PARAMETERS OPTIMIZATION FOR 3D PRINTER BY USING STATISTICAL TECHNIQUE

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This report is submitted in fulfillment of the requirement for the degree of Bachelor of Mechanical Engineering

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SUPERVISOR'S DECLARATION

I declare that this project report entitled "Parameters Optimization for 3D Printer by Using Statistical Technique" is the result of my own work except as cited in the references

Signature : ....

Name : ....

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APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature : ....

Name of Supervisor : ....

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ABSTRACT

3D printer is widely used in producing and manufacturing prototypes as well as functional parts due to its ability to make three dimensional object by layering technique and also its various options of materials. It is found that mechanical properties of 3D printed part are affected by the values of the process parameters used in the 3D printing process. In this project, the process parameter of layer thickness, raster orientation and infill density are set as the manipulated variables while tensile strength of the 3D printed part is set as the responding variable. This project aims to identify the relationship between the input process parameters and the tensile strength of FDM printed part, the correlation among the input process parameters, the significance of input parameters towards the responding variable and also the optimized value of the input process parameters to maximize the tensile strength of the FDM printed part. Taguchi orthogonal array is used to determine the total number of experiment runs and combination of levels of each input process parameters that are needed to be executed. Multiple regression model analysis, analysis of variance and Taguchi signal-to-noise ratio are statistical methods that are used to identify the relationship, correlation, significance and optimum values of the input process parameters in maximizing the tensile strength of the FDM printed part. It is obtained that the tensile strength of the FDM printed part is inceasing with the increasing value of the layer thickness, raster orientation as well as infill density. There is no correlation between the input process parameters. Raster orientation is significant in maximizing the tensile strength of the FDM printed part. The optimum value of each input process parameters in maximizing the tensile strength of the FDM printed part is 0.28mm, 90° and 40%.

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ABSTRAK

Pencetak 3D digunakan secara meluas dalam menghasilkan dan mengeluarkan prototaip serta bahagian berfungsi kerana keupayaannya untuk membuat objek tiga dimensi dengan teknik lapisan dan juga pelbagai pilihan bahan yang boleh digunakan. Didapati sifat mekanikal bahagian cetakan 3D dipengaruhi oleh nilai parameter proses yang digunakan dalam proses cetakan 3D. Dalam projek ini, parameter proses ketebalan lapisan, orientasi raster dan ketumpatan isian ditetapkan sebagai pembolehubah yang dimanipulasi manakala kekuatan tegangan hasil cetakan 3D ditetapkan sebagai pembolehubah bergerak balas. Projek ini bertujuan untuk mengenal pasti hubungan antara parameter proses input dan kekuatan tegangan bahagian cetakan FDM, korelasi antara parameter proses input, parameter proses input yg penting dan juga nilai optimum parameter proses input untuk memaksimumkan kekuatan tegangan hasil cetakan FDM. Tatasusunan ortogonal Taguchi digunakan untuk menentukan jumlah bilangan larian percubaan dan gabungan tahap setiap parameter proses input yang diperlukan untuk dilaksanakan. Analisis model regresi berbilang, analisis varians dan nisbah isyarat-kepada-bunyi Taguchi adalah kaedah statistik yang digunakan untuk mengenal pasti hubungan, korelasi, kepentingan dan nilai optimum parameter proses input dalam memaksimumkan kekuatan tegangan bahagian cetakan FDM. Didapati bahawa kekuatan tegangan bahagian cetakan FDM semakin meningkat dengan peningkatan nilai ketebalan lapisan, orientasi raster serta ketumpatan isian. Tiada korelasi antara parameter proses input. Orientasi raster adalah penting dalam memaksimumkan kekuatan tegangan hasil cetakan FDM. Nilai optimum bagi setiap parameter proses input dalam memaksimumkan kekuatan tegangan hasil cetakan FDM ialah 0.28mm, 90° dan 40%.

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I would like to thank my lab assistant, Encik Faizul for teaching me on how to use universal testing machine to obtain the tensile strength of 3D printed part. His help plays a big role in obtaining data for my project. I am also blessed to have my parents who have supported me morally and financially to complete this project. Completing this project without their supports will be very challenging for me.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
PETG	Polyethylene Terephthalate Glycol
ANOVA	Analysis of Variance
CAD	Computer Aided Design
STL	Stereo-lithography
FDM	Fused Deposition Modelling
S/N	Signal-to-Noise
UTM	Universal Testing Machine
SS	Sum of Square

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CHAPTER 1

INTRODUCTION

1.1 Background

3D printing is categorized as additive manufacturing or layer manufacturing technology. It could use various types and forms of materials to build a three dimensional object. It has been developing progressively in improving and widening its functionality. It has been used for manufacturing prototypes, tools and functional end products. There are several existing technologies regarding 3D printing which are selective laser sintering/ melting, laser-cutting of sheet material, electron beam melting, laser-photo resin curing, fusing of melted filament material and many others. Although these technologies are commercially available, there are a wide range of qualities and built parts of the machines that needed to be considered (Tontowi et al., 2017).

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Fusing of melted filament material or known as FDM is different from conventional technique of injection moulding product formation as there is no usage of any moulding or housing to form the product in FDM process. It only extrudes heated material on a flat surface platform called as building platform which is made of material such as glass or steel layer by layer until a complete 3D model of the product is formed (Nazan et al., 2017).

There are few steps involved in generating a FDM part using a 3D printer. The first step is to create a three dimensional solid model using any available CAD software such as Solidworks or CATIA software. The three dimensional model is then exported to the FDM software in STL format. This format tessellating the model and reduce it into a set of triangles. The model in STL format is horizontally sliced into many thin sections that will be generated layer by layer in FDM process. These thin sections are in a form of two dimensional contours which resemble three dimensional model when they are stacked up together. The FDM software will then generate a process plan for the FDM machine's hardware to operate based on the information (Montero et al., n.d.).

