

EFFECT OF PROCESS PARAMETERS ON VOID FORMATION IN FUSED DEPOSITION MODELLING (FDM) PART

Mohd Nizam Sudin^{*}, Nazri Md Daud, Faiz Redza Ramli, and Mohd Asri Yusuff

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Abstract

A void is a structural defect resulting from the 3D printing process. The presence of voids compromises the structural integrity of a 3D-printed component, resulting in a reduction in durability and functionality. Currently, the only technique used to correlate FDM process parameters with mechanical properties is tensile testing. Nonetheless, this method is time-consuming and expensive. Therefore, the purpose of this study is to determine the viability of employing an alternative method to establish this connection. This study examined the parameters of infill density, infill pattern, raster angle, and part shape. While pressurized gas release was used to evaluate the printed material based on bubble formation, the printed object was evaluated based on bubble formation. Subsequently, the qualitative relationship between these parameters, void formation, and mechanical properties was determined. According to the results of this study, the relationship between the studied parameters, the tensile test, and the mechanical properties of the FDM part was consistent with the relationship between the studied parameters and the formation of bubbles and voids. 3D-printed parts with the lowest possible bubble intensity when using a 100% infill density, a grid infill pattern, and a 45° raster angle. The shape of the component was found to have the least impact on the formation of the bubble. This study concluded that using a 100% infill density, grid infill pattern, and 45° raster angle results in the least amount of void formation, and that the effect of shape difference on void formation in 3D-printed parts is negligible. The results of this study could be used to predict the mechanical properties of a component as a function of void formation during the (Pressurised gas release) PGR test. In the future, imaging-based quantitative analysis of voids will be required to validate this finding.

Keywords: FDM, Process parameter, Void formation, Slicing software

Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia.
E-mail: nizamsudin@utem.edu.my

^{*} Corresponding author

Introduction

In the past, product design was simple and checkered. This is due to the fact that its aesthetic value is limited by limited manufacturing technology, which ultimately affects the overall efficiency of the product. As the world advanced through a technological revolution, manufacturing technology began to expand upon the discovery of new methods that would break the bounds of limited technology. One of the new methods in manufacturing technology that has been used to date is known as additive manufacturing (AM) where the aim of AM is to make intricately designed parts efficiently in terms of cost and time of production (Mohan *et al.*, 2017). AM is widely used in industry with a variety of processes, such as FDM, ink jet modelling, selective laser sintering (SLS) and many others. Each of these processes has the same concept of production but differs from application to material use, layer construction and cost (Mohan *et al.*, 2017).

FDM is one of the AM processes in which the material filament is extruded layer by layer on a flat heat bed to form a 3D part. The material filament made of thermoplastics such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) which comes in wire form is fed into a 3D printer extruder. The extruder consists of a heating element which is used to melt the material filament before being extruded. In most 3D printers, the extruder moves on two axes, namely the x-axis and the z-axis, while the y-axis varies on the basis of two movements of the heat bed. The movement of the extruder is controlled by the programming code generated by the 3D model designed in the CAD software.

Each FDM process starts with the creation of the desired product in the form of a 3D model using the CAD software, which is then exported to the slicing software. Slicing software is described as a 3D CAD file (e.g. STL file) for 3D printing purposes (Šljivic *et al.*, 2019). In other words, slicing software converts a 3D CAD file to a programming code for 3D printers to be read and executed. The programme code is referred to as G-Code. G-Code consists of a set of instructions containing the values of the extruder coordinates and several slicing parameters, such as the angle of the raster, the pattern of the raster, the temperature of the bed, the temperature of the extruder, the thickness of the layer, the pattern of infill and the density of the infill (Baumann *et al.*, 2017). Slicing parameters play a key role in determining the quality of 3D printed parts (Gordeev *et al.*, 2018). Quality, such as mechanical properties, can affect

the performance of 3D printed parts that are crucial to real-world applications. A number of researchers have therefore carried out studies on different cutting parameters in order to obtain optimum values for certain parameters.

Unlike some traditional manufacturing processes, AM depends on structural and process parameters in addition to material properties when determining part properties. Dudescu and Racz (2017) evaluated the effect of process parameters on the mechanical properties (tensile stress, tensile strain, and Young's Modulus) of 3D-printed specimens, taking into account various raster orientations, infill rates, and infill patterns. The samples were printed at various angles, including 0°, 30°, 45°, and 90°, with an infill rate ranging from 20% to 100% and six distinct infill patterns. All of these parameters were discovered to have a significant impact on the mechanical properties of ABS specimens. Wu *et al.* (2015) investigated the impact of layer thickness and raster angle on the mechanical properties of 3D-printed polyether-ether-ketone (PEEK). Samples with three distinct layer thicknesses (200, 300, and 400 μ m) and raster angles (0°, 30°, and 45°) were constructed and tested for tensile, compressive, and bending strengths. At a layer thickness of 300 μ m and a raster angle of 0°, the optimal mechanical properties of PEEK samples were found.

