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Investigation on Influence of Infill Pattern and Layer Thickness on Mechanical Strength of PLA Material in 3D Printing Technology

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Abstract: This report is influencing infill density and layer thickness on mechanical strength of Poly-lactic Acid (PLA) material in three-dimensional printing machine. According to use Additive Manufacturing technology in PLA material used Fused Deposition Modeling (FDM) technique. In this project, nine samples are tested for different infill pattern (Zig zag, Triangles & Grid) and different layer thickness (0.2, 0.1 & 0.15) mm by using Taguchi Method. Here we demonstrate an empirical method utilizing a statistical design of experiment technique and standardized mechanical testing which ultimately exposes trends and variable interactions specific to our selected additive manufacturing process. We collect data then converted to stress and strain values in order to construct stress vs. strain diagram and try to use a few basic formulas, mechanical properties such as modulus, yield stress, ultimate tensile stress, and percent elongation were able to be determined for each geometrical infill density and thickness layers. The results for each sample were then compared and made design of experiments (DoE) for research best design and quality. A computer simulation like NX was also done in order to reflect on the predictability of the printed specimen's performance. The aim of doing this report is how to operate 3D printing and use relevant application such as NX, Cura Software, Weka, Minitab, MATLAB and implementation of tensile strength for our samples.

Key words: *Additive Manufacture Technology, Fused Deposition Modeling, three-dimensional printing, Tensile Strength, Infill density percentage, Layer thickness layers, Poly-lactic Acid, Design of Experiments.*

Introduction

Our world is changing with new technologies in every second. "Complexity is free" is a phrase often used when discussing additive manufacturing (AM), which allows for almost any geometric form to be fabricated. Traditional manufacturing methods impose several limitations to the geometry of a part, especially when balancing fabrication technique and cost. This burden of free complexity can be very costly when performing design for manufacture (DFM), where the intended manufacturing method is AM. Three-dimensional (3D) printing is getting important in product development sector for industry manufacturing. By using 3D printing, able to produce complex prototype products with advance functions/ parameters like variety of printer speed, temperature, infill pattern and so on.

We reviewed some related research papers for our project. In the literatures, there were several studies investigating such as Ref: [1], and it gives us to understand how to approach the main points by using methods and tools. The research paper which is Reference [2], the next one is Reference [3] and fourth paper is Reference [4], they got us know why the infill design and how infill parameters effected on mechanical strength. The last one is Reference [5] and it gave us how layer thickness is influence on property of PLA including mechanical strength of it. These studies are simple in scope, as they do not examine the interaction or non-linearity with different build parameters (e.g. layer thickness vs. infill pattern), nor do they apply statistical methods to determine treatments that will

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efficiently explore the design space to better understand relationships between parameters and mechanical properties. Instead, these studies investigate the mechanical properties' dependence on infill shapes, infill parameters, infill design of the printed products, and by using the different layer thickness in the design process. It is possible to favor properties such as tensile strength or ductility.

This paper investigates the effect of two primary printing parameters on tensile properties of 3D printed poly-lactic acid (PLA): layer thickness and infill pattern, on several mechanical properties including strength, stiffness, and ductility. The goal of this investigation is to examine both the individual effects of the printing parameters on the mechanical properties, as well as the coupled or interactive effects. A design of experiments approach with two factors was employed to explore and examine relationships between the printing parameters and standardized mechanical testing results.

We used some methods and tools to analyze the results. Taguchi method was used to make the testing experiments of the product qualities and development of designs for studying variations by using Minitab tool. Tensile testing method was used to test the results of PLA strength depending on the different parameters. Then, in order to make regression we will use Weka software to find the solutions. Furthermore, we will get the equation from making regression. We will use ANNOVA tool to support other statistical tools meanwhile MATLAB tool will be used to make optimization. Finally, we will find the final solution of our problem.

2. Experiments

2.1 Experimental Set Up

2.1.1 Sample Design

It is necessary to know the properties of the material used in order to anticipate its behavior and to prevent breakage whenever making the product design. In material science and engineering field , the most commonly used for testing are tensile testing which also known as tension testing to measure the technical properties such as ultimate tensile strength, breaking strength, maximum elongation and reduction in area .From the these results , yield strength, and strain-hardening characteristics can be determined.

The following recommendations of the standards sample design for the specimen is used to perform the tensile test.