The concept used in FDM machine hardware is that a filament is fed through a heating element. The filament is heated into a semi-molten state. Then, the filament goes through a nozzle and deposited onto the constructing part. Since the material which is the filament is extruded in semi molten state, it will fuse with any material around it that has already been deposited. The nozzle head moves along the X-Y plane depositing the material according to the part in STL file and then moves vertically along Z plane to deposit a new layer of two dimensional contour. These will be repeated until a full physical representation of the original CAD model have been deposited (Montero et al., n.d.).

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1.2 Problem Statement

Additive manufacturing has become an integral part in engineering process. There are more parts that are printed with 3D printer are being used for functional purposes rather than for being prototypes (Hernandez et al., 2016). Mechanical properties of 3D printed parts is important in evaluating and determining the printing quality (Wu et al., 2015). Characteristics and efficiency of FDM printed parts are affected by its process parameters (Dey & Yodo, 2019). Different setting of the process parameters could lead to different values of mechanical properties such as tensile strength of FDM printed part. Selecting an optimum combination of the process parameters will produce a FDM printed part with desired qualities (Dey & Yodo, 2019). The examples of process parameters for 3D printer are raster width, raster orientation, layer thickness, air gap, build orientation, extrusion temperature, infill pattern and density. The description for the process parameters are as in Table 1.2.1.

Table 1. 2. 1: Process Parameters

Process Parameters	Definitions
Layer thickness	The height of deposited layers along Z axis which is the vertical axis of 3D printer
Raster orientation	The angle between the direction of deposited bead and the X axis of the building platform of 3D printer
Air gap	The gap between two adjacent deposited beads on the building platform of 3D printer for each layer
Raster width	The width of deposited bead
Build orientation	The orientation of a part being produced on building platform
Infill density	The percentage of infill volume filled with material
Infill pattern	The pattern of internal structure
Extrusion temperature	The temperature set to heat the filament during FDM process

There are a lot of researchers have been analyzing and optimizing various process parameters to achieve desirable properties of FDM printed part. Tensile strength is one of the important desirable mechanical properties for FDM printed parts. Hernandez et al. (2016) studied to determine the optimum mechanical properties in terms of tensile, compressive and flexural of 3D printed parts with varying build orientation. Ismail and Rukiya (2014) tested

FDM printed parts for their tensile strength, flexural strength and surface roughness by setting five different raster orientations and three different build orientation.

Letcher (2017) studied the correlation between process parameters and mechanical properties of FDM printed part. The process parameters are number of layers, layer thickness and raster orientation while the mechanical properties tested are ultimate tensile strength, modulus of elasticity, maximum force and maximum elongation. Wu et al. (2015) studied the influence of layer thickness and raster angle on the mechanical properties such as tensile, compressive and bending strength of 3D printed part. Montero et al. (n.d) investigated the effects of varying process parameters of FDM such as raster orientation, air gap, raster width, color and model temperature on the tensile strength of 3d printed parts.

1.3 Objective

The objectives of this project are:

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1. To determine the relationship between input process parameters and the tensile strength of FDM printed part.
2. To identify if there is a correlation between the input process parameters.
3. To determine whether the input process parameters are significant in maximizing the tensile strength of FDM printed part.
4. To obtain the level of contribution for each input process parameters in maximizing tensile strength of FDM printed part.
5. To determine the optimum values of input process parameters in maximizing tensile strength of FDM printed part.

1.4 Scope

The scopes of this project are:

1. An experiment is designed using Taguchi orthogonal array. The input process parameters for FDM printing are layer thickness (0.16mm, 0.20mm and 0.28mm), raster orientation (0°, 45° and 90°) and infill density (20%, 30% and 40%). The orthogonal array shows the amount of experiment runs that needed to be executed. Each experiment runs will have different combinations levels of layer thickness, raster orientation and infill density.
2. Specimens with measurements of ASTM D638 Type I standard are printed using a FDM printer. PETG filament is used as the printing material. The settings of layer thickness, raster orientation and infill density for the printing will be based on the combination levels of each factors in the experiment runs. The other process parameters are set constant based on the standard printing setting in Ultimaker Cura software. The printing settings used are line infill pattern, 220°C printing temperature, 80°C build plate temperature, 50mm/s printing speed, 100% fan speed, skirt build plate adhesion, 1.6mm wall thickness and four wall line count.
3. The FDM printed parts are tested using a universal testing machine to determine their maximum tensile strength before fracture.
4. The tensile strength of FDM printed specimens are analysed using statistical method such as multiple regression analysis, analysis of variance and Taguchi signal-to-noise ratio. The multiple regression analysis is used to obtain a regression equation and to determine the correlation between each input process parameters. The analysis of variance is used to identify whether the input process parameters are significant in maximizing the tensile strength of the FDM printed specimen. The signal-to-noise

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ratio is used to determine the level of contribution and optimum values for each input process parameters in maximizing the tensile strength of FDM printed specimen.

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CHAPTER 2

LITERATURE REVIEW

Several articles that are related with this project has been reviewed and summarized according to several sub-topics. A table has been made to highlight the main points of the literature review as in Table 2.0.1. It shows the details of the studies that are carried out by other researchers that are important as the reference for this project.

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2.1 Test Specimen

Shape and dimensions of a specimen are made according to the type of standard used in mechanical testing of the specimen. Each mechanical testing use different kind of standards. As the example, Hernandez et al. (2016) used ASTM D638 Type I which is a dog bone shaped specimen in testing tensile strength while ASTM D695 for compression test. The type of standard used also depends on the type of material used to manufacture the specimen. Thermoplastic is a common material used in FDM process, therefore researchers used standard that is suitable for testing mechanical properties of thermoplastic in their studies on FDM process. As the example, Hernandez et al. (2016) used ASTM D638 Type I which is a dog bone shaped specimen in testing tensile strength. It has total length of 165 mm, total width of 19 mm, depth of 7 mm, narrow width of 13 mm, narrow length of 57 mm, radius fillet of 76 mm and gage length of 50 mm. Croccolo et al. (2013) used specimen according to ASTM D638-10 but with modified fillet radius which is from 76mm to 244mm to avoid unacceptable ruptures at the fillet region. Durgun and Ertan (2014) used ISO 527:1997 standard for tensile specimen. Liu et al. (2017) designed its specimen according to GB/T 1040.2-2006 which is suitable for tensile testing. Panda et al. (2014) made specimen based on ISO 604-1973 standard for testing the tensile of the specimen.

