Experimental investigation of the influence of fabrication conditions on dynamic viscoelastic properties of PC-ABS processed parts by FDM process

Omar Ahmed Mohamed¹, Syed Hasan Masood¹, Jahar Lal Bhowmik²

¹ Department of Mechanical and Product Design Engineering, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia.
² Department of Statistics, Data Science and Epidemiology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia.
E-mail: Omar.Ahmed.Mohamed@outlook.com

Abstract. This paper presents optimization studies on manufacturing parameters for fused deposition modelling (FDM). Layer thickness, air gap, raster angle, build orientation, road width and number of contours are the process variables considered for optimization. Dynamic modulus and glass transition temperature were considered as response parameters. Experiments were designed using fractional factorial design. The effect of each process parameter was investigated using developed regression models and through analysis of variance (ANOVA) technique. The surface characteristics are studied using scanning electron microscope (SEM). Further, performance of optimum conditions was determined and validated by confirmation experiment.

Keyword: FDM, process parameters, fractional factorial design, optimization, ANOVA

1. Introduction

Additive manufacturing (AM) refers to a process by which three dimensional computer aided design (CAD) model is used to build up the product using layer by layer of deposition of material. The automotive industry has used AM to make tool prototypes and functional products. Several AM technologies have been developed such as fused deposition modeling (FDM), selective laser sintering (SLS), inkjet modelling. Unlike conventional manufacturing technologies involving machining or casting, AM joins materials together to build products with short production runs. These technologies distinguish themselves from each other in terms of method of building part, speed, accuracy and materials used. In comparison with other AM technologies, FDM developed by Stratasys, is receiving unprecedented attention because it is simple, environmentally clean, safe and produces non-toxic physical prototypes. Although FDM process has many advantages over other AM technologies, the quality and mechanical properties of processed parts by FDM technology is still limited compared to conventional manufacturing processes. This is due to the fact that the mechanical properties of fabricated parts by FDM greatly depend on various process parameters fixed at the time of fabrication. This process has a complex mechanism in manufacturing products and it involves conflicting processing conditions making the printing mechanism more difficult to understand on how these processing conditions affect together on the functionality and mechanical performance of built parts.
Recently several studies were conducted [1-9] in the area of optimization of building conditions to improve the mechanical properties of FDM manufactured prototypes. However, the effect of manufacturing conditions on the dynamic mechanical thermal properties of FDM fabricated parts has not been studied as there has been no systematic approach that considered the influence of all parameters simultaneously. Moreover, there has been no study on how to select optimal manufacturing parameters to maximize the dynamic mechanical thermal properties under thermal and cyclic loading conditions. Thus, substantial efforts are in demand to fill this research gap. The purpose of the present study is to investigate the effect of several FDM manufacturing parameters (layer thickness, air gap, raster angle, build orientation, road width and number of contours) on the dynamic mechanical thermal properties under cyclic loading conditions. Mathematical models have been developed and evaluated in this study through fractional factorial design and through analysis of variance (ANOVA) technique in order to establish functional relationships between input variables and the dynamic mechanical thermal properties by considering all printing parameters simultaneously instead of considering one factor with single response at a time.

2. Experimental details

2.1. Specimen Preparation

In this study, a total of 16 specimens were fabricated using FDM Fortus 400 mc by Stratasys. The material used for test samples is Polycarbonate/Acrylonitrile-Butadiene-Styrene (PC-ABS) blend supplied by Stratasys. This material was selected in this study because this material is a relatively new for FDM process and it has wide application in industry. It is necessary to obtain more knowledge on its behavior and performance under different manufacturing conditions.

2.2. Measurement of dynamic mechanical thermal properties

The dynamic mechanical thermal properties were measured using Dynamic Mechanical Thermal Analyzer (DMTA; Model- 2980, supplied by TA Instrument (USA). The shape of test sample is rectangular having dimensions of 35×12.5×3.5 mm as per ASTM standard [10]. The single cantilever mode of deformation was used under the test temperature range from 35 °C to 170 °C with a heating rate of 3°C/min and amplitude of 15 µm at a fixed frequency of 1 Hz under nitrogen atmosphere. Dynamic modulus and glass transition temperature of each sample were recorded as a function of temperature. Further measurements have been conducted to obtain the average value from a set of each property. The Thermal Advantage Software supplied by TA Instrument was used to collect the data. The maximum dynamic modulus was calculated from the DMA results, while glass transition temperature was determined as the peak in tan delta (mechanical damping). The dynamic modulus is an indicator of viscoelasticity, which is the ratio of stress to strain under vibratory and cyclic conditions. Glass transition temperature measures the material transitions from a hard state, glassy material to a soft and rubbery material state. In fact, Glass transition temperature depends mainly on the degree of polymerization for PC-ABS blend. However, this study has revealed that the manufacturing conditions could also affect the glass transition temperature.

