PROCESSING PARAMETER OPTIMIZATION OF FDM BASED ON ROBUST DESIGN

Zhang Jianfeng[1], *Peng Anhua*[2]

(1. College of Mechanical Engineering, Yangzhou University, Yangzhou, 225009, P. R. China;
2. Engineering Training Center, Huaihai Institute of Technology, Lianyungang, 222005, P. R. China)

Abstract: The influence of processing parameters on the precision of parts fabricated by fused deposition modeling (FDM) technology is studied based on a series of performed experiments. Processing parameters of FDM in terms of wire-width compensation, extrusion velocity, filing velocity, and layer thickness are chosen as the control factors. Robust design analysis and multi-index fuzzy comprehensive assessment method are used to obtain the optimal parameters. Results show that the influencing degrees of these four factors on the precision of as-processed parts are different. The optimizations of individual parameters and their combined effects are of the same importance for a high precision manufacturing.

Key words: fused deposition modeling (FDM); robust design; fuzzy comprehensive assessment; parameter optimization

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INTRODUCTION

Fused deposition modeling (FDM) technology has widespread applications in rapid prototyping manufacturing. Compared with traditional technology, FDM has considerable advantages in manufacture costs, efficiency, adaptability, and flexibility. However, fabricating precision of FDM is relatively lower at present. Therefore, how to improve the precision of prototyping parts is still a hot issue on rapid prototyping manufacturing. The precision of parts directly affects the quality of the final product, especially when the parts are used as plastic mould, EDM electrode, and so on for bulk production. Processing parameter optimization is the major method in improving the precision of parts during rapid prototyping. The current research is mainly focused on the influence of single processing parameter on dimensional accuracy of parts[1-2]. Multi-parameter coupling effect on dimensional accuracy of parts has not been sufficiently studied. For this reason, the optimal scheme is difficult to be obtained in most cases. Thus, the quality of prototyping parts cannot fully meet the requirement of design.

In this paper, robust design analysis and multi-index fuzzy comprehensive assessment method are developed to optimize the processing parameters of FDM. The optimal combination of the processing parameters can be used for a high precision manufacturing.

1 ROBUST DESIGN METHOD

Robust design is an optimal design method for quality engineering which is proposed from the industrial products and process quality control. Signal-to-noise ratio (SNR) and orthogonal array are two main tools of robust design[3].

SNR is used to measure the index fluctua-

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E-mail: zhangjf@yzu.edu.cn

tions in parameter design. It is the core of parameter design. As a measure index of performance evaluation, in theory, the greater the SNR is, the better the performance is. Two indexes, size error and warpage, are studied in the experiments. Theoretically speaking, the smaller these two indexes are, the higher product precision is. Size error and warpage have smaller-the-better characteristic, which means that the closer to zero the performance indexes of the product are, the better the performance is. Zero is the ideal value of SNR. As to the index of smaller-the-better (STB) characteristic, SNR η is defined as[4]

$$\eta = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where n is the number of replicate tests, y_i the index value of the ith experiment.

Orthogonal array has two features: equivalent conjugation and comprehensive comparison[5], so exhaustive experimentation can be replaced by a small number of experiments. For this reason, the costs of manpower, materials and time in the experimental process can be saved greatly. Equivalent conjugation refers that all levels of each factor are selected uniformly, and each combination of every two levels is tested in n times orthogonal experiments. Comprehensive comparison is defined as data comparison of one factor in various levels under the condition that other factors are equal. Standardized orthogonal array is expressed by symbol $L_K(P^J)$, where L is the orthogonal array of the experimental program arranged, K the number of experimental programs or experimental conditions, namely, K represents different combinations of every level and the number of orthogonal array rows, P the number of levels, and J the number of orthogonal array columns, which shows the maximum number of arranged factors.

