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The Effects of FDM Printing Parameters on the Compression Properties of Polymethylmethacrylate (PMMA) using Finite Element Analysis

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Abstract: 3D printing technology has become a favored alternative in fabricating parts due to its flexibility in product customization. Recently, an abundant number of studies have been conducted to improve the overall quality of the 3D printed parts. One of the essential qualities is to provide mechanical properties that fulfill the functionality of the final product. Thus, providing the best option in tailoring the mechanical properties of 3D printed parts is very useful. This paper investigates the effects of printing parameters on the compression properties of Polymethylmethacrylate (PMMA) using finite element analysis (FEA). Taguchi's 3^3 design-of-experiment methods were used to design the experiment for the following printing parameters: shell thickness, type of infill, and infill density. The compressive test was performed using Ansys software and the variables under study were strain and total deformation. The results obtained from the FEA simulation show that the compressive strain and total deformation are mainly influenced by infill density, followed by the type of infill and shell thickness. It is deduced from the study that the optimum printing parameters with higher infill density (70%) and combination with triangular infill pattern are able to hold the structure more rigidly, therefore providing more resistance against deformation. This study proposed a platform for determining the mechanical properties of 3D models for FDM printed parts using FEA analysis.

Keywords: 3D printing, PMMA, finite element analysis, deformation

1. Introduction

Rapid prototyping (RP) technology known as additive manufacturing (AM), has been the chosen technology in recent years. There are various AM technologies such as fused deposition modeling (FDM) [1], selective laser sintering [2], stereolithography [3], and many more. These technologies provide different mechanisms and systems which focus on different applications. In general, the process starts from creating 3D models from computer-aided design (CAD) which will be converted into a standard triangular language (STL) format. The.STL file is then transferred to the 3D printing machine to generate the layered solid path for printing [4].

Among these AM technologies, FDM is a popular choice due to its cost and simple mechanism [5]. FDM working principle is simple where the material in filament form will be pushed by the motor through the heating chamber and deposited layer by layer [6], [7]. The most common material used for this technology is acrylonitrile butadiene styrene

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(ABS) and polylactic acid (PLA). Over the years, polymethylmethacrylate (PMMA) has been considered as an alternative FDM material for biomedical applications such as tissue engineering and 3D models for implants [8], [9]. Other studies also mentioned the application of PMMA in the fabrication of microfluidic chips using FDM technology [10].

Despite being the popular choice among the users, FDM possesses some drawbacks that need to be improved [11]. Based on this study, approximately 20% deviation of the printed parts from the original CAD design show some weaknesses of the FDM systems. A lot of studies pertaining to FDM have been conducted to tailor the mechanical performance of the printed part suitable for its end application. A previous study has been done on FDM printed parts by putting constrained conditions on the printing process [12]. Finding from this study shows that the tensile strength values for PLA material varied between samples properties showing the inconsistency of the printed parts. The result showed that the inter-bond layer has a great effect on the mechanical properties. Another study had identified the main factor which contributes to stress values based on several printing parameters [13]. The study intended to address the limitations of the printed parts by using different materials and shows that PMMA possesses better impact strength in comparison to thermoplastic polyurethane (TPU). Previous studies have mainly investigated the mechanical properties of FDM printed parts by experimental means and very few works have focused on using finite element analysis (FEA). This present study intends to conduct the FEA analysis on the compressive test of FDM printed parts by manipulating several printing parameters which are shell thickness, type of infill, and infill density.

2. Methodology

2.1 Design of Experiment

Taguchi's 3^3 design-of-experiment methods were used to design the experiment as shown in Table 1 using Minitab software (Minitab, USA) in Taguchi Array with a total of 9 design samples. Three levels of shell thickness, type of infill, and infill density were determined. Fig. 1 and 2 show the different types of infill patterns and infill density used in this study.

Table 1: Printing setting for the simulation

No.	Shell thickness (mm)	Type of infill pattern	Infill density (%)
1	0.4	Square shape	70
2	0.8	Triangular shape	50
3	1.2	Hexagonal shape	30

