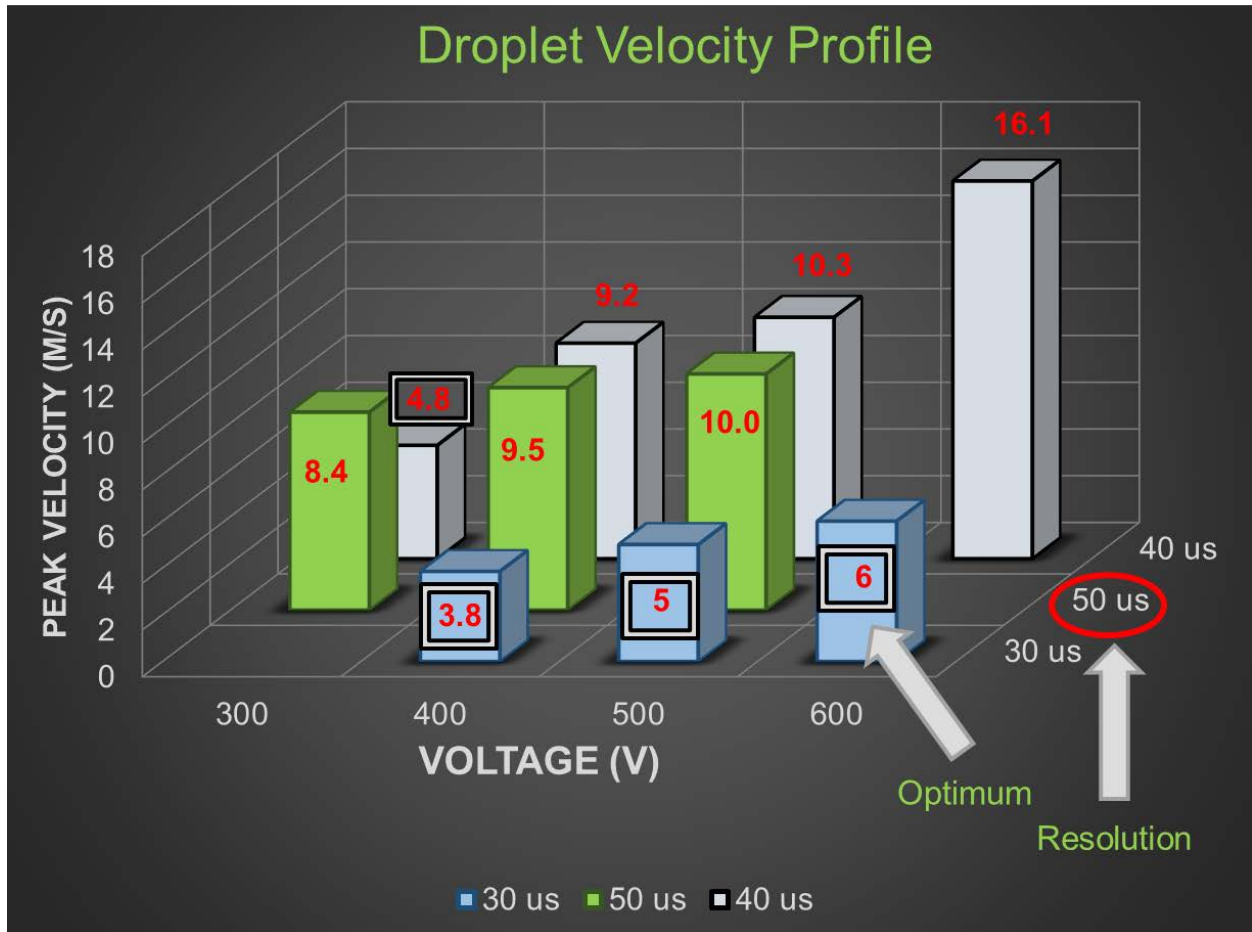


Figure 5: Droplet Velocity Profile (m/s)

This study is restricted and is applicable only to the 500 um nozzle variant and the results vary for design changes along with the orifice length and diameter. For the purpose of brevity, these are not included in this research. The first case for the optimum settings is shown in Figure 5. Within the optimum range, for each cycle of the waveform, a single droplet is ejected which contracts into a spherical shape, Figure 6A . The fluid meniscus in this case retracts in and extrudes out of the nozzle. However, overdriving the system at higher droplet firing times and/or Voltages leads to multiple drop ejections. In this case, primary drop with a series of satellite droplets are ejected. Some of them merge with the main drop. Typically the velocity of the trailing droplets are less as compared to the primary drop and they follow different trajectories, Figure 6B. At times, this may lead to a chaotic outburst and/or spraying which is detrimental to the build process. The droplet size and velocity can be controlled by nozzle diameter, applied voltage, viscosity, temperature and surface tension of the melt pool.

