Mechanical Properties of Fused Deposition Modeling Parts

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Abstract—**This research aimed to study effect of fabrication parameters on the mechanical property of three-dimensional printing part. Materials used in this study was Acrylonitrile butadiene styrene. There were two sections of experiments. The first section focused on the effect of the layer thickness and in-fill on the mechanical properties whereas the second section focused on the effect of built orientation on the mechanical properties. All samples were fabricated using Fused Deposition Modeling (FDM) technique. The samples' geometry was according to ASTM-D638 Type I. Values of mechanical property were obtained by tensile test. According to the result, it had been found that the in-fill and built orientation were influenced parameters to mechanical property. No significant change in the mechanical property was observed for different layer thickness.**

Index Terms—**Three-dimensional Printing, Fused Deposit Modeling, Mechanical Property**

I. Introduction

Three dimensional fabrication (3D-F) technology has become increasingly important nowadays in many field of industries with different purposes, for example automotive component manufacturing [1], aircraft component manufacturing [2], mold and die [3], and medical use [4]. 3D-F technology is based on layer manufacturing technique which is to additively deposit material layer-by-layer. Key advantage of 3D-F is an ability to manufacture complicated geometry products which conventional manufacturing processes such as Computer Numerical Control (CNC) milling/turning or other forming methods cannot be performed [2].

The principle of 3D-F is to convert 3D Computer Aided Design (CAD) model into stack of two-dimensional (2D) cross-sectional layers along vertical direction [6] (normally Z axis). Each cross-sectional layer (normally XY plane) composes of geometric model boundary. Area inside the boundary is where the material will be filled to construct the physical part [5]. During the fabrication process, the lowest 2D cross-sectional layers is printed first whereas the higher 2D cross-sectional layers are printed later until it reaches to the highest 2D cross-sectional layer.

Nowadays, there are several of 3D-F system available for different materials type, i.e. ceramics, metal and polymer. Current designation of system is commonly based on material type of method of production. Some of 3D-F are provided below:

1) 3D metal fabrication

It is also known as selective laser melting/sintering (SLM/SLS). It is a technique where the laser is used to fuse the power of material for constructing physical part [2]. Common materials which can be fabricated using this 3D-F are cobalt-chromium [6], stainless steel [2], and titanium [7].

2) Stereolithography apparatus (SLA)

It is a method where laser is used to cure the liquid monomer to solid polymer (forming crosslink network in material) for constructing physical part. Common polymeric materials which can be fabricated using this 3D-F is epoxy-base polymer [8]. In addition, SLA can also be applied to construct ceramics parts by mixing ceramics into monomer liquid. After the part is solidified, ceramics is trapped inside. After that polymer is burnt and leaves the polymer ceramic structure.

3) Fused Deposit Modeling

It is a method where the polymer is melted by heat and inject through the nozzle to deposit the material on platform [9]. A wide range of polymer can be fabricated using this technique including,

Polyethylene Terephthalate (PET) [10], Acrylonitrile butadiene styrene (ABS) [10], Polylactic-acid (PLA) [11] etc.

In this paper, Fused Deposit Modeling (FDM) is under interest which it is widely used across the industries. Many of FDM finished parts tend to be used for geometric prototyping, where many of them can also be used as products. For purpose of fabrication for product, mechanical properties of finished part is significant. This is because part needs to have sufficient strength to withstand loads. In addition, product development process using Computer Aided Engineering (CAE) technology, mechanical properties are used as an input of calculation in CAE and confirms the usability based on CAE result. There is limited study on the mechanical properties of materials fabricated from FDM. To best of authors' knowledge, previous studies on 3D-F has intensively focused on 3D metal fabrication [2, 6, 7] and SLA [2, 8]. Even studies on FDM have been conducted [2, 10, 11], but the effect of the parameters on mechanical property based on software options attached to the machine.

In order to provide data of FDM parts which will be used further in many purpose as aforementioned. This study assesses their mechanical properties based on various fabrication parameters has not been studied yet.

II. METHODOLOGY

Three level orthogonal array (full factorial DOE) technique was used to create experimental set. The fabrication parameters considered in DOE includes layer thickness, in-fill, and part built orientation. Each of parameters has its definition as follows:

1) Layer Thickness

It is an interval of material deposition layer along vertical axis in FDM process.

2) In-fill

The density of material deposited inside FDM part. Higher in-fill means denser part.