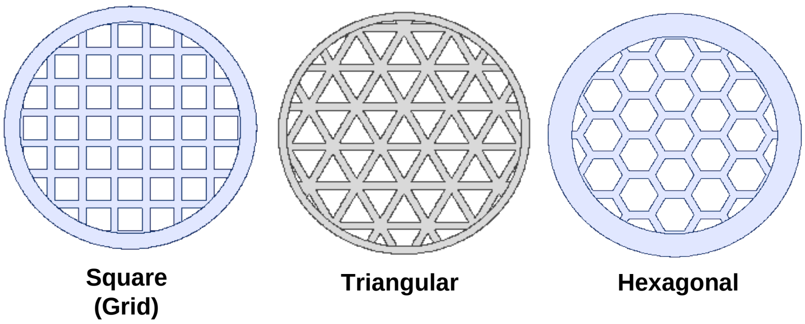

Fig. 1 - Type of infill

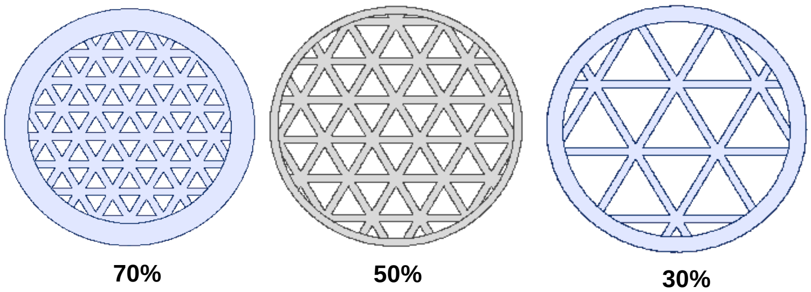

Fig. 2 - Different infill density structures for the sample

2.2 Simulation Model

The cylindrical simulation model was developed per ASTM D695 (Determination of Compressive Properties) standards [12] and designed using Autodesk Inventor Software (Autodesk, USA) with a diameter (D) of 12.7mm and length (L) of 25.4mm. The infill design was designed using Creo® Software to create a similar internal structure (type of infill) and infill density (lattice distance) used in common slicer software like Repetier Host Software. The final file was imported to the Inventor software to finalize the design model as shown in Fig. 3.

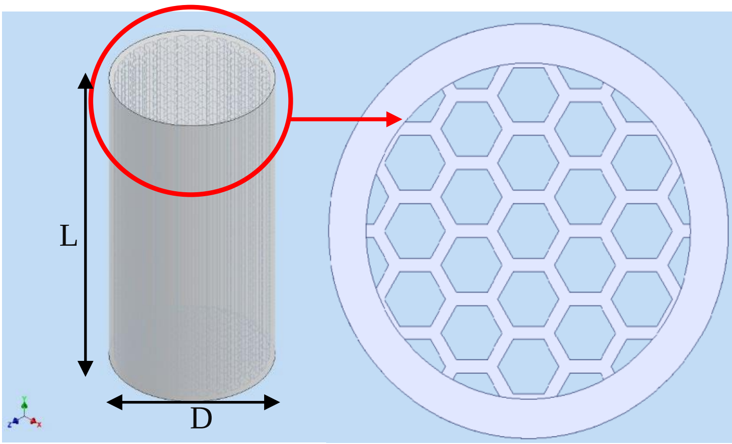

Fig. 3 - Internal hexagonal structure design

2.3 Finite Element Analysis (FEA)

The FEA was conducted by manipulating several printing parameters based on Table 1. The simulation was performed to investigate the strain and deformation of the sample. Some boundary conditions for the simulation were set up including the type of analysis which is static structural and the default meshing process using Inventor Software (Autodesk, USA). The average element size set for the simulation is 0.100 and curved mesh elements have been turned on. For the type of mesh, isotropic triangles were used as provided in the setting. Polymethylmethacrylate (PMMA) material was used in this study and the applied compression load is 5kN on the surface load with a fixed surface at the bottom as shown Fig. 4. Table 2 shows the material properties of PMMA used in the simulation.

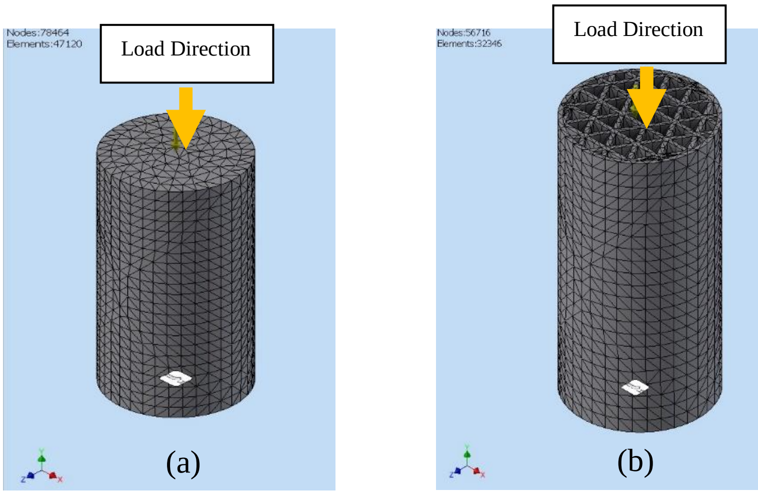

Fig. 4: Meshing density and load direction (a) surface structure of triangular pattern at 50% density and (b) internal structure of triangular pattern at 50% density

