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INFLUENCE OF FDM PROCESS VARIABLES' ON TENSILE STRENGTH, WEIGHT, AND ACTUAL PRINTING TIME WHEN USING ABS FILAMENT

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Abstract: The main advantage of the Fused Deposition Modelling (FDM) 3D printing technology is that products can be manufactured by adjusting the levels of the manufacturing process variables. In this paper, the main factors affecting product weight and effective printing time, while maintaining the required durability in the fused deposition modelling process for absorbable butadiene-styrene (ABS) thermoplastic products are investigated. Three process variables, namely, infill density, layer thickness and infill pattern, were set at different levels to study their effect on product durability, product weight and effective printing time. Tensile stress was adopted as the standard for product durability.
It was found that both the infill pattern and the infill density greatly affect the strength of the specimen. In particular, as the latter increases, the specimen's strength increases. It has also emerged that the infill density affects the weight of the specimen, such that decreasing the infill density reduces the weight of printed specimens for all kinds of infill patterns. It was also found that the thickness of the layer has a greater impact on effective printing time than the other two studied factors.

Keywords: FDM, ABS, process parameters, tensile strength, product weight, and printing time.

1. INTRODUCTION

One of the most promising industrial technologies for the near future is additive manufacturing (AM). Despite the widespread use of this technology, it still requires further research [1]. FDM printers are programmed extrusion machines used to print computer-aided design (CAD) models into physical parts. Printing is done using a G-code program obtained from a specialized program that uses the solid 3D model in STL format. This solid model is sliced in layers before the G-code program is maked. These layers are printed one by one using thermoplastic materials through a nozzle, where the layers are deposited onto the printing platform. The extruder moves along the x-y plane such that the printer has controlled movements in three directions (X, Y and Z). Figure 1 shows the main components of the FDM printing machine.

A quick rapid prototype modelling procedure, Fused Deposition Modelling (FDM), uses molten thermoplastic filaments to construct a part. Through this procedure (FDM), new geometries can be created by depositing successive layers on top of each other in sequence [2].

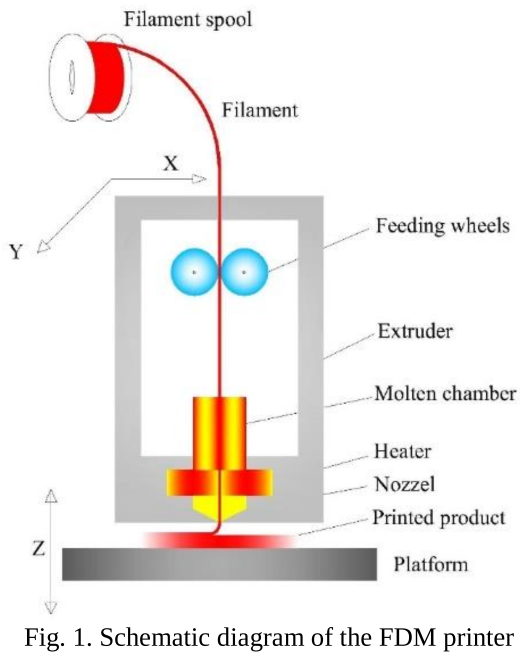


Fig. 1. Schematic diagram of the FDM printer

FDM uses a semi-molten thermoplastic filament extruded through a nozzle, which eventually hardens at room temperature [3].

The FDM process involves several variables that have a significant impact on the specifications of the built models. Each one of these variables has an impact on the final specimens for the created models [4]. The challenge is to combine the process (FDM) variables in such a way that maximizes their positive

