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Effect of Vacuum Assisted Fused Deposition Modeling on 3D Printed ABS Microstructure

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Abstract

Fused deposition modeling (FDM) or commonly known as the 3D printer is one of the most used and accessible additive manufacturing (AM) technology commonly used for prototyping and product applications. Easily produced from a drawn 3D CAD model, FDM can 3D print any intricate parts and the products are based on polymer material such as ABS. FDM works by depositing a thin layer of extruded polymer filament on a build platform layer by layer to create a solid 3D part. Nonetheless, FDM is still far behind regarding product quality such as mechanical strength. In order to produce a functional part, high strength is required to prevent stress and strain failure. Studies found out that one of the main reasons behind poor strength was the imperfect bonding between layers at z-axis. During the printing process, the bonding process occurred to quick, and the layers did not fused properly. Therefore, the current progress in FDM slowed down and prevented to be fully utilised as end-use parts. This paper presents a microstructure study on the effect of integrating vacuum system with FDM to improve 3D printed specimen's tensile strength. The results indicated positive improvements of tensile strength when printed using vacuum assisted compared to normal atmospheric ones. The microstructure observation from scanning electron microscope showed the specimens produced under vacuum assisted had a superior bonding between layers.

Keywords: fused deposition modeling, 3d printing, vacuum, scanning electron microscope, microstructure.

INTRODUCTION

Fused deposition modeling (FDM) is an extrusion-based additive manufacturing technology that produces a solid 3D object from a polymer based filament. FDM performs by pulling a filament into a heated nozzle and extrudes a thin layer from the nozzle tip and deposits onto a flat platform in x and y-axis. Upon completion of the first layer, the nozzle head ascends, or the platform descends to create another new layer and bonds on contact with thermal energy. Thus, the layer by layer process creates a solid 3D object [1]. FDM is different compared to other manufacturing processes such as injection moulding, milling, lathe and CNC machining. FDM is capable of producing highly complex parts without any expensive tooling needed. FDM can produce custom parts quickly and cheap as well in a small batch production [2]. However, the known poor mechanical strength from the printed part was weak and easily broken especially at z-axis. The anisotropic behaviour possessed by printed part due to layer orientation had caused undesirable results [3]. Therefore, the strength of FDM part was nowhere near the strength of injection moulding part. Several authors mentioned that one of the main reasons for poor mechanical tensile strength was the incomplete bonding in between each layer during extrusion. The fact that the extruded semi-molten filament above 200ºC rapidly cooled upon exposure to the room temperature has become an issue [4], [5]. This has prevented complete bonding from occurring, and as a consequence, poor strength was produced.

In quest of improving the tensile strength of printed part, a possible solution was introduced by integrating a vacuum system with FDM system to resolve the poor bonding issue. Vacuum technology is used intensively in many applications, industries and studies. The ability to remove air and fluid to create a vacuum allows various applications such as electron beam melting, x-ray tubes, food processing and casting [6]. Not only that, but research areas also require vacuum such as biotechnology, plasma research and space simulation. Vacuum reduces the air molecules inside the chamber which in term reduces the transfer of thermal energy via convection. Thus heat loss can be minimised and maintained at the period of time depending on how strong vacuum was used.

A new approach of using two different technologies was introduced to test their compatibility and reliability to improve the tensile strength. A FDM 3D printer was placed inside a vacuum chamber and sealed completely. A vacuum system will draw the air out leaving partial vacuum inside the chamber. The manipulated variables will be four levels of vacuum pressure, 30 (1 atm), 27, 24, and 21 inHg. The constant variables are 0.25 mm layer thickness, 260ºC nozzle temperature, 90ºC heated bed, z-orientation and ABS material.

BACKGROUND STUDY

Fused deposition modeling (FDM) is one of the additive manufacturing technologies. FDM has become a popular and affordable not only to industries and researchers but hobbyists as well [7]. Incoming new polymer materials such as wood and metal allow a wide range of applications. Scott Crump, the co-founder of Stratasys developed a working FDM system using an extrusion-based technique to mechanically extruding semi-molten polymer using a layer by layer approach [8]. FDM performs by reading G-codes to guide each of the motor axes according to the design dimensions. To do that, a 3D CAD model needs to be drawn and saved into a STL format. This STL format will allow the user to adjust the parameters (infill percentage, layer thickness, speed, etc.) inside the slicing software. Upon confirming the parameters, the model was sliced into layers with support (if needed) and usually saved into G-codes. From this point onwards, the FDM automatically produces the part without human intervention. The heated nozzle will draw the filament into it using a geared extruder with selected temperature based on the material used. Then the nozzle extrudes a thin semi-molten filament just above the build platform in x and y-axis. Either the nozzle or the platform will move in the z-axis to create a gap for a new layer to be deposited. After deposition, the layer bonded together in seconds. The process repeats until a whole solid part is produced [9]. FDM possesses several advantages compared to other manufacturing methods. FDM, as well as other AM technologies, produced little wastes since it used a layer by layer method and no material was discarded. The infill design such as honeycomb has a higher strength to weight ratio [10]. FDM also produced part quickly and cheap regarding small batch production where challenging and complex part was deemed difficult for traditional manufacturing processes.