2 EXPERIMENTAL MEASUREMENT AND RESULTS

In the system of FDM rapid prototyping, 12 important processing parameters should be concerned[6]: layer thickness, nozzle diameter, nozzle temperature, ambient temperature, extrusion velocity, filling velocity, filling way, grid spacing, compensation of theoretical outline, value of scanning bias, turn-on delay time, and turn-off delay time. In addition, other factors also affect the quality of parts, such as thread material, encrypted layer and its parameter setting, way of cold air blowing in forming room, idle stroke velocity, forming angle of workpiece relative to the worktable surface, and addition of support, etc. The practice indicates that factors mentioned above have more or less effects on the prototype accuracy, but only the minority of them plays the leading role, namely wire-width compensation, extrusion velocity, filling velocity, layer thickness and temperature. In actual process of molding, the spray nozzle temperature changing can cause the separation of prototype from bottom board of molding parts easily. Therefore, temperature is not listed as a control factor, and the data used in experiments directly selected from the professional manufacturer recommendation. In this paper, four processing parameters are selected as the control factors. They are wire-width compensation (A), extrusion velocity (B), filling velocity (C), and layer thickness (D). Three levels are assigned to each control factor. The values of each control factor associated with each level are shown in Table 1.

Table 1 Control factors and their levels for robust design analysis

Level	A/mm	B/(mm · s^{-1})	C/(mm · s^{-1})	D/mm
1	0.17	20.00	20.00	0.15
2	0.20	25.00	30.00	0.25
3	0.25	30.00	40.00	0.30

The orthogonal array is chosen according to the number of control factors and levels. Every column of the orthogonal array has already been filled up, and so experimental error cannot be estimated. If a bigger orthogonal array is chosen, the workload will increase sharply. In order to improve the accuracy of statistic analysis and calculate the random error conveniently, repeating experiment is often adopted. Each experiment repeats three times under the same conditions. Experimental error can be obtained by observing the data fluctuation.

The size of test parts machined on MEM-300 forming machine is 60 mm×20 mm×9 mm. ABS plastic is selected as experimental material, spray nozzle temperature is set to 230 ℃, ambient temperature 50 ℃, spray nozzle diameter 0.3 mm, net lattice spacing 2.0 mm, and filling way is bidirectional opposite-sided linear scanning. After post-processing the test parts, the parts are measured twice by vernier calipers at interval of long distance in the directions of length and width. The error value can be obtained from the difference between measured and theoretical values. The mean value of errors measured four times is listed in Table 2. For each test part, the warpage of four corners is measured, the mean values are shown in Table 2.

Table 2 Experimental measurement results

No.	Level				Dimensional accuracy/μm			η_1	η'_1	Warpage/μm			η_2	η'_2
	A	B	C	D	y_1	y_2	y_3			y_1	y_2	y_3		
1	1	1	1	1	2.1	2.4	2.6	−7.5	29.9	10.6	11.2	12.3	−21.1	11.3
2	1	2	2	2	3.6	3.9	4.0	−11.7	25.7	12.5	13.1	12.4	−22.1	10.3
3	1	3	3	3	14.5	15.2	16.1	−23.7	13.7	40.1	41.2	39.6	−32.1	0.3
4	2	1	2	3	−3.6	−3.1	0.8	−8.9	28.5	41.6	42.5	40.8	−32.4	0.0
5	2	2	3	1	3.8	4.1	3.2	−11.4	26.0	20.1	22.1	23.4	−26.8	5.6
6	2	3	1	2	40.2	37.8	35.2	−31.5	5.9	28.9	31.2	33.4	−29.9	2.5
7	3	1	3	2	52.1	48.8	47.2	−33.9	3.5	30.5	32.6	35.7	−30.4	2.0
8	3	2	1	3	35.6	37.4	40.2	−31.5	5.9	35.6	40.7	37.8	−31.6	0.8
9	3	3	2	1	75.8	76.9	68.7	−37.4	0.0	25.6	26.9	30.8	−28.9	3.5

3 FUZZY COMPREHENSIVE ASSESSMENT OF EXPERIMENTAL DATABASE

3.1 Single-index assessment

For convenient analysis, set

$$\eta'_i = \eta_i - \min \eta_i \tag{2}$$

where i is the examined index, $i=1,2$, η'_1 and η'_2 are calculated respectively and listed in Table 2. The mean values and range values of examined indexes corresponding to the level of control factors are calculated and shown in Table 3, in which K_{lj} is the mean values corresponding to j level of l impact factor, $K_{lj} = \dfrac{\sum_{k=1}^{3} \eta'_{lj}}{3}$, k the number of experiments, R_l the biggest difference values between three levels of impact factor l, $R_l = (K_{lj})_{\max} - (K_{lj})_{\min}$. The bigger the range of the mean values of different levels is, the greater the influence degree of the impact factor on the examined index is. The range values of Table 3 show that the significance influence order of impact factor on the dimensional accuracy is A, B, D, C, and that on the warpage is D, A, B, C. The greater the factor at a level corresponding to the mean values of examined index is, the better the capability of examined index in this level is. According to the mean values of examined indexes shown in Table 3, the following conclusions can be drawn: the optimal combination of processing parameters is $A_1B_1C_2D_1$ if the main purpose is improving size error accuracy, and that is $A_1B_2C_1D_3$ if the main purpose is reducing warpage deformation.

