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Process parameters optimization for 3d printing of continuous carbon fiber reinforced composite

Jiu-Ming Xie[1], Xuejun Zhou[1], Yuesen Liu[1], Jiawen Zhang[1], Wei Wang[1]

[1]Tianjin Sino-German University of Applied Science, School of Mechanical Engineering. Yashen Road, n. 2, Jinnan District, 300000, Tianjin, China.

e-mail: xiejiuming1983@163.com, zhouxuejun1978@163.com, 18669889350@163.com, zhangjiawenjx@163.com, wangwei@tsguas.edu.cn

ABSTRACT

In order to enhance the quality and mechanical properties of 3D printing carbon fiber reinforced composite (CFRP) workpiece, this paper prepares 3D printing CFRP laminates by proposing a layered coherent composite scanning path, and carries out orthogonal tests and single factor tests to disclose the effects of different process parameters (i.e., layer thickness, first layer thickness, nozzle temperature and printing speed) on the mechanical performance of the CFRP workpieces. Moreover, The grey relation analysis method is used to analyze the multi-objective parameters of the orthogonal tests results and the process parameters of 3D printing CFRP are optimized based on the tests results. The research results show that the process parameters of 3D printed CFRP can be ranked as delamination thickness, nozzle temperature, first layer thickness and printing speed, in descending order of the impact on the mechanical property of the CFRP laminates. the optimal process parameters for 3D printing include a layer thickness of 0.25 mm, a first layer thickness e of 0.2 mm, a nozzle temperature of 180°C, and printing speed of 45 mm/s. Under this parameter combination, the tensile strength, bending strength, and the interlaminar shear strength (ILSS) of the samples are 52.77 MPa, 276.63 MPa and 38.56 Mpa respectively, and the grey correlation degree increased to 0.845.

Keywords: CFRP; FDM; Orthogonal Experiment; Single Objective Parameters; Multi-Objective Parameters; Optimization Of Process Parameters.

1. INTRODUCTION

The technology of 3D printing carbon fiber reinforced composite (CFRP) is more and more widely used in aerospace [1]. The introduction should The combination of CFRP and 3D printing technology can simultaneously integrate the excellent characteristics of continuous CFRP and the advantages of free forming of 3D printing technology, improving the mechanical properties of traditional 3D printing products significantly [2, 3]. It has the advantages of fast forming speed, low printing cost, and no need for skilled workers in production [4]. At the same time, it can manufacture parts with complex structures, and the fiber content can be dynamically adjusted according to demand, with high flexibility and broad application prospects [5–7].

During the process of 3D printing CFRP, the process parameters such as layer thickness, first layer thickness, nozzle temperature, extrusion speed, printing speed, path planning, filling density, etc., and the interaction between the process parameters, have great impacts on the quality and mechanical properties of the produces [8–10]. Therefore, during the process of 3D printing CFRP, it is very important to analyze the influence of various process parameters on the quality of products, optimize the process parameters, and obtain the best 3D printing process parameters, which is essential for the optimization of the mechanical properties of the products [11–13].

In this paper, the 3D printing process of Kexcelled peek K10CF CFRP was taken as the research object, and four printing process parameters, including layer thickness, first layer thickness, nozzle temperature and printing speed were selected as factors. Orthogonal tests, single objective tests and multi-objective tests were designed to analyze the tensile strength, bending strength and interlayer shear strength (ILSS) of 3D printed laminates. In light of the test results, the author discussed how each process parameter affects the mechanical performance of the 3D printing CFRP laminates, and then optimized the process parameters of 3D printing. The

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research findings shed new light on process optimization, quality control, and molding mechanism of the 3D printing CFRP.

2. MATERIALS AND METHODS

2.1. Experimental materials

The 3D printed CFRP is Kexcelled peek K10CF supplied by Hanshuo High-tech Materials (Tianjin) Co., LTD. The characteristic parameters are listed in Table 1.

The 3D printed wires of CFRP are shown in the Figure 1.

2.2. Specimen preparation

The 3D printed wires of CFRP need to be dried before printing. The 3D printing process adopts Fused Placement Modeling (FDM) [14, 15], and the FDM printer is Sermoon D3, provided by Shenzhen CREALITY 3D Technology Co., Ltd, as shown in Figure 2.

Before printing the model, it is necessary to use Ultimaker Cura slicing software to complete the slicing process of the laminates, transforming the 3D model into G code that the printer can read and recognize.