2.2 Material

There are various materials that can be used in FDM process. Dey and Yodo (2019) have listed several materials of filaments that can be used in FDM process which are:

1. Acrylonitrile butadiene styrene (ABS)
2. Polylactic acid (PLA)
3. Polycarbonates (PCs)
4. Polyether ether ketone (PEEK)
5. Polyetherimide (PEI)
6. Nylon

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ABS and PLA are two common materials that are widely used in FDM process (Dey & Yodo, 2019). These filament materials are used based on their properties. Durgun and Ertan (2014) and Hernandez et al. (2016) used Acrylonitrile Butadiene Styrene (ABS) P430 as the material of their test specimen because it has high mechanical strength and convenient for FDM process. Croccolo et al. (2013) used specimen of ABS M30 which is a common material used in FDM process. Panda et al. (2014) used ABS P400 as the material for FDM process. Liu et al (2017) used Poly-lactic Acid (PLA) as the material of the filament for FDM process.

2.3 Machine/Equipment

3D printer is needed to carry out FDM process. There are many 3D printers available in the market which comes with various properties and characteristics. There are also various types of universal testing machine for testing tensile strengths. Hernandez et al. (2016) used uPrint SE Plus 3D printer which has fixed settings of process parameters and MTS 810 Material Test System Load Unit as testing machine. Durgun and Ertan (2014) printed their specimen using a Dimension 3D Printer machine and tested tensile strength using a Zwick/Roell test system. Liu et al. (2017) fabricated specimens using Desktop 3D Printer MakerBot Replicator 2 and measuring ultimate load for calculating tensile strength using microcomputer-controlled electronic universal testing machine (WDW-10). Panda et al. (2014) carried out the FDM process using Stratasys Fortus 400mc machine.

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2.4 Process Parameters

Properties of specimen printed by FDM process are influenced by the setting of its process parameters. Various settings will produce different properties of the FDM printed part. There are many examples of process parameters in FDM process stated under problem statement of this paper. There are many studies have been made to determine the best settings of FDM process parameters to obtain the required or optimal mechanical properties of FDM printed part. As the example, Hernandez et al. (2016) studied the effects of different build orientations on the tensile, compression and 4-point flexure on the part printed with five different build orientations which are 0° in xy plane, 45° and 90° in xy and z plane.

The result shows that the part printed in 90° in xy plane has the highest tensile strength than other build orientations but only with small different. Croccolo et al. (2013) developed an analytical model to estimate the mechanical properties of FDM printed part which are strength and stiffness properties based on the setting of number of contour, build orientation, bead width, raster angle, air gap and layer thickness. Durgun and Ertan (2014) printed FDM parts with raster orientation of 0°, 30°, 45°, 60° and 90° and build orientation of horizontal, vertical and perpendicular to test on the surface roughness, tensile strength and flexural strength of FDM part. They found that build orientation has more significant effect to the mechanical properties than the raster orientation. Liu et al. (2017) studied on layer thickness, deposition style, deposition orientation, raster gap and width as the factors in contributing to the tensile strength, flexural strength and impact strength of FDM part. Panda et al (2014) studied the relationship between layer thickness, raster angle and width with air gap on the tensile strength of FDM printed part.

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2.5 Statistical Method

Statistical methods are mainly used for two purposes which are to design the experiment and also to find the optimum combination of process parameters in producing FDM part with desired properties. Liu et al. (2017) used Taguchi method in designing experiment and Analysis of Variance (ANOVA) to study the influences of layer thickness, deposition style, deposition orientation, raster gap and raster width on the tensile strength, flexural strength and impact strength of FDM part. Liu et al. (2017) also determined the optimal combination of the process parameter based on grey relational analysis. Panda et al. (2014) applied Particle Swarm Optimization (PSO) to find combination of layer thickness, raster angle, raster width and air gap that results in good strength.

Genetic programming is also used by Panda et al. (2014) to approximate the relationship between the process parameters with tensile strength of FDM printed part. Differential evolution also used in this paper to estimate the accuracy and convergence characteristic (Panda et al., 2014).

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Table 2. 0. 1: Summary of Studies on Tensile Strength of FDM Printed Part

Reference	Machine/Equipment	Material / Model	Statistical Method	Process Parameters	Result
(Hernandez et al., 2016)	FDM • uPrint SE Plus 3D printer (has fixed setting of parameters) Tensile Testing • MTS 810 Material Test System Load Unit	Material • ABS P430 Model • ASTM D638 Type I for tensile testing	-	Build orientation; • 0°, 45° and 90° in xy plane • 45° and 90° in z plane	Part printed in 90° in xy plane has the highest tensile strength
(Croccolo et al., 2013)	Only FDM machine and Tensile test machine are mentioned. The model name are not specified.	Material • ABS M30 Model • ASTM D638-10 with modified fillet radius to prevent unacceptable rupture at fillet region.	-	Number of contour, build orientation, bead width, raster angle, air gap and layer thickness	-

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(Durgun & Ertan, 2014)	FDM • Dimension 3D Printer Tensile Testing • Zwick/Roell test system	Material • ABS P430 Model • ISO 527:1997	-	Build orientation • Horizontal, vertical and perpendicular Raster angle • 0°, 30°, 45°, 60° and 90°	Build orientation has higher effect to the mechanical properties than the raster angle
(Liu et al., 2017)	FDM • Desktop 3D Printer MakerBot Replicator 2 Tensile Testing • microcomputer-controlled electronic universal testing machine (WDW-10)	Material • Polylactic Acid (PLA) Model • GB/T 1040.2-2006	• Taguchi Method • Analysis of Variance (ANNOVA) • Grey Relational Analysis	Deposition orientation, layer thickness and deposition style, raster width, and raster gap	-
(Panda et al., 2014)	FDM • Stratasys Fortus 400mc machine	Material • ABS P400 Model • ISO 604-1973	• Particle Swarm Optimization (PSO) • Genetic Programming (GP) • Differential Evolution (DE)	Layer thickness, raster angle, raster width and air gap	-

