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Carbon Emission Model Analysis of Fdm Molding Process

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Abstract

3D printing, as an emerging manufacturing technology, has the characteristics of on-demand printing and inventory reduction, which to some extent reduces carbon emissions during product production. To study the carbon emissions during FDM molding process, the entire lifecycle theory is used to divide the molding process into stages, and a carbon emission quantification model is established using the carbon emission factor method; The Box Behnken experimental design method was used to conduct carbon emission experiments, selecting four factors: filling rate, printing speed, layer height, and nozzle temperature. The response surface methodology was used to analyze the impact of single and dual factor interactions on carbon emissions. Research has shown that among single factors, filling rate, printing speed, and layer height have a significant impact on carbon emissions; The impact of printing speed and layer height on carbon emissions is most significant in the dual factor interaction. A quadratic fitting formula between the influencing factors of carbon emissions and carbon emissions was obtained by combining the interaction of single and double factors on carbon emissions.

Keywords*: Carbon emissions; Life cycle assessment; Additive manufacturing; FDM*

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I. INTRODUCTION

China has proposed the goal of reaching the peak of carbon by 2030 and achieving carbon neutrality by 2060, carbon emissions have received widespread attention.As a new manufacturing technology, 3D printing has the characteristics of printing on demand and reducing inventory, which has reduced the carbon emissions in the production process of products to a certain extent. FDM technology has become one of the widely used 3D printing technologies due to its low cost and ease of use. Contrary to the traditional manufacturing process of subtracting products from bulk materials, 3D printing adopts a layer by layer "addition" manufacturing process, which greatly reduces material waste during manufacturing.[1,2]

Life cycle assessment, as a quantitative evaluation method from cradle to grave, has been widely applied in the calculation and analysis of carbon emissions and energy consumption. Many theory of computation and practical models have been formed, such as process based LCA (P-LCA), input output based LCA (IO-LCA), hybrid LCA (H-LCA) and measurement method[3].

The process based carbon emission calculation method refers to the method of quantifying carbon emissions based on activity data of carbon emission sources and corresponding carbon emission factors of unit activity levels.[4] This method is often referred to as the "emission coefficient method", "process analysis method", etc. According to the basic concept of this method, the carbon emissions per unit product i or unit process j can be calculated according to equation (1).

$$E_{i(j)} = \varepsilon_{i(j)} q_{i(j)} \tag{1}$$

In which， $E_{i(j)}$—Calculated carbon emissions per unit product i or unit process j E_i or E_j, $\varepsilon_{i(j)}$—The carbon emission factor of unit product i or unit process j, i.e. the carbon emissions per unit activity level, $q_{i(j)}$—Activity level of unit product i or unit process j.

Then, based on the composition of the product system, the carbon emissions E of the product system can be calculated, as shown in formula (2)

$$E = \sum_{i(j)} E_{i(j)} \tag{2}$$

Barros et al.[5] conducted a comparative analysis on the impact of user configuration in 3D printing product LCA, and the results showed that product design and user CAD expertise affect the usage time of computers and printers, which has a certain impact on the environment. Saade et al.[6] analyzed 52 literature on the environmental impact of additive manufacturing lifecycle, and comprehensively analyzed the selection of modeling methods, definition of system boundaries, data sources, impact assessment methods, uncertainty and sensitivity. It was found that the impact of 3D printing on the environment in different industries depends on the different printing methods. Lindemann et al.[7] developed a calculation model for evaluating life cycle costs applicable to the field of additive manufacturing, and applied example calculations to demonstrate that the design, production, operation, and maintenance stages are the largest sources of life cycle costs, with construction rate, machine cost, material cost, and utilization rate being the most critical factors in the production cost of additive manufacturing.