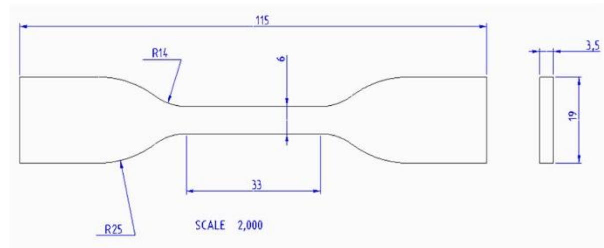


Figure (2.1) Sample diagram of specimen

Distance between grips = 65 mm
Gage length = 25 mm
NX design -- > STL file

These test specimens have two shoulders and a gage (section) in between. The shoulders are large so they can be readily gripped and the distance between two gripped shoulders are 65 mm, whereas the gauge section has a smaller cross-section with the length of 25 mm so that the deformation and failure can occur in this area.

2.1.2 Material Properties

Contents of the journal in 3D printing variety of materials can be available, such as ABS and PLA plastics, glass filled polyamide, stereo lithography materials (epoxy resins), polyamide (nylon), silver, titanium, steel, wax, photopolymers and polycarbonate. Among them Acrylonitrile Butadiene Styrene **(**ABS**)** and Polylactic acid (PLA) are most popular printing materials.

Both of ABS and PLA are thermoplastic and they become soft and moldable state when heated and then return to the solid state when it is cooled by room temperature. Both of them are best material for FMD process by building up the layer to create the good finish final parts. The table below shows the comparison between main material properties of ABS and PLA.

Table (2.1) ABS and PLA material properties comparison

Properties*	ABS	PLA
Tensile Strength**	27 MPa	37 MPa
Elongation	3.5 - 50%	6%
Flexural Modulus	2.1 - 7.6 GPa	4 GPa
Density	1.0 - 1.4 g/cm^3	1.3 g/cm^3
Melting Point	N/A (amorphous)	173 °C
Biodegradable	No	Yes, under the correct conditions
Glass Transition Temperature	105 °C	60 °C
Common Products	LEGO, electronic housings	Cups, plastic bags, cutlery

I. Part accuracy

Generally, the tolerances and accuracy of FDM printed components are mostly dependent upon printer calibration and model designs. However, ABS and PLA can be used to produce dimensionally accurate parts with good finished surface.

Due to its lower printing temperature, PLA, when properly cooled, is less likely to deviate (making it easier to print with) and can print sharper corners and features compared to ABS.

II. Strength

With similar tensile strengths, ABS and PLA are both adequate for many prototyping applications. ABSs have a higher flexural strength and better elongation before breaking, whereas PLA remains popular for rapid prototyping when form is more tensile strength than ABS.

III. Surface finish and post processing

For both ABS and PLA, the print layers will be visible after printing through FDM process. ABS typically print in a matte surface while PLA is semi-transparent, often resulting in a polish finish surface.

IV. Temperature

PLA is easy to use in 3D printer has a melting temperature of around 190-210 degree Celsius so it can easily be melted also it cools faster.

V. Biodegradability

PLA is stable in general room temperature conditions and will biodegrade within 50 days in industrial composters and 48 months in water. ABS is not biodegradable; however, it is recyclable. PLA is regularly used to produce food related items.

Overall, PLA is great for experimentation and is just another reason for its material properties to use in our FDM process.

2.1.3 Process to Experiments (phase one)

The graph below shows the process flow of the experiment.

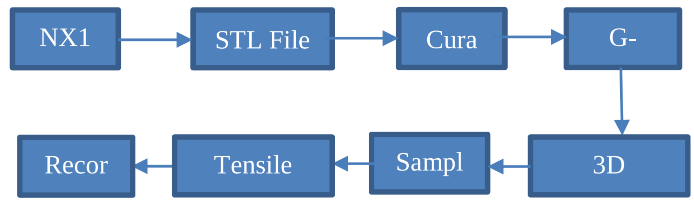


Diagram (2.1) Flow Chart of Experiment

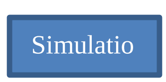
1. At the very beginning of the phase one, the standard sample design of the specimen is drawn in NX CAD modeling software.
2. This drawing is exported as STL file.
3. In Cura software we run this STL file and define the parameters such as temperature, layer thickness, pattern and so on.
4. Then change this into G-code to produce the real sample in 3D printer.
5. Produce the sample specimen in 3D printer
6. Placed them into tensile test machine and do experiments and record it.

2.1.4 Process to Experiments (phase two)

In this phase two the results data from the tensile testing have to analyze, optimize and simulate by specified tools.

The experimental results data is analyzed by Weka, Taguchi and excel to get the Influence factors and regression function.

Optimization with MATLAB and excel to get the optimized number.



Numerical simulation and actual simulation which are to validate the result from optimized values.

2.1.5 Preparation

In preparation process for this project, applied two software which are NX 10 for design products and Cura for parameter selection. Followed to our design then drew in NX 10 then convert .stl file to input data into Cura software. The following figures are the three different patterns when we run simulation in Cura.

