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Simulation of Heat Transfer in Vacuum Environment for Fused Deposition Modeling Process

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Abstract: Fused Deposition Modeling (FDM) has been around for several decades and is currently one of the most used Additive Manufacturing (AM) technologies. In FDM, objects are produced by adding material layer by layer. The material extruded from the FDM's nozzle tip was in the hot semi-molten state above 200°C. Hence when the FDM process involves temperature gradients, the thermal stresses would be present and affects the product quality such as the mechanical strength. This study presents a method to design and analysis of vacuum chamber and examines how the heat transfers from a constant heat source to the surrounding in a low-level vacuum through finite element analysis simulations. A vacuum chamber was successfully designed and could sustain 100 kPA and the thermal simulations showed that, the heat loss from deposited material decreased as the vacuum level increased. The heat transfer from convection was reduced and rapid cooling can be removed. The reduced heat loss will prevent stress to build up and accumulate around the product and improves the specimen's strength. Results from this study can be used to predict the suitable vacuum environment for improving FDM's print quality.

Key words: Fused deposition modeling, simulation, finite element analysis, heat transfer, affects, quality

INTRODUCTION

Fused deposition modeling belongs to one of the additive manufacturing processes where materials are added to make objects from 3D Model CAD data in layer upon layer (additive) as opposed to subtractive and formative manufacturing methodologies. Industrialised by stratasys, FDM uses heated thermoplastic filaments extruded from the nozzle tip onto the build platform (Raut *et al*., 2014). From the year 2016-2017, FDM was ranked the most used technology by 36% in AM across the world followed by Selective Laser Sintering (SLS) 33% and Stereolithography (SLA) 25% (Moreau, 2017). The recent open source model, RepRap caused FDM machine to be affordable and greatly increasing the numbers of the user, especially, researchers. The principal mechanism of FDM is that a thermoplastic filament is fed through an extruder, heated into a semi-molten state and came out from the nozzle. The semi-molten state material fuses and bonds with the previous layer. The x and y-axis will move the nozzle based on the specimens geometry and z-axis to depositing a new layer on top the previous ones. This unique feature allows FDM to produce complex objects where other manufacturing methods were found to be difficult to achieve. Hence, time and cost can be significantly reduced (Nickel *et al*., 2001; Gao *et al*., 2015).

Although, FDM is a great AM technology, it is not well explored yet. Many FDM objects produced experience stresses. The rapid cooling from glass transition temperature to room temperature causes inner stress to develop (Sun *et al*., 2008; Sood *et al*., 2009). At such deformation occurs in the form of cracking, warping and delamination. Deformation usually happens at the bottom of the printed object and increases as the object height becomes higher. Besides with the higher extruded temperature onto a previously deposited layer and heat loss to the surrounding, conduction and convection take place. There will be a repetition of heating and cooling as the printing height increases (Sood *et al*., 2012). This irregularity will develop un-uniform stress and alterations to the layer bonding. Another similar study was conducted where uncontrollable temperature affects the print quality, especially in mechanical strength. The movement of 3-axes (x, y and z) changes the temperature based on the positioning of the nozzle head. As a result,

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different cooling rate caused poor bonding strength between the adjoining layers (Nelaturi and Shapiro, 2015). A model was developed to analyse the bond formation through observation of thermal modeling and cooling temperature profiles of the extruded filament. It was found out that as soon as the filaments are extruded onto the previous layer, the temperature rapidly drops while the neck growth was formed (Bellehumeur *et al.*, 2004). It was suggested better control of the temperature would produce better results.

Vacuum system has been used extensively in many areas of application such as research studies and industries (Jousten, 2016). A perfect vacuum is a space where no matter exists (Wu *et al.*, 2012). Although, perfect vacuum is currently impossible to achieve, different level of vacuum has been used. Vacuum is capable of limiting heat transfer by either conduction or convection. Heat transfer occurs when there’s a difference temperature between two bodies and stops when both reach an equilibrium temperature. At one atmospheric pressure, the air particles were large and capable to transfer heat through the air. However, as the pressure decreases (vacuum) the number of air molecules are getting less and the medium for the heat transfer will be limited (O’Hanlon, 2005). The use of vacuum system could be favourable for FDM process for which the stress developed from the rapid cooling can be reduced, since, heat loss happens through the mode of conduction, convection and radiation (Lienhard, 2013). However, major problems found to occur by convective heat transfer. Hence, the change of pressure affects the thermal behaviour as well.