II. QUANTITATIVE MODEL

According to the principle of life cycle assessment, the FDM forming process can be divided into raw material preparation stage, manufacturing stage, transportation stage, usage stage, and recycling stage. This article selects FDM 3D printed I-shaped specimens as the research object. Due to the fact that I-shaped specimens do not require post-processing operations such as support or precision machining, they need to be printed immediately in the laboratory and are limited by experimental conditions. Therefore, this article constructs an experimental system and scheme to study the carbon emissions during the process printing stage of raw material preparation and manufacturing stages.

The raw material preparation stage is the first stage of the product lifecycle, mainly to obtain the materials required for subsequent stages. The main raw materials involved in FDM 3D printing include PLA, ABS, TPU, etc. This stage mainly involves the consumption of material resources. The quantitative model for this stage is as follows.

$$E_p = \sum_{i=1}^{n} M_i \cdot EF_i \tag{3}$$

In which， E_P—Carbon emissions during raw material preparation stage(KgCO$_{2e}$), M_i—Quality of Class i raw materials(kg), EF_i—Carbon emission factors for Class i raw materials(KgCO2e/kg).Table1 shows the common carbon emission factors of fused deposition materials.

Table 1 Common carbon emission factors of fused deposition materials

materials	carbon emission factors（$kgCO_{2e}/kg$）
ABS	3.17
PLA	0.587
PVC	3.18
PC	7.7984

The manufacturing stage is the process of computer design and making raw materials usable as finished products, mainly including 3D printing model design and processing, specimen printing, de support, and precision machining. This stage mainly involves energy consumption, as shown in formula (4):

$$E_m = P_m \cdot EF_p \tag{4}$$

In which， E_m —Carbon emissions during the manufacturing phase($KgCO_{2e}$), P_m —Electric energy consumed during the manufacturing phase(KW.h), EF_p —Electric energy carbon emission factor($KgCO_{2e}$/KW.h).

Table 2 shows the average carbon dioxide emission factors of China's regional power grid from 2010 to 2012（$KgCO_2$/KW.h）

Table 2 Average carbon dioxide emission factors of China's regional power grid from 2010 to 2012（$KgCO_2$/KW.h）

	Name of China's regional power grid					
	North	Northeast	East	Central	Northwest	South
2012	0.8843	0.7769	0.7035	0.5257	0.6671	0.5271
2011	0.8967	0.8189	0.7129	0.5955	0.6860	0.5748
2010	0.8845	0.8045	0.7182	0.5676	0.6958	0.5960

III. CARBON EMISSION TEST DURING FDM MOLDING PROCESS

Test System

The experimental system is shown in Figure 1, where the Creativity Ender-3S1 3D printer is used for printing I-shaped specimens, and the material is PLA. During the printing process, the power and printing time of the process printing stage are measured using a PW9901 (232 communication) intelligent electrical parameter measuring instrument. After the specimen is formed, its mass is measured using the FA1204E electronic balance, and then the carbon emissions during the raw material preparation stage and the process printing stage in the manufacturing stage are calculated using the carbon emission quantification model proposed earlier.

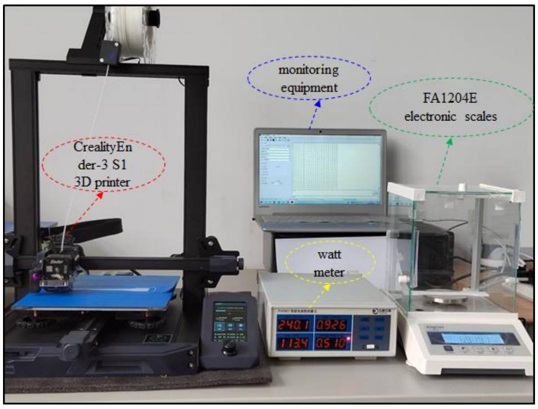


Figure 1 FDM Forming Process Printing Test System

The Creativity Ender-3 S1 3D printer mainly consists of a printing platform, nozzle components, display screen, material breakage detection, spool support, motor, etc., with a printing accuracy of ± 0.1mm. Table3 shows the printer equipment parameters. FA1204E electronic balance, with a minimum measurement reading of 0.1mg and a maximum weighing of 120g.

