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# Investigation of dynamic elastic deformation of parts processed by fused deposition modeling additive manufacturing

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**A B S T R A C T**

Fused deposition modeling (FDM) has been recognized as an effective technology to manufacture 3D dimensional parts directly from a digital computer aided design (CAD) model in a layer-by-layer style. Although it has become a significantly important manufacturing process, but it is still not well accepted additive manufacturing technology for load-carrying parts under dynamic and cyclic conditions due to many processing parameters affecting the part properties. The purpose of this study is to characterize the FDM manufactured parts by detecting how the individual and interactive FDM process parameters will influence the performance of manufactured products under dynamic and cyclic conditions. Experiments were conducted through fractional factorial design and artificial neural network (ANN). Effect of each parameter on the dynamic modulus of elasticity was investigated using analysis of variance (ANOVA) technique. Furthermore, optimal processing parameters were determined and validated by conducting verification experiment. The results showed that both ANN and fractional factorial models provided good quality predictions, yet the ANN showed the superiority of a properly trained ANN in capturing the nonlinear relationship of the system over fractional factorial for both data fitting and estimation capabilities.



**A R T I C L E I N F O**

*Keywords:*
Additive manufacturing
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Dynamic modulus of elasticity
Fraction factorial design
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## 1. Introduction

Fused deposition modeling (FDM) process is the most popular Stratasys-patented additive manufacturing technology. FDM is gaining importance in many manufacturing applications due to its ability to create complex prototypes without requiring any tools [1]. This process builds 3D shapes from a digital CAD file in a layer-by-layer format from the bottom by melting and extruding a fine filament of thermoplastic from the extrusion nozzle onto a base. The nozzle moves horizontally and vertically over the build table to translate the dimensions of part into the X, Y and Z axes.

Over the past decade, FDM process has gained increasing attention in the field of 3D manufacturing products. Although FDM has become a more sophisticated and the range of available materials continuing to grow, the application of this process in various industries is still not yet a fully accepted as a mature technique due to lower mechanical performance and performance of the fabricated parts compared with traditional manufacturing processes such as sheet metal forming, thermoforming and injection molding. The main reason for poor mechanical performance of FDM built parts is the existence of a great number of intervening processing conditions affecting the overall part quality[1]. For instance, incorrect settings of operating parameters can cause defects on the manufactured products, such as void structures. Hence, it is essential to understand and optimize the impact of operating conditions during on the processed prototypes.

During last couple of decade's extensive research has been carried out with limited success on optimizing FDM operating parameters for various quality characteristics such as mechanical properties, surface roughness, build quality and dimensional accuracy. For example, Wang et al. [2] reported that the mechanical performance can highly affected by part direction. This study also revealed that the highest mechanical strength can be obtained when the part was manufactured with minimum z-height. Rayegani and Onwubolu [3] have carried out an experiment on the impact of FDM operating conditions on mechanical strength of build parts. The results from this study have shown that small road width, negative air gap and zero build direction can improve the mechanical strength significantly. Sood et al. [4] concluded that thick layers and rasters with zero raster to raster air gap improve the mechanical characteristics significantly. Christiyan et al [5]reported that using low printing speed and low layer thickness can effectively improve the mechanical performance of FDM built prototypes. Impens and Urbanic [6] investigated the influence of post-processing settings on the mechanical characteristics for built parts. They found that build direction is the key factor in optimizing tensile and compression strengths for processed parts. Recently, Lanzotti et al. [7] studied the impact of process parameters like infill direction, slice height and perimeters on the prototype strength. This study reported that high variation in the mechanical strength can be noticed by changing in the level of each processing parameters. Very few studies have been made on the investigation of the effect of processing parameters on mechanical properties under cyclic loading conditions. For example, Arivazhagan et al [8] examined the influence of built style, road width, and raster pattern on the dynamic mechanical performance of polycarbonate manufactured part. Arivazhagan et al [9]conducted similar study on the effect of FDM operating conditions but on the part made by ABS material. In both studies, they conducted their experiments based on the trial and error approach. Their results indicated that the maximum dynamic performance can be obtained by using solid build style, 45° raster pattern and 0.454 mm road width.

Although during last decade a remarkable progress has been made in FDM process parameters optimization technique, but most of the existing literature focused only on improving the mechanical properties under static leading conditions. In fact, the parts manufactured by the FDM process are also subject to vibratory and cyclic conditions for long-term prediction with wide range of temperatures. There are two studies done so far on dynamic mechanical properties. However, they are expensive due to the use of one-factor-at-a-time (OFAT) method as well as they are limited in terms of the number of processing parameters being investigated and type of dynamic mechanical property observed. OFAT method cannot lead to optimal process settings and the relationships between the processing conditions and dynamic mechanical response using this approach are still unclear.