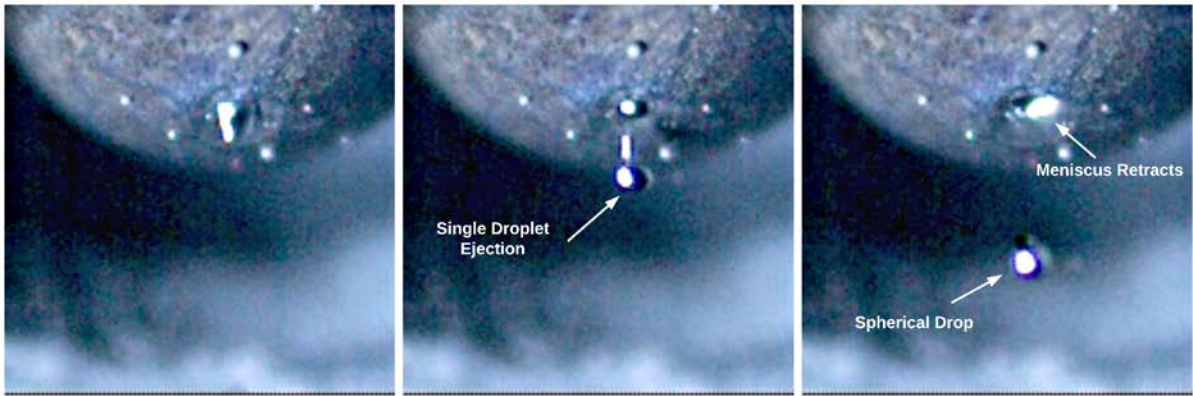


Figure 6 A: Idealized Droplet Ejection Sequence

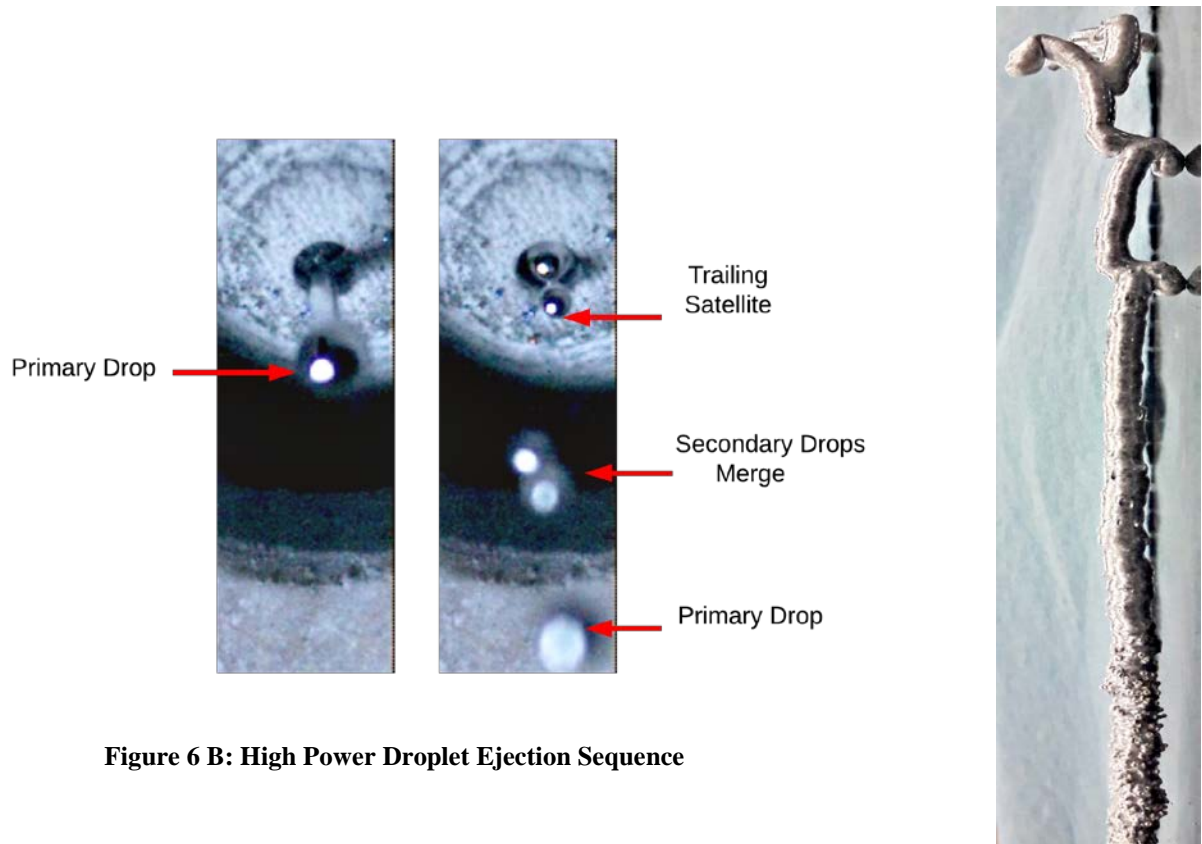


Figure 6 B: High Power Droplet Ejection Sequence

Figure 6 C: Example for droplet fusion with creation of long bridging strands

Another interesting feature of these studies is the ability to produce long bridging strands. Using carefully optimized parameters overhangs/ self supporting structures of around 45 have been replicated, Figure 6C.

