Multi-Response Optimization of Process Parameter in Fused Deposition Modelling by Response Surface Methodology

Mohd Shahir Kasim, Nurul Hatiqah Harun, Mohammad Shah All Hafiz, Saiful Bahri Mohamed, W Noor Fatihah W. Mohamad

Abstract*: *This paper reported on the effect of ambient temperature, layer thickness, and part angle on the surface roughness and dimensional accuracy. The response surface methodology (RSM) was employed by using historical data in the experiment to determine the significant factors and their interactions on the fused deposition modelling (FDM) performance. Three controllable variables namely ambient temperature (30 °C, 45 °C, 60 °C), layer thickness (0.178 mm, 0.267 mm, 0.356 mm) and part angle (22.5°, 45°, 67.5°) have been studied. A total of 29 numbers of experiments had been conducted, including two replications at the center point. The results showed that all the parameter variables have significant effects on the part surface roughness and dimensional accuracy. Layer thickness is the most dominant factors affecting surface roughness. Meanwhile, the ambient temperature was the most dominant in determining part dimensional accuracy. The responses of various factors had been illustrated in the cross-sectional sample analysis. The optimum parameter required for minimum surface roughness and dimensional accuracy was at ambient temperature 30 °C, layer thickness 0.18 mm and part angle 67.38°. The optimization has produced maximum productivity with RaH 3.21 µm, RaV 11.78 µm, and RaS 12.79 µm. Meanwhile, dimensional accuracy height eror 3.21%, width error 3.70% and angle 0.38°.

Keywords*: *Rapid prototyping, Fused deposition modelling, Optimization, Response surface methodology.

I. INTRODUCTION

Rapid Prototyping (RP) is referred to a technology used to produce a physical model or a prototype directly from three-dimensional computer-aided-design data in a very short time [1], [2]. Fused Deposition Modelling (FDM) is one of the most popular RP techniques available in the market. The potential of the technique is seemed to be popular as this technique helps to optimize the product development cost and time to the market and creating complex parts with precise dimension [3], [4]. RP has been extensively used by manufacturers from different industries such as automotive, consumer products, business machines, medical and aerospace industry to accelerate their product cycle to the market [5], [6]. The application of RP technology in production capable to reduce the development time by 30-50% [7] due to minimum human intervention including the use of a traditional tool such as jigs and fixture [8]. However, there are still limitations in terms of FDM performance, such as surface roughness and dimensional accuracy. Creation of a part with good surface roughness and dimensional accuracy is critical issue as it can affect the part accuracy, post-processing cost, and functionality of the parts. The improvement of surface roughness and dimensional accuracy are key issues that need to be addressed for successful implementation of RP technology [9], [10]. As RP is moving towards rapid manufacturing, there is an increasing demand on obtaining good quality parts with good surface roughness and accuracy. Rapid manufacturing is the process of using RP to construct parts that directly used as a finished product or components. Therefore, the creation of a part with good surface roughness and dimensional accuracy is critical as it can affect the part accuracy, post-processing costs, and functionality of the parts [11]. RP has been used as a master pattern for a broad range of manufacturing process. However, the application of RP as a master pattern is limited due to the bad surface roughness and dimensional accuracy. The surface roughness value for FDM by using ABS material is ranged between 9 µm and 40 µm [12]. Meanwhile, the percentage of accuracy for FDM is between 0.03 % to 2.21 % in length and 0.32 % to 5.86 % in width [13]. The nature of investment casting will duplicate whatever kind of surface condition that the master pattern presents [14]. Therefore, the quality of RP as a master pattern needs to be improved. Since the past few years, several studies have been made by numerous researches to improve the RP performance by using proper adjustment of parameters and post-processing technique. However, the proposed post-processing technique are costly and time-consuming as it adds more steps in the final process.

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Meanwhile, the parameters optimization is more flexible, less time consuming and cheaper compared to the post-processing technique. The technique involves controlling various input parameters to the fabricated part, and it is believed to have a significant effect on the RP performance [15]. RSM is widely used due to capability in determining prediction model of experiment, studied by Kasim et al. [16], Ganesan et al. [17], and Sulaiman et al. [18] found the error of the model were 3%, 6% and 8% respectively.

Based on the current research, the effect of ambient temperature on the surface roughness and dimensional accuracy of FDM built parts less reported in the literatures. Environmental factors such as temperature and relative humidity have been believed to be the sources of error affecting the surface finish and dimensional accuracy [19], [20]. Besides, temperature fluctuations during production also believed could lead to delamination and higher surface roughness. Several parameters have been studied by previous researchers to improve the FDM performance. However, to the best of author's knowledge studies on the effect of ambient temperature in improving the surface roughness and dimensional accuracy of FDM built parts have been limited to a certain extent. Besides, temperature fluctuations during production also believed could lead to delamination and higher surface roughness [21]. Therefore, this research wants to study and demonstrates how optimizing these parameters can improve FDM performance.

II. RESEARCH METHODOLOGY

ABS 3D printer filament with 1.75 mm diameter was used to fabricate the sample. The mechanical properties of ABS material as listed in Table 1. Each sample is fabricated by Folger Tech FDM machine (Model: RepRap 2020 Prusa i3) as shown in Figure 1. Repetier-Host version 1.6.2 was used for editing software during the fabrication. The ambient temperature was validated by the Pico USB TC-08 thermocouple logger type.

Table 1. ABS mechanical properties [22]

Properties	Constant
Process temperature	230-260 ºC
Tensile strength	22 MPa
Tensile elongation	40%
Flexural Strength	43 MPa
Flexural Modulus	2260 MPa
Heat Deflection Temperature	88 °C
Melt flow index	5.5 g/10 min
Molding Shrinkage	0.4-0.6%

The value of the fabricated sample surface roughness (Ra) was measured according to the ISO 3274: 1997 standard [23] by using Mitutoyo SJ-301 model. The averages Ra were produced after 10 repetitive of measurement. The dimensional accuracy was measured by Zeiss Contura G2 CMM machine. In addition, an optical microscope was used to observe the surface of the sample texture.

