



# Experimental Study of the Wear Performance of Fused Deposition Modeling Printed Polycarbonate-Acrylonitrile Butadiene Styrene Parts Using Definitive Screening Design and Machine Learning-Genetic Algorithm

Omar Ahmed Mohamed, Syed Hasan Masood, and Jahar Lal Bhowmik

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The purpose of this study is to investigate the influence of fused deposition modeling (FDM) process parameters on the tribological behavior of PC-ABS built prototypes. Wear resistance of FDM manufactured parts in relation to the variation of FDM process parameters was analyzed and studied using definitive screening design and analysis of variance technique. The worn surfaces of some fabricated samples were also analyzed and investigated in this study by scanning electron microscope. Genetic algorithm was applied to optimize the wear resistance and to identify the exact effect of the input parameters. The results obtained from this study would have an impact on the FDM product performance in various industrial applications. This study demonstrates how the manufacturing parameters can be understood in FDM additive manufacturing technology. By implementing a similar approach, the optimum setting of process parameters, which gives the best tribological properties, can be determined whenever a new material is used for the FDM process.

**Keywords** ANOVA, definitive screening design, fused deposition modeling (FDM), genetic algorithm, process parameters, wear resistance

## 1. Introduction

Fused deposition modeling (FDM) is a commonly used additive manufacturing technology for high-throughput production of polymer parts. The FDM process has been used in the industrial manufacture of various products for the aerospace, electrical, telecommunication, electronic and automobile industries. High productivity rate, low manufacturing costs, excellent mechanical properties of the materials are some of the key features of the FDM process (Ref 1). When compared to other additive manufacturing (AM) technologies, FDM process has several advantages such as low cost of materials, low equipment costs, easy and safe to use, and no risk of material contamination (Ref 2-7). FDM is a layered manufacturing technology which refers to a process in which the part is manufactured layer-by-layer manner whereby a heat-softened material filament is extruded through the nozzle head into the build sheet directly from three-dimensional model data (Ref 8).

Due to the rapid continuous development and expansion of the plastic part manufacturing technologies to produce better quality products in a short processing time, there is an increasing demand in all areas of industry to replace the trial and error method of optimizing process parameters with intelligence optimization approach. The industrial practice of FDM has not changed significantly over the past few years. One drawback to FDM process is that the mechanical properties are strongly depend on a large number of conflicting process conditions, which mean the process requires more expertise and time to optimize (Ref 9-11). Similar to other AM technologies, FDM has a complex mechanism in producing part and is characterized by several critical process variables. This makes the relationship between the process conditions and the technical properties more challenging in interpreting the results in understanding the nonlinear correlation and interaction between the parameters. To create a good quality of FDM printed product, the FDM printing parameters have to be investigated and optimized. Knowledge of the use of the correct FDM process parameters is very important for additive manufacturing practitioners to produce products with high mechanical properties (Ref 12).

Wear resistance is one of the most important and useful mechanical properties of FDM products of interacting surfaces in relative motion (Ref 13). With the development of printable materials by additive manufacturing processes, the need for understanding the wear resistance of printed parts processed by the additive manufacturing processes is becoming important. The wear resistance of the FDM processed products is among the significant mechanical properties influenced by FDM manufacturing parameters. The study of the wear resistance is of great practical importance in the functioning of many engineered products such as mechanical, electro-mechanical, and biological parts (Ref 14, 15). Real criteria for FDM materials selection in a given application requires the wear

**Omar Ahmed Mohamed**, Aerostructures Innovation Research (AIR) Hub, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; **Syed Hasan Masood**, Department of Mechanical and Product Design Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; and **Jahar Lal Bhowmik**, Department of Health Science and Biostatistics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia. Contact e-mail: Omar.Ahmed.Mohamed@outlook.com.

characterization of the printed products under conditions that are most closely related to their possible functions and practical application.

In the past few years, many researchers (Ref 10, 16-24) have attempted to investigate the influence of different FDM process parameters on various mechanical properties. The majority of the literature has focused on the understanding and investigation of the effect of FDM process parameters on tensile strength, flexural modulus, compression strength and impact strength. However, the study of the effect of FDM process parameters on the wear properties on the built part has not been studied in details. So far, a literature review (Ref 1, 13, 25-27) confirms to date that only a few published studies have been performed to optimize the wear properties of FDM printed parts by determining the correct setting of the process conditions using different optimization techniques.

Although the aforementioned literatures provide relationships between process parameters and tribological properties for ABS materials (Ref 28-34), the effect of FDM process parameters on the wear resistance of PC-ABS material has not yet been addressed quantitatively. In addition, the current studies about the effect of FDM process parameters on the wear resistance were done using very few process variables (layer thickness, raster angle, part direction and air gap), but more FDM process parameters need to be considered which can make wider application of the results in various industries. Therefore, this study examines the relationship between the six selected process parameters (layer thickness, air gap, raster angle, build orientation, road width and number of contours) and the wear resistance using definitive screening design, genetic algorithm and analysis of variance (ANOVA) technique. The objective of this study is to extend process knowledge on FDM by maximizing the wear resistance of PC-ABS blend, increase FDM process control, and enable part wear resistance prediction by carrying out a comprehensive investigation of FDM through integration of definitive screening design and genetic algorithm which has not been considered in past studies. By establishing such relationship, the industry can benefit greatly from the understanding of the wear resistance of PC-ABS material in relation to change in FDM process parameters along with saving time and cost. Instead of performing a conventional design of experiment, this study proposes a novel approach of a definitive screening design (DSD) combined with genetic algorithm (GA) which allows the significant reduction of the number of runs required for optimization while minimizing aliasing. Using this approach, the manufacturing engineers can quantitatively evaluate and optimize the FDM process parameters in relation to the mechanical properties of the parts with minimum cost and materials consumption.