In the process of printing path planning, taking into the advantages and disadvantages of reciprocating linear scanning and offset scanning, this paper proposes a layered coherent composite scanning path [16–18], as shown in Figure 3.

The interlayer coherent layered composite scanning path can start the printing work of the next layer directly from the end of the scanning layer as the starting point of the next layer, avoiding the wire drawing phenomenon and time loss caused by empty stroke during the printing process, and then improving the surface quality of the formed part and shortening the forming time.

Table 1: The characteristic parameters of Kexcelled peek K10CF.

INDEX	VALUE/HORIZONTAL PRINTING
Diameter (mm)	1.75 ± 0.03
Melt index (g/10min)	10-15
Hot deformation temperature (°C)	~200
Density (g/cm^3)	1.15
Resin content (%)	20 ± 1
Tensile strength (MPa)	85-90
Tensile elongation at break (%)	4-5
Bending strength (MPa)	120-130
Bending modulus (MPa)	3200-3400
Diameter (mm)	1.75 ± 0.03

Figure 1: The 3D printed wires of CFRP.

Figure 2: The FDM printer.

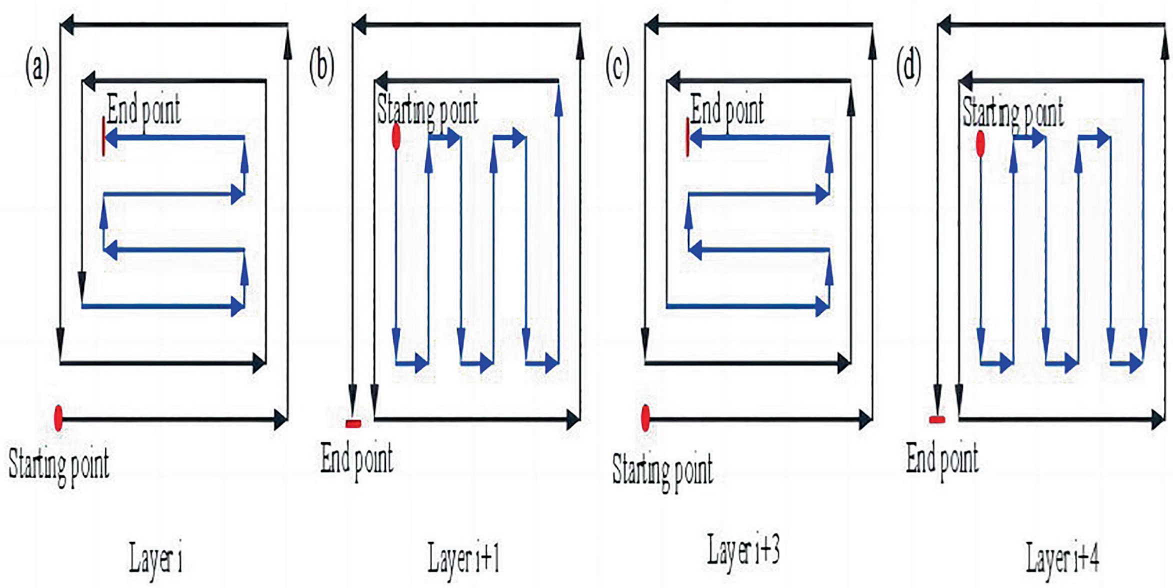

Figure 3: Layered coherent composite scanning path.

2.3. Characterization and testing

According to the ASTM D3039 test standard [19], each tensile test sample was prepared into a Rectangular with a width of 25 mm and a total length of 250 mm and subjected to tensile loading at 2 mm/min with the standard strain rate of 0.01 min^{-1}.

According to the ASTM D790 test standard [20], each bending test sample was prepared with a span thickness ratio of 32:1 and a width of 13 mm, prestressed to 5 N, and subjected to bending at 1 mm/min with the test length exceeding the span by 20%.

According to the ASTM D2344 test standard [21], each ILSS test sample was prepared with a width of 25 mm and a length of 250 mm, and subjected to shearing at 2 mm/min.

MTS universal material testing machine was used to conduct mechanical properties experiment, as shown in Figure 4.

Figure 4: Equipment for testing.