Table 3 Printer Equipment Parameters

Factors	Coding and Level		
	Low(-1)	Middle (0)	High(1)
Fill rate A(%)	10	40	70
Printing speed B(mm/s)	30	65	100
Floor height C(mm)	0.1	0.2	0.3
Nozzle temperatureD(°C)	200	210	220

Analysis of test results

The FDM 3D printed sample is shown in Figure 2. The carbon emissions during the FDM molding process under the influence of four factors can be calculated using a carbon emission quantification model, and the results are shown in Table 4.

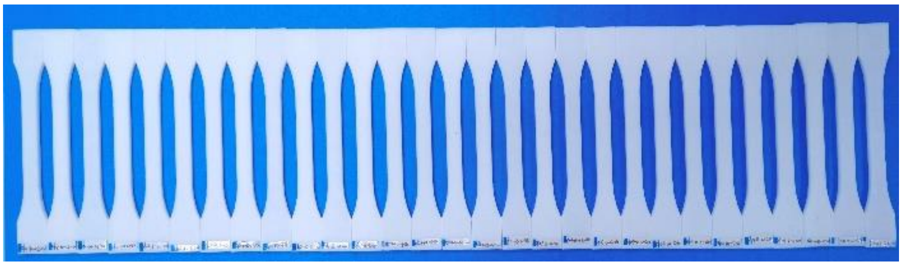


Figure 2 Printing the Sample

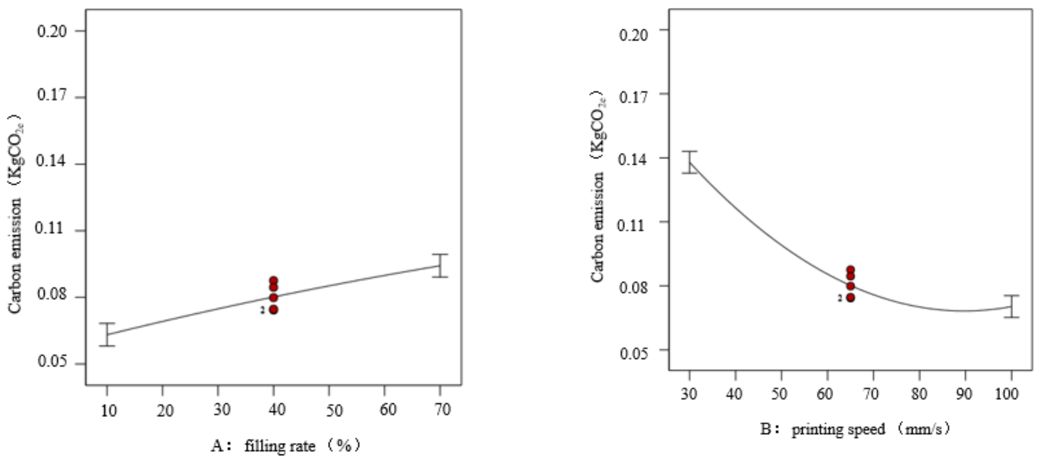
Table 4 Carbon emissions during FDM molding process under single factor action

No.	A (%)	B (mm/s)	C (mm)	D (℃)	Ep+Em ($kgCO_{2e}$)	No.	A (%)	B (mm/s)	C (mm)	D (℃)	Ep+Em ($kgCO_{2e}$)
1	10	30	0.2	210	0.1114	16	40	100	0.3	210	0.0951
2	70	30	0.2	210	0.1488	17	10	65	0.1	210	0.1265
3	10	100	0.2	210	0.0569	18	70	65	0.1	210	0.1607
4	70	100	0.2	210	0.0742	19	10	65	0.3	210	0.0474
5	40	65	0.1	200	0.1391	20	70	65	0.3	210	0.1051
6	40	65	0.3	200	0.0558	21	40	30	0.2	200	0.1286
7	40	65	0.1	220	0.1406	22	40	100	0.2	200	0.0607
8	40	65	0.3	220	0.0549	23	40	30	0.2	220	0.1330
9	10	65	0.2	200	0.0642	24	40	100	0.2	220	0.0612
10	70	65	0.2	200	0.0874	25	40	65	0.2	210	0.0743
11	10	65	0.2	220	0.0648	26	40	65	0.2	210	0.7776
12	70	65	0.2	220	0.0871	27	40	65	0.2	210	0.0725
13	40	30	0.1	210	0.2510	28	40	65	0.2	210	0.0867
14	40	100	0.1	210	0.1152	29	40	65	0.2	210	0.0741
15	40	30	0.3	210	0.0961						