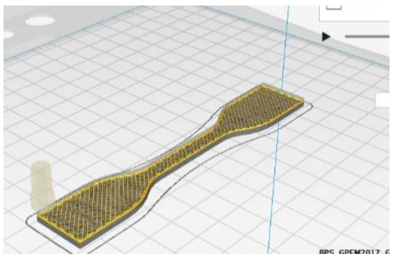


Figure (2.2) ZigZag Pattern in Simulation

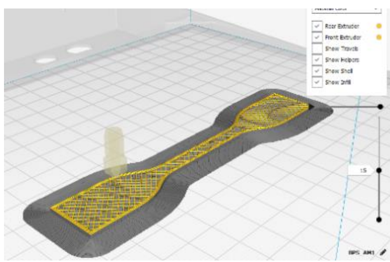


Figure (2.3) Grid Pattern in Simulation

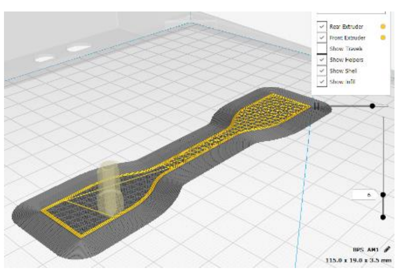


Figure (2.4) Triangle Pattern in Simulation

2.1.6 Printing

After designed of our samples in NX 10 & Cura, need to print out in Fused Deposition Modelling (FDM) 3D printing machine. In GPEM lab had five Builder 3D printing machines. In these machines can print two type of plastic material which are ABS and PLA. But in our product used PLA to build samples as mentioned before. The detail information for these printing machines are as per below.

- Print Technology : FDM
- Build volume : 220 (L) x 210 (B) x 164 (H) mm
- Printer Dimension : 385 (L) x 370(B) x 400(H) mm
- Weight : 15kg
- Print speed : 10~80 mm/s
- Nozzle diameter : 0.4 mm
- Operating Temperature for nozzle : 180~250’C
- Power : 12 W

Using by these 3D printing machine then put some parameter for our samples. Need to fit following parameters in Cura software to make the G-code for the printing in 3D printing machine.

Parameter	Value	Unit
Printing speed	50	mm/sec
Infill density	30	%
Printing Temperature	215	Degree Celsius
Shell wall thickness	0.8	mm
Printing location	Center	-
Orientation Angle	0	Degree

Table (2.2) Fixing parameters

According to our project requirements, kept two factors that are “Infill pattern” and “Layer thickness” then other parameters are changed with three levels. For infill pattern, choice three types of pattern which are Zigzag, Grid and Triangle. For more details can see in the following table.

Sample number	Infill Pattern	Layer Thickness (mm)	Time (min)	Length (mm)	Weight (g)
1	Zigzag	0.20	26	1.57	5
2	Zigzag	0.15	29	1.43	4
3	Zigzag	0.10	36	1.31	4
4	Grid	0.20	26	1.54	5
5	Grid	0.15	29	1.40	4
6	Grid	0.10	36	1.28	4
7	Triangle	0.20	26	1.54	5
8	Triangle	0.15	29	1.39	4
9	Triangle	0.10	37	1.27	4

Table(2.3) Experiments of Printing

Based on these data made three batches for experiments. Each batch had nine samples so total is twenty seven samples for print. Following figures are the real printing samples with three different pattern.

Pattern#1
(ZigZag)

Figure (2.5) ZigZag Pattern in Reality Printing

Pattern#2
(Grid)

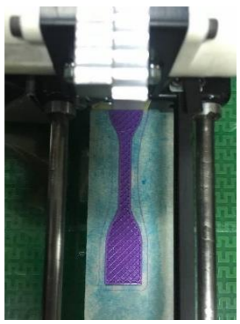


Figure (2.6) Grid Pattern in Real Printing

Pattern#3
(Triangle)

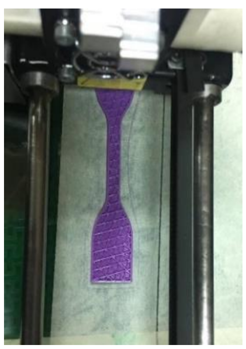


Figure (2.7) Triangle Pattern in Real Printing

During printing process faced little challenge for our group. For example, unfamilier with printing machine, lack of preparation, gcode files unreadable, machine's minor problem and so on. Following photo is record for failure samples durin our printin process.

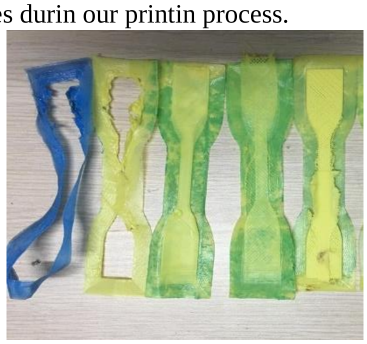


Figure (2.8) Some Failure Samples

After finished printing all samples, made marking and prepare with calibration tools to check dimensions and thickness then move to tensile testing process.

