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Experimental investigation on flexural properties of FDM processed Nylon 12 parts using RSM

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Abstract. Fused deposition modelling (FDM) is one of the leading additive manufacturing technologies for producing plastic parts in a layer by layer manner from a digital file. The actual levels of processed parameters of the manufactured parts using fused deposition modelling (FDM) are considered the major obstruction to optimize the mechanical properties. As a result of the FDM parameters and the interaction among them the parts’ mechanical properties of the manufactured parts are affected, thus, many experiments have been dedicated to find the proper parameter setting. This paper presents a study on the influence of three FDM process parameters (air gap, raster angle, and build orientation) on the flexural strength of the FDM Nylon 12 manufactured parts. Response surface methodology (RSM) is used as a statistical technique to analyse results. Analysis of variance (ANOVA) method is also used to test the significance of parameters. The results indicate that the air gap and raster angle are the most influential parameters affecting the flexural strength.

Keyword: FDM, RSM, process parameters, flexural properties

1. Introduction

Cycle time reduction is considered as a most significant factor in term of manufacturing fields as a result of the marketplace competitions, which supports rapid manufacturing (RM) over traditional manufacturing processes. RM process builds the most complex geometry parts in a layer by layer technique. The parts are produced with low cost without using special tools [1, 2]. RM offers some functional assembly techniques by joining sub-assemblies in one part using computer aided design (CAD) file that will provide time, object’s parts and storage reductions. The compatibility of the available materials can be considered one of the RM obstructions, which would restrict RM applications [1, 3]. Many approaches have been developed to overcome these barriers. One of these approaches is to develop new materials having superior mechanical properties than the conventional materials. The other approaches are to adjust the process parameters prior to the manufacturing process so that the mechanical properties can be optimized [4]. The second approach is considered the most suitable approach because the proper adjustment of the process parameters will modify the mechanical properties of the product in a short time without huge cost. Thus, the selection of best FDM process parameters is important and must be studied in order to understand the influence of various process parameters on the mechanical properties [5].

Many studies have been conducted to obtain the premium settings of the FDM process parameters associated with the best mechanical properties. Ahn et al.[6] reported that air gap and build orientation are considered the most significant parameters affecting the tensile, flexural, impact strength, and
anisotropic structure. However, other FDM parameters, such as raster width, layer thickness and model temperature have less effect on the mechanical properties. Sood et al. [1] revealed that at small build orientation the tensile and flexural strength were reduced due to the large number of layers. Imtiyaz and Shaikh. [7] found that the build orientation and layer thickness have a great effect on stair stepping errors, and therefore, have effect on the mechanical properties. Torrado & Roberson. [8] reported that the printed samples in vertical build orientation might be difficult because of the capability of a given 3D printer platform. Furthermore, they reported that XYZ (faux vertical specimens) is the optimal and is considered to be more resistible. Smith and Dean [9] studied the effect of build orientation on the tensile strength of FDM built parts, and the results are compared with the material properties. Rezaie et al. [10] proposed a methodology to determine the optimal FDM process parameters for the production of topological optimised FDM build part. Peng et al. [11] examined the influence of raster width, extrusion velocity, filling velocity and slice height on dimensional accuracy, warp deformation and processing time. It is clear from the literature that several studies have been conducted to investigate the effect of FDM process parameters for ABS material. However, there has been no experimental study conducted to examine and optimize the effect of FDM process parameters to attain the proper performance of Nylon 12 manufactured parts. Therefore, this study aims to investigate the influence of the manufacturing parameters on the flexural strength of FDM Nylon 12 parts. In this study, response surface methodology (RSM) is used to develop an empirical model to establish a functional relationship between the FDM process parameters and the flexural strength. Analysis of Variances (ANOVA) is also used to test the significance of parameters.

2. Experimental details

The experimental design has been done on all 60 specimens, which were fabricated by Nylon 12 as a tested material using Stratasys FDM Fortus 450 mc. The dimensions of each specimen are 62.5 mm in length, 12 mm in width and 3 mm in thickness. The flexural strength of the printed samples was measured using Zwick Roell machine. Average of three readings for each test has been conducted to get an accurate reading. Nylon 12 has many brilliant features such as good temperature resistance, high fatigue resistance and high impact strength in different industrial applications. In this study, the selected FDM process parameters and their levels are listed in Table 1 and are illustrated graphically in Figure 1, which are air gap (A), part build orientation (B) and raster angle (R). Minitab 17 software is used to plan and analyse the design of experiment. The rest of FDM parameters were kept as a constant at their levels in order to inspect the real effects of the three particular important parameters (i.e. air gap, build orientation, and raster angle) as reported in the previous studies. RSM based face cantered composite design (FCCD) is used to establish the relationships between FDM process parameters and the flexural strength. ANOVA is also used to develop the regression model and to assess the effect of each parameter on the flexural strength. The FCCD matrix is shown in Table 2.