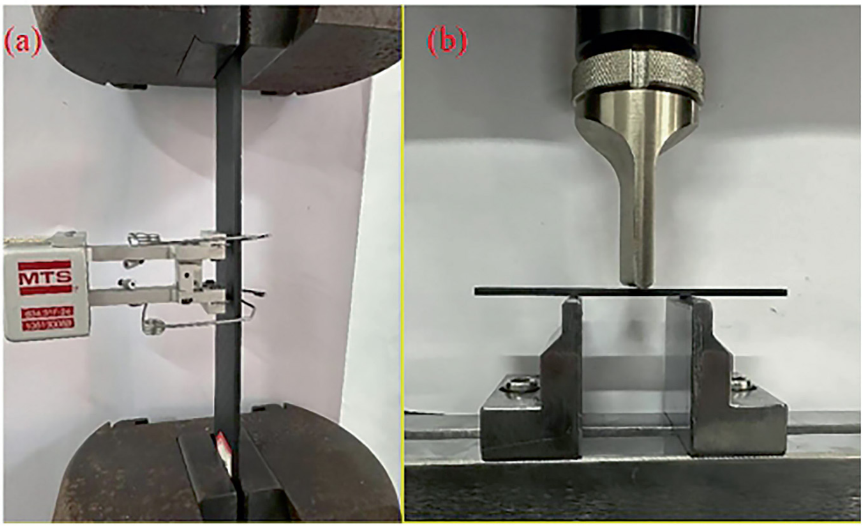

Figure 5: Equipment for testing.

In some experiments, as shown in Figure 5, an extensometer was added during the stretching process to measure the mechanical properties more accurately and improve the accuracy of the experimental data. In the bending test, the support and indenter of the sample adopt a circular arc with a radius of 3 mm, which can ensure that the sample can remain stable and avoid falling after bending when the sample is subjected to load and bending.

2.4. Test orthogonal plan

The quality of 3D printed CFRP laminates is influenced by many process parameters. This paper mainly targets four process parameters, namely, layer thickness, first layer thickness, nozzle temperature and printing speed. Table 2 shows the levels of the five parameters in the orthogonal tests.

Table 2: The levels of the four parameters in the orthogonal tests.

LEVEL	A LAYER THICKNESS (mm)	B FIRST LAYER THICKNESS (mm)	C NOZZLE TEMPERATURE (°C)	D PRINTING SPEED (mm/s)
1	0.15	0.15	180	35
2	0.20	0.20	200	40
3	0.25	0.25	220	45

Table 3: Orthogonal test schedule.

TEST NO.	INFLUENCING FACTORS			
	A	B	C	D
1	0.15	0.15	180	35
2	0.15	0.20	200	40
3	0.15	0.25	220	45
4	0.20	0.15	200	45
5	0.20	0.20	220	35
6	0.20	0.25	180	40
7	0.25	0.15	220	40
8	0.25	0.20	180	45
9	0.25	0.25	200	35

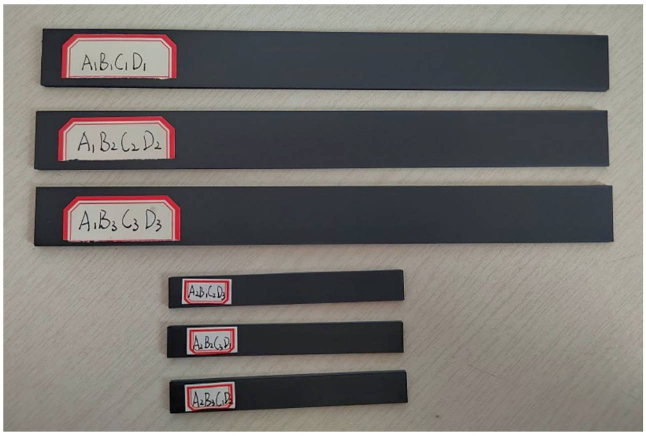

Figure 6: Parts of the test samples.

The orthogonal tests mainly investigate the effects of the four parameters on the mechanical performance of the laminates made through 3D printing, without considering the interaction between the parameters. The L_9 (3^4) orthogonal scheduling as shown in Table 3 was adopted for the tests.

The standard samples were prepared successively according to Table 3, and the printed test samples were placed in a ventilated and dry environment for 24 hours. Subsequently, the tensile strength, bending strength and interlayer shear strength of the samples were tested on the universal material testing machine. In order to reduce the influence of random factors on the experimental results, 10 samples were prepared for each group of process parameters. The final measurement results were averaged and the measurement error was represented by Standard Deviation. Part of the samples are shown in Figure 6.

3. RESULTS AND DISCUSSION OF SINGLE OBJECTIVE PARAMETERS TESTS

3.1. Results of orthogonal experimental

In the process of experiments, the smaller deviation between the actual value measured and the expected value, the better its mechanical properties, that is, the test object is evaluated by the characteristics of the expectation [22]. The calculation formula of its characteristics is expressed as follows:

$$\Delta x = \left| x_c - x_0 \right| \tag{1}$$

Where, x_c is the ideal mechanical property of the 3D printed sample, x_0 is the actual mechanical property of the sample size.

