OPTIMIZING 3D PRINTING PARAMETERS FOR BEST MECHANICAL PROPERTIES

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DECLARATION

I hereby declare that this report entitle “Optimizing 3D printing parameters for best mechanical properties” is the result of my own research except as cited in the reference. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

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Date : ………………………

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ABSTRACT

A large number of manufacturing companies are pursuing to additive manufacturing technology, since this technology is absolutely amazing for customized product. As additive manufacturing becomes widely adopted for modeling, prototyping, rapid tooling and short-run applications, the quality control become crucial to be developed in manufacturing business.

The intent of this study is to discuss the response quality characteristics control of additive manufacturing technology which subject to critical printing parameters optimization. Fused deposition modelling (FDM) is one of commonly adopted 3D printing system in manufacturing industries.

For FDM 3D printing process, layer thickness, infill pattern, extrusion temperature and print speed are the critical printing parameter considered for optimization. Five response to be considered for printing parameters studies, which is ultimate tensile strength, compressive modulus, surface roughness, dimensional accuracy and manufacturing time.

Taguchi L9 orthogonal array method is designed for optimization of printing parameters to achieve best quality characteristics of printed parts. Optimum parameters values and effectiveness of printing parameters were analysed using signal to noise ratio (S/N ratio) and analysis of variance (ANOVA). Verification experiment were be conducted to discuss the printing performance of optimum conditions.

ABSTRAK

Sebilangan besar syarikat pembuatan sedang mengikuti teknologi pembuatan menambah, kerana teknologi ini sangat menakjubkan untuk produk tersuai. Pembuatan menambah digunakan secara meluas untuk pemodelan, prototaip, perkakas cepat dan aplikasi jangka pendek, kawalan kualiti menjadi penting untuk dibangunkan dalam perniagaan perkilangan.

Tujuan kajian ini adalah untuk membincangkan ciri-ciri kawalan kualiti tindak balas bagi teknologi pembuatan tambahan yang tertakluk kepada pengoptimuman parameter percetakan kritikal. Pemodelan deposisi bercampur (FDM) adalah salah satu system pencetakan 3D yang lazim digunakan dalam industri perkilangan.

Untuk FDM 3D proses percetakan, ketebalan lapisan, corak infill, suhu penyemperitan dan kelajuan cetakan adalah parameter percetakan kritikal yang dipertimbangkan untuk pengoptimuman. Lima tindak balas yang perlu dipertimbangkan untuk kajian parameter percetakan, iaitu kekuatan tegangan muktamad, modulus mampatan, kekasaran permukaan, ketepatan dimensi dan masa pembuatan.

Kaedah orthogonal array Taguchi L9 digunakan bagi pengoptimuman parameter percetakan untuk mencapai ciri-ciri kualiti terbaik bagi bahagian bercetak. Nilai parameter optimum dan keberkesanan parameter percetakan akan dianalisis dengan isyarat kepada nisbah hingar (nisbah S/N) dan analisis varians (ANOVA). Eksperimen pengesahan telah dijalankan dan menunjukkan ralat sebanyak -% berbanding kes ideal.

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CHAPTER 1: INTRODUCTION

1.0 RESEARCH BACKGROUND

Additive manufacturing (AM) or 3D printing is officially defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". [1] A technology that enable three dimensional object being created on basis adding layer by layer.

ASTM recognises seven methods of AM, few of the most widely adopted AM technologies are fused deposition modelling (FDM), stereo-lithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), and digital light processing (DLP). A wide variety of polymers, metal alloys, composites and ceramics can be developed as the material for additive manufacturing application. Amongst these materials, polymers is the first material that widely used for prototyping. [2]

AM technology has highly exploded for the industrial use worldwide. In accordance with the Wohlers report (2013) [3], it provides a lot of information on developments and trends for additive manufacturing technology. A growth trend of industrial additive manufacturing system sales worldwide was represented graphically in Figure 1.0. A graph in Figure 1 clearly justified the trends for usage of industrial AM system have increased significantly from past to future.

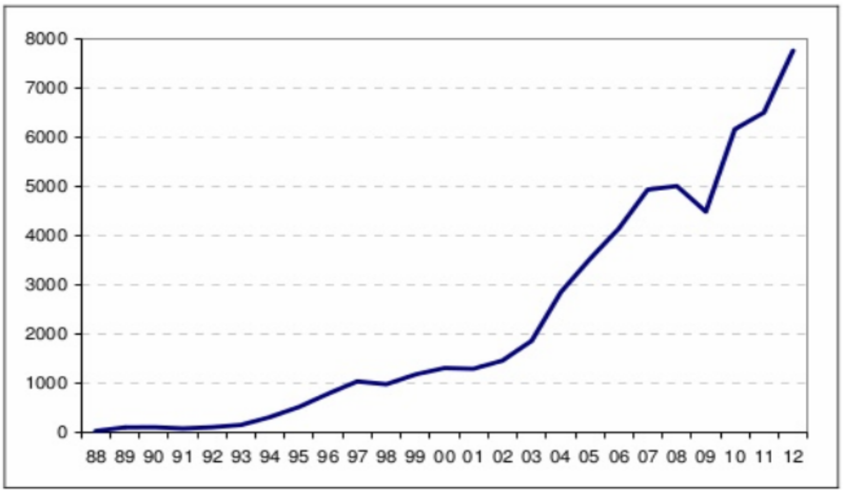


Figure 1.0. Trends of industrial additive manufacturing

The worldwide country that installed the industrial AM systems from 1988 through the end of 2012 is demonstrated in Figure 1.1. A chart is shown in Figure 1.1 to represents installation industrial AM systems of every countries in cumulative percentage. U.S. takes the majority lead of installed base which total 38%, and follow by Japan (9.7%) and Germany (9.4%) respectively. [3]