This study investigates a possible solution to control the rate of cooling temperature in FDM process using a vacuum system. Through design and analysis method, a suitable vacuum chamber is developed and put into a finite element analysis to simulate how heat source from the FDM transfers to the colder surrounding temperature under different vacuum pressures.

MATERIALS AND METHODS

A vacuum chamber was designed, so that, a FDM can fit into it and does not obstruct any of its movement. The FDM used will be Up Plus 2 as shown in Fig. 1. Up Plus 2 was overall in a rectangular shape. Chambers comes in many shapes and sizes. Some are in cylindrical, ellipsoid, pyramid, cone, diamond and box. The size must be larger than the FDM does not hinder the operations. These two criteria help to reduce the volume inside to prevent chamber failure due to high pressure and increase the air removal rate. Material choice is important to with stand the high pressure and to prevent failure due to yield.

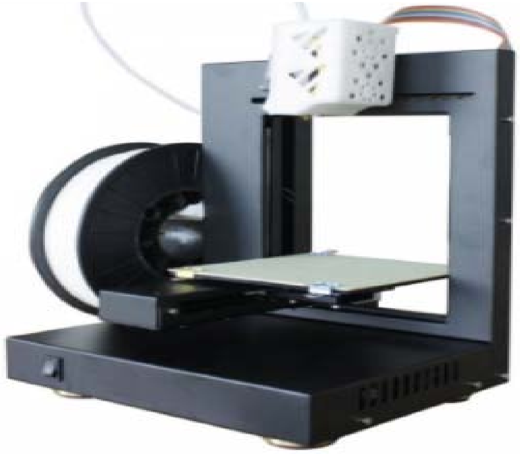

Fig. 1: Up Plus 2 FDM

Table 1: Simulations input data

Input	Values
Simulation physical time	3600 sec
Time step interval	60 sec
Gravity	-9.81 m/sec^2
Air pressure	30, 20, 10, 5, 1 Hg
Air velocity	Steady state
Air type	Laminar and turbulent
Wall condition	Adiabatic wall
Initial temperature	20.05°C (default)
Constant nozzle/heat bed temperature	260/100°C

A structural analysis simulation was carried out to determine the chamber’s strength by sustaining medium vacuum pressure. The inner pressure was 1.325 kPA which led to a compressive force for 100 kPa. The vacuum chamber was assumed to be perfectly sealed (adhesive bonding) at all parts and no shear was allowed. The contact sets were globally bonded. PMMA material was selected as the material choice and fixed geometries were placed on both support stands with no translation and rotation. The degree of freedom was restricted to one only. Although, the chamber was loaded, displacements can still occur from deformation. The meshed used was Voronoi-Delaunay triangulation meshed with the highest quality. The results obtained were von Mises stress, displacement and factor of safety. Upon completion of the chamber test, a solid works flow simulation was conducted to study the heat flow in a vacuum environment. Two different simulations were conducted, one with heat bed only and another heat bed and nozzle. The input data was as follow in Table 1.

The analysis carried out was internal simulation covering inside the vacuum chamber. The FDM was simulated for 1 h with one-minute interval. The gravity was set at -9.81 m/sec^2. Afterwards, steady state air gas with laminar and turbulent was selected. The wall was adiabatic prevent any heat gain or loss outside the chamber system. The initial temperature was 20°C and the constant temperature for nozzle (260°C) and heat bed (100°C). The results displayed heat contours, vectors and streamlines. The heat flow was observed and the graph of temperature versus time was plotted.

RESULTS AND DISCUSSION

A vacuum chamber was designed in a rectangular box. PMMA material chosen inhibits excellent optical properties, abrasion resistance, hardness and stiffness. The inner dimensions were 350×390×400 mm with 12 mm wall thickness as shown in Fig. 2.

