Numerical Simulation of Extrusion Additive Manufacturing: Fused Deposition Modeling

A. Verma[1], P. Vishnoi[1] , V. Sukhotskiy[2] and E. P. Furlani[1,2]

[1]Dept. of Chemical and Biological Engineering,
[2]Dept. of Electrical Engineering,
University at Buffalo, The State University of New York, Buffalo NY
Email: aditiver@buffalo.edu , pvishnoi@buffalo.edu

ABSTRACT

We demonstrate a 3D computational fluid dynamic (CFD) model for simulating the Fused Deposition Modeling (FDM) additive manufacturing process. In FDM, a thermoplastic material is melted, extruded and deposited in a pre-defined computer controlled pattern to form a desired 3D structure. The CFD model predicts the flow, layer-by-layer deposition and solidification of the thermoplastic, heat transfer and pressure drops throughout the system and residual stresses in the formed structure. It takes into account key parameters including the material feed mechanism; the dimensions, orientation and velocity of the extruder nozzle relative to the substrate; the extrusion velocity and the substrate temperature. The model is developed using the commercial CFD program, *FLOW-3D*. It is well suited for parametric analysis to elucidate underlying mechanisms of the FDM process and it enables the rational design of novel rapid prototyping applications.

Keywords: Fused deposition modeling, CFD modeling of additive manufacturing,, FDM rapid prototyping and manufacturing, CFD modeling of FDM.

1 INTRODUCTION

Fused Deposition Modeling (FDM), also commonly referred to Extrusion-based Additive Manufacturing is widely used for solidified free-form fabrication applications. Additive Manufacturing technologies in general are advancing rapidly as applications of rapid prototyping for finished product development and manufacturing proliferate. FDM involves the use of relatively inexpensive machinery wherein a thermoplastic material (e.g. polylactide, PLA) is melted, extruded and deposited in a pre-defined computer controlled pattern to form a desired 3D structure [1]. This technology is very versatile and new applications are frequently reported. However, despite the widespread and growing use of FDM, relatively few rigorous process models exist and rational design for applications is lacking. Accurate numerical models that include a complete set of tunable parameters are required to obtain desired characteristics and quality of the finished printed structure. In this paper, we present a fully coupled thermo-fluidic computational model of the FDM printing process. The key tunable parameters taken into account in this model include the material feed mechanism; the dimensions, orientation and velocity of the extruder nozzle relative to the substrate; the extrusion velocity and the substrate temperature. Given this input and appropriate material properties and boundary conditions, the model predicts the flow, layer-by-layer deposition and solidification of the thermoplastic, heat transfer and pressure drops throughout the system and residual stresses in the formed structure. The model is developed using the commercial CFD program, *FLOW-3D* (www.flow3d.com)

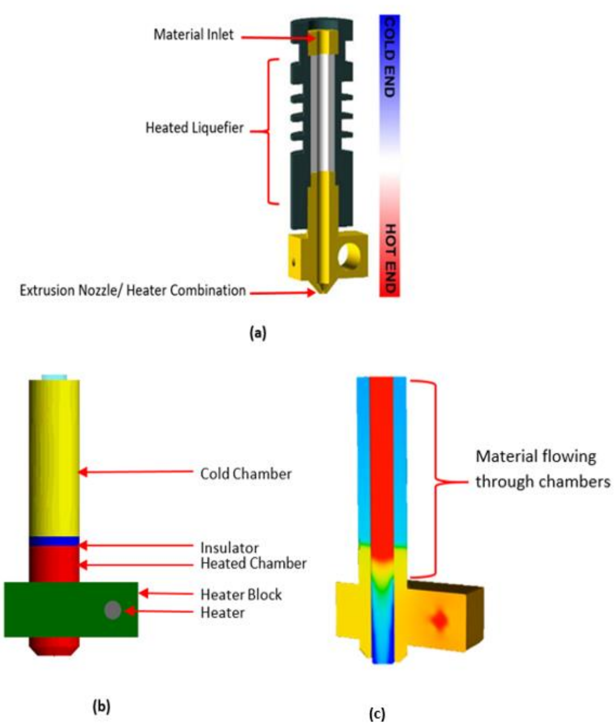

Figure 1: (a) Illustration of the typical AM Extrusion Process - Fused Deposition Modeling, showing the material feel, heated liquefier and the extrusion nozzle. (b) CFD Model defining the various components of the FDM process. (c) Material flowing through the thermally controlled chambers to form the finished product.

and is well suited for parametric analysis. It can be used to investigate underlying mechanisms of the FDM process and for the rational design of novel FDM-based rapid prototyping applications.

