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Taguchi-based Optimisation of Process Parameters of Fused Deposition Modelling for Improved Part Quality

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Abstract

This paper presents results of the experimental work on the effect of the main fused deposition Modelling (FDM) process variable parameters such as layer thickness (A), air gap (B), raster width (C), contour width (D) and raster orientation (E) on the quality characteristics such as surface roughness (SR) and tensile strength (TS). Parts produced by FDM produced parts tend to involve surface error or weak tensile strength. New composite ABS- M30i biomedical material was used in this experimental work to build parts. Taguchi design (L32) was used to obtain the experimentation runs. Numbers of analytical methods such as regression analysis, Analysis of Variance (ANOVA), Signal to Noise (S/N) ratio were used to determine the influence of the FDM process parameters settings. Results show that these parameters have significant effect on the finished products at various levels. It was found that the surface roughness and tensile strength of processed parts are greatly influenced by air gap parameter. SEM work was done to validate the experimental results.

Keywords: Fused deposition modelling (FDM), biomedical Acrylonitrile butadiene styrene (ABS M30i), surface roughness (SR), tensile strength (TS), bonding of atoms and molecules, Scanning Electron Microscopy (SEM)

1. Introduction

Fused deposition modelling (FDM) system was introduced to the market in 1991. FDM is a fast growing rapid prototyping (RP) process that integrates computer aided design (CAD), polymer science, computer numerical control, and extrusion technologies to produce three dimensional (3D) solid objects directly from a CAD data without the use of tooling with minimum human intervention. In this process, a thermoplastic polymer is extruded through a heated nozzle to deposit the layers [1]. In order to recognize and predict the performance of FDM processed parts, the quality characteristics of the produced parts and the influence of the process variable parameters must be investigated. Still no comprehensive data are available to the new introduced FDM materials, particularly for ABS M30i biomedical material, which was used in this study. In relevant empirical studies, the parametric optimization were used to develop the quality characteristics of FDM parts or the process performance where number of FDM process parameters were studied and optimized, in instance, Lee at al. [2] investigated the elasticity performance of ABS material. Similarly, Ahn et al. [3] attempted a study to improve the tensile strength of ABS material processed parts by FDM, also Masood et al. [4] investigated the FDM parts which processed using Polycarbonate. In addition, Anitha et al. [5] optimized the FDM process parameters that improve the surface roughness of building parts, while [6, 7, 8] have looked to dimensional accuracy of FDM parts. These previous studies were investigated a single outcome quality response while some works were done in parametric optimization by investigating multiple quality objectives ‘‘responses’’ [4, 9, 10]. They suggested building a functional part is attributed to various loading environments in actual practice. Consequently, process parameters require to be studied in such method that they collectively optimize rather than single quality response simultaneously.

In this research, multi-objectives experimentation was implemented where the key properties of FDM building parts: surface roughness (SR) and tensile strength (TS) were investigated. Five parameters were optimized are: layer thickness (A), air gap (B), raster width (C), contour width (D) and raster orientation (E). In order to develop an experimentation plan the application of Design of Experiment (DOE) were used. Hence, the Taguchi design L32 was chosen based on the number of the selected parameters and variable settings (levels). The Taguchi method is a powerful statistical method that used to develop an experimentation plan, which help to reduce both cost and time of the experiment [11, 12].

2. Methodology

2.1 Definition of selected process parameters

Some of the main FDM variable parameters are considered in this research to evaluate the correlation between these parameters and the proposed response characteristics, other parameters such as chamber temperature, model temperature, humidity, and speed of deposition were considered as constant or can be assumed as source of noise in this experimentation work.

The definitions of FDM variable parameters in this study as following:

- (A) denotes the layer thickness which is recognized as the height of deposited slice from the FDM nozzle as shown in Figure 1. The layer thickness parameter was used to examine the influence of building thicker or thinner layers on the outcome quality.
- (B) assigns to the air gap parameter which is defined as the space between the beads of deposited FDM material (Figure 2). Hence, the influence of applying positive and negative gap between the deposited beads was investigated.
- (C) denotes the raster width or road width which refers to the width of the deposition path related to tip size Also refers to the tool path width of the raster pattern used to fill interior regions of the part curves which is shown in Figure 3. Narrow and wide filling pattern (roads) were examined.
- (D) refers to the contour width which is defines as the boundary that surrounds the raster tool-path in each part as shown in Figure 4. Thus, thin and thick deposited boundaries were considered in this experiment.
- (E) denotes the raster orientation which is measured from the X-axis on the bottom part layer as shown in Figure 5 Also it refers to the direction of the beads of material (roads) relative to the loading of the part. The deposited roads can be built at different angles to fill the interior part. The effect of this filling according to the raster angle applied was also investigated, where using loose angles at (45°/90°) and tighter angles at (45°/-45°) of deposited roads.