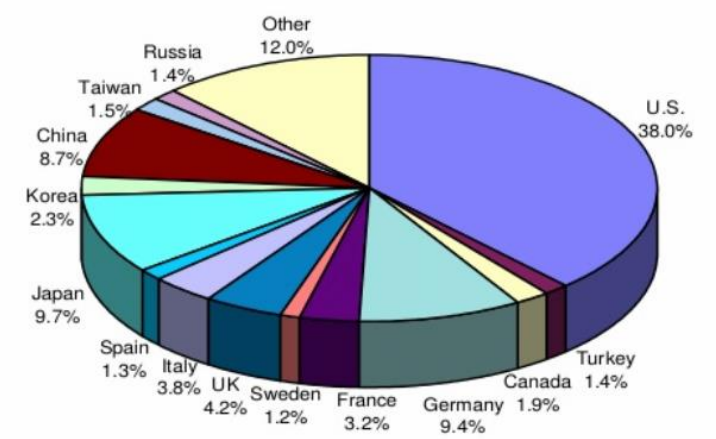


Figure 1.1. Percentage of countries installed AM systems

AM technology is becoming more interest to be used for industrial needs, since it offers many benefits. Depends on the business services, AM can be often be more productive and cost effective for small series of customized products. [4] However, conventional technology is prefer for mass production since AM has relatively slow production rate.

As additive manufacturing technology continue to thorough deeply the manufacturing industry, standardize for quality control will need to be developed. A lot of investigations on quality control in AM have been studied in past researches. Present study is intended to continue a deeper development of controlling quality for printed part with fused deposition modelling (FDM) system. Main study is to focused on the performance and quality aspect of final part, which subject to critical printing parameters.

1.1 PROJECT INTRODUCTION

3D printing is an additive manufacturing process that creates a solid three dimensional physical object by adding layer upon layer of material from a digital design [5]. Additive manufacturing technology presently is getting more innovative and advanced. Additive manufacturing technology consists of multiple applications, it is most commonly used for modeling, prototyping, rapid tooling and short-run applications.

A large number of manufacturing companies are pursuing to additive manufacturing technology, since this technology is absolutely amazing for customized product. Upon additive manufacturing technology, a product able be customized in most economical method. 3D printing is a new integrated manufacturing technology that involves a variety of disciplines, it has shown excellent potential to reduce both the cycle time and cost of product development. [5]

A variety of materials and methods adopted in additive manufacturing technology. Amongst these technologies, one of the most commonly used is fused deposition modelling (FDM). FDM is a filament-based technology where a temperature-controlled head extrudes a thermoplastic material layer by layer onto a build platform [6]. Fused deposition modelling (FDM) is a popular rapid prototyping technology largely utilised in industries to build complex geometrical efficient parts in short time.

Process parameter setting plays an important role to evaluate the quality of printed part. Process parameter is important to be studied in order to optimize a best quality characteristics to the parts developed by FDM process. Based on past studies, controlling critical printing parameters is the most common approach to achieve high quality parts. Generally, printed parts must meet some specific requirements regarding dimensions, reliability of material properties and surface quality. A high quality of printed part can be determined in terms of dimension, mechanical properties and surface quality.

Present studies focused on the influence of process parameters on the quality characteristics of the parts. Process parameter as manipulated variable can be improve based on the response characteristic of printed part. The quality characteristics of printed part to be investigate are mechanical properties, dimensional accuracy, and effect of geometry feature. Material used for printing purpose is poly-lactic acid (PLA). FDM printed part was investigated by orthogonal experimental design. Orthogonal experimental design is a powerful methods for manufacturing process optimizations that provide optimum scenarios to make the desired outcome [7]. The extent of the effects of the experimental factors on the experimental results, and the optimal levels of the experimental factors are discussed.

1.1.1 LOW COST, SELF-ASSEMBLED DIY 3D PRINTER

A low cost, self-assembled DIY 3D printer with FDM based as shown in Figure 1.2 was studied entirely for current project, which is available in CNC Machining Lab. 3D printer is a machine that allows the creation of physical object from a three-dimensional digital model by additive manufacturing process. Current market price of DIY 3D printer is cheap which cost around RM1300-RM2300 [8]. Low cost is the main reason that encourage people to study, since it enables a part being fabricated economically. However, some limitations can be detected from 3D printer. Therefore, a study of 3D printer is necessary to clarify limitations in order to prevent future people make mistake while operating the 3D printer.

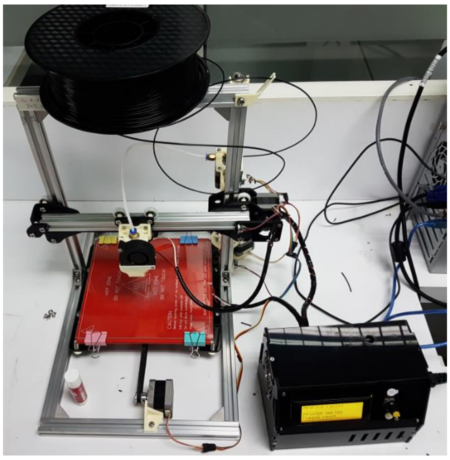


Figure 1.2. FDM based 3D printer

1.1.2 3D PRINTING FILAMENT (PLA)

Thermoplastic is raw material for 3D printer to be studied. In project, poly-lactic acid (PLA) 3D printing filament was installed for printing purpose. PLA is commonly used printing material for 3D printer. Diameter of 3D printing filament is 1.75mm and white colour. Recommended print temperature of this printing filament is within the range of 195-230℃ as shown in Figure 1.3.

