COMPUTATIONAL MODELING OF DROPLET DEPOSITION AND COALESCEENCE FOR DROP-WISE ADDITIVE MANUFACTURING

by

PRIYANSHU VISHNOI
7th August 2018

A thesis submitted to the faculty of the
Graduate School of
the University at Buffalo, State University of New York
in partial fulfilment of the requirements for the
degree of

Master of Science

Department of Chemical and Biological Engineering
DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in this thesis.

This thesis has also not been submitted for any degree in any university previously.

Priyanshu Vishnoi
7th August, 2018
Acknowledgement

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.” These lines by Sir William Bragg always fascinates me as a science student to keep working towards my goal. I keep in mind that the road to my goals and targets is an arduous one, and only through perseverance will I be able to accomplish them. This work could not have been completed without the constant support and guidance of my professors, co-workers, family and friends.

First and foremost, I would like to thank my advisor, Dr. Edward P. Furlani, for his supervision and giving me this wonderful opportunity to work under him on some of the most exciting projects. His invaluable assistance and never-ending support, on both technical and personal levels have always inspired me to keep going forward. Had it not been for his invaluable constructive comments and suggestions, this work would not have been completed. He was always patient with me during hard times and the faith he showed in me was a huge motivation to keep working and deliver the results in the best way possible. It was an honor to be a student of such a multi-talented personality, who was not only a great scientist but also a father figure for me. He will be dearly missed.

My sincere thanks to my current advisor, Dr. Mike T. Swihart for taking me as his student during the latter part of my degree His invaluable suggestions in improving this work has made it look presentable. It was his guidance and constructive comments because of which this work could be completed.

Special thanks to Dr. Haiqing Lin for serving as my committee member and devoting his time towards my research.
I would like to express my profound gratitude to my group members and friends Viktor Sukhotskiy, Aditi Verma, Ioannis Karampelas, Shruti Jose and Gourav Garg for their constant guidance, active participation, lively discussions, and providing support and feedback throughout my research.

Above all, my deepest gratitude and heartfelt thanks to my beloved parents, Dr. Sanjay Vishnoi and Dr. Alka Vishnoi, and my loving sister Sonakshi Vishnoi, for their everlasting love and motivation. Whatever I am today is because of the belief they had in me and the support they provided. I shall forever be in their debt.
Abstract

Drop-on-demand additive manufacturing is a novel 3D printing technique. Additive manufacturing (AM) is a bottom-up manufacturing process in which material is joined or solidified under computer control to create a three-dimensional object. In this thesis, we analyze an innovative additive manufacturing method that involves the drop-on-demand (DOD) printing of molten aluminum droplets to build three-dimensional (3D) metal structures of arbitrary shape. Aluminum alloy Aluminum 6061 is used as the metal in our study. This technique is based on magnetohydrodynamic (MHD) droplet generation. In conventional three-dimensional (3D) metal printing technique such as Selective Laser Melting (SLM), Direct Laser Fabrication (DLF), Electron Beam Solid Fabrication (EBSF) and related methods, an object is created by layer-by-layer patterned deposition of heated material on a moving substrate. In MHD-base DOD additive manufacturing of liquid metal, a metal spooled wire (approximately 1 mm diameter) is fed into a ceramic reservoir where it is resistively heated to form molten metal. The molten metal flows from the reservoir into an ejection chamber via capillary forces. The assembly of ejection chamber and ejection reservoir is also known as the printhead. The printhead is surrounded by a solenoid copper coil that is electrically pulsed to produce a transient magnetic field ($B$) within it. The magnetic field, in turn induces a circulating current density ($J$), that back couples to the transient magnetic field thereby generating a MHD Lorentz force density ($f_{MHD}$) within the molten metal in the ejection chamber, whose radial component creates a transient “effective pressure”
A pulse that ejects a liquid metal droplet through the orifice. The metal droplet travels through the argon-gas atmosphere and deposits on the object being fabricated. The argon gas shroud is needed to prevent oxidation of liquid aluminum. We present an analysis of a commercial MHD-based printing system under development by Vader Systems (www.vadersystems.com) and introduce a computational model that helps to predict system performance. We discuss the underlying physics and the thermos-fluidic aspects of droplet deposition. We also demonstrate the use of Computational Fluid Dynamics (CFD) to analyze the effects of various parameters on droplet deposition, coalescence and solidification, and ultimately on the final printed structure. A finite-volume thermo-fluidic analysis was performed using the commercially available CFD software Flow-3D (www.flow3d.com). Computational simulations were performed to understand and analyze the droplet-air and droplet-substrate interactions, and to study the effects of various parameters on the final printed structures. The presented models provide insight into the underlying mechanism behind droplet deposition and droplet solidification on the surface. We also demonstrate good agreement between our computational models and measured data.
Chapter 1: Introduction

Additive Manufacturing & 3D Printing

Additive Manufacturing (AM), also referred to as 3D printing, involves manufacturing of a 3D structure in a sequential layer-by-layer fashion. Objects of almost any shape, size or geometry can be fabricated based upon a digital model from a Computer-Aided Design (CAD) file. In recent years, the demand for high-end customized metal parts has increased multifold. Cost of production and product quality are two major factors when considering a particular manufacturing technique. When developing a prototype, it is important to consider different tools available and the various processes used for producing different parts within a novel design. Prototype production can be broadly categorized into two brackets: Additive manufacturing (3D printed parts) and Subtractive Manufacturing (Casting methods or injection molding and Computer Numerical Controlled (CNC) machined parts). Subtractive manufacturing is the most commercially available technology for fabrication of metal parts. It can typically be divided into casting methods and CNC machined parts, which are fully developed but limited. Casting is a manufacturing process in which metal, in its liquefied form, is poured into a hollow cavity of desired shape (known as mold) and then allowed to solidify. The solidified metal takes the shape of mold and is then ejected out of it. On the other hand, CNC machining makes use of cutting tools to eliminate material from a block of a pre-existing part. Conventional technologies make use of drills, lathes and milling machines to execute the process. Subtractive manufacturing is especially appropriate for large objects or mass production. Additive manufacturing, on the other hand, is a process in which 3D objects are fabricated.
by successive deposition of material in layers, whether the material is polymer, plastic, metal, concrete etc., such that it takes a predesigned shape. 3D printing has always been advantageous for rapid prototype development, but in recent times it has started to make its impact on the manufacturing world as well. It is especially useful for rapid prototyping of metallic structures that are problematic or too costly for the conventional methods. More recently, AM is being used to manufacture end-use products in aircraft, dental restorations, medical implants, automobiles, and even fashion products.

