Study on Effects of FDM 3D Printing Parameters on Mechanical Properties of Polylactic Acid

Yu Zhu¹, Yingchao Gao¹, Jie Jiang²*, Hai Gu²*, Shuaishuai Lv¹, Hongjun Ni¹, Xingxing Wang¹ and Chaofan Jia¹

¹School of Mechanical Engineering, Nantong University, Nantong, Jiangsu, 226019, China
²Jiangsu Key Laboratory of 3D Printing Equipment and Application Technology, Nantong Institute of Technology, Nantong, Jiangsu 226002, China

*Corresponding author’s e-mail: guhaint@ntit.edu.cn (H. Gu), jiangjie@ntit.edu.cn (J. Jiang)

Abstract. In view of the existing problems of complexity of process parameters and the difficulty in determining the optimal process in the field of 3D printing, polylactic acid (PLA) samples were prepared by fused deposition modeling (FDM). Orthogonal experiments were designed with 3D printing parameters (layer height, filling density and printing speed) as factors. The effects of layer height, filling density and printing speed on the tensile and compressive properties of PLA were studied. When layer height is 0.15 mm, the filling density is 100%, and the printing speed is 30 mm/s, the sample has the best comprehensive mechanical properties.

1. Introduction

3D printing technology, as a rapid prototyping technology, can slice the geometric model of the product and use plastic or metal as the raw material to print the real components layer by layer. Therefore, it is also called additive manufacturing technique [1-2]. Compared with traditional manufacturing technology, 3D printing technology has obvious advantages in manufacturing products with complex shapes and structures. In the automotive, medical, aerospace and other fields [3-5], small-volume production and high-end customized products are becoming mainstream, so 3D printing has broad development prospects.

Fused deposition modeling (FDM) is one of the most widely used 3D printing technologies. Filaments of thermoplastic materials such as polylactic acid (PLA) and acrylonitrile-butadiene-styrene copolymer (ABS) are mainly used as raw materials [6-7]. Under the control of computer, the printing material is extruded by the heated nozzle, stacked layer by layer, and finally the solid parts are obtained [8]. However, compared with traditional injection molded parts, 3D printed parts have the disadvantages of poor mechanical properties and surface quality [9]. Therefore, studying 3D printing parameters is of great significance for improving the mechanical properties of 3D printed products.

Orthogonal experimental design is a method for studying multi-factor and multi-level experiments. Orthogonal experiment method can select a group of representative points from the comprehensive experiment to carry out the experiment, which can reduce the number and the cost of experiments, so it has been widely used in many research fields.

In this paper, the orthogonal test method was used to study the effect of 3D printing parameters on the tensile and compressive strength of PLA. Layer height, filling density and printing speed were taken
2. Experimental

Three-dimensional model of mechanical test sample was designed by Solidworks and derived into STL file. Tensile samples were type I specimens in GB/T 1040.2-2006, and compressive samples were square cylinders in GB/T 1041-1992. STL files were imported into the slicing software Cura Engine. The software sliced according to the 3D printing parameters, and generated Gcode files to be imported into the 3D printer (Shenzhen Creality 3D Technology Co., Ltd.) to print samples. The tensile and compressed samples obtained by printing were shown in Figure 1.

![Figure 1. (a) Tensile sample, (b) Compressive sample](image)

Tensile property was tested according to GB/T 1040.2-2006, and the test speed was 5 mm/min. Compression property was tested according to GB/T 1041-1992, and the test speed was 1 mm/min.

3. Results and discussion

The orthogonal experimental design was used to arrange the 3D printing parameters of PLA. Layer height, filling density and printing speed were taken as factors. Each factor was taken at four levels, without considering the interaction between the factors. The tensile strength and compressive strength were selected as evaluation indexes. The design was based on the orthogonal experimental table of L₁₆(₄⁵), as shown in Table 1.

| Experiment Number | Layer height (mm) | Filling density (%) | Printing speed (mm/s) | Blank column | Tensile strength (MPa) | Compressive strength (MPa) |
|-------------------|-------------------|---------------------|-----------------------|--------------|------------------------|---------------------------|
| 1                 | 1 (0.15)          | 1 (40)              | 1 (30)                | 1            | 37.72                  | 44.35                     |
| 2                 | 1                 | 2 (60)              | 2 (40)                | 2            | 33.96                  | 42.82                     |
| 3                 | 1                 | 3 (80)              | 3 (50)                | 3            | 37.35                  | 47.85                     |
| 4                 | 1                 | 4 (100)             | 4 (60)                | 4            | 45.47                  | 67.71                     |
| 5                 | 2 (0.20)          | 1                   | 2                     | 3            | 34.37                  | 38.70                     |
| 6                 | 2                 | 2                   | 1                     | 4            | 41.63                  | 50.93                     |
| 7                 | 2                 | 3                   | 4                     | 1            | 26.26                  | 36.03                     |
| 8                 | 2                 | 4                   | 3                     | 2            | 40.00                  | 77.53                     |
| 9                 | 3 (0.25)          | 1                   | 3                     | 4            | 27.22                  | 31.97                     |
| 10                | 3                 | 2                   | 4                     | 3            | 18.45                  | 25.39                     |
| 11                | 3                 | 3                   | 1                     | 2            | 40.36                  | 53.64                     |
| 12                | 3                 | 4                   | 2                     | 1            | 39.57                  | 67.42                     |
| 13                | 4 (0.30)          | 1                   | 4                     | 2            | 15.98                  | 13.39                     |
| 14                | 4                 | 2                   | 3                     | 1            | 17.27                  | 12.26                     |
| 15                | 4                 | 3                   | 2                     | 4            | 19.94                  | 16.10                     |
| 16                | 4                 | 4                   | 1                     | 3            | 34.47                  | 53.98                     |