3.0 Result and Discussion

Nine sample models were simulated using Autodesk Inventor simulation software (Autodesk, USA) and the data were recorded in Table 3. Sample number 3 showed the highest compressive strain and total deformation value with 0.1508 and 2.884 mm respectively. On the other hand, sample number 8 shows the lowest compressive strain value, which is 0.0020, and the lowest total deformation value of 0.502mm. Analysis of Variance (ANOVA) was used to evaluate the P-value and identify the printing parameter that affects the most on compressive strain and total deformation value. Table 4 shows the ANOVA analysis for the study.

Table 2 - Material properties of PMMA

Property	PMMA
Density(g/cm^3)	1.15-1.19
Melting point (°C)	220-240
Tensile strength (MPa)	72
Tensile Modulus (GPa)	3.1
Elongation of break	5
Compressive strength (MPa)	83-124

Table 3 - FEA simulation for compressive strain and total deformation

No.	Shell thickness (mm)	Type of infill pattern	Infill density (%)	Compressive strain	Total deformation, (mm)
1	0.4	Square (Grid)	70	0.0101	0.61
2	0.4	Triangular	50	0.0065	0.688
3	0.4	Hexagonal	30	0.1508	2.884
4	0.8	Square (Grid)	50	0.0205	0.7295
5	0.8	Triangular	30	0.0958	1.051
6	0.8	Hexagonal	70	0.0385	0.6911
7	1.2	Square (Grid)	30	0.0801	0.9898
8	1.2	Triangular	70	0.0020	0.502
9	1.2	Hexagonal	50	0.0479	0.8111

Table 4 - Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Shell thickness (mm)	2	0.000242	0.000121	0.62	0.618
Type of infill pattern	2	0.003744	0.001872	9.57	0.095
Infill density (%)	2	0.015580	0.007790	39.81	0.025
Error	2	0.000391	0.000196		
Total	8	0.019956			

Based on ANOVA analysis, it is concluded that infill density (%) is the most significant factor affecting the compressive strain and total deformation with a P-value of 0.025. Meanwhile, infill density with a P-value of 0.095 and shell thickness with a P-value of 0.618 show no significant effect. However, the type of infill shows quite a promising P-value which closely gives a significant effect to the strain and total deformation value. The lowest 0.02 strain value shows that 70% of infill density provides the highest rigidity and the strongest structure to sustain the load. On the other hand, sample with 30% of infill density experienced the highest compressive strain and total deformation which indicates a weak structure to hold the load as seen in Fig. 5 and 6 below. The interaction plot in Fig. 7 shows the effect of infill density on the compressive strain and deformation value. The result from this simulation study agrees with the finding in the previous experimental result where the percentage of infill provides a significant impact on the compressive properties [14]. It was concluded that a higher infill percentage provides higher compressive strength for the printed parts. The previous study has shown that 80% infill percentage provides higher compressive strength for PLA parts compared to 20% [15]. Another study shows a similar result where the percentage of infill was found to be the most significant process parameter that affects the compressive strength of PLA printed parts [16].