Additive manufacturing can be used to fabricate highly complex structures that can still be extremely light and stable. It has been in practice for more than 15 years. The term AM encompasses many technologies including subsets like 3D printing, Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), layered manufacturing and additive fabrication. An area of particular and intense interest is AM of metal objects. Conventional metal AM technologies make use of lasers or electron-beams (EBs) as directed energy sources to fuse together specially prepared metal powder. Laser-based AM techniques include Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS) and Laser Solid Forming (LSF). The EB technologies include Electron Beam Melting (EBM), in which an EB is used to selectively melt the layer of metal in its powdered form. However, these processes have drawbacks including both production costs and complex process control, which are due to the energy-intensive equipment needed to convert metal into powder form prior to fabrication, and the precise melting and fusing of the powder to form a desired 3D structure. Fused Deposition Modeling (FDM) is another AM technology that
can print 3D structures using both metals and thermoplastics as feed material. Table 1 describes various AM technologies developed over the years.

*Table 1: AM technologies classified according to their type and describing the materials that can be used as feed input.*

<table>
<thead>
<tr>
<th>Type</th>
<th>Technologies</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>Fused Deposition Modeling (FDM)</td>
<td>Thermoplastics, Eutectic Metals, Edible Materials</td>
</tr>
<tr>
<td>Wire</td>
<td>Electron Beam Freeform Fabrication</td>
<td>Almost any metal alloy</td>
</tr>
<tr>
<td>Granular</td>
<td>Direct Laser Sintering (DLS)</td>
<td>Almost any metal alloy</td>
</tr>
<tr>
<td></td>
<td>Electron Beam Melting (EBM)</td>
<td>Titanium alloys</td>
</tr>
<tr>
<td></td>
<td>Selective Heat Sintering (SHS)</td>
<td>Thermoplastic powder</td>
</tr>
<tr>
<td></td>
<td>Selective Laser Sintering (SLS)</td>
<td>Thermoplastics, metals/ceramic powder</td>
</tr>
<tr>
<td></td>
<td>Powder bed and inkjet head 3D printing, Plaster-based 3D printing</td>
<td>Plaster, Metals, Ceramic powder</td>
</tr>
<tr>
<td>Laminated</td>
<td>Laminated object manufacturing (LOM)</td>
<td>Paper, metal foil, plastic film</td>
</tr>
<tr>
<td>Light Curing</td>
<td>Stereolithography (SLA)</td>
<td>Photopolymer</td>
</tr>
<tr>
<td></td>
<td>Direct light processing (DLP)</td>
<td>Photopolymer</td>
</tr>
<tr>
<td>Drop-on-Demand</td>
<td>Magnetojet</td>
<td>Aluminum alloys</td>
</tr>
<tr>
<td></td>
<td>Piston-based ejection</td>
<td>Tin</td>
</tr>
<tr>
<td></td>
<td>Pneumatic-based ejection</td>
<td>Electrical Solder</td>
</tr>
</tbody>
</table>

An alternate 3D printing technique utilizes liquid metal to additively manufacture metal objects. This process, generally referred to as “material jetting” uses droplet generators and molten droplets in the nano- and pico-liter range and can be implemented in two distinct modes: continuous jet and drop-on-demand. It is analogous to inkjet printing and offers rapid manufacturing of parts directly from computer models by sequential printing.
of two dimensional layers. Conventional inkjet technology has been used to print a variety of functional media and devices by depositing and patterning materials that range from polymers to living cells. Molten metal printing can be used directly to print cores and shells thus eliminating initial tooling cost. In the continuous jet method, a liquid metal jet is formed and caused to break up via a perturbation stimulus into a continuous stream of well-defined droplets (volume and velocity) at a fixed distance from the nozzle. The droplets needed for fabrication are deposited on the build substrate, the other droplets are deflected. In contrast, in the drop-on-demand method, well-defined droplets are ejected from a nozzle and deposited on a build substrate as needed. The precision of the DOD jetting process enables a reduction in material waste, and thus reduction in cost and increase in efficiency. Figure 2 shows various continuous and DOD ejection systems.

Additive manufacturing can be applied to print 3D structures of various substances such as ceramics, metals, metal composites and polymers. In recent times, direct printing of metals based on droplet ejection techniques has been a subject of research. Still, challenges remain in realizing the optimum operating parameters of operation that include the following:

i) Thermal management: The droplet generator (printhead) has to operate at a temperature above the melting point of the metal being printed. At such high temperatures, there is a possibility of thermal damage and degradation to the printhead assembly and hence, an efficient cooling system is a primary requirement. Also, this limits the number of metals that can be used as feed and the thermal gradients might induce mechanical stresses that are undesirable and affect the strength of the solidified structure.
ii) Droplet ejection: Droplet ejection control is the most important process parameter when it comes to process throughput. Several factors contribute to the stable droplet ejection such as high contact angle and surface tension of the metals, the capillary priming of nozzles, maintaining the axial stability of ejected droplets and selectively varying the droplet size, if required.
iii) Droplet patterning (deposition, coalescence and solidification): Droplet patterning controls the shape and strength of the 3D structure. Droplets need to deposit smoothly on the moving substrate. Oxidation of metal droplets need to be avoided as it affects the resolution of 3D solid structures and also interferes with the droplet coalescence. Thermal gradients need to be controlled between droplet-atmosphere and droplet-substrate surface to ensure proper droplet coalescence and solidification.
The focus of this work is on drop-on-demand metal printing in which droplets of metal are ejected through the orifice at a regular, desired interval in order to form 3D structures on the substrate. Drop-on-demand 3D printers are commonly made up of a small-sized orifice, a reservoir and a printhead that generates a pressure pulse so as to create a discontinuity in the ejected fluid stream. The source of actuation of pressure pulse could be thermal, piezoelectric or electromagnetic (as shown in Figure 2). In order to build accurate droplet patterning, a substrate is set up beneath the printhead. The substrate moves at a pre-programmed velocity, which must be matched to the frequency of the droplet ejection. Droplet ejection frequency varies according to the shape of the structure to be printed. In this work we provide an overview of a novel DOD metal AM technique based on magnetohydrodynamic (MHD) droplet ejection that can be used to create 3D structures with complex geometries. We also demonstrate a computational model that is used to predict system performance and explore critical performance parameters. The MHD-based printing system is under development by Vader Systems (www.vadersystems.com) under the tradename Magnetojet™. The underlying physics of droplet generation and the thermos-fluidic aspects of droplet deposition, coalescence and solidification are described in the following sections. The operating principle of this process is based on MHD, which exploits a Lorentz Force acting on induced currents within the conducting molten metal as a droplet ejection mechanism. The ejected droplets impact the moving substrate where they coalesce, cool and solidify to form extended solid structures. Solid structures of arbitrary shape and size can be fabricated in a layer-by-layer fashion with the help of this technology. In this thesis, we describe the Magnetojet™ process, introduce a computational model that can guide process design, and discuss
key technological challenges. Sample 3D structures printed by Magnetojet™ are also included in this thesis.