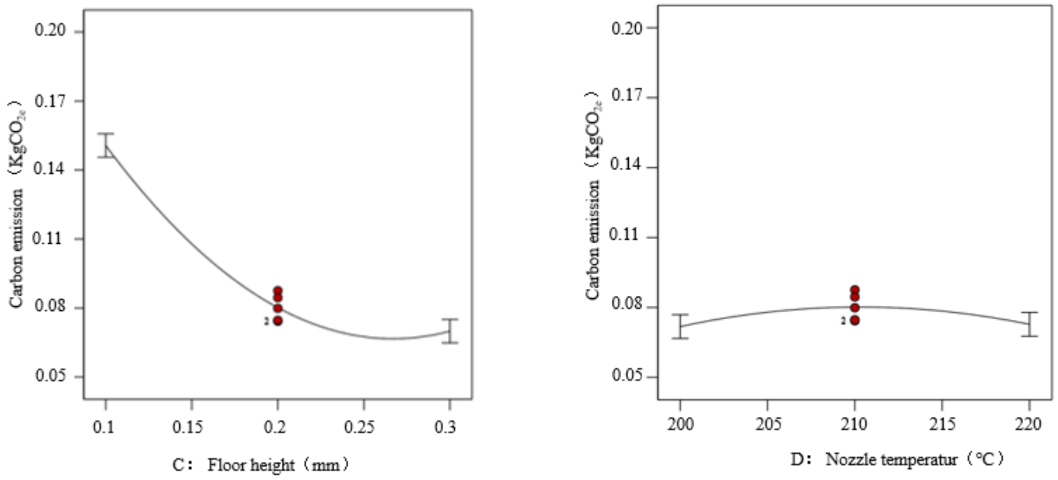
By analyzing the experimental data, regression coefficients for single factor and constant terms were obtained, and significance P and F values were obtained. F value is the statistical value of F-test (the ratio of the mean square between groups to the mean square within groups), which is used to evaluate the difference between groups. P value refers to the probability that the F-test is greater than the calculated value, and $P<0.05$ indicates that the model has a significant impact. Table 5 shows the single factor regression coefficients and F-value, P-value

Table 5 Single factor regression coefficients and F-value, P-value

Factor term	Coefficient	95% Confidence interval		F	P
		Low	High		
Constant term	0.0802	0.0723	0.0881	53.9	＜0.0001
A	0.0155	0.0104	0.0206	42.61	＜0.0001
B	-0.0338	-0.0389	-0.0287	201.6	＜0.0001
C	-0.0404	-0.0455	-0.0352	287.32	＜0.0001
D	0.0005	-0.0046	0.0056	0.1414	0.8417



(a) The impact of filling rate on carbon emissions (b) The impact of printing speed on carbon emissions



(c) The impact of filling rate on carbon emissions (d) The impact of filling rate on carbon emissions