## 2. Materials and Methods

The flow diagram of the experimental methodology which demonstrates the sequence of work done is presented in Fig. 1. All testing specimens were manufactured by FDM Fortus 400 system. The computer aided design (CAD) models for all samples were created using Pro Engineer V5 CAD software then the CAD models were exported as Standard Tessellation Language (STL) file. After that, the STL is imported to the FDM Insight software version 9.1) to slice and to set all process

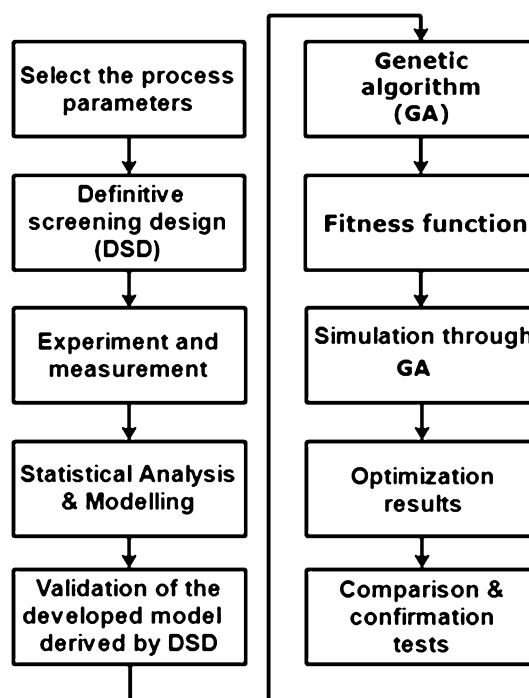


Fig. 1 Flow diagram of the experimental methodology

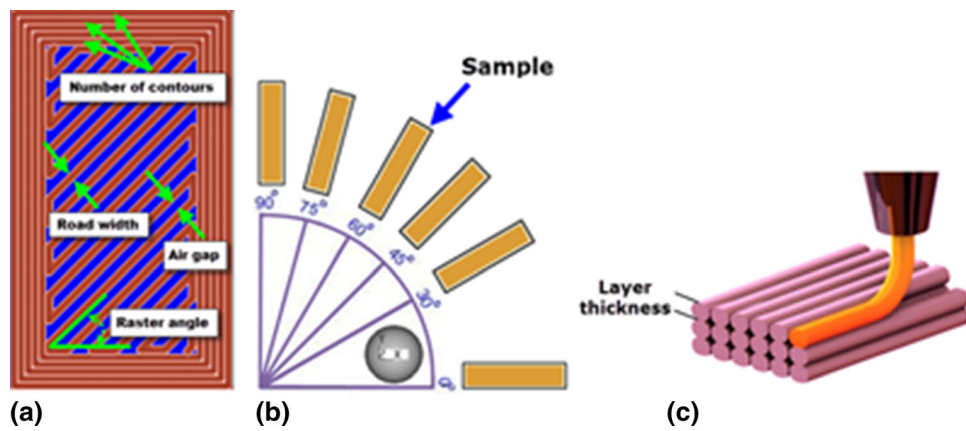
Table 1 Printing parameters and their levels

Factors	Units	Symbols	Levels		
			Low	Center	High
Layer thickness	mm	A	0.127	0.2540	0.3302
Air gap	mm	B	0	0.25	0.5
Raster angle	deg	C	0	45	90
Build orientation	deg	D	0	45	90
Road width	mm	E	0.4572	0.5177	0.5782
Number of contours	...	F	1	5	10

parameters for all specimens per the experimental design matrix (see Table 1). The polymer wear specimens considered in the experiments were 35 mm in length and 6 mm in diameter. In this study, Polycarbonate/Acrylonitrile-Butadiene-Styrene (PC-ABS) material was used as a substrate material for the tribological studies. PC-ABS blend is an amorphous engineering thermoplastic which consists of mixed PC and ABS materials. This material has a density of 1.098g/cm<sup>3</sup>. PC-ABS blend is commonly used in aerospace, automotive, and electronics applications (Ref 35, 36). This PC-ABS blend material, supplied for the FDM system by Stratasys, is ideal for direct manufacturing of prototypes, tooling and functional prototyping. It combines the most desirable mechanical properties such as superior mechanical strength and heat resistance along with the high flexibility. The sliding wear tests were conducted on a Nanovea pin-on-disk T50 tribometer without any lubricants as per ASTM G99 standard guideline. Sliding wear tests were performed under ambient conditions over a number of 10000 cycles and the applied load was 10 N at a fixed speed of 300 revolutions per minute (rpm). A plain EN31 steel disk with diameter of 14 mm was used as the counterpart.

**Table 2 DSD matrix of experiments and measured wear resistance**

Run	A	B	C	D	E	F	Wear resistance, m/mm <sup>3</sup>
1	0.127	0	0	90	0.4572	10	38.2320
2	0.3302	0.25	0	90	0.5782	1	31.1511
3	0.127	0.5	45	90	0.4572	1	59.9419
4	0.127	0.5	0	0	0.5782	5	82.7355
5	0.127	0	90	45	0.5782	1	67.8463
6	0.3302	0.5	0	45	0.4572	10	30.3305
7	0.2540	0	0	0	0.4572	1	44.7293
8	0.3302	0.5	90	0	0.5177	1	82.1615
9	0.127	0.25	90	0	0.4572	10	79.0686
10	0.3302	0	90	90	0.4572	5	54.2297
11	0.2540	0.5	90	90	0.5782	10	58.9891
12	0.2540	0.25	45	45	0.5177	1	55.0176
13	0.3302	0	45	0	0.5782	10	47.1937
14	0.2540	0.25	45	45	0.5177	5	54.8552
15	0.2540	0.25	45	45	0.5177	5	53.4000
16	0.2540	0.25	45	45	0.5177	5	52.1300