**Magnetohydrodynamics**

The Magnetojet™ process is based on the fundamentals of magnetohydrodynamics (MHD). MHD, as the name suggests, is the study of the application of electromagnetic field forces to electrically conducting fluids such as liquid metals, plasmas, salt water, and electrolytes. The field of MHD was introduced in 1907. The fundamental concept behind MHD is that magnetic fields can induce currents in a moving conducting fluid, which in turn polarizes the fluid and reciprocally changes the magnetic field itself. MHD has a wide range of applications in fields including geophysics, astrophysics, sensors, magnetic drug targeting, power generation. It is widely used in continuous casting of metals.

MHD spans two branches of physics, classical fluid dynamics and electromagnetics. The governing equations of MHD for Newtonian fluid include the Navier-Stokes equation, mass continuity and Maxwell equation. The differential forms of these equations are:

\[
\mu \frac{\delta p}{\delta t} + \rho u \nabla u = -\nabla p + \mu \nabla^2 u + f_{\text{MHD}} \tag{1}
\]

\[
\frac{\delta \rho}{\delta t} + \nabla (\rho u) = 0 \tag{2}
\]

\[
f_{\text{MHD}} = J \times B + \rho E \tag{3}
\]

\[
\nabla \times E = -\frac{\delta B}{\delta t} \tag{4}
\]
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \]  
\[ \mathbf{J} = \sigma \mathbf{E} + \sigma \mathbf{u} \times \mathbf{B} \]

In addition to the above relations, we have

\[ \nabla \cdot \mathbf{B} = 0 \]  
\[ \nabla \cdot \mathbf{J} = 0 \]

Where \( u \) = fluid velocity, \( \rho \) = fluid density, \( p \) = fluid pressure, \( \mathbf{J} \) = current density, \( \mu_f \) = fluid dynamic viscosity, \( \mathbf{B} \) = Magnetic flux density, \( \sigma \) = electrical conductivity. The MHD body force density \((N/m^3)\) is defined in equation (3).

In this DOD process, a spooled metal wire, approximately 1 mm in diameter, is continuously fed to a ceramic reservoir of the nozzle where it is resistively heated to form 3 mL of molten aluminum. The molten metal flows from the reservoir into a nozzle via capillary forces. The nozzle is surrounded by a copper coil that is electrically pulsed to produce a transient magnetic field \( \mathbf{B} \) within it. The magnetic field, in turn, induces a circulating current density \( \mathbf{J} \), that back couples to the transient magnetic field thereby generating a magnetohydrodynamic Lorentz force density \( f_{MHD} \) within the ejection chamber, whose radial component creates a transient “effective pressure” pulse that
ejects a liquid metal droplet through the orifice. Figure 3 and Figure 4 give a detailed view of actuation using the MHD principle and Lorentz force.

**The Lorentz Force**

![Conceptual schematic of MHD jetting process.](image)

A point charge in the presence of electromagnetic fields experiences a combination of electrical and magnetic force. Charges move in the magnetic field and encounter “Lorentz” force, named after Dutch physicist Hendrick Lorentz, that is perpendicular to both their velocity and the induced magnetic field:

\[
F_q = q(v \times B)
\]  

(9)
The charged particle gains energy from an electric field, but not from a magnetic field. This is because the magnetic force is always perpendicular to the particle’s motion, and hence, does no work on it. Figure 5 shows the description of Lorentz force on the charged particles. The positive and negative charges experience Lorentz forces in opposite directions (though both perpendicular to the current flow). The velocity and pressure of a conducting liquid metal can be altered by the Lorentz force. The Lorentz force is used in many devices including mass spectrometers, velocity filters, cyclotrons and other circular path accelerators, magnetrons, electrical generators, and loudspeakers.
Figure 4: Schematic illustration of action of the Lorentz force (F) on charged particles.
Chapter 2: Process Description and Computational Models

Process Description

The Magnetojet™ printing process has been used to create aluminum parts with a repetition rate up to 1000 droplets/sec, with a droplet placement resolution of 500 µm. It has achieved a mass deposition rate of up to 1 lb per hour based on a single orifice that generates droplets with a 500 µm diameter. In addition, it is a relatively low cost process that can print parts with improved mechanical properties owing to the presence of a unique metal grain structure. In this chapter, we describe the fundamental principles of Magnetojet™ printing and introduce computational models that predict droplet deposition, coalescence and solidification and can be used to optimize the process. Sample 3D structures printed by Magnetojet™ are also demonstrated in this presentation.
Vader Systems have developed and commercialized a prototype printing system with a printhead consisting of a two-part refractory nozzle, a water-cooled solenoid coil and an argon gas shroud. Aluminum wire enters the reservoir 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. Liquefaction of aluminum wire takes place at 1123-1223 K (850-950°C) by resistively heating the cylindrical titanium dioride refractory reservoir. As new metal enters the reservoir, it is melted by thermal conduction from the already melted molten metal and the refractory nozzle. MagnetoJet follows the
electromagnetic droplet ejection mechanism. A short voltage pulse is applied to the coil, which can be divided into positive and negative pressure events. During the positive cycle, positive voltage is applied to the electromagnetic coil. This positive voltage leads to linearly increasing electric current within the coil that induces linearly increasing axial magnetic flux density through the nozzle. Because of the increasing magnetic field, clockwise (top view) circulating eddy currents are induced within the liquefied metal thus creating an inward directed Lorentz force density within the nozzle that can be thought of as an effective pseudo pressure that acts to eject a droplet. During the negative cycle: complementary events happen. Negative voltage is applied to the electromagnetic coil leading to linearly decreasing electric current which is cut off when it reaches zero. The linearly decreasing electric current induces linearly decreasing magnetic flux density. As a result of this, counter-clockwise circulating eddy current are generated in the liquefied metal thus creating an outward directed Lorentz force density, which can be considered as an effective negative pseudo pressure. The coupling between the magnetic field and the electric current results in a Lorentz force that provides a pseudo-pressure for jetting the molten metal onto a build platform. The lower part of the nozzle contains an orifice, ranging from 100-500 µm in diameter, through which liquid metal droplets are ejected. The metal droplet travels through an argon shroud, which envelops the reservoir and the orifice, and is deposited on a stainless steel substrate that is heated to a temperature below the melting point of the deposited metal. The droplets coalesce and solidify on the substrate to produce extended solid structures through layer-by-layer deposition, which is achieved by moving the substrate using computer numerical control (CNC)
and computer aided design (CAD) file. Figure 6 depicts a cross sectional view of the printhead and other essential components of the MagnetoJet process. The size of droplets varies from 50-550 µm in diameter, depending on the orifice geometry, diameter, ejection frequency and pulse duration. Steady droplet ejection rates ranging from 40-1000 Hz with short burst ups up to 5000 Hz have been achieved with the machine prototype. Common aluminum alloys such as 4043, 6061 and 7075 have been used to successfully print solid metal structures.