2.1.7 Testing

In GPEM lab can test SHIMADZU tensile test machine which is made in Japan with TRAPEZIUM X software. These machines can determine tensile, compression, flexural (bending), peel, shear, tear and seal strength for various material using relevant ASTM and ISO methods. And can select manual adjustment for position of tools. In our case want to test tensile with different pattern and layer thickness. Before testing need to set up basic data in the software as per below information.

Machine Name : **Shimadzu**	
Apply Software :**Trapezium X**	
Test Mode	Tension
Test Speed	1.5 mm/min
Max: Force	1000N
Min: Force	5N
Unit	SI
Specimen	Plastic, Plate
Testing direction	Up

Table(2.4) Information of Tension Machine

Our testing process divided by three batches each batch had nine samples. We did dimension measurements like width, thickness and gauge height of samples with calibration tool before testing. When finished input data, have to calibrate between machine and software in zero force and positions. Before starting the testing, we need to check samples depositions are fix or not and also need to tight with tools.

Figure (2.9) Tension Testing Machine in GPEM Lab

After testing with machine, export data with PDF and excel file into computer then can compare results for further experimental processes.

2.2 Design Experiments

2.2.1 Taguchi Method

Taguchi method is a well-known technique that provides a systematic and efficient methodology for process optimization and this is a powerful tool for the design of high-quality systems. Besides, this is an engineering methodology for obtaining product and process condition, which are minimally sensitive to the various causes of variation, and which produce high-quality products with low development and manufacturing costs. Taguchi approach to design of experiments is easy to adopt and apply for users with limited knowledge of statistics, hence gained wide popularity in the engineering and scientific community. The objective of using Taguchi method in this paper is to investigate the mechanical strength of Poly-lactic Acid (PLA) materials which is used in 3D printing by using two factors which are infill pattern parameters and layer thickness parameters.

2.2.2 Matrix Design

The following control parameters which are given in Table 2.2 were selected for the investigation since they have influence on the mechanical strength of PLA. Then we had chosen two factors and three levels for this research. Signal to noise ratio and orthogonal array are two major tools used in robust design. The S/N ratio characteristics can be divided into three categories when the characteristic is continuous (a) Nominal is the best (b) Smaller is better (c) Larger is better characteristics. For the resistance of maximum applied force, the solution is “Larger is better” and S/N ratio is determined according to the following equation:

$$S/NS = -10 \log (1/n\ \Sigma\ 1/ y^2)$$

Where, S/NS = signal to noise ratio, n = Number of observations,

y = Observed data

The influence of each control factor can be more clearly presented with response graphs. Optimal conditions of control factors can be easily determined from S/N response graphs. Parameters design is the key step in Taguchi method to achieve reliable results without increasing the experimental costs.

Matrix Design				
Factors	**Description**	**Level 1**	**Level 2**	**Level 3**
A	Infill Pattern	Zig Zag	Grid	Triangle
B	Layer Thickness	0.2	0.15	0.1

Table 2.5 Matrix Design for Parameters

2.2.3 Experiments and Data Collection

Orthogonal array and Data collection before Printing

Orthogonal array of L9 was selected based on the number of factor and level in Table [2.3]. Taguchi technique is used to identify the key factors that make the greatest contributions to the variation in response parameters of interest. Taguchi recommends orthogonal array (OA) for laying out of the experiments which is significant part of this method. Instead of varying one factor at a time, all factors are varied simultaneously as per the design array and the response values are observed. It can evaluate several factors in a minimum number of tests. Then, we collected the data of each item by batches before testing as per below Table [2.4]. In this research, we tested three batches to get the best result.

Batch 1_Measurement

Item No.	Width	Thickness	Guage Height
1_1	6.06	3.27	64.62
2_1	6.04	3.37	65.29
3_1	6.08	3.55	64.97
4_1	6.11	3.38	65.14
5_1	6.07	3.27	65.52
6_1	6	3.59	64.56
7_1	6.04	3.31	64.69
8_1	6.08	3.28	65.08
9_1	6.05	3.32	65.13

Batch 2_Measurement

Item No.	Width	Thickness	Guage Height
1_2	6.19	3.35	64.95
2_2	6.21	3.37	65.05
3_2	6.16	3.33	65
4_2	6.12	3.34	64.64
5_2	6.03	3.34	63.75
6_2	6.06	3.56	64.61
7_2	6.04	3.33	64.07
8_2	6.04	3.56	64.24
9_2	6.07	3.37	65.02