3.1 Analysis of range

The range analysis method is convenient to obtain the optimization results of the experiment by simple calculation and judgment. In this experiment, the best combination can be obtained by comparing the average value K and range R of tensile and compressive strength of each printing parameter.

The range analysis of tensile and compressive strength is shown in Table 2 and 3. By comparing the
range R, layer height has the greatest influence on the tensile strength. The filling density and the printing speed have similar effects, both of them are smaller than layer height. The optimal combination is A_1B_4C_1. For compression strength, filling density has the greatest influence, followed by layer height and printing speed. The optimal combination is B_4A_2C_1.

In order to analyze the influence of different levels of factors on tensile and compressive strength more intuitively, the range analysis results are plotted as line charts, as shown in Figure 2.

### Table 2. The range analysis of tensile strength

| Analysis value | Layer height | Filling density | Printing speed | Blank column |
|----------------|--------------|-----------------|----------------|--------------|
| k_1            | 38.62        | 28.82           | 38.55          | 30.20        |
| k_2            | 35.56        | 27.83           | 31.96          | 32.57        |
| k_3            | 31.40        | 30.97           | 30.46          | 31.16        |
| k_4            | 21.91        | 39.88           | 26.54          | 33.56        |
| **Range R**    | **16.71**    | **12.05**       | **12.01**      | **3.36**     |

### Table 3. The range analysis of compression strength

| Analysis value | Layer height | Filling density | Printing speed | Blank column |
|----------------|--------------|-----------------|----------------|--------------|
| k_1            | 50.68        | 32.10           | 50.73          | 40.02        |
| k_2            | 50.80        | 32.85           | 41.26          | 46.85        |
| k_3            | 44.61        | 38.41           | 42.40          | 41.48        |
| k_4            | 23.93        | 66.66           | 35.63          | 41.68        |
| **Range R**    | **26.86**    | **34.56**       | **15.10**      | **6.83**     |

Figure 2. Effect of Printing Parameters on Tensile and Compressive Strength

Layer height is the distance between the nozzle and the upper layer during printing. With the increase of layer height, the tensile strength decreases gradually, while the compressive strength does not change obviously when the layer height increases from 0.15 mm to 0.20 mm, and then decreases gradually. When a smaller layer height is used, the more layers are printed, the tighter the bond between the print layers is, which is beneficial to the improvement of the mechanical properties of the material. At the same time, the side of the sample with a smaller print layer height is smoother when viewed from the side of the sample.

Filling density reflects the compactness of filling in the shell of 3D printing parts. When the filling density increases, the tensile strength decreases slightly from 0.15 mm to 0.20 mm, and then increases gradually, while the compressive strength increases continuously. When the filling density increases from 80% to 100%, the tensile strength and compressive strength increase significantly, increasing by 28.77% and 73.55%, respectively. The larger the filling density, the more material consumed by the sample, which makes the internal structure more compact. When 100% filling density is used, solid filling can effectively avoid the formation and development of internal defects in the process of tension and compression, so the mechanical properties of the material are significantly enhanced.

Printing speed is the horizontal movement speed of the nozzle during printing. With the increase of printing speed, the tensile strength increases gradually and the compressive strength decreases on the whole, but the printing speed increases slightly at 50 mm/s. When the printing speed increases, the
uniformity of the extruder decreases due to the high-speed movement of the extruder, and even leads to instantaneous wire breakage, thus forming defects in the sample. At the same time, when printing one of the layers, the upper layer of surface material has not been completely cooled, resulting in uneven bonding between the upper and lower layers, which reduces the mechanical properties of the material.

3.2. Analysis of variance
The analysis of variance (ANOVA) is an efficient statistical test method. The analysis of variance can test the significant degree of the influence of relevant factors on the experimental results in the course of the experiment. The variance analysis table of tensile and compressive strength was obtained by using data analysis software Minitab, as shown in Table 4 and 5.

From Table 4 and 5, it can be seen that for tensile strength, the influence of printing layer height is very significant, and the influence of filling density and printing speed is significant. For compression strength, the effect of layer height and filling density is very significant, and the effect of printing speed is significant.