**Introduction to the Computational Model**

Computational simulations were performed prior to prototype fabrication and during the design cycle to optimize selected process parameters for performance. The focus of this study is on droplet-air interaction and droplet-substrate interaction. Computational Fluid Dynamics (CFD) analyses were performed using the multiphysics Flow-3D (www.flow3d.com) software to study the thermo-fluidic aspects of droplet deposition, coalescence and solidification. Solidification of droplets on the substrate is influenced by various factors such as droplet ejection frequency, droplet temperature, velocity, size, center-to-center droplet spacing, substrate and surrounding temperature and others. Aluminum alloy 6061 is used in running simulations and machine tests. Aluminum 6061 consists of magnesium and silicon as the alloying elements. 6061 is the most common alloy used for aluminum extrusion. The significant properties of aluminum 6061 used in the simulations are: solidus temperature = 847 K, liquidus temperature = 905 K, specific heat = 1.176 J/g/K, Latent Heat of Fusion = 397.5 J/g, Surface
Tension Coefficient = 870 g/s². Density, viscosity and thermal conductivity are used as a function of temperature. Contact angle between aluminum droplet and substrate is taken as 70°. Spherical droplets of aluminum at 1023 K impact a stainless steel substrate, kept at 473 K, from a height of 3 mm. Oxidation of molten aluminum takes place in the presence of oxygen, leading to the formation of Al₂O₃ oxide skin. Formation of oxide could impede the ejection of metal droplets, as well as reduce the quality of the printed object. In order to prevent metal oxidation, an inert environment is maintained around the nozzle with the help of argon gas shroud. In order to fabricate precise 3D metal solid structures, droplet patterning, coalescence and solidification are critical. In this process, droplets are ejected with a velocity ranging from 1-10 m/s and travel through the argon-shielded atmosphere before impacting the substrate surface. Thermal diffusion from the droplet to the surrounding atmosphere takes place during flight and after impacting the substrate surface, droplet solidification takes place owing to the thermal diffusion from droplet to substrate, and from continued heat transfer from droplet to air. The substrate is heated to a temperature that is below the melting point of the metal. This reduces the temperature gradient between droplet and substrate and hence, slows down the rate of thermal diffusion. This promotes smoother coalescence with the neighboring droplets (intralayer) and between layers (interlayer) as well as the growth of favorable metal microstructures, thus creating 3D solid structures with low porosity and no undesired layering artifacts. In the droplet deposition model, we designed CFD models to investigate the droplet deposition, coalescence and solidification on a heated substrate. A Finite Volume thermo-fluidic analysis was performed using the solidification model in Flow-3D. These models solve
the Navier-Stokes equation for incompressible flow taking into account thermo-fluidic heat transfer, subject to appropriate initial and boundary conditions, i.e.

Navier-Stokes:

\[
\frac{\partial \rho}{\partial t} + \rho u \cdot \nabla u = -\nabla p + \mu \nabla^2 u + f_{MHD} 
\]  
(10)

Where the induced force density \( f_{MHD} \) is given by

\[
f_{MHD} = J \times B + \rho E
\]  
(11)

\[
J = \sigma E + \sigma u \times B
\]  
(12)

\[
\nabla \times E = \frac{\delta B}{\delta t}
\]  
(13)

Thermo-fluidic heat transfer:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) = k \nabla^2 T
\]  
(14)

Where \( \rho \) is the density of liquid metal, \( \mu \) is the viscosity of liquid metal, \( u \) and \( p \) are the velocity and pressure, \( B \) is the magnetic flux density, \( E \) is the electric field induced in the liquid metal by the time-varying magnetic field, \( J \) is the corresponding current density, \( \sigma \) is the electrical conductivity of the liquid metal, \( C_p \) is the specific heat at constant pressure, \( k \) is the thermal conductivity of the material (solid or liquid) and \( T \) is the temperature.
Flow-3D Models and Parameters

a.) Solidification Model

The solidification model simulates the effects of solid-liquid phase change. This model does not take into account crystalline structures or formation of grain boundaries but rather models the fluid to solid phase change as a continuum. Flow-3D investigates the molten metal liquid to solid phase change as it impacts the heated substrate. The solidification model is used in concurrence with the heat transfer model. The latent heat is released linearly as the material cools from the liquidus to solidus temperature.

The rigidity can be modeled based on the coherency point which refers to the state of a solidifying alloy at which a coherent dendrite network is established during the grain formation and the alloy starts to develop additional mechanical resistance because of this. Effects of solidification model are accounted for in one of the two ways: either by using enhanced viscosity of solidified fluid or through use of a drag force.

The viscosity-based model is applied when the solidified phase is deformable and can still move. The viscosity of the partially solidified metal depends on the solid fraction. The viscosity varies linearly with the solid fraction. A constant finite viscosity, higher than that of the liquid phase, is assigned to the solidified fluid. The viscosity of the liquid/solid mixture is calculated as a solid-fraction weighted average of the viscosities of the liquid and solidified phase. When the solid fraction is zero, the model takes the viscosity of the liquid and when the solid fraction is one, the viscosity is equal to a user specified viscosity.