Durgun and Ertan (2014) discovered that build orientation influenced surface roughness and mechanical behavior more than raster angle, especially on the tensile and flexural strength (Raut *et al.*, 2014) and the tensile and compressive strength (Ashtankar *et al.*, 2013), where tensile and compressive strength decreased with increasing build orientation from 0° to 90°. In both instances, 0° orientation provides the greatest strength, whereas 90° orientation provides the least. In contrast, (Savvakis *et al.*, 2014) found that build orientation has no significant effect on the tensile strength of the parts, whereas layer thickness has an inverse relationship with tensile strength. According to Afrose *et al.* (2014), the maximum tensile stress is observed in parts printed in the X orientation. In comparison to the part built in the Y and 45° orientations, it was between 60 and 64 percent of the injection-molded part.

Meanwhile, the effect of material on the strength of the part has been intensively studied (Haq *et al.*, 2018; Kariz *et al.*, 2018; Osman *et al.*, 2018; Camargo *et al.*, 2019; Sezer and Eren, 2019; Yang *et al.*, 2019) and these studies have led some to development a new filament material for the FDM process (Singh *et al.*, 2016; Jia *et al.*, 2017; Depuydt *et al.*, 2019; Ahmad *et al.*, 2020; Cali *et al.*,

2020; Wang *et al.*, 2020). As a result, significant improvement in part strength has been achieved through this effort. In spite of the material, some concentrate to manipulate FDM parameters and then optimize the group parameter for the targeted mechanical performance (Alhazmi and Backar, 2020; Gao *et al.*, 2020; Heidari-Raran *et al.*, 2020). However, both of these approaches have simply concentrated on obtaining the required output without attempting to explore the underlying causality of this phenomenon (Hill and Haghi, 2014).

In reality, the quality of mesostructure is vital contributor to tensile strength of FDM part (Luzanin *et al.*, 2019). The early attempt to link the mesostructure to the strength of the part has been made by (Sun *et al.*, 2008). The investigated area was the bonding strength of the filament and the contact between the filament (Sun *et al.*, 2008). Others focus on the void presented in the FDM part (He *et al.*, 2020; Hernandez-Contreras *et al.*, 2020; Naveed, 2020). Despite void is considered to be a defect, its presence is sometimes desired, depending on the FDM part's intended application. It is desired to reduce a part's weight and/or improve its functionality, but it is undesirable for applications requiring optimal mechanical performance.

FDM voids are classified as raster gap voids, partial neck growth voids, sub-perimeter voids, intra-bead voids, and infill voids (Tao *et al.*, 2021). Internal voids are formed as a result of insufficient neck growth between adjacent intra-layer and inter-layer rasters. Gap voids formed by gaps between the rasters are distinctly visible (Gurralla and Regalla, 2014). Due to physical limitations, sub-perimeter voids are created between turning rasters along the perimeter of an FDM layer, and their presence is visible. Intra-bead voids are unique to FDM parts made of composite materials, whereas infill voids are manageable and required for low strength applications. The higher infill densities would result in a structure that is more solid (less infill void) and generally more robust. The infill patterns have unique beneficial effects on reducing the weight and increasing the strength of FDM components. For instance, gyroid infill increases a part's strength in all three dimensions (X, Y, and Z) while maintaining the lowest possible weight (Downing *et al.*, 2021).

Square-shaped nozzles have a higher tensile strength and a smaller void geometry than circular-shaped nozzles. It was discovered that contact angles and bead orientation play a significant role in the formation of void contents when the shape of the FDM nozzle is changed from circular to square (Kumar *et al.*, 2019). As a result of infill-patterns and density triangular infill, there were fewer voids.

Increased raster width results in fewer voids per unit area (Eiliat and Urbanic, 2016), and thinner layer height results in smaller voids (Fischer *et al.*, 2022). Void decreases the tensile strength (Rajpurohit and Dave, 2018). Generally, the presence of voids reduces FDM part strength due to stress concentration (Tao *et al.*, 2021).