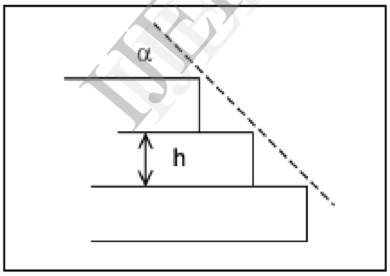

Figure 1 height of slices or layout of layer thickness [13]

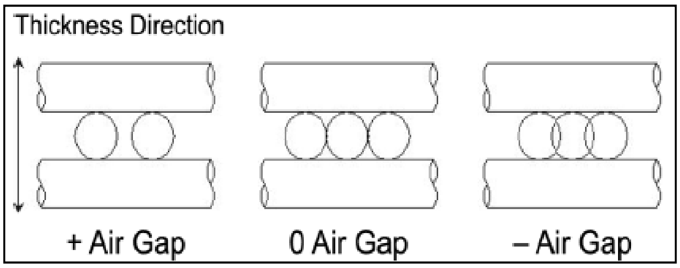

Figure 2 air gap application [1]

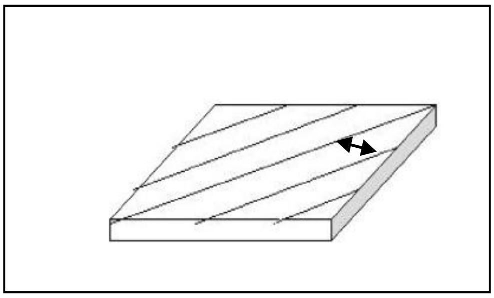

Figure 3 raster width parameter [1]

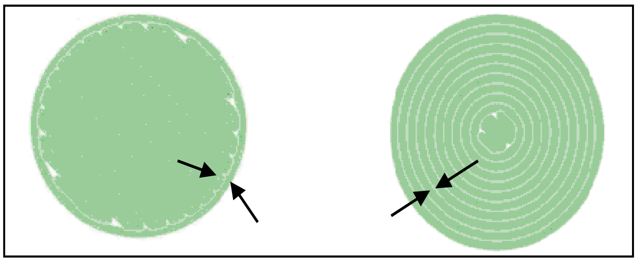

Figure 4 contour boundary surrounds the raster tool-path in two building styles [14]

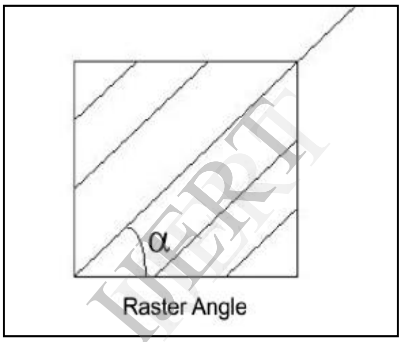

Figure 5 raster angle parameter [1]

2.2 Experimentation setup

Several experimentation runs were performed prior to the main experiment, to select the levels of the selected process parameters in this study. Also, a simulation phase was carried out by Insight FDM software to evaluate the influence of the process parameters settings on the time and cost of the experiment, In order to select the optimum settings which reducing time and cost consumption.

For example, two levels of layer thickness were selected, as using lower level than 0.245 mm will increase greatly the time and cost of building parts. Also decreasing layer thickness setting for more than 0.353 mm will sacrifice the quality of the building part surface, but will save more time and cost to built part. In addition, two levels were considered to the air gap parameter. Setting up the air gap parameter for lower than (–0.01) mm or increase it more than 0 mm, has produced a considerable defected surface.

Taguchi method has proved a powerful statistical tool to develop an experimentation plan [15, 16 and 17]. The Taguchi design was obtained to develop a experimentation plan for five parameters and two levels. Process parameters and their setting levels are presented in Table 1.

Table 1 Selected parameters of FDM

Fixed parameters	**Setting**	**Variable parameters**	**symbol**	**Low level**	**High level**	**Unit**
Building style	Raster and perimeter	Layer thickness	A	0.254	0.353	mm
Envelope temperature	70ºC	Air gap	B	0	-0.01	mm
Building material	ABS-M30i	Raster width	C	0.508	0.80	mm
Material colour	Ivory	Contour width	D	0.508	0.80	mm
orientation	Automatic orientation	Raster Orientation	E	$45^o/-45^o$	$45^o/90^o$	degree

2.2.1 Optimisation of process parameters using Taguchi method

Optimisation techniques, such as Taguchi's method can be utilized as effective method due to its cost and time efficiency. The Taguchi design used in this study the objective value approach as Signal to Noise (S/N) ratio, which is assigned as the quality characteristic weight. Factors that affect the system performance can be divided into the following two categories: controllable factors and noise factors. Noise factors cannot be controlled during the manufacturing process such as chamber temperature, humidity, and model temperature, etc., this method is also generally used in most cases when the design of robust experiment transforms the magnitude of quality dispersion into Signal to Noise ratio. In this study, the S/N ratio is used to obtain least variation and the optimal quality design. For surface roughness, the objective was to obtain the smaller values for minimum surface errors, thus using S/N ratio (small is better). The formula for the smaller is better S/N ratio as following:

$$\eta = -10 \log \frac{1}{n} \sum_{i=1}^{n} y_i^2$$

For tensile strength (TS), the objective optimal value is larger is better as following:

$$\eta = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$$

where η: S/N ratio; *yi*: the *ith* result of the experiment; n: the repeated times of the experiment. Further experiment is then implemented to validate the results in order to confirm whether the experiment is successful [11, 12, and 18].

Designed part was used in addition to measure the surface roughness response on the top of the part. Also In order to conduct the tensile strength response, the dimensions of the specimens have been produced according to British standards ISO 527. In stage of building preparations, the ABS M30i biomedical material was loaded into FDM to process the experimentation parts. Then designed model is converted into an STL file using a specific translator on the CAD system. The STL file is then sent to the FDM slicing and pre- processing software called QuickSlice depending on the model, where the designer select appropriate orientation, creating supports, part slicing and other parameters for part building.