3) Built orientation

The direction which FDM part is built.

Material used for mechanical test was ABS which its mechanical properties were shown Table I. All samples were fabricated with Zortrax M200. The software which used to prepare manufacturing conditions and generate the code for machine control was Z-suit v1.12.2.

TABLE I
MECHANICAL PROPERTIES OF ABS MATERIAL USED IN THIS EXPERIMENT [12]

Mechanical Properties	Metric	Test Method
Tensile Strength	30.46 MPa	ISO 527:1998
Breaking Stress	25.89 MPa	ISO 527:1998
Elongation at max Tensile Stress	4.52%	ISO 527:1998
Elongation at Break	11.08%	ISO 527:1998
Bending Stress	46.30 MPa	ISO 178:2011
Flexural Modulus	1.08 GPa	ISO 178:2011
Izod Impact, Notched	8.93 kJ/m2	ISO 180:2004

The experiment was divided into two sections. First section focused on layer thickness and in-fill. For second section, only one condition in the first experiment was selected for fabricating in various built orientations to study effect of built orientation to mechanical property.

A. Experimental Design

In Z-suit v1.12.2 (normal print setting mode), it provides a wide range of layer thickness selection in fixed values and provides three fill-in conditions (Maximum, High, Medium, and Low).

For the first section of experiment which aimed to study effect of layer thickness and in-fill to mechanical property. Then, the three levels are identified as in Table II.

TABLE II
DESIGNATION OF PARAMETERS IN EACH LEVEL

Level	Layer Thickness (mm)	In-fill
1	0.09	Low
2	0.14	Medium
3	0.19	High

For full factorial design with three level for each parameter (3^2), it has total of 9 experimental condition as summarized in Table III.

TABLE III
DESIGNATION OF PARAMETERS IN EACH LEVEL

Condition	Layer Thickness (mm)	In-fill	Specimen Weight (g)
1	0.09	Low	15
2	0.09	Medium	16
3	0.09	High	17
4	0.14	Low	15
5	0.14	Medium	16
6	0.14	High	17
7	0.19	Low	15
8	0.19	Medium	16
9	0.19	High	17

Experimental condition No.9 is selected to test effect of built orientation to mechanical property. There was flat, edge, and upright orientation [8, 9], as shown in Fig. 1. Therefore, additional three experimental conditions were included.

B. Specimens and Fabrication

Specimens were created as 3D geometric model which dimension specified according to the ASTM D638 standard Type I specimen [13]. Samples had 165 mm in total length, 57 mm in length of narrow section, and 7 mm in thickness.

Three sample were tested for each conditions (n=3). This allows calculation of average and standard deviation of all interested mechanical values. In fabrication process, the nozzle diameter of 0.4 mm and the filament diameter of 1.75 mm were used. In addition, extruder temperature of 380°C, heating bed temperature of 80°C was set.
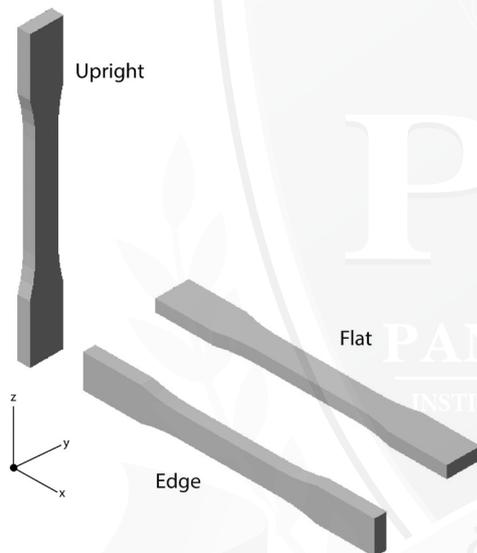

Fig. 1. Build Orientation

All samples in the first section of experiment were fabricated in edge orientation whereas the second section of experiment were fabricated in edge, flat, and upright orientation. Fig. 2 shows the fabrication process.
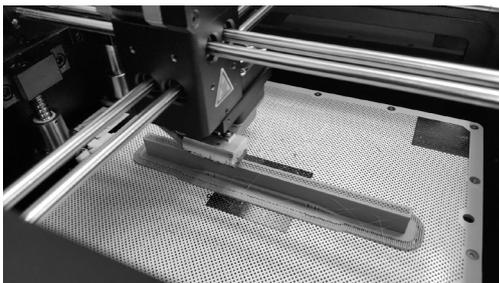