In consensus, all the research agreed that the bonding strength of filament in FDM part is a thermally driven process and relies on the bridge formed between filament known as 'neck'. It is quite evident that the strength of the bond depends on the rate of growth of the neck formed (wetting) as a result of molecular diffusion, cross linking and growth possibly at their interface which is typically a sintering process (Gurralla and Regalla, 2012). The size of neck form between filament determine the quality of bonding quality.

In addition to density measurement, imaging techniques, such as Optical microscope (OM), Scanning electron microscopy (SEM), and Micro computed tomography (CT), are frequently employed in the existing literature to study FDM voids. OM is a common technique for analyzing the mesostructures of printed parts, whereas SEM is commonly used to examine the microstructures. Both OM and SEM are capable of capturing 2D imaging data in the X, Y, and Z planes (axes). In addition, images orthogonal to FDM layers can be utilized to analyze raster gap voids, partial neck growth voids, and intra-bead voids. Similarly, sub-perimeter voids may be examined using images parallel to FDM layers. In addition to the imaging capabilities of OM and SEM, CT can reconstruct highly accurate 3D models from scanned specimens (Tao *et al.*, 2021).

Due to fast cooling of filament upon deposited on the platform the formation of neck is stop before each adjacent filament completely fused. As a result, partially contact occurred and void is introduced into the part. The properties of void effect the mechanical of FDM part, this include the shape, size and density of the void. The review of the literature confirmed the effect of process parameter on voids and mechanical properties, as well as the relationship between voids and mechanical properties. Currently, however, the presence of void in FDM parts is only investigated using imaging techniques, which are both time-consuming and expensive. Due to this, the purpose of this study is to investigate the effect of certain printing parameters on void formation in FDM parts and to aid in the prediction of FDM mechanical properties as a result of parameter changes using a simpler method based on the observation of bubble formation.

Materials and Methods

The flow chart of the research is shown in Figure 1. Three common model shapes were generated by the Autodesk Fusion 360 software. The shapes were cuboid, cylindrical, and prism. The overall dimension of all shapes was equal to 40 mm $\times$ 40 mm $\times$ 70 mm in length, width and height, and the thickness of all shapes was equal to 3 mm as shown in Figure 2. The model was saved in STL file format and then sent to Ultimate Cura software for the slicing process before it was printed. Each shape was printed at three different infill densities (30%, 60%, 100%), three different infill patterns (grid, tri-hexagon, gyroid) and three different raster angles (0°, 45°, 90°). The part that shared printing parameter was printed simultaneously to save printing time. After completion of the slicing process, the sliced model was transferred to the 3D printer using the SD card. The 3D printing used in this study was Creality Eder 3 with a printing area of 220 mm $\times$ 220 mm $\times$ 250 mm. Figure 3 shows the progress of a cuboid model printing process.

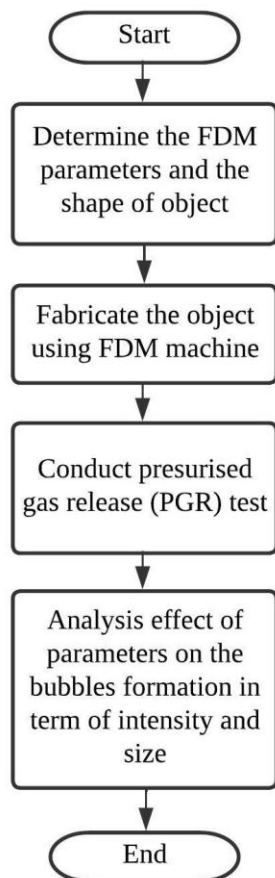


Figure 1. Flow chart of the research

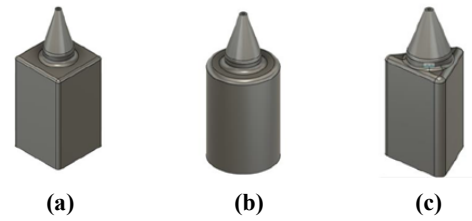


Figure 2. 3D model of part (a) cuboid (b) cylinder (c) prism

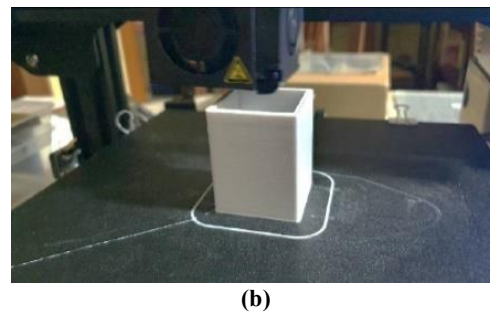
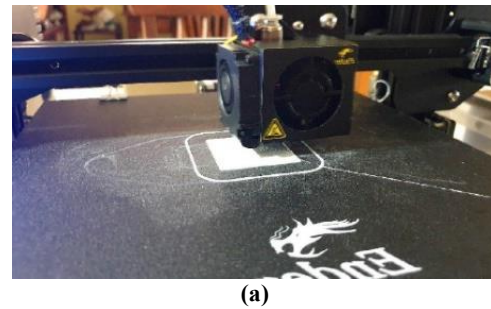