Finite element analysis estimated the von Mises stress was 2.403e7 Pa as shown in Fig. 3 which was lower than the compressive yield strength 4.5e7 Pa. Von Mises stress states that, when the energy of distortion achieves the same energy from the uniaxial tension, failure occurs. The maximum stress was located at the joint between the walls. The pressure exerted perpendicularly on each side of the walls caused the joint to withstand the stress from both sides. The vacuum chamber was safe from this criterion.

Displacement was carried out to determine the level of deflection of the wall. From Fig. 4, the deflection estimated was 7.02 mm in the middle of 414×400 mm wall. This wall is the largest in dimensions and experienced the largest displacement. However, the FDM's operation was not affected much by the wall's bending.

The factor of safety was necessary to ensure the structural model to fail even beyond the expected load. The minimum vacuum chamber's Factor of Safety (FOS) was 1.7 as shown in Fig. 5. To achieve FOS more than one, the ultimate stress had to be more than von Mises stress. The lowest FOS was found in between the joints on the walls due to stress exerted by the walls. The FOS for the vacuum chamber was at the acceptable range.

Upon confirming the suitability design of vacuum chamber, the behaviour of heat flow in vacuum environment was analysed. First thermal simulation involves only 140×140×3 mm heat bed. Starting from steady state, two vacuum levels (30 and 18 in Hg) were simulated and the cut plot results on 60th min were shown in Fig. 5.

The thermal flow in 30 in Hg which was one atmospheric dispersed more heat from heat compared to 18 in Hg. Moreover, the minimum temperature, 21.88°C in 30 in Hg was higher compared to 21.40°C in 18 in Hg. This shown that, vacuum pressure limits the heat travel through air molecules in a vacuum environment. Next, a nozzle and heat bed were simulated together to compare

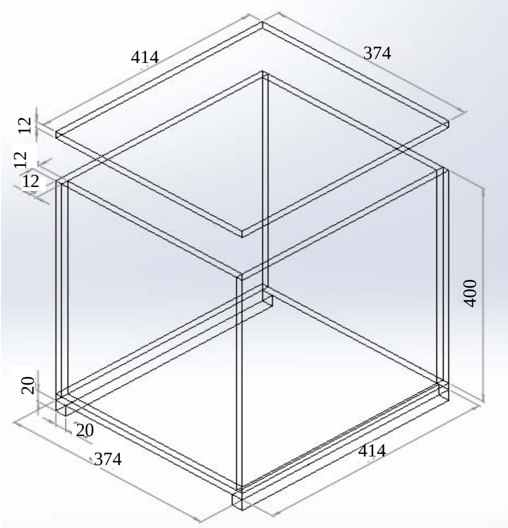

Fig. 2: Vacuum chamber dimension (mm)