2.3 Measurement and testing

The surface roughness was measured by the standardized surface roughness apparatus Taylor Hobson's surface texture measuring equipment (Talisurf) on the flat top of the produced part. The procedure followed is according to the British standards BS ISO 4287:1997. The assessment length L, of 2.500 mm was used for the measurement of surface roughness. The samples were measured at a speed of 0.200 mm/s. Thirty two parts were measured by Talisurf. Each average surface roughness (R_a) value is an average of five different readings. Also the measurements were performed in the direction of built layers. Tensile strength testing has been done according to ISO 527 for the plastic determination of tensile properties. In this stage of experimentation, testing of three tensile test specimens per thirty-two runs was done using the ZWICK ROELL 2000. This was done to find out if there is any correlation between the elongation of the produced parts and the optimised parameters.

3. Results and analysis

According to the SR response, Figure 6 shows the distribution of the resulting data appears to be normal but cyclic in nature from minimum to maximum and then minimum. S/N ratio will be used to explain this phenomenon. From Figure 6 it can be seen that the R_a value is lower in some runs and higher in others, which means that the combination of parameters in each run has impact on the surface roughness characteristic for the processed FDM parts.

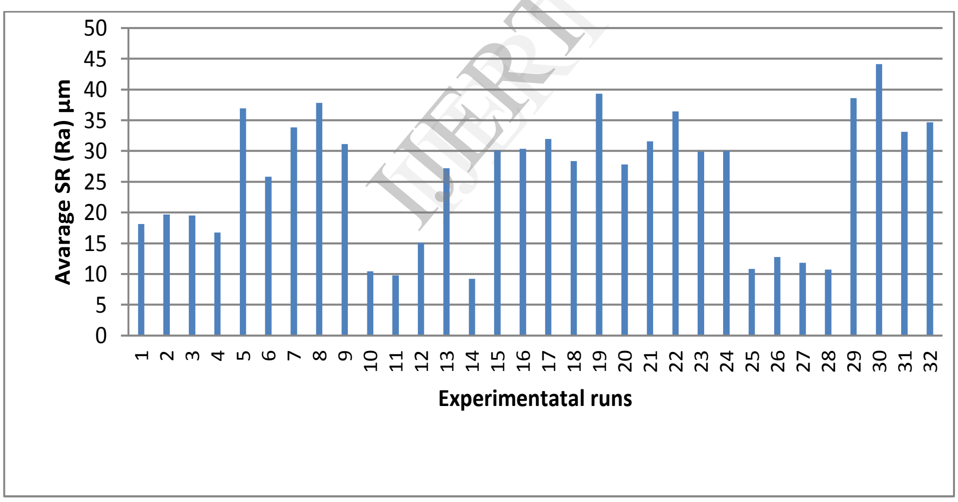

Figure 6 resulted roughness from 32 experimentation runs expressed by µm

Furthermore, Figure 7 shows the stress versus strain results for the average of tested specimens for each run. It can be seen that every run has a unique results and depending on the combination of parameter settings which has been set in the Taguchi randomized runs. It can be seen that the combination of parameters settings in run 10 has the highest tensile strength 36.8 MPa. Also in Figure 8 it has exhibited higher ductility than other runs according to its elongation at break at break or percentage strain.