During the experiment, the tensile strength, bending strength, and interlayer shear strength of the test pieces were measured and the standard deviation were calculated, representing ΔT, ΔB and ΔS respectively. The specific values are shown in Table 4.

Table 4: The results of orthogonal experimental.

TEST NO.	FACTORS AND LEVELS				MECHANICAL PROPERTY DEVIATION		
	A	B	C	D	ΔT	ΔB	ΔS
1	1	1	1	1	39.36	29.21	30.19
2	1	2	2	2	56.25	30.96	49.83
3	1	3	3	3	41.83	32.58	39.52
4	2	1	2	3	54.46	36.66	12.95
5	2	2	3	1	51.80	44.05	18.24
6	2	3	1	2	58.92	34.23	10.05
7	3	1	3	2	50.18	46.87	9.26
8	3	2	1	3	61.37	35.41	13.73
9	3	3	2	1	53.16	49.19	11.37

Table 5: Tensile strength mechanical property deviation.

LEVELS	PROCESS PARAMETERS			
	A	B	C	D
1	45.81	48.00	53.22	48.11
2	55.06	56.47	54.63	55.12
3	54.90	51.30	47.94	52.55
Deviation	9.25	8.47	6.69	7.01
Rank of Influence	1	2	4	3

Table 6: Bending strength mechanical property deviation.

LEVELS	PROCESS PARAMETERS			
	A	B	C	D
1	30.92	37.58	32.95	40.82
2	38.31	36.81	38.94	37.35
3	43.83	38.67	41.17	34.88
Deviation	12.91	1.86	8.22	5.94
Rank of Influence	1	4	2	3

Table 7: ILSS mechanical property deviation.

LEVELS	PROCESS PARAMETERS			
	A	B	C	D
1	39.85	17.47	17.99	19.93
2	13.75	27.27	24.72	23.05
3	11.45	20.31	22.34	22.07
Deviation	28.4	10.10	6.83	3.22
Rank of Influence	1	2	3	4

According to the calculation results of orthogonal experiments in Table 4, the deviations of mechanical properties of test targets are shown in Table 5, Table 6 and Table 7 respectively.

Combined with the data in Table 5, Table 6 and Table 7, we can intuitively see the effects of layer thickness, first layer thickness, nozzle temperature and printing speed on the mechanical properties of 3D printed CFRP laminates. The horizontal combinations with the smallest deviation of factor level are the best process parameter combinations. Therefore, the optimal process parameter combination in tensile strength of molded parts is $A_1B_1C_3D_1$. That is, the layer thickness is 0.15 mm, the first layer thickness is 0.15mm, the nozzle temperature 220°C and the printing speed is 35 mm/min. Similarly, the optimal process parameter combination in bending strength is $A_1B_2C_1D_3$ and in interlayer shear strength is $A_3B_1C_1D_1$.

3.2. Analysis of variance of experimental results

The optimal level of each process parameter cannot directly reflect whether it has a significant influence on the test target or not, moreover, the influence of experimental error on experimental results cannot be avoided. In order to improve the accuracy of the experimental analysis, variance analysis should be performed on the deviations of tensile strength, bending strength and interlayer shear strength [23, 24].

The analysis of variance (ANOVA), mainly aims to reduce the influence of uncontrollable factors on experimental results, reduce experimental errors, and more accurately identify the influence law of various factors on experimental objectives. In variance, F-test method is commonly used to analyze the influence degree of each factor on the target, and it is expressed by the ratio F of the mean square error and the mean square error finally.

Table 8: ANOVA table of tensile strength.

VARIANCE SOURCE	DEGREE OF FREEDOM	SUM OF SQUARES	MEAN SQUARE DEVIATION	F VALUE
A	2	42.1892	21.0946	48.0038
B	2	12.4615	6.2308	14.2386
C	2	2.6751	1.3376	1.6533
D	2	8.0307	4.0154	9.4586
Error	2	0.7836	0.3918	
Sum	8	66.1401		

Table 9: ANOVA table of bending strength.

VARIANCE SOURCE	DEGREE OF FREEDOM	SUM OF SQUARES	MEAN SQUARE DEVIATION	F VALUE
A	2	265.0114	132.5057	21.0762
B	2	18.5228	9.2614	1.9655
C	2	16.7803	8.3902	1.4214
D	2	5.0254	2.5127	0.3393
Error	2	12.0227	6.0114	
Sum	8	317.3626		

Table 10: ANOVA table of interlayer shear strength.