Although FDM seems great to produce highly complex parts, it is still weak in term of mechanical strength. The part snapped easily upon little force compared to injection mould. FDM issues were the most discussed topic among researchers. Parts produced from FDM were weak regarding strength, especially tensile and flexural strength. The parts possessed anisotropic properties where all forces measured are different everywhere. They are dependent to the build orientations [11], [12]. It was found out that inter-layer bonds at z-axis were the weakest compared to other axes [13]. Hence many solutions were introduced by researchers to improve the mechanical strength. One study was conducted focusing on the infill by compositing higher strength resin into the air gap inside the structure. A syringe with resin was injected into the gap and left to dry. The whole strength was increased by 45 % and stiffness by 25 % respectively. The hardened resin provided an internal structural strength which was useful for functional load component [14]. Besides that, a mathematical model was introduced to improve mechanical strength via selecting the best process parameters. Group method of data handling (GMDH) uses parameters such as layer thickness, part orientation, raster angle, raster width, and air gap to improve tensile strength. The predicted model was in good correlation with the measured value [15]. Other than that, more materials were introduced to improve the base strength. For example, a composite polymer of ABS with a metal such as iron and copper for FDM was studied. With 40 % metal ratio, the ABS was mixed with metal powder, compounded thermally inside an extruder and compression moulding. The mechanical properties were increased due to the metallic fillers boosting up the strength [16]. A new material of polyether-ether-ketone (PEEK) was compared with ABS. Different raster angles and layer thicknesses were printed. The results produced an average of 108 % higher than ABS [17].

There were several numbers of studies focuses on the microstructure of specimens after the mechanical test. A flexural test was conducted with 45degree raster angle. The specimen was then observed under scanning electron microscope (SEM) and found crack propagation along the load direction. The pattern was erratic and not uniform. The clustered fibre was bent and ruptured individually in a brittle manner. However, at 0/90 degree raster angle, the fibre offered higher resistance to bending because their direction is parallel to the bending plane [18]. Another study was conducted to study the effect of temperature on the ABS printed parts. It was found out that non-uniform temperature gradient causes stress. The stress slowly builds up and leads to distortion, dimensional inaccuracy and inner layer cracking as observed under SEM. The reason behind was the heat dissipated too quickly. Conduction and convection from the temperature gap caused the material to solidify quickly. Bonding on another layer on top caused re-melting on the previous layer. The inconsistent temperature change was what caused the stress [19]. Another study was conducted for tensile and flexural tests. SEM revealed that from the tensile test, positive air gap caused a flow of material towards the adjacent layers in between the gap and increased the bonding strength. Thus, strength improved from the air gap. SEM image on the ruptured surface showed that pulling of the raster and perimeter layers happened in a plane about normal to a tensile stress [20].

The vacuum system in an emptiness where there will be an absence of air molecules in a confined space. As the pressure increases, the number of molecules reduces. At one atmosphere, the molecules collide with each other, transferring energy from one to another. Higher density molecules easily transmit energy to lower density molecules. Conversely, if the air molecules are reduced, there will be less medium for the transfer of energy to occur. Therefore, the change of physical properties of air pressure will affect the thermal behaviour as well [21], [22]. Heat transfer is a form of energy. Heat transfer occurs when there is a difference in between two bodies of temperature and eventually stops when both reached an equilibrium temperature. Heat transfer works in three different ways, conduction, convection and radiation. In FDM machine, heat will transfer in three ways. Conduction takes place in the FDM machine itself, while radiation still happens since it does not require any medium. Lastly, convection takes place around the FDM machine, where lower density heat rises while higher density cold air dense which builds natural thermal convection [23]. Convection happens when there is a medium in the air to travel. If there is no medium such as vacuum, heat cannot transfer by convection except radiation. A perfect vacuum is impossible to achieve but however, for practical applications, different level of vacuum can be used to limit heat transfer via convection.