Fig. 2. Sample Fabrication

C. Tensile Test

The mechanical properties of all specimens were examined by using the Universal Testing Machine (UTM) (Instron 5982, Instron Inc., U.S.A). Specimen were attached with the extensometer to measure the displacement. The tests were performed at room temperature with a constant crosshead speed of 5 mm/min, as shown in Fig. 3. The load was applied to the specimen until the test specimen until fractures. Elastic modulus, yield strength, elongation at yield, ultimate tensile strength (UTS), and elongation at UTS were measured of calculated accordingly.

Fig. 3. Tensile Test

III. Result

For the results of tensile tests of the FDM parts, average values of Elastic Modulus (ES), Yield Strength (YS), Ultimate Tensile Strength (UTS), elongation at YS, and elongation at UTS are in consideration. Table IV shows the effect of layer thickness and in-fill to these properties whereas Table V shows the effect of built orientation on the mechanical property. Fig. 4 shows the stress-strain curve for specimens fabricated by each condition in the first section of experiment whereas Fig. 5 shows the stress-strain curve for specimens fabricated by each condition in the second section of experiment.

TABLE IV
EFFECT OF LAYER THICKNESS AND IN-FILL CONDITIONS TO MECHANICAL PROPERTIES

Condition	Layer Thickness (mm)	In-fill	E (MPa)	YS (MPa)	UTS (MPa)	Elongation at YS (‰ε)	Elongation at UTS (% ε)
1	0.09	Low	902.15 ± 21.38	12.63 ± 0.10	14.90 ± 0.20	1.59 ± 0.02	2.36 ± 0.21
2	0.09	Medium	945.44 ± 46.05	13.15 ± 0.43	14.90 ± 0.72	1.58 ± 0.02	2.23 ± 0.11
3	0.09	High	953.31 ± 73.49	13.20 ± 0.89	15.00 ± 1.19	1.58 ± 0.02	2.28 ± 0.04
4	0.14	Low	887.87 ± 17.54	12.85 ± 0.47	13.90 ± 0.37	1.64 ± 0.05	2.07 ± 0.04
5	0.14	Medium	950.73 ± 16.83	13.44 ± 0.26	14.60 ± 0.20	1.61 ± 0.05	2.08 ± 0.06
6	0.14	High	976.28 ± 5.66	13.93 ± 0.41	15.30 ± 0.48	1.62 ± 0.03	2.09 ± 0.04
7	0.19	Low	885.27 ± 11.35	13.21 ± 0.09	14.40 ± 0.04	1.69 ± 0.03	2.19 ± 0.01
8	0.19	Medium	919.84 ± 21.34	13.22 ± 0.11	14.40 ± 0.01	1.63 ± 0.05	2.09 ± 0.01
9	0.19	High	891.37 ± 9.80	13.28 ± 0.32	15.20 ± 0.18	1.68 ± 0.04	2.33 ± 0.03