This paper differs from all previous studies in several ways. Firstly, unlike previous studies, which focused on the effect of FDM processing parameters on the static mechanical properties of the manufactured parts, this study examines the effect of FDM process conditions on the dynamic mechanical properties that resulted in understanding the material behaviour under cyclic loading conditions. Secondly, unlike most previous studies that aimed at investigating the influence of only few FDM process parameters, this paper considers the effect of six FDM processing parameters including a new variable – number of contours – which was not studied in the published literature before. Finally, unlike most previous studies, this study explores whether there is a significant relationship between the FDM process parameters and dynamic mechanical property, namely dynamic modulus of elasticity using fraction factorial design, regression analysis and artificial neural network (ANN). Results show that optimal process parameters lead to achieve desired dynamic modulus of elasticity of FDM produced part. Results obtained from this study would be useful for industry application and would help to produce the end user products with desired dynamic mechanical properties. It also can be used as a guide for planning and carrying out future studies.

## 2. Materials and methods

The experiments in this study were designed and performed using fraction factorial design. Fraction factorial design experimental design is commonly used to determine the most critical factors in the early stages of experimental work, when several process parameters are likely to be investigated as well as when the knowledge about the process is usually unavailable[10, 11]. This study used the stipulated conditions according to the fraction factorial design to plan the experiments. A total of 16 experiments were conducted at two levels of each input parameter. Two level fraction factorial experiment involves an experimental design in which each parameter is investigated at two levels. The early stages of experimental work and investigation usually involve the study of a large number of parameters to determine the vital parameters important for the system. Two level fraction factorial design is used in these stages to find out unnecessary factors so that attention can then be made only on the critical factors. The data were analysed using STATISTICA software. The experimental design used in this study considered the following processing parameters to investigate their effect on the dynamic modulus of elasticity; layer thickness (A), air gap (B), raster angle (C), build orientation (D), road width (E) and the number of contours (F). The selected process parameters and their levels are presented in Table 1 and they are selected according to the previous studies and FDM machine manufacturer (Stratasys) guide. The FDM build parameters are presented in Fig. 1.

**Table 1** FDM process parameters and their levels

| Factors | Units | Code | Levels | |
|---|---|---|---|---|
| | | | Low | High |
| Layer thickness | mm | A | 0.127 | 0.3302 |
| Air gap | mm | B | 0 | 0.5 |
| Raster angle | deg | C | 0 | 90 |
| Build orientation | deg | D | 0 | 90 |
| Road width | mm | E | 0.4572 | 0.5782 |
| Number of contours | - | F | 1 | 10 |

A total of 16 samples having dimension of 35 (length) mm × 12.5 mm (width) × 3.5 mm (thickness) were fabricated by FDM Fortus 400 as per designed plan presented in Table 2 and tested according to ASTM D5418 [12] and TA instrument manufacturer recommendations [13]. All samples are made by PC-ABS material which has amorphous structures. Dynamic modulus of elasticity is a viscoelastic property that exhibit both viscous and elastic behaviors which is present in the material or manufactured part during undergoing deformation. It is the ratio of peak dynamic stress to peak dynamic strain under vibration and harmonic loading. Therefore, dynamic modulus of elasticity measures the sample and material resistance to deformation [14].