The drag-based flow model is built upon the porous media drag concept. By neglecting the volume change associated with a phase change and assuming that solid material
is at rest with respect to the computational mesh, we can approximate the solidification process (i.e. state of zero flow velocity) by using a drag coefficient that is a function of the local solid fraction. Solidification implies a rigidity and resistance to the flow. This rigidity is dependent upon the coherent solid fraction. For low solid fractions, i.e. below point of coherency, the viscosity is a function of solid fraction. For solid fraction larger than the coherent solid fraction, a Darcy type drag force with a drag coefficient proportional to the function of solid fraction is used. If the solid fraction exceeds the point of rigidity, the critical solid fraction, the drag becomes infinite and there can be no flow with respect to the computational grid.

In this work, we use the porous media drag based solidification model with no shrinkage. The critical solid fraction value was taken to be 0.67. Release of the latent heat of fusion was linear with temperature. The liquidus temperature was specified at 905 K and the solidus temperature at 847 K.

Because density is also a function of temperature, the temperature dependent values were used, as shown in Figure 6.
b.) Surface Tension Model

Surface tension force acts in a plane tangent to any sharp interface. The interface can be between a gas and liquid or between two immiscible liquids. The force occurs because of the differences in the inter-molecular forces between the two materials. In Flow-3D, we model surface tension with a free surface or sharp interface between two fluids. The activation of surface tension model requires the user to set a surface tension coefficient at the interface and contact angle at the point of contact of the fluid-fluid interface and the solid surface. The contact angle controls the wetting behavior where the interface meets solid wall boundaries and solid components. Wetting of liquids can be divided into two classes: reactive and non-reactive. In our case, reactive wetting takes place as aluminum rapidly reacts with many of the common elements.
found in refractory ceramics to form oxides and other compounds. But since reactive wetting complicates the fluidic analysis greatly, it is ignored in this surface tension model. The contact angle ($\theta_c$), measured through the liquid, is defined as the angle between the tangent at the point where liquid-vapor interface meets the solid surface, and the solid surface. The contact angle can take values between 0.0 (complete wetting) and 180° (completely non-wetting). Surface tension coefficient ($\sigma$) can be a constant or a function of temperature. The temperature dependent relationship of surface tension coefficient is given by:

$$\sigma = \sigma_0 - \frac{d\sigma}{dt} (T - T^*)$$  \hspace{1cm} (15)

Where $\sigma$ is the computed surface tension coefficient, $\sigma_0$ is the user-defined value of surface tension coefficient, $\frac{d\sigma}{dt}$ is the temperature-dependence of surface tension coefficient, $T$ is the local temperature, and $T^*$ is the user-defined reference temperature. For aluminum 6061 used in our model, $\sigma_0 = 870 \text{ g/s}^2$, $\frac{d\sigma}{dt} = 0.152 \text{ g/s}^2/\text{K}$ and $T^* = 953 \text{ K}$.

c.) Viscosity and Turbulence

Viscosity is a fluid property that arises from intermolecular forces and manifests as a resistance to flow. Fluid viscosity is a key parameter in the Navier-Stokes equations. When modeling confined flows, it is important to define the slip conditions at the fluid-solid interface. Slip conditions describe the fluid velocity near and in contact with the material boundary (wall). There are generally three types of slip conditions in CFD: no
slip, partial slip and free slip. A free slip condition is one in which the surface offers no resistance to the flow and the fluid velocity profile is unchanged. This condition is often used to describe a boundary between two fluids. Partial slip conditions offer some resistance to the fluid flow and there is a partial reduction in fluid velocity at the boundary. The no-slip condition is one in which the fluid velocity is zero at the fluid/solid interface.

In a partial-slip boundary condition, the slip velocity at the boundary is directly proportional to the shear stress, and the friction coefficient is the parameter that is used as a constant of proportionality and can be applied to both solid components and solid/liquid interface. As the friction coefficient approaches infinity, the slip velocity approaches zero (no-slip condition). A positive, finite friction coefficient corresponds to the partial slip condition. In Flow-3D the static friction coefficient is set to -1.0, so all unspecified components have no-slip condition by default. In this analysis, we assume flow is laminar and viscosity is used as a function of temperature, as shown in Figure 7.
d.) Heat transfer Model

Flow-3D’s heat transfer model is used to study the thermal behavior of the printing process. The heat transfer model solves full conjugate heat transfer equations, taking into account the heat transfer between fluid, solid, and ambient air regions (referred as void) through conduction, convection, and radiation. It computes the dynamic surface temperature of the deposited layer. This model predicts the heat transfer that takes place during the droplet’s flight to the substrate and the cooling of the droplet once it impacts the substrate surface. We have used the first-order fluid advection option in conjunction with fluid to solid heat transfer, which is efficient and robust for most heat transfer problems. There are four different types of heat transfer models that can be defined for the substrate in the geometry specifications: (a) Full heat
transfer (b) Dynamic uniform temperature (c) Prescribed uniform temperature and (d) Static temperature. Dynamic uniform temperature, prescribed uniform temperature and static temperature do not solve for conduction and hence, we have used the full heat transfer mode to account for conduction in the component. The general equation solved for dynamic structure temperature is:

$$
(1-V_r) \rho_w C_w \frac{\delta T_w}{\delta t} - \frac{\delta [K_w (1-A_r) \frac{\delta T_w}{\delta x}]}{\delta x} - \frac{\delta [K_w (1-A_r) \frac{\delta T_w}{\delta y}]}{\delta y} - \frac{\delta [K_w (1-A_r) \frac{\delta T_w}{\delta z}]}{\delta z} = T_{SOR}
$$

(16)

Where $T_w =$ solid structure temperature, $\rho_w =$ Solid material density, $C_w =$ Solid specific heat, $K_w =$ Solid thermal conductivity, $T_{SOR} =$Specific energy source term composed of contributions from specified external sources and solid-liquid heat transfer.

Fluid calculations are performed with the energy transport equation for heat transfer between fluid and substrate surface. Flow-3D calculates heat transfer from the boundaries having known temperatures. The surface temperature of the substrate is specified and the local energy source rate is calculated as:

$$
q = h W_s (T_w - T)
$$

(17)

Where $h =$ heat transfer coefficient for solid/fluid heat transfer, $W_s =$ surface area of the substrate in contact with the fluid, $T_w =$ structure surface temperature, $T =$ fluid surface temperature.