METHODOLOGY

A vacuum system was fabricated based on the shape of the FDM machine, Up Plus 2 as shown in Figure 1. The chamber was made from acrylic and the its dimension was 350 x 390 x 400 mm with 12 mm wall thickness.

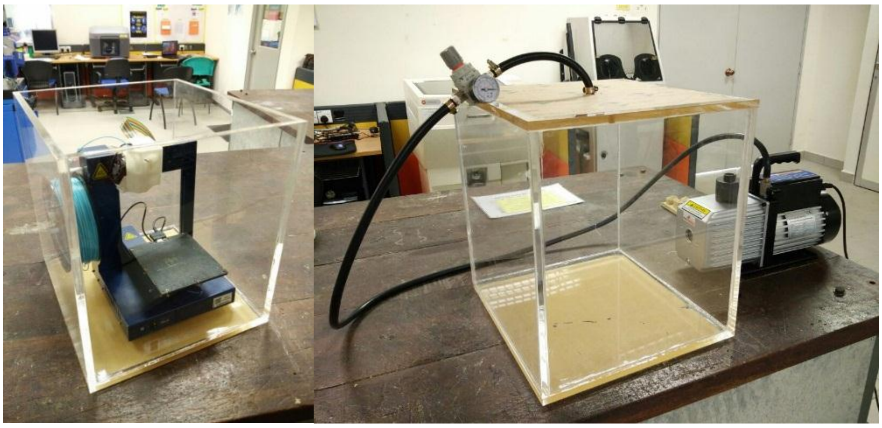

Figure 1: Vacuum system for Up Plus 2

The specimens were first drawn using CAD software, SolidWorks according to ASTM D638 Type IV. The file was saved into STL file and imported into UP Plus 2 software. The software parameter was set to ABS, 0.25 mm layer thickness, medium air gap, and placed in standing upright. The specimens were produced under different vacuum pressures which were 30 inHg, 27 inHg, 24 inHg and 21 inHg. Three specimens were produced at the same time as shown in Figure 2. The printed specimens were labelled and kept in separate plastic seals.

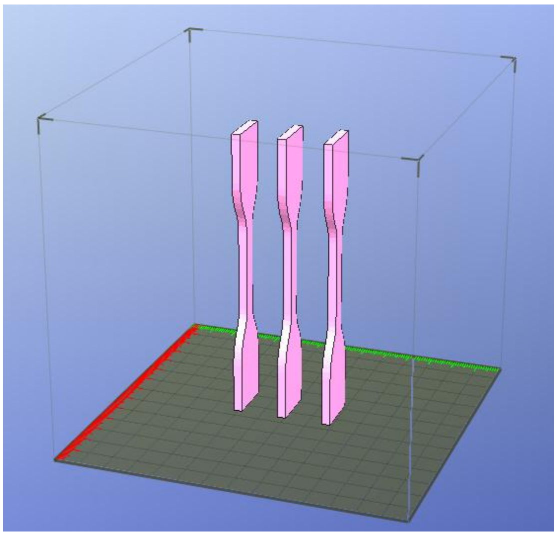

Figure 2: Upright position for 3D print

The tensile test was conducted in a controlled manner to prevent unexpected errors in the results. The UTM machine used was Autograph Universal Testing Machine with Trapezium software. The force set was 10 kN, cross head speed at 5 mm/min. The stress and strain data were recorded, and the specimens were kept back into the sealed plastics. The broken specimens of lowest vacuum pressure, 30 inHg and highest vacuum pressure, 21 inHg were observed under scanning electron microscope.

RESULTS AND DISCUSSION

Tensile tests were conducted on all the specimens, and their strength based on the effect of vacuum pressure were tabulated as follow;

Table 1: Maximum stress and strain for ABS specimens

Vacuum pressure, inHg	Average Stress, N/mm^2	Average Strain, %
30 (1 atm)	17.2948	4.7268
27	18.2292	5.5556
24	18.3007	5.2111
21	19.7202	5.0687

From Table 1, it was shown that maximum stress increases as the vacuum pressure increase from 30 inHg to 21 inHg. Highest vacuum pressure, 21 inHg produced the highest strength at 19.7202 N/mm^2 with 14.0238 % improvements. At 30 inHg, the pressure was at one atmosphere. As the vacuum pressure increased to 27 inHg, the specimens were able to sustain higher stress by giving 5.4028 % improvement. As the vacuum pressure further increases to 24 inHg, the percentage of improvements with 30 inHg as a benchmark was 5.8162 %. From the results obtained, vacuum pressure improves the tensile strength. Vacuum system allows the FDM to operate under low-pressure environment where the heat could sustain longer around the printing area which improves the neck formation at the bonding surfaces. To verify the results, SEM analysis was conducted to observe the microstructure on the fractured surfaces. 30 inHg (1 atm) and 21 inHg were compared as shown in Figure 3.

