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Posted Date: 2 December 2024

doi: 10.20944/preprints202412.0097.v1

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Article

# Research on Effects of FDM Process Parameters on Mechanical Properties of Polylactic Acid Based on Orthogonal Experiments

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**Abstract:** Using polylactic acid (PLA) filament as the printing material for fused deposition modeling (FDM), and tensile and bending strength as optimization indexes, the influence of four process parameters, printing speed, layer thickness, nozzle temperature, and raster angle, on mechanical properties of PLA specimens in FDM are investigated by orthogonal experiments. The mechanical responses of the printed specimens are explored through tensile and three-point bending tests. Range analysis method is used to investigate the effects of various process parameters on mechanical properties. The optimal combination of printing parameters is obtained through comprehensive evaluation method and comprehensive scoring method, and the correctness of the results is experimentally verified. The optimal process parameters are  $h=0.1\text{mm}$ ,  $t=210\text{ }^\circ\text{C}$ ,  $v=40\text{ mm/s}$ , and  $\theta=45^\circ/45^\circ$ , and the corresponding tensile strength and bending strength are 26.34MPa and 41.54MPa, respectively.

**Keywords:** PLA; fused deposition modeling; process parameters; mechanical properties; orthogonal experiment

## 1. Introduction

Additive manufacturing, also known as 3D printing, has significant advantages in manufacturing complex structural materials [1]. As one of them, fused deposition modeling (FDM) has been widely used in aerospace, automotive, construction, medical and other fields [2–5] due to its high molding efficiency, simple operation, low pollution, easy material acquisition, and low cost of printing equipment and consumables. Polylactic acid (PLA), as the mainstream material of FDM technology, has advantages such as strong plasticity, high elastic modulus and good biodegradability [6]. The quality and performance of PLA printed products have received widespread attention. At present, the factors that constrain the development of PLA-FDM, in addition to product structure, material properties, and molding equipment, are also urgent issues that need to be addressed regarding the impact of various process parameters in the molding process on the performance of printed products.

In FDM, process parameters such as printing speed, layer thickness, nozzle temperature, and printing path have a significant impact on mechanical properties [7]. Therefore, scholars have conducted extensive research on this. The sample printed with smaller layer thickness has a lower porosity and improved mechanical strength [8]. Spišák et al. [9,10] showed that optimizing different scanning paths is beneficial for improving the tensile strength of products in the main force direction. According to the theory of thermal diffusion, an appropriately high temperature is helpful to the diffusion of molecular chains between polymers. Subsequently, during the cooling process, the curling of molecular chains causes entanglement of interlayer molecular chains, enhancing the bonding force between polymers and increasing their tensile strength [11]. The printing speed affects the interlayer cooling time. When the printing speed is high, the interlayer cooling time is short. When

the printing speed is sufficient, the bonding effect between layers is enhanced, which is conducive to improving the mechanical properties of the product [12,13].

FDM is a process of multiple parameters interacting and influencing each other. In recent years, most research on FDM process parameters has mainly focused on the effects of single parameters such as printing direction [14], filling mode [15], printing speed and extrusion temperature [16], annealing treatment time and temperature [17,18] on mechanical properties. There is relatively little research on the comprehensive effects of multiple parameter changes on mechanical properties [19]. Therefore, it is necessary to comprehensively evaluate the mechanical properties of printed materials under the joint action of multiple parameters, and screen the optimal parameter combination of printed materials under the joint evaluation of multiple indicators.