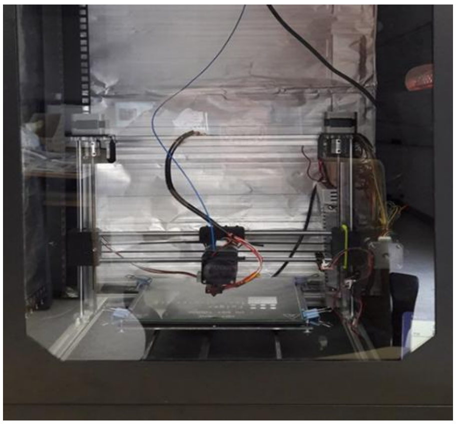

Figure 1. Folger Tech FDM machine

The samples used in this study is to evaluate the machining performance on the parts surface quality and dimensional accuracy on every quarter angle in 90°. Three samples were designed on different part angles; 22.5°, 45º, and 67.5º. The variable factors and parameter range listed in Table 2 shows a set an experiment plan to fabricate. There are three levels of manipulated factors, namely ambient temperature (At), layer thickness (Lt), and part angle (Pt).

Table 2. Manipulated factors and levels

Factors/levels	-1	0	1
Ambient Temperature (ºC)	30	45	60
Layer Thickness (mm)	0.178	0.267	0.356
Part Angle (º)	22.5	45	67.5

The selection of parameter ranges is based on several factors:

1. Ambient temperature: The selection ranges were between 30-60 ºC [24]. The range was selected based on the machine capability to avoid machine component failure. The maximum ambient temperature was set at 60 ºC. Whereas, the minimum ambient temperature of 30 ºC to avoid ABS part delamination.
2. Layer thickness: The layer thickness ranges were 0.178, 0.267, and 0.356 mm as widely practiced by previous researchers [25], [26]. The previous studied proved that the minimum layer thickness produces a better surface quality. Adjusting too much layer thickness may cause inaccuracy and rougher surface roughness.
3. Part angle: The part angle is to study the effect of angle between vertical and surface tangents, which is also known as the staircase effect. Three samples design with different parts angle (22.5º, 45º, and 67.5º) had been fabricated to study the effect of surface roughness and dimensional accuracy on every quarter angle in 90°.

III. RESULT AND DISCUSSION

The results were presented and discussed by statistical and scientific methods using RSM historical data analysis. The development of mathematical models, together with a statistical analysis on the surface roughness and dimensional accuracy of the FDM parts by the effect of variable parameters, had been discussed thoroughly. Then, followed by determining the optimum value parameters to obtain the lowest surface roughness and good dimensional accuracy with model validation.

A. Surface Roughness

Figure 2 shows the result of surface roughness measurement for 29 numbers of experiments. The graph arrangement showed are according to the DOE design scheme which the dominating factor cannot be identified, thus ANOVA will be used to categorize of the controlled input affected the surface roughnes. Ten number of surface roughness measurement were collected per sample and the average surface roughness were calculated as the output response. The results obtained were divided into three different parts of measurement location; horizontal surface roughness (RaH), vertical surface roughness (RaV) and slanted surface roughness (RaS).

The ability of the FDM machine to produce parts with lower surface roughness shows that combinations of these variable parameters are competitive for FDM machine. The results obtained were between 2.60-39.55 µm, where there were some surface roughness values, which was better than investment casting surface finish (3.125 µm).

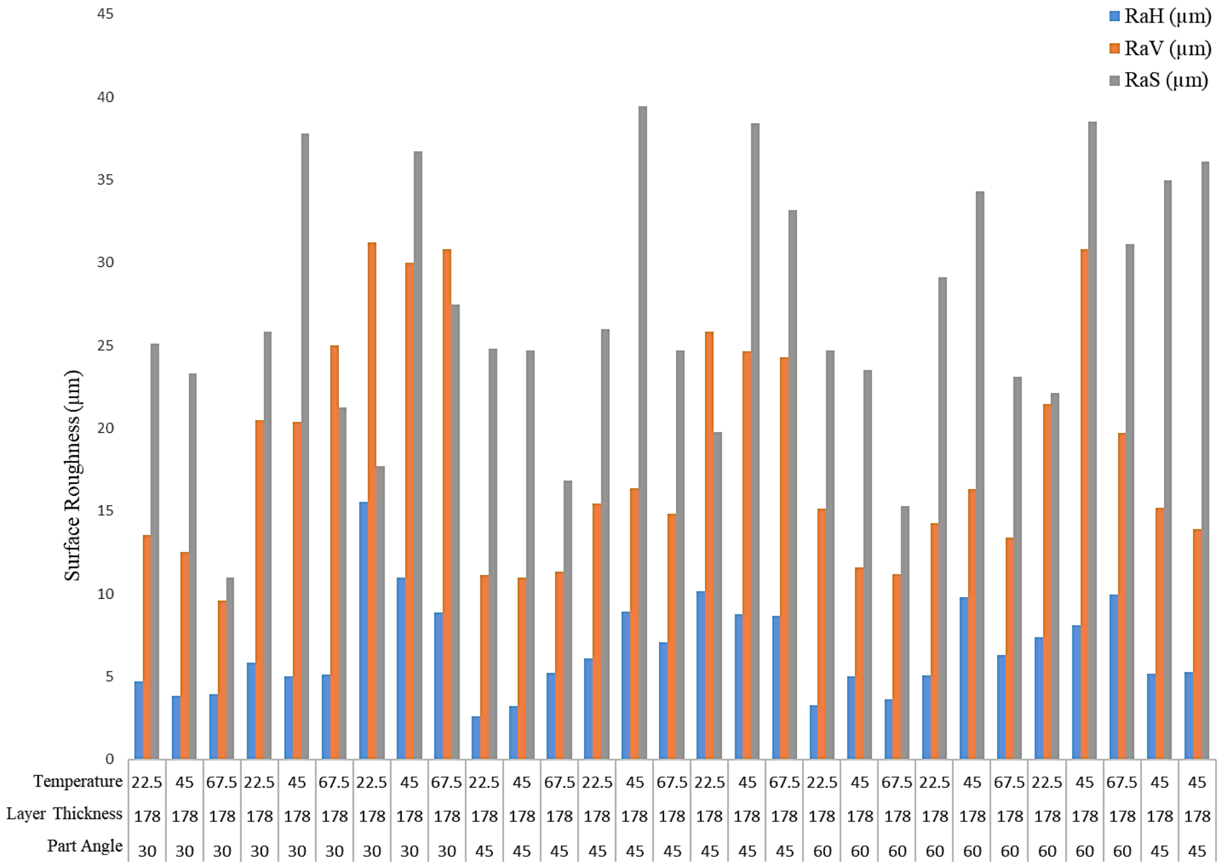

Figure 2. Surface Roughness result

Analysis of variance for horizontal surface roughness (RaH)