VARIANCE SOURCE	DEGREE OF FREEDOM	SUM OF SQUARES	MEAN SQUARE DEVIATION	F VALUE
A	2	224.1452	112.0726	15.4213
B	2	34.9415	17.4708	2.3386
C	2	9.0853	4.5427	1.6619
D	2	2.0546	1.0273	1.1305
Error	2	13.9677	6.9839	
Sum	8	275.109		

Table 11: ILSS mechanical property deviation.

TEST NO.	GREY GENERATING		
	ΔT	ΔB	ΔS
1	0.000000	0.000000	0.421726
2	0.901814	0.290852	0.000000
3	0.081517	0.407931	0.218020
4	0.873906	0.694945	0.817542
5	0.731883	0.883137	1.000000
6	0.946603	0.502219	0.538717
7	0.688318	0.940086	0.383123
8	1.000000	0.616353	0.901015
9	0.721884	1.000000	0.714551

In this paper, ANOVA analysis was used to obtain variance analysis of tensile strength, bending strength and interlayer shear strength respectively, and the specific results as shown in Table 8, Table 9 and Table 10.

In the process of variance analysis, the degree of influence of each factor on the test target is usually judged based on the size of the F value. Therefore, combining the data in the table, it can be concluded that the influence of the four factors on the tensile strength of 3D printed CFRP panels is A > B > D > C. Among them, factor A has the most significant impact on the test target; The influence pattern on bending strength is A > B > C > D, and the same factor A has the most significant impact on the testing target; The influence pattern on shear strength is A > B > C > D, where factor A has a significant impact on the test target.

4. RESULTS AND DISCUSSION OF MULTI-OBJECTIVE PARAMETERS TESTS

4.1. Grey generating

The results single objective analysis is only a combination of all parameters on a single property. In order to find a set of process parameter combinations suitable for tensile, bending and shearing properties, grey correlation analysis based on orthogonal experiment was selected to further analyze the mechanical properties of CFRP laminate, so as to obtain the optimal process parameter combination of mechanical properties [25].

Gray sequence generation, also known as sequence preprocessing, is actually the process of converting objects with different dimensions into objects with the same dimension or order of magnitude [26]. Through dimensionless processing of the original sequence and making each object have the same dimension, different objects can be compared and analyzed. The processing method of sequence dimensionless quantization is mainly based on the averaging operator, initial value operator and interval operator [27, 28]. This paper selects the interval operator method according to the actual demand, and its calculation formula is expressed as follows:

$$x_{ij} = \frac{\max\ y_{ij} - y_{ij}}{\max\ y_{ij} - \min\ y_{ij}} \tag{2}$$

Where, x_{ij} represents the sequence obtained after infinite tempering treatment, y_{ij} represents the value of group j parameters in the i test in the sequence;

According to the rigid-free quantization of the tensile strength of the sample, the calculation results are shown in Table 11.

4.2. Calculation of grey correlation coefficient and grey correlation degree

When calculating the grey correlation coefficient, set X_0 as a reference sequence set, that is:

$$X_0 = \left(x_{01}, x_{02}, \dots \dots, x_{0n}\right) \tag{3}$$

Then the formula for calculating gray correlation coefficient is as follows:

Table 12: The results of grey generating.

TEST NO.	GREY CORRELATION COEFFICIENT			GREY CORRELATION DEGREE
	ΔT	ΔB	ΔS	
1	1.000000	1.000000	0.425973	1.000000
2	0.425572	0.768295	1.000000	0.780516
3	0.930113	0.679022	0.819307	0.831274
4	0.495928	0.570934	0.504308	0.527317
5	0.547440	0.480039	0.429861	0.486322
6	0.452632	0.628897	0.599088	0.556475
7	0.571566	0.452642	0.681567	0.569828
8	0.426957	0.592101	0.468526	0.510023
9	0.520535	0.425621	0.542697	0.505791

$$\xi\left(x_{oi}, x_{ij}\right) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{ij} + \rho\Delta_{\max}} \tag{4}$$

Where,

$$\Delta_{ij} = \left|x_{0j} - x_{ij}\right| \tag{5}$$

ρ is the resolution coefficient, $0 \le \rho \le 1$, where the resolution is 0.5.

