Solid Freeform Fabrication 2021: Proceedings of the 32nd Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Initial Development of a Simulation Model of a Radiation-based Print Heating System for Fused Deposition Modeling

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Abstract

Fused Deposition Modeling (FDM) has become a standard 3D printing process for thermoplastics. However, the process results in different strength characteristics along each cardinal direction of a part attributed to different bonding times between filaments. The resulting anisotropic characteristics are an obstacle when considering FDM printed parts for mechanical purposes. Work at Arizona State University has demonstrated a method using laser-based heating to achieve improved polymer bonding without loss of dimensional accuracy. In this research we consider the possibilities of reheating the filament via radiative heat transfer to achieve the same outcome. By exploring the approach in simulation and conducting confirmation experiments, we evaluate the ability to increase strength in FDM components by post-deposition controlled radiative heat-transfer.

Introduction

Using FDM printing as a production process can unlock many different possibilities for manufacturers. Although more traditional processes dominate the field of plastic component production such as injection molding, FDM printing offers some definite advantages over these processes. Traditional plastic production processes lend themselves to large scale production more than small batches. Injection Molding specifically can be prohibitively expensive for small batch production due to the cost of the large machinery and mold designs. FDM printing has a much lower capital cost and can be a good choice for smaller production runs of product. However, for engineering applications that require the part to be as capable as the bulk material properties, FDM printing cannot retain that level of strength and varies in different directions. This anisotropy of a print's strength limits the application of FDM printed parts and has been the subject of many previous studies [1-10].

FDM parts also benefit from the relative freedom of shape and structure that the print can make. Additive manufacturing is known for being able to create geometry and structure that would be impractical or even impossible in more traditional manufacturing processes and FDM printing is no exception. Methods of improving a component such as Topology Optimization can be applied via an FDM process. Again however, the lack of uniform strength not only complicates the application of these novel optimization techniques but can render them impractical.

The reasons for the anisotropic strength characteristics of an FDM printed part are innate to the process itself. By using an extrusion nozzle to deposit filament layer by layer onto a printed component, the process creates various amounts of fusion between filaments throughout the part. The bond strength between filaments is directly influenced by the temperature gradient between the previously deposited material and the depositing material. The process itself varies the temperature of the previously deposited material by allowing various amounts of time to pass before returning to deposit the next layer of material, either because the print's geometry changes as the print moves up to the next layer, or various other print characteristics change such as the z distance from the heated build plate or any speed characteristics of the extruder head and nozzle. Additionally, the strength of bonds within a given layer can vary as well for similar reasons. In most cases, the previously deposited material will cool to below the glass transition temperature of the filament material, and when that occurs, the strength of the bonding between the deposited and depositing material can reduce drastically. If the temperature difference between the two materials could be reduced by reheating the deposited material closer to or through the glass transition temperature of the filament, the printed component could have increased strength, and the FDM process could be better utilized by engineering applications [1-10].

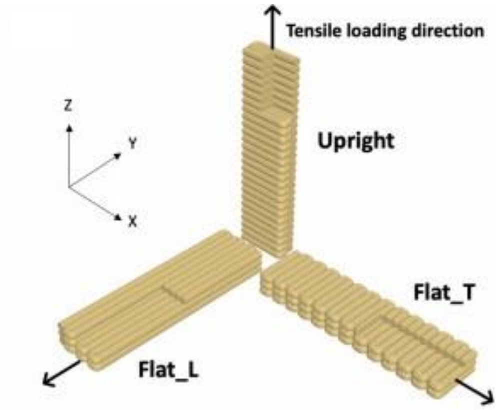

Figure 1. This figure demonstrates the different cardinal directions of a FDM print. Flat_L represents the tensile loading along the filament direction. Flat_T demonstrates loading across a layer and perpendicular to the filament direction. The upright shows the tensile loading between layers. Image used from [11].

The initial work described here collected information about and summarized the current state and understanding of the issue presented, the anisotropic properties of FDM printing and current solutions to reduce the anisotropy. Several approaches to the issue have been taken with a variety of results and conclusions [1,3,4,8,9,10]. This preceding work provides the understanding and logical basis for the investigation of radiation-based pre-deposition heating methods. This research will conduct experimentation to qualify the amount of strength that can be gained by introducing a radiation source during the printing process. Prints will be conducted that apply radiation heating via heat lamps to the printing process to raise the deposited material's temperature during the print. Test specimens of different print orientation will be tested from normal printing procedures and from printing with added radiation sources. The different orientations of the print will coincide with the tensile states of the major bonding directions of the print, as shown in Figure 1. Concurrently, a simulation of the printing process' heat transfer will be constructed to better understand the increased energy within the bonding region between the filament and previously deposited material in the deposition zone. By achieving agreement between the simulation and experiments, the simulation will then provide a means to predict the increased strength in a printed component based on the temperature gradient in the deposition zone. Finally, simulation and experimental results will be compared against results from previous work to further evaluate the findings of this work.