The ANOVA shows the results of the reduced cubic model was found to be significant with P-values 0.0001 and F-value 13.77 (Table 3) supported with the mathematical model equation as shown in Equation 1. There were three model terms with P-value less than 0.05. The significant model terms are B. It has the highest F-value of 86.36 compared to the other references. Table 4 shows the model is 82% reliable (R^2) with small standard deviation (0.09) through 68% of the prediction R^2.

$$Log_{10}\ (RaH) = 2.530 - 0.053A - 15.115B - 6.704\times10^{-3}C + 0.394A.B + 1.598\times10^{-4}A.C + 34.223B^2 - 0.777A.B^2 \quad (1)$$

Surface roughness further analysis is then had been done by using an optical microscope. Figure 3 shows a magnified surface roughness analysis for the best RaH; sample 10 with Ra value 2.60 µm. The image shows that surface roughness in sample 10 was nicely stacking together and ideally in shape with measured layer thickness reading 0.18 mm, which nearly the parameter value 0.178 mm. Sample 10 has produced good surface roughness due to the effect of ambient temperature where the temperature has melted the filaments during the layering process and caused the filaments to stack together during the layering process nicely.

Table 3. RaH ANOVA result

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	0.79	7	0.11	13.77	< 0.0001	significant
A-Temperature	0.017	1	0.017	2.02	0.17	
B-Layer thickness	0.71	1	0.71	86.36	< 0.0001	
C-Part angle	2.17×10^{-3}	1	2.17×10^{-3}	0.27	0.6116	
AB	9.23×10^{-3}	1	9.23×10^{-3}	1.13	0.3001	
AC	0.035	1	0.035	4.27	0.0513	
B^2	2.25×10^{-4}	1	2.25×10^{-4}	0.028	0.8698	
AB^2	0.034	1	0.034	4.17	0.054	
Residual	0.17	21	8.18×10^{-3}			
Lack of Fit	0.14	19	7.12×10^{-3}	0.39	0.8962	not significant
Pure Error	0.036	2	0.018			
Cor Total	0.96	28				

Table 4. R2 analysis for response surface Log_{10} model of RaH performance

Std. Dev.	0.09	R-Squared	0.82
Mean	0.79	Adj R-Squared	0.76
C.V. %	11.49	Pred R-Squared	0.68
PRESS	0.31	Adeq Precision	12.29

Surface roughness further analysis is then had been done by using an optical microscope. Figure 3 shows a magnified surface roughness analysis for the best RaH; sample 10 with Ra value 2.60 µm. The image shows that surface roughness in sample 10 was nicely stacking together and ideally in shape with measured layer thickness reading 0.18 mm, which nearly the parameter value 0.178 mm. Sample 10 has produced good surface roughness due to the effect of ambient temperature where the temperature has melted the filaments during the layering process and caused the filaments to stack together during the layering process nicely.

Meanwhile, Figure 4 shows a magnified surface roughness view for the worst RaH; sample 7 with Ra value 15.54 µm. The figure shows that the layer thickness was not nicely stacking together with some cracking in between. Cracking or warping in FDM surface roughness was believed due to the cooling effect after filaments material deposited from the nozzle. Deformation in higher layers is called cracking. Meanwhile, deformation at the base is known as warping. This is happening due to the stress in-between two layers, which will separate these layers, which will leave a crack in the object [27].

This finding was corresponding with the theory where, different in the surface roughness structured was happened due to the effect of ambient temperature and layer thickness. This finding was also parallel with [26], who also found that layer thickness has a significant influence on the part surface roughness. Therefore, ideally shape deposited filaments have produced lower surface roughness compared than the other. This indicates that the combination of ambient temperature and layer thickness has given a significant influence on the part surface roughness.

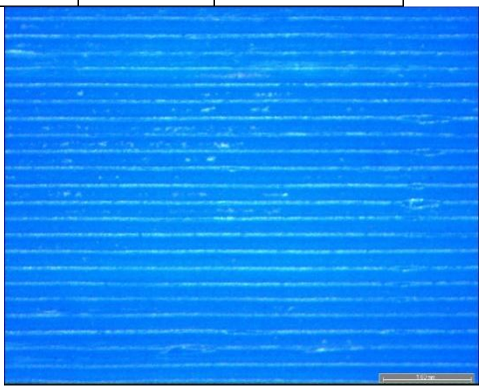

Figure 3. Surface roughness view of the best RaH sample 10 with parameter value; At: 45 °C, Lt: 0.178 mm and Pa: 22.5°

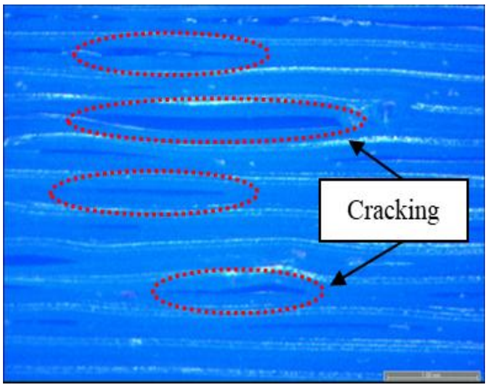

Figure 4. Surface roughness view of the worst RaH sample 7 with parameter value; At: 30 °C, Lt: 0.356 mm and Pa: 22.5°

Analysis of variance for vertical surface roughness (RaV)

Based on ANOVA in Table 5, the reduced quadratic model was found to be significant with P-values <0.001, and F-value is 37.14. The significant responses are B, A and A2. It was sorted by priority and dominant in determining the vertical surface roughness. B has the highest F-value of 166.15 compared to the other references. Equation 2 shows the mathematical model equation for the RaV model with 81% of prediction R2 (Table 6).