Figure 1.3. PLA 3D filament

1.1.3 TAGUCHI METHODS

Taguchi design is a proficient tool or method of conducting the design of experiments which are based on well-defined guidelines. This methods involves a set of arrays called orthogonal arrays. Select an appropriate orthogonal array is critical for significance of success, criterions were provided for standard selection. Taguchi uses the following convention for naming the orthogonal arrays: $L_a (b^c)$, [9]

where

a is the number of experimental runs

b is the number of levels of each factor

c is the number of variables or levels

Taguchi methods was applied for strategy of experimental design in present studies, the fundamental is to reduce the number of experiments. It is one of the great benefits of Taguchi orthogonal array. Taguchi constructed a special set of general design guidelines for factorial experiments that cover many applications. As compared with full factorial design, all possible combinations are identified for a given set of factors. However, Taguchi methods only requires to identify small set from all the selected possibilities. Therefore, number of experiments is reduced to a certain fixed standard according to guidelines given. [9]

1.2 PROBLEM STATEMENT

Low cost, self-assembled DIY 3D printer with FDM based has limitations on the quality characteristics of printed parts. However, it enables a part being fabricated in low cost. Budget is one of the main constraint while people are processing a project. Therefore, the main objective of present studies is to optimize the critical 3D printing parameters so that enable to fabricate a high quality characteristics part economically in terms of properties, dimension, and geometry features.

1.3 SCOPE OF PROJECT

Two types of 3D printer are available in School of Mechanical Engineering, which is DIY self-assembled 3D printer with FDM based and commercial 30 Object 3D printer. There are much difference between both of the printers. As compared between the printers, the functionality of DIY-self assembled 3D printer is extremely poor. In other words, the quality characteristics of printed object is not good enough. However, DIY self-assembled 3D printer has one significance advantage which is low cost. Low investments cost, low material cost, and low fabrication cost are the main reasons that encourage people to explore DIY system for use in certain applications.

In general, present project is to deals with optimizing 3D printing parameters of DIY self-assembled 3D printer for best mechanical properties. Therefore, DIY self-assembled 3D printer can be consistently used to print an object economically with high quality characteristic in terms of properties, dimension, and geometry features. In order to complete the project systematically, it will be sub-divide into three sub-phase which is design phase, experiment phase and analysis phase.

In design phase, it mainly considered as test specimen design. Different shapes of test specimens are designed for distinct experiment purpose. All test specimens will designed in SolidWorks, a 3D modelling software (CAD) and exported as a STL file. The STL file uses a mesh of polygons to define a three-dimensional model's surfaces and retains the information in three-dimensional space which will be used by the slicing software to generate a G-code file.

In experiment phase, Taguchi orthogonal design is used as the strategy of experimentation to find cause and effect relationships with a process or system. Three experiments will be conducted to investigate the properties of test specimens which is tensile strength test, compression test, and surface roughness test. Therefore, three different design of test specimens with distinct process parameters will be printed. In details, the test specimens for surface roughness test also being used to study the dimensional accuracy. Manufacturing time for each test specimens is recorded for further analysis. Also, the effect of geometric features of each printed test specimens will be studied.

In analysis phase, five variety experimental results have to analysed which is ultimate tensile strength, compressive modulus, surface roughness, dimensional accuracy, and manufacturing time. Purpose of analysis is to verify and optimize the experimental results obtained. Since Taguchi method was adopted for experimentation, S/N ratio analysis approach is applied to analyse the experimental results. The printing parameters also were analysed using ANOVA. Minitab, an analysis data software is used to precisely analyse the overall results. Also, observation on the possible effect of geometric features of each printed test specimens is clarified carefully. As a result, a theoretical conclusion can be concluded.

1.4 RESEARCH OBJECTIVES

The research objectives of present studies are listed as following

- To study low cost, self-assembled DIY 3D printer with FDM based
- To optimize the critical printing parameters for a best quality characteristics of printed part in terms of mechanical properties, dimensional accuracy and geometric features.
- To analyse the effect of experimental factors on the experimental results using analysis software (Minitab)
- To find out an optimized printing parameters for best quality characteristics on printed part.

CHAPTER 2: LITERATURE REVIEW

Additive manufacturing (AM) is new trend of advanced technology that apply for part manufacturing. AM provided better benefits in terms of cost, manufacturing time, safety issue, quality aspect to meet the manufacturing requirements as compared to conventional subtractive manufacturing technology. Past studies have many concern closely to AM to characterize functions and capabilities for prototyping parts to meet certain defined requirements. There are wide range of researches that address the quality aspects for part manufacturing in distinct condition of 3D printing parameters. The following research will mainly focused on the quality aspects of final printed part with respect to distinct combination of 3D printing parameters.

2.0 TREND OF ADDITIVE MANUFACTURING (AM)

The use of additive manufactruing technology or 3D printing for the production of parts for final products has increased continuously from past. A growth trend of AM revenues is shown on the graph of production of part for final product in Figure 2.0 soucre from Wohlers Report 2014. [10]

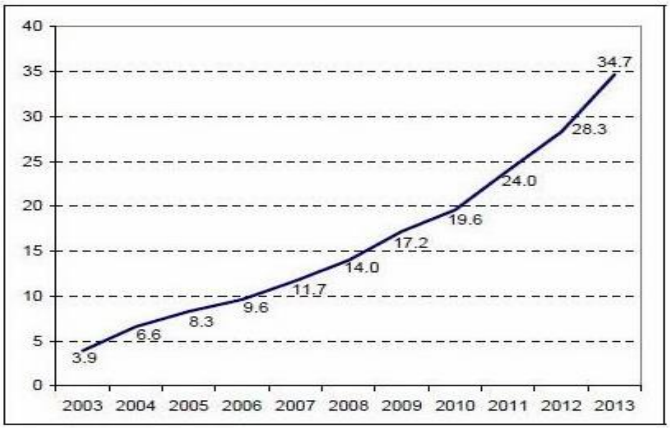


Figure 2.0. Production of part for final product

According to research of Wohlers Report 2014, it found that revenues from the production of parts for final products represents 34.7% of the entire market for additive manufacturing (AM) and 3D printing. There are a tremendously increased from year 2013 to 2014, final part production from 28.3% rose to 34.7% on 3D printing products and services worldwide.