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CHAPTER 3

METHODOLOGY

3.1 Test Specimen

The specimen used in this project is Type I of ASTM D638-14. ASTM standard is used according to the required standard by the Universal Testing Machine (UTM) in Universiti Teknikal Malaysia Melaka (UTeM). Type I of ASTM D638- 14 is known to be used in testing the tensile strength of rigid or semi-rigid plastic specimen which is very suitable for this project as the material used for FDM process is thermoplastic (Anonymous, 2015). A three dimensional model of the specimen is drawn using CATIA V5 software as in Figure 3.1.1. The main dimensions of the model is as shown in Figure 3.1.2. This model is then saved as STL file to be exported in FDM software.

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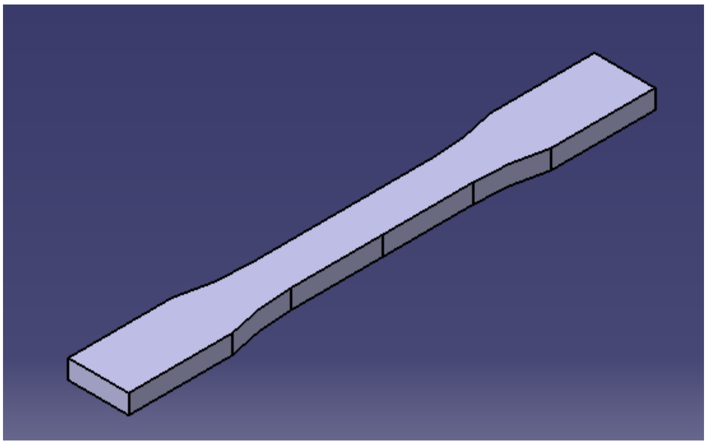

Figure 3. 1. 1: 3D Model Specimen in CATIA V5 Software

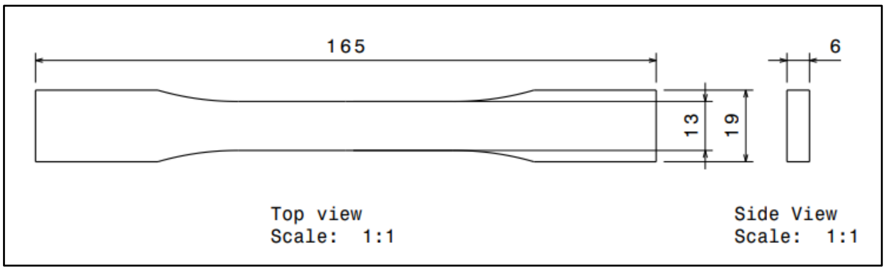

Figure 3. 1. 2: The Dimension of Specimen (mm)

3.2 FDM Process

FDM process is carried out by using Creality 3D Ender 3 Pro machine as in Figure 3.2.2. The material of the filament used for the printing is Polyethylene Terephthalate Glycol (PETG). The filament is 1.75mm in diameter and has a range of 200°C to 260°C printing temperature. PETG contains glycol which makes it to be more durable than PLA. The glycol in PETG also cause the printing temperature and the crystallization to be low. The low temperatures make the finished printed part to be easily removed from the printing bed. PETG is used in this project instead of ABS and PLA because it is not commonly used in the studies for FDM process. The FDM printed specimen is as shown in Figure 3.2.1. The input process parameters are layer thickness (0.16mm, 0.20mm and 0.28mm), raster orientation (0°, 45° and 90°) and infill density (20%, 30% and 40%). The design of the experiment is identified using Taguchi orthogonal array method where three factors and three levels for each factor are set as the setting in the Minitab software. A Taguchi orthogonal array of L9 (3^3) is generated in the software. The details of the input process parameters are shown in Table 3.2.1. The total number of experiment runs for three factors and three levels for each factor is equal to 9. Each experiment runs will be printed four times for tensile strength testing by using Creality 3D Ender 3 Pro machine as shown in Figure 3.2.2.

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Figure 3. 2. 1: FDM Printed Specimen

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Figure 3. 2. 2: Creality Ender Pro 3D Printer

Table 3. 2. 1: Input Process Parameters and their Values

No of runs	Process Parameters		
	Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)
1	0.16	0	20
2	0.16	45	30
3	0.16	90	40
4	0.20	0	30
5	0.20	45	40
6	0.20	90	20
7	0.28	0	40
8	0.28	45	20
9	0.28	90	30

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3.3 Testing Tensile Strength

A total of 36 printed samples are tested for their tensile strength. The tests are conducted based on ASTM D638 standard by using universal testing machine called Instron 5585 model that is located at High Performance Structure (HIPS) laboratory in Universiti Teknikal Malaysia Melaka (UTeM). The universal testing machine is shown in Figure 3.3.1. The testing speed used is 5mm/min according to the Type I of ASTM D638-14 specimen requirement. The tensile strength of each samples will be collected and recorded according to their combination of process parameters to be further analysed.

Figure 3. 3. 1: Instron 5585

3.4 Statistical Method

The statistical methods that are used in this project are Taguchi orthogonal array, multiple regression analysis, analysis of variance and also signal-to-noise ratio.

3.4.1 Taguchi Orthogonal Array

Taguchi orthogonal array is a type of fractional factorial design that is made based on a design matrix created by Dr. Genichi Taguchi. It can be used for designing an experiment that requires testing of multiple combinations of multiple factors with multiple levels. All of the factors in Taguchi orthogonal arrays are considered and weighted equally so that they can be evaluated independently despite of being a fractional factorial design. In Taguchi orthogonal array designed experiment, only main effects and interactions between two factors are considered.