2.3. Design of experiment

A factorial design is a type of experimental design and is often used to understand the effect of independent variables on the dependent variable. In this study, two-level fractional factorial design was used to investigate the influence of six process variables (layer thickness, air gap, raster angle, build orientation, road width and number of contours) on the dynamic modulus and glass transition temperature. Table 1 shows the selected process parameters and their levels, while Table 2 shows fractional factorial design matrix. The process parameters and their levels were selected based on the
previous studies, their significance, and FDM machine manufacturer. To study the impact of these parameters on the dynamic modulus and glass transition temperature, a two-factor interaction (2FI) model is used and can be expressed by Equation (1).

\[
Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{15} X_1 X_5 + \beta_{16} X_1 X_6 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{25} X_2 X_5 + \beta_{26} X_2 X_6 + \beta_{34} X_3 X_4 + \beta_{35} X_3 X_5 + \beta_{36} X_3 X_6 + \beta_{45} X_4 X_5 + \beta_{46} X_4 X_6 + \beta_{56} X_5 X_6 + \varepsilon
\]  

(1)

where \( \beta_0 \) is the intercept of the regression equation, \( \beta_i \) is the linear regression coefficient, for the main effect \( \beta_{ij} \) is the regression coefficient for the interaction effect, \( X_i \) and \( X_j \) are the coded predictors, \( \varepsilon \) is the random error, and \( X_1, X_2, X_3, X_4, X_5, \) and \( X_6 \) are the six process parameters.

| Table 1. FDM process parameters and their levels |
|-----------------------------------------------|
| **Factors** | **Units** | **Symbols** | **Levels** |
| Layer thickness | mm | \( X_1 \) | 0.127 | 0.3302 |
| Air gap | mm | \( X_2 \) | 0 | 0.5 |
| Raster angle | deg | \( X_3 \) | 0 | 90 |
| Build orientation | deg | \( X_4 \) | 0 | 90 |
| Road width | mm | \( X_5 \) | 0.4572 | 0.5782 |
| Number of contours | - | \( X_6 \) | 1 | 10 |

| Table 2. Fractional factorial design matrix |
|---------------------------------------------|
| **Run** | **\( X_1 \)** | **\( X_2 \)** | **\( X_3 \)** | **\( X_4 \)** | **\( X_5 \)** | **\( X_6 \)** | **Dynamic modulus (Mpa)** | **Glass transition temperature (°C)** |
| 1 | 0.127 | 0.5 | 90 | 0 | 0.4572 | 1 | 445.43 | 144.44 |
| 2 | 0.127 | 0 | 90 | 90 | 0.4572 | 10 | 1129.49 | 146.67 |
| 3 | 0.3302 | 0.5 | 90 | 0 | 0.5782 | 1 | 495.14 | 145.70 |
| 4 | 0.3302 | 0 | 90 | 0 | 0.4572 | 10 | 1472.51 | 149.75 |
| 5 | 0.127 | 0 | 90 | 0 | 0.5782 | 10 | 1271.65 | 149.55 |
| 6 | 0.3302 | 0 | 90 | 90 | 0.4572 | 10 | 1321.44 | 147.87 |
| 7 | 0.127 | 0 | 0 | 90 | 0.4572 | 10 | 1331.56 | 149.44 |
| 8 | 0.3302 | 0.5 | 0 | 90 | 0.4572 | 1 | 444.35 | 145.59 |
| 9 | 0.127 | 0.5 | 0 | 90 | 0.5782 | 1 | 580.88 | 145.38 |
| 10 | 0.127 | 0.5 | 0 | 0 | 0.5782 | 10 | 1343.12 | 147.27 |
| 11 | 0.127 | 0 | 90 | 90 | 0.5782 | 1 | 1120.58 | 147.66 |
| 12 | 0.3302 | 0 | 0 | 90 | 0.5782 | 10 | 1306.99 | 147.87 |
| 13 | 0.3302 | 0.5 | 90 | 90 | 0.5782 | 10 | 1394.39 | 147.92 |
| 14 | 0.3302 | 0 | 0 | 0 | 0.5782 | 1 | 1258.68 | 147.22 |
| 15 | 0.3302 | 0 | 0 | 0 | 0.4572 | 10 | 1206.60 | 147.48 |