2.1 IMPACT ON ECONOMIC AND SOCIETY

A lot of past researches have explained evidently about the profitability of additive manufacturing (AM) or 3D printing. An increased on economic scale of AM is a proof of current trending. According to Alexandru Pîrjan & Dana-Mihaela Petroşanu studies [11], the evolution of 3D printing technology is analysed in terms of applications and numerous social, economic, geopolitical, security and environmental consequences. The importance and social impact of 3D printing technology is significantly influence the human's life, the economy and modern society day to day. Impact of 3D printing will gradually increase in the future, leading to significant transformations, redefining our everyday life, economy and society. AM technology is worth to be studied since it offer many application benefits such as cost effective, manufacturing time, technique requirement, safety issues and etc.

2.2 FUSED DEPOSITION MODELLING (FDM)

Fused deposition modelling (FDM) is a filament-based technology where a temperature-controlled head extrudes a thermoplastic material layer by layer onto a build platform. A simple working principles of FDM technology is shown in Figure 2.1 from the research of Ala'aldin Alafaghania, Ala Qattawia, Buraaq Alrawia & Arturo Guzmana. [12] Fused deposition modelling (FDM) is a popular RP technology largely utilise in industries to build complex geometrical efficient parts in short time. In past, FDM largely utilised for rapid prototyping tool for visualization and validation of designs. However, the recent development of FDM is driving from rapid prototyping to rapid manufacturing. Printing parameters is important to evaluate the quality and functionality of printed part in FDM system.

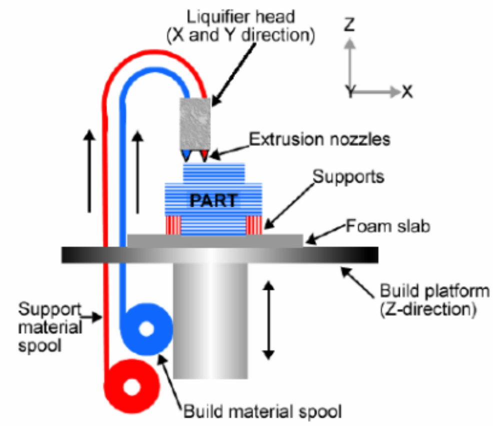


Figure 2.1. Working principles of FDM

2.3 CRITICAL PRINTING PARAMETERS

Main objective of current study is to optimize the critical 3D printing parameters for a best quality characteristics of part printed in terms of mechanical properties and dimensional accuracy by fused deposition modelling (FDM) process. For FDM technology, the quality aspects of final product is affected by printing parameters based on the research of Tomasz Koziora & Czesław Kunderaa (2017). [13] Optimal printing parameters is important for quality management and quality control of printed part. Different setting of printing parameters will cause the deviation of quality aspect of printed part. Printing parameters may need modify to obtain a best selected quality with respect to specific defined requirements. The following are some of the critical printing parameters of FDM based system from past studies:

- Layer thickness
- Raster angle
- Print speed
- Nozzle and platen temperature
- Cooling fan speed
- Infill densities and patterns

2.4 METHODS PROPOSED FOR PARAMETRIC OPTIMIZATION

In order to optimize printing parameters, it is requires a powerful tool. Taguchi orthogonal array method is one of the powerful tool that majority to been selected for optimization purpose. Realized that Taguchi orthogonal array have been applied in numerous past studies for optimize parameters. Therefore, it proved the reliability and accurateness of particular tool. In accordance to the Sorana D. Bolboaca & Lorentz Jantschi (2007) research, [14] the aims of Taguchi orthogonal array is to minimize the number of experimental runs while maintaining the preciseness. Orthogonal design is depend on number of factors with different levels, then estimated for the smallest number of experimental runs. Proper selection of printing parameters is the core for present study.

2.5 CRITICAL PRINTING PARAMETERS SELECTION

In order to produce a good quality part from FDM printing system, it is desired for proper control of printing parameters. Found that there are many studies investigated on printing parameters, to understand the influence on mechanical properties, accuracy and performance of printed part resulted from the distinct setting of printing parameters.

For example, one study focused on three type of printing parameters were studied from C K Basavaraj & M Vishwas research [15], which is layer thickness, orientation angle, and shell thickness. Printing process FDM system is utilised to produce the test samples for examine the performance on ultimate tensile strength, dimensional accuracy and manufacturing time. The material used for the studies of process parameter is Nylon, and Taguchi L_9 orthogonal array is used for determined the experimental runs. Based on the analysis result from S/N ratio and ANOVA, it shown that layer thickness is most significance influence on the printing performance. Each contributed 82.25%, 86.11% and 82.06% respectively on ultimate tensile strength, dimensional accuracy, and manufacturing time. Therefore, it is important to examine layer thickness in present study.

Realized that both of the shell thickness and orientation angle are not essential according to the analysed results, since it only varied rarely on quality of printed part. Also, shell thickness selection is normally based on manufacturing requirements. It is often changes due to the dynamic requirements. In regular principles, tensile strength and manufacturing time will increased as shell thickness increased since the wall become thicker. As a result, shell thickness and raster angle are not very important to investigate.

For additional message on mechanical properties, a study from Vijay.B.Nidagundia, R.Keshavamurthy & C.P.S.Prakash [16] that related to ultimate tensile strength, surface roughness, dimensional accuracy and manufacturing time were considered. Printing parameters of layer thickness, orientation angle, and fill angle are studied for determine the performance of FDM printed part. From this study, it proved that layer thickness is the most critical printing parameter. That is because it has most significance effect on performance of printed part from the analysed result from S/N ratio and ANOVA. Also, realized that major researches are involving layer thickness test. Therefore, I decided to justify the result obtained from research and also study with other printing. CAD model is normally design uniformly, it is impossible or rarely to fabricate a part in uneven angle in printing system. Therefore, I realized that orientation angle is not proper in real situation.