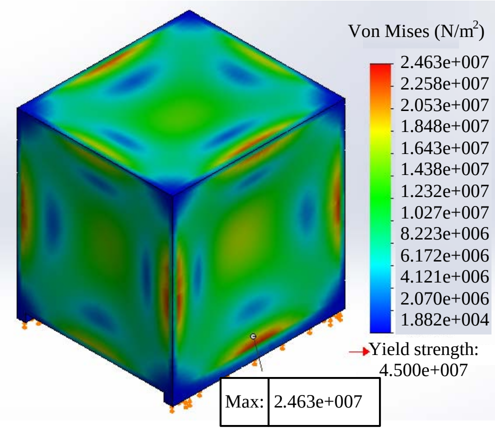

Fig. 3: Von Mises stress

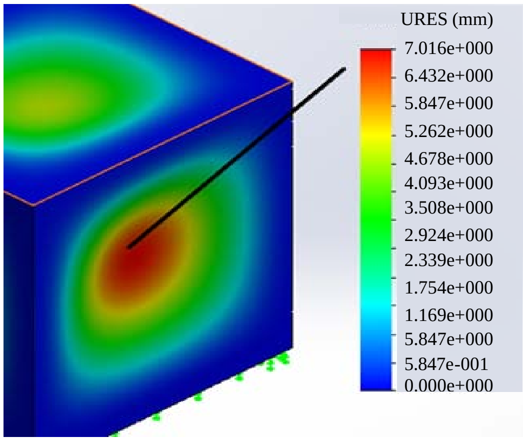

Fig. 4: Chamber wall's static displacement

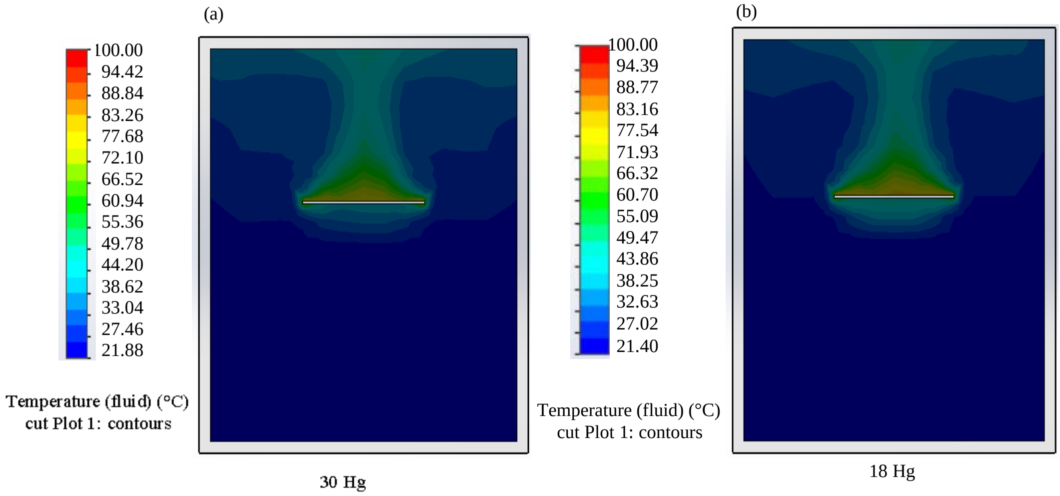

Fig. 5: Heat flow from heat bed in: a) 30 and b) 18 Hg

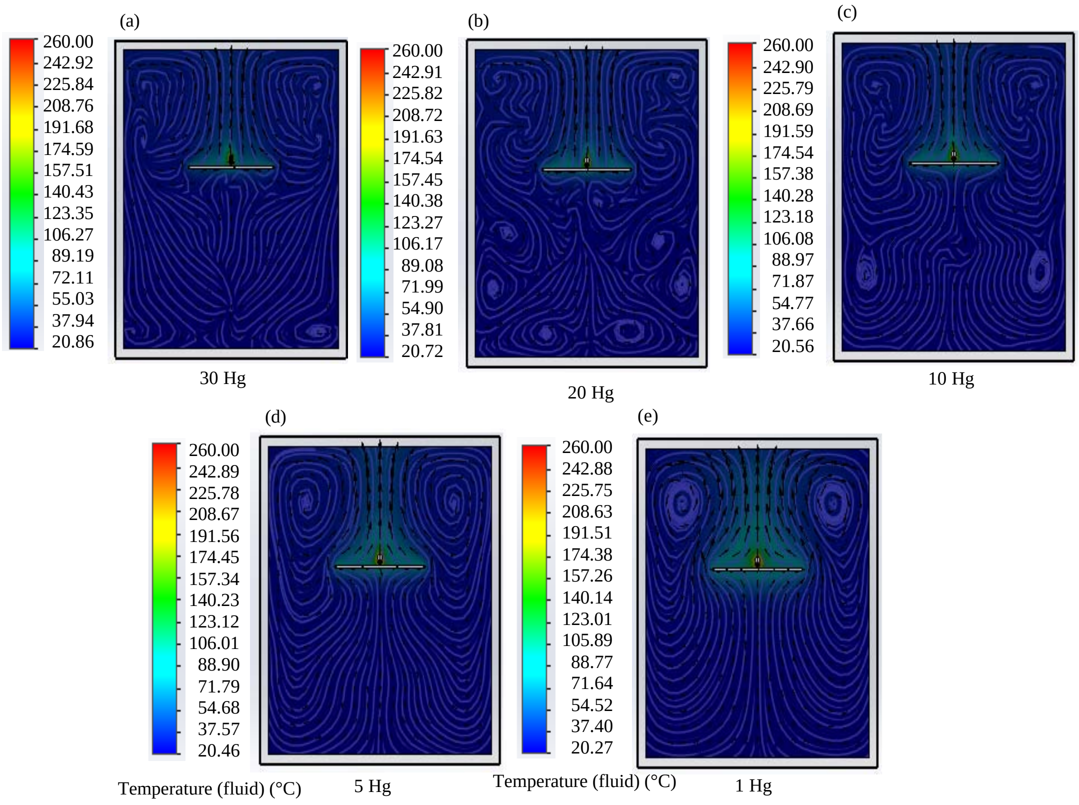

Fig. 6: Different heat flow measured from various vacuum pressures: a) 30; b) 20; c) 10; d) 5 and e) 1 Hg

the results taken. Using same inputs the simulation was repeated with 30, 20, 10, 5 and 1 in Hg. The results were shown in Fig. 6.

From the 5 different simulations, they all dispersed heat upwards, outwards and downwards since, the hot air was less dense than cold air. The differences found between them were the air flow pattern and the minimum temperature at the surrounding. At 30 in Hg where at normal atmospheric pressure level, the number of air particles was more compared to vacuum pressure. The turbulent flow and the free mean path was large thus random and non-parallel air flow can be seen. The

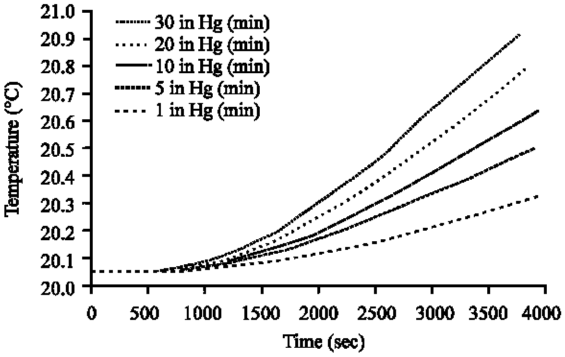

Fig. 7: Minimum temperature versus time

molecules collide against each other. Hence, these collisions promote heat to transfer easily via. convection and FDM produced object was poor in quality. However as the pressure decreases to 20 in Hg onwards, the air molecules decreased. The air flow was getting different which was in a viscous state. From 15 in Hg, the flow turned into laminar and more parallel layers were observed. In 1 in Hg, best flow was detected. The flow is smooth on both right and left sides. With almost parallel-like layer flow, the heat flow rose up and down without any collisions.