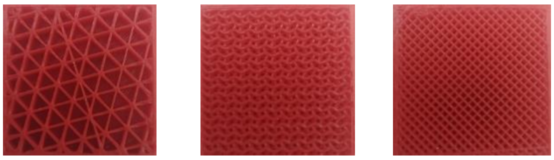
impact [5]. At present, FDM is not only used to produce prototypes but also functional parts, such as for the aerospace and dental industries [6]. The FDM process is done by printing the extruded filament material in successive 2D layers on top of each other on the platform to form the final product [7].
Many researchers are working on inventing novel materials that may be used to fabricate parts in numerous sectors, such as aerospace, healthcare, telecommunications, among others. There are a few drawbacks, however, to using the FDM technique to fabricate functioning parts [8]. Garg et al. [9] investigated how component construction orientation (X, Y, and Z) as well as the raster angle affect tensile strength and surface roughness in a three-dimensional environment. The evaluation of ABS produced using the FDM technique was conducted. The number of upper and lower surface layers, infill spacing and layer precision were investigated by Peko et al. [10], with experiments being carried out on ABS. For mathematical modelling, optimization, and ANOVA analysis were utilized. The process variables that resulted in maximum tensile strength and lowest cost were determined. Alvarez et al. [11] took several variables into account in printing ABS parts, including temperature, speed, and infill percentage. The authors investigated the mechanical properties of ABS printed items. That is, test specimens were printed with the fill ratio altered, whilst all other printing factors were fixed in order to define this impact. An FDM rapid prototyping machine that produced an ABS-compliant prototype was investigated by Lee et al. [12]. Analysis of variance (ANOVA) and an orthogonal matrix were utilized to analyse the process variables to ascertain the best elastic performance. In addition to finding the ideal process variables of the FDM procedure, this study also identified the primary process variables that affected prototype performance.
From reviewing the previous research, it is clear that the process variables for FDM have a significant impact on the mechanical properties and weight of the printed parts in that they can be optimized through the appropriate selection and modification of these variables. Therefore, this study aims to evaluate the effect of three variables (infill density, layer thickness, and infill pattern) on the tensile properties of 3D printed samples using (ABS) as a building material. This study also dealt with the effect of these variables on the weight of samples and the printing time.

2. TESTING VARIABLES

There are many variables in the FDM extrusion process, which can be modified to improve the properties of the prints. In this study, three process variables were examined, namely infill pattern, infill density, and layer thickness. These variables were adjusted at different levels to verify the effect of each on product durability, product weight and effective printing time.

2.1 Infill pattern

The Ultimaker Cura software used in this study allows for changing the filling pattern of the printed structure. Three different printing patterns, triangle, gyroid and line patterns were adopted, as shown in Figure 2.



(a) (b) (c)

Fig. 2. Infill: (a) triangle, (b) gyroid, (c) line

2.2 Filling density

The density of the filler determines the amount of thermoplastics used within the printed structure. A higher filling density means there is more thermoplastic material inside the prints, thus resulting in a somewhat stronger part. The amount of material that will be printed inside the printed part's outer shell is referred to as filling density. Figure 3 illustrates infill density inside the outer shell.

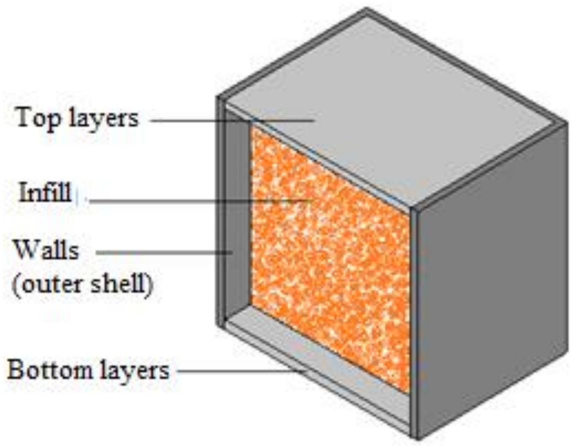


Fig. 3. Filling density inside the outer shell

Filling density is commonly expressed as a percentage of the total rather than as a unit of measurement. This means that if the filling density is set to 100 percent, the printed part will be totally solid, with no empty space inside. Similarly, if 0% is specified, the printed portion will have only an outer shell and be empty inside. Figure 4 shows different levels of filling density.

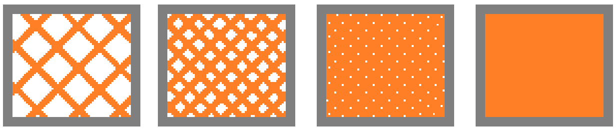


Fig.. 4 Filling density: (a) 20%, (b) 40%, (c) 80%, d) 100%

In this study, three levels of filling density of 50%, 60% and 70% were adopted for the models to investigate their effect on the properties of the final models.