**Fig. 2** (a) Tool path parameters, (b) build orientation, and (c) layer thickness

The ambient temperature was approximately 75.2 K (24 °C) and the relative humidity roughly  $40 \pm 10\%$ . Before and after each test, the surfaces of the block specimens and rotating wear disk were cleaned with ethanol and acetone, followed by drying. The wear resistance of each sample was calculated by Eq 1. The wear rate was determined using Eq 2 by weighing the samples before and after testing through digital precision weighing with a precision of 0.001 g. Scanning Electron Microscopy (SEM) was used in this study to characterize the morphology for some samples. The samples were mounted onto a metal stub and sputter-coated with gold for 60 sec to make the samples electro-conductive. Then, the coated samples were inserted in the SEM to generate a variety of images at different magnifications.

$$\text{Wear resistance}(\text{m}/\text{mm}^3) = 1/\text{WR} \quad (\text{Eq 1})$$

where  $WR$  is the wear rate ( $\text{mm}^3/\text{m}$ )

$$\text{WR} = \frac{W_b - W_a}{\rho D} \quad (\text{Eq 2})$$

where  $W_b$  is the weight in gram before testing,  $W_a$  is the weight after testing,  $\rho$  is the material density ( $\text{g}/\text{mm}^3$ ) and  $D$  is the sliding distance (m).

A design of experiments (DoE) approach was used in this study to determine the relationship between the FDM process parameters as shown in Table 1, and wear resistance of FDM built parts. In order to investigate the effects of six process parameters simultaneously, with three levels each, while minimizing the number of printing sample jobs, the choice was made to use the newly developed class of three level experimental design known as definitive screening design (DSD). This technique determines the main effects, two-factor interactions and quadratic effects at a low cost (Ref 37). The main advantages of DSD over the traditional experimental designs are:

1. DSD requires minimum number of runs.
2. The main effects (not confounded) are independent of interaction effects.
3. The interaction effects are not confounded with each other.
4. Quadratic effects are estimable because they are orthogonal to the main effects and they are not confounded with the interaction effects.
5. In cases of studying the six variables such as in this study, DSD will be a powerful method of estimating full quadratic model with less number of runs.

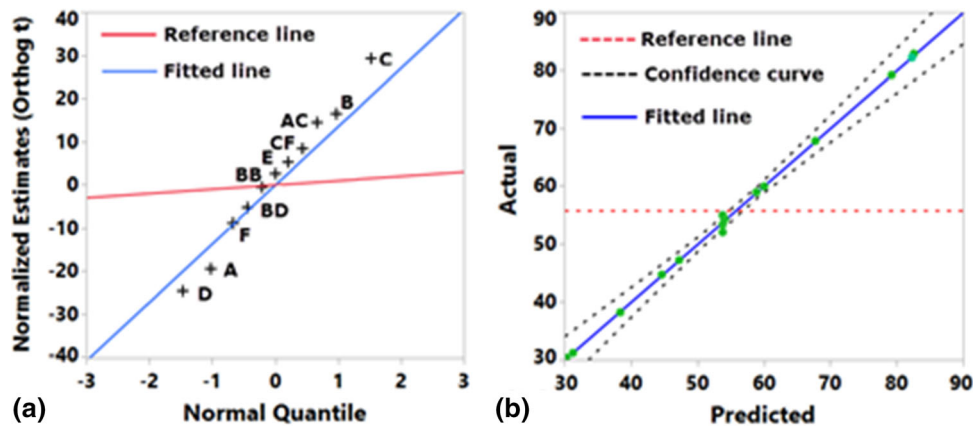


Fig. 3 (a) Normal probability plot, and (b) predicted versus actual plot

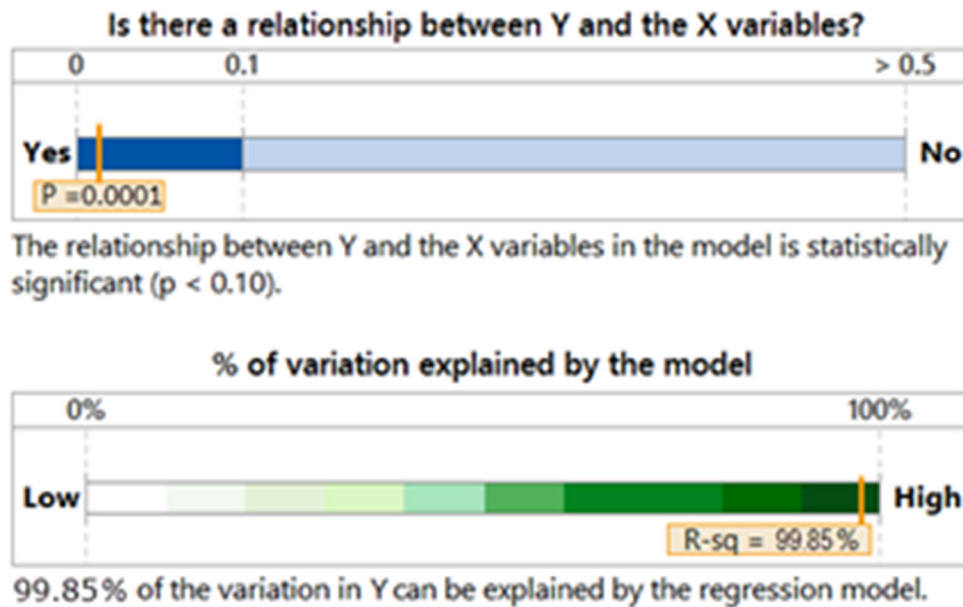


Fig. 4 Multiple regression analysis

Table 3 ANOVA results

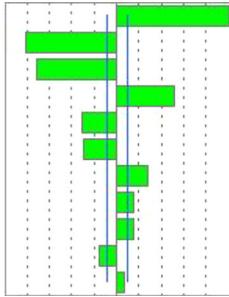
Source	Degree of freedom	Sum of squares	Mean square	F Value	P-value
Model	11	3913.2621	355.751	247.8092	<0.0001
Lack of Fit	1	0.2077242	0.20772	0.1126	0.7593
Pure Error	7	11.2769	3.28087	...	...
C. Total	19	3924.7667	...	...	...