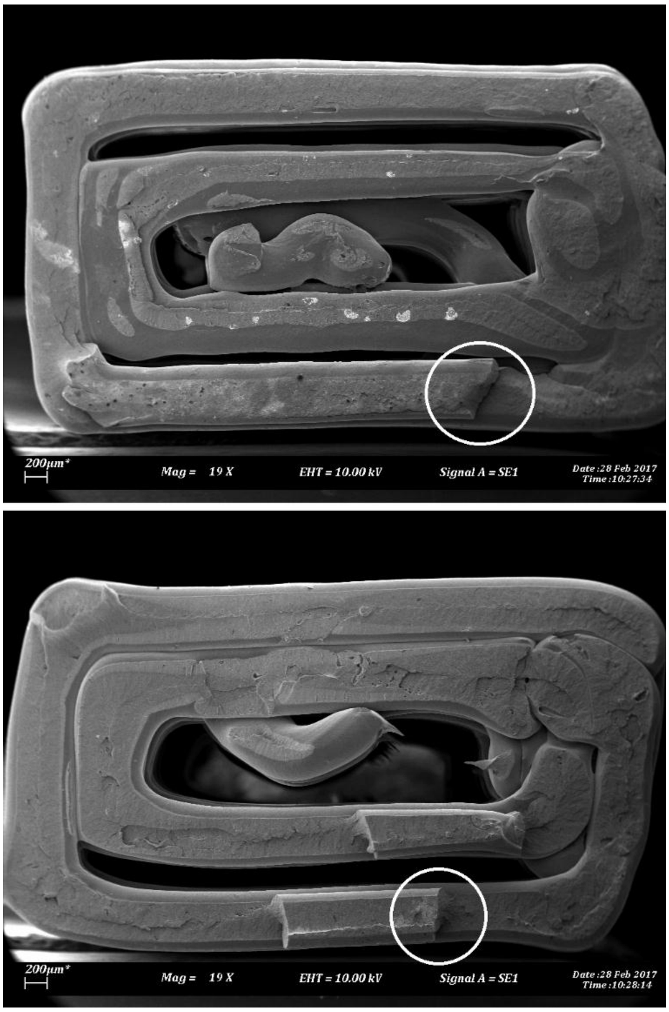

Figure 3: 0.25 mm layer thickness at 30 inHg (top) and 21 inHg (bottom)

The specimens were magnified 19 times at 200 microns. The Figure 3 showed two different specimens, one produced at 30 inHg and another at 21 inHg. Based on the comparisons, specimen produced under 21 inHg showed a better bonding formation compared to 30 inHg. The first noticeable difference was the surface contact area. There was two colour difference seen, light grey (contact surface) and dark grey (non-contact surface). The specimen produced under 30 inHg had less light grey area and more on dark grey. The surface contact was little compared to the 21 inHg specimen. This signified that at 30 inHg (1 atm), the deposited filament cooled down too fast before it has sufficient time to bond with the previous layer. However, for 21 inHg specimen, the deposited ABS had adequate time to bond better onto the previous layer since the vacuum reduced the heat transfer. At both light grey area, 30 inHg had a significant amount of porosity which degrades the bonding formation and led to poor tensile strength. Hence, rapid cooling caused stress, delamination and deterioration. Lastly, at the circled part, where there is a left out bits of deposited layer. Specimen at 30 inHg showed a crack between two layers while 21 inHg specimens showed the top layer was still fused together with the bottom layer despite showing improved bonding.

CONCLUSIONS

The bonding formation was proven to be affected by temperature change. At such, vacuum system was able to maintain the heat longer for the layer to bond better during the deposition process. The microstructure of specimens produced under vacuum pressure (21 inHg) had a superior bonding compared to the one produced under normal atmospheric pressure (30 inHg). The vacuum assisted FDM created a low-pressure environment where the convection process can be reduced. Rapid cooling and heating can be minimised to reduce stress concentration. The fusion between layers was much more efficient to create stronger bonds. This process does not require any increase in temperature but just to maintain long enough time for sufficient bonding to occur.

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