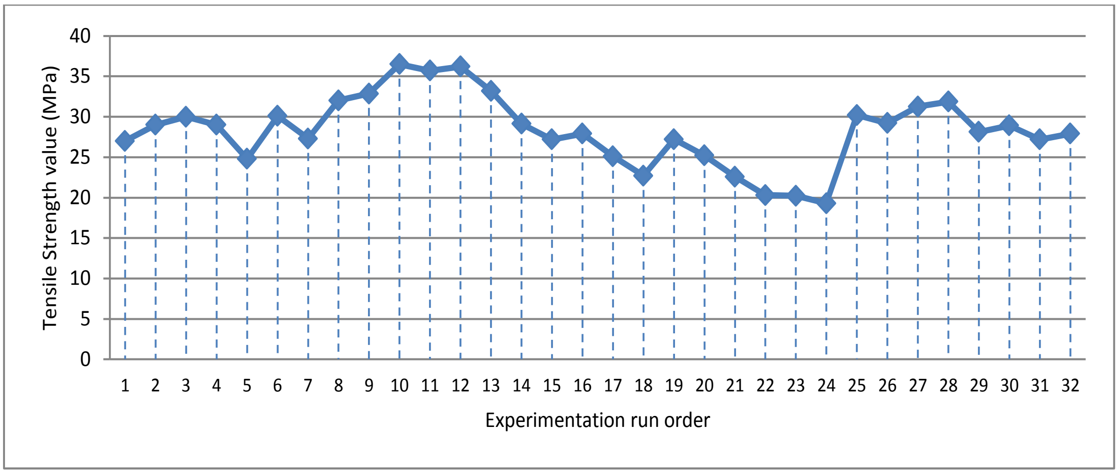

Figure 7 UTS results of experimentation runs

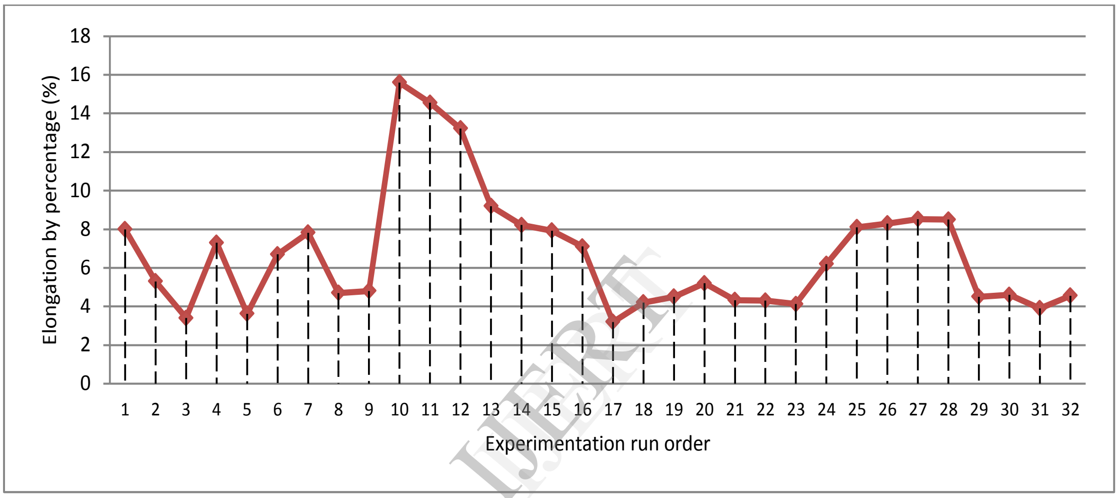

Figure 8 elongation percentages during testing

Analysis of Variance (ANOVA) uses the P-value to determine the significant FDM parameter that influences the SR response. These methods of analysis are using hypothesis test according to the probability or P-value, therefore if the P-value is below the α-value, the higher the probability to reject the null hypothesis and consequently considering the parameter of the interaction as significant. In this experiment the testing value user for the hypothesis analysis is $\alpha = 0.05$ which is common testing value. Table 2 ANOVA shows that only the air gap and raster width are significant hence they P-value below α value. Also they have the highest F factor but no interaction was significant.

The Adj MS and Adj SS indicate to the delta variation or the influence by applying low and high level of each process parameter, these values will be used to compare the influence of parameters on each response characteristic. Raster width has the highest influence according to Adj MS, while air gap has less influence at lower Adj MS value.

For TS das, from the ANOVA table (Table 3), it can be seen that layer thickness, air gap and raster width are significant. Also it has shown that no interactions were significant according to P-value. Layer thickness has the highest contribution influence on tensile strength according to the highest Adj MS value, then air gap and raster width. According to the SR response date of S/N ratio, Figure 9 shows the three parameters that have higher S/N ratio (small is better) and raster

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width, air gap and layer thickness. Low level in both raster width and layer thickness parameters has higher S/N ratio, while high level in air gap has higher S/N ratio. Layer thickness and raster width parameters were found significant to influence the SR response of FDM processed parts in agreement to [5,19] and previous reports where using thinner layers or roads can produce better resolution of part's surface.

Table 2 ANOVA table (response: SR)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	249.76	249.76	249.76	2.88	0.109
B	1	427.78	427.78	427.78	4.93	0.041
C	1	1096.06	1096.06	1096.06	12.63	0.003
D	1	3.35	3.35	3.35	0.04	0.847
E	1	39.69	39.69	39.69	0.46	0.508
A*B	1	17.49	17.49	17.49	0.20	0.659
A*C	1	0.37	0.37	0.37	0.00	0.949
A*D	1	60.78	60.78	60.78	0.70	0.415
A*E	1	90.12	90.12	90.12	1.04	0.323
B*C	1	221.66	221.66	221.66	2.55	0.130
B*D	1	0.88	0.88	0.88	0.01	0.921
B*E	1	5.04	5.04	5.04	0.06	0.813
C*D	1	49.15	49.15	49.15	0.57	0.463
C*E	1	1.61	1.61	1.61	0.02	0.893
D*E	1	11.21	11.21	11.21	0.13	0.724
Residual Error	16	1388.29	1388.29	86.77		
Total	31	3663.24				

Table 3 ANOVA (response: TS)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	155.497	155.497	155.497	29.82	0.000
B	1	208.080	208.080	208.080	39.90	0.000
C	1	87.715	87.715	87.715	16.82	0.001
D	1	1.073	1.073	1.073	0.21	0.656
E	1	0.918	0.918	0.918	0.18	0.680
A*B	1	15.736	15.736	15.736	3.02	0.102
A*C	1	0.401	0.401	0.401	0.08	0.785
A*D	1	0.001	0.001	0.001	0.00	0.989
A*E	1	10.557	10.557	10.557	2.02	0.174
B*C	1	7.527	7.527	7.527	1.44	0.247
B*D	1	4.263	4.263	4.263	0.82	0.379
B*E	1	0.080	0.080	0.080	0.02	0.903
C*D	1	14.933	14.933	14.933	2.86	0.110
C*E	1	0.702	0.702	0.702	0.13	0.718
D*E	1	0.047	0.047	0.047	0.01	0.926
Residual Error	16	83.440	83.440	5.215		
Total	31	590.969				