Surface roughness is critical to define quality characteristic of printed part, it provides appearance and situation of surface texture. According Ognjan Lužanin, Dejan Movrin and Miroslav Plančak research [17], extrusion speed and extrusion temperature are two printing parameters have greatest impact on the surface quality of FDM-built parts. Similarly, the test samples were printed through FDM printing system. PLA was used as material to been studied. Extrusion speed and extrusion temperature are the controllable parameters to examine the surface roughness of printed parts, while other critical parameters are fixed parameters. This study mainly investigated on effect to surface roughness of printed parts, also arithmetic average of the roughness profile (Ra) is considered as the surface parameters units. The result indicated that the extrusion speed is highly affected the surface quality of printed part which contributed approximately 91.69%. Found that there are also other critical printing parameters will affecting on surface roughness.

Another study of Nor Aiman Sukindar, Mohd Kharul Anuar, Mohd Ariffin, B.T Hang Tuah Baharudin, Che Nor Aiza Jaafar and Mohd Idris Shah Ismail (2017) [18] investigated on the surface quality with similar FDM printing system and material used.

Focused on surface quality of part that control by layer height, raster angle, extruder temperature, printing speed, and percent infill. The analysed result indicated that raster angle, extruder temperature, and layer thickness are the most influential process parameters of the surface quality of the final product. It shown a different results between previous studies. As a conclusion, a relevant investigation have been carried out in present study in order to verify the result.

2.6 EFFECT ON GEOMETRY FEATURES

Effect on geometry features is important rather than mechanical properties and surface roughness. Realized that not every setting of printing parameters will provide the proper standard shape and size. Improper printing parameters may cause the deviation of shape and size of final printed part. According Alvaro Goyanes, Pamela Robles Martineza, Asma Buanz, Abdul W. Basit, Simon Gaisford research [19], it indicated the existence of effect on different shape and geometry to be produced even the setting of printing parameters are similar.

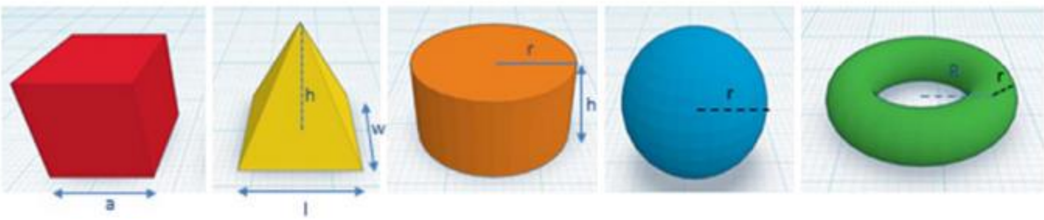


Figure 2.2. 3D geometric shape

Samples with different geometries (cube, pyramid, cylinder, sphere and torus) are printed as shown in Figure 2.2 to been studied. Result shown that it is no dependence on the surface area but rather on surface are to volume ratio. A variation in terms of surface area, surface area/volume ratio and weight respectively are determined.

Build orientation is one of the important printing parameter to be considered for test sample calibration. In order to have a verified study, proper build orientation is necessary. Different build orientation (X, Y, Z) will significant influence the outer and inner geometry features of printed part based on the study of J.M. Chacóna, M.A. Caminerob, E. García-Plazab, P.J. Núñezb [20]. As shown in Figure 2.3, it found that flaws are happened in all the three parts. However, all parts are faced different flaws.

Therefore, realized that build orientation is very sensitive to geometrical feature. In order to study on geometrical feature properly, it is needed to ensure the build orientation of all test samples are similar.

Figure 2.3. Part printed from X, Y and Z build orientation

CHAPTER 3: METHODOLOGY

This project consists of three main phases, which is design phase, experiment phase and analysis phase. The following methodology will cover all details of such phases, such as procedure, sample type and size, design of experiment and data analysis techniques applied within the experimentation.

3.0 PROCEDURE

The order of sequence of project is followed as analysis phase, experiment phase, and analysis phase. Multiple steps are required to satisfy the conditions within the phases for project accomplishment. A workflow for the overall project’ steps was sketched as shown in Figure 3.0 to illustrate every sections to be covered. Firstly, test specimens were designed using CAD software. The 3D models were then processed through slicing software. After slicing process, test specimens were printed out. Geometric features of test specimens were observed and then tested for several experiments. Data obtained from each experiment was collected, and then analyse the data. Summary of the following steps will be discussed as following:

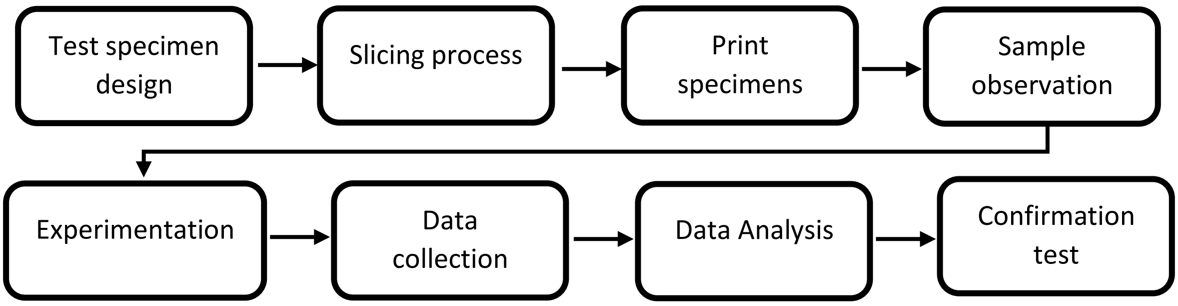


Figure 3.0 Workflow of project procedures

1) Test specimen design

Total three kinds of specimen are needed in present studies, each specimen will used for different experiment. All test specimens were designed using 3D CAD software, SolidWorks. There are tensile specimen, cylinder specimen and cube specimen for tensile test, compression test, surface roughness test and dimensional accuracy study individually. In order for slicing process, 3D model is required to export as a STL file. The STL file uses a mesh of polygons to describe the surface geometry of a three-dimensional model without any representation of colour, texture or other common model attributes. The geometric information will retains in three-dimensional space which will be used by the slicing software to generate a G-code file. [21]

