**Optimization of print parameters to reduce warpage in fused deposition modeling**

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Three-dimensional printing, a form of additive manufacturing that uses a digital design to create structures and other materials, has grown into a widely used technology in many major industries. It has also expanded to the commercial side, with a variety of products for consumer use. It is becoming an attractive research project for chemical, material, and biomedical projects due to its advantages of easy operation, low cost, and high manufacturing speeds (Zhuang et al., 2017). Moreover, 3D printing is being used for rapid prototyping and manufacturing in situations where complex structures are required, including construction, dentistry, medicine, electronics, automotive, robots, military, oceanography, aerospace, and defense industries (Zhuang et al., 2017).

In 3D printing, parts are manufactured by layer. Computer software is used in 3D printing to slice a 3D digital model in one direction, usually the Z-axis, and create a set of commands for the printer to create a layer. Different techniques are used to convert a digital design into a solid part, most notably stereolithography (SLA), selective laser sintering (SLS), with the most common being fused deposition modeling (FDM) (Dizon, Espera, Chen, & Advincula, 2018). SLA printing implements photopolymerization, a process in which light links chains of molecules to create polymers, and uses the polymers formed to create the solid body of an object. SLS printing is a relatively new technology that uses a laser to sinter a powdered material and create a solid structure. SLS printing methods are used in direct metal laser sintering (DMSL) to melt and fuse powdered metal together with a laser. DMSL, SLS, and SLA, although having substantial capability, are expensive and are primarily only used in specific industrial applications. FDM printing, however, is employed in most commercial 3D printers. In FDM printing, a solid thermoplastic filament is melted and then extruded onto a bed to create a two-dimensional layer. The extruded semi-liquid polymer solidifies virtually immediately after leaving the extruder (less than one second after), and another layer is printed on top of it repeatedly to create a three-dimensional solid object from the digital design. The unique quality of FDM printing to melt and cool thermoplastics layer by layer, along with its high speeds and low costs, has led it to be the most commonly used technique for 3D printing (Dizon et al., 2018).

Polylactic acid (PLA) is the most widely used commercial thermoplastic filament for 3D printing with FDM because it is derived from renewable lactic acid as well as its biodegradable and bioactive nature (Trhlíková, Zmeskal, Psencik, & Florian, 2016). PLA’s melting temperature, around 180° C to 220° C, is lower than those of other filament materials such as acrylonitrile butadiene styrene (ABS), which is around 105° C; therefore, high-temperature areas pose a problem for objects created with it (Zhuang et al., 2017). Compared to ABS, PLA has a better print quality and lower costs (Trhlíková et al., 2016).

However, FDM printing involves processing filament through thermal cycles which can cause distortions in the objects. During the printing process, after a layer of plastic is deposited, the cooling of the layer causes the plastic to contract and create stress along the object’s lateral surfaces, and an increased rate of cooling increases the stress (Ultimaker). This stress is greatest at corners of objects, causing the corners to be pulled both upwards and inwards. Any detachment of the object from the printer bed can cause issues with printing successive layers. The repeated heating and cooling cycles during the printing process repeats this issue for almost every layer, resulting in varying print qualities and levels of warpage. Armillotta, Bellotti, and Cavallaro in 2018 suggested a physical explanation of distortion after analyzing the warpage problem: the extension of thermal stresses to multiple layers due to heat conduction from the last layer.

The thermal conduction of a material is defined by Mathur as the flow of heat through an unequally heated body from places of higher to places of lower temperature (Mathur, 1970). Thus, conduction is the transfer of heat through many molecules until there exists a dynamic thermal equilibrium (or steady-state), where there is no net movement of heat through the object. The thermal conductivity of a material essentially gives a measure of the material’s ability to transfer heat via conduction. It also expresses the anisotropy of an object and is evaluated using Fourier’s Law for Heat Conduction, which states that heat flux density, or rate of heat transfer, is directly proportional to the negative temperature gradient and the thermal conductivity as shown in Equation 1,

(1)

where is the heat flux density or rate of heat transfer, k is the thermal conductivity, and ∇T is the temperature gradient.

Unlike conduction, convection is a major process in objects that are either hollow or porous, with air pockets scattered around the internal structure. Natural convection uses buoyancy forces and the different densities of warm and cold air to force the warmer air upwards, creating a cycle in which the warm air and cold air circulate through a space. Natural convection is evaluated most often with Newton’s Law of Cooling, which, in convection, states the rate of heat transfer is directly proportional to the area of the object, the heat transfer coefficient of a material, and the difference between the object’s surface temperature and the air temperature as shown in Equation 2,

(2)

where is the heat flux density or rate of heat transfer, *h* is the heat transfer coefficient, *A* is the surface area of the object, *T(t)* is the temperature of the object at time *t*, and *TA* is the ambient or air temperature.