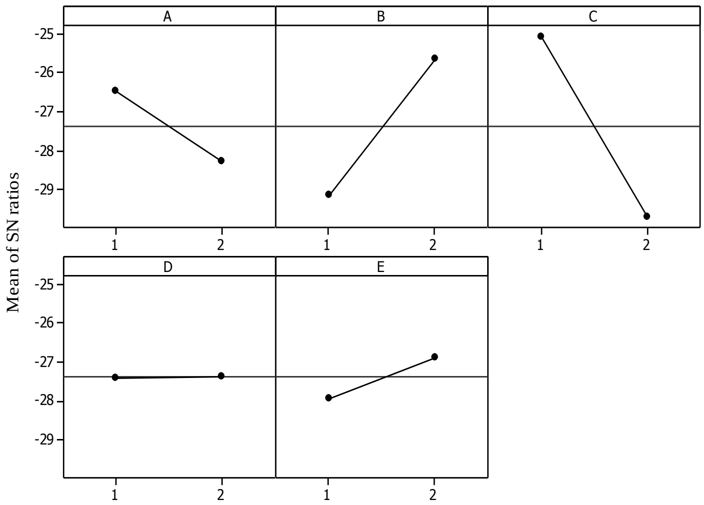

Figure 9 Signal to noise ratio: smaller is better (response: SR)

However, little knowledge in optimizing the air gap parameter was done previously in investigating the surface roughness characteristic. The hypothesis study has shown that air gap parameter influence greatly the surface quality of the processed experimentation parts. The influence of the air gap can be noticed in Figure 10, where two oscilloscopic evaluation curve generated by Talisurf. The generated curve of run number 3 and run number 14 show the influence of FDM parameters on the surface quality. Both runs have been set to (low level) of 0.254 mm of layer thickness. Figure 10 (A) shows run number 3, which resulted R_a value = 19.51 µm. In this run, air gap parameter was set to default setting (low level) or 0 mm, the texture of deposited roads can be recognized by sine wave which is generated by the measured area of the produced part. Figure 10 (B) shows the influence of the air gap between deposited roads, where Figure 10 (B) shows run 14 which results R_a= 8.45 µm. Moreover, Scanning Electron Microscope (SEM) work was done to examine the surface of some parts. In Figure 11 (A), the SEM images show gaps between the deposited roads which may cause rough surface. In contrast, Figure 11 (B) and (C) more uniform surface according to the overlapped deposited roads or filling the gaps between the roads. This is likely has cause firmer and smoother surface. Building parts in default settings may not assure adhesion of roads; although that the space between roads assumed to be built at 0 mm. Consequently this is causing heat residual stresses, which may exist between, built roads, this phenomenon can affect negatively the mechanical properties of the part and incur rougher surface.

