Influence of infill nature on spatial temperature variation during 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 layer 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 a substantial capability, are expensive and are primarily only used in industry. FDM printing, however, is seen in many commercial 3D printers due to its lower costs. In FDM printing, the 3D printer melts a solid thermoplastic filament and then extrudes this polymer 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 to create a three-dimensional solid object from the digital design. This 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).

Most additive manufacturing technologies, including FDM, involves processing materials 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 hypothesis for the 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.

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,

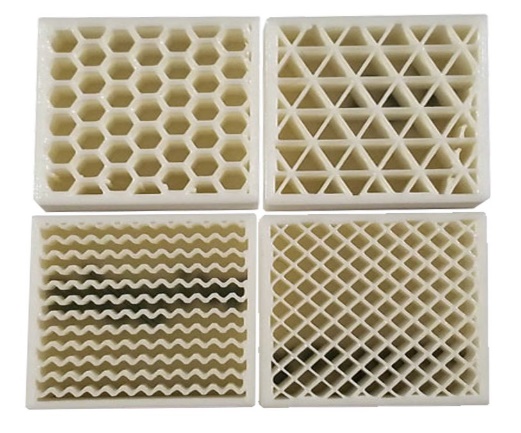
(2)

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 a good indication of the temperature distribution of an object.

Plastics such as PLA are typically used as insulators for heat transfer due to the lack of free electrons to flow through it (Flaata, Michna, & Letcher, 2017). The structure of plastics also contributes to this because of the more tightly bound electrons in the material (Zhuang et al., 2017). However, the discontinuous nature of the media of plastics causes the heat properties of a plastic object to be anisotropic, allowing these to be changed with different internal structures because of conduction through plastic and natural convection through air gaps (Han, 2016).

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 (Han, 2016). These internal structures are termed infills in 3D printing and have many patterns that leave various amounts of empty space in the printed parts. The most common infill types are hexagonal or honeycomb, triangular, wiggle, and rectilinear as shown in Figure 1.



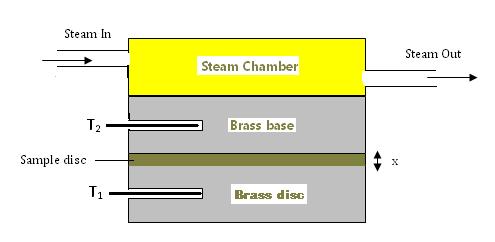
**Figure 1:** *Types of 3D printing infills. Hexagonal/honeycomb (top right), triangular (top left), wiggle (bottom left), and rectilinear (bottom right).*

Additionally, 3D printers use varying infill percentages. 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. Each infill type and percentage combination offers 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).

Various infill patterns and percentages in 3D printing affects the thermal properties of the object, causing them to become anisotropic, because of the use of a discontinuous medium, plastic. Zhuang et al. in 2017 supported this by using FDM printing of conductive PLA and ABS and adjusting the layer deposition to create materials with anisotropic heat distribution. Within a printed object, conduction and convection occur and allow heat to be transferred throughout the material. However, conduction takes priority over convection in plastics. The plastic within the structure has a higher thermal conductivity than air, allowing it to transfer more heat than air. Han in 2016 studied the thermal conductivity of PLA using both a simulation and experimental results and found that the only major discrepancy between the results, although being minimal, was the natural convection caused by the air gaps; however, this is mainly because Han used relatively large infill percentages and therefore had less air convection. Different infill patterns and percentages would then influence the amount of convection. Kim and Viskanta in 1984, however, 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). Because of this, plastic has a much greater impact on the thermal conductivity and overall temperature distribution of a 3D printed object than air, leading to the question of the correlation between infill nature and spatial temperature distribution of 3D printed objects.

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. In fiberglass, major changes in bulk density started with a bulk density of 0.07 lb/ft3 having a radiant conductivity of approximately 58810.7 m4kg/s, 0.8 lb/ft3 having a radiant conductivity of 2940.5 m4kg/s, and 1.3 lb/ft3 having a radiant conductivity of 1764.3 m4kg/s, fitting a curve decreasing at a decreasing rate. 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. More recently, the effect of fin position and porosity on heat transfer in a heat exchanger was studied by Mehrizi, Farhadi, Sedighi, and Delevar (2013). They found that in fin 1, 2, and 3 of their experiment (which were in an order of decreasing porosity), the heat transfer rate is increased and the Nusselt number grew 1.2, 2.36, and 0.7 times respectively. The Nusselt number, Nu, is the ratio of convective heat transfer to conductive heat transfer normal to a boundary within a fluid, which, in pin-fins, is air. Because they found the Nusselt number to grow with increasing porosity, the conductive heat transfer increases with increasing porosity. Through this research, there is a possibility that the infill of a 3D printed object could vary the heat transfer via conduction throughout an object and, based on the Armillotta, Bellotti, and Cavallaro hypothesis, influence warpage (2018).

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. The optimal fin widths they tested were 0.31 mm, 0.25 mm, and 0.08 mm; the optimal cell heights were 2 mm, 5 mm, and 10 mm; and the thermal conductivity increased respectively from 0.5 to 5 to 300 W/mK, showing again how the thermal conductivity increases with density.

The most commonly used method of measuring thermal conductivity of a bad conductor is through the Lees’ Disc Method and Apparatus (Mathur, 1970). The Lee’s Disc Apparatus is a steady state method of finding thermal conductivity for bad conductors and is shown in Figure 2.

**Figure 2:** *Diagram of Lee’s Disc Apparatus.*

The rate of heat transfer by conduction at a steady state can be modeled using Equation 3, a modified form of Equation 1,

(3)

where is the rate of heat transfer, *k* is thermal conductivity, *A* is the area of the sample in contact with the metal disc, *T1* is the input temperature of the steam, *T2* is the output temperature at the bottom of the sample, and *x* is the thickness of the sample. To calculate the thermal conductivity, however, must be found. Because *T2* and *T1* are constant when the system is at a steady-state, the rate of heat loss of the lower disc must be equal to the rate of heat transfer across the discs by conduction. To calculate the rate of heat loss, the sample disc is removed and the lower brass disc is heated up to the upper brass disc temperature of *T2* and allowed to cool to room temperature. The temperature as it cools is recorded and a cooling curve is created using Equation 4,

where *m* is the mass of the brass disc, *C* is the specific heat capacity of the brass, and is the rate of cooling of the brass disc at *T2*. Since this is at a steady-state and the temperature change must be constant, the heat conducted through the sample per second, Equation 3 is equal to the heat radiated per second from the exposed portion of the metallic disc, Equation 4 as modeled in Equation 5 (Mathur, 1970).

(4)

(5)

Equation 5 can be used to calculate the thermal conductivity of a bad conductor, such as plastic, using the Lees’ Disc Method.

Despite research similar to the Lees’ Disc method exists, there is still a lack of research in the overall spatial temperature distribution of materials, especially in plastics. 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).

Most importantly, there is a lack of research on spatial temperature distribution of materials, especially plastic, and factors that affect it, such as internal structure. The research in this study aims to find the correlation between infill pattern and infill percentage on the spatial temperature distribution of 3D printed objects. Simulation research by Han in 2016 shows that various infill percentage nearly directly effects the thermal conductivity; however, he fails to account for natural convection as well as infill patterns. Contrary to all of the previously conducted research, this study attempts to directly find the relationship between specific combinations of infill percentage and infill types with spatial temperature distribution as a result of the creation of a temperature gradient through conduction and natural convection in 3D printed objects while printing.

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