2) Slicing process

An open source slicing software, named "Repetier Host" is used as the 3D model slicing software that compatible with 3D printer. 3D model of each test specimen was sliced into layers and coded into the G-code file language using open source slicing software. The slicing software takes a STL file and slices the 3D model into layers which will be printed from the bottom layer to the top layer. The G-code will generate automatically through the layer slicing process for 3D model. G-code is the coding that widely used to control machines by computer for manufacturing purpose. The basic coordinates of X, Y, and Z is used to define the position of model which provide information for tool movement in G-code. [21] Therefore, 3D printer uses to print the physical piece layer by layer comply with G-code.

3) Printing

A low cost, self-assembled 3D printer with FDM based is used for specimens printing. All test specimens were extruded layer by layer onto a build platform. Poly-lactic acid (PLA) thermoplastic printing filaments is the material used for the 3D printer. The main concern for printing is the calibration of Z-axis offset, it is necessary to ensure that extruding nozzle is contact ideally with build platform at the first moment. In addition, the estimated manufacturing time of each specimen that simulated from slicing software was recorded for study.

4) Sample observation

All printed test specimens were observed comprehensively with sight (naked eyes) and touch senses. Geometric features is the topic to be studied in observation, it is important since it defines the appearance of printed test specimens. It act as flaw detection, the purpose is to detect any flaw, uneven and discontinuity of printed test specimens.

5) Experimentation

After observation, all the test specimens were prepared for experimentation. Total four experiments to be carry out, which is tensile test, compression test, surface roughness test and dimensional accuracy test. A 3300 series dual column universal testing systems, named “Instron 3367” was used for the tensile test and compression test. Tensile rate of 1mm/min was set up for tensile specimens, whereas compress rate of 0.05in/min for cylinder specimens. Surface roughness tester, MITUTOYO SV 400 is used for surface roughness test. Each cube specimen was measured the surface roughness in terms of different faces. For dimensional accuracy, a digital calliper is the tool that used for measurement. Dimension of X, Y and Z axes (length, width and height) was measured for volume calculation.

6) Data collection

For tensile test, all the associated tensile properties of each tensile specimen was computed from universal testing systems. These simulated tensile properties are maximum load, young’s modulus, maximum extension, maximum tensile stress, maximum tensile strain, true tensile strain and true tensile stress. Maximum tensile stress or ultimate tensile strength (UTS) was selected for final analysis. Similar case for compression test, the simulated compressive properties are maximum load, young’s modulus, maximum extension, maximum compressive stress and maximum compressive strain. However, the young’s modulus or compressive modulus was selected for optimization analysis. For surface roughness, surface roughness of four distinct faces for each cube specimen was measured. In addition, each face was measured in both directions of vertical and horizontal, while the mean of two directions was considered for optimization. For dimensional accuracy, dimension of X, Y and Z axes (length, width and height) of each cube specimen was measured for volume calculation and optimization purpose.

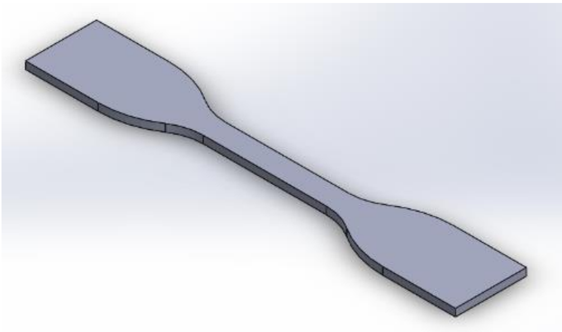
7) Data analysis

Taguchi L9 orthogonal array was selected as the standard for process optimization purpose. The response variables are including ultimate tensile strength, compressive modulus, R_a surface roughness, total volume and manufacturing time. Two approaches were performed to analyze all the response variables to be study, which are signal to noise ratio (S/N ratio) approach and analysis of variance (ANOVA) approach. Taguchi method emphasizes the importance of studying the response variation using the signal to noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter (noise factor). Analysis of variance (ANOVA) implies the significance of each process parameter contributed to response variable. Therefore, optimization of process parameters can be concluded reasonably corresponding to the analysed result.

3.1 SAMPLE TYPE AND SIZE

All the test specimens were designed by using 3D CAD software, SolidWorks. Total three different kinds of test specimen to be designed for carry out each experiment respectively. For all the response variables, a sample of printed test specimens from FDM based 3D printer was examined individually. According to Taguchi L_9 (3^4) orthogonal array, the sample size needed for each experiment is 9 printed test specimens. Each of the 9 printed specimens for each experiment utilized own combination set of printing parameters individually with varying levels for each parameter. The details of each test specimen corresponding to the specific experiment was discussed in Table 3.0.

Table 3.0. Details of test specimens

Tensile test
Tensile test is performed as per ASTM D638, standard test method for tensile properties of plastics. ASTM D638 Type I specimen was selected as the standard for all tensile test specimens, this standard is most commonly used and highly recommended. [22] The test specimen was drawn by SolidWorks as shown in Figure 3.1, and the detail is provided as a CAD drawing in Appendix A.  **Figure 3.1** Tensile test specimen CAD model **Sample size**: 9
Compression test
Compression test is performed as per ASTM D695, standard test method for compressive properties of rigid plastics. Test specimen can either be cylinders and prisms of standardized dimensions. Cylinders was selected as standard for particular

test, and the dimensions are 12.7mm (½ in) in diameter and 25.4mm (1 in) height. [23] Cylinder was drawn by SolidWorks as shown in Figure 3.2, and the detail is provided as a CAD drawing in Appendix B.