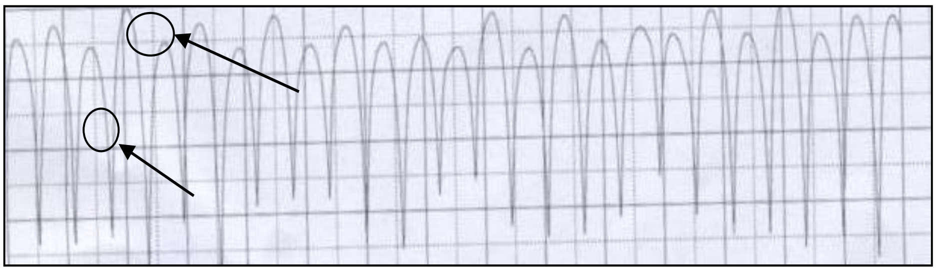

Figure 10 (A) Run No.3 oscilloscopic curve

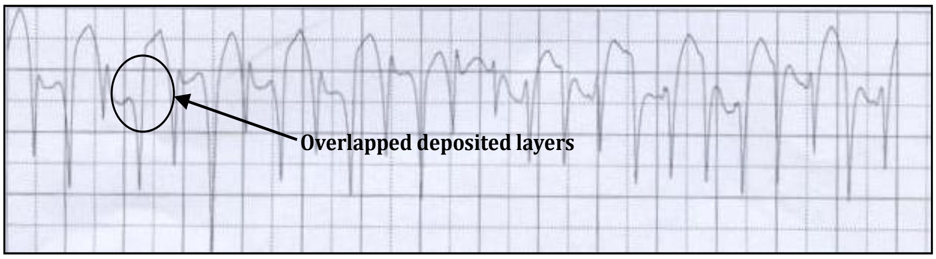

Figure 10 (B) Run No.14 oscilloscopic curve

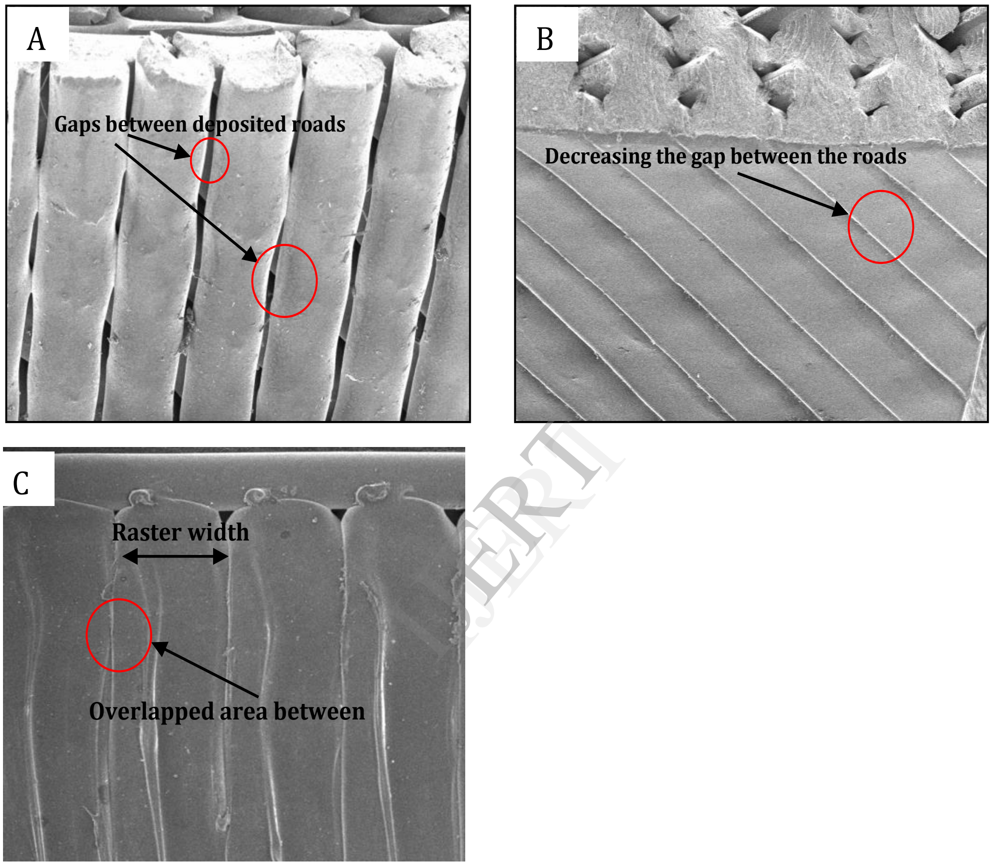

Figure 11 SEM work for negative air gap effect

Figure 12 shows the schematic diagram for the formation of bond between the molecules of ABS material and also illustrates the influence of the air gap - raster width – layer thickness parameters on surface roughness as concluded according to analysis results. In layer-by-layer fabrication the surface of part is stepped if the height of molecules is increased then the height of the step is increased too and the surface becomes rougher. Building part with negative air gap for -0.01 mm makes the molecules of ABS overlapped and the height of the steps between molecules. This works with the application of raster width at low level which reduces the width of the molecules while the layer thickness application at low level reduces the height of molecules, this in effect reduces the height of the steps between the deposited beads of material. Not many studies yet included the air gap parameter in their experiments to determine its correlation to the outcome of the SR response. In the majority of studies [5, 20, 21], the layer thickness and the raster width parameters were focused and also found significantly influence the surface roughness of the FDM building parts. In this study, the air gap parameter was found significantly correlated to surface roughness.

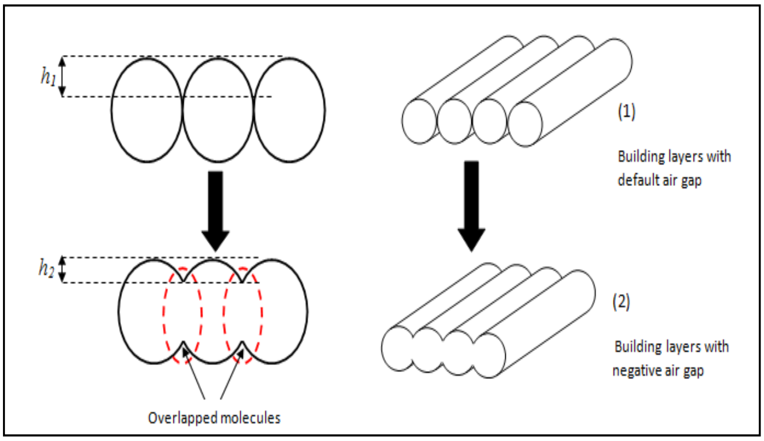

Figure 12 SEM work for negative air gap effect

Figure 13 shows the plot for the S/N ratio of the TS response. Layer thickness and raster width at low level has larger S/N ratio. Also air gap has larger S/N ratio at high level. It is likely that these significant factors influence inherently the fusion of ABS molecules. Moreover, previous studies reported that the degree of fusion and stacking between deposited beads play an importance role in the strength of the FDM parts where the molecules structure influences the stiffness of the parts [14, 22]. It has been found in this experimentation work that the experimental runs, which include air gap parameter, set to below 0 mm at -0.01 mm have exhibited better tensile strength and ductility than other experimental runs.

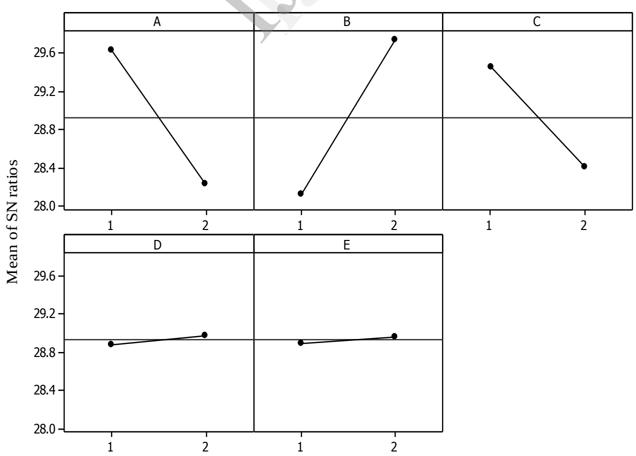

Figure 13 Signal to noise ratio: larger is better (response: TS)

According to the SEM pictures in Figure 14, two experimental runs were taken to demonstrate the influence of the air gap, (A) the air gap set to 0 mm, and (B) the air gap set to -0.01mm. Figure 14 (B) in contrast shows overlapped beads, also Figure 14 (C) shows deposited overlapped roads vertically where observed higher tensile strength. This is likely because when the molecules of ABS material were overlapped then the bonding between these molecules became stronger. Similarly, Figure 14 (A) the picture shows high level of layer thickness parameter where consequently the width of the ABS beads was increased, while in Figure 14 (B) the picture shows the low level of the layer thickness where the width of the ABS bead was minimized and the porosity between the ABS beads minimized too. This phenomenon can be interrupted that when layer thickness was reduced then consequently that affect the fibre width (w) and was reduced too (see Figure 14(B)).