Figure 3. The progress of cuboid model printing process (a) initial (b) final



Figure 4. Experimental setup

All samples were tested using a method called PGR. The experimental set-up of this method is shown in Figure 4. The compressed air was supplied through a hose to the tested model for 5 minutes. The model tested was immersed in the water in a transparent container. The color was added to the water to

enhance the visibility of the bubbles formed. The test for each sample was recorded as a video for the analysis. Based on the video recorded, the intensity of the bubbles was compared to different parameters and the shape of the sample.

Results and Discussion

Figure 5 shows a comparison of the gas bubble formation of cuboid printed parts with three different infill densities, 30%, 60% and 100% respectively. The compressed air was supplied for 5 minutes to ensure the consistency of the formation of gas. The observation shows a clear difference in the intensity of the formation of the gas bubble on the surface of the printed part. At an infill density of 30%, the gas bubble appears to be the most intense, while at a 100% infill density, the gas bubble appears to have formed the least intense. As a result, the formation of void is reduced as the percentage of infill density increases. This result was consistent with the cross-section view of the part generated by the slicing software for the various infill densities, as shown in Figure 6, and the study of Abeykoon *et al.* (2020), who concluded that void size is proportional to infill density. Samples printed with a 100% infill density contained extremely small voids. As a result, increasing infill density has the potential to reduce the void fraction and increase the tensile modulus.

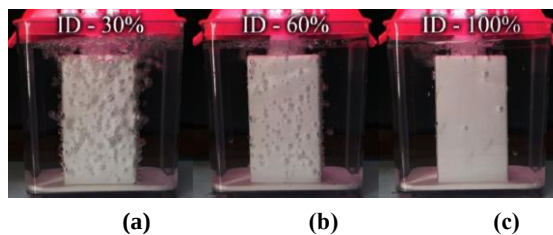


Figure 5. Comparison of the intensity of the bubble formed at different infill density (a) 30% (b) 60% (c) 100%

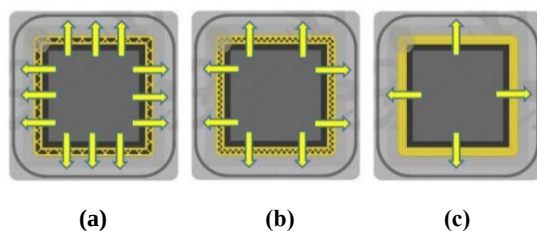


Figure 6. Cross sectional view of part for different infill density (a) 30% (b) 60% (c) 100% generated by slicing software

Observations on the effect of the infill pattern on the formation of bubbles in FDM printed parts are shown in Figure 7. It was obvious that the intensity of the bubble formed differs from that of the change in the infill pattern. Parts with gyroid infill pattern produced more intense bubbles compared to grid and tri-hexagon infill patterns. The least intensity of the bubble was observed for the part with the grid fill pattern. However, this results in a slight inconsistency compared to the cross sectional diagram of the sliced part generated by the slicing software as shown in Figure 8. It was clear that the tri-hexagon infill pattern had a larger void size compared to the grid and the gyroid infill pattern. Right, the intensity of the bubble is supposed to be the highest for the tri-hexagonal infill pattern. Further investigation found that although the void of the part with a tri-hexagonal infill pattern was larger in size, but is much more enclosed between the inner and outer walls, while the gyroid infill pattern is much more exposed to the opening between the inner and outer walls, causing more gas movement out of the part through the wall, resulting in more bubble formation on the surface of the part with gyroid infill pattern. The impact resistance of printed parts with triangle, grid, quarter cube, and tri-hexagon infill patterns demonstrates that the triangle infill pattern absorbed the most energy and provided the stiffest structure. The intensity of void in FDM printed parts has an effect on their capacity to absorb energy (Aloyaydi *et al.*, 2019). Since the study focuses on the intensity of the bubble, the size of the bubble due to the infill pattern effect was not known because it is outside the scope of this study.