IV. Part Build Characterization

Uniform microspheres were fabricated for Aluminum 4043 series by optimizing process parameters in order to allow droplets to solidify in flight, Figure 7. These include reducing the nozzle orifice geometry and maintaining the printhead at slightly elevated temperatures than the melting point of the metal. Furthermore, the travel path for the z axis of the printhead was also held higher at around 8 inches.

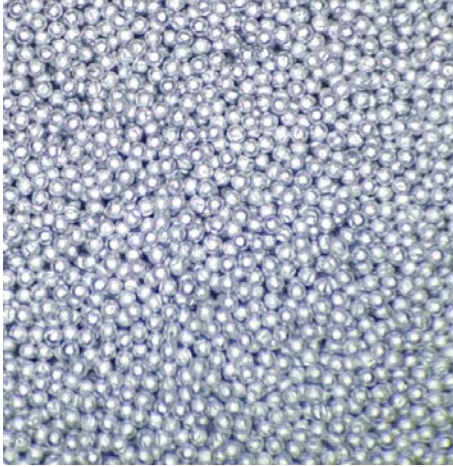


Figure 7 A : 150 micron Aluminium 4043 microspheres

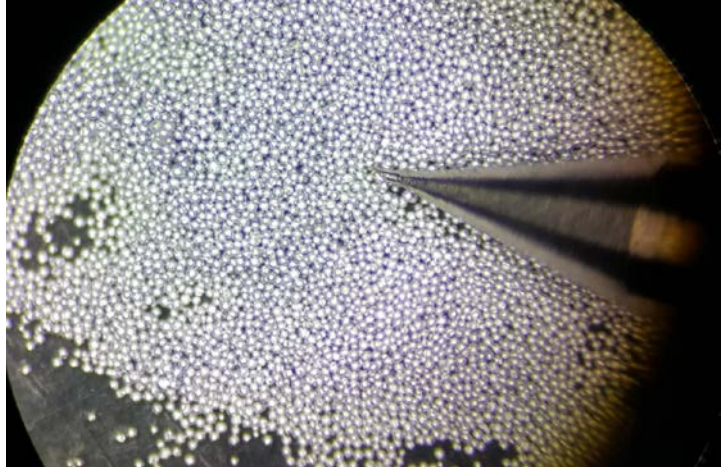


Figure 7 B : 50 micron Aluminium 4043 microspheres

The Figure 8 highlights the parting of adjacent layers for Al 6061 3D printed structure commonly referred to as delamination. This is due to partial melting between layers. The adjacent and the underlying solidified layers need to be successfully remelted. These are macroscopic defects which cannot be fixed by post processing techniques.



Figure 8: Aluminium 6061 3D printed part



Figure 7: Aluminium 4043 3D printed part

However, optimizing the temperature gradients ensure both inter and intra layer welding between successive layers. This was achieved by raising the substrate temperatures to 500°C, Figure 9. There are a sequence of steps involved in the transition from machine fabricated to end-use parts for applications. The finished part typically adheres to the stainless-steel substrate and is cut off using a chisel. Next, the part is water cooled to ensure rapid solidification. A conventional CNC milling operation connected with subtractive manufacturing is employed to confirm a smooth surface finish. Grinding with a belt sander for the flat ends followed by a rotary tool polishing is adequate for standard finishing. Other polishing techniques will be explored for further variants to meet smaller resolution tolerances.

Conclusions and Summary

In this paper, a novel drive principle for a magnetically driven microdroplet generator for the use with liquid metal is proposed. The Jet design is integrated in a Modular approach and has no moving parts except for the input metal wire feed. This offers potential advantages including ease in manufacture and maintenance, fewer failure modes, simplicity in design and compactness. The Fabrication process for the Magnetojet is Surface Tension smoothed with rapid cooling.

The results presented emphasize the possibilities in the integrated manufacturing process taking advantage of high-speed deposition and low cost 3D printing. Wire feed systems proposed in Figure 2 can operate at lower material cost, accurate drop placement and resolution owing to the drop on demand technique, near-net shape fabrication and lesser need for tooling. Furthermore, novel gantry systems for positioning multiple heads and attenuate their motion for subsequent jetting profiles will be explored. This would facilitate large subsystem and component fabrication.

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