Table 5. RaV ANOVA result

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	0.0460	5	9.21×10^{-3}	37.14	< 0.0001	significant
A-Temperature	2.11×10^{-3}	1	2.11×10^{-3}	8.52	0.0077	
B-Layer thickness	0.0412	1	0.0412	166.15	< 0.0001	
C-Part angle	5.57×10^{-4}	1	5.57×10^{-4}	2.23	0.1474	
AB	9.57×10^{-4}	1	9.57×10^{-4}	3.86	0.0617	
A^2	1.22×10^{-3}	1	1.22×10^{-3}	4.92	0.0367	
Residual	5.70×10^{-3}	23	2.48×10^{-4}			
Lack of Fit	5.48×10^{-3}	21	2.61×10^{-4}	2.37	0.3385	not significant
Pure Error	2.20×10^{-4}	2	1.10×10^{-4}			
Cor Total	0.0517	28				

Table 6. R2 analysis for response surface reciprocal square root model of RaV performance

Std. Dev.	0.016	R-Squared	0.89
Mean	0.245	Adj R-Squared	0.87
C.V. %	6.429	Pred R-Squared	0.81
PRESS	0.010	Adeq Precision	19.54

$$1.0/\sqrt{RaV} = 0.313 + 4.284 \times 10^{-3}A - 0.838B + 2.473\times10^{-4}C + 6.688\times10^{-3}A.B - 5.941 \times 10^{-5}A^2 \quad (2)$$

Figure 5 shows a magnified surface roughness view of the deposited filaments for the best RaV; sample 3 with Ra value 9.30 µm. Figure 5 shows the filaments were nicely deposited together with diameter 0.18 mm, which nearly the parameter value 0.178 mm.

Meanwhile, Figure 6 shows the surface roughness view of the deposited filaments for the worst RaV, sample 7 with Ra value 31.66 µm. Figure 6 shows the filaments were not in nicely deposited with cracking in between. The measured filaments diameter shows a deviation value of 0.036 mm from the actual value of 0.356 mm. The result is identical with RaH result where sample 7 shows the worst surface roughness which believed happen due to the effect of layer thickness where higher layer thickness will produce rougher surface roughness compared than lower layer thickness.

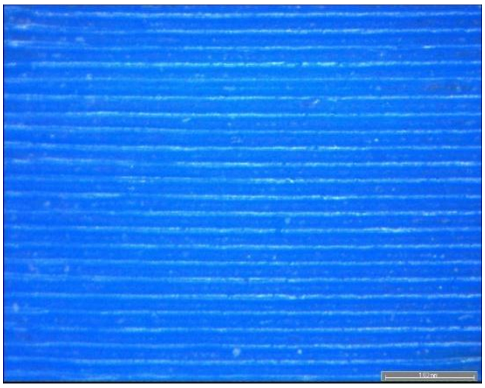

Figure 5. Surface roughness view of the best RaV sample 3 with parameter value; At: 30 °C, Lt: 0.178 mm and Pa: 67.5°

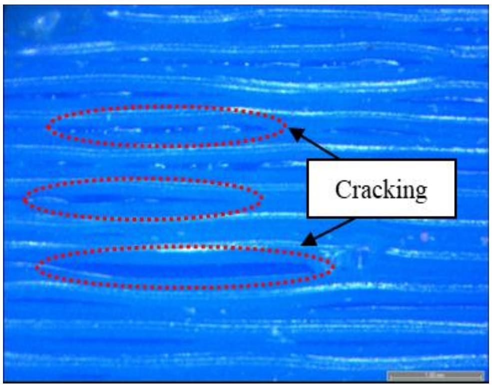

Figure 6. Surface roughness view of the worst RaV sample 7 with parameter value; At: 30 °C, Lt: 0.356 mm and Pa: 22.5°

Analysis of variance for slanted surface roughness (RaS)

Table 7 shows the reduced cubic model of the ANOVA was found to be significant with P-values of <0.0001, and F-value is 47.19. The mathematical model of the ANOVA shown in Equation 3. The significant responses are C^2, BC, B, B^2, C, and A. Among the designation, C^2 is dominant in determining the surface roughness in slanted. C^2 has the highest F-value of 96.99 compared to the other references. Table 8 shows a strong R2 result with a value of 93% for the model prediction of R2 with value of 87%.

$$\text{Log}_{10}(\text{RaS}) = 0.702 + 1.329\times10^{-3}A + 3.254B + 0.012C + 0.054B.C - 9.127B^2 - 3.049\times10^{-4}C^2 \quad (3)$$

Figure 7 shows a magnified surface roughness view of the deposited filaments for the best RaS; sample 3 with Ra value 10.86 µm. It shows the filaments were nicely deposited together. Meanwhile, Figure 8 shows the surface roughness view of the deposited filaments for the worst RaS, sample 14 with Ra value 39.55 µm. It shows some distorted filaments occur. The distortion effect happened due to melting, stacking and overlapping between layers. Figure 7 and 8, both shows the staircase effect for the deposited filament in an angle area.

Table 7. RaS ANOVA result

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	0.47	6	0.078	47.19	< 0.0001	significant
A-Temperature	7.16×10^{-3}	1	7.16×10^{-3}	4.33	0.0493	
B-Layer thickness	0.095	1	0.095	57.48	< 0.0001	
C-Part angle	7.97×10^{-3}	1	7.97×10^{-3}	4.82	0.0389	
BC	0.14	1	0.14	85.29	< 0.0001	
B^2	0.035	1	0.035	21.27	0.0001	
C^2	0.16	1	0.16	96.99	< 0.0001	
Residual	0.036	22	1.65×10^{-3}			
Lack of Fit	0.035	20	1.75×10^{-3}	2.39	0.336	not significant
Pure Error	1.46×10^{-3}	2	7.29×10^{-4}			
Cor Total	0.5	28				

Table 8. R2 analysis for response surface Log_{10} model of RaS performance

Std. Dev.	0.04	R-Squared	0.93
Mean	1.41	Adj R-Squared	0.91
C.V. %	2.87	Pred R-Squared	0.87
PRESS	0.07	Adeq Precision	23.48

Further analysis of filaments distortion has been conducted by comparing with the same part angle value 45° as shown in Figure 9. The distortion filaments were observed in both samples. However, the RaS sample 11 shows less surface roughness value compared than in sample 14. It is believed that happened due to the effect of layer thickness. Layer thickness has found significant in determining RaS follow by the interaction of layer thickness and part angle. Increase in layer thickness will result in the increase of the stair-stepping effect. Therefore, the surface roughness increases with an increase in layer thickness. This finding corresponded with Vasudevarao [24] who also found that layer thickness and part angle are the main factors in determining FDM surface roughness.

