Effect of Fabrication Parameters and Material Features on Tensile Strength of FDM Built Parts

Zhenhui Shen1,a, Haiyan Hua2, Shuanqiang Yang1 and Yangmei Zhang1

1Engineering College, Fujian Jiangxia University, University Town, Fuzhou, P.R.China
2School of Mechanical and Automotive Engineering, Fujian University of Technology, University Town, Fuzhou, P.R.China
*Corresponding author: a shenzhenhui@fjjxu.edu.cn

Abstract. This paper presents experimental investigations on influence of fabrication parameters and material features viz., layer thickness, build orientation, processing material and processing quality on tensile strength of parts built by fused deposition modelling (FDM). The specimen is designed according to GB/T 1040.2/1BA/1 which maintains the tensile strength test. And the experimental factor levels are setup on account of the fabrication parameters and processing materials of the processing equipment for FDM. Then Taguchi’s parameter design is applied to find optimum factor levels to maximize the tensile strength of FDM built parts. As the experiment plan is designed base on orthogonal test design with mixed levels, tensile strength of each test is obtained and the signal to noise ratio which defined to evaluate the influence and variation is obtain as well. Then main effect plot is drawn and analysis of variance is performed to find optimal level of fabrication parameters to maximize the tensile strength of FDM built parts. Finally, the effect of fabrication parameters and material features on tensile strength of FDM built parts are obtained.

1. Introduction
Fused deposition modeling (FDM), as one kind of additive manufacturing, has been used widely to reduce build time of product especially for parts with complex shapes. Nevertheless, it has been proposed that improvement of mechanical properties, dimensional accuracy, shape precision and repeatability of FDM built parts are key issues to be addressed for successful implementation of FDM [1].

Several attempts have been performed to improve mechanical properties of FDM built parts by made appropriate adjustments of fabrication parameters. Some studies have reported the influence of layer thickness, filling angle and melt temperature on mechanical properties of thermoplastic urethane [2] while some other studies have reported the effects of fused deposition modeling process parameters on the tensile properties of fused deposition modeling-fabricated carbon fiber-reinforced plastic composite parts [3]. And some of the studies have highlighted the effects of FDM process parameters viz., infill percentage, infill speed and layer thickness on the tensile properties such as percentage elongation at peak, percentage elongation at break and yield stress of the 3D functional prototypes [4]. Recent studies have made attempts to perform the compatibility analysis of two dissimilar polymers namely acrylonitrile butadiene styrene (ABS) and polyamide 6 (PA6) by establishing their melt flow properties [5]. However, the existing researches considered less factors...
affecting mechanical properties of FDM built parts and different processing equipment always processes with various fabrication parameters. Therefore, the present work focuses considerably on a study of the effect of fabrication parameters and material features on tensile strength of FDM built parts. The specimen is designed according to the tensile strength testing criteria for plastics. And the factors with levels are selected from fabrication parameters and kinds of materials. Then Taguchi’s parameter design is applied. In addition, the optimum factor level with significant factors to improve tensile strength of the FDM built parts are discussed.

2. Experimental Setups
The tensile strength of each specimen is tested according to GB/T 1040.2/1BA/1 [6,7]. The UP Plus 2 produced by Beijing Tiertime Technology Co. Ltd is selected as processing equipment for FDM. The maximal volume of built product is 140 x 140 x 135 mm and the diameter of the filament is 1.75 mm. Considering the limited volume of built product, the standard test specimen is designed according to tensile strength testing standard and shown in Figure 1. The total length of the specimen is set to 100 mm while the gauge length is 25 mm. And the thickness of the specimen is set to 4 mm.

The fabrication parameters of the processing equipment include processing quality, layer thickness, fill mode, sealing surface setting, support setting, extruder temperature, platform temperature, and so on. And the kinds of materials can be processed by the processing equipment include ABS, polycarbonate, polylactic acid (PLA), and so on. As not all the fabrication parameters have a great effect on tensile strength of FDM built parts, the affecting factors like layer thickness, build orientation, processing material and processing quality are selected as experimental factors and represented as A, B, C and D, respectively. The level value of each factors are shown in Table 1. The factor of layer thickness has 5 levels, valued 0.15 mm ~ 0.40 mm with interval of 0.05 mm while the factor of build orientation has 3 levels, valued flat, sidelong and upright, as shown in Figure 2. And the factor of processing material has 2 levels, includes ABS and PLA. Similarly, the factor of processing quality has 2 levels, includes normal and fine. Therefore, the factors have mixed levels.