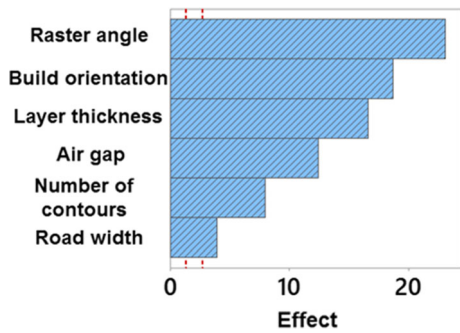
$R^2 = 99.85\%$ ,  $R^2$  Adj =  $99.45\%$ ,  $R^2$  Pred  $99.73\%$ , Root Mean Square Error (RMSE) = 1.198.

DSD involves  $(2F + 1)$  number of runs, where F is the total number of factors. Hence, to study the effect of the six FDM process parameters on the wear resistance of the built parts, a total number of 13 runs  $(2 \times 6 + 1 = 13)$  plus one center point are needed (Ref 37). However, in order to detect nonlinear relationships between the input process parameters and the wear resistance, three center points were added. This resulted in sixteen runs with different parameter sets. Thus, a total amount

of 16 PC-ABS pin samples were fabricated by FDM Fortus 400 system as per definitive screening design matrix presented in Table 2. The average value for each wear resistance was obtained from a set of values of three tested samples. The FDM process parameters are selected based on the previous studies (Ref 10, 16-24), equipment manufacturer and their significance. The selected process parameters are shown graphically in Fig. 2.

**Table 4** Parameter estimates

Term	Estimate	Std Error	F Value	Plot	P-value
C	11.48588	0.380853	30.16		<0.0001
D	- 9.36028	0.380853	- 24.58		<0.0001
A	- 8.149356	0.378302	- 21.54		<0.0001
B	5.9383844	0.379986	15.63		<0.0001
BD	- 5.749208	0.624236	- 9.21		0.0008
F	- 3.347099	0.379405	- 8.82		0.0009
CF	5.1427207	0.621884	8.27		0.0012
AC	2.8016583	0.622879	4.50		0.0108
E	1.7072044	0.379986	4.49		0.0109
DE	- 2.528404	0.566925	- 4.46		0.0112
BB	1.4914131	0.774344	1.93		0.1264



**Fig. 5** Pareto chart

The objective of this study is to maximize the wear resistance of FDM built part in relation to the process parameters. To investigate the effects of FDM process parameters quantitatively, multiple regression analysis was conducted based on quadratic regression model. All of the experiment results were analyzed using JMP and Minitab 17 software. The experimental data are fitted using quadratic polynomial regression model as expressed in Eq 3:

$$Y = \beta_0 + \sum_{i=1}^6 \beta_i X_i + \sum_{i=1}^6 \beta_{ii} X_i^2 + \sum_{i < j}^6 \beta_{ij} X_i X_j + \varepsilon \tag{Eq 3}$$

where  $Y$  is the response variable (wear resistance),  $\beta_0$  is the constant term of the regression model,  $X_i$  and  $X_j$  are dimensionless coded independent variables,  $\beta_i$  is the coefficient of the linear regression term,  $\beta_{ii}$  is the coefficient of quadratic term,  $\beta_{ij}$  is the coefficient of interaction term, and  $\varepsilon$  is the residual term.

In order to ensure that the quadratic model for wear resistance of the regression analysis fits the data well, all of the experimental data were checked through the residual plots to verify that the quadratic model exhibits normal distribution.

To determine the optimum FDM process parameters for maximizing the wear resistance, genetic algorithm (GA) was applied in this study. GA is a versatile nontraditional optimization technique which gives the exact and approximate optimal setting of the process variables because its working principle is based on the genetics and natural selection (Ref 38). GA is

commonly used to solve complex optimization problems in research and in machine learning. GA is usually characterized by the following aspects:

- GA works with the artificial genetic strings and not with the parameters in themselves.
- GA gives a number of potential solutions to the problem rather than giving a single solution and it does not need auxiliary knowledge.
- GA applies probabilistic transition procedures, not deterministic procedures.

### 3. Results and Discussion

Figure 3 shows the residual graphs of the wear resistance of PC-ABS built part as a function of the independent variables. It can be seen from the normal probability plot presented in Fig. 3(a) that all the residuals are following a straight line, demonstrating that the residual errors are normally distributed and scattered and the points tend to cluster along the 45 degree line. This indicates an adequate signal for the regression equation. Figure 3(b) shows the correlation between actual and predicted values. It can be observed from this Figure that the predicted values are in very good agreement with the actual (experimental) values, indicating that a goodness of quadratic model and its suitability to fit the data.

Multiple regression analysis results presented in Fig. 4 show that there is a strong relationship between the wear resistance of FDM built parts and the process parameters. This is evidenced by low probability value ( $p = 0.001$ ). Moreover, Fig. 4 indicates that 99.84% of the variation of the data can be explained by the quadratic model, suggesting that only 0.16% of total variation cannot be described by the model. This also means the difference (error) between the prediction and actual values (physical values) is 0.16%. This verifies the goodness of fit of the quadratic model.