The fluid transfers heat to the void according to:

$$
q_v = h_v W_v (T_v - T)
$$

(18)
Where \( h_v \) = heat transfer coefficient for fluid/void heat transfer, \( W_v \) = heat transfer surface area, \( T_v \) = void temperature, \( T \) = fluid temperature.

**Chapter 3: CFD Modeling**

This chapter describes the Flow-3D CFD model that describes droplet deposition, coalescence and solidification on a heated substrate. A droplet is initiated above the substrate to simulate the conditions of droplet’s flight in the air and its subsequent impact and solidification on the substrate. A number of droplets are printed, first in a straight line and then extending the model to print layered structures with one layer on top of the other to examine the droplet interaction with the neighboring droplets (intralayer) and between layers (interlayer). Later, this model was further extended to build inclined structures, with angle of inclination between the structure and the substrate varying from 45° to 90°. A number of variables effect the quality of print structures, including:

1. Initial temperature of the droplet.
2. Initial temperature of the substrate.
3. Z-direction velocity of the droplet with which it travels in the air.
4. Ejection frequency of the droplets.
5. Droplet Overlap Fraction, which is defined as the ratio of maximum overlap length between any two droplets to the outside diameter of either droplet.

A finite volume thermo-fluidic analysis was performed using the solidification model in Flow-3D. Flow-3D employs the Volume of Fluid (VOF) approach to track the interface between two fluids, which in this case is liquid aluminum and air. It evaluates the fluid
flow variables throughout the computational domain at each time step using the Navier-Stokes equation. The temperature-dependent physical properties of molten aluminum 6061, such as density, viscosity, heat capacity and thermal conductivity used as input in the model.

**Boundary Conditions**

The following boundary conditions have been used in our analysis:

**Wall Boundary:** The wall boundary condition applies a no-slip condition at the boundary, as well as no velocity normal to the boundary. Hence, the fluid in contact with the solid surface has zero velocity relative to the solid. The wall boundary condition, in this case, is applied at the substrate surface.

**Pressure Boundary:** In a pressure boundary condition, we specify the pressure at the boundary. There are two types of pressure boundary conditions that can be applied in Flow-3D: static pressure and stagnation pressure. In a static pressure condition, the pressure across the boundary is considered to be continuous and the velocity at the boundary is assigned a value based on zero normal-derivative conditions across the boundary. On the other hand, the stagnation pressure boundary condition assumes stagnant conditions outside the boundary, i.e. the fluid velocity upstream from the boundary is zero. The static pressure boundary condition is less specific than the stagnation pressure boundary condition since it says nothing about the fluid velocity outside the boundary (other than it is supposed to be the same as the velocity at the boundary). Hence, stagnation pressure boundary condition is used for all the simulations.
We have modeled droplet deposition, coalescence and solidification on a heated substrate as a function of droplet ejection frequency and center-to-center spacing between the droplets. In these models, spherical droplets of aluminum having a diameter of 450 µm, travelling with a z-direction velocity of 2.5 m/s impact a heated stainless steel substrate from a height of 3 mm. The initial temperature of droplet is 1023 K and that of substrate is 473 K. The droplets in our models are modeled using the Droplet Source Model of Flow-3D which generates a sequence of molten aluminum droplets at specified time periods, in the atmosphere above the substrate. Droplet source model allows us to model droplets at specific locations, velocities and rate of generation, with varying size and initial temperature. In this work, we have designed various structures using molten aluminum droplets, ranging from 10 to 30 in number. The morphology of inclined pillars was studied as a function of droplet overlap fraction. When building pillar structures using drop-on-demand process, control of the droplet overlap fraction is critical. This variable is controlled by the relative velocities of the droplet and the moving substrate during experiments, and via x-coordinate placement of the droplet in the model. The droplets are generated at fixed x, y and z-coordinates defined by the user.

The droplets defined in our simulation have the same y and z coordinates, but different x coordinates so as to vary the droplet separation and hence the droplet overlap fraction so as to fabricate different structures, including inclined structures or layer-by-layer structures. The droplets are generated at a fixed rate (frequency) defined by the time interval between consecutive droplets. The droplets are assigned zero velocity in
the x and y directions and a velocity ranging from 2-3 m/s in negative z direction. The thermal properties of the stainless steel substrate are:
Heat transfer coefficient to the atmosphere $= 2000 \text{erg/s/cm}^2/\text{K}$
Thermal conductivity of the substrate $= 7.54 \times 10^6 \text{erg/s/cm/K}$
Density $\times$ Specific Heat $= 3.78547 \times 10^7 \text{dyne/cm}^2/\text{K}$

The substrate temperature in our simulations is set at 473 K, which of course can be varied to study its effect on droplet coalescence and solidification. Figure 9 describes the computational domain, complete with initial droplet, void pointer and the substrate.

In Flow-3D, pointers have been used to define the extent and properties of regions of fluid or void for all contiguous cells. Void pointers only require the specification of a location and the properties. All open volume in contact with the specified location is then assigned the properties associated with the pointer. Void pointers can also be used to specify the heat transfer type, identifying unique void regions to which a certain set of heat transfer coefficients are applied. Void parameters can also be used to define not only the initial state of a void region but also its pressure and temperature during the simulation by using a tabular definition of these parameters vs time.

Because our void pointer corresponds to atmospheric conditions, these features are not exploited. The pointer is initialized with the temperature of 300 K and 1 atmosphere, and allows heat transfer with the environment during droplet's flight from the orifice to the substrate. The following boundary conditions have been set in our simulation:

X minimum: Specified pressure
X maximum: Specified pressure
Y minimum: Specified pressure

Y maximum: Specified pressure

Z minimum: Wall

Z maximum: Specified pressure

Figure 8: Flow-3D computational domain showing droplet initialization, void pointer and substrate.
Chapter 4: Results and Discussion

In this chapter, we discuss the results of our simulation runs and analyze, in detail, the effects of various parameters such as droplet ejection frequency, overlap fraction, and droplet and substrate initial temperature. High resolution images are generated with Flow-3D to effectively communicate the findings of our simulation runs. We started with a very basic model in which 10 droplets were printed in a straight line and then went on to simulate printing of more complex structures.