In this project, Taguchi orthogonal array is used to design the experiment. The formation of the array is executed using Minitab software. A setting of three factors and three levels are selected which results in a Taguchi orthogonal array of L9 (3^3). The name of the

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input process parameters: layer thickness, raster orientation and infill density are put into the settings with their values. The array generated shows the number of experiments runs and combinations levels of the input process parameters that are needed to be printed using FDM process. The array is shown in Table 3.2.1.

3.4.2 Multiple Regression Analysis

A multiple regression analysis is used to study the strength of relationship between a dependent variable and more than one independent variables. In this project, the independent variables are input process parameters: layer thickness, raster orientation and infill density while the dependent variable is tensile strength of FDM printed specimen. The analysis also creates a fit regression equation that describe a relationship between predicted tensile strength of FDM printed specimen and input process parameters: layer thickness, raster orientation and infill density.

A measure on how well the multiple regression equation fits with the relationship between the tensile strength of FDM printed specimen and input process parameters: layer thickness, raster orientation and infill density is determined from the value of coefficient of determination (R^2). Coefficient of determination is a proportion of predicted variation in dependent variable based on the independent variables. Equation (3.4.2) represents the formula for coefficient of determination:

$$R^2 = \frac{SSR}{SST} \qquad (3.4.2)$$

where SSR is sum of square due to regression and SST is the total of sum of squares. SSR is known as the deviation of predicted dependent variable values from their mean values while SST is the deviation of the observed dependent variables from their mean values. High value of R^2 means that the observed dependent variable which is the tensile strength of FDM printed specimen in this project does not scatter much from the regression equation plot and the regression equation can be said to fit well with the relationship between the tensile strength of FDM printed specimen and input process parameters: layer thickness, raster orientation and infill density.

Variation inflation factor (VIF) is used to determine whether a multicollinearity exists among the input process parameters: layer thickness, raster orientation and infill density in the regression equation. The multicollinearity is said to be present when there are two or more independent variables that are moderately or highly correlated to each other. VIF measures how much the variation in the coefficients of the regression equation will occur when there is a multicollinearity among the input process parameters.

3.4.3 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) table is also generated during the multiple regression analysis is executed in Minitab software. P-values for regression equation and each input process parameters: layer thickness, raster orientation are stated in the ANOVA table. P-value is the probability of obtaining the experimental data with an assumption that null hypothesis is correct. Two null hypotheses testing have been carried out: for the regression equation and for the significance of the independent variables. First null hypothesis is for regression equation which states that the regression equation does not explain the variance occurred in the tensile strength of FDM printed specimen. The second null hypothesis is for each input process parameters: layer thickness, raster orientation and infill density which states that there is no statistically significant association between each of the input process parameters with the dependent variable. A significance level (α) of 0.05 is set for the regression model and the input process parameters. If the p-value generated is lower than 0.05, the null hypothesis will be rejected. If the p-value is greater than 0.05, the null hypothesis will be not rejected.

3.4.4 Signal to Noise Ratio

Taguchi design is used to determine control factors that are responsible in reducing variability of a process by minimizing the effects caused by noise factors. Control factors are process parameters that can be controlled while noise factors are the opposite. Noise factors can only be controlled through an experimentation. In Taguchi designed experiment, noise factors are manipulated which cause the variability to happen and then optimum control factor values that makes the process become robust and resistant from getting affected by noise factors are identified.

The optimum control factor values are the one that has the highest value of S/N ratio. Signal-to-noise ratio measures the variation of response corresponding to the nominal values under different condition of noise factors. There are four types of signal-to-noise ratio settings in Minitab software. The settings are as in Table 3.4.2.1.

Response table for signal-to-noise ratio is used to determine the amount of contribution of each input process parameters in maximizing the tensile strength of FDM printed specimens. The amount of contribution is represented by the values of delta. The higher the value of delta means that the higher the contribution of the input process parameter in maximizing the tensile strength of FDM printed specimen.

Main effects plot for signal-to-noise (S/N) ratios graph is generated based on the data of the tensile strength that is obtained from UTM machine. The graph is built to find the optimum values for each input process parameters: layer thickness, raster orientation and infill density in maximizing the tensile strength of FDM printed part. The optimum values are the levels of each input process parameters that have the highest S/N ratio.

Table 3. 4. 2. 1: Signal-to-Noise Ratio Settings in Minitab Software

Signal-to-Noise (S/N) Ratio	Aim of the Experiment	Characteristics of Data	Signal-to-Noise (S/N) Ratio Formulas
Larger is better	To maximize the responding variable	Positive value	$-10\ log_{10}\ (\frac{\Sigma\left(\frac{1}{Y^2}\right)}{n})$
Nominal is best	To target the value of responding variable and base the (S/N) ratio on standard deviations.	Positive value, zero or negative value	$-10\ log_{10}\ (s^2)$
Nominal is best (default setting)	To target the value of responding variable and base the (S/N) ratio on means and standard deviations.	Non-negative with an "absolute zero" in which the standard deviation is zero when the mean is zero	$10\ log_{10}(\frac{\bar{Y}^2}{s^2})$
Smaller is better	To minimize the responding variable	Non-negative with a target value of zero	$-10\ log_{10}\ (\frac{\Sigma(Y^2)}{n})$

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3.5 Flowchart

A three dimensional model of the specimen is created using CATIA V5 software based on ASTM D638-14 Type I standard which is a dog boned shaped specimen. The file is then saved in STL format to be exported into FDM software. All the settings of the process parameters are put into the FDM process according to Table 3.2.1. The samples are then printed for four times for each experiment runs using Creality 3D Ender 3 Pro machine. The printed specimen are then tested with universal testing machine to determine their tensile strength. The data are recorded to be analysed using statistical method to obtain the objectives of this project. If the objectives of this project are achieved, then the project will be proceeded to report writing. If the objectives are not achieved, then initial steps will be repeated. The methodology of this project is summarized in a flow chart in Figure 3.5.1.