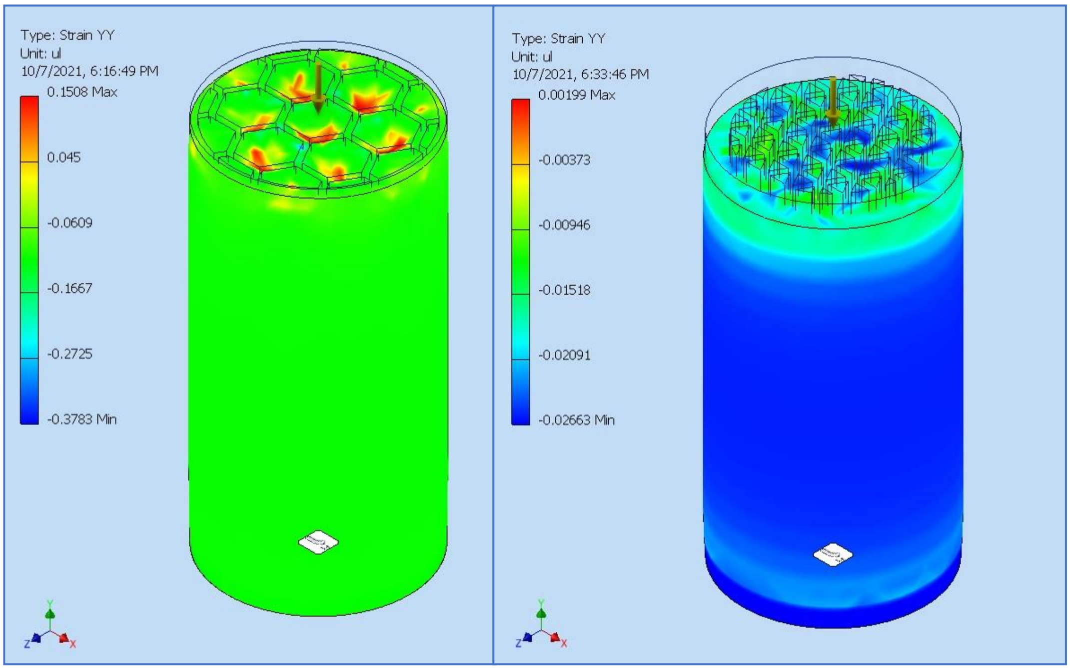

Fig. 5 - Compressive strain result for samples 3 (left) and 8 (right)

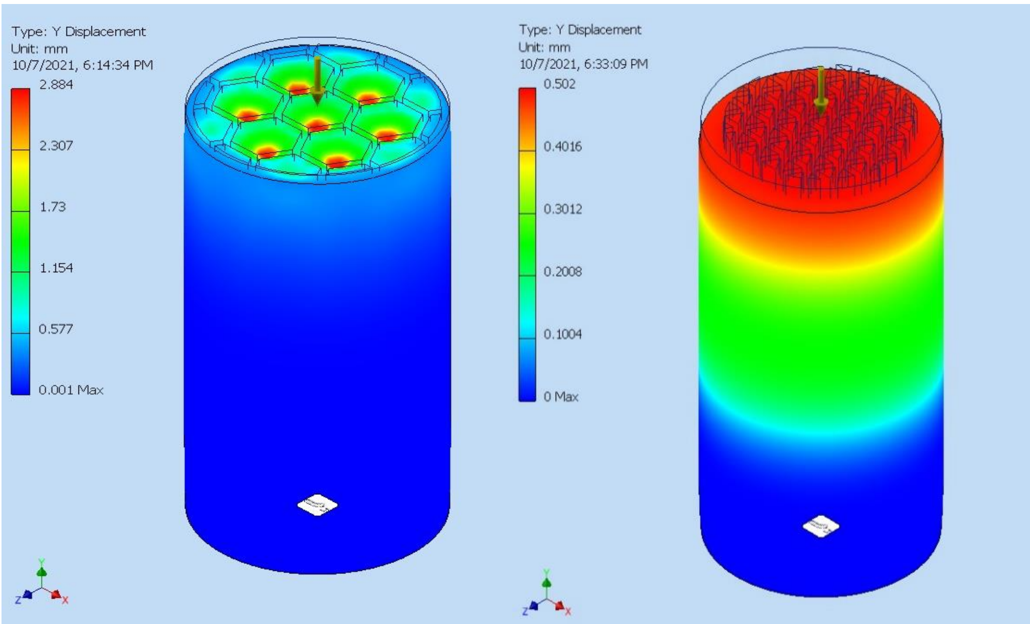

Fig. 6 - Total deformation result for samples 3 (left) and 8 (right)

3.1 Optimization of FDM Printing Parameter

To get the desired outcome of the printed product, the printing parameters need to be tailored accordingly to the application. From the ANOVA analysis, the infill density is the dominant factor in affecting the value of compressive strain and total deformation. Using 70% infill density imparts a stronger and more rigid structure to the printed parts. This setting is very suitable for parts that need to sustain a high load. However, this setting parameter will take a longer printing time. Another factor that can also be considered is the type of infill. Even though from the ANOVA analysis, the P-value for parameter type of infill is 0.095, this parameter can still be considered to have a direct impact on the mechanical properties of the 3D printed part. Previous studies have shown that the type of infill does affect the mechanical properties of the printed parts [17], [18]. Fig. 8 shows the main effect plot for the type of infill. It can be seen that type of infill number 2 which is a triangular infill pattern contributes to the lowest compressive strain and deformation value. Thus, a triangular infill pattern is the best option to consider for imparting strength on printed parts.