TABLE V
EFFECT OF ORIENTATION TO MECHANICAL PROPERTIES

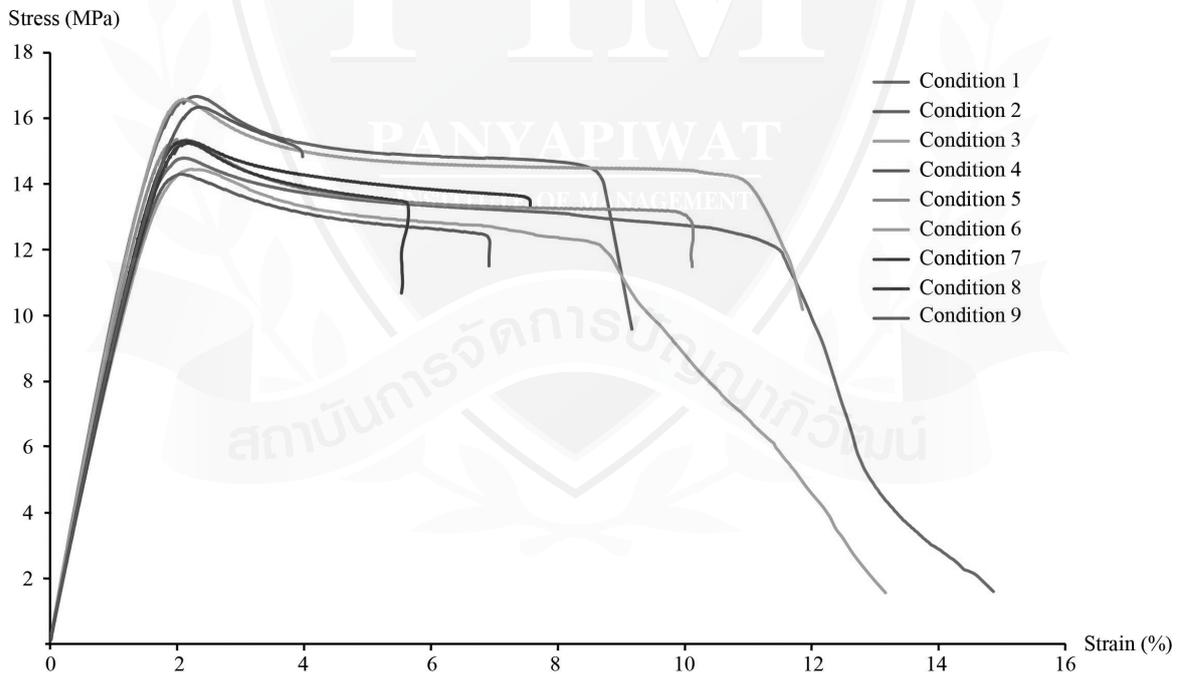| Layer Thickness (mm)	In-fill	Orientation	ES (MPa)	YS (MPa)	UTS (MPa)	Elongation at YS (% ε)	Elongation at UTS (% ε)
0.09	High	Edge	891.37 ± 9.80	13.28 ± 0.32	15.20 ± 0.18	1.68 ± 0.04	2.33 ± 0.03
0.09	High	Flat	774.07 ± 35.12	12.00 ± 0.34	13.15 ± 0.43	1.47 ± 0.06	2.38 ± 0.05
0.09	High	Upright	1021.57 ± 20.04	5.18 ± 0.95	5.18 ± 0.95	0.53 ± 0.08	0.53 ± 0.08

Fig. 4. Example of Stress-strain curve for specimens fabricated by each conditions in the first section of the experiment
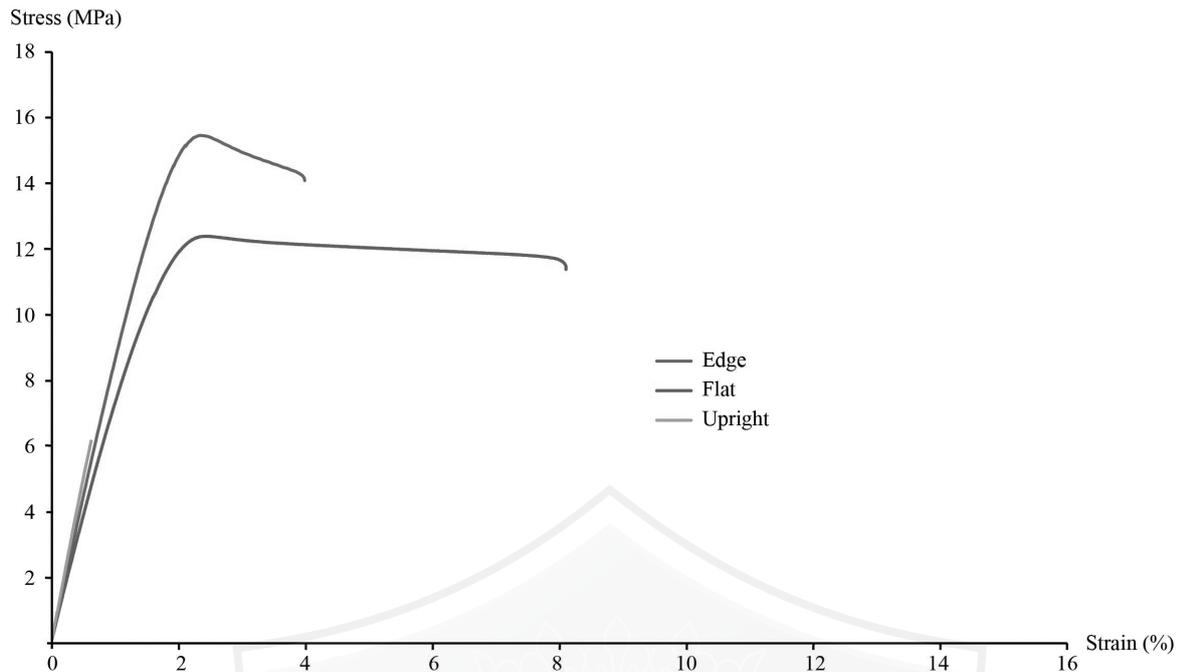
Stress (MPa)