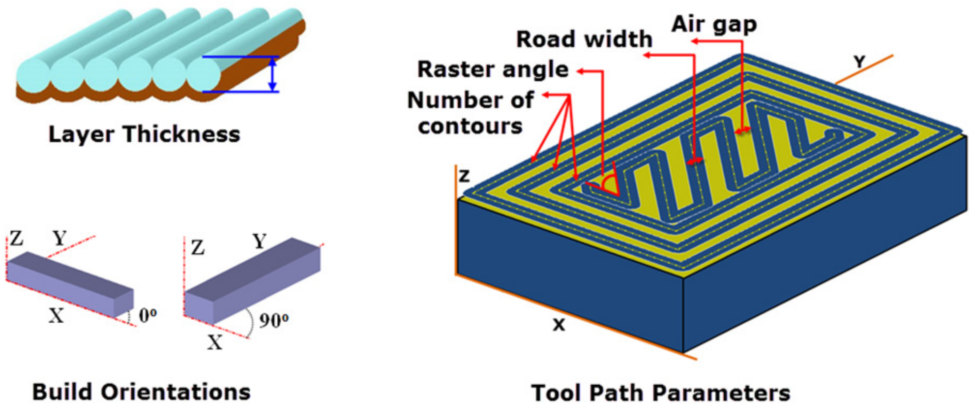


**Fig. 1** FDM build parameters

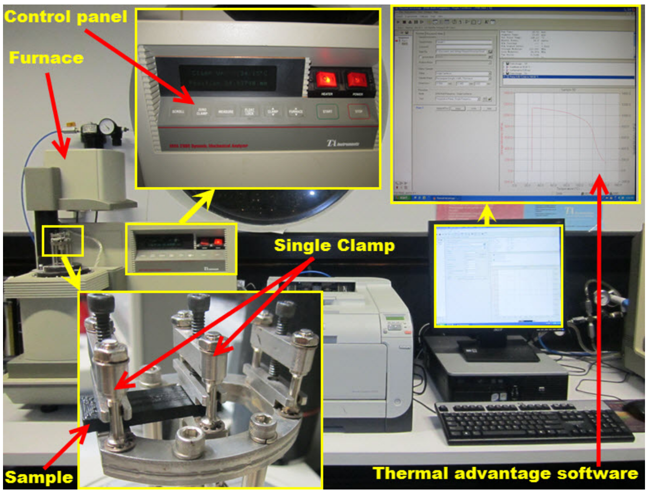


**Fig. 2** Schematic illustration of dynamic mechanical test

The dynamic mechanical response in terms of dynamic modulus of elasticity of the 16 samples was measured using 2980 Dynamic Mechanical Instrument in the bending mode with single cantilever. Dynamic mechanical measurement was done with single frequency of 1 Hz with a heating rate of 3 °C /min, oscillation amplitude of 15 µm, and the temperature ranges between 35-170 °C with soaking time of 5 min. The stress-strain curve, which was generated by dynamic mechanical machine and analysed by Thermal Advantage Software, has been used to determine the maximum dynamic modulus of elasticity for each experimental run according to fraction factorial design matrix plan. The average of the maximum values of dynamic modulus of elasticity was taken from a set of tested samples. The experimental design plan in terms of coded parameter with the measured dynamic modulus of elasticity is presented in Table 2.

**Table 2** Experimental design matrix

| Run | A | B | C | D | E | F | Dynamic modulus of elasticity (MPa) |
|---|---|---|---|---|---|---|---|
| 1 | 0.127 | 0.5 | 90 | 0 | 0.4572 | 1 | 4.255 |
| 2 | 0.127 | 0.5 | 90 | 90 | 0.4572 | 10 | 11.028 |
| 3 | 0.127 | 0 | 90 | 0 | 0.5782 | 10 | 12.339 |
| 4 | 0.127 | 0 | 0 | 90 | 0.4572 | 10 | 12.946 |
| 5 | 0.127 | 0.5 | 0 | 90 | 0.5782 | 1 | 5.542 |
| 6 | 0.127 | 0.5 | 0 | 0 | 0.5782 | 10 | 13.056 |
| 7 | 0.127 | 0 | 90 | 90 | 0.5782 | 1 | 10.881 |
| 8 | 0.127 | 0 | 0 | 0 | 0.4572 | 1 | 12.228 |
| 9 | 0.3302 | 0.5 | 90 | 0 | 0.5782 | 1 | 4.732 |
| 10 | 0.3302 | 0 | 90 | 0 | 0.4572 | 10 | 14.287 |
| 11 | 0.3302 | 0 | 90 | 90 | 0.4572 | 1 | 12.829 |
| 12 | 0.3302 | 0.5 | 0 | 90 | 0.4572 | 1 | 4.240 |
| 13 | 0.3302 | 0 | 0 | 90 | 0.5782 | 10 | 12.771 |
| 14 | 0.3302 | 0.5 | 90 | 90 | 0.5782 | 10 | 11.504 |
| 15 | 0.3302 | 0 | 0 | 0 | 0.5782 | 1 | 12.054 |
| 16 | 0.3302 | 0.5 | 0 | 0 | 0.4572 | 10 | 11.753 |

## 3. Results and discussion

The relationships between measured dynamic modulus of elasticity and the FDM process parameters were developed by fitting the data in a two-factor interaction (2FI) model presented in Eq. 1, where, Y is the predicted response (dynamic modulus of elasticity), $\beta_0$ is a constant intercept, $\beta_i$ is the coefficient for the linear terms, $\beta_{ij}$ is the interaction coefficient, $X_i$ and $X_j$ are the coded factors, and and $\varepsilon$ is the random error term.

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

The ANOVA technique was employed to test the significance of the main effects and the two-factor interaction effects for maximum dynamic modulus of elasticity. The experimental results for maximum dynamic modulus of elasticity in relation to process parameters are shown in Fig. 3(a) using half-normal plot ($\alpha = 0.05$). For each of the F test (Fisher's test) 0.05 level of significance is used to analyze the data obtained from factorial design experiment. Typically, the higher value of F-ratio indicates higher impact of that factor on the dynamic modulus of elasticity. Backward elimination of insignificant effects was applied. Insignificant linear terms were included in the regression model if they have significant interaction effect with other main effect. The correlation coefficient ($R^2$) is used to measure how well the developed model accurately represents the experimental data. The $R^2$ value is between 0 % and 100 %. It is clear from ANOVA result presented in Table 3 that the values of $R^2$ (98.38 %), adjusted $R^2$ (97.30 %) and predicted $R^2$ (94.89 %) are considerably high and hence the developed regression model fits the experimental data well. The final developed regression model for dynamic modulus of elasticity (in MPa) is presented in Eq. 2:

$$\begin{aligned} Dynamic\ modulus\ of\ elasticity = {} & 12.879 - 3.634A - 15.957B - 0.028C + \\ & 0.121F + 0.107AC + 1.346BF \end{aligned} \tag{2}$$

It can be concluded from Fig. 3(a) that the points which are located away from the fitted line indicate the significant model terms for dynamic modulus of elasticity. Findings from this plot confirmed that the air gap (B), number of contours (F) and their interaction have a significant influence on dynamic modulus of elasticity. However, layer thickness (A) is not a significant factor, but its interaction with raster angle (C) has a strong influence on dynamic modulus of elasticity. The assumptions can be tested and checked through the normal probability plot. The normal probability plot presented in Fig. 3(b) shows that the experimental data fall linearly close to the fitted line, which demonstrates that the model perfectly describes the population data.