The grey correlation degree is calculated as follows:

$$\Gamma\left(x_0, x_i\right) = \sum_{i=1}^{n} w_j \xi\left(x_0, x_i\right) \; i = 1, 2, ..., m \tag{6}$$

Where, w_j is the weight coefficient of the experimental index, which is determined by the experimenter according to the actual situation.

$$\sum_{i=1}^{n} w_j = 1 \tag{7}$$

In the orthogonal test, the small hope feature is used to analyze the test target, so 0 is selected as the reference sequence, and the grey correlation coefficient and grey correlation degree are calculated in combination with formula (4) and (6), as shown in Table 12.

4.3. Grey relational degree analysis

Through the above calculation process, the goal of different orders of magnitude is transformed into the same order of magnitude. In order to determine the level and extent of factors affecting the mechanical properties of 3D printed carbon fiber reinforced composite, range and variance analysis of grey correlation degree are required. The analysis results are shown in Table 13 and Table 14.

It can be seen from the Table 14 that A3B2C1D3 is the optimal combination of process parameters for multiple indexes, that is, That is, the layer thickness is 0.25 mm, the first layer thickness is 0.2 mm, the nozzle temperature 180°C and the printing speed is 45 mm/min. The influence degree of these four factors on the size error of molded parts is A > C > B > D, in which the influence of A and C is the most significant.

4.4. Experimental verification

According to the above analysis, the best process parameter combination A3B2C1D3 was used to print the carbon fiber reinforced composite laminate, and its tensile strength, bending strength and shear strength were tested. At this time, the tensile strength, bending strength and in-plane shear strength of the

Table 13: Range analysis table of grey relation grade.

LEVELS	PROCESS PARAMETERS			
	A	B	C	D
1	3.924	3.482	2.696	2.817
2	2.355	2.578	3.265	3.101
3	2.286	3.006	2.991	2.776
Deviation	1.638	0.476	0.569	0.325

Table 14: ANVON table of grey relation grade.

VARIANCE SOURCE	DEGREE OF FREEDOM	SUM OF SQUARES	MEAN SQUARE DEVIATION	F VALUE
A	2	0.2167	0.1084	118.6245
B	2	0.4282	0.2141	50.2668
C	2	0.3435	0.1718	1.9242
D	2	0.0139	0.0070	1.1073
Error	2	0.0064	0.0032	
Sum	8	1.0087		

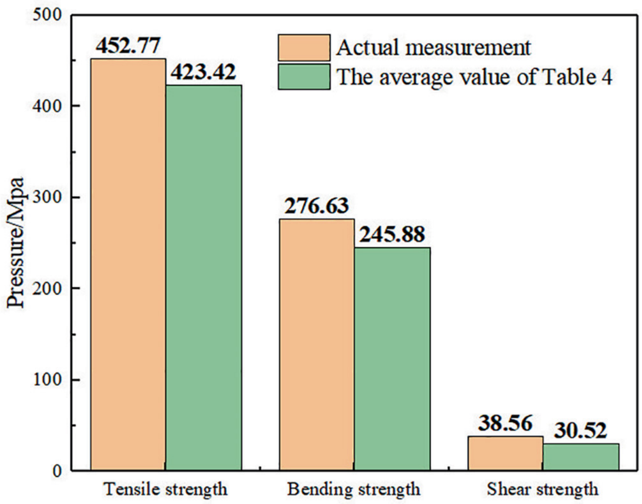

Figure 7: Comparison between actual measurement results and the average values in Table 4.

specimens were obtained. Compare the actual measurement results with the average values in Table 4, as shown in Figure 7.

By comparing this result with the grey correlation degree of the best parameter combination in Table 12, the grey correlation degree of time is increased to 0.845, which proves that this set of parameter combination is the best among all parameters.

5. CONCLUSIONS

The following conclusions were drawn from the study on the process parameters in 3d printing of continuous carbon fiber reinforced composite: (i) The effects of processing parameters of 3D printed carbon fiber reinforced composites on the mechanical properties of CFRP laminates can be analyzed by orthogonal test, single factor test and grey correlation analysis, and the optimization of processing parameters can be realized; (ii) During 3D printing CFRP laminates, the process parameters can be ranked as layer thickness, first layer thickness, printing speed and nozzle temperature in descending order of their impact on the tensile strength; As layer thickness, first layer thickness, nozzle temperature and printing speed in descending order of their impact on the bending strength; And as layer thickness, first layer thickness, nozzle temperature and printing speed in descending order of their impact on the ILSS. (iii) The 3D printing CFRP laminates achieved the optimal mechanical performance under the layer thickness of 0.25 mm, the first layer thickness of 0.2 mm, the nozzle temperature of 180°C and the printing speed of 45 mm/min. Under this parameter combination, the tensile strength, bending strength and the ILSS of the laminates were respectively 452.77 MPa, 276.63 MPa, and 38.56 MPa. And the grey correlation degree of time is increased to 0.845.