### Table 4. Variance analysis of tensile strength

| Factors             | SS    | df | MS  | F     | Significance level |
|---------------------|-------|----|-----|-------|--------------------|
| Layer height        | 634.42| 3  | 211.47 | 12.19 | **                 |
| Filling density     | 362.18| 3  | 120.73 | 6.96  | *                  |
| Printing speed      | 299.84| 3  | 99.95  | 5.77  | *                  |
| Error               | 26.58 | 3  | 8.86  |       |                    |
| Error△              | 77.45 | 6  | 12.91 |       |                    |

F0.05(3,6) = 4.76 F0.01(3,6) = 9.78

### Table 5. Variance analysis of compressive strength

| Factors             | SS    | df | MS  | F     | Significance level |
|---------------------|-------|----|-----|-------|--------------------|
| Layer height        | 1940.03| 3  | 646.68 | 26.03 | **                 |
| Filling density     | 3206.39| 3  | 1068.80 | 43.01 | **                 |
| Printing speed      | 465.74 | 3  | 155.25 | 6.25  | *                  |
| Error               | 107.08 | 3  | 35.69  |       |                    |
| Error△              | 149.11 | 6  | 24.85  |       |                    |

F0.05(3,6) = 4.76 F0.01(3,6) = 9.78

3.3. Determination and Verification of Optimal Scheme

Based on the results of range and variance analysis, the optimal scheme is determined. The optimal combination of tensile strength is A1B4C1 and compressive strength is B4A2C1. As shown in Figure 2, When the layer height is increased from 0.15 mm to 0.20 mm, the average compressive strength of the sample is reduced by only 0.12 MPa, however, the tensile strength increased by 3.06 MPa. Therefore, when the scheme is A1B4C1, that is, layer height is 0.15 mm, the filling density is 100%, and the printing speed is 30 mm/s, the specimen can obtain the highest tensile strength and compressive strength.

According to the optimal scheme A1B4C1, a group of tensile and compressive samples are made by 3D printing technology, and mechanical experiments are carried out. The results shows that the tensile strength of PLA samples is 58.25 MPa and the compressive strength is 86.11 Mpa. Therefore, the mechanical properties of PLA are improved and the optimization effect is obvious.

4. Conclusion

(1) For the tensile strength, the influence of the layer height is the greatest, and the filling density is similar to the printing speed, which is smaller than the layer height. For compression strength, the filling density has the greatest impact, followed by the layer height, and the smallest is the print speed.

(2) When layer height is 0.15 mm, the filling density is 100%, and the printing speed is 30 mm/s, the samples can obtain the highest tensile strength and compressive strength, 58.25 MPa and 86.11 Mpa respectively. The optimized scheme has certain guiding significance for improving the mechanical properties of 3D printing products.
Acknowledgments
This work was financially supported by a project funded by the Open Fund Project of Jiangsu Key Laboratory of 3D Printing Equipment and Application Technology (Nantong Institute of Technology) (2018KFKT11). A Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), Key Research and Development Program of Jiangsu (Industry Prospects and Common Key Technologies) (BE2018093), Jiangsu Wall Material Innovation Research Project (201702, 201703), Nantong Applied Research Project (JC2018115, JCZ18024); Teaching Reform Project of Nantong University(2018B31), Priority Discipline Construction Program of Jiangsu Province (2016-9), Qing Lan Project of Jiangsu Province (2016-15), Nantong Science and Technology Commission of China(CP12016002).

References
[1] Xiaoli L, Jianxiong Ma, Ping L, et al. 3D Printing Technology and Its Application Trend[J]. Process Automation Instrumentation, 2014, 35(1):1-5.
[2] Fengzhen L, Mingxin L, Yunhua W, et al. Research Progress on Application of 3D Printing Technology in Medical Field[J]. Materials China, 2016, 35(5):381-385.
[3] Jian L, Zhengjun L, Haiqing G U, et al. Domestic developing status of 3D printing in China[J]. Manufacturing Technology & Machine Tool, 2015, 3: 17-25.
[4] Zhen-Ying Y, Bo Y U. Application and Research Progress of 3D Printing in Automotive Plastic Parts Design[J]. China Plastics Industry, 2017, 45(5):11-15.
[5] FRAZIER W E. Metal additive manufacturing: A review[J]. Journal of Materials Engineering and Performance, 2014, 23(6): 1917-1928.
[6] Lee J Y, An J, Chua C K. Fundamentals and applications of 3D printing for novel materials[J]. Applied Materials Today, 2017, 7:120-133.
[7] Singh S, Ramakrishna S, Singh R. Material issues in additive manufacturing: A review[J]. Journal of Manufacturing Processes, 2017, 25:185-200.
[8] Bellini A, Selçuk Güçeri. Mechanical characterization of parts fabricated using fused deposition modeling[J]. Rapid Prototyping Journal, 2003, 9(4):252-264.
[9] Yusheng S. The industrial application and industrialization development of 3D printing technology[J]. Machine Design and Manufacturing Engineering, 2016(2):11-16.