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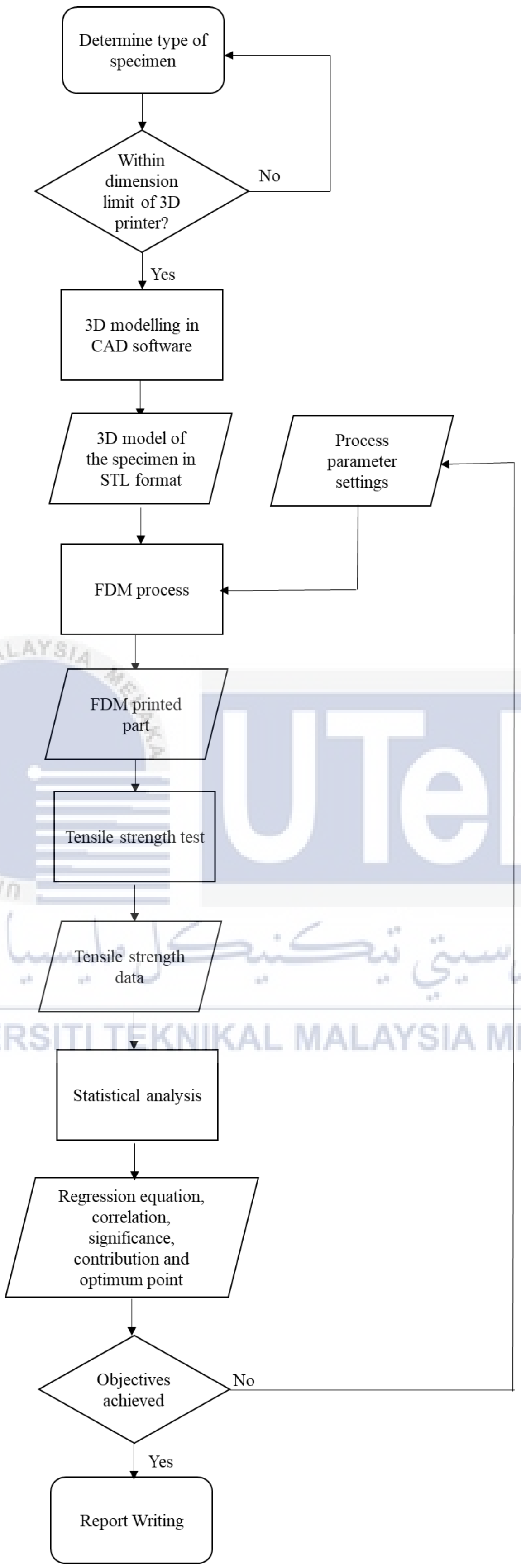

Figure 3. 5. 1: Flowchart of Methodology

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CHAPTER 4

RESULT AND DISCUSSION

4.1 Tensile Strength of FDM Printed Part

The tensile strength of the FDM printed specimens are measured using Instron 5585 universal testing machine and are recorded as in Table 4.1.1. There are four readings for each experiment runs. The average values are calculated for each experiment runs.

Table 4. 1. 1: Tensile Strength of FDM Printed Part

No of runs	Input Process Parameters			Tensile Strength (MPa)				
	Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)	Reading 1	Reading 2	Reading 3	Reading 4	Average
1	0.16	0	20	8.96	8.16	8.44	9.00	8.64
2	0.16	45	30	11.33	11.42	12.12	11.04	11.48
3	0.16	90	40	34.00	30.26	33.53	31.24	32.26
4	0.20	0	30	9.30	10.30	8.28	9.41	9.32
5	0.20	45	40	11.07	14.73	13.97	17.70	14.37
6	0.20	90	20	24.13	26.09	30.28	29.86	27.59
7	0.28	0	40	9.50	9.95	12.08	10.75	10.57
8	0.28	45	20	13.48	18.89	14.77	16.97	16.03
9	0.28	90	30	32.77	32.01	33.75	33.00	32.88

4.2 Multiple Regression Analysis

A multiple regression model analysis is made on the tensile strengths of FDM printed specimens by using Minitab software. A regression equation obtained is as in Eq. (4.2):

$$Y = 0.31 + 21.8X_1 + 0.2378X_2 + 0.082X_3 \quad (4.2)$$

where Y is the predicted tensile strength of FDM printed specimen (MPa), X_1 is layer thickness (mm), X_2 is raster orientation (mm) and X_3 is infill density (%). Based on the regression equation, the coefficients for layer thickness, raster orientation and infill density are 21.8, 0.2378 and 0.082. The coefficients represent the mean change in the tensile strength of FDM printed specimen given a unit change of the input process parameters. Positive signs indicates that the increase in value of the input process parameter will result in increasing value of the tensile strength of FDM printed specimen. If the value of layer thickness increase by one unit while the other independent variables are kept constant, the tensile strength of FDM printed specimen will increase about 21.8 in average. If the value of raster orientation increase by one unit while the other independent variables are kept constant, the tensile strength of FDM printed specimen will increase about 0.2378 in average. If the value of infill density increase by one unit while the other independent variables are kept constant, the tensile strength of FDM printed specimen will increase about 0.082 in average.

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Coefficient of determination for the regression equation is generated in Minitab software as in Table 4.2.1. The value of R^2 in the table shows that the regression equation fits about 88.33% with the relationship between the tensile strength of FDM printed specimen and input process parameters: layer thickness, raster orientation and infill density. The value of R^2 is considered to fit well with the tensile strength data.

Table 4. 2. 1: Coefficient of Determination

Standard Deviation, S	Coefficient of Determination, R^2 (%)	Adjusted Coefficient of Determination, R^2(adjusted) (%)	Predicted Coefficient of Determination, R^2(predicted) (%)
4.30516	88.33	81.33	63.73

Variation inflation factor (VIF) is used to determine whether a multicollinearity exists among the input process parameters: layer thickness, raster orientation and infill density in the regression equation. The values of VIF for each input process parameters are as shown in the Table 4.2.2. The VIF for all of the input process parameters: layer thickness, raster orientation and infill density are equal to 1.00 which means that there is no correlation among the input process parameters: layer thickness, raster orientation and also infill density.