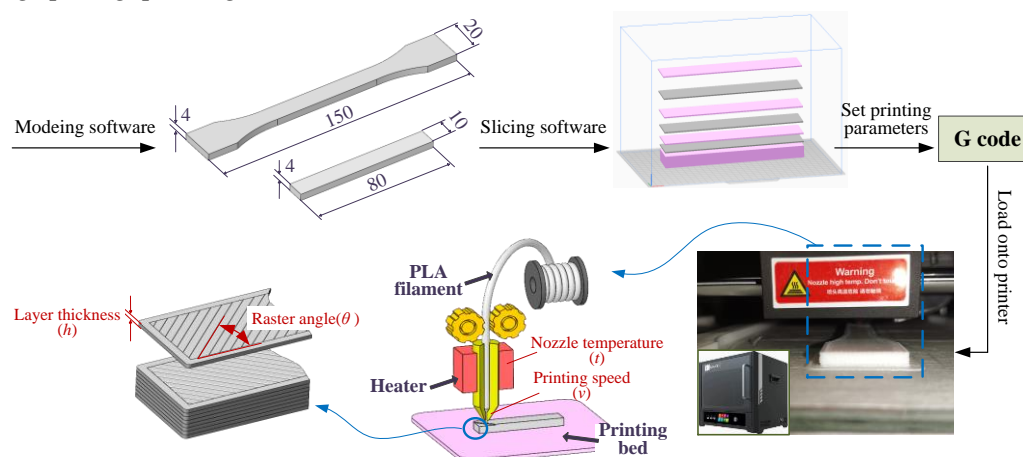
For the FDM of PLA filament, this article takes the tensile and bending strength of the specimens as optimization indicators, selects four process parameters that affect the mechanical properties of printed parts to design orthogonal experiments, and uses range analysis, comprehensive evaluation method, and comprehensive scoring method to optimize the best forming process parameters, achieving quality improvement of FDM parts.

## 2. FDM Principle and Process Parameters

The schematic diagram of the preparation and printing process of PLA-FDM is shown in Figure 1.

In preparation stage: first, according to the experimental requirements and standards, the three-dimensional models of tensile and bending test specimens are designed in modeling software (such as SolidWorks used in this article). Second, the models are imported into slicing software (such as Ultimaker Cura used in this article) in STL format, and then the printing parameters are set and the slicing work is completed. Third, generate G code and import it into the FDM printer.

In printing process: the PLA filament enters the nozzle under the push of two driving rollers, and is molten and extruded under the action of heater at the printing temperature. Then, according to the predetermined trajectory of each layer, the printing work is carried out at the printing speed until the whole specimen is formed. The process parameters that affect the mechanical properties of printed parts mainly include printing speed, layer thickness, nozzle temperature, raster angle, printing spacing, printing track, etc [20].



**Figure 1.** Schematic diagram of preparation and printing process for PLA-FDM.

In order to explore the influence of various process parameters on the mechanical properties of FDM printed parts, this paper studied the effects of printing speed, layer thickness, nozzle temperature and raster angle on the tensile and bending properties of PLA-FDM specimens based on orthogonal experiments. Each parameter is defined as follows:

- a. Printing speed( $v$ ). The movement speed of the printer nozzle.
- b. Layer thickness( $h$ ). The thickness of each layer of stacked material.

c. Nozzle temperature ( $t$ ). The pre-set nozzle temperature, and the heater is used to keep this temperature constant during the printing process.

d. Raster angle( $\theta$ ): The angle between the filament stacking path and the contour reference.

### 3. Experimental

#### 3.1. Preparation of PLA Specimens

The PLA filament (from Shenzhen Aurora Technology Co.,Ltd.) is printed by a commercial 3D printing machine (from Aurora™). The other printing parameters used in this paper are listed in Table 1.

**Table 1.** Fixed FDM process parameters.

	FDM parameters	Values
PLA parameters	Filament diameter(mm)	1.75
	Density(kg/m <sup>3</sup> )	1250
FDM process parameters	Nozzle diameter(mm)	0.4
	Filling rate(%)	100
	Printing bed temperature(°C)	70

#### 3.2. Experimental Design

Four FDM parameters, including layer thickness (A), nozzle temperature (B), printing speed (C), and raster angle (D), are chosen to investigate on the mechanical properties of PLA printed parts, and the orthogonal test array L9(3<sup>4</sup>) is designed. The four parameters, three levels, and their values are shown in Table 2.