3. Results and discussion

3.1. Development of regression models

The relationship between input variables (layer thickness \( X_1 \), air gap \( X_2 \), raster angle \( X_3 \), build orientation \( X_4 \), road width \( X_5 \) and number of contours \( X_6 \)) and the output responses (dynamic modulus and glass transition temperature) can be expressed as:
Regression analysis was executed to calculate the values of the coefficient of the two-factor interaction model using statistical software package STATISTICA® 12. Insignificant terms were eliminated from the models using backward elimination technique. By substituting the values in Equation (1), the final two-factor interaction model of dynamic modulus and glass transition temperature in terms of coded factors is developed as below:

\[
Y = F(X_1, X_2, X_3, X_4, X_5, X_6) \quad (2)
\]

\[
\text{Dynamic modulus} = 1265.78329 - 1709.36844 B + 7.98967F + 144.72181 BF \quad (3)
\]

\[
\text{Glass transition temperature} = 144.74665 + 3.26617 * A - 4.92149 * B - 2.04218E - 003 * C + 2.60305E - 003 * D + 3.77189 * E + 0.23549 * F \quad (4)
\]

3.2. Analysis of developed mathematical models

Analysis of variance (ANOVA) technique was employed to test the significance of regression models and their respective variables. F value was used to check the adequacy of the developed models. ANOVA results for dynamic modulus and glass transition temperature are given in Tables 3 and 4, respectively. According to Tables 3 and 4, the “Prob > F” value of the two-factor interaction model is less than 0.0001 which indicates that the model is significant. The figure 1 (a) shows Pareto Chart of the standardized effects for dynamic modulus which indicates that the effects of air gap (X_2) and number of contours (X_6) and interaction between air gap (X_2) and number of contours (X_6) are significant and plays dominant role for dynamic modulus improvement. The figure 1 (b) shows that the process parameters such as layer thickness (X_1), air gap (X_2), road width (X_5) and number of contours (X_6) have strong impact on glass transition temperature.

**Figure 1.** Pareto chart of the standardized effects of the process parameters for (a) dynamic modulus, and (b) results for glass transition temperature.

**Table 3.** ANOVA results for dynamic modulus

| Source  | Sum of Squares | DOF | Mean Square | F Value | P-value | Remarks |
|---------|----------------|-----|-------------|---------|---------|---------|
| Model   | 1.891E+006     | 3   | 6.302E+005  | 74.72   | < 0.0001| Significant |
| B-B     | 8.343E+005     | 1   | 8.343E+005  | 98.92   | < 0.0001| Significant |
| F-F     | 6.321E+005     | 1   | 6.321E+005  | 74.95   | < 0.0001| Significant |
| BF      | 4.241E+005     | 1   | 4.241E+005  | 50.29   | < 0.0001| Significant |
| Residual| 1.012E+005     | 12  | 8433.69     | -       | -       | - |
| Cor Total| 1.992E+006    | 15  | -           | -       | -       | - |

R^2 = 94.92%, Adjusted R^2 = 93.65%, Predicted R^2 = 90.97%, Adequate Precision = 18.406
Table 4. ANOVA results for glass transition temperature

| Source | Sum of Squares | DOF | Mean Square | F Value | P-value | Remarks |
|--------|----------------|-----|-------------|---------|---------|---------|
| Model  | 45.14          | 6   | 7.52        | 442.43  | < 0.0001| Significant |
| A-A    | 1.76           | 1   | 1.76        | 103.62  | < 0.0001| Significant |
| B-B    | 24.22          | 1   | 24.22       | 1424.43 | < 0.0001| Significant |
| C-C    | 0.14           | 1   | 0.14        | 7.95    | 0.0201  | Significant |
| D-D    | 0.22           | 1   | 0.22        | 12.91   | 0.0058  | Significant |
| E-E    | 0.83           | 1   | 0.83        | 49.00   | < 0.0001| Significant |
| F-F    | 17.97          | 1   | 17.97       | 1056.67 | < 0.0001| Significant |
| Residual | 0.15       | 9   | 0.017       | -       | -       | -       |
| Cor Total | 45.29      | 15  | -           | -       | -       | -       |

R² = 99.66%, Adjusted R² = 99.44%, Predicted R² = 98.93%, Adequate Precision = 70.936

The coefficient of determination R² values in two-factor interaction model for dynamic modulus and glass transition temperature are 94.92% and 99.66%, and these are very close to 1, which indicate that there is a strong relationship between the experimental results and predicted results for dynamic modulus and glass transition temperature. Figure 2 shows the predicted versus the experimental data for dynamic modulus and glass transition temperature. This plot shows a good agreement exists between the experimental values and the predicted values obtained by the developed model, which also means the developed models are able to fit the experimental data well.