The analysis of variance (ANOVA) was conducted to investigate the significance of the factors and results are presented in Table 3. It can be noticed that the FDM process parameters play a key role in the wear resistance of the printed part. Based on ANOVA results, the quadratic model is significant as the p-value being smaller than 0.0001 and the

$F$ -value is 247.8092. Meanwhile, the lack-of-fit test for the wear resistance regression model is not significant as the  $p$ -value is larger than 0.05. The parameter estimates result shown in Table 4 also shows that the process parameters such as  $A$ ,  $B$ ,  $C$ ,  $D$ ,  $E$ ,  $F$ ,  $AC$ ,  $BD$ ,  $DE$ , and  $CF$  are significant model terms.

By sorting the  $F$ -value through Pareto chart as shown in Fig. 5, the most critical factors were raster angle ( $C$ ), build orientation ( $D$ ) and layer thickness ( $A$ ) followed by air gap. The regression coefficients and regression equation presented in Eq 4 in terms of actual values were obtained for process output parameters using JMP statistical software. Equation 4 is the empirical model for the wear resistance as a function of the FDM process parameters of layer thickness ( $A$ ), air gap ( $B$ ), raster angle ( $C$ ), build orientation ( $D$ ), road width ( $E$ ) and number of contours ( $F$ ) in coded units.

$$\begin{aligned} \text{Wearresistance} = & 55.44 - 8.15 \times \left[ \frac{(A-0.2286)}{0.1016} \right] + 5.94 \times \left[ \frac{(B-0.25)}{0.25} \right] \\ & + 11.49 \times \left[ \frac{(C-45)}{45} \right] - 9.36 \times \left[ \frac{(D-45)}{45} \right] \\ & + 1.71 \times \left[ \frac{(E-0.5177)}{0.0605} \right] - 3.35 \times \left[ \frac{(F-5.5)}{4.5} \right] \\ & + \left[ \frac{(B-0.25)}{0.25} \right] \times \left\{ \left[ \frac{(B-0.25)}{0.25} \right] \times 1.49 \right\} + \left[ \frac{(A-0.2286)}{0.1016} \right] \\ & \times \left\{ \left[ \frac{(C-45)}{45} \right] \times 2.80 \right\} + \left[ \frac{(B-0.25)}{0.25} \right] \times \left\{ \left[ \frac{(D-45)}{45} \right] \times -5.75 \right\} \\ & + \left[ \frac{(D-45)}{45} \right] \times \left\{ \left[ \frac{(E-0.5177)}{0.0605} \right] \times -2.53 \right\} \\ & + \left[ \frac{(C-45)}{45} \right] \times \left\{ \left[ \frac{(F-5.5)}{4.5} \right] \times 5.14 \right\} \end{aligned} \quad (\text{Eq4})$$

The effect of the FDM process parameters on the wear resistance of manufactured part can be studied by the main effects plot presented in Fig. 6. It can be noticed from Fig. 6 that the wear resistance of FDM built part decreases with the increase in layer thickness from 0.127 to 0.3302 mm. The smaller the layer thickness, the smoother the processed surface will be. The smoother surfaces give lower coefficients of friction, hence wear resistance improves with using lower layer

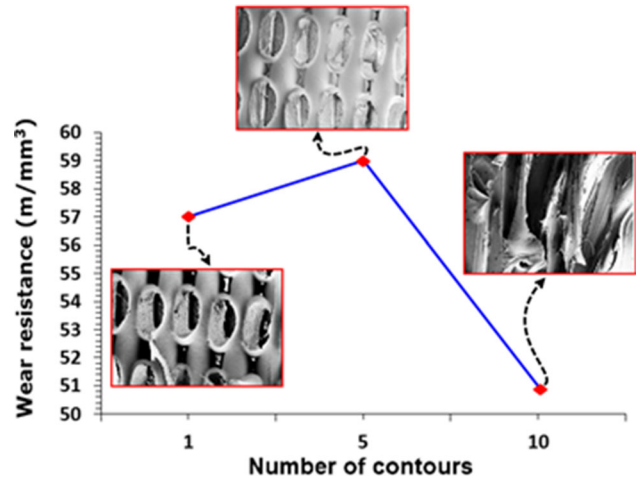


Fig. 7 Effect the number of contours on the wear resistance and part microstructure