Fig. 4(a) shows the predicted values versus the actual values plot. This plot shows that the fitted values of response are in high correlation with the actual values, which demonstrates an adequate signal for regression model. Fig. 4(b) represents the externally residual versus run number order of dynamic modulus of elasticity. It is clear from Fig. 4(b) that there are no outliers found in the residuals plot. All residuals are consistently distributed along the run number. Fig. 4(c) shows leverage versus run number to ensure that no run has high value of leverage which may affect the model. This figure shows that all runs are fitted exactly with no residual and with no high leverage.

**Table 3** ANOVA results

| Source | Sum of squares | Degree of freedom | Mean square | F- Value | Prob > F |
|---|---|---|---|---|---|
| Model | 182.11 | 6 | 30.35 | 91.25 | < 0.0001 |
| A | 0.22 | 1 | 0.22 | 0.67 | 0.4327 |
| B | 73.21 | 1 | 73.21 | 220.09 | < 0.0001 |
| C | 0.47 | 1 | 0.47 | 1.40 | 0.2664 |
| F | 67.75 | 1 | 67.75 | 203.67 | < 0.0001 |
| AC | 3.80 | 1 | 3.80 | 11.44 | 0.0081 |
| BF | 36.66 | 1 | 36.66 | 110.22 | < 0.0001 |
| Residual | 2.99 | 9 | 0.33 | - | - |
| Total | 185.11 | 15 | - | - | - |

$R^2$ = 98.38 %, Adjusted $R^2$ = 97.30 %, Predicted $R^2$ = 94.89 %, Adequate precision = 25.454

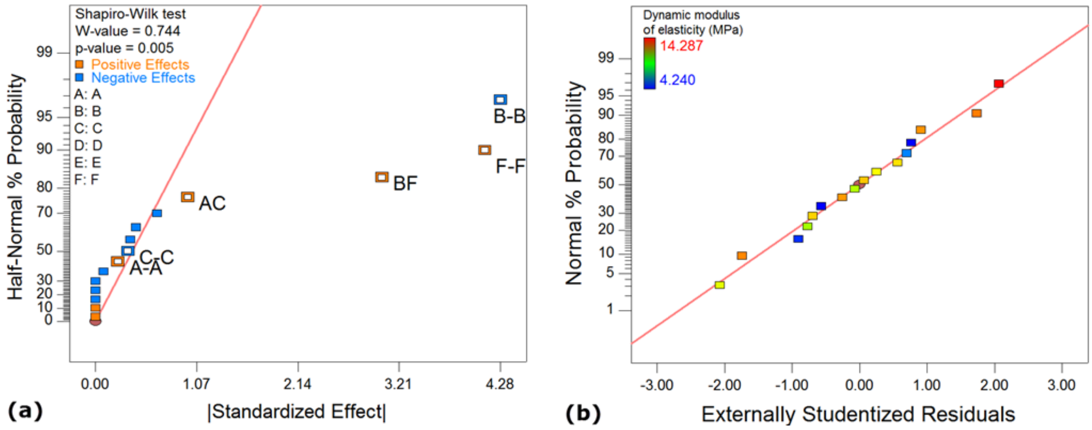


**Fig. 3** (a) half normal probability plot of the standardized effects, and (b) normal probability plot, for dynamic modulus of elasticity