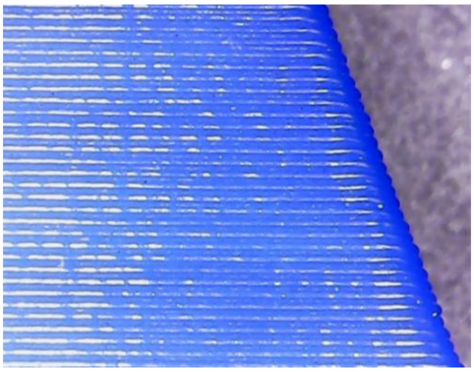

Figure 7. Surface roughness view of the best RaS sample 3 with parameter value; At: 30 °C, Lt: 0.178 mm and Pa: 67.5°

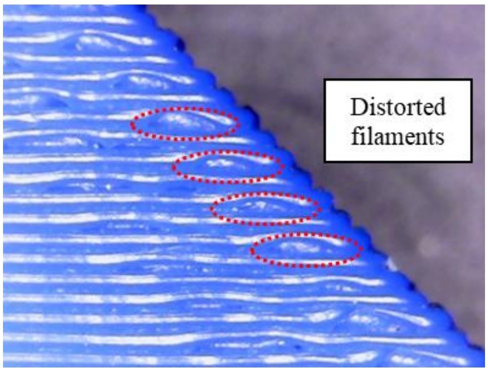

Figure 8. Surface roughness view of the worst RaS sample 14 with parameter value; At: 45 °C, Lt: 0.267 mm and Pa: 45°

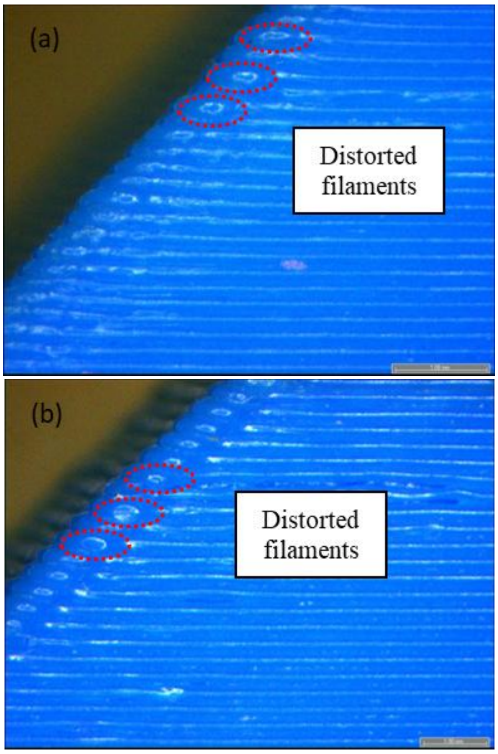

Figure 9. Distorted filaments comparison (a) Sample 11 and (b) Sample 14, with parameter value; At: 45 °C, Lt: 0.178 mm and Pa: 45° and At: 45 °C, Lt: 0.267 mm and Pa: 45° respectively

B. Dimensional Accuracy

Figure 10 shows the result of dimensional accuracy for 29 numbers of experiments. However, the graph arrangement showed are according to the DOE design scheme which the dominating factor cannot be identified, thus ANOVA will be used to categorize of the controlled input affected the output. Three different locations of measurement; height, width, and angle have been measured by using the CMM machine. The parts measurement has been measured in percentage except for angle in degree. The machinability to produce low percentage error shows that the combination of parameters is competitive for rapid prototyping.