Summary of Prior Work

Previous research into methods to increase the bond strength of FDM printing thermoplastics was successful. Several approaches to the issue were attempted with a variety of results and side effects. The different approaches to increase the deposited material temperature were a variety of heat transfer methods as well as mediums. Heating the entire chamber of a print was conducted by Stratasys and is still used today. Convectively heating locally to the deposition zone was attempted and had limited success. Directly heating the print has also been accomplished. And heating the deposition zone via a laser-based radiation heating process has also demonstrated success.

Many FDM printers on the market today provide a heated chamber to improve the mechanical properties of a 3D print [11]. By increasing the temperature of the entire build chamber, the temperature difference between the deposited filament and the rest of the component was reduced resulting in stronger bonds. This also had limited heat annealing properties for the part improving the properties further as shown in Figure 2. However, higher risk of dimensional instability or print failure is a side-effect. The closer the supporting structure of the previously deposited filament is to the glass transition temperature of the material, the more likely the print will move, twist, bend, or stretch during the printing process. So, although the process does succeed in providing stronger parts with reduced variance of strength, the process has a limit to its application due to the loss of dimensional accuracy and higher risk of print failure as the temperature increases. The heated chamber concept can also increase the cost and reduce the life of an FDM printing system as it would depend on heat resistant hardware and would be subject to higher thermal stresses during its function. Thus, open frame heating and reheating applications can offer significant advantages to a heated chamber system.

Seth Partain at The University of Montana attempted to use convective heat transfer to locally pre-heat the deposition zone of an FDM print [9]. Although the strength of the component was increased, his research noted that some loss of dimensional accuracy would occur with the increase of power and air current. This was a direct result of the heat transfer method imparting some kinetic energy into the component once it had been raised closer to the material’s glass transition temperature. By blowing air onto the print at precisely where the print is the least rigid (the deposition zone) the resulting part can have dimensional issues and undesired features as a result such as part drift or waviness. This causes the convective heat transfer method to have a reduced use for engineering applications.

A radiation-based heating approach has the potential to ignore these issues entirely and result in an enhancement of the FDM process without reducing the dimensional accuracy or raising the risk of print failure. Research was done to explore the validity of such a printing method by Ravi, Deshpande, and Hsu at Arizona State University [10]. They used a laser on one end of a printer and applied laser energy into the print during the printing process for ABS test specimens. However, this method, combined with the spiraling print path, produced a print that had pre-deposition heating on one side and post-deposition heating on the other side of the symmetrical axis. The test specimen was a standard flexural strength testing specimen. Their findings supported the idea that adding energy into the deposited material can increase the overall strength characteristics of the printed components. However, by using multiple methods of adding radiation energy into the part (pre and post-deposition) as well as using flexural bend testing, this study did not show specific gains in bond strength in the individual cardinal directions. They observed a 50% increase in the flexural strength of their specimens once printed with their in-process laser heating system. The specimens also exhibited increased ductility and some plastic deformation compared to the brittle behavior of the normally printed specimens. The major drawbacks of the laser system in this study were shown to be pitting and void formation within the print. This pitting was shown to be a result of high laser power into the material causing vaporization on the outer surface of the previously deposited material.

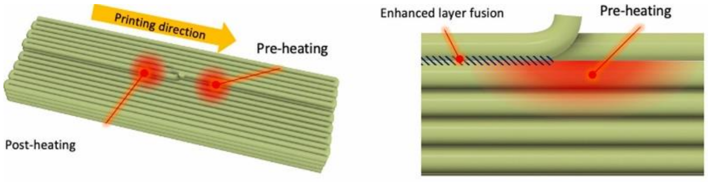

Figure 2. This image provides an example of a pre-heating and a post-heating region in an FDM printed part. Image used from [11].

Additionally, research by Sabyrov, Abilgaziyev, and Ali demonstrated the same technology as well [1]. Their research used a laser in a similar manner to the previous study but used PLA as the printing material. Also, the printed specimens for their experiments were standard tensile testing specimens that were aligned to have the filament run the length of the specimens. Their study did show an increase of approximately 10% in the tensile strength of the printed part when compared to the control specimens. However, this study did not experiment with the other cardinal directions to verify if this technology can reduce the differences in the strengths in each direction. It was also found to have similar issues with pitting and void formation in the PLA specimens like that observed by the previous study.