| Factors | A   | B       | C  | D      |
|---------|-----|---------|----|--------|
| Levels  | A   | B       | C  | D      |
| 1       | 0.15 mm | Flat | ABS | Normal |
| 2       | 0.20 mm | Sidelong | PLA | Fine   |
| 3       | 0.25 mm | Upright |     |        |
| 4       | 0.30 mm |       |     |        |
| 5       | 0.35 mm |       |     |        |
| 6       | 0.40 mm |       |     |        |
According to Taguchi’s parameter design, an experiment plan is designed based on orthogonal test design (OTD) with mixed levels. The number of tests in the experiment plan is 27 and expressed by N. Each test in experiment plan is performed by M times and M is set to 5. Figure 3 shows the FDM printing of the specimen and Figure 4 shows the tensile strength testing of the specimen. The selected test equipment is WDW-50 which produced by Jinan Hansen Instru Co. Ltd. The speed of testing is set to 1 mm/min and the gauge length of extensometer is set to 50 mm.

3. Result Analysis and Discussion
As the specimens have been built and test, the tensile strength of each specimen is taken. According to Taguchi’s parameter design, signal to noise (S/N) ratio is applied to evaluate the influence and variation caused by each factor to the total variation observed in the tensile strength of the FDM built
parts. Since the objective of the design is to maximize tensile strength of the FDM built parts, larger the better quality characteristic is considered. Hence, the S/N ratio $\eta_i$ of experiment $i$ ($i = 1, 2, \ldots, N$) can be expressed by

$$\eta_i = -10 \times \log \left( \frac{L_i}{M} \right)$$

(1)

and

$$L_i = \sum_{j=1}^{M} \frac{1}{t_{ij}}$$

(2)

Where $t_{ij}$ ($j = 1, 2, \ldots, M$) represents the tensile strength of $j$th operation in each test. Then tensile strength of each test is converted to S/N ratio which is shown in Table 2. The S/N ratio for tensile strength varies from 19.00 to 30.68. The main effect plot for S/N ratio shown in Figure 5 as well as the response of S/N ratio shown in Table 3 are used to predict optimum factor level with significant factors. The result shows that the optimal factor levels are as follows: layer thickness of 0.15 mm, build orientation of sidelong, processing material of PLA, processing quality of normal.

Considering the influence caused by layer thickness only, the tensile strength changes as follows: $0.15 \text{ mm} > 0.25 \text{ mm} > 0.35 \text{ mm} > 0.40 \text{ mm} > 0.30 \text{ mm} > 0.20 \text{ mm}$. The reason of this is that the deformed caused by heat of molten material become larger while deform caused by sum up of each printed layer become smaller when the layer thickness increased. And the deform effects the interfacial strength between adjacent layers directly. As a result, tensile strength reaches the maximum value when the layer thickness is 0.15 mm and gets the minimum value when the layer thickness is 0.20 mm.

Considering the influence caused by build orientation only, the tensile strength varies as follows: sidelong $> flat$ $> upright$. As the build orientation is in the same direction with the applied load in the test, FDM part built by orientation of upright possesses minimum tensile strength. Compared with FDM part built by orientation of flat, FDM part built by orientation of sidelong gets greater tensile strength on account of the larger amount of orthotropic layers.

Considering the influence caused by processing material only, FDM parts built by PLA get greater tensile strength than FDM parts built by ABS. The ABS is the graft copolymer of acrylonitrile, butadiene and styrene. As an amorphous polymer material, the ABS possesses high impact strength. But the ABS possesses low tensile strength as the amount of branched chains is so large that free stretching of the backbone is suppressed. Moreover, the PLA possesses high tensile strength on account of its large amount of hydrogen-bonds.

Considering the influence caused by processing quality only, normal quality built FDM parts gain greater tensile strength when compared with fine quality built FDM parts. For the processing equipment, the higher the processing quality, the slower the processing speed. When processing with fine quality, the extrusion speed of the material is faster than the moving speed of the nozzle which gives rise to accumulations of redundant material at both sides of nozzle. As a result, the defection of deposition is increased and the tensile strength is decreased.

According to the response of S/N ratio, the effect of factors on tensile strength of FDM built parts ranks as follows: build orientation $> layer thickness > processing material > processing quality$. Then the relative influence of each factor on tensile strength is analysed by analysis of variance (ANOVA). Parameters of ANOVA like degrees of freedom (DOF), sum of square deviation (SS), mean square (MS), F-ratio (F) and p-value (P) are calculated and shown in Table 4. It is observed that layer
Table 2. S/N ratio of tensile strength in experiment plan