Batch 3_Measurement

Item No.	Width	Thickness	Guage Height
1_3	6.34	3.42	64.13
2_3	6.07	3.41	64.67
3_3	6.06	3.52	64.41
4_3	6.13	3.47	64.49
5_3	6.03	3.47	64.85
6_3	6.27	3.42	64.93
7_3	6.03	3.46	64.07
8_3	6.1	3.32	65.09
9_3	6.05	3.46	65.08

Table (2.6) Data collections of each batch before testing

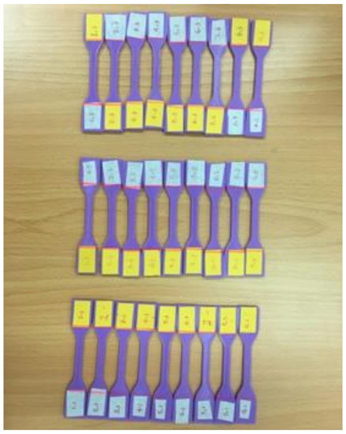


Figure 2.10 Printed items for three batches

Orthogonal array and Data Collection After Printing

As we mentioned above paragraph, we had L9 orthogonal array and we tested all three batches by collecting data batch by batch after testing in tensile machine as per below Table 2.3. Moreover, we did check the situations of cutoff point in specimens. We had seen all cutoff points of specimens are almost same places at the bottle neck of specimens in Figure [2.8].

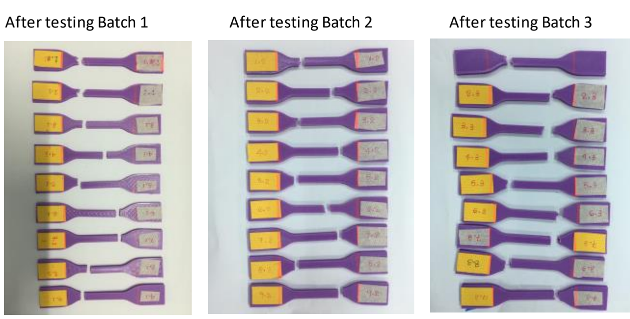


Figure [2.11] Specimens After testing

L9 orthogonal array_Test 1

A	B	Item No.	Tensile strength
1	1	1_1	565.2745
1	2	2_1	502.0698
1	3	3_1	415.5556
2	1	4_1	624.8553
2	2	5_1	540.0737
2	3	6_1	482.6864
3	1	7_1	668.7164
3	2	8_1	568.4376
3	3	9_1	484.4507

L9 orthogonal array_Test 2

A	B	Item No.	Tensile strength
1	1	1_2	599.8532
1	2	2_2	542.2115
1	3	3_2	458.8286
2	1	4_2	645.7646
2	2	5_2	576.7743
2	3	6_2	451.4535
3	1	7_2	646.9329
3	2	8_2	543.1573
3	3	9_2	440.1207

L9 orthogonal array_Test 3

A	B	Item No.	Tensile strength
1	1	1_3	565.7991
1	2	2_3	541.9413
1	3	3_3	465.1626
2	1	4_3	566.5064
2	2	5_3	448.1316
2	3	6_3	358.7723
3	1	7_3	587.0978
3	2	8_3	464.3758
3	3	9_3	449.9912

Table [2.7] Orthogonal array for three batches and their tensile test results

2.2.4 Results

The results of the experiments are analyzed to achieve the following objectives.

1. To establish the optimum conditions for the influence in 3D printing
2. To estimate the contributions of individual parameter to the responses
3. To predict the response under optimum conditions.
4. To run the confirmation test for validation.

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trend of influence of each parameter.

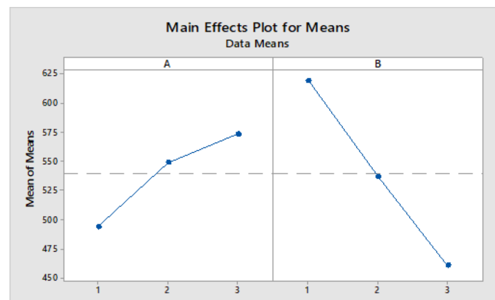


Figure (2.12) Main effects plot for Means of Batch 1

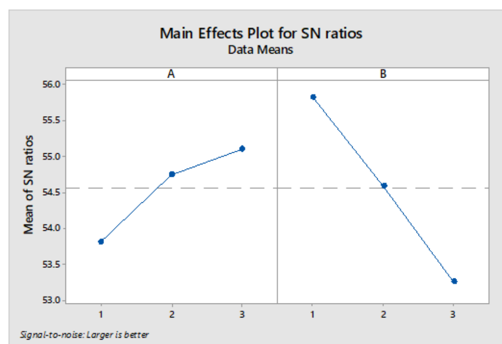


Figure (2.13) Main effects plot for SN ratios of Batch 1

Factor A for batch 1 in S/N ratios had occurred at triangles infill pattern as the largest value while factor B is seen at 0.2mm layer thickness as the biggest meanwhile we chose “lager is better” in it. Furthermore, the results of main effects for means are same as S/N ratios. Then, we made second time experiments in order to observe the possibilities of correct results. The results are shown in following. To obtain the best S/N ratio, the configuration and results are analyzed using the ANOVA method in [6]. Analysis results show in Fig. (2.14) and Fig. (2.15)