More research has been conducted to explore similar methods of re-heating the previously deposited material, especially in a localized manner to limit the amount of dimensional drift of the print and the energy required. Experiments have been conducted to investigate the heating functionality of pre and post heating via a hot metal surface held close to the print by attaching it to the printing nozzle [4]. Other experimentation has included infrared heating of a BAMM printing process in a pre-deposition manner [3].

Technical Approach

This research will conduct experiments using tensile testing specimens. The specimens will be exposed to radiative heating via heat lamps to increase the energy of the deposition zone during printing. This will also have the effect of reheating the entire print during the printing process. A set of 10 specimens will be printed for each cardinal direction of the print (5 control and 5 radiatively heated). The specimens for the experiment will be simple dog bone specimens printed to the shape described in ASTM/ANSI Standard D638 as shown in Figure 3. To allow the use of the Psylotech uTS tensile testing load frame, the specimens were reduced in length to 130 millimeters. The specimens will be printed using Hatchbox black 1.75-millimeter diameter ABS filament on an open frame Ender 3 V2 FDM printer. Half of the specimens will be exposed to a radiative heat source consisting of two 150-Watt heating lamps spaced 5 inches away from the center of the print volume on opposite sides so as to heat all edges of the specimen as well as the top surface. A total of 15 control (unirradiated) specimens and 15 irradiated specimens will be tested on the Psylotech load frame. This experiment will allow for the characterization of the difference in resulting bond strengths for the intrafilament, intralayer and interlayer directions. This information will increase our understanding of the increased capabilities of radiatively heating FDM components during printing.

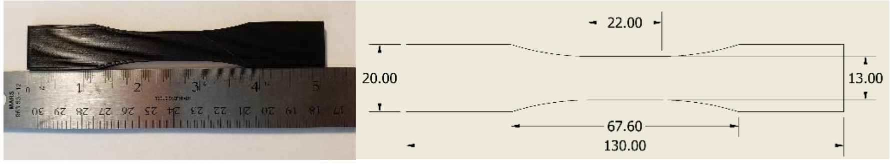

Figure 3. The picture on the left shows an ABS specimen printed along the filament direction. The drawing on the right displays all the dimensions for the test specimens.

In support of the experimental testing, the Discrete Element Method (DEM) model of the build process developed in [12] will be modified to follow a g-code input and to include radiative heat transfer into and out of the system. Further information about the DEM model can be found in [12] but for completeness, some of the mathematical foundation is presented here.

In a typical DEM approach, a discrete element of spherical shape is used to represent an element. Spheres are a preferred shape because it makes contact calculations a simple matter of determining if the distance between the centroids of the two elements A and B is less than or equal to $R_A + R_B$. If the distance is equal to or less than this value, the elements are in contact. In this application, our goal is to simulate a filament, which will be composed of a series of elements like pearls on a string. However, for FDM materials, the initial spherical shape "slumps" to form a filament with an oblong cross-section upon deposition. While a higher fidelity DEM model could be used to account for this mechanical slumping behavior, our initial model assumes that the element remains round and will have a diameter equal to the layer height of the printed part. Consequently, the filament width is equal to the layer height. The validity of this assumption is discussed in [12]. Since, the layer height values range from (0.2 mm to 0.4mm) on most FDM printers, the resulting Biot number (Bi) < 0.1, and hence, each element is considered to be a lumped capacity model with a uniform temperature distribution across the cross-sectional area of an element.

Based on these assumptions, we can define some of the mathematical properties of the elements. The surface area of the element is that of a sphere with a radius, R.

$$A = 4\pi R^2 \tag{1}$$

Similarly, the element has a volume of a sphere of radius, R.