When an object is heated or cooled using one of the methods of heat transfer, points of higher temperatures and lower temperatures are created, causing a temperature gradient where heat flows from the hotter areas to the cooler areas. This gradient is the spatial rate of change of heat flow, which is influenced by the thermal conductivity of the material, and the direction of heat flow, which is influenced by the position of the heat source with respect to the rest of the object (Trhlíková et al., 2016). When there is a temperature gradient in a material, the temperature distribution of the object changes as some areas are heated more than others. Each type of heat transfer process, including convection, conduction, and radiation, influences the temperature distribution differently (Kim & Viskanta, 1984). Measuring the temperature of an object at different points and at various time intervals can give an accurate indication of the temperature distribution of an object.

Most modern 3D printers do not print a fully dense structure to reduce time and cost for each print; instead, objects are made with different internal structures called infills (Han, 2016). The infill percentage of a structure is the ratio of air, or empty space, to plastic within the structure, with 0% being completely hollow and 100% being fully dense. Varying infill percentage has multiple advantages. For example, prints with higher densities, or infill percentages, have higher tensile strength, are less easily compressed, and are more resistant to bending (Baich, Manogharan, & Marie, 2015). Lowering the infill percentage decreases the time taken for the object to be printed. Additionally, 3D printers offer customization options for different print parameters, including layer height and wall thickness. Layer height is the height of each layer that is extruded from the 3D printer, and affects the printing speed, resolution, and overall smoothness. Wall thickness refers to the distance between one surface of a model to the opposite sheer surface. Both wall thickness and layer height also impact the print time and print densities.

Within a printed object, conduction and convection occur and allow heat to be transferred throughout the material. Research shows that conduction takes priority over convection in plastics and enclosed spaces. The plastic within the structure has a higher thermal conductivity than air, allowing it to transfer more heat than air. Kim and Viskanta in 1984 show that increased wall heat conduction reduces the average temperature differences in a cavity, stabilizes the heat flow, and, most importantly, reduces the rate of heat transfer by natural convection. The most significant impact of their research is that they, along with Wang, Yang, Zhang, and Pan in 2015, who studied surface radiation on heat transfer on heat transfer in a horizontally porous layer, find that conduction is the superior heat transfer process in an enclosure such as the internal structure of a 3D printed object (2009). Generalizing their results supports the idea that plastic has a much greater impact on the thermal conductivity and overall temperature distribution of a 3D printed object than air. However, Han in 2016 simulated the thermal conductivity of PLA and found that increased densities led to a decrease in thermal conductivity. He noted that the only major discrepancy between the results, although being minimal, could be due to the natural convection caused by the air gaps.

Studies have been done on the heat transfer and thermal conductivity of porous structures for various materials, but none have studied extensively plastic, PLA, or the specific internal pattern on the heat transfer. Deng et al. in 2018 investigated the effect of 3D printed hollow structures in sand mold manufacturing and found that more hollow structures could be used as heat insulators due to the increased number of air cavities and less solid material. Their research shows how increased porosity in sand molds leads to a decrease in thermal conductivity. Larkin and Churchill in 1959 studied the heat transfer through radiation in porous insulations theoretically and experimentally. They found that increasing bulk density of fiberglass and foam glass decreases the amount of radiant heat transfer. They also found that the bulk density increased the amount of heat transfer through conduction but were unable to produce explicit values for the trend.

Although there is much research on the thermal conductivity and heat transfer properties of porous media of different materials, there is limited research on the heat transfer of plastic itself. Zhuang et al. in 2017 were able to create objects with anisotropic heat distribution through 3D printing. Additionally, efforts have been made to 3D print heat exchangers; for example, Haertel and Nellis in 2017 used various designs through density-based topology optimization to create a fully developed 3D printed heat exchanger. They found that more thin walls and higher unit cell heights within the heat exchanger increased thermal conductivity.

Current research in heat transfer does not focus on the thermodynamics and heat transfer properties of the objects; rather, research focuses on application of 3D printing to various industries (Deng et. al., 2018). Additionally, research on the heat transfer of porous materials does not focus on the heat transfer properties of plastic. There is also limited research on the heat transfer effects in additive manufacturing, and research has only begun to start recently. For example, Zhang et. al in 2017 numerically analyzed the influence of conditions while 3D printing on heat transfer. Their research offers only an extremely specific mathematical model during and after printing; however, the conditions set by the researchers are impractical for use of the model in any other situation. For example, they assumed the objects printed were pore-free, essentially a 100% infill, which is impossible to recreate because of the slight errors in the extrusion of plastic from a 3D printer. They also neglected heat radiation within the object, polymer crystallization and energy balance, and thermal expansion (Zhang et. al, 2017). There is also limited research on warpage in 3D printing as an effect of temperature distribution.

Most studies support the idea that increased density will increase the distribution of temperature. In this study, the effect of multiple print parameters (wall thickness, layer height, infill percentage, and infill type) on the spatiotemporal temperature distribution, and ultimately warpage, is investigated and used to optimize the values of the print parameters to reduce warpage.