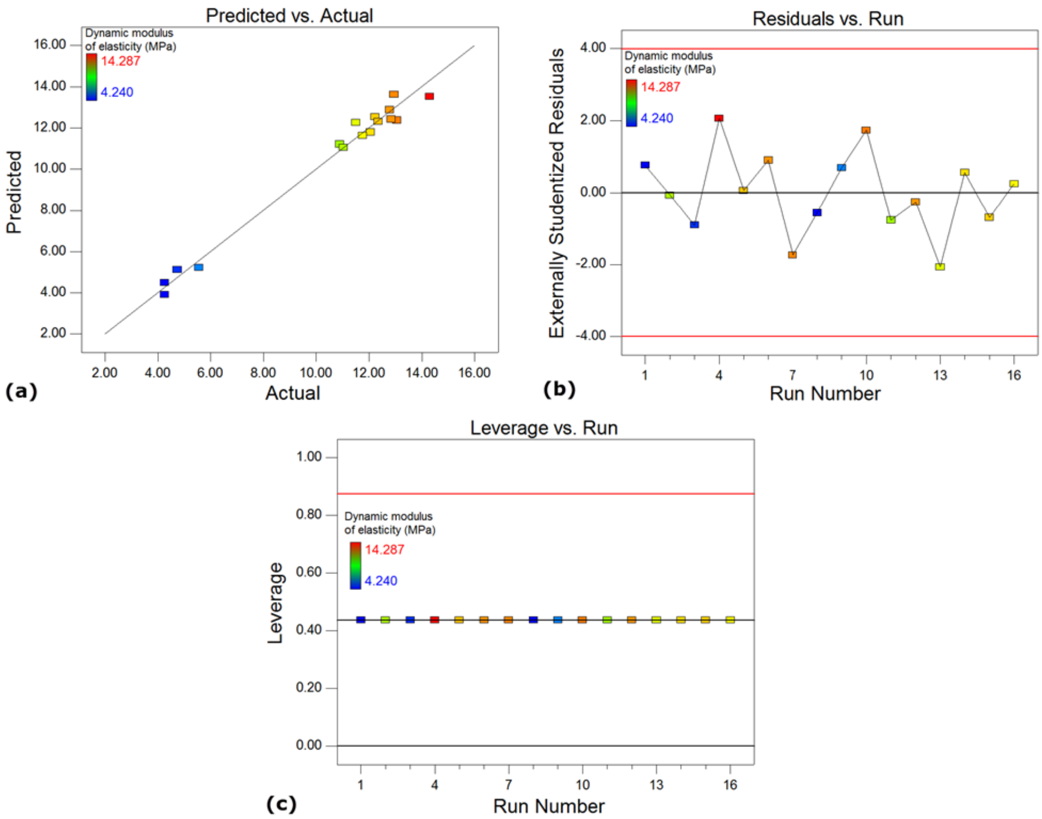


**Fig. 4** (a) predicted versus actual plot, (b) residual versus run number plot, and (c) leverage versus run number plot

Effect of layer thickness (slice thickness) on the dynamic modulus of elasticity of the parts can be seen in Fig. 5. With the increase in slice thickness, dynamic modulus of elasticity of the part slightly increased. It is because as the layer thickness increases, it produces thick rasters with minimum number of layer. This leads to the improvement in dynamic mechanical properties of the built part. Nevertheless, if the part is fabricated with thin layers, there would be micro-voids and tear in a part surface (see Fig. 6). Thus the sample processed with thin layers exhibits lower mechanical performance. Fig. 5 reveals the influence of air gap on the dynamic modulus of elasticity. It is found that with an increase in air gap, dynamic modulus of elasticity decreases gradually. The main reason is that when the air gap increases, a close raster and deposited beads are generated, which leads to a dense structure resulting in improvement in dynamic modulus of elasticity of parts.

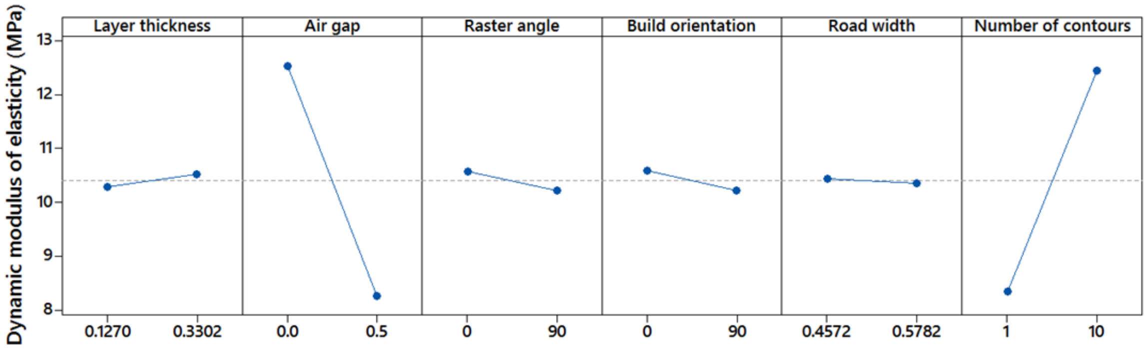


**Fig. 5** Effect of various operating conditions on dynamic modulus of elasticity

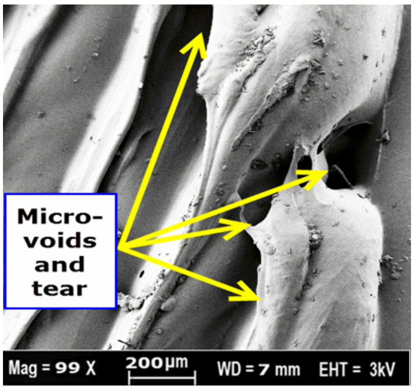


**Fig. 6** Microstructure observation of the effect of thin layer on the properties of the manufactured part

Fig. 5 also shows the impact of raster angle (raster pattern) on the dynamic modulus of elasticity on the samples built through FDM. It has been observed the dynamic modulus of elasticity for the manufactured part decreases with increasing raster angle from 0° to 90°. The main reason behind this phenomenon is that when the raster angle increases, the energy absorbed by the manufactured part decreases. This is due to the fact that at raster angle of 90° an adhesive failure occurs at the bonding interface level of the deposited layers (see Fig. 7). This leads to reduction in the dynamic modulus of elasticity of the processed part. Fig. 7 clearly shows the phenomena behind the influence of two raster's angles on the dynamic modulus of elasticity.