$$V = \frac{4}{3}\pi R^3 \tag{2}$$

Since the thermal energy stored in an element is a function of the volume, density, heat capacity and the temperature of the element we can write

$$U_{deposition} = \rho V C_p \left(T_{deposition} - T_{amb}\right) \tag{3}$$

Here, we make another assumption, that the resulting element has "good" contact with any adjacent elements such that the area in contact is given by

$$A_{contact} = \frac{A}{6} \tag{4}$$

While a true rigid sphere would have only point contact with its neighbor, this contact approximation is that of a cube in contact with other cubes. Since in reality our sphere is not rigid, but is in fact "mushy", this assumption is probably closer to the reality, although it is not also imperfect. Thus, by applying Fourier's Law, we can find that the conductive heat transfer is

$$\dot{Q}_C = \frac{\left(T_A - T_B\right)}{R_{th}} \tag{5}$$

where the thermal resistance R_{th} is

$$R_{th} = \frac{L}{kA_{contact}} \tag{6}$$

where L is the characteristic length, and k is the material conductivity. For this model, the characteristic length is given by

$$L = \frac{V}{A_{contact}} = \frac{R}{3} \tag{7}$$

We can apply similar techniques to model convection and radiation effects on each of the six faces of the element. In [12], it was assumed that only free convection is present, and that radiative heat transfer is negligible. However, in this research, radiative heat transfer is clearly significant as it is the mechanism by which the elements are reheated prior to the deposition of adjacent elements. Since we will be modeling the radiative heat transfer into the element, we will also model the radiative heat transfer out of the elements. Thus, we can determine that the internal energy, U_i, of the element at a time t_i, is given by:

$$U_i = U_{i-1} - \dot{Q}_{conduction}\Delta t - \dot{Q}_{convection}\Delta t + \dot{Q}_{radiationIN}\Delta t - \dot{Q}_{radiationOUT}\Delta t \quad and \quad \Delta t = t_i - t_{i-1} \tag{8}$$

and so, the temperature T_i, of the element is given by rearranging Equation (3) as

$$T_i = \frac{U_i}{\rho C_p V} + T_{ambient} \tag{9}$$

where we assume that the deposition time, t_i, of the element is at $i = 0$. At deposition, the temperature of the element is that of the extruder, which we refer to as the deposition temperature.

Results from the simulations of this model can be compared to the experimental results to estimate the resulting times for bonds to form between elements connected within a filament (intrafilament bonds), for elements connected between filaments (intralayer bonds) and for elements connected between layers (interlayer bonds). Since each of these bonding modes in the primary bond loaded in tension depending upon the build orientation, there should be sufficient experimental data to determine the correlation if any between the relative bond strengths. This work will also evaluate the assumption made in [12] that radiative cooling is insignificant in typical FDM applications.

Results to Date

Figure 4. The test bed for the printing of the specimens. It consists of an Ender 3 V2 FDM printer and two 150 Watt heat lamps. The heat lamps have been placed to point directly at the center of the build plate at the same height and are 5 inches away from that point. By placing the heat lamps in opposing positions the part can be equally bathed in radiation.

As of this writing, the DEM model and physical experiments are incomplete. The software to translate and interpret supplied g-code from an Ender Pro 3D printer shown in Figure 4 has been developed and is being integrated with he DEM model developed in [12]. Baseline testing of several proof-of-concept specimens has verified the functionality of the tensile testing equipment and the repeatability of the defined printing process parameters. The proof-of-concept irradiated specimens experiences excessive dimensional distortions and so the radiative heat load is being modified to produce samples that fall within the tolerances specified in the D638 standard. We expect to have additional results to present at the symposium and final draft of our paper.

Conclusions and Future Work

After this work’s conclusion, a DEM model of the heat transfer within a Rep-Rap g-code driven part and the initial information needed to gain insight into a component’s increased strength via simulation will be available. Future work will be needed to improve on the model’s accuracy both in temperature simulation as well as strength prediction. Additionally, using the model with different materials will require additional testing and changes to the model. Finally, work will be needed to adapt the model to a more targeted form of radiative preheating such as the laser process discussed. This will also require validating using similar experiments and test specimens to allow for prediction of increased strength. Also, using the model to compare simulations of different kinetic-less preheating methods such as nozzle integrated preheaters, will provide better insight to compare these different approaches to one another.

An additional extension of this work would be to replace the heat lamps with a directed energy source, such as a laser beam. This would allow for a finer tuning of the deposition of energy into the previously deposited material but would also require additional modeling to represent the characteristics of the laser beam used. Fortunately, substantial work on this problem exists for SLS applications which can be applied to this task [13-18].

The knowledge obtained from these models could be leveraged in a slicer algorithm for enhanced g-code optimization. One of the great advantages of FDM printing is the ability to print geometry that would be problematic or impossible with other methods, and by linking the knowledge and tools gained through this research and others to topology optimization, the engineering applications of FDM printing can be greatly enhanced.

Acknowledgements

The authors would like to express their appreciation to the Department of Mechanical Engineering at Clemson University for their support of this research. The conclusions presented in this paper are those of the authors and do not represent the opinions of the Department of Mechanical Engineering or Clemson University.

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