**Table 1.** Fixed process parameters (factors) and their level.

| Factors         | Units | Level 1 | Level 2 | Level 3 |
|-----------------|-------|---------|---------|---------|
| Air gap         | mm    | 0       | 0.1     | 0.2     |
| Raster angle    | deg   | 0       | 30      | 60      |
| Build orientation | deg   | Y-orientation (flat) | Y-orientation (flat) | Z-orientation (upright) |

![Figure 1. FDM process parameters](image-url)
Table 2. FCCD experimental design matrix and measured data.

| Run | Air gap | Raster angle | Build orientation | Flexural strength (MPa) |
|-----|---------|--------------|-------------------|------------------------|
| 1   | 0.2     | 30           | 45                | 32.4                   |
| 2   | 0.1     | 60           | 45                | 41.6                   |
| 3   | 0.1     | 30           | 45                | 44.2                   |
| 4   | 0.1     | 30           | 45                | 44.1                   |
| 5   | 0.1     | 30           | 90                | 55.2                   |
| 6   | 0.1     | 0            | 45                | 37.9                   |
| 7   | 0.1     | 30           | 0                 | 41.9                   |
| 8   | 0       | 30           | 45                | 67.3                   |
| 9   | 0.1     | 30           | 45                | 46.1                   |
| 10  | 0       | 0            | 90                | 51                     |
| 11  | 0.2     | 60           | 90                | 50.7                   |
| 12  | 0.2     | 0            | 0                 | 33.4                   |
| 13  | 0.1     | 30           | 45                | 45.6                   |
| 14  | 0       | 60           | 0                 | 66.9                   |
| 15  | 0.1     | 30           | 45                | 46.2                   |
| 16  | 0.2     | 60           | 0                 | 28.9                   |
| 17  | 0.1     | 30           | 45                | 45.7                   |
| 18  | 0.2     | 0            | 90                | 32.4                   |
| 19  | 0       | 60           | 90                | 41.6                   |
| 20  | 0       | 0            | 0                 | 44.2                   |

3. Results and Discussions

The results of flexural strength test were collected directly from the testing machine screen and were used directly in Minitab 17 software. Figure 2 shows the main effect plot of each FDM process parameters for the flexural strength. The quadratic response surface model was used to fit the experimental data. The predictive regression model in terms of coded units is giving below.

Flexural strength (MPa) = 52.43 − 207.0 A + 0.599 R − 0.133 B + 320 A * A − 0.00766 R * R + 0.00094 B * B + 0.021 A * R + 1.092 A * B − 0.00086 R * B  (1)

From ANOVA results presented in Table 3, it can be noticed that there is a significant individual contribution of factor A: air gap with P-value of 0.003. Air gap has a linear influence on the flexural strength. It can be noticed from Figure 2 that an inverse proportionality between air gap and flexural strength as a result of a sharp linear degradation curve. The flexural strength decreases with the increases in air gap from low level to the higher level. This significance reason underlies of the strong bonding.
among deposited beads as a result of high temperature diffusion towards the bottom layers’ effects and the reduction of distortion of rasters contributes to some increase in the flexural strength. The lowest flexural strength was represented by specimen No. 16 as can be seen in Table 2, while the highest value was obtained by specimen No. 8. The microstructure observations for sample No. 16 and sample No. 8 are presented in Figure 3.

Table 3. Analysis of variance (ANOVA) result.

| Source             | DF | Adj SS | Adj MS | F-value | P-value |
|--------------------|----|--------|--------|---------|---------|
| Model              | 11 | 1577.67| 143.425| 3.09    | 0.060   |
| Block              | 2  | 250.05 | 125.023| 2.69    | 0.128   |
| Linear             | 3  | 987.82 | 329.275| 7.09    | 0.012   |
| A                  | 1  | 868.62 | 868.624| 18.71   | 0.003   |
| R                  | 1  | 94.86  | 94.864 | 2.04    | 0.191   |
| B                  | 1  | 24.34  | 24.336 | 0.52    | 0.490   |
| Square             | 3  | 129.88 | 43.293 | 0.93    | 0.468   |
| A*A                | 1  | 27.52  | 27.520 | 0.59    | 0.463   |
| R*R                | 1  | 127.72 | 127.723| 2.75    | 0.136   |
| B*B                | 1  | 9.71   | 9.710  | 0.21    | 0.660   |
| 2-Way interaction  | 3  | 203.90 | 67.968 | 1.46    | 0.296   |
| A*R                | 1  | 0.03   | 0.031  | 0.00    | 0.980   |
| A*B                | 1  | 193.06 | 193.061| 4.16    | 0.076   |
| R*B                | 1  | 10.81  | 10.811 | 0.23    | 0.642   |
| Error              | 8  | 371.42 | 46.427 |         |         |
| Lack-of-Fit        | 5  | 371.16 | 74.232 | 873.32  | 0.000   |
| Pure error         | 3  | 0.26   | 0.085  |         |         |
| Total              | 19 | 1949.09|        |         |         |

Figure 3. Micrographs images for (a-b) sample No.16, and (c-d) for sample No.8.

The rest of parameters in term of linear, square, and interaction terms have insignificant influence on the flexural strength. However, they have a marginal effect on the flexural strength in case of individual and interactional terms. Individually, Figure 2 shows that the flexural strength has lower value at 0° and
60° raster angle, while it has higher value at 30°. Moreover, flexural strength has high value at 90° Z- orientation (upright), while it has lower value at 0° and 45° Y-orientation (flat). In term of interaction models the fitted means plots illustrate the parameters’ interaction influences on the mean of flexural strength (Figure 4). The flexural strength will be high values at the interactions of:
- Air gap 0.1 mm and 90°-part build orientation
- Raster angle 30° and 45°-part build orientation interaction
- There is no interaction between air gap and raster angle.

![Figure 4. Interaction effect of FDM parameters on the flexural strength.](image)

4. Conclusions

Design of Experiment methodology based on FCCCD method was used to establish the functional relationship between three process parameters and the flexural strength. The considered process parameters are air gap, part build orientation and raster angle and their levels are (0, 0.1, 0.2), (0°, 45°, 90°), and (0°, 30°, 60°) respectively, which have been examined in term of their validity and significant influence on the flexural strength. The observed results throughout this study show that at zero air gap, flexural strength will increase as a result of improving the temperature diffusion among the adjacent rasters, creates strong bonding and reduce the distortion

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