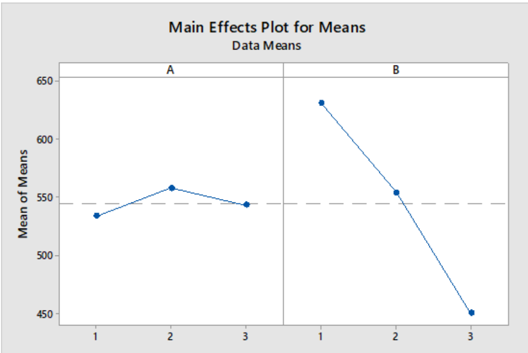


Figure (2.14) Main effects plot for Means of Batch 2

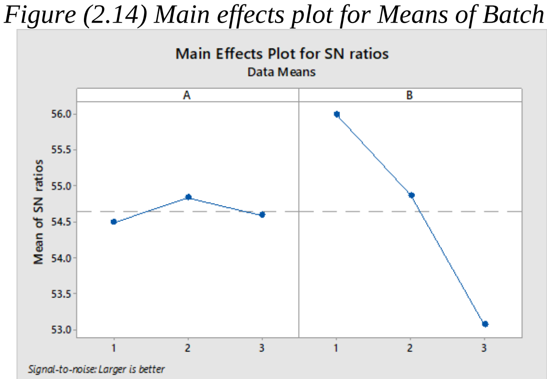


Figure (2.15) Main effects plot for SN ratios of Batch 2

S/N ratios of factor A was moved to number two which is represented to “Grid” infill pattern and it was the largest value meanwhile factor B was at the number one same as batch one. Additionally, the results of main effects of means are shown and the output was nearly symmetrical with S/N ratios. However, the results of two experiments are different in S/N ratios. We then tried third batch of testing to observe the best solution. At that batch, we discovered the peak point at infill pattern number one which represented Zig zag Pattern in both of S/N ratios and main effects while layer thickness was the same peak point at 0.2 which means at number one of factor B.

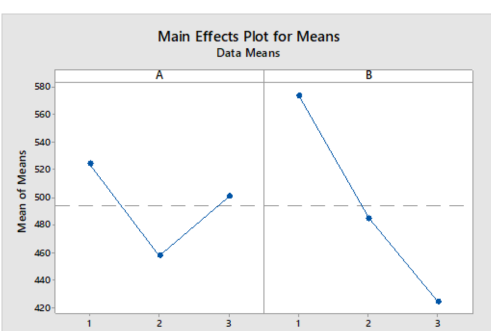


Figure (2.16) Main effects plot for Means of Batch 3

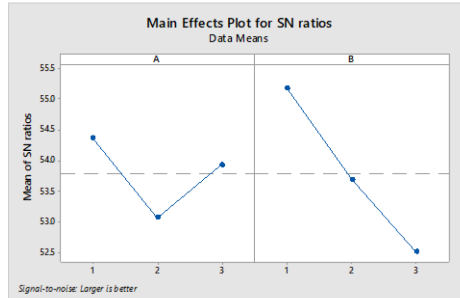


Figure (2.17) Main effects plot for SN ratios of Batch 3

In order to conclude results, we had found out the output of three batches and we observed that the results of infill pattern had changes in every batch although layer thickness had same peak point at number one which means 0.2 mm.

3. Optimization

3.1 Weka Software

Weka is a machine learning software which contains tools for data preparation, classification, regression, clustering, association rules mining, and visualization. Development started from 1997 and inspired for Weka bird in New Zealand which is flightless bird with an inquisitive nature. Weka is open source software issued under the GNU General Public License. Nowadays, Weka can used in many different application areas, for educational purposes and research.

The objective for using this software in our project is to optimize our samples data, comparison of correlation coefficient between samples and to know linear regression equations for each group. In these projects, divided into three parts for regression. Each part had nine samples and parameters are layer thickness (X_1), infill pattern (X_2) and tensile result force (ε). In the following data shows more detail of our regression experiments.

3.1.1 Linear Regression Model Equation

One problem in this case is cannot put directly patterns name into the software. So, have to convert pattern features to number. Therefore, we printed three different pattern and tested with the tensile machine then compare the results and evaluate it.

Pattern	Shape	Result (Force)	Evaluate
#1	ZigZag	517 N	1
#2	Grid	624 N	2
#3	Triangle	668 N	3

Table (3.1) Pattern Evaluation Results

Based on these results, we evaluated less value into number one and biggest value into number three. After that run into the Weka software with equation.