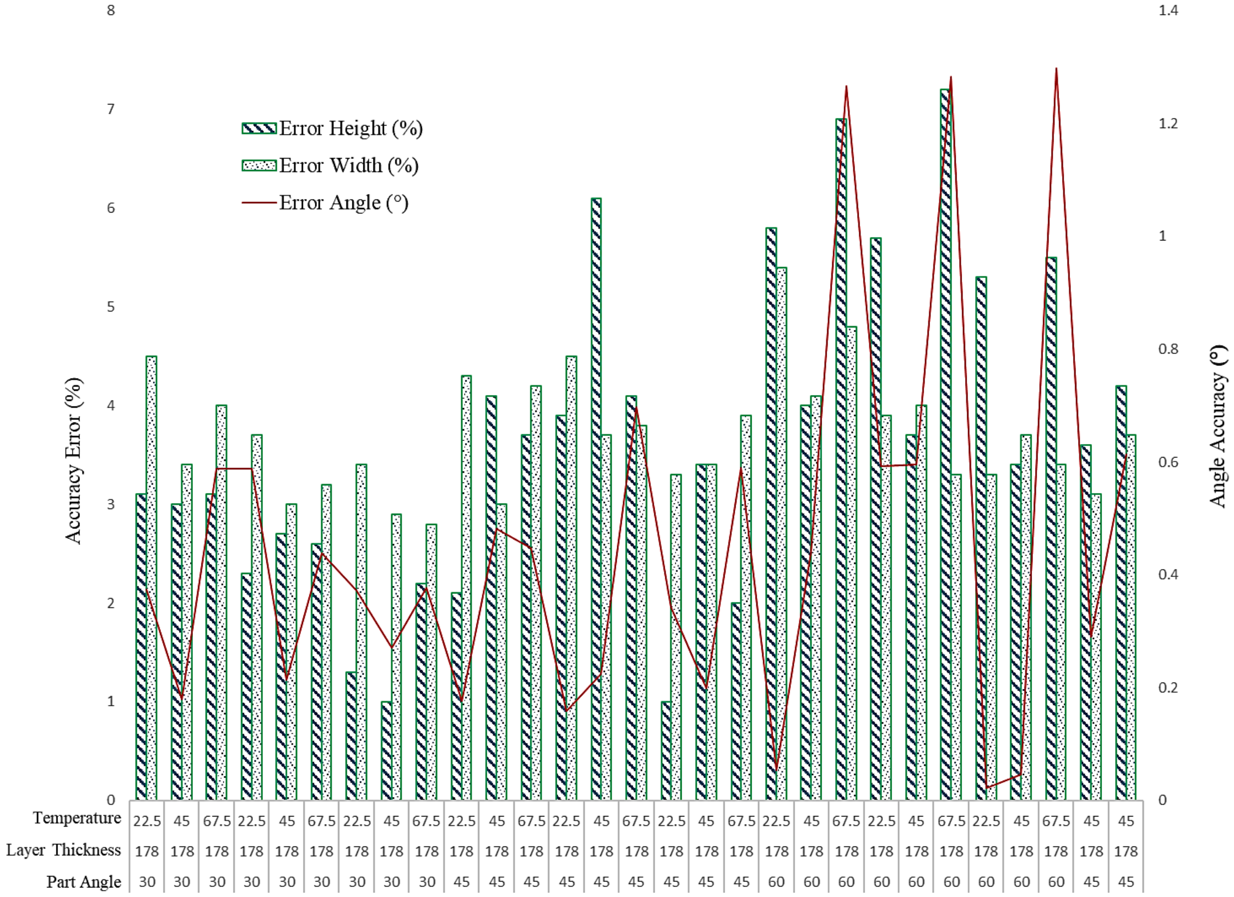

Figure 10. Dimensional accuracy result

Analysis of variance for height dimensional accuracy error

Table 9 shows the analysis of variance for height dimensional accuracy error by using RSM. Based on the ANOVA result, surface reduced linear model was found to be significant with P-values <0.0001 and F-value 13.2 supported with the mathematical model equation as shown in Equation 4. The significant response is A and B. Among the designation, A is dominant in determining the dimensional height accuracy error. It has the highest F-value of 32.1 compared to B. The R^2 values was 0.61 and prediction R^2 0.49 (Table 10).

% Height dimensional accuracy error = $0.351 + 0.097A - 6.679B + 0.017C$ (4)

Table 9. ANOVA of height dimensional accuracy error

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	47.06	3	15.69	13.2	< 0.0001	significant
A-Temperature	38.14	1	38.14	32.1	< 0.0001	
B-Layer thickness	6.36	1	6.36	5.35	0.0292	
C-Part angle	2.57	1	2.57	2.16	0.1539	
Residual	29.7	25	1.19			
Lack of Fit	26.3	23	1.14	0.67	0.7536	not significant
Pure Error	3.41	2	1.7			
Cor Total	76.77	28				

Table 10. R2 analysis for response surface model of height dimensional accuracy error

Std. Dev.	1.09	R-Squared	0.61
Mean	3.69	Adj R-Squared	0.57
C.V. %	29.54	Pred R-Squared	0.49
PRESS	39	Adeq Precision	12.00

Figure 11 shows a magnified cross-sectional shape of the deposited filaments for the best height dimensional. Figure 11 shows that the filaments were in semi-ellipse shape with the range value of 0.37 – 0.42 mm. This is because at low-temperature filament rounding is less pronounced compared than in high temperature.

Meanwhile, Figure 12 shows the cross-sectional shape of the deposited filaments for the worst height dimensional accuracy, sample 24 with a percentage error of 7.2%. Figure 12 shows the filaments were closely deposited and staking together with the range value of 0.27 – 0.42 mm. Ambient temperature was found to be the significant factors in determining dimensional height accuracy. This finding corresponded with Vasudevarao and Halidi [24], [28] who also found that temperature does have a significant influence in determining ABS diameter. This is because the higher ambient temperature has caused the filaments to melt and overlapping with each other during the layering process. Consequently, will deviate from the actual dimension.

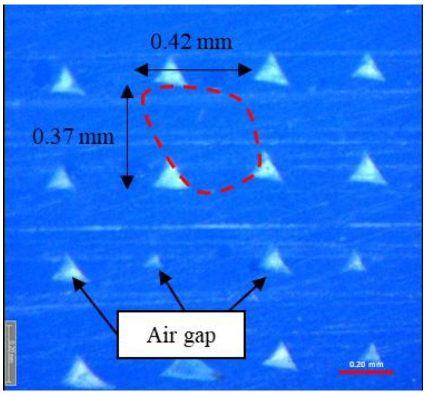

Figure 11. Cross-sectional view of the best height dimensional accuracy error sample 8 with parameter value; At: 30 °C, Lt: 0.356 mm and Pa: 45°

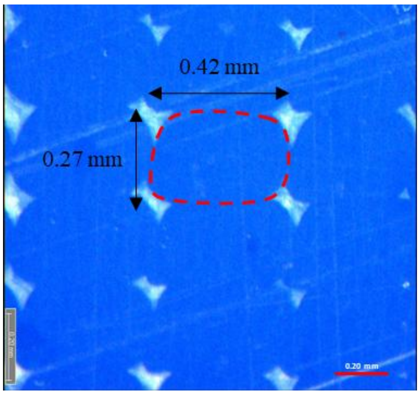

Figure 12. Cross-sectional view of the worst height dimensional accuracy error sample 24 with parameter value; At: 60 °C, Lt: 0.267 mm and Pa: 67.5°

Analysis of variance for width dimensional accuracy error

ANOVA results for width dimensional accuracy error shows the reduce cubic model was found to be significant with P-values <0.0001 and F-value 8.07. (Table 11). The significant responses are B and A. B is the dominant factor influencing the width accuracy. It has the highest F-value of 15.34 compared to the other references. Equation 5 shows the mathematical model equation for the width dimensional accuracy model with R^2 value of 0.49 and predicted R^2 of 0.32 (Table 12).

% Width dimensional accuracy error = $4.469 + 0.019A - 4.744B - 7.160 \times 10^{-3}C$ (5)

Figure 13 shows a magnified cross-sectional shape of the deposited filaments for the best width dimensional accuracy; sample 9 with a percentage error of 2.8%. It shows the filaments were in semi-ellipse shape with the range value of 0.37 – 0.44 mm. Meanwhile, Figure 14 shows the cross-sectional shape of the deposited filaments for the worst width dimensional accuracy, sample 19 with a percentage error of 5.42 % where the filaments were closely deposited and staking together with a diameter value of the range value of 0.24 – 0.65 mm.