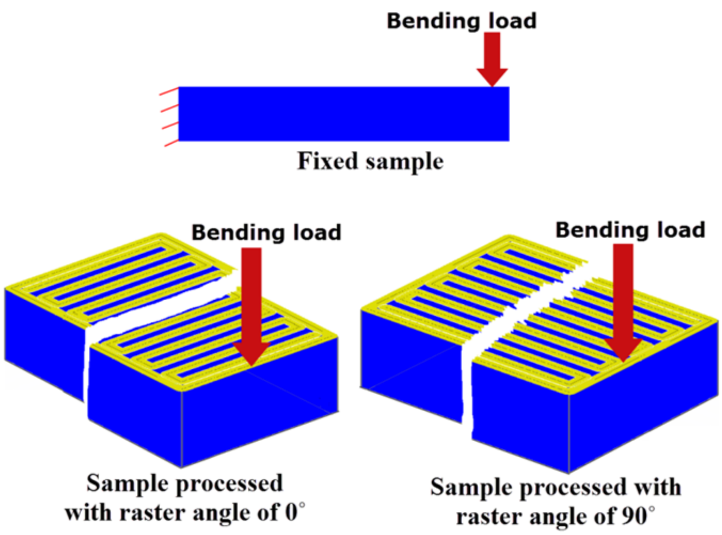


**Fig. 7** Failure of different rasters under periodic bending load

The effect of build orientation on dynamic modulus of elasticity is illustrated in Fig. 5. To acquire high deformation resistance for the fabricate part, it is preferable to manufacturing the part along the X-axis (0°) as this can greatly improve the curve definition for rasters, and can decrease stair-stepping effect. Fig. 5 indicates that the road width has no effect on the dynamic modulus of elasticity. Thus this factor has been removed from the regression model expressed which is by Eq. 2. However, in general it is advisable to use thin road width as thin road width provides finer raters and layers, which helps in filling more spaces on the part structure. Thus the built parts tend to have better mechanical properties, better dimensional accuracy and improved surface roughness. The effect of number of contours on dynamic modulus of elasticity is shown in Fig. 5. The results indicate that higher values of dynamic modulus of elasticity can be obtained by considering 10 contours. The maximum contour lines can guarantee elevated absorb and discharge energy levels and help the part to return to its original position after the stress is released. Because the reason for this improvement is maximum number of contours reduces the number of rasters, which helps to create the solid and dense structure (see Fig. 8) and hence increases the dynamic modulus of elasticity.

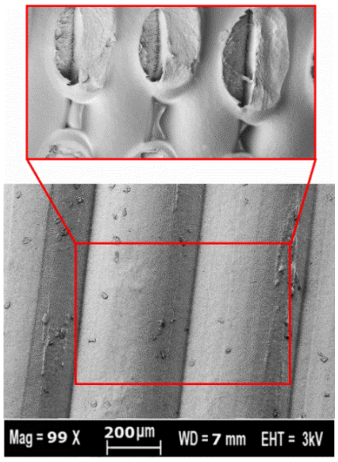


**Fig. 8** Microstructure observation of the effect of 10 contours on the properties of the manufactured part

Fig. 9 portrays the dual influence of air gap and number of contours on dynamic modulus of elasticity at a constant level of the other processing parameters. It can be concluded that maximum dynamic modulus of elasticity is feasible with a combination of low air gap and higher number of contours. However, an interesting phenomenon can be noticed from Fig. 9 that using highest value of air gap along with maximum number of contours higher dynamic modulus of elasticity can still be obtained. This is because the part still has solid structure under this parametric combination, and hence this combination of process parameters helps to improve the mechanical properties while reducing the production cost as positive air gap minimizes the processing time.