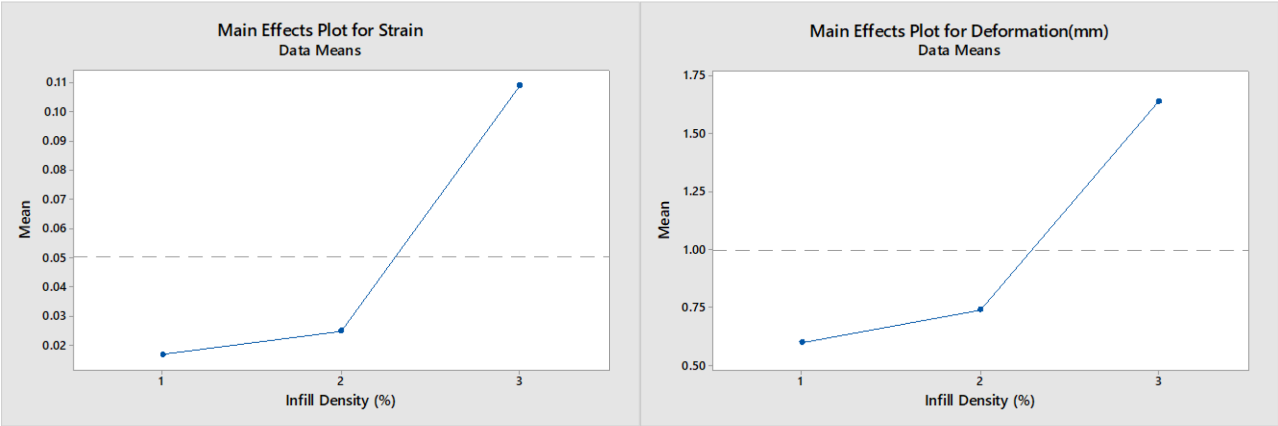

Fig. 7 - Main effect plot of infill density (%)

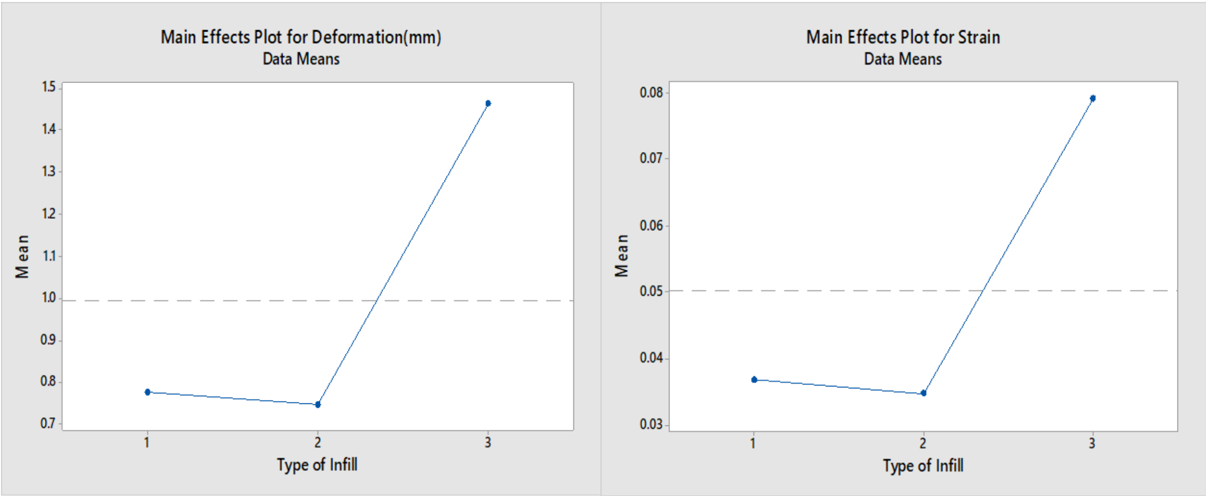

Fig. 8 - Main effect plot of type of infill

4.0 Conclusion

FEA simulation was performed on the PMMA FE models by manipulating three different parameters which are infill density, type of infill, and shell thickness (mm). The ANOVA analysis shows that infill density has the highest significant impact on the compressive strain and deformation value. Type of infill and shell thickness, however, have a slightly lower influence compared to infill density. From this study, it can be concluded that to increase rigidity and strength of the structure, infill density should be increased, and triangular shape can also be considered. Nevertheless, the printing parameters can be manipulated based on the different applications.

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