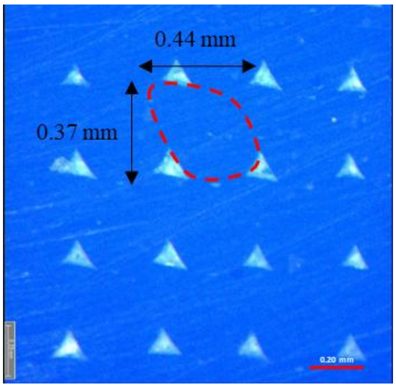

Figure 13. Cross-sectional view of the best width dimensional accuracy error sample 9 with parameter value; At: 30 °C, Lt: 0.356 mm and Pa: 67.5°

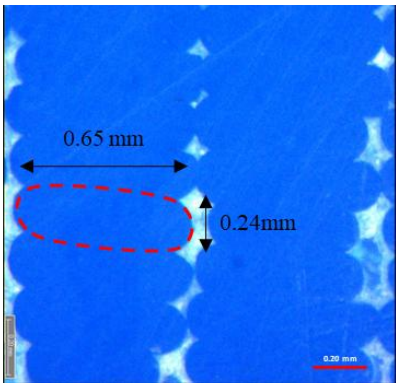

Figure 14. Cross-sectional view of the worst width dimensional accuracy error sample 19 with parameter value; At: 60 °C, Lt: 0.178 mm and Pa: 22.5°

Table 11. ANOVA of width dimensional accuracy error

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	5.07	3	1.69	8.07	0.0006	significant
A-Temperature	1.39	1	1.39	6.64	0.0163	
B-Layer thickness	3.21	1	3.21	15.34	0.0006	
C-Part angle	0.47	1	0.47	2.23	0.1476	
Residual	5.23	25	0.21			
Lack of Fit	4.99	23	0.22	1.81	0.4174	not significant
Pure Error	0.24	2	0.12			
Cor Total	10.29	28				

Table 12. R2 analysis for response surface model of width dimensional accuracy error

Std. Dev.	0.46	R-Squared	0.49
Mean	3.71	Adj R-Squared	0.43
C.V. %	12.32	Pred R-Squared	0.32
PRESS	7.04	Adeq Precision	10.14

Ambient temperature and part angle were found to be the significant factors in determining width dimensional accuracy. Higher ambient temperature has caused the filaments to melt and overlapping with each other during the layering process. Thus, the dimension will deviate from the actual value. This finding was also parallel with Sood [29], who found that shrinkage is dominant in determining width dimensional accuracy. In FDM, heat is dissipated by conduction and forced convection, and the reduction in temperature caused by these processes forces the material to solidify onto the surrounding filaments quickly. Bonding between the filaments is caused by local re-melting of previously solidified material and diffusion. This results in uneven heating and cooling of material and develops non-uniform temperature gradients. As a result, uniform stress will not be developed in the deposited material and it may not regain its original dimension completely.

Analysis of variance for angle dimensional accuracy

Table 13 shows the analysis of variance for angle dimensional accuracy. The ANOVA results show that reduce the quadratic model was found to be significant with P-values <0.0001 and F-value 12.91. The mathematical model of the ANOVA shown in Equation 6. The significant responses are C, AC, C^2, and A. Among the designation response, C is the most dominant in determining the dimensional angle accuracy. It has the highest F-value of 24.59 compared to the other references. Table 14 shows the model R^2 was 0.78 with a standard deviation value of 0.18 and predicted R^2 of 0.62.

Table 13. Angle dimensional accuracy

Source	Sum of Squares	df	Mean Square	F-value	P-value Prob>F	
Model	2.54	6	0.42	12.91	< 0.0001	significant
A-Temperature	0.27	1	0.27	8.15	0.0092	
B-Layer Thickness	0.014	1	0.014	0.41	0.5264	
C-Part Angle	1.03	1	1.03	31.47	< 0.0001	
AC	0.8	1	0.8	24.59	< 0.0001	
B^2	0.11	1	0.11	3.34	0.0813	
C^2	0.35	1	0.35	10.79	0.0034	
Residual	0.72	22	0.033			
Pure Error	0.63	20	0.032	0.73	0.7249	not significant
Cor Total	0.087	2	0.044			

Table 14. R2 analysis for response surface model of angle dimensional accuracy

Std. Dev.	0.18	R-Squared	0.78
Mean	0.46	Adj R-Squared	0.72
C.V. %	39.68	Pred R-Squared	0.62
PRESS	1.25	Adeq Precision	12.95

$$\text{Angle dimensional accuracy} = + 0.953 - 0.026A + 8.281B - 0.065C + 7.672\times10^{-4}A.C - 16.085B^2 + 4.525\times10^{-4}C^2 \quad (6)$$

Figure 15 shows a magnified cross-sectional shape of the deposited filaments for the best angle dimensional accuracy; sample 25 with error angle of 0.022°. Meanwhile, Figure 16 shows the cross-sectional shape of the deposited filaments for the worst angle dimensional accuracy, sample 27 with error angle 1.297°. Figure 15 and 16 shows the filaments were both in semi-ellipse shape with diameter value 0.36 mm respectively.

The interaction of ambient temperature and part angle has found to be the significant factors in determining dimensional angle accuracy. This finding corresponded with Górski [30] who also found that angle orientation plays a vital influence in dimensional accuracy of FDM parts

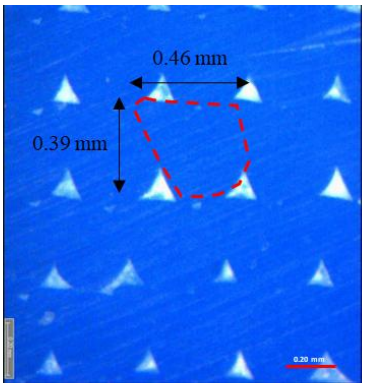

Figure 15. Cross-sectional view of the best angle dimensional accuracy sample 25 with parameter value; At: 60 °C, Lt: 0.356 mm and Pa: 22.5°

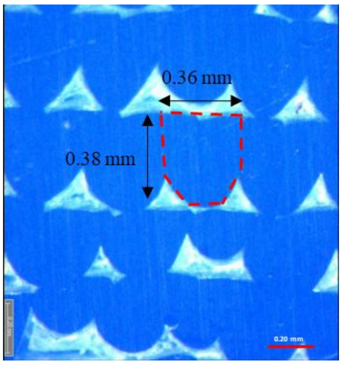

Figure 16. Cross-sectional view of the worst angle dimensional accuracy sample 27 with parameter value; At: 60 °C, Lt: 0.356 mm and Pa: 67.5°

C. Response Validation

Based on each ANOVA results, the developed mathematical model used to determine the prediction of the responses. The predicted value of each response is validate through the experiment. Table 15 also showed the result validation of the experiment executed to confirm the actual performance of the RP on varied ambient temperature and layer thickness on 22.5° of part angle.