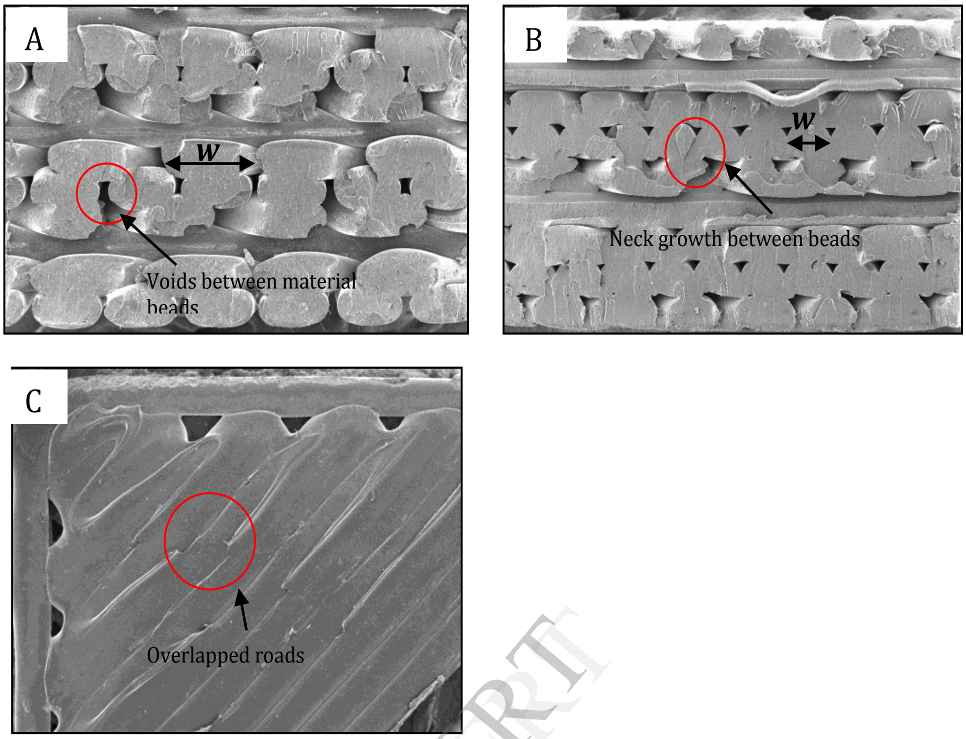

Figure 14 SEM detecting pictures of air gap influence on tensile strength

In this condition, the low level of layer thickness minimized the porosity between the ABS beads and therefor increased the amount of beads into the fracture; this condition has led to reinforce the composite structure of the building part. Similarly, the raster width parameter in horizontal direction, which found that, correlated to the tensile strength of FDM. Figure 15 showing the influence of FDM parameters on the SR and TS characteristics, these percentage were obtained according to the delta variation for means of analyzed parameters. It can be concluded that ABS-M30i is an anisotropic material, which highly depends on the FDM variable process parameters. The surface of the manufactured parts was the most affected or reacted by the involved process parameters in this study and at high percentage when compared with their influences on the tensile strength of the produced parts.

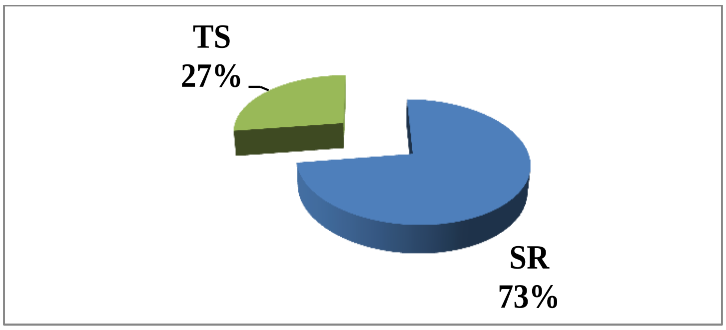

Figure 15 Influence of FDM parameters on the SR and TS characteristics

4. Validation of optimum results

From the results, the predicted combination of the optimum parameters settings of FDM process that was assumed to improve SR response is layer thickness at low level, air gap at high level and raster width at low level. The final stage confirms whether these predicted parameters levels could actually minimize average surface roughness value or not. The part used for confirmation results were produced using predicted optimum settings while other FDM parameters that were insignificant were set to default settings. Then an average of five readings of R_a value were recorded to be compared with some experimental runs, which produced lower R_a within experimental runs as shown in Figure 16.