Figure 3 Impact of single factor on carbon emissions

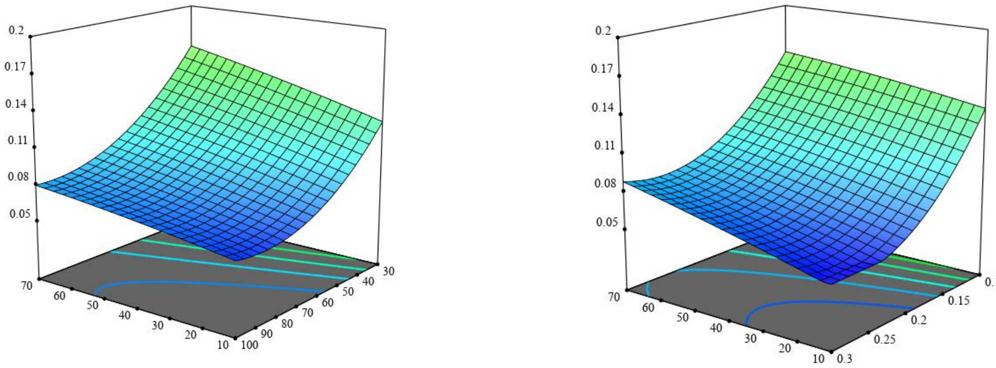
From Figure 3 (a), it can be seen that as the filling rate increases, carbon emissions increase linearly. This is because the increase in filling rate increases the use of raw materials, which increases material consumption and leads to an increase in carbon emissions. However, it should be noted that from the simulation results in Section 3, it can be seen that the filling rate has a certain pattern of influence on the strength of printed specimens. Therefore, under the premise of given specimen strength, selecting an appropriate filling rate can reduce carbon emissions during FDM molding process. From Figure 3 (b), it can be seen that as the printing speed increases, carbon emissions gradually decrease and tend to flatten out. This is because the increase in printing speed shortens the printing time of the specimen, which reduces energy consumption and carbon emissions during FDM molding. The printing speed of the 3D printer affects the surface quality of the specimen, and excessive printing speed will lead to a decrease in quality. From Figure 3 (c), it can be seen that as the height of the layer increases, carbon emissions gradually decrease. This is because as the height of the layer increases, on the one hand, it reduces the use of raw materials, and on the other hand, it shortens printing time, reducing carbon emissions from both material and energy sources. From Figure 3 (d), it can be seen that as the nozzle temperature increases, carbon emissions first increase and then decrease, but the overall trend of change is very small, indicating that the impact of temperature on carbon emissions is not significant.

On the basis of single factor influence, this article analyzes the interaction between two factors. The regression coefficients, F-values, and significance P-values of the interaction and quadratic terms were obtained, as shown in Table 6.

Table 6 Regression coefficients, F-values, and significance P-values of interaction and quadratic terms

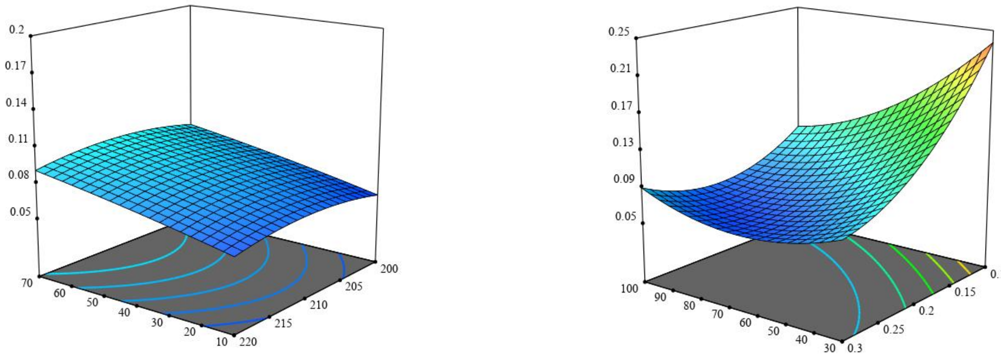
Factor term	Coefficient	95% Confidence interval		F	P
		Low	High		
AB	-0.0050	-0.0139	0.0038	1.48	0.2436
AC	0.0045	-0.0044	0.0133	1.18	0.2965
AD	-0.0002	-0.0091	0.0086	0.0034	0.9541
BC	0.0337	0.0248	0.0425	66.76	＜0.0001
BD	-0.0010	-0.0098	0.0079	0.0569	0.8149
CD	-0.0006	-0.0094	0.0083	0.0207	0.8876
A^2	-0.0015	-0.0084	0.0055	0.2089	0.6547
B^2	0.0239	0.0170	0.0309	54.63	＜0.0001
C^2	0.0301	0.0232	0.0371	86.65	＜0.0001
D^2	-0.0079	-0.0150	-0.0010	5.97	0.0284