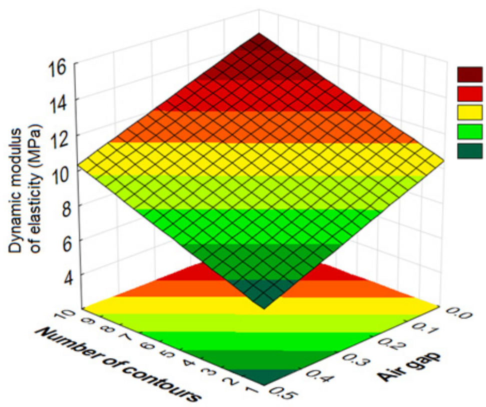


**Fig. 9** Combined effect of air gap and number of contours on dynamic modulus of elasticity

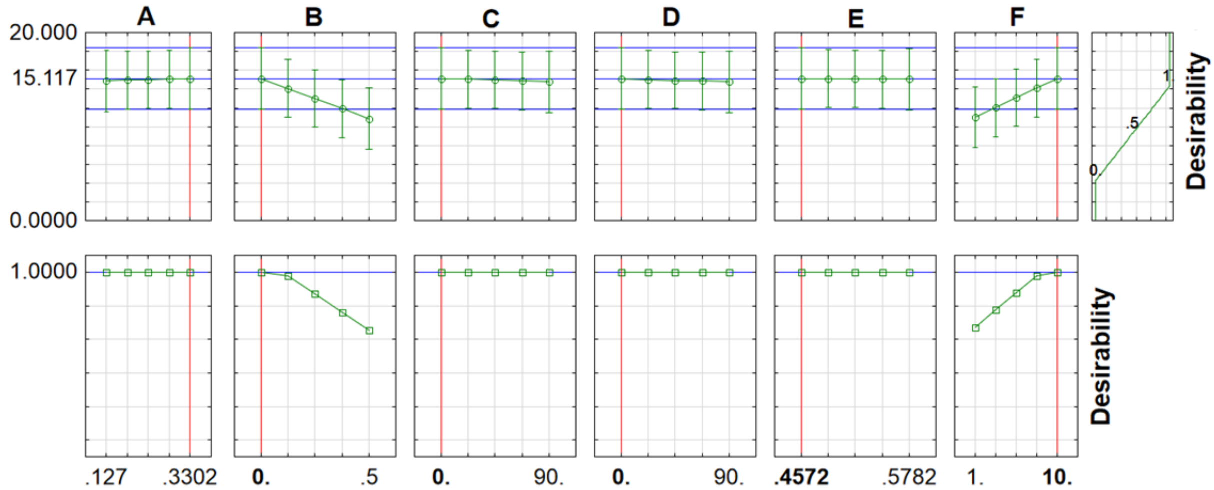


**Fig. 10** Optimization results

Process optimization was conducted to find the optimal parameter setting to maximize dynamic modulus of elasticity of the part. In this investigation the search-based optimization process described by Derringer function has been used. Accordingly, the optimal parameter setting to optimize the dynamic modulus of elasticity of the part is presented in Fig. 10. Overall, it can be concluded that the optimal parameter setting is: A = 0.3302 mm, B = zero air gap, C = 0°, D = 0°, D = 0.4572 mm and F = 10. Confirmation experiment was also done at the predicted dynamic modulus of elasticity under the optimal parameter setting. The results from the confirmation experiment has shown that maximum dynamic modulus of elasticity of 14.6289 MPa was obtained, which is in a very good agreement with the predicted value of 15.117 MPa.

The desirability index for each of the parameter combination obtained for each experimental run presented in the design matrix of Table 2 was determined in order to compare each desirability index for each experimental run with the optimal process parameter (Fig.10). This helps us to understand how each set of parameter combination in experimental design matrix in Table 2 satisfies the dynamic modulus of elasticity. It can be noticed from Fig. 11 that the optimal process parameter presented in Fig. 10 has the highest desirability index of 1. This indicates that the optimal process parameter is highly desirable for achieving a high dynamic modulus of elasticity of FDM fabricated part.

For comparison purpose, the data used for the optimization of dynamic modulus of elasticity by fractional factorial design has also been used for optimization by artificial neural network (ANN) based on multilayer perception (MLP). In this case, the K-fold cross-validation neural network was used, as it is the best method for small data sets. This is due to the fact that it makes an efficient and accurate use of limited data. The K-fold cross-validation method divides the experimental data into K subgroups. Each of the K sets is then used to validate the prediction and model fit is done on the rest of the experimental data. The model provides the highest coef-

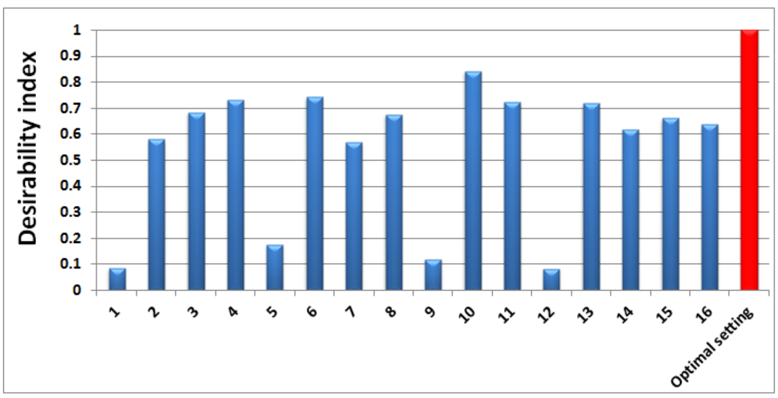


**Fig. 11** Desirability index for experimental runs and the optimal process setting

ficient determination ($R^2$) and the lowest selection error is selected as the final model. Fig. 12 shows schematic diagram of ANN used in this study. It was observed that the optimal number of neurons in the hidden layer is 3 (MLP 6-3-1) with an observed training performance of 99.92 % and a root mean squared error (RMSE) of 0.093 as shown in Table 4.