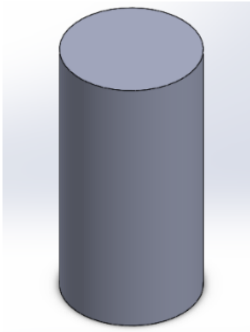


Figure 3.2. Cylinder test specimen CAD model

Sample size: 9

Surface roughness test & Dimensional accuracy test

For surface roughness, cube specimen with dimensions of 10mm×10mm×10m was designed by SolidWorks as shown in Figure 3.3. Surface roughness value, R_a in both vertical and horizontal directions will be measured for study.

For dimensional accuracy, dimensions of X, Y and Z axes (length, width and height) of cube specimen was measured for volume calculation. Calculated volume will be recorded for study.

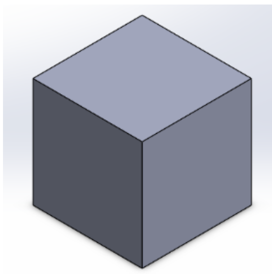


Figure 3.3. Cube shape test specimen CAD model

Sample size: 9

3.2 DESIGN OF EXPERIMENT

Taguchi method is a structured approach for determining the optimize combination of control variables corresponding to response variables. Taguchi methods involve the interrelation between experiment design theory and quality loss function concept for technical problem solving. [7] Taguchi method is widely used in many manufacturing plants for process control. Taguchi has to develop a method based on "orthogonal array" experiments which aim to reduce the number of trials in experiment for optimizing the control parameters. Orthogonal array is determined by total degree of freedom, the degrees of freedom for four parameters in each of three levels were calculated as follows: [7]

Degree of Freedom (DOF) = number of levels -1

For each factor, calculated DOF is:

For layer thickness (mm)	DOF = 3 – 1 = 2
For infill pattern	DOF = 3 – 1 = 2
For extrusion temperature (°C)	DOF = 3 – 1 = 2
Print speed (mm/s)	DOF = 3 – 1 = 2

Total degree of freedom (DOF) = 1 + (number of factors × (number of levels -1))

Calculation of total DOF is:

Total degree of freedom (DOF) = 1 + (4 × (3 -1)) = 9

Two requirements must be fulfil for orthogonal array selection, which is

- Total number of runs for experiment in orthogonal design ≥ total DOF
- Selected orthogonal array should be able to accommodate the factor level combinations in the experiment

According to the calculated total degree of freedom, thus L_9 (3^4) orthogonal array is selected to well study all the critical printing parameters that will affect the outcome significantly. L_9 of orthogonal array means the array (number of trials) requires 9 runs for one specific experimental outcome. Whereas, (3^4) indicates that the experiment design consists of 4 main critical factors (process parameters) at 3 levels for each factor. The printing parameters involved and their levels to be studied is tabulated in Table 3.1. The details of L_9 (3^4) orthogonal array for the project is tabulated as shown in Table 3.2.

Table 3.1. 3D Printing Process Parameters

Process Parameters	**Levels**		
	1	**2**	**3**
Layer thickness (mm)	0.1	0.2	0.3
Infill pattern	Line	Concentric	Honeycomb
Extrusion temperature (°C)	185	192	200
Print speed (mm/s)	40	45	50

Table 3.2. $L_9\,(3^4)$ Orthogonal Array for Experimental Performance

Experiment	**Printing parameters**				**Performance Parameter values**
	Layer thickness	**Infill pattern**	**Extrusion temperature**	**Print speed**	
1	1	1	1	1	P1
2	1	2	2	2	P2
3	1	3	3	3	P3
4	2	1	2	3	P4
5	2	2	3	1	P5
6	2	3	1	2	P6
7	3	1	3	2	P7
8	3	2	1	3	P8
9	3	3	2	1	P9

Purpose of the experiments is to obtain the performance parameter values that resulted from each respective experimental outcome. Mechanical properties (tensile strength and compressive modulus), dimensional accuracy, and surface roughness in terms of respective process parameter will be experimented. In addition, the manufacturing time to print the test specimens is including for further studied. In this study, four critical process parameters were layer thickness, infill pattern, extrusion temperature and print speed. Response variables were ultimate tensile strength, compressive modulus, surface roughness, dimensional accuracy and manufacturing time. A metrics as shown in Figure 3.4 is illustrated to show information graphically. The equipment and test specimen used for each experiment was discussed in Table 3.3 for more information.

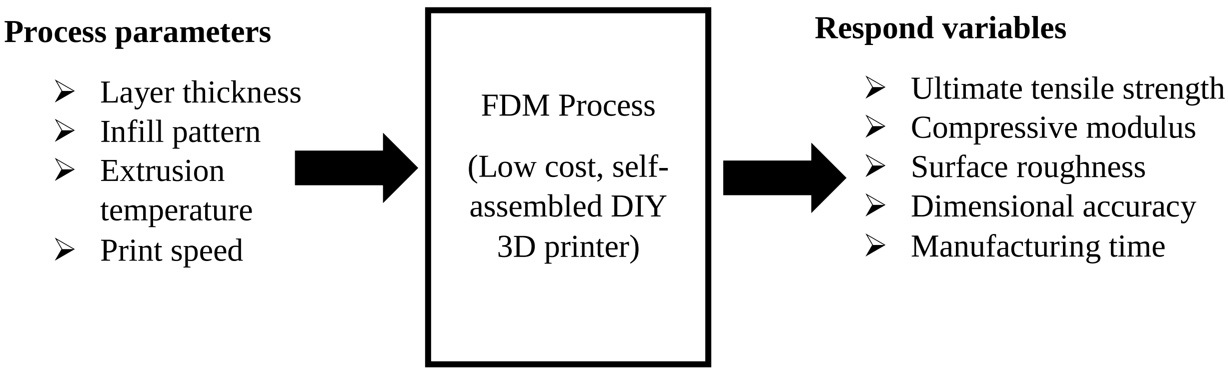


Figure 3.4. Metrics of experiment

3.3 DATA ANALYSIS

In analysis phase, a statistical analysis software called "Minitab" is used for data analysis. Two approaches are performed to analyze the data of each experimental results, which is signal to noise ratio (S/N ratio) and analysis of variance (ANOVA).