Table 4. 2. 2: Coefficient of Regression Equation

Term	Coefficient	Standard Error Coefficient	T-value	P-value	Variation Inflation, VI
Constant	0.31	8.40	0.04	0.972	
Layer Thickness (mm)	21.8	28.8	0.76	0.483	1.00
Raster Orientation (degree)	0.2378	0.0391	6.09	0.002	1.00
Infill Density (%)	0.082	0.176	0.47	0.659	1.00

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4.3 Analysis of Variance

Analysis of variance (ANOVA) table for the multiple regression analysis is obtained as in Table 4.3.1. Two null hypothesis have been tested: for the regression equation and for the significance of each input process parameters. The first null hypothesis is for regression equation which states that the regression equation does not explain the variance occurred in the tensile strength of FDM printed specimen. The second null hypothesis is for each input process parameters: layer thickness, raster orientation and infill density which states that there is no statistically significant association between each of the input process parameters with the dependent variable. The significance level (α) used for the hypotheses testing is 0.05. The p-value for the regression equation is 0.009 which is lower than the significance level. The null hypothesis for regression equation is rejected. This means that the regression equation does explain the variance of the tensile strength of FDM printed specimen. The p-value for raster orientation is 0.002 which is lower than the significance level. The null hypothesis for input process parameter is rejected. The raster orientation has a statistically significant association with the tensile strength of FDM printed specimen. The p-values for layer thickness and infill density: 0.483 and 0.659 are greater than the significance level. The null hypothesis is not rejected which means that the layer thickness and infill density do not have statistically significant associations with the tensile strength of FDM printed specimen.

Table 4. 3. 1: Analysis of Variance (ANOVA)

Source	Degree of Freedom, DF	Adjusted Sum of Square, adj SS	Adjusted Mean of Square, adj MS	F-value	P-value
Regression	3	701.639	233.880	12.62	0.009
Layer Thickness (mm)	1	10.631	10.631	0.57	0.483
Raster Orientation (degree)	1	686.940	686.940	37.06	0.002
Infill Density (%)	1	4.067	4.067	0.22	0.659
Error	5	92.672	18.534		
Total	8	794.311			

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4.4 Signal-to-Noise Ratio Analysis

Response table for signal-to-noise ratio is generated in Minitab software as shown in the Table 4.4.1. The response table is set to larger is better as this project targets to achieve the optimization of the input process parameters: layer thickness, raster orientation and infill density in maximizing the tensile strength of FDM printed specimen. The value of delta represents the amount of contribution of each input process parameters: layer thickness, raster orientation and infill density in maximizing the tensile strength of FDM printed specimens. Based on Table 4.4.1, raster orientation has the highest value of delta followed by the layer thickness and also infill density which means that raster orientation has the highest contribution in maximizing the tensile strength of FDM printed specimen followed by layer thickness in the second rank and infill density in the third rank.

Table 4. 4. 1: Response Table for Signal-to-Noise Ratio

Level	Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)
1	23.37	19.53	23.88
2	23.78	22.82	23.64
3	24.97	29.78	24.60
Delta	1.61	10.24	0.96
Rank	2	1	3

Main effects plot for signal-to-noise (S/N) ratio is generated from Minitab software as in Figure 4.4.1. The setting for the signal-to-noise (S/N) ratio is set to larger is better because the objective is to find the optimum value of input process parameters: layer thickness, raster orientation and infill density in maximizing tensile strength of the FDM printed part.

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The optimum values are the levels of each input process parameters that have the highest mean of S/N ratio from main effects plot for S/N ratios in Figure 4.4.1. The optimum values for each input process parameters: layer thickness, raster orientation and infill density in maximizing tensile strength of the FDM printed specimens are 0.28 mm, 90° and 40%.

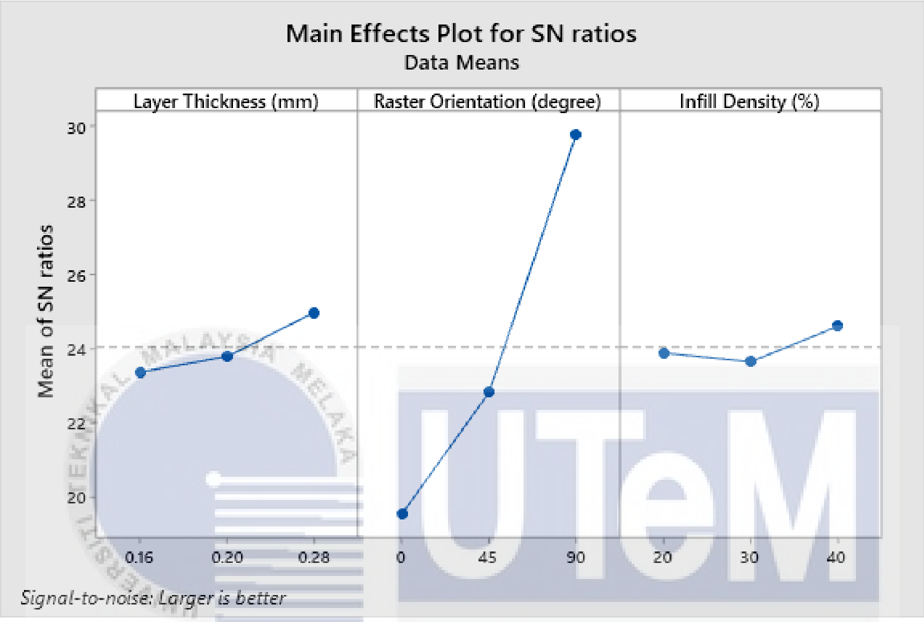

Figure 4. 4. 1: Main Effects Plot for Signal-to-Noise Ratios

4.5 Verification of Regression Model by Data from Experiment

The tensile strength of the optimization values cannot be found in Table 4.4.1 as there is no experiment run with the input process parameters: layer thickness, raster orientation and infill density of 0.28mm, 90° and 40%. A prediction is made by substituting the optimized value of input process parameter into the regression equation. The predicted value of the tensile strength is as shown in Table 4.5.1 which is 31. 096 MPa.