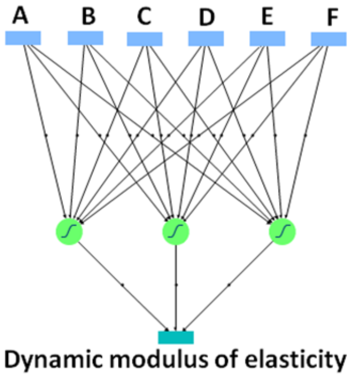


**Fig. 12** Schematic diagram of developed ANN model

**Table 4** Training and validation results of ANN model

| Training | | Validation | |
|---|---|---|---|
| Measures | Value | Measures | Value |
| $R^2$ | 99.92391 % | $R^2$ | 89.43943 % |
| RMSE | 0.0926835 | RMSE | 1.0694804 |
| Mean absolute deviation | 0.0434715 | Mean absolute deviation | 0.9250841 |
| -Log likelihood | -9.596264 | -Log likelihood | 8.916669 |
| SSE | 0.0859023 | SSE | 6.8627305 |
| Sum frequency | 10 | Sum frequency | 6 |

The predicted values obtained by ANN and fractional factorial model are compared and illustrated in Fig. 13. The results demonstrate that ANN model is slightly better than the fractional factorial model. Results indicate that the ANN model prediction line is much closer to the line of experimental data than the fractional factorial model. The higher performance and accuracy of the ANN can be attributed to its ability to determine the nonlinearity of relationships of the process, while the fractional factorial is restricted to a two-factor interaction (2FI) polynomial.

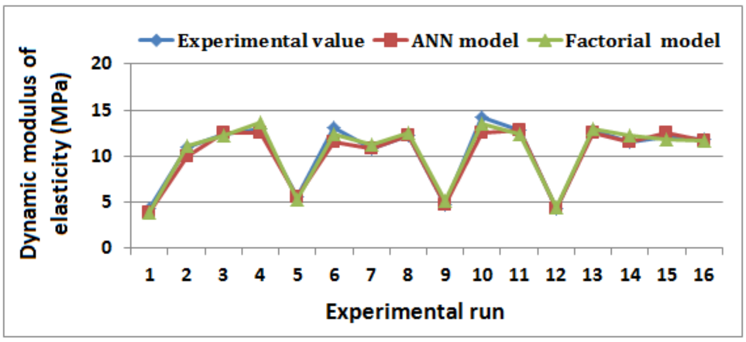


**Fig. 13** An illustration of model comparison between predicted values and actual values of ANN and fractional factorial models for dynamic modulus of elasticity

## 4. Conclusion

In this study, dynamic modulus of elasticity of PC-ABS parts made by FDM was investigated using fraction factorial design. Since no study has been found in the literature review on the effect of processing parameters on dynamic modulus of elasticity of the manufactured parts by FDM, this study can provide important information to guide the future researches. On the basis of the results achieved from this work, the following conclusions can be made:

- With increasing the layer thickness there is a marginal improvement in dynamic modulus of elasticity of the parts. This is due to the fact that thick layers lead to minimum number of layers, which consistently improve the deformation resistance of the manufactured part by the FDM process.
- With the increase in the contour lines there is a continuous improvement in dynamic modulus of elasticity of the manufactured parts. The reason is number of contours reduces the number of rasters, which helps to minimize the porosity in the processed part.
- On the contrary, with increase in air gap, raster angle, build orientation and road width, there is a decrease in dynamic modulus of elasticity of built parts.
- Positive value of air gap is not desirable as it makes the part less dense.
- Lowest value of raster angle is preferred as it produces less number of rasters.
- Building the part at X-axis (0°) can improve the curve definition for rasters, and can minimize the stair-stepping effect.
- It was noticed that minimum road widths give slightly better properties as minimum road width creates finer and thin rasters and layers, which fills more spaces on the part structure.
- Maximum dynamic mechanical performance in terms of dynamic modulus of elasticity can be achieved using optimized operating parameter setting: A = 0.3302 mm, B = zero air gap, C = 0°, D = 0°, E = 0.4572 mm and F = 10. Results obtained from this study would help to manufacture the end user products with better dynamic mechanical performance.
- The ANN model was found to have greater predictive capability of dynamic modulus of elasticity of built parts in comparison to the fractional factorial model in terms of the coefficient of determination ($R^2$) and the absolute average deviation even with limited number of experiments.
- The limitation of this study is that all process parameters were studied only at two levels. Therefore, number of levels should be increased in future work so that more accurate response of the manufactured part in relation to process parameters can be assessed.

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