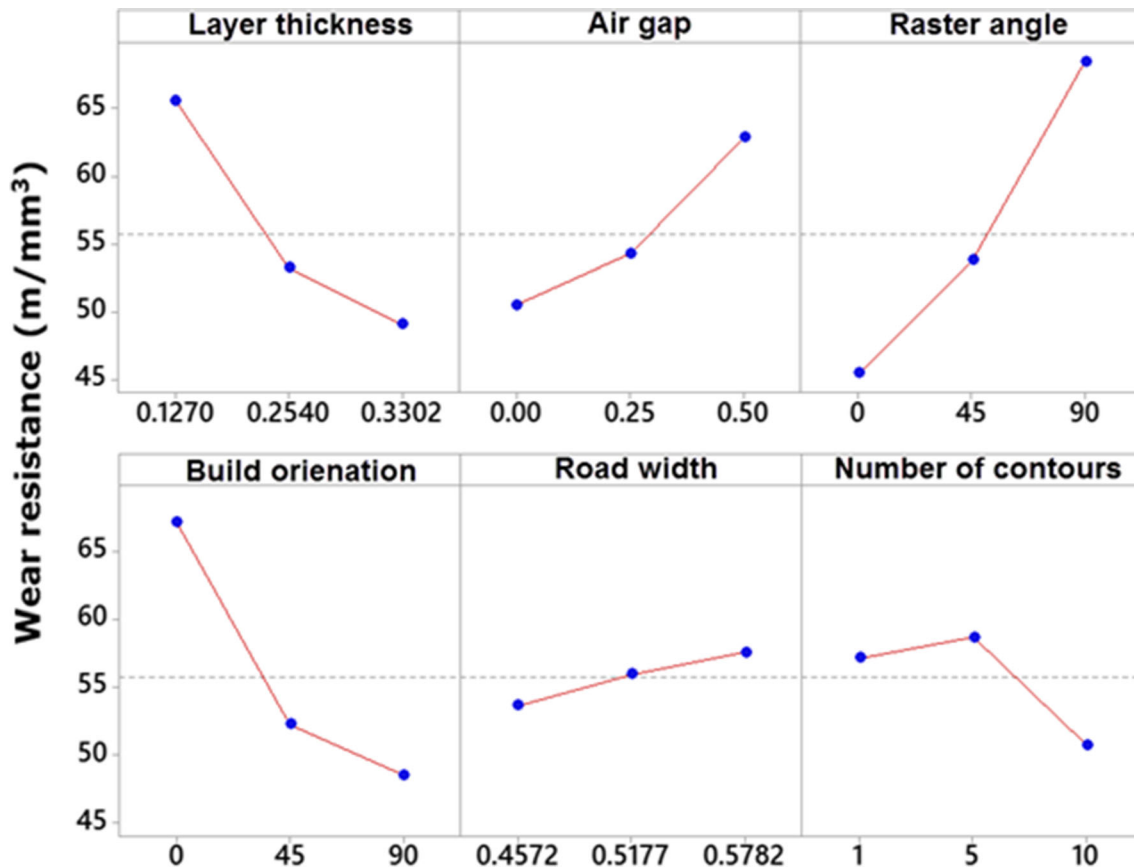
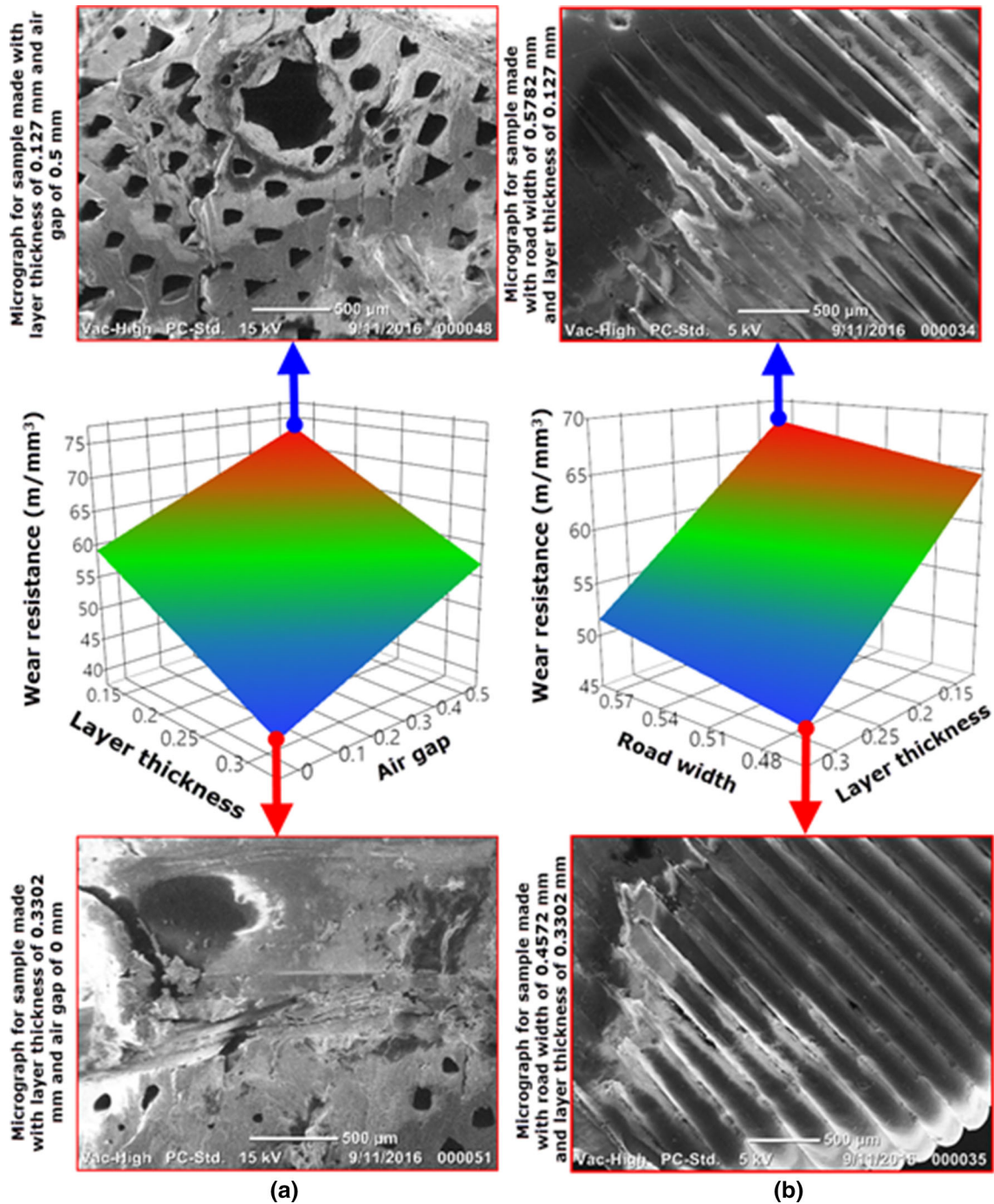


Fig. 6 Main effect plot



**Fig. 8** Morphology of worn surfaces under (a) combination of air gap and layer thickness, and (b) combination of road width and layer thickness

thickness. However, the manufacturing process will take longer time for thin layers as the machine is required to print more layers. From Fig. 6, it can also be seen that the wear resistance is increased with the increase in air gap. This is unexpected as air gap between deposited rasters can make the part brittle. However, the results obtained from this study show that the wear resistance of FDM built part can be improved by processing the part with higher values of air gap. A possible explanation of this outcome is that as the air gap increases between built rasters from 0 to 0.5 mm, a smaller amount of material removal and less interfacial contact area can be

achieved. Thus, the wear resistance is improved significantly. Raster angle also has a significant impact on the wear resistance as can be observed in Fig. 6. The variation of the wear resistance with respect to raster angle (Fig. 6) reveals that as the raster angle increases, the wear resistance of FDM printed part also increases. This is due to the fact that at high raster angle of  $90^\circ$ , the part rasters and alignment of the molecules are parallel to the applied load, resulting in much lower coefficients of friction between the FDM sample surface and the sliding wear disk surface.