Table 4. 5. 1: Predicted Tensile Strength

Optimized Input Process Parameters			Predicted Tensile Strength (MPa)
Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)	
0.28	90	40	31.096

An experiment is executed four times using the optimized setting of 0.28mm layer thickness, 90° raster orientation and 40% infill density. The average value of tensile strength obtained is as shown in Table 4.5.2 which is 33.03 MPa.

Table 4. 5. 2: Actual Tensile Strength

Optimized Input Process Parameters			Actual Tensile Strength (MPa)				
Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)	Reading 1	Reading 2	Reading 3	Reading 4	Average
0.28	90	40	32.50	33.76	32.89	32.97	33.03

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Percentage of error is calculated to find the difference between the predicted value obtained from the regression equation and the actual value obtained from the experiment. The value of predicted tensile strength is 5.86% lower than the actual tensile strength of FDM printed specimen as shown in Table 4.5.3. It is found that the tensile strength of FDM printed part with optimized input process parameters are the highest compared to the other setting of input process parameters.

Table 4. 5. 3: Percentage of Error

Optimized Input Process Parameters			Tensile Strength (MPa)		Percentage of Error (%)
Layer Thickness (mm)	Raster Orientation (degree)	Infill Density (%)	Predicted	Actual	
0.28	90	40	31.096	33.030	5.86

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CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As conclusion, all of the objectives have been achieved in this project. The relationship between the input process parameters and the tensile strength of FDM printed part are represented by the regression equation that is obtained in multiple regression analysis. The regression equation shows that the increase in value of the input process parameters will result in increasing value of the tensile strength of the FDM printed part. The variation inflation of 1.00 for each input process parameters: layer thickness, raster orientation and infill density means that there is no correlation between the input process parameters. In analysis of variance, only raster orientation has a statistically significant association with the tensile strength of the FDM printed part. The response table for signal-to-noise ratio shows that the raster orientation has the highest contribution in maximizing the tensile strength of the FDM printed part followed by layer thickness and infill density. The optimum values for the layer thickness, raster orientation and infill density are obtained based on the main effect plot for signal-to-noise ratio which are 0.28mm, 90° and 40%. The tensile strength of the FDM printed part is calculated by using the regression equation and also verified with experimentation. The maximum tensile strength obtained in the regression equation is 31.96MPa which is 5.86% lower than the experimentation which is 33.03MPa. The value of the tensile strength of the FDM printed part using the optimized input process parameter has the highest tensile strength among all of the experiment runs.

For future work, more process parameters such as raster gap, infill pattern or extrusion temperature can be manipulated and set as the input process parameter for this project which is to maximize tensile strength of FDM printed part. The material other than PETG also can be used as the filament such as flexible material like nylon or thermoplastic polyurethane (TPU). The response for the project also can be added such as dimensional accuracy, manufacturing time or surface roughness which are categorized as the important mechanical properties. Last but not least, various optimization method can be used instead of using the statistical technique.

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REFERENCES

Croccolo, D., De Agostinis, M., & Olmi, G. (2013). Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30. *Computational Materials Science*, *79*, 506–518. https://doi.org/10.1016/j.commatsci.2013.06.041

Dey, A., & Yodo, N. (2019). *A Systematic Survey of FDM Process Parameter Optimization and Their Influence on Part Characteristics*.

Durgun, I., & Ertan, R. (2014). Experimental investigation of FDM process for improvement of mechanical properties and production cost. *Rapid Prototyping Journal*, *20*(3), 228–235. https://doi.org/10.1108/RPJ-10-2012-0091

Hernandez, R., Slaughter, D., Whaley, D., Tate, J., & Asiabanpour, B. (2016). *Analyzing the Tensile, Compressive, and Flexural Properties of 3D Printed ABS P430 Plastic Based on Printing Orientation Using Fused Deposition Modeling*. 939–950.

Liu, X., Zhang, M., Li, S., Si, L., Peng, J., & Hu, Y. (2017). Mechanical property parametric appraisal of fused deposition modeling parts based on the gray Taguchi method. *International Journal of Advanced Manufacturing Technology*, *89*(5–8), 2387–2397. https://doi.org/10.1007/s00170-016-9263-3

Materials, P., & Materials, E. I. (2015). *Standard Test Method for Tensile Properties of Plastics 1*. https://doi.org/10.1520/D0638-14.1

Montero, M., Roundy, S., Odell, D., Ahn, S., & Wright, P. K. (n.d.). *Material Characterization of Fused Deposition Modeling (FDM) ABS by Designed Experiments*.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1–21.

Nazan, M. A., Ramli, F. R., & Sudin, M. N. (2017). *Process parameter optimization of 3D printer using Response Surface Method PROCESS PARAMETER OPTIMIZATION OF 3D PRINTER USING RESPONSE SURFACE METHOD*. *April*.

Panda, B. N., Bahubalendruni, M. V. A. R., & Biswal, B. B. (2014). Comparative Evaluation of Optimization Algorithms at Training of Genetic Programming for Tensile Strength Prediction of FDM Processed Part. *Procedia Materials Science, 5*, 2250–2257. https://doi.org/10.1016/j.mspro.2014.07.441

Tontowi, A. E., Ramdani, L., Erdizon, R. V, & Baroroh, D. K. (2017). *Optimization of 3D-Printer Process Parameters for Improving Quality of Polylactic Acid Printed Part*. *May*. https://doi.org/10.21817/ijet/2017/v9i2/170902044

Wu, W., Geng, P., Li, G., Zhao, D., Zhang, H., & Zhao, J. (2015). *Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS*. 5834–5846. https://doi.org/10.3390/ma8095271

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