Through the significance analysis of multifactor interaction, it can be seen that the secondary term P values of factors A and D are all greater than 0.05, while the secondary term P values of factors B and C are all less than 0.05. In the dual factor interaction phase, the P values of AB, AD, and AC are greater than 0.05, and only the interaction term P value of factor BC is less than 0.05. This indicates that in the multi factor interaction, only the interaction of factor BC has the most significant impact on carbon emissions, When other factors interact, their impact on carbon emissions is not significant, with the order of BC>AB>AC>BD>CD>AD. The two-dimensional and three-dimensional diagrams of the interaction between two factors are shown in Figure 4.



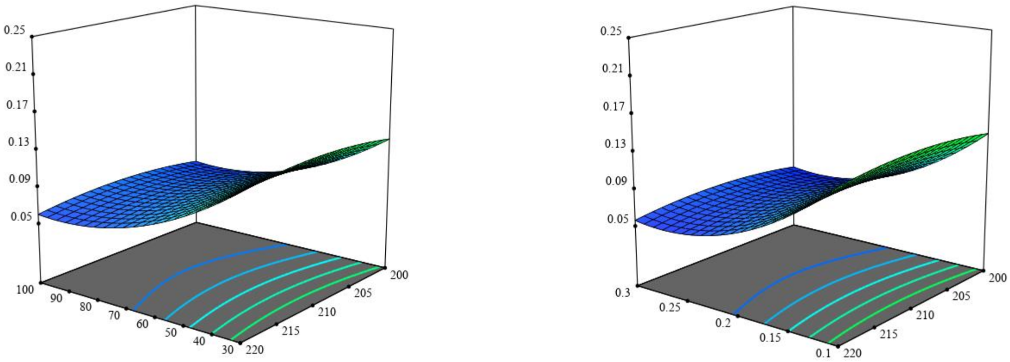
(a) The impact of the interaction between filling rate and printing speed on carbon emissions

(b) The impact of the interaction between filling rate and layer height on carbon emissions



(c) The impact of the interaction between filling rate and nozzle temperature on carbon emissions

(d) The impact of the interaction between printing speed and nozzle temperature on carbon emissions



(e) The impact of the interaction between printing speed and nozzle temperature on carbon emissions

(f) The impact of the interaction between printing speed and nozzle temperature on carbon emissions

Figure 4 Comparison of two-dimensional and three-dimensional images of the impact of multiple factor interactions on carbon emissions

From Figure 4 (a), it can be seen that the interaction between the filling rate and printing speed is weak. When the filling rate is constant, the carbon emissions gradually decrease with the increase of printing speed. When the printing speed is constant, as the filling rate increases, the carbon emissions increase. When the filling rate is less than 20% and the printing speed is greater than 70mm/s, the carbon emissions tend to stabilize. When the filling rate is 10% and the printing speed is 100mm/s, the carbon emissions are the smallest. At this time, the sample consumption is the least, the printing time is the shortest, and both material consumption and energy consumption reach the minimum values. Therefore, the carbon emissions are the smallest. On the contrary, the filling rate is the highest, while the printing speed is the lowest, and the carbon emissions are the highest. Similarly, from Figure 4 (b), it can be seen that the interaction between the filling rate and layer height is similar to the interaction between the filling rate and printing speed, but its impact on carbon emissions is not significant. When the filling rate is 10% and the layer height is 0.3mm, the carbon emissions are taken as the minimum value.