Fig. 5. Example of Stress-strain curve for specimens fabricated by different build orientation

In the first section of the experiment (Table IV), the result reveals that there is no difference in YS, UTS, elongation at YS and elongation at UTS in all conditions which ranged from 12.63-13.93 MPa, and 13.90-15.20 MPa, respectively. For the same layer thickness condition, values of ES depend on in-fill condition, the higher amount of in-fill leads, the greater ES, excepted for the condition 9 where the higher in-fill is not greater than condition 7 and 8. For the same in-fill condition, ES of the sample part fabricated using 0.09 and 0.19 mm layer thickness condition presents the lowest value of each in-fill group. In the low in-fill group, ES of 0.14 and 0.19 mm layer thickness is almost equivalent. The low, medium, and high in-fill group present the lowest ES observed in layer thickness of 0.19.

The second section of experiment (Table V) shows that the upright presents the highest ES, but the lowest YS, UTS, elongation at YS, and elongation at UTS. Sample fabricated in flat orientation presents the lower ES and YS values than edge orientation.

In addition to the numeric results, there is no obvious yield point in the stress-strain curve of upright specimens.

IV. Discussion

Mechanical properties play an important role for application of use. Newsday, FDM parts are not be only used as prototype, but it is used as products in many field, especially medicine. This is because the more biomaterials are available as alternatives, such as PLA and ABS. In product design process, it is crucial to understand the critical aspect of fabrication process which influences the strength. One of the applications use of FDM part has to be cautioned is

the use as mechanical validation models for testing accuracy of numerical models, for example, CAE by means of finite element analysis (FEM).

From the results, it can be seen that mechanical properties of FDM part is anisotropy where the mechanical properties depends on direction of fabrication. This finding correlates with various previous studies who tested on different materials, for example the work of Bagsik et al. [14], Szykiedans et al. [10], and Ahn et al. [9].

In-fill is considered to be an influencer to mechanical property of FDM part, especially on ES. Although the value of YS and UTS has changed slightly over different in-fill conditions, but they still present greater values where higher in-fill is presented. The greater mechanical property can be explained simply by the more infill provides the more density to the part. The more part density reveals the more strength.

Layer thickness did not influence the mechanical properties as it is believed [15]. Generally, the smaller slice thickness presents the better mechanical properties. This may concern with selection of layer thickness interval used to FDM part fabrication in this study which is not different enough. Nevertheless, from this study, since the slice thickness presents no significant influence on mechanical strength, it had better to use the larger slice thickness of 0.19 mm to reduce the fabrication time. The fabrication time used for 0.09 mm slice thickness is twice to those use 0.19 mm slice thickness. Condition 3 presents high S.D. deviations of ES, this may be from the data collected on UTM in the elastic region, nevertheless, the S.D. of others mechanical properties is in low magnitude, the represented average values is still considered reliable.

Limitation of this study includes (1) the ability to change the in-fill direction in fabrication due to software version, (2) the tests is only in major axis (X, Y, and Z axis) orientations, (3) the batch test has not been performed to examine the reliability of fabrication process, and (4) the material is limited to ABS.

These limitation should be taken in to account in further study.

V. CONCLUSIONS

This study investigated the effect of FDM fabrication parameters, i.e. layer thickness and infill, and built orientation to mechanical property. Full factorial technique was used to determine the number of tested conditions. Tensile samples which had shape according to ASTM D638 fabricated with different fabrication conditions were used to test under tensile loading using UTM. The result was found that in-fill and built orientation are factors influenced the strength of the FDM part. Increasing of in-fill raises the strength of the part whereas the edge orientation presents the highest strength among others. Fabrication in upright orientation would make the FDM part more brittle. Interestingly, layer thickness presents a little effect on the mechanical properties of FDM part.

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