Single layer model

Ten droplets were modeled in a straight line. The droplets have a diameter of 250 µm and a flight velocity of 5 m/s. The initial temperature of droplets was 973 K and that of the substrate is 673 K. The ejection frequency of droplets is 100 Hz. The material

Figure 9: Temperature distribution of the solidified single layer structure.
properties of molten aluminum and stainless steel substrate are provided to the model. Overlap fraction in this case is taken as 0.02, so that there is a small overlap, and hence slight re-melting of the already deposited droplet takes place as a new droplet impacts the substrate. Figure 10 shows the morphology and temperature distribution of the deposited layer at the end of the simulation, at a point where they have nearly reached the substrate temperature.

This basic model was further modified to print more complex structures. A three-layered structure was printed with 5 droplets in a single layer. Three layers were printed at various droplet ejection frequencies to analyze the effect of ejection frequency on the printed structure. Various parameters, such as droplet diameter, flight velocity, initial droplet and substrate temperature, were changed to match the parameters that are used by Vader Systems in their experiments. Next, inclined structures were modeled to study their morphology as a function of droplet overlap fraction. Overlap fraction was varied from 0.5 to 1.0 at a fixed droplet ejection frequency for this analysis. In order to study the effect of ejection frequency on the inclined structure, simulations were run at various frequencies, varying from 50 Hz to 200 Hz, keeping the droplet overlap fraction constant.

**Effect of Droplet Overlap Fraction**

Ten droplets were modeled at an overlap fraction of 0.5, 0.8, 0.9 and 1.0. in this analysis, spherical droplets of molten aluminum at 1023 K impact a stainless steel substrate, kept at 473 K, from a height of 3 mm. the droplets have a diameter of 450 µm and travel with an initial velocity of 2.5 m/s. various droplet ejection frequencies were studied and we observed that at frequencies above 100 Hz, the temperature of
the solidified droplet remained too high when the next droplet arrived, such that when the next droplet impacts it, excessive re-melting takes place and the structure is not stable. This effect was also observed during experiments, with the frequency limited to 20 Hz to ensure full coalescence and solidification of each droplet. Figure 11 presents the structures of 10 droplets at an ejection frequency of 100 Hz with an overlap fraction of 0.5, 0.8, 0.9 and 1.0 (vertical pillar). In Figure 11 (a) the overlap fraction is assumed to be 0.5 and the result is a flat coalesced layer. In Figure 11 (b), the overlap fraction is 0.8 which leads to formation of an inclined structure at 45°. In Figure 11 (c), the overlap fraction is increased to 0.9 which subsequently leads to an increase in angle of inclination with the horizontal substrate whereas in Figure 11 (d) the overlap fraction is 1.0, which produces a vertical pillar. Pillars with a range of inclination angles can be fabricated by varying the overlap fraction.

Furthermore, 30 droplets were modeled in two different simulations, one with overlap fraction of 0.8 and the other with an overlap fraction of 0.9 to form a V-shaped structure. The frequency of droplet ejection was reduced to 50 Hz for these analysis. All the other parameters are kept the same as before. Both simulations were run for a total of 0.6 seconds. Figure 12 shows the morphology and temperature distribution in the structures at the end of the simulation.
Figure 10: The effect of droplet overlap fraction on the printed structure: (a) 10 droplets at 100 Hz, 0.5 O.F. (b) 10 droplets at 100 Hz, 0.80 O.F. (c) 10 droplets at 100 Hz, 0.90 O.F. (d) 10 droplets at 100 Hz, 1.0 O.F.
Figure 11: Temperature distribution (in K) in a structure of 30 droplets with (a) 0.80 O.F. (b) 0.90 O.F.
Effect of Droplet Ejection Frequency

In the drop-on demand additive manufacturing process, droplet ejection frequency is a major parameter that not only affects droplet coalescence and solidification, but also the quality of final printed structure and the throughput of the printing process. Ejection frequency especially plays a major role while printing inclined structures, as with inclined structures we require an optimum degree of re-melting to obtain smooth coalescence. Otherwise the printed structure may be deformed.

Firstly, effect of droplet ejection frequency is shown in layered structures. Three-layered structures were printed with 5 droplets in each layer, at 400 Hz and 200 Hz. The droplets have a diameter of 458 µm and a flight velocity of 3 m/s. Droplets with an initial temperature of 1223 K impact the substrate surface, kept at 573 K, from a height of 400 mm. Figure 13 presents the three-layered structures with one layer on top of the other, printed with droplet ejection frequencies of 400 Hz and 200 Hz. Figure 13 (a) shows the layer-by-layer temperature distribution and morphology in 3 layers printed at 400 Hz, whereas Figure 13 (b) depicts the layer-by-layer temperature distribution and morphology in 3 layers printed at 200 Hz. Results shown in Figure 13 indicate that in case of layered structures, as we decrease the frequency segmented lines are produced while at a higher frequency of 400 Hz, we get smooth structures without artifacts. This is mainly due to the fact that at lower frequencies droplets have longer time to cool down before the subsequent droplet impacts it. Also, the droplets solidify from their outward surface inward, hence when the next droplet impacts it, the re-melting and hence the coalescence is incomplete, leading to segmented appearance in their final structure. Whereas at higher frequencies, there is less time for a droplet to cool before the subsequent droplet impacts
it and hence proper re-melting and coalescence takes place leading to a smooth printed structure. However, frequency cannot be increased too much otherwise there will be excessive re-melting and the structure won’t be able to retain its shape.
Figure 12: Layer-by-layer temperature distribution and morphology in three-layered structures printed at: (a) 400 Hz and (b) 200 Hz
Next, effect of droplet ejection frequency was analyzed on inclined structures. In the case of inclined structures, ejection frequency is an extremely important parameter that affects the shape and stability of the printed structure. For printing inclined structures, the parameters used were slightly different that the ones used for layered structures. Droplets of molten aluminum having an initial temperature of 1023 K impact the stainless steel substrate, which was held at 473 K, from a height of 3 mm. Droplets have a diameter of 450 µm and a flight velocity of 2.5 m/s. Various simulations were run in which frequency was varied with a set of droplet overlap fractions. Droplet overlap fraction was set at one value and frequency was varied then the same analysis was performed for another droplet overlap fraction.