In current industrial applications, 3D printing technology has shown its unique potential, especially in the free forming of CFRP. This technology not only broadens the application range of CFRP in aerospace, automobile manufacturing, medical equipment and other fields, but also makes it increasingly popular in these fields due to its high material utilization rate, low manufacturing cost and remarkable production efficiency. However, compared with traditional molding methods such as compression molding, CFRP manufactured by 3D printing technology is still insufficient in mechanical properties. Therefore, future research directions will focus on how to improve the mechanical properties of 3D printed CFRP to further promote its application and development in various fields.

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7. BIBLIOGRAPHY

[1] KIZAWA, H., NAGAO, E., SHIMAMURA, M., *et al*., "Scaffold-free 3D bio-printed human liver tissue stably maintains metabolic functions useful for drug discovery", *Biochemistry and Biophysics Reports*, v. 10, pp. 186–191, 2017. doi: http://doi.org/10.1016/j.bbrep.2017.04.004. PubMed PMID: 28955746.

[2] YANG, C., TIAN, X., LIU, T., *et al*., "3D printing for continuous fiber reinforced thermoplastic composites mechanism and performance", *Rapid Prototyping Journal*, v. 23, n. 1, pp. 209–215, 2017. doi: http://doi.org/10.1108/RPJ-08-2015-0098.

[3] TIAN, X.Y., YANG, C.F., LI, D.C., *et al*., "Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites", *Composites Part A Applied Science & Manufacturing*, v. 88, n. A, pp. 198–205, 2016. doi: http://doi.org/10.1016/j.compositesa.2016.05.032.

[4] MURARIU, A.C., SRBU, N.A., COCARD, M., *et al*., "Influence of 3D printing parameters on mechanical properties of the PLA parts made by FDM additive manufacturing process", *Engineering Innovations*, v. 2, pp. 7–20, 2022. doi: http://doi.org/10.4028/p-4isiu8.

[5] KAKARAPARTHI, S., TATARA, R.A., CHEN, N., "A new boundary interlock geometry design pattern to strengthen FDM part multi-material interface", *Manufacturing Letters*, v. 33, pp. 664–669, 2022. doi: http://doi.org/10.1016/j.mfglet.2022.07.082.

[6] XIE, J.M., SHE, C., SUN, J., *et al*., "Preparation and mechanical properties of aluminum alloy 5a02/cfrtp laminates", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20220318, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2022-0318.

[7] DURGUN, I., ERTAN, R., "Experimental investigation of FDM process for improvement of mechanical properties and production cost", *Rapid Prototyping Journal*, v. 20, n. 3, pp. 228–235, 2014. doi: http://doi.org/10.1108/RPJ-10-2012-0091.

[8] AMENDOLA, A., HERNÃNDEZ-NAVA, E., GOODALL, R., *et al*., "On the additive manufacturing, post-tensioning and testing of bi-material tensegrity structures", *Composite Structures*, v. 131, pp. 66–71, 2015. doi: http://doi.org/10.1016/j.compstruct.2015.04.038.

[9] YU, Y.D., MENG, C.L., "How the filling patterns influence the comprehensive performance on FDM specimens based of PLA filament", *Journal of Harbin University of Science and Technology*, v. 23, n. 3, pp. 60–65, 2018.

[10] HAN, J., WANG, Y.K., TIAN, X.Q., *et al*., "Design and study of fused deposition modeling(FDM) 3D printing process parameters optimization", *Manufacturing Technology & Machine Tool*, n. 6, pp. 139–142, 2016.

[11] XIE, J.M., ZHOU, X.J., WU, J., *et al*., "Mechanism of curing behavior for CFRP compression molding under thermo-mechanical-chemical multi-field coupling", *Matéria (Rio de Janeiro)*, v. 27, n. 3, pp. e20220108, 2022. doi: http://doi.org/10.1590/1517-7076-rmat-2022-0108.

[12] PALANISAMY, G., KUMARASAMY, V., "Rehabilitation of damaged RC exterior beam-column joint using various configurations of CFRP laminates subjected to cyclic excitations", *Matéria (Rio de Janeiro)*, v. 28, n. 2, pp. e20230110, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0110.