The quadratic response model equation:

$y = \beta + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_1 X_2 + \beta_5 X_2^2 + \varepsilon$

Put $\mu_1 = X_1^2$, $\mu_2 = X_1 X_2$, $\mu_3 = X_2^2$

Then find in the Weka software by using these equation

$y = \beta + \beta_1 X_1 + \beta_2 X_2 + \beta_3 \mu_1 + \beta_4 \mu_2 + \beta_5 \mu_3 + \varepsilon$

Batch#1
Linear Regression Model Equation:
$y = 1241.71 X_1 + 74.36 X_2 + 172.73 X_1 X_2 + (-15.12) X_2^2 + 222.89$
Summary:

Correlation coefficient	0.9302
Mean absolute error	25.1504
Root mean squared error	27.712
Relative absolute error	37.0219 %
Root relative squared error	33.5541 %
Total Number of Instances	9

Batch#2
Linear Regression Model Equation:
$y = 2679.56 X_1 + (-5422.18) X_1^2 + 377.129 X_1 X_2 + (-13.054) X_2^2 + 221.8964$
Summary:

Correlation coefficient	0.9693
Mean absolute error	17.6716
Root mean squared error	19.677
Relative absolute error	24.4352 %
Root relative squared error	23.0661 %
Total Number of Instances	9

Batch#3
Linear Regression Model Equation:
$y = 4955.98 X_1^2 + 374.43$
Summary:

Correlation coefficient	0.7552
Mean absolute error	41.3668
Root mean squared error	47.5619
Relative absolute error	58.1495 %
Root relative squared error	59.516 %
Total Number of Instances	9

Based on above results, the maximum value of correlation coefficient is occurred in Part#2 which is 0.9693. So, we choose these parts for our next experiments process such as Minitab to find what we expert in our project.

3.2 Optimization by MATLAB Software

3.2.1 MATLAB Software

MATLAB is a programming platform designed specifically for engineers and scientists. The heart of MATLAB is the MATLAB language, a matrix-based language allowing the most natural expression of computational mathematics. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:
Math and computation
Algorithm development
Modeling, simulation, and prototyping
Data analysis, exploration, and visualization
Scientific and engineering graphics
Application development, including Graphical User Interface building
MATLAB can be used for several mathematical and engineering calculations and simulations. In this study, we used MATLAB optimization tool to optimize the regression equation which was derived from Weka and MS excel software in order to find the most optimal solution which give the highest mechanical properties of the product.

3.2.2 Optimization

After comparing the correlation coefficient of three tests, test batch 2 was chosen because of its highest correlation coefficient value. Therefore, the regression equation of batch 2 was optimized by genetic algorithm in [7] to find the optimal values. MATLAB optimization tool are used with the lower boundaries 0.1 and 1 and upper boundaries 0.2 and 3 regarding to the minimum and maximum levels of experiments. The MATLAB software only minimizes the equation and hence the regression equation was changed from f(x) to –f(x) in order to maximize the equation. The linear regression equation from Weka was optimized by MATLAB as below:

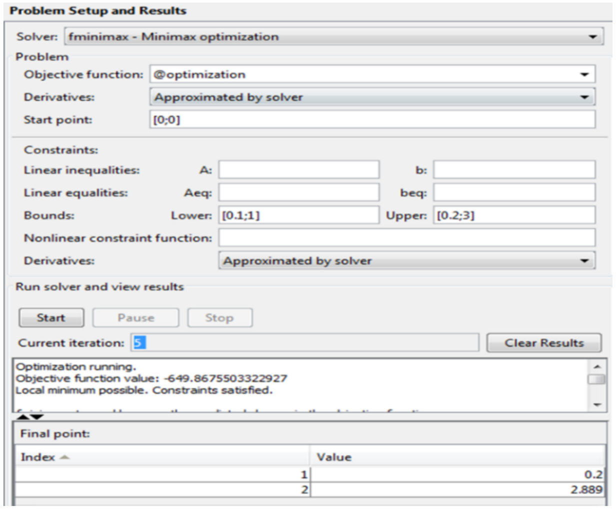


Figure (3.1) Optimization by MATLAB

According to the optimization results as above, the optimized solution for this study is as follow:

Layer Thickness – 0.2 mm
Infill Pattern – Triangle
Maximum applied force – 649.87 N

The maximum applied force is bigger than the forces from the experiments and hence the optimization is acceptable.