Table 15. Experiment validation result

Content	Validation 1		Validation 2		Validation 3	
	Prediction	Experiment	Prediction	Experiment	Prediction	Experiment
Ambient Temperature	30 °C		38 °C		40 °C	
Layer Thickness	0.23 mm		0.22 mm		0.18 mm	
Part Angle	22.5°		22.5°		22.5°	
RaH (µm)	5.06	4.63	4.77	4.39	3.96	4.26
RaV (µm)	16.48	15.55	14.01	14.71	11.62	12.35
RaS (µm)	25.41	24.66	25.8	25.45	23.94	23.17
H Error (%)	2.1	2.34	2.95	2.63	3.42	2.98
W Error (%)	3.77	4.34	3.97	4.67	4.2	3.44
Error Angle	0.51	0.55	0.43	0.46	0.33	0.3

Hills and Trucano (1999) justified that an acceptable percentage of error for any engineering experiments is should be ±10% [31]. However, Cetin and his clique (2011) stated which The reliable statistical analyses, error value must be less than 20% [32]. Therefore, in these validation trials, the error between the results of actual experiments and prediction is within the acceptable reliable value which less than 20%. Figure 17, 18, and 19 are illustrated the percentage error value for each of the validation parameter runs.

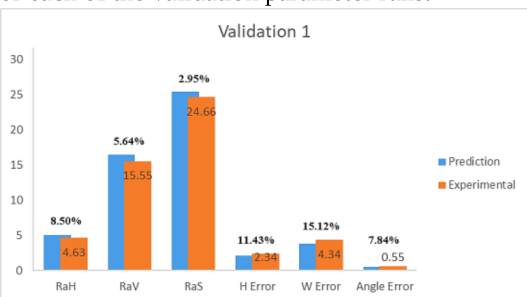

Figure 17. Illustration of percentage error for validation 1

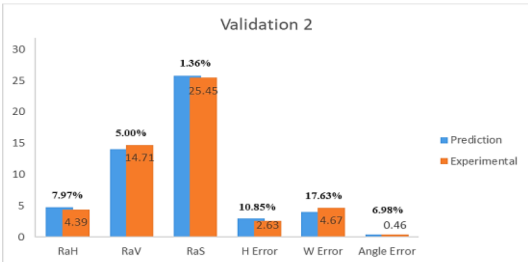

Figure 18. Illustration of percentage error for validation 2

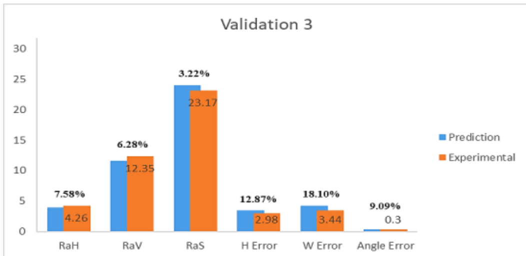

Figure 19. Illustration of percentage error for validation 3

D. Multiple Response Optimization

The optimum condition is required to achieve the best surface roughness and dimensional accuracy. Multiple response optimization has been conducted by using response optimization module available in Design Expert software (Version 10) to optimize the various parameters input. Table 16 list the goal and limit value for the factors and response. A minimum value of surface roughness and percentage error in dimensional accuracy are the desirable value that needs to be achieved.

Table 16. Goals and limit for multiple response optimization

Factor/response	Goal	Lower Limit	Upper Limit
Ambient Temperature (°C)	In range	30	60
Layer Thickness (mm)	In range	0.178	0.356
Part angle (°)	In range	22.5	67.5
RaH (µm)	Minimize	2.60	15.54
RaV (µm)	Minimize	9.61	31.25
RaS (µm)	Minimize	10.97	39.46
Height Error (%)	Minimize	1.00	7.20
Width Error (%)	Minimize	2.80	5.40
Angle (°)	Minimize	0.022	1.297

Multi-response optimization then has transformed all the desired goals into a single equivalent objective by using desirability approach. Desirability level that is closer to 1, indicates that the goals are easy to reach. In other words, higher values of desirability function indicate that the corresponding factor combination is closer to the optimal [33]. Table 17 lists the optimum value solutions obtained with the highest desirability value of 0.745.

IV. CONCLUSION

In this study, the effect of layer thickness, ambient temperature, and part angle on FDM performance has been studied. Based on the result, it is observed that all the parameter variables have significant effects on the part surface roughness and dimensional accuracy. Layer thickness is the most dominant factors affecting surface roughness. Meanwhile, ambient temperature is the most dominant in determining part dimensional accuracy.

The optimization is made based on the combination of set parameters to achieve multiple response optimization such as lowest surface roughness and high dimensional accuracy. The optimum set of parameters were ambient temperature 30 °C, layer thickness 0.18 mm, and part angle 67.38°. It produced maximum productivity with RaH 3.59, RaV 11.78, and RaS 12.79. Meanwhile, dimensional accuracy with height error 3.21%, width error 3.70% and angle 0.38º.

Table 17. Multiple response optimizations solutions

1 Solution	Experimental Factor			Surface Roughness Response			Dimensional Accuracy Response			Desirability
	Ambient Temperature (ºC)	Layer Thickness (mm)	Part Angle (°)	RaH (µm)	RaV (µm)	RaS (µm)	Height Error (%)	Width Error (%)	Angle (º)	
	30	0.18	67.5	3.59	11.78	12.79	3.21	3.7	0.38	0.745

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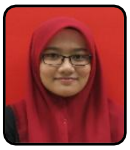

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