**Table 2.** Four parameters and three levels in orthogonal experiment.

FDM parameter	Number	Level 1	Level 2	Level 3
Layer thickness (mm)	A	0.1	0.2	0.3
Nozzle temperature (°C)	B	190	210	230
Printing speed (mm/s)	C	20	40	60
Raster angle (°)	D	45/-45	30/-60	0/90

#### 3.3. Mechanical Properties Test

Tensile and bending strength of various samples are conducted using Microcomputer controlled electronic universal testing machine (TEM104C, Shenzhen Wance Testing Machine Co., Ltd.), as shown in Figure 2. The experimental process follows ISO527-1:2012 and ISO178:2010, respectively. And the PLA specimens after tension and bending are shown in Figure 3.



**Figure 2.** The tensile and bending tests.



**Figure 3.** PLA specimens after tension and bending.

## 4. Results and Discussion

### 4.1. Orthogonal Experimental Results

In this paper, nine groups of comparative tests are conducted according to the orthogonal experiments of  $L9(3^4)$ . Each group conducted five experiments, and the average value is taken as the experimental result for subsequent analysis. As shown in Table 3, there is a significant difference in tensile and bending strength among the experimental groups under different parameter combinations.

**Table 3.** Orthogonal experimental results.

Test number	Parameter				Index	
	A	B	C	D	Tensile strength (MPa)	bending strength (MPa)
Test 1	1	1	1	1	25.65	31.27
Test 2	1	2	2	2	25.33	29.88
Test 3	1	3	3	3	21.05	31.83
Test 4	2	1	2	3	21.01	32.06
Test 5	2	2	3	1	24.17	33.68
Test 6	2	3	1	2	22.82	26.1
Test 7	3	1	3	2	16.5	26.03
Test 8	3	2	1	3	23.85	22.31

Test 9	3	3	2	1	24.79	29.21
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#### 4.2. Comprehensive Evaluation of Orthogonal Experimental Results

The steps for calculating and analyzing the results of orthogonal experiments are as follows:

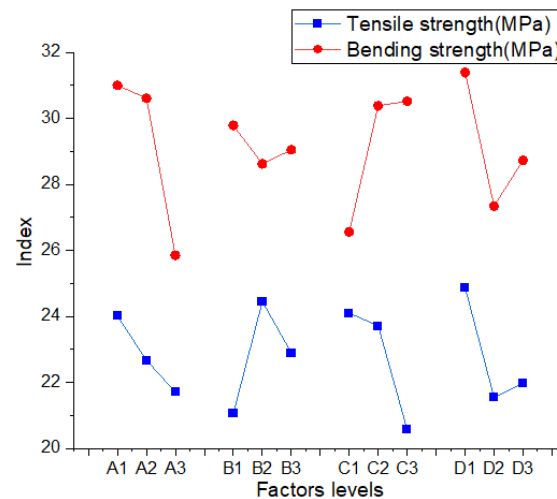
1. Calculate  $K_i$ :  $K_i$  is the sum of the indexes for the same level. Taking parameter A in the tensile strength index experiment as an example.

$$K_1 = y_1 + y_2 + y_3 = 25.65 + 25.33 + 21.05 = 72.03$$

$$K_2 = y_4 + y_5 + y_6 = 21.01 + 24.17 + 22.82 = 68$$

$$K_3 = y_7 + y_8 + y_9 = 16.5 + 23.85 + 24.79 = 65.14$$

2. Calculate  $k_i$ :  $k_i$  is the average values of each parameter at the same level, that is,  $k_i = K_i/3$ .
3. Calculate  $R$ :  $R = \max(k_i) - \min(k_i)$ , is the range to measure the variation of the experimental values.
4. Draw parameter-index trend graph: Taking the parameter level as the X-axis and the average value  $k_i$  as the Y-axis, the relationship between mechanical properties and different levels of each parameter can be visually displayed and analyzed, as shown in Figure 4.