The variation of the wear resistance with respect to the change in build orientation can also be seen in Fig. 6. It can be observed from this figure that the wear resistance reduces dramatically as the build orientation increases. This is due to the fact that as the build orientation increases from 0 to 90°, the stair-step effect is increased. This leads to increased surface defects and surface roughness and hence reduced wear resistance of the built part. Road width has a little influence on the part wear resistance. However, higher value of road width tends to improve the wear resistance slightly. This is due to the fact that higher value of road width produces thicker roads which may have good wear resistance. However, thicker roads can make the part surface rougher than the thinner road widths, which may also increase the amount of wear. But this depends on the interaction effect of road width with other process parameters. For instance, when the part is printed with lower thinner layer thickness and thicker road width then the microstructure of the printed part will be stronger as this combination of two parameters helps in improving the quality of melting and bonding interface between interlayers.

From the main effect plot (Fig. 6), it can be seen that in the beginning, when the number of contours is increased, the wear resistance is also slightly increased. As an increase in the number of contours produces multiple interior and exterior walls in the structure of the part, this consecutively increases the interface bonding strength and hence provides a high wear resistance. It can also be observed that when the number of

contours is 5, the wear resistance reaches the maximum value due to the 5 contours providing a more uniform roughness of the sample surface. With the progressive increase in the number of contours from 5 to 10, successive large numbers of walls are built, resulting in a large amount of polymer fibers, causing irregular surface profile and large deformation and thus resulting in reduced wear resistance of FDM built part. This outcome can be clearly seen in Fig. 7.

The effect of variations in the process parameters on the wear resistance of FDM produced parts was further investigated through SEM images combined with 3D response surface plots. Morphology of the FDM worn surfaces generated during sliding wear test with varying layer thickness, air gap and road width is shown in Fig. 8(a), (b). It is evident from Fig. 8(a) that the worn surface of the specimen fabricated with a combination of lower value of layer thickness and higher value of air gap showed smoother surface with little microstructure voids as compared to the specimen, which were fabricated with higher value of layer thickness and lower value of air gap. This is unexpected observation as the presence of higher air gap between rasters can always make the part weaker compared to the part fabricated with no air gap. A possible explanation for this apparent effect is that when the sample is processed by higher value of air gap between rasters then a relatively small volume of material removal can be achieved during dry sliding contact between surfaces. The existence of plastic deformation vestiges and fracture can also be observed on the worn surfaces of FDM manufactured part with higher value of layer thickness and lower value of air gap.

From Fig. 8(b), it can also be seen that the worn surface of FDM processed sample with a lower value of road width and a higher value of layer thickness was very rough and marked by deep grooves, while the worn surface of FDM built specimen with a combination of the higher value of road width and a lower value of layer thickness shows a relatively smoother counter face and wear marks due to the reduction in deep grooves. This is due to the fact that thinner layers will result in a better surface finish and surface flatness, leading to a higher wear resistance to friction. In tribology, parts with poor surface finish commonly wear faster and have higher friction coefficients compared to smooth parts. It was quantitatively shown in the previous studies (Ref 39) that the friction coefficient depended on surface roughness where the smooth surfaces minimize the friction coefficients. In this study, the surface roughness was measured in terms of arithmetic average roughness (Ra) using Surtronic 25 Surface Finish Tester as per ISO 4287:1997 (Ref 40). It can be seen from Fig. 9 that with the increase in surface roughness (high value of surface roughness means rough surface), a prominent increase in the coefficient of friction is noticed. A similar finding was also observed in a study conducted (Ref 41) for acrylonitrile butadiene styrene (ABS) material made by FDM.

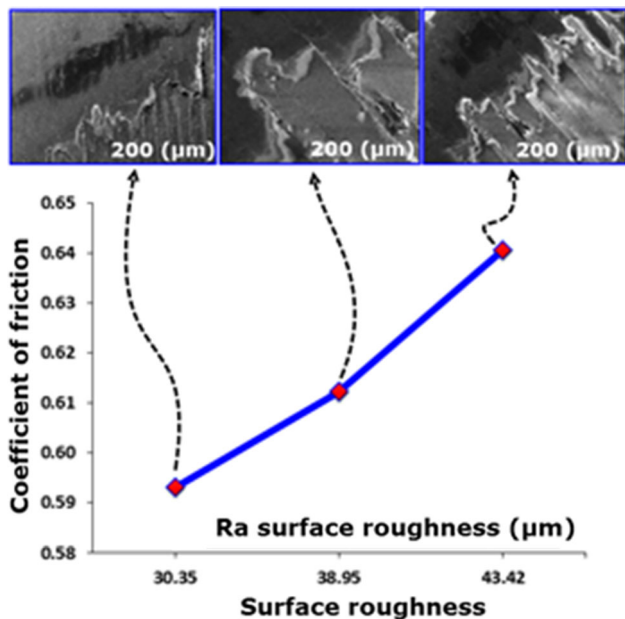


Fig. 9 Effect of surface roughness on the coefficient of friction

Table 5 Optimized process parameters and the confirmation experiment

Optimized process parameters							
Layer thickness, mm	Air gap, mm	Raster angle	Build orientation	Road width, mm	Number of contours	Wear rate (GA results)	Wear rate (experiment results)
0.127	0.45	88.9°	0.002°	0.5777	5	98.85211	95.7732