2 COMPUTATION MODEL

We adapted a commercial CFD software *FLOW-3D* to model the thermo-fluidic behavior of the thermoplastic (i.e. PLA) melting, extrusion, deposition and solidification in the FDM process. An extrusion nozzle for this process is shown in **Figure 1**. This is comprised of heater that melts the feedstock material before extrusion. As the nozzle moves over the build platform to fabricate a pre-specified geometry, it deposits a thin layer of heated flowing material, which is extruded. The material solidifies quickly once deposited. Solid layers are created by following a horizontal movement where the extruded threads are deposited side-by-side inside an obtrusive boundary [1, 3]. 3D solid structures can be formed by continuous computer controlled patterning and solidification of the extruded threads. Parametric analyses was performed to reduce internal residual stresses due to uneven cooling of the deposited material, as well as achieve a more uniform extrusion velocity to create smoother structures. Two different structures were simulated, single and multilayer extrusions.

In the FDM process, PLA is extruded at a designated flow rate from a sub-millimeter nozzle of the printhead assembly. In our work, a nozzle having a diameter of 0.3 mm is used to extrude molten PLA at a volumetric flow rate of 2 mm^3/s. The flowing PLA, having a temperature of 185°C, impacts the substrate surface which is preheated to 70°C so as to reduce the temperature gradient between the two, leading to smooth thermal diffusion under atmospheric pressure. A parametric study of this process was conducted with the Heat transfer and Solidification models coupled to the Navier-Stokes solver in FLOW-3D. The equations governing heat and mass transfer are as follows:

Navier-Stokes:

$$\rho\left(\frac{\partial v}{\partial t}+v.\nabla v\right)=-\nabla p+\mu\nabla^2 v \quad (1)$$

Incompressibility:

$$\nabla\bullet v = 0 \quad (2)$$

Heat transfer:

$$\rho c_p\left(\frac{\partial T}{\partial t} + v\bullet\nabla T\right)= k\nabla^2 T, \quad (3)$$

where ν , p are the velocity and pressure in the fluid. These equations are solved using the Volume-of-Fluid (VOF) method, which is implemented using a finite-differencing numerical scheme that employs a structured finite-difference mesh. Different equation sets and numerical schemes are used for the fluid and stress analysis, respectively.

2.1 Heat Transfer Model

Flow 3D's Heat Transfer model computes the dynamic structure temperature of the deposited PLA layer. The general equation solved for dynamic structure temperature is:

$$(1-V_F)\rho_w C_w\frac{\partial T_w}{\partial t}-\frac{\partial\left[k_w(1-A_x)\frac{\partial T_w}{\partial x}\right]}{\partial x} -R\frac{\partial\left[k_w(1-A_y)R\frac{\partial T_w}{\partial y}\right]}{\partial y} -\frac{\partial\left[k_w(1-A_z)\frac{\partial T_w}{\partial z}\right]}{\partial z}=T_{SOR} \quad (4)$$

Where:

T_w - Solid structure temperature

ρ_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 boundaries having a known temperature. The surface temperature of the substrate is specified and the local energy-source rate is calculated as:

$$q=hW_A(T_w-T) \quad (5)$$

Where,

h - Heat transfer coefficient to the fluid

W_A - Surface area of the substrate in contact with the fluid

T - Fluid surface temperature

T_w - Heat structure surface temperature

The fluid transfers heat to the ambient air regions (referred as void) according to:

$$q_v = h_v W_v (T_v - T) \quad (6)$$

Where,

h_v - Heat transfer coefficient for fluid/void heat transfer

W_v - Heat transfer surface area

T_v - Ambient region (void) temperature

T - Fluid Temperature

2.2 Solidification Model

The solidification model simulates the effects of solid-liquid phase change. The latent heat is released linearly as the material cools from the liquidus to the solidus temperature. Solidification implies a rigidity and resistance to flow. This rigidity is dependent upon the coherent solid fraction. For low solid fractions, i.e. below the point of coherency, the viscosity is a function of solid fraction. For solid fraction larger than the coherent solid fraction, a Darcy type of 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.

3 RESULTS & DISCUSSIONS

A parametric CFD analysis was performed to explore the viability of this approach. The FLOW-3D CFD program (www.flow3d.com) was used for the analysis. FLOW-3D uses the Volume of fluid (VOF) method to track the free-surface and a solidification model to track a change of phase that is based on porous media drag as described above.

Using a mesh discretization (e.g. Δx) of 0.3 mm, the temperature distribution in the deposited layer was studied during and after the completion of the FDM process. Two printing conditions were observed: (a) single layer deposition and (b) multilayer deposition. As seen in the thermal distribution of single layer, **Figure 2**, the temperature of the single layer decreases rapidly once deposited onto the substrate and gradually approaches a steady state of solidification. It was observed that PLA spreads more evenly and smoothly onto the substrate with a low flow rate of the feed.