One noticeable difference is the minimum temperature found. At 30 in Hg, the minimum temperature was 20.86°C while 1 in Hg was 20.27°C. It showed that the heat was harder to travel in a vacuum environment. The graph between minimum temperature and time was plotted as shown in Fig. 7.

Multiple data were obtained for every 1 min interval with a total of 60 min. Approximately starting from 10 min onward, the lines began to change and the gap increases with time. The 1 in Hg had the lowest minimum temperature while 30 in Hg had the highest minimum temperature. The 1 in Hg could be possibly the ideal environment for the FDM operations. The maintained heat source influences the bonding during layer by layer build and reduces the stress concentration.

CONCLUSION

The design and analysis of vacuum chamber as well as heat transfer analysis showed that, the air pressure affects the convective heat transfer. The vacuum chamber was able to sustain 100 kPa of pressure with a safety factor of 1.7. The maximum displacement was 7.02 mm. The chamber design was acceptable and selected for further analysis by carrying out a heat transfer analysis inside the chamber. As the vacuum pressure increases by lowering the pressure to absolute 10 in Hg till 1 in Hg, the heat flow is smooth and heat was concentrated around the FDM operation area. This proper heat flow without ruckus could improve the quality of object produced by FDM. The pressure inside the vacuum chamber reduced the air molecules and caused ineffective convective heat transfer. Therefore, the minimum temperature was found to be lower in a higher vacuum environment.

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