**Figure 4.** Trend graph between properties indexes and parameters levels.

According to the  $R$ -value, we can determine the influence orders of the various factors, and according to the factor-index trend graph, we can obtain the optimal combination of process parameters for each index. Then the results for each index are listed in Table 4. We can see that, for tensile strength, the order of influence of the four parameters is  $C > B > D > A$ , and the optimal parameter combination is A1B2C1D1. And for bending strength, the influence order is  $A > D > C > B$ , and the optimum parameter combination is A1B1C3D1. Meanwhile, from the experimental results, the impact mechanism of the four process parameters on the mechanical properties of PLA-FDM parts can be summarized as follows:

**Table 4.** Analysis results of the orthogonal experiments.

Properties		A	B	C	D
Tensile strength	K1	72.03	63.15	72.31	74.61
	K2	68	73.35	71.13	64.65
	K3	65.14	68.67	61.72	65.91
	k1	24.01	21.05	24.1	24.87
	k2	22.67	24.45	23.71	21.55
	k3	21.71	22.89	20.57	21.97

	R	2.3	3.4	3.53	3.32
	Order	C>B>D>A			
	Optimal combination	A1B2C1D1			
Bending strength	K1	92.99	89.36	79.68	94.16
	K2	91.84	85.87	91.14	82.02
	K3	77.55	87.14	91.55	86.2
	k1	31	29.79	26.56	31.39
	k2	30.61	28.62	30.38	27.34
	k3	25.85	29.05	30.52	28.73
	R	5.15	1.16	3.96	4.05
	Order	A>D>C>B			
	Optimal combination	A1B1C3D1			

**Layer thickness.** The trend graph in Figure 4 shows that as the layer thickness increases, both the tensile strength and bending strength of the test samples decrease. The reason is that the increase in layer thickness leads to an increase in interlayer porosity. Meanwhile, for parts of the same height, an increase in layer thickness means a decrease in the number of layers, which reduces the internal filaments used to resist external forces. The above two reasons jointly lead to the weakening of the mechanical properties of the parts. Therefore, A1 ( $h=0.1\text{mm}$ ) is chosen as the optimal level.

**Nozzle temperature.** Compared with other parameters, the nozzle temperature has relatively small effect on overall mechanical properties of PLA specimens. An appropriately high temperature can enhance the PLA melt fluidity, which is conducive to the full diffusion and fusion of molecular chains, forming a good interface between printed filaments. However, excessively high nozzle temperatures can easily lead to strong resin fluidity, even decomposition and vaporization, which is not conducive to printing. Usually, the reasonable range for 3D printing nozzle temperature is between the glass transition temperature and thermal decomposition temperature of the PLA materials. Thus, B2 ( $t=210^\circ\text{C}$ ) can be choice as the optimal level.

**Printing speed.** From the trend graph, we can see that as the printing speed increases, the tensile strength decreases and the bending strength increases, with opposite trends. Overall, when the speed increases from 20 to 40 mm/s, the tensile strength decreases very little, but the bending strength increases a lot. However, when the speed increases from 40 to 60 mm/s, the bending strength increases very little, but the tensile strength decreases more. Therefore, choosing 40 mm/s is more appropriate. This is because when the speed increases to a certain stage, the fluidity of PLA resin is good, and when adjacent molten filaments come into contact with each other, the interface temperature and bonding performance are good. If the printing speed is too high, the effective contact time between filaments decreases, resulting in a deterioration of their bonding strength.

**Raster angle:** The raster angle represents the angle between the movement directions of the molten filaments in each layer during the printing process. When angle changes, only the stacking angles of adjacent layers filaments are different, but the density of the internal "fiber bundles" in the sample does not change. When the material sample is subjected to stress, the filaments are oriented to resist fracture along external forces. From trend graph, D1 ( $\theta=45/-45^\circ$ ) should be selected as the optimal level.

In summary, the optimal process parameter combination is A1B2C2D1, which is  $h=0.1\text{mm}$ ,  $t=210^\circ\text{C}$ ,  $v=40\text{ mm/s}$ , and  $\theta=45/-45^\circ$ .