2.3 Layer thickness

The setting that determines the height of each printed layer called layer thickness. Generally, when we choose a thicker layer, the printed part will have less fine detail, while when a layer with less thickness is chosen, a higher level of detail can be obtained. Moreover, the thinner the layer, the more time it will take to print the part, as there will be more layers to print. When prototypes are to be printed, a higher layer thickness is often chosen, which will save time.
Three levels of layer thickness were adopted in this study: 0.2, 0.25 and 0.3 mm to investigate their effect on the properties of the printed part.

3. EXPERIMENTAL WORK

The most option of FDM is that the printed parts can be made with different fill densities. This allows for material, cost and time savings along with a reduction in the final product's weight. For this study, we investigated how the tensile strength weight and printing time of Acrylonitrile Butadiene Styrene (ABS) material are affected by layer thickness, infill pattern and infill density. ABS was selected for the 3D printing of several tensile specimens using the Ultimaker 2+ printer, with a filament wire diameter of 1.75mm. The tensile specimen was selected for the tests, because of the simplicity of specimen preparation and its suitability for FDM. The 3D tensile specimen was designed according to ASTM D638-03 [13], as illustrated in Figure 5.

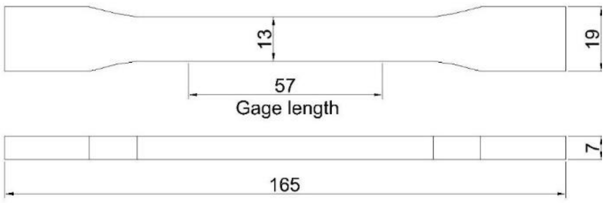


Fig. 5. Printed dog-bone shaped specimen

The Taguchi method was used in this study as a method based on statistics to enhance the manufacturing process variables. Taguchi method ensures a significant reduction in the number of experiments to be studied [14]. The orthogonal matrix and signal-to-noise ratio were used to investigate the process's performance for the three aforementioned variables: infill density, infill pattern and layer thickness. For the conducted experiments, a suitable orthogonal array (L9) was selected, tensile strength, specimen weight and effective printing time were measured and the signal-to-noise ratio was calculated. Nine specimens were printed using the Ultimaker 2+ FDM 3D printer. For software and print configurations, tool path (G-code) computation was performed using Cura software.
The methodology for preparing the 3D printing specimens is illustrated in Figure 6.

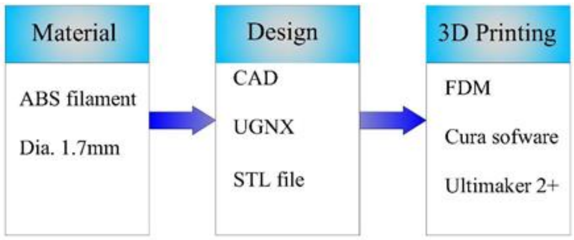


Fig. 6. Preparing 3D printing specimen

3.1. Process flow steps

The process flow for the experiment is presented in Figure 7.

1. In the UGNX CAD software, a standard specimen design was created for the specimen.
2. The specimen design drawing was then converted to STL format.
3. 3D-slicing performed in Cura software.
4. Ran these STL files with the Cura software and specified printing process variables.
5. The STL file was then converted to G-code, which was used to print the specimen.
6. The specimen was printed using the Ultimaker 2+ printing machine Figure 8.
7. The specimens were tensile tested and measurements were taken.