From Figure 4 (c), it can be seen that the interaction between filling rate and nozzle temperature has no significant impact on carbon emissions. When the nozzle temperature is constant, as the filling rate increases, carbon emissions gradually increase. When the filling rate is constant, changes in nozzle temperature have almost no effect on carbon emissions. Similarly, as shown in Figure 4 (d), when the nozzle temperature is constant, the faster the printing speed, the smaller the carbon emissions. When the printing speed is constant, the impact of changes in nozzle temperature on carbon emissions is not significant. As shown in Figure 4 (e), when the nozzle temperature is constant, the higher the layer height, the less carbon emissions. The increase and decrease in nozzle temperature have no significant impact on carbon emissions when the layer height is fixed.

Based on the analysis results of the interaction between single and double factors, a quadratic fitting formula was obtained for the four influencing factors of filling rate, printing speed, layer height, and nozzle temperature, which are related to the carbon emissions during FDM molding process, as shown in formula (5).

$$E_{GHG(optimization)} = 0.0802+0.0155A- 0.0338B - 0.0404C+0.0005D-0.0050AB + 0.0045AC - 0.0002AD+0.0337BC - 0.0010BD- 0.0006CD-0.0015A^2 +0.0239B^2 +0.0301C^2 - 0.0079D^2 \quad (5)$$

From Figure 5, it can be seen that the actual experimental values are in good agreement with the predicted values. The model has a complex correlation coefficient of R2=0.9818, and the random distribution of points in Figure 6 indicates that the standardized residual is independent of the predicted values, demonstrating the effectiveness of the quadratic response regression equation.

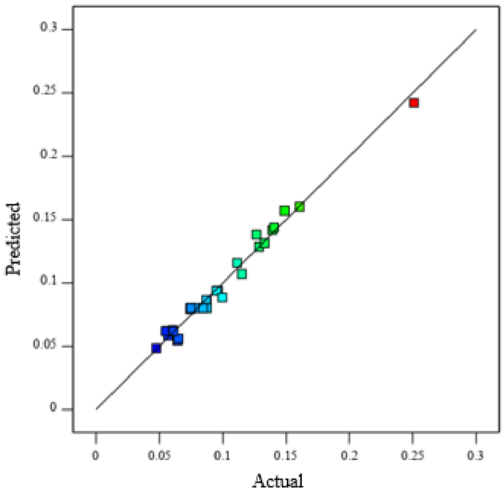


Figure 5 Comparison of predicted and actual values

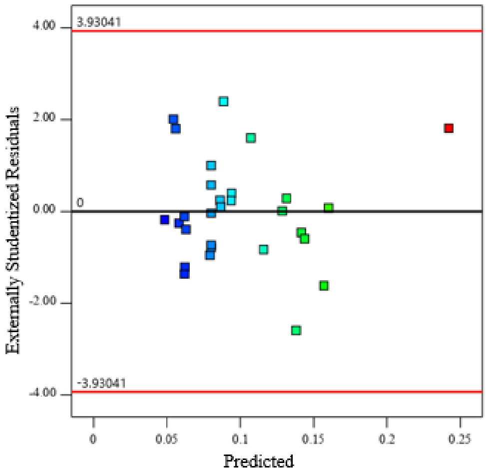


Figure 6 Trends of predicted values and residuals

IV. CONCLUSION

(1) As the filling rate increases, the carbon emissions gradually increase and show a linear growth trend; As the printing speed increases, the carbon emissions decrease and gradually flatten out; Similar to the trend of printing speed impact, as the height of the layer increases, the carbon emissions gradually decrease; The change in nozzle temperature has no significant impact on carbon emissions.

(2) The interaction between printing speed and layer height has the most significant impact on carbon emissions under the interaction of two factors. The minimum carbon emissions occur when the printing speed is greater than 80mm/s and the layer height is greater than 0.2mm

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