![Figure 2](image-url). Predicted values versus the experimental values

3.3. Influence of process parameters on the properties

Figure 3 and 4 shows the influence of fabrication parameters on dynamic modulus and glass transition temperature, respectively. The graphs show how the dynamic modulus and glass transition temperature change as each variable moves from low to higher level by varying one factor at a time while keeping other variables constant at their center levels. It can be seen from figure 3 and 4 that there is an increase in dynamic modulus and glass transition temperature as the layer thickness increases from 0.127 mm to 0.3302 mm. This is due to the fact that the increase in layer thickness leads to less number of layers and less thermal cycles necessary to build part, resulting in reduction in cooling time and reduction in interlayer distortion, which is the main factor responsible for the weaker interlayer bonding. It can also be observed from figure 3 and 4 that the air gap has a strong impact on dynamic modulus and glass transition temperature. With the increase in air gap from zero to 0.5 mm, there is a considerable reduction in dynamic modulus and glass transition temperature. This result is expected because positive value of air gap means the ratsers are not closer to each other, resulting in brittle structure of FDM built part.
Raster angle has a little impact on dynamic modulus and glass transition temperature, but its effect on glass transition temperature is more visible as can be seen in figure 3 and 4. It was observed that 0° of raster angle provides better mechanical properties. This is because 0° of raster angle creates less number of rasters required to build part. It also reduces the amount of sharp corners between the end point of a raster segment and the start point of the next raster segment. Build orientation has very little or no impact on dynamic modulus and glass transition temperature. With the increase in build orientation (0°-90°) there is little decrease in dynamic modulus but there is an increase in glass transition temperature as shown in figure 3 and 4. A possible explanation is that the uses of the lowest value or highest value of build orientation helps in reducing the stair-stepping effects. It is evident that road width has marginal impact on dynamic modulus, but it has significant influence on glass transition temperature as can be seen in figure 3 and 4. This is due to the fact that thinner road widths create finer rasters and hence incomplete filling can be eliminated resulting in dense structure with good deformation resistance. However, thicker road widths increase the width of the entire perimeter of the deposited rasters, resulting in decreasing the cooling cycles and interlayer distortion. Number of contours is the most influential variable on both dynamic modulus and glass transition temperature. From figure 3 and 4, it can be concluded that with increasing number of contours, there has been a

Figure 3. Main effect plot for dynamic modulus

Figure 4. Main effect plot for glass transition temperature
noticeable improvement in dynamic modules and glass transition temperature. This is because maximum number of contours reduces the number of raster necessary for manufacturing a part. This helps to minimize the porosity and voids in the microstructure (see figure 5).

![Fully dense structure with maximum number of contours](image)

**Figure 5.** SEM image for the effect of number of contours on the microstructure

The developed mathematical models show an interesting phenomenon in the part processed with 10 contours and positive air gap through interaction effect plot as shown in figure 6. As discussed earlier, the positive air gap leads to poor part structure and poor mechanical performance of FDM build part. But interaction effect between the number of contours and air gap shows that it is also possible to obtain high mechanical properties by using 0.5 mm of air gap and 10 contours. A possible explanation is that the processed part under this parameter setting is still solid and has good deformation resistance to the applied load. This interesting result is useful not only to improve the mechanical properties, but also to reduce the manufacturing time.

![Interaction effect between air gap and number of contours](image)

**Figure 6.** Interaction effect between air gap and number of contours

3.4. **Optimization of response**

The optimization of process parameters was carried out using MINITAB®17 to get maximum dynamic modulus and glass transition temperature using MINITAB®17. In this regard the mathematical models developed in this study (Equations (3) and (4)) were used to get the optimum values for the parameters. Figure 7 shows the optimum values for all process parameters. The predicted values of maximum dynamic modulus and glass transition temperature are 1466.72MPa and
150.5952°C, respectively. Confirmation experiments were done to verify the results by manufacturing additional samples using the optimized process parameters. The results from the confirmation tests show that maximum dynamic modulus of 1463.738 MPa and maximum glass transition temperature of 150.14 °C were obtained, which agreed well with the predicted values.

![Optimization plot](image)

**Figure 7.** Optimization plot

4. Conclusions

In this study, the influence of printing parameters on dynamic viscoelastic properties of PC-ABS processed parts by FDM was investigated. Fractional factorial design was adopted to study the effect of variation in processing parameters such as layer thickness, air gap, raster angle, build orientation, road width and number of contours on the dynamic modulus and glass transition temperature. ANOVA results have shown that air gap and number of contours and interaction between air gap and number of contours are significant factors and plays dominant role for dynamic modulus improvement. But the process parameters such as layer thickness, air gap, road width, and number of contours have strong influence on glass transition temperature. ANOVA results also demonstrated that a regression model with high coefficient determination values for the dynamic modulus and glass transition temperature, respectively, ensure a satisfactory adjustment of the two factor interaction regression model with the experimental data. The optimization of process parameters indicates that the maximum dynamic modulus and glass transition temperature were 1466.72MPa and 150.5952°C, respectively using the optimized process conditions. The results from the confirmation experiments agreed well with the predicted values.

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