#### 4.3. Comprehensive Scoring of Orthogonal Experimental Results

The comprehensive scoring method is to determine the proportion of different indicators based on their different importance during the experimental process, convert multi indicator experimental results into single indicator experimental results, and then optimize the experimental results based

on the analysis of single indicators. This article uses formulas (1) and (2) to calculate the membership and comprehensive scores of tensile strength and bending strength.

$$U = \frac{A - A_{\min}}{A_{\max} - A_{\min}} \quad (1)$$

$$T = 0.5 \times U_T + 0.5 \times U_B \quad (2)$$

Here,  $U$ -Membership degree of each index,  $0 \leq U \leq 1$ ;

$U_T$ -Membership degree of tensile strength;

$U_B$ -Membership degree of bending strength;

$A$ -Index value;

$A_{\max}$ - Maximum index value;

$A_{\min}$ - Minimum index value;

$T$ -Comprehensive score;

Considering the overall performance of mechanical properties, the weights for tensile and bending strength are both taken as 0.5. The analysis results of the comprehensive scoring method are shown in Table 5 and Table 6.

**Table 5.** Comprehensive score.

Test number	Tensile strength (MPa)	Bending strength (MPa)	$U_T$	$U_B$	$T$
Test 1	25.65	31.27	1	0.79	0.89
Test 2	25.33	29.88	0.97	0.67	0.82
Test 3	21.05	31.83	0.5	0.84	0.67
Test 4	21.01	32.06	0.49	0.86	0.68
Test 5	24.17	33.68	0.84	1	0.92
Test 6	22.82	26.1	0.69	0.33	0.51
Test 7	16.5	26.03	0	0.33	0.16
Test 8	23.85	22.31	0.8	0	0.4
Test 9	24.79	29.21	0.91	0.61	0.76

**Table 6.** Comprehensive scoring analysis results.

	A	B	C	D
K1	2.38	1.73	1.81	2.57
K2	2.11	2.14	2.25	1.49
K3	1.32	1.94	1.75	1.74
k1	0.79	0.58	0.6	0.86
k2	0.7	0.71	0.75	0.5
k3	0.44	0.65	0.58	0.58
R	0.35	0.13	0.17	0.36
Order	D>A>C>B			
Optimal combination	A1B2C2D1			

Analysis shows that the optimal parameter for the comprehensive scoring method is also A1B2C2D1, which is consistent with the comprehensive balance method. This further verifies the rationality and correctness of the comprehensive balance method and comprehensive scoring method based on orthogonal experiments. Due to the fact that the optimal parameter combination does not

belong to one of the 9 orthogonal table experiments, experimental validation is required, and the validation results are shown in Table 7.

**Table 7.** Experimental verification of optimal parameters combination.

Optimal combination	Tensile strength (MPa)	Bending strength (MPa)
A1B2C2D1	26.34	41.54

From Table 7, it can be seen that compared with the results in the orthogonal experimental table mentioned earlier, both indexes of the optimal parameter combination have significantly improved, proving the correctness of the optimal printing parameter combination.

## 5. Conclusions

PLA is one of the most widely used polymers in FDM. This article investigates the influence of process parameters such as printing speed, layer thickness, nozzle temperature, and raster angle on the mechanical properties of PLA printed parts in FDM based on orthogonal experiments.

Orthogonal experiments are designed for the indexes of tensile and bending strength. Through range analysis, the influence order of process parameters that affect tensile and bending strength is determined as follows: raster angle, layer thickness, printing speed, and nozzle temperature. The influence laws of different parameters are obtained, with layer thickness and raster angle having the same influence laws on the two indexes, and the impact of printing speed and nozzle temperature is completely opposite.

The optimal process parameter combination can be determined as A1B2C2D1 through comprehensive evaluation method and comprehensive scoring method, which is  $h=0.1\text{mm}$ ,  $t=210\text{ }^\circ\text{C}$ ,  $v=40\text{ mm/s}$ , and  $\theta=45/45\text{ }^\circ$ . At this point, the tensile strength is 26.34MPa, the bending strength is 41.54MPa, and the mechanical properties are significantly improved.

**Acknowledgments:** This work was supported by the College Student Innovation and Entrepreneurship Training Program Project and Key Lab. of Manufacturing Equipment of Shaanxi Province, (Grant No.JXZZZB-2022-05).

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