[13] KALIYAPPAN, S.P., PAKKIRISAMY, P., "Behavior of reinforced concrete beam with CFRP and GFRP laminates", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230222, 2023. http://doi.org/10.1590/1517-7076-rmat-2023-0222.

[14] SHEN, B.X., GUAN, Y.P., "A design of color mixing fused deposition modeling 3D printer", *Journal of Beijing Information Science & Technology University: Natural Science Edition*, v. 31, n. 5, pp. 60–63, 2016.

[15] YADAV, D., CHHABRA, D., GARG, R.K., *et al*., "Optimization of FDM 3D printing process parameters for multi-material using artificial neural network", *Materials Today: Proceedings*, v. 21, n. 3, pp. 1583–1591, 2020. doi: http://doi.org/10.1016/j.matpr.2019.11.225.

[16] PARK, J.H., LYU, M.Y., KWON, S.Y., *et al*., "Temperature analysis of nozzle in a FDM type 3D printer through computer simulation and experiment", *Elastomers and Composites*, v. 51, n. 4, pp. 301–307, 2016. doi: http://doi.org/10.7473/EC.2016.51.4.301.

[17] XIA, H., LU, J., TRYGGVASON, G., "Fully resolved numerical simulations of fused deposition modeling. Part II - solidification, residual stresses and modeling of the nozzle", *Rapid Prototyping Journal*, v. 24, n. 6, pp. 973–987, 2018. doi: http://doi.org/10.1108/RPJ-11-2017-0233.

[18] YANG, M., LAI, M.G., LIU, S.J., "3D printing path planning algorithm for thin walled and complex devices", *Science and Engineering of Composite Materials*, v. 28, n. 1, pp. 327–334, 2021. doi: http://doi.org/10.1515/secm-2021-0032.

[19] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *ASTM D3039-8: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, California, Los Angeles, Wiley, 2005.

[20] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *ASTM D790-03: Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, California, Los Angeles, Wiley, 2003.

[21] AMERICAN SOCIETY FOR TESTING AND MATERIALS, *ASTM D2344-13: Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates,* California, Los Angeles, Wiley, 2003.

[22] MOHAMED, O.A., MASOOD, S.H., BHOWMIK, J.L., "Optimization of fused deposition modeling process parameters: a review of current research and future prospects", *Advances in Manufacturing*, v. 3, n. 1, pp. 42–53, 2015. doi: http://doi.org/10.1007/s40436-014-0097-7.

[23] NYIRANZEYIMANA, G., MUTUA, J.M., OCHUKU MBUYA, T., *et al*., "Fused deposition modelling (FDM) process parameter optimization to minimize residual stresses of 3 d printed carbon fiber nylon 12 hip joint implant", *Materialwissenschaft und Werkstofftechnik*, v. 53, n. 10, pp. 1184–1199, 2022. doi: http://doi.org/10.1002/mawe.202100320.

[24] INSAF, B., CONSTANTIN, D.A., ALIN, D.R., *et al*., "Accuracy investigation of fused deposition modelling (FDM) processed ABS and ULTRAT parts", *International Journal of Manufacturing, Materials, and Mechanical Engineering*, v. 12, n. 1, pp. 1–19, 2022. doi: http://doi.org/10.4018/IJMMME.293225.

[25] NAGARAJ, C., MISHRA, D., TIRUPATI, T., "Optimization of the FDM process parameters to attain the desired strength of ABS specimens", *International Journal of Recent Technology and Engineering*, v. 8, n. 4, pp. 1589–1593, 2019. doi: http://doi.org/10.35940/ijrte.C3854.118419.

[26] DEY, A., YODO, N., "A systematic survey of FDM process parameter optimization and their influence on part characteristics", *Journal of Manufacturing and Materials Processing*, v. 3, n. 3, pp. 64, 2019. doi: http://doi.org/10.3390/jmmp3030064.

[27] XU, J.G., XU, F., GAO, G., "The effect of 3D printing process parameters on the mechanical properties of PLA parts", *Journal of Physics: Conference Series*, v. 2133, n. 1, pp. 9, 2021. doi: http://doi.org/10.1088/1742-6596/2133/1/012026.

[28] MUSLIM, M., ESSAM, S., HAZRAT, M.A., "Process parameter optimization for 3D printed investment casting wax pattern and its post-processing technique", *Applied Sciences (Basel, Switzerland)*, v. 12, n. 14, pp. 6847, 2022. doi: http://doi.org/10.3390/app12146847.