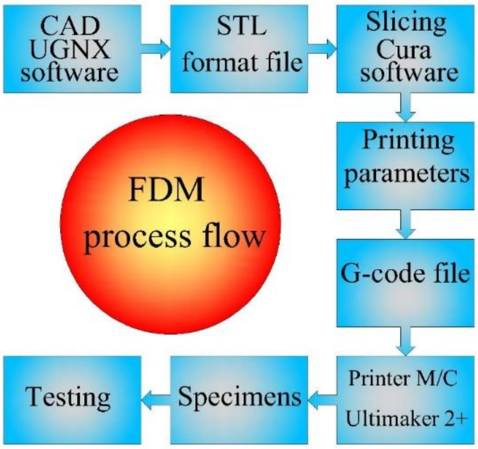


Fig. 7. Process Flow

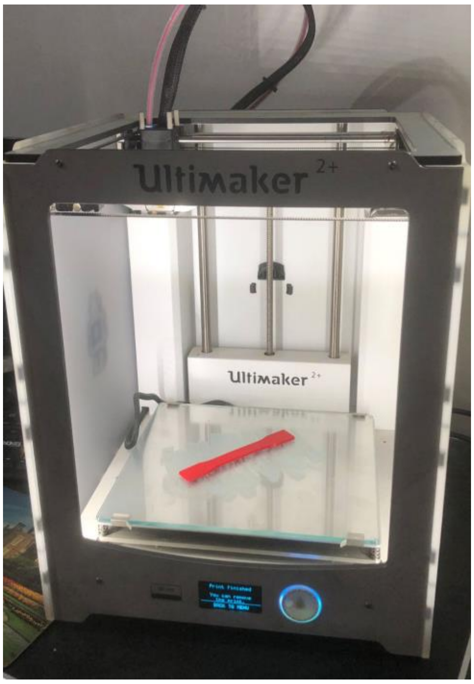


Fig. 8. Ultimaker 2+ FDM Machine

The tensile tests were carried out according to ASTM D638-03 using a tensile machine (universal testing machine shown in Figure 9, at a speed of 55 mm/sec. Two specimens were made for each test trial, with Ultimaker 2+ and tensile strength measured as the mean of the two readings was adopted for subsequent analyses.

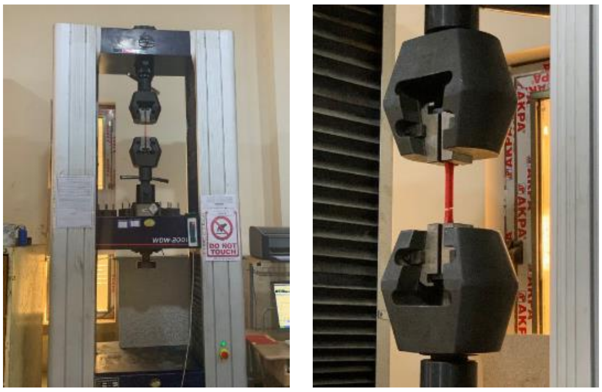


Fig. 9. Tension Testing Machine

Table 1 illustrates the variables and the levels that were adopted.

Table 1. Levels of the process variables

Variable	Infill density %	Layer thickness mm	Infill pattern
Level 1	50	0.2	triangle
Level 2	60	0.25	gyroid
Level 3	70	0.3	line
Mat. ABS, raster angle 45°. Printing speed (55 mm/s), nozzle temp. 250 °C, platform temp. 100 °C All tests were performed at 25 ± 2 °C.			

Table 2 shows the layout of experiments according to Taguchi's design of the orthogonal array (L9).

Table 2. Layout of experiments

Run order	Levels of the factors		
	Infill density	layer thickness	Infill pattern
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The tensile test results of the specimens, their weight, and the time taken to print each of them are illustrated in Table 3.

Table 3. Results of the tested specimens

Run Order	tensile strength Mpa	Specimen weight (g)	printing time (min)
1	43.33	10	56
2	34.19	10	55
3	33.5	10	45
4	29.42	11	55
5	41.05	11	52
6	45.15	11	50
7	46.77	12	52
8	49.76	12	54
9	36.66	12	53

Figure 10 depicts the specimens after the tensile testing process.

Fig. 10. Tested specimens

4. RESULT AND DISCUSSION

Through Minitab, a response table can be calculated for each factor (signal-to-noise ratio). Where response tables indicate which factor has the greatest influence on the response and which level of the

factor correlates with higher or lower response characteristic values.
Minitab provides three S/N ratios: bigger is better, smaller is better, and nominal is best. Where the appropriate type of these ratios is used depends on the type of application.
To indicate which factor has the greatest influence on tensile strength (response), S/N values bigger is better (equation 1) were utilized.

$$S/_N = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i}\right)^2\right] \qquad (1)$$

Table 4 illustrates the response values for signal to noise ratio for tensile strength.

Table 4. Response for S/N ratio for tensile strength

No. of Level	Infill density	Layer thickness	Infill pattern
Level 1	31.30	31.84	33.26
Level 2	31.58	32.29	30.44
Level 3	32.87	31.63	32.06
Delta	1.57	0.67	2.81
Rank	2	3	1

Through the statistical analysis according to the data in Table 4, it was found that: the infill pattern variable has the most influence (rank 1) on tensile strength; the infill density is the second effective variable (rank 2) for tensile strength; and the layer thickness is the least influential (rank 3). Figure 11 indicates the signal-to-noise ratios of the main effects in Minitab that can be used to optimize a set of variables for increasing the tensile strength of the specimen.