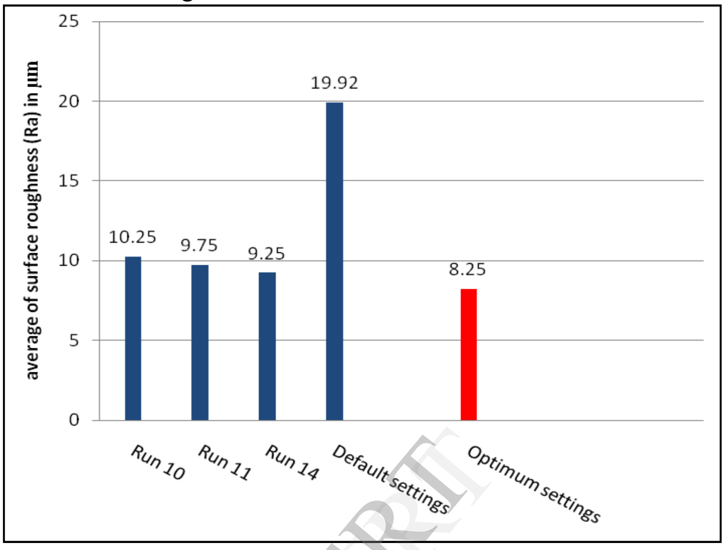

Figure 16 Validation run compared with other experimental runs (response:SR)

Figure 16 shows some experimental runs with lower R_a values in comparison to the default and optimum settings. All these runs were at layer thickness = 0.254 mm. It can be seen from Figure 16 that the optimum setting run has a lower R_a value of 8.25µm that was lower than other experimental runs and the default settings run. This result confirms that by applying these optimum parameters settings that was predicted earlier in the analysis can significantly reduced R_a value and minimize variability of the process. This result is significant as it can be used in tooling applications for rapid manufacturing.

For the TS response, confirmation run has been achieved for average of five tensile parts, in order to confirm the predicted optimum parameters settings that affect and increase tensile strength. The optimum parameters used in this confirmation step are: layer thickness and raster width at low level and air gap and at high level. Figure 17 shows the confirmation run where the predicted parameters settings were applied. It shows the confirmation run to validate optimum parameters settings in comparison to the default settings run and other experimental runs. It has confirmed that by applying the optimum parameters settings the tensile strength is increased.

In addition, In order to verify the influence of these optimum parameters in the analysis study, Table 4 provides a comparison between the predicted results against the actual results, which is according to the S/N ratio and the mean of results. From Table 4 the accuracy of the predicted resulted can be estimated. A small different can be noticed between predicted and the actual results associated with SR and TS responses. This small different between the predicted and the actual results confirmed that using these combinations could significantly improve the SR and TS outcomes.

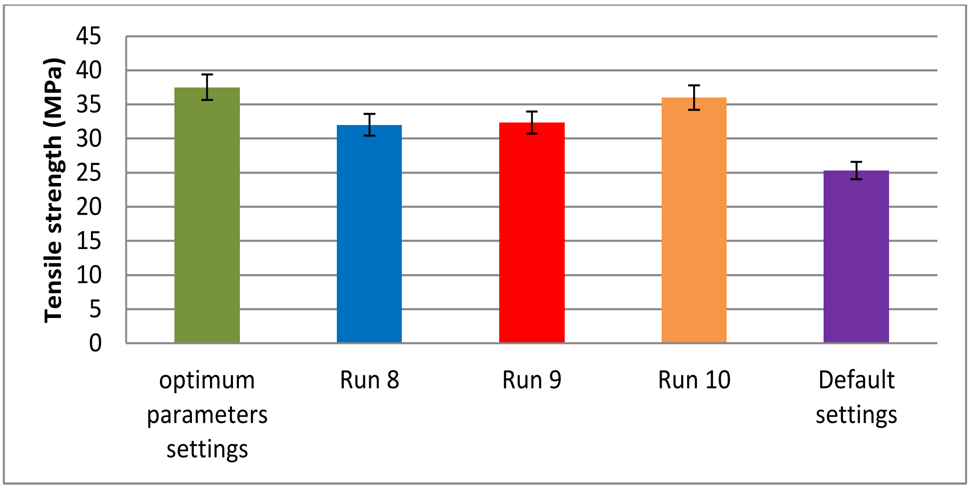

Figure 17 optimum parameters result versus experimentation and default settings

Table 4 Verification of experiment results (predicted versus actual)

Correlation		Predicted		Actual	
Response	**Optimum settings combination**	**S/N ratio**	**Means**	**S/N ratio**	**Means**
SR	A_1 /B_2 /A_1	-22.4316	13.7869 µm	-25.056	8.25 µm
TS	A1/B2 /C1	30.9642	29.70 MPa	29.707	37.51 MPa

5. Conclusion

In this paper, the surface roughness and tensile strength of FDM parts were investigated. Taguchi method L32 was used as the experimentation plan and parametric optimisation to evaluate the key characteristics based five variable parameters: layer thickness (A), air gap (B), raster width (C), contour width (D), and raster orientation (E). Some parts were initially produced by default settings to assess the capability of the FDM process regarding the key properties that were investigated later in this study. It can be concluded from this study that setting layer thickness and raster width at low level could minimize the surface roughness in addition to the air gap at -0.01 mm. Also the results demonstrated that adjusting layer thickness and raster width at low level and the air gap at -0.01 mm could obtain higher tensile strength. Finally, validation runs were carried out to confirm the predicted results according to Taguchi analysis tool. The results of validation runs confirmed the predicted analysis.

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