| Exp. No. | Factor | S/N ratio |
|----------|--------|-----------|
|          | A      | B         | C         | D         |
| 1        | 1      | 1         | 1         | 1         | 30.14     |
| 2        | 1      | 1         | 2         | 2         | 30.17     |
| 3        | 1      | 2         | 1         | 1         | 30.39     |
| 4        | 1      | 2         | 2         | 1         | 30.68     |
| 5        | 1      | 3         | 1         | 1         | 25.23     |
| 6        | 1      | 3         | 1         | 2         | 25.72     |
| 7        | 2      | 1         | 1         | 1         | 26.09     |
| 8        | 2      | 1         | 2         | 2         | 27.65     |
| 9        | 2      | 2         | 1         | 1         | 28.06     |
| 10       | 2      | 2         | 2         | 1         | 28.74     |
| 11       | 2      | 3         | 1         | 1         | 19.97     |
| 12       | 2      | 3         | 1         | 2         | 19.00     |
| 13       | 3      | 1         | 1         | 1         | 29.28     |
| 14       | 3      | 1         | 2         | 2         | 30.29     |
| 15       | 3      | 2         | 1         | 1         | 30.19     |
| 16       | 3      | 2         | 2         | 1         | 30.43     |
| 17       | 3      | 3         | 1         | 1         | 24.01     |
| 18       | 3      | 3         | 1         | 2         | 23.67     |
| 19       | 4      | 1         | 1         | 1         | 25.68     |
| 20       | 4      | 2         | 1         | 2         | 26.57     |
| 21       | 4      | 3         | 2         | 1         | 28.24     |
| 22       | 5      | 1         | 1         | 1         | 26.35     |
| 23       | 5      | 2         | 1         | 2         | 28.12     |
| 24       | 5      | 3         | 2         | 1         | 28.89     |
| 25       | 6      | 1         | 1         | 1         | 27.32     |
| 26       | 6      | 2         | 1         | 2         | 27.30     |
| 27       | 6      | 3         | 2         | 1         | 28.36     |

Figure 5. Main effect plot for S/N ratio
Table 3. Response of S/N ratio

| Level | Factor |   |   |
|-------|--------|---|---|
|       | A      | B | C |
| 1     | 28.72  | 28.11 | 26.28 | 27.67 |
| 2     | 24.92  | 28.94 | 29.27 | 26.50 |
| 3     | 27.98  | 24.79 |       |      |
| 4     | 26.83  |       |       |      |
| 5     | 27.79  |       |       |      |
| 6     | 27.66  |       |       |      |
| Delta | 3.80   | 4.15 | 2.99 | 1.17 |
| Rank  | 2      | 1  | 3  | 4   |

Table 4. ANOVA table for S/N ratio

| Source | DOF | SS    | MS   | F      | P     |
|--------|-----|-------|------|--------|-------|
| A      | 5   | 50.677| 10.135| 4.550  | 0.008 |
| B      | 2   | 86.836| 43.418| 19.500 | 0.000 |
| C      | 1   | 53.597| 53.597| 24.080 | 0.000 |
| D      | 1   | 6.107 | 6.107 | 2.740  | 0.116 |
| Error  | 17  | 37.843| 2.226 |        |       |
| Total  | 26  | 235.061|      |        |       |

4. Conclusion

In the present work, effect of four factors viz., layer thickness, build orientation, processing material and processing quality at mixed levels is studied on tensile strength of FDM built part. Taguchi’s parameter design is used to find the significance of factors before recommending optimum factor levels. The main effect for S/N ratio is plotted and the response as well as ANOVA of S/N ratio is calculated. Based on the experiment studies carried out, some of the important findings are as follows:

1. For the maximum tensile strength, the optimal level settings of the FDM fabrication parameters are as follows: layer thickness of 0.15 mm, build orientation of sidelong, processing material of PLA, processing quality of normal.

2. The build orientation, layer thickness and processing material have significant influence on tensile strength of the FDM built part. And to control the tensile strength, the build orientation has the greatest influence.

Thus, this study may be suitable for an optimization of the FDM characteristics with a larger number of process parameters for achieving a better part fabrication quality at a quicker rate.

Acknowledgments

This work is supported by the Education Scientific Research Project for the Young Teacher of Fujian Province, China (Grant No. JAT170613), the Natural Science Foundation of Fujian Province, China (Grant No. 2016J01727) and the Scientific Research Foundation Project of Fujian University of Technology, China (Grant No. GY-Z14075).

References

[1] A.K. Sood, R.K. Ohdar, S.S. Mahapatra, M. & D. 30, 4243(2009).
[2] B. Chi, H. Ma, X. Liu, C. Wang, Z. Jiao, W. Yang, P. 46, 9(2017).
[3] F. Ning, W. Cong, Y. Hu, H. Wang, J.C.M 51,451(2017).
[4] R. Sharma, R. Singh, R. Penna, F. Fraternali, C.P.B 132, 237(2018).
[5] R. Kumar, R. Singh, I.P.S Ahuja, M. 120, 11(2018).
[6] Standardization Administration of the People's Republic of China. GB/T 1040.1-2006(2006).
[7] Standardization Administration of the People's Republic of China. GB/T 1040.2-2006(2006).