Fig. 11. S/N ratio for tensile strength

From the graph of the S/N ratios in Figure 11, it can be seen that infill pattern has the most influence on tensile strength of the three considered factors, the triangle infill pattern has the best resistance. The infill density is the second most effective factor for tensile strength, with the layer thickness being least influential. To indicate which factor has the greatest influence on the weight of the specimen (response), S/N smaller is better (equation 2) was utilized.

$$S/_N = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n}(y)^2\right] \qquad (2)$$

Table 5 illustrates the response values for signal to noise ratio for the weight of the printed part.

Table 5. Response for S/N ratio for weight

No. of Level	Infill density	Layer thickness	Infill pattern
Level 1	-20.00	-20.80	-20.80
Level 2	-20.83	-20.80	-20.80
Level 3	-21.58	-20.80	-20.80
Delta	1.58	0.00	0.00
Rank	1	2.5	2.5

Through the statistical analysis according to the data of Table 5, it was found that: the infill density has the most influence on the weight of the printed part. The infill pattern and layer thickness variables have the same effect on the weight of the printed part.
Figure 12, indicates the signal-to-noise ratios of the main effects that can be used to optimize a set of variables for reducing the weight of the specimen.

Fig. 12. S/N ratio for weight

From the graph of the S/N ratios in Figure 12, it can be seen that the infill density has the greatest influence on the weight of the printed part. As the density reduces, the weight of the printed part also decreases for all types of infill pattern. The other two variables (infill pattern and layer thickness) have the same effect on the weight of the printed part.
Using the smaller is the better, S/N ratio (equation 2) was used to optimize a set of variables to reduce specimen effective printing time.
Table 6 illustrates the response values for signal to noise ratio for effective printing time of the printed part.

Table 6. Response for S/N ratio for printing time

No. of Level	Infill density	Layer thickness	Infill pattern
Level 1	-34.28	-34.70	-34.53
Level 2	-34.37	-34.59	-34.70
Level 3	-34.48	-33.84	-33.90
Delta	0.21	0.85	0.80
Rank	3	1	2

The statistical analysis according to the data in Table 6, shows that: layer thickness variable has the most influence (rank 1) on effective printing time. The infill pattern is the second most effective variable (rank 2), the line infill pattern is better, whilst the infill density is the least influential variable (rank 3). Figure 13, indicates the signal-to-noise ratios of the main effects that can be used to optimize a set of variables for reducing the effective printing time of the specimen.

Fig. 13. S/N ratio for effective printing time

From the graph of S/N ratios in Figure 13, it is clear that layer thickness has the most influence on the part's effective printing time. The infill pattern is the second most effective, whilst the infill density is the least.

5. CONCLUSIONS

In this paper, the functional relationship between some process variables and specimen weight and effective printing time (taking into account the required durability of the specimen) has been developed for the FDM process, with the process variables taken into consideration being layer thickness, infill density and infill pattern have been investigated.

As a result of the experiments carried out, the following conclusions can be drawn:

- The tensile strength is more affected by infill pattern than infill density or layer thickness.
- The tensile strength of the triangle infill pattern is the highest.
- A gyroid infill pattern gives less tensile strength.
- Regarding the weight of printed objects, infill density has a greater impact than infill pattern or layer thickness.
- The weight of printed parts is affected by layer thickness and infill pattern in the same way.
- The effective printing time is more affected by layer thickness than infill pattern or infill density.

From the results obtained by tensile tests, it can be concluded that the infill pattern and infill density have an effect on the tensile strength. With an increase of the density from 50% to 70%, the tensile strength of all kinds of infill patterns increases, maximum strength with 70% density. Therefore, if a product needs maximum tensile properties, it should be 3D printed with 100% infill density. Also, if the designer wants to save time and reduce the amount of 3D printed material, by reducing the infill density from 100% to 70%, then the 3D prints (ABS material) will lose up to 10% of its strength. If used as models or prototypes, 3D prints usually do not require a great deal of tensile strength, because they are not usually subjected to heavy treatment or stress. As a result, a medium infill density (50-70%) can be employed to reduce the effective printing time and weight of the printed object, thus significantly lowering the cost.

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