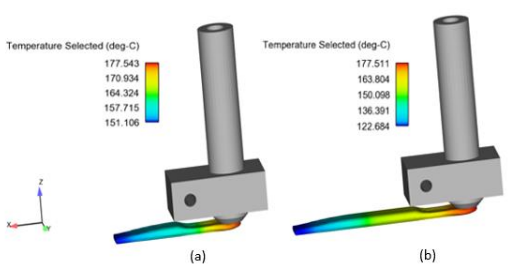

Figure 2: Thermal distribution of single layer PLA with a substrate surface temperature maintained at 70^0C and a flowrate of 0.00212 cm^3/sec. (a) Temperature distribution at t=0.0555sec (b) Temperature distribution at t=0.089sec

On the other hand for higher printing speeds or layer thicknesses, the cooling rate of the deposition is lower. To have a structure without any artifacts and with desirable thermal coalescence, the printing speed and -z printhead velocity is adjusted continuously.

Figure 3 shows the thermal distribution for a double layer in an additive manner. Whenever an element is deposited on an existing layer, the element below will be reheated [1]. As shown in the figure, the temperature difference between both the layers can be substantial. The single layer has already cooled down extensively. When a new layer comes in contact with the cooled layer, the heat transfer between the layers takes place through conduction and at the same time dissipates heat into the surroundings. This sometimes leads to poor bonding between multilayers and irregularities in the overall structure. In a multilayer structure the overall cooling rate of each layer becomes significant for inter layer bonding strength and coalescence. Another parameter of critical importance is the printing speed. A higher printing speed renders a lower interlayer

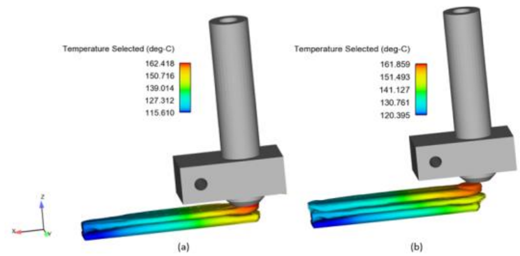

Figure 3: Thermal distribution of multi-layer PLA with a substrate surface temperature maintained at 70^0C and a flowrate of 0.002 cm^3/sec. (a) Temperature distribution at t=0.2356sec (b) Temperature distribution at t=0.388sec

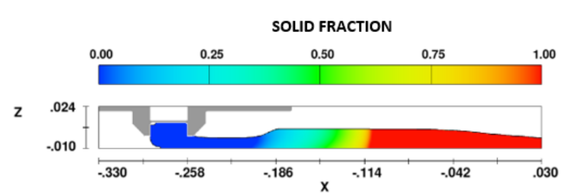

Figure 4: Single layer solidification of PLA during the FDM process in XZ plane at t=0.90sec.

cooling time. The effect of printing speed has not been adequately researched yet. These results show how the printing speed is directly correlated to the structure constructed using the FDM process.

The ability to control the patterning and solidification of layers on the substrate is critical to the formation of precision 3D solid structures. Controlling solidification to create well-formed 3D structures without undesired artifacts or voids is problematic as it involves the control of thermal diffusion within the layers to the surrounding materials. By using the solidification model as defined above we were able to reduce the temperature gradient, thereby reducing the internal stress on the layers and ultimately improving the feasibility of the FDM process. Figure 4 shows an overview of the solidification process for a single layer formation of the extruding material ranging from t=0 sec to t=0.9 sec.

4 CONCLUSIONS

We have demonstrated a rigorous 3D CFD-based model of extrusion based FDM additive manufacturing process. One can use the model to investigate fundamental mechanisms of the FDM process that cannot be easily explored via experimentation. Single layer as well as multi-layer numerical simulations have been performed to study the influence of process parameters and establish proof-of-concept in advance of fabrication.

The commercialization of this technology is well underway but many challenges remain in realizing optimum printing performance in terms of throughput, efficiency, resolution and quality. These challenges encompass thermal management, material selection and control of the feedstock among other. The ability to print 3D structures on demand holds potential for transformative advances across a broad range of existing technologies and accelerate the development cycle of new technologies.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank David Souders and Ioannis Karampelas from *Flow Science* for the unwavering technical support and informative discussions.

REFERENCES

[1] Zhang, Y and Chou, Y.K. (2006). “Three-dimensional finite element analysis simulations of the fused deposition modelling process” Proceedings of the institution of the Mechanical Engineers: Part E **220**(10):1663-1671.

[2] Turner, B. et al (2014) "A review of melt extrusion additive manufacturing processes: I. Process design and modeling", Rapid Prototyping Journal **20**(3):192-204

[3] Pennington, R.C. et al (2005). “Significant factors in the dimensional accuracy of fused deposition modeling” Proceedings of the institution of the Mechanical Engineers: Part E **219**(1): 89-92

[4] Sun, Q. et al (2008). "Effect of processing conditions on bonding quality of FDM polymer filaments", Rapid Prototyping Journal **14**(2): 72-80

[5] Comminal, R. et al (2018). "Numerical modeling of stand deposition flow in extrusion - based additive manufacturing", Additive Manufacturing **20**: 68-76