Signal to noise ratio (S/N ratio)

Signal-to-noise ratio is defined as the ratio of the strength of a power signal to its background noise, mostly expressed as unit of decibels (dB). Higher numbers generally mean a better desired result in case, since it means that the useful data (signal) is beyond the unwanted data (noise).

$$\text{S/R ratio} = \frac{P(Signal)}{P(Noise)}$$

However, Professor Taguchi does not give a formal definition and rules of S/N ratio. Professor Taguchi serve the notion of signal to noise ratio (S/N ratio) as a concept for parametric optimization which aim to reducing the variability of the functional performance of a outcome by the best setting of the related parameters. [24] Research shown that a Taguchi method is resulted from the marriage of design of experiment (DOE) with optimization of control parameters to obtain best setting of parameters. [24] Professor Taguchi's signal-to-noise ratios (S/N ratio), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

Taguchi method emphasizes the importance of studying the response variation using the signal to noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter (noise factor). In "Minitab" software, signal to noise (S/N) ratio is calculated separately for each combination of control factor levels in the design. S/N ratio is characterized into four categories: Two kind of nominal is the best, smaller is better and larger is better. [25]

Larger is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the larger-is-better S/N ratio using base 10 log is:

$$S/N = -10 \times \log (\Sigma(1/Y^2)/n)$$

where
Y = responses for the given factor level combination
n = number of responses in the factor level combination.

Smaller is better
The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the smaller-is-better S/N ratio using base 10 log is:

$$S/N = -10 \times \log (\Sigma(Y^2)/n)$$

where
Y = responses for the given factor level combination
n = number of responses in the factor level combination.

Nominal is best (I)
The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the nominal-is-best (I) S/N ratio using base 10 log is:

$$S/N = -10 \times \log (s^2)$$

where
s = standard deviation of the responses for all noise factors for the given factor level combination.

Nominal is best (II)
The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the nominal-is-best (II) S/N ratio using base 10 log is:

$$S/N = 10 \times \log (\bar{Y}^2/s^2)$$

Adjusted formula also provided for the nominal-is-best S/N ratio. The formula is:

$$S/N = 10 \times \log ((\bar{Y}^2\text{-}s^2/n)/s^2)$$

where
$\bar{Y}$ = mean of responses for the given factor level combination
s = standard deviation of the responses for the given factor level combination.
n = number of responses in the factor level combination.

Analysis of variance (ANOVA)

ANOVA assess the importance of one or more factors by comparing the response variable means at the different factor levels. Analysis of variance (ANOVA) is a statistical models used to analyse the differences between group means. ANOVA test is perform commonly to find out hypothesis whether the experiment results obtained are significant. Two hypothesis will concluded in ANOVA test, which are null hypothesis states that all population means (factor level means) are equal while the alternative hypothesis states that at least one is different. [26]

In such analysis phase, analysis of variance (ANOVA) is used to evaluate differences in the average performance. Also, it helps testing the significance of all main factors (control parameters) which can be easily understand from the percentage of contribution of each parameter. Statistically, there is also a tool called "F test" to study which design parameters have a significant effect on the quality characteristic. [27] It is traditionally used to determine the significance of a factor. While P-value defines the significance rate of the process parameters on the experimental outcome.

There are several steps required to accomplish an ANOVA test. The basic property of ANOVA is regarding to degrees of freedom (DOF), sum of squares (SS) and variance or mean squares (MS), F-ratio and P-value. The basic formulas of ANOVA are: [26]

Degree of freedom (DOF)

- $DOF_{(Factor)} = k - 1$ ……………..……..….(1)
- $DOF_{(Error)} = N - k$ ……………………...(2)
- $DOF_{(Total)} = DOF_{(Factor)} + DOF_{(Error)}$ ……(3)

Where
k = number of factor levels
N = Total number of scores

Sum of squares (SS)

- $SS_{(Total)} = \sum_i^k (x_i - \bar{\bar{x}})^2$…………………………………………..……(4)
- $SS_{(Error)} = \sum_1 (x_{i1} - \overline{x_1})^2 + \sum_2 (x_{i2} - \overline{x_2})^2 + \ldots + \sum_k (x_{ik} - \overline{x_k})^2$ ……(5)
- $SS_{(Factor)} = SS_{(Total)} - SS_{(Error)}$ …………………………………………...(6)

$$\bar{\bar{x}} = \frac{G}{N}$$

where
k = number of conditions
x_i = mean score for each (i^th^) condition
$\bar{\bar{x}}$ = grand mean.
G = Grand total of scores
N = Total number of scores
x_{i1} = the score of the i^th^ subject in group 1
x_{i2} = the score of the i^th^ subject in group 2
x_{ik} = the score of the i^th^ subject in group k.

Variance or mean squares (MS)

- $MS_{(Factor)} = SS_{(Factor)} / DOF_{(Factor)}$ ……(7)
- $MS_{(Error)} = SS_{(Error)} / DOF_{(Error)}$ ………(8)

F-ratio

$$F = MS_{(Factor)} / MS_{(Error)} \quad \ldots\ldots(10)$$