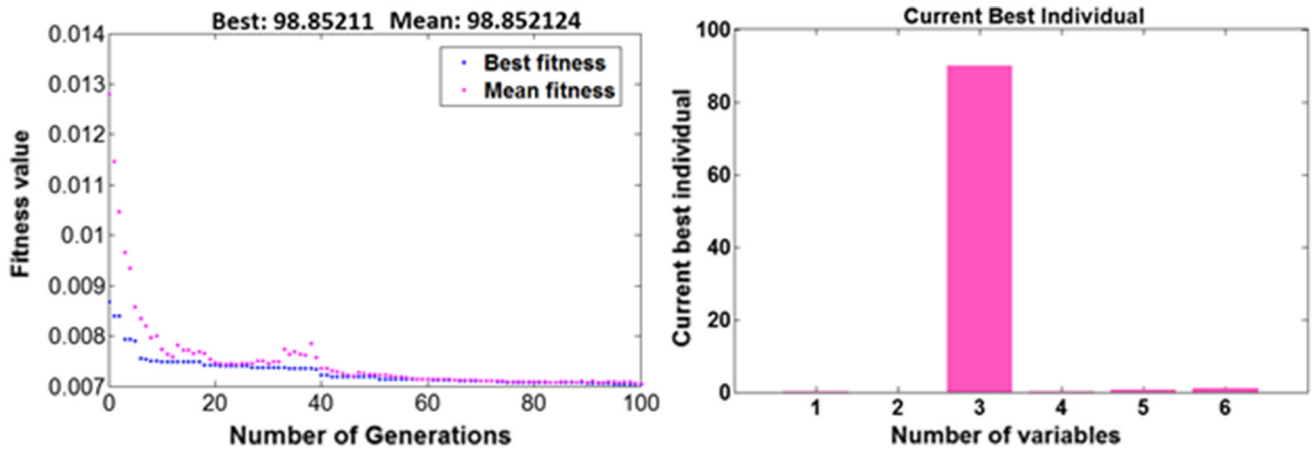


Fig. 10 Best and mean value of wear resistance

#### 4. Optimization through Genetic Algorithm

In this study, GA is adopted to determine the optimum FDM process parameters by obtaining the best and mean fitness values of wear rate and actual effect of the input variables. The mathematical equation developed through the DSD which is given in Eq 4, was used in the optimization process as a fitness function in GA. The input parameters are used to produce the chromosomes in the population.

In GA, the upper and lower bounds of input variables were assigned to optimize the wear rate by finding the optimal variables setting within the parameter limits. The best and mean fitness values of wear rate were produced by the algorithm and the optimal variables setting to minimize the wear rate is obtained after 100 simulations. The optimized values of the process variables obtained through GA were then compared to confirmation experiment and the results of this comparison are shown in Table 5. Figure 10 shows the best and mean fitness values of wear rate. From Fig. 10, it can be observed that the maximum wear resistance (optimal value) obtained in the last simulation is 98.85211  $\text{m/mm}^3$  and it compares well with the maximum wear resistance of 95.7732  $\text{m/mm}^3$  obtained from the confirmation experiment. After the testing, as shown in Table 5, the parameters settings, which gave the optimal wear rate, are determined as: layer thickness of 0.127 mm, air gap of 0.45 mm, raster angle of 88.9°, build orientation of 0.002°, road width of 0.5777 mm and 5 contours.

#### 5. Conclusions

Based on the experimental results obtained from this study, the following conclusions can be drawn:

1. The wear resistance of FDM printed part increases with the increase in air gap, raster angle and road width, whereas it reduces with the increase in layer thickness and build orientation. However, the wear resistance initially increased up to a center level of the number of contours then it starts decreasing with further increase in number of contours beyond the center level.

2. This study noted that the lowest and highest values for number of contours have less wear resistance when compared to the wear resistance at the center level of this variable. Hence, the optimum settings for number of contours must be at the center level to maximize the wear resistance of the printed parts by FDM process.
3. With the increase in air gap, the wear resistance of the printed parts by FDM can be improved significantly. A possible explanation of this outcome is that as the air gap increases between built rasters from 0 to 0.5 mm, a smaller amount of material removal and less interfacial contact area can be achieved.
4. It was noticed that the increase in raster angle, the wear resistance of the parts is also increased. This is due to the fact that at high raster angle of 90°, the part rasters and alignment of the molecules are parallel to the applied load, resulting in much lower coefficients of friction.
5. Any increase in road width would slightly improve the wear resistance of the part. This is because the higher value of road width produces thicker roads, resulting in good wear resistance.
6. Based on the SEM results of the worn surfaces, the FDM part processed by lower values of layer thickness was smoother compared to the FDM part manufactured by higher values of layer thickness.
7. The optimization results obtained through genetic algorithm have shown that the layer thickness of 0.127 mm, air gap of 0.45 mm, raster angle of 88.9, build orientation of 0.002, road width of 0.5777 mm and 5 contours are the optimal process conditions, which can be used to maximize the wear resistance of FDM manufactured parts.
8. Verification results of the experiment demonstrated that the experimental value of the wear resistance was in a good agreement with the predicted value.
9. Definitive screening design combined with the genetic algorithm showed greater improvements in the wear resistance using the optimized process parameters in the FDM process.
10. The results also showed that the integrated approach of definitive screening design and genetic algorithm was

instrumental in the selection of suitable process parameters for typical application.

## Conflict of interest

There is no conflict of interest.

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