**Droplet Overlap Fraction = 0.8**

10 droplets were modeled, having an overlap fraction of 0.8. Two simulations were run, one at 50 Hz and then at 100 Hz. All the other parameters were fixed as described above. Figure 14 shows the morphology and temperature distribution, in Kelvin, in the inclined structures at the end of the simulation run. Figure 14 (a) shows the temperature distribution for the structure printed at 100 Hz and Figure 14 (b) shows the same for the structure printed at 50 Hz. At higher frequency of 100 Hz, as can be seen in Figure 14 (a), there is too much material at the substrate surface. The reason behind this is that at this frequency, before the deposited droplet reaches optimum solidification, the subsequent droplet impacts it and this leads to excessive re-melting and hence instead of getting a steady erect structure, aluminum solidifies on the substrate. The structure starts growing in the vertical direction only after a certain number of droplets, leading to a bend in the structure near its base. However, upon decreasing the frequency, as in
Figure 14 (b), we get a much steadier structure that grows in a stable way in both horizontal and vertical directions.

**Droplet Overlap Fraction = 0.9**

Keeping all other parameters the same, droplet overlap fraction was increased to 0.9 and structures at varying frequency were printed. 30 droplets were modeled in two separate simulations at 100 Hz and 50 Hz. Figure 15 shows the morphology and temperature distribution in the structure at the end of the simulation. Figure 15 (a) shows the temperature distribution in the structure at 100 Hz and Figure 15 (b) shows the temperature distribution at 50 Hz. Quite similar to the findings in our previous analysis with 0.8 overlap fraction, the structure with higher frequency (100 Hz) has a lot of material deposition near its base. This also leads to a reduction in height of the pillar, as can be seen by comparing the two figures. In Figure 15 (b) optimum re-melting takes place when the subsequent droplet impacts the already deposited droplet. The deposited droplet has sufficient time to cool down so that when a new droplet strikes it, an optimum amount of re-melting takes place and the structure is built in a steady fashion.

When building inclined structures, control of re-melting is very important for proper coalescence, and is achieved by controlling droplet ejection frequency. For inclined structures the maximum ejection frequency is limited, in contrast to the layered structure for which better structures were produced at higher frequencies. One of the major reasons behind this is that in inclined structures we have the problem of molten metal dripping down the structure if excessive re-melting takes place whereas in layered structures there is no such issue.
Figure 13: Temperature distribution (in K) in an inclined structure of 10 droplets with droplet overlap fraction of 0.80 printed at (a) 100 Hz and (b) 200 Hz
Figure 14: Temperature distribution (in K) in a V-shaped structure of 30 droplets having an overlap fraction of 0.9, printed at (a) 100 Hz and (b) 50 Hz.
Summary

In this chapter, we have presented and discussed the findings of various simulation runs that modeled droplet deposition, coalescence and solidification on the substrate using the commercially available CFD software Flow-3D. A parametric analysis was performed to optimize the performance parameters in molten metal drop-on-demand printing. A number of factors affect the quality of the 3D printed structure, such as droplet diameter, ejection frequency, flight velocity, droplet overlap fraction, initial droplet temperature, substrate temperature and so on. Optimization of performance parameters depends on the shape of the structure to be printed. Several prototypical structures were printed with molten aluminum, starting with a single layered structure and then extending the model to print layered and inclined structures. All the parameters used in these models were representative of those used in experiments at Vader Systems. Effects of droplet overlap fraction and droplet ejection frequency on the shape and quality of the printed structures were analyzed. Simulations were run with a range of droplet overlap fractions, varying from 0.5 to 1.0, keeping all other parameters constant. Droplet overlap fraction is an important parameter that ultimately determines the angle of inclination of the structure with the substrate. An overlap fraction of 0.5 led to a flat coalesced layer, overlap fractions of 0.8 and 0.9 resulted in inclined structures, with an angle of inclination of 45° measured with 0.80 overlap fraction, whereas with an overlap fraction of 1.0 we obtain a vertical pillar, as expected. Any angle of inclination can be achieved by adjusting the droplet overlap fraction. Then, the effect of droplet ejection frequency was analyzed on the quality of printed structure. Various simulation runs were performed by varying the frequency for a
particular structure. For printing structures in a straight line and in layers, a relatively high frequency of droplet ejection can be used without distorting the structure. In fact, printing with high frequency is preferable in these structures as it leads to a better printed structure, without any segments or surface artifacts, than the low frequency ones. On the other hand, while printing inclined structures, low droplet ejection frequency is favorable so as to limit the re-melting and ensure proper coalescence.

**Conclusion**

In this thesis, we have presented a CFD analysis of molten aluminum droplet deposition, coalescence and solidification on a heated stainless steel substrate for molten metal drop-on-demand additive manufacturing. The Magnetojet™ process is able to manufacture parts via a layer-by-layer approach using aluminum alloys such as 4043, 6061 and 7075. In this process, droplets of sub-millimeter size are ejected from the printhead by MHD force up to kHz frequencies. Deposition rates up to 1 lb/hr have been achieved based on 500-micron droplet size. The process is extremely cost effective since it uses metal wire feedstock, thus eliminating the need of specially prepared powder. Still, challenges remain in realizing the optimum operating parameters of operation, and improvement of overall process performance. Isolating the critical droplet deposition parameters will allow the process to build a broader range of metallic structures, such as inclined pillars, horizontal overhangs etc. with high mechanical strength and minimum material wastage. To address this, we have presented a computational modeling approach, focusing on the droplet deposition model. This model can be used for a rational study and design of Magnetojet™ process, as well as similar drop-on-demand processes and will be improved in the
future to include additional physics, in order to faithfully model the process in its entirety.

**Future Work Recommendations**

The models and results described in Chapter 3 and 4 represent an apt description of drop-on-demand additive manufacturing process. However, these models can be further extended to evaluate and analyze more complex properties of the solidified structure. The solidification model used in our simulations can be developed even further via activation of Thermal Stress Evaluation (TSE) model. It is designed to use finite element method (FEM) to simulate and analyze the stresses and deformation within the solidified fluid region. TSE model can be activated by defining fluid density and at least two elastic properties out of Bulk Modulus, Shear Modulus, Young’s Modulus and Poisson Ratio. We designed our simulations with Aluminum 6061. Similar models can be designed for other metals and their alloys, especially the ones with high melting point such as iron, titanium, and nickel to analyze the coalescence and solidification and thus, printing at high temperature.
References