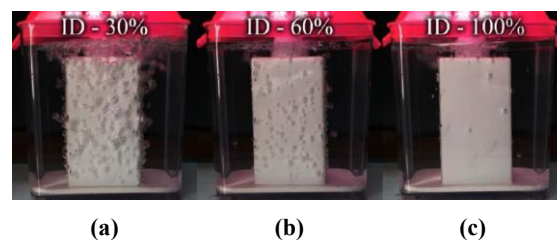


Figure 7. Comparison of the intensity of bubble formed at different infill pattern (a) grid (b) tri-hexagon (c) gyroid.

A comparison was made between parts produced with a different angle of raster. The three raster angles used in this study were 0°, 45° and 90°. The result shown in Figure 9 shows that the part printed with a raster angle of 45° produced the least bubble, while the part with a raster angle of 0° and

90° produced more bubbles compared to the part with a raster angle of 45°. However, it was difficult to determine which raster angle produced more bubbles, since this study relies solely on the observation of naked eyes. However, this result appeared to be an agreement with the cross-section view of the slicing part as shown in Figure 10. It was clear that the 0° and 90° angles of the raster produced almost similar voids. However, the part with a raster angle of 45° outperformed the other two parts due to an angled pattern resulting in less opening between the outer and the inner wall.

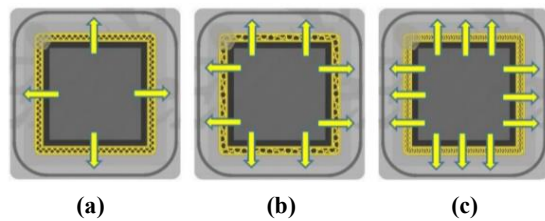


Figure 8. Cross sectional view of part for different infill pattern (a) grid (b) tri-hexagon (c) gyroid generated by the slicing software

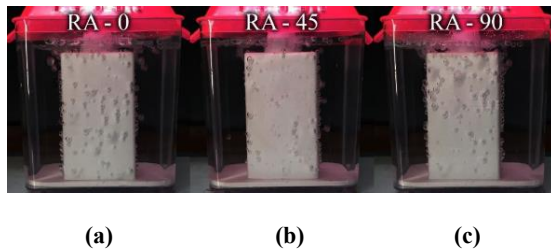


Figure 9. Comparison of the intensity of bubble formed at different infill angle (a) 0° (b) 45° (c) 90°

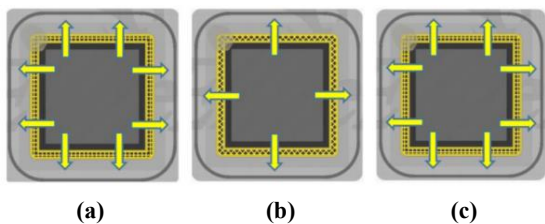


Figure 10. Cross sectional view of part for different infill angle (a) 0° (b) 45° (c) 90° generated by the slicing software

Cross-checking the effect of different slicing parameters; the infill density, the infill pattern and the raster angle for the other shape of the product found the same result as shown in Figure 11. With

regard to the influence of the shape of the part, it was found that, in many circumstances, the cylinder part produced more bubbles than the cuboid and the tri-hexagonal part. This is because the surface area of the cylindrical part is higher than that of the other two.



Figure 11. Overall comparison of the formation of the bubble; to the right is between the different slicing parameters and to the bottom is between the different shape of the part

Conclusions

The objective of the study is to investigate the effect of FDM slicing parameters; infill density, infill pattern and raster angle and the shape of the part on the void in the printed part during the FDM process. This paper reports a part of the study involving only pure observation of a bubble produced by part of certain slicing parameters. The PGR method was used to achieve the study's objective. In general, the study found that the selected slicing parameters studied had a significant impact on the intensity of the bubble produced by the part with different parameters set. The part with an infill density of 100%, an infill grid pattern and a raster angle of 45° produced the least bubbles during the experiment. Meanwhile, the comparison between the different shapes of the part found that there was the least influence of the shape of the part on the formation of the bubble during the experiment. Since the study relies on observation, the results analysis may not be accurate. Thus, at this time, it could be assumed that the minimal formation of the bubble would indicate the least number of voids in the part. However, this hypothesis would be further investigated by examining the cross-section view of the part under the SEM to confirm the relationship between the bubble intensity and the void formation of the part during the FDM printing process. Future research must establish the connection between void properties (such as size and quantity) and bubble formation.

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