3.2.3 Comparison with Excel Regression and Optimization

In order to check the reliability of the optimization, the data was also analyzed by MS Excel to derive regression function and optimize value. To derive the regression function, the data analysis tool of Excel was used. The regression function and coefficients derived from Excel is as follow:

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.996025885							
R Square	0.992067563							
Adjusted R Square	0.978846835							
Standard Error	11.69758394							
Observations	9							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	5	51339.09564	10267.82	75.0388	0.00238167			
Residual	3	410.5004098	136.8335					
Total	8	51749.59605						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.*	
Intercept	184.9499	83.99122312	2.202015	0.114955	-82.34765769	452.24746	-82.347	
X Variable 1	2775.937667	1024.234642	2.710256	0.073149	-483.634087	6035.5094	-483.63	
X Variable 2	33.46596667	37.75378981	0.886427	0.440677	-86.68344223	153.61538	-86.683	
X Variable 3	-5422.18	3308.57637	-1.63883	0.199779	-15951.54664	5107.1866	-15951	
X Variable 4	328.938	116.9758394	2.812017	0.067181	-43.33132777	701.20733	-43.331	
X Variable 5	-19.4801	8.271440925	-2.3551	0.099842	-45.80351661	6.8433166	-45.803	

Layer Thickness(X1)	**Infill Pattern(X2)**	**X1^2**	**X1xX2**	**X2^2**	**Force (N)**
0.2	2.547901675	0.04	0.50958	6.491803	649.6775978

Table (3.1) Regression and Optimization by Excel

Y=2775.987667X1+33.466X2-5422.18(X1)^2+328.938X1X2-19.4801(X2)^2+184.9499

The R Square value is 0.992 and significance F is 0.0023, it means that the analysis is reliable and less probability of error. After the regression function is derived, the equation was optimized by solver tool of Excel and the result is as follow:

Layer Thickness – 0.2 mm
Infill Pattern – 2.55 ~ 3 – Triangle
Maximum applied force – 649.68 N

It is obvious that the optimization result of both Excel and MATLAB is almost the same. Therefore, the optimization results are reliable and can go to simulation.

3.3 Validation

3.3.1 Actual Simulation

In order to validate the optimizations results, the actual simulation with optimized values was run. The number of experiments for this simulation is three to make sure the results are reliable. After printing three specimens with layer thickness-0.2 mm and infill pattern- triangle and testing with tensile test machine, the results as below were recorded.

Figure (3.2) Optimization of test results

According to the results from testing, the mean value of maximum force of three tests is approximately around 609.655 N. Comparing to the optimum value 649.87, there is a difference about 40 N between optimization and actual simulation. However, the difference is not much significant and the other factors such as machine condition, ambient temperature, human's error in testing and so on can affect the results. Therefore, the optimization result with respect to simulation result can be concluded that the results are acceptable and valid.

4. Results and Discussions

According to the results from DOE and optimization, the influence of the layer thickness is much higher than the influence of the infill pattern. It is significant that the higher layer thickness will give the higher mechanical applied force and strength. Although there are many types of infill pattern, the most common infill patterns were analyzed in this study. Among these three infill patterns, the triangle pattern can give the highest strength. Moreover, triangle pattern can be printed with least material consumption according to the Cura software calculation. However, the influence of infill patterns is not significant according to the Taguchi and coefficients from regression function. According to the validation from simulations, the value of optimized parameters and resulted force can be determined as reliable results. The other effects of printing such as machine condition, ambient temperature, skill of temperature, amount of glue applied and so on affected the results more or less.

For the future work, the other types of pattern should be analyzed not only in term of mechanical properties but also in term of cost, material consumption, surface finish and environmental aspects. Moreover, new types of pattern which is more sustainable than current pattern can be created based on the previous studies. Furthermore, the number of experiments should be increased to get more accurate data and results. It would also be helpful to conduct more FEA trials and simulations with different deflections, stresses, and strain. The need to print and test more specimens of each study could help reduce the higher values in standard deviation in the E-Equivalent modulus.

Simulation	Width	Thickness	Gaguge Length	Max Force(N)
Test 1	6.15	3.42	64.66	598..87
Test 2	6.08	3.34	63.89	607.86
Test 3	6.05	3.35	64.3	611.45
			Mean Value	**609.655**

5. Conclusion

Additive manufacturing is expected as the one of most promising maker technologies which can boost the future production technology. However, the technology is still under development stage and need a lot of research to move to commercialization stage. Therefore, the similar studies on effect of parameters to improve the quality of product, scale of product and productivity of machine. This study used DOE, regression function and optimization tools with the help of software such as MATLAB, Minitab, Excel and Weka to do data analysis and optimization. Some conclusions are made as follows:

- Layer thickness have higher influence than infill pattern on mechanical properties
- The higher the layer thickness the higher the mechanical strength
- Triangle pattern gives the highest mechanical strength and lowest material consumption
- Zig Zag pattern gives the lowest mechanical strength
- Unstable machine condition, operation error and other factors can affect the results of printing

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