Table 3　Mean values and range values of examined indexes

Index	A			B			C			D		
	K_{A_1}	K_{A_2}	K_{A_3}	K_{B_1}	K_{B_2}	K_{B_3}	K_{C_1}	K_{C_2}	K_{C_3}	K_{D_1}	K_{D_2}	K_{D_3}
Dimensional accuracy	23.1	20.1	3.1	20.6	19.2	9.8	13.9	18.1	14.4	18.6	11.7	16.0
R_{1l}		20.0			10.8			4.2			6.9	
Warpage deformation	7.3	2.7	2.1	4.4	5.6	2.1	4.9	4.6	2.6	0.37	4.9	6.8
R_{2l}		5.2			3.5			2.3			6.4	

3.2　Multi-index comprehensive assessment

In the process of FDM, dimensional accuracy and warpage deformation are contradictory in many cases. That is to say, if the combination of parameters has a higher dimensional accuracy, it has a greater amount of warpage deformations. Therefore, if we want to machine parts with high dimensional accuracy and low warpage deformation, fuzzy comprehensive assessment for every impact factor should be carried out and the best parameter constitution balance between two indexes can be found at the same time.

3.2.1　Fuzzy procession for mean values of indexes

The becoming membership grade of observed value to the comment grade is called index value fuzzification[7]. Normalized transform is usually used to achieve this goal. The so-called normalized transform refers to the process of mapping the index values into interval [0, 1], and the mean values of examined indexes of all levels are transformed to constitute a fuzzy set, that is

$$r_{lj} = \frac{K_{lj}}{\sum_{j=1}^{3} K_{lj}} \tag{3}$$

where r_{lj} is the fuzzy numbers of corresponding mean value and the membership grade, and satisfies $\sum_{j=1}^{3} r_{lj} = 1$. The results are shown in Table 4.

Table 4　Mean values of indexes after fuzzy processing

Index	A			B			C			D		
	r_{A_1}	r_{A_2}	r_{A_3}	r_{B_1}	r_{B_2}	r_{B_3}	r_{C_1}	r_{C_2}	r_{C_3}	r_{D_1}	r_{D_2}	r_{D_3}
Dimensional accuracy	0.50	0.43	0.07	0.42	0.39	0.19	0.30	0.40	0.30	0.40	0.25	0.35
Warpag deformation	0.60	0.22	0.18	0.36	0.46	0.18	0.40	0.38	0.22	0.04	0.40	0.56

3.2.2　Determination of weight vector

When using fuzzy comprehensive assessment, the key to achieve the optimal design is correctly determining weight vector $\omega = (\omega_1, \omega_2, \cdots, \omega_i)$, which can be reached by analytic hierarchy process (AHP). Because of the comparative complex calculation, the weight vecrtor generally determained by experience. The warpage deformation can be dealt by after-treatment, for example grinding, and so on. The size error is a global error and difficult to be eliminated by after-treatment, so reducing size error for the case is particularly important to improve the precision of parts. The weight of size error is set to 0.8 and the weight of warpage deformation 0.2, so the gotten weight vector is $\omega = (0.8, 0.2)$.

3.2.3　Comprehensive assessment

Comprehensive assessment vector $\boldsymbol{B}_l$ is

$$\boldsymbol{B}_l = \omega \circ \widetilde{\boldsymbol{R}}_l \tag{4}$$

where $\boldsymbol{B}_l = (b_{l1}, b_{l2}, b_{l3})$ is the comprehensive assessment result of the examined index corresponding to three levels of factor l[8], " $\circ$ " the fuzzy computing operator, the common fuzzy computing operator uses $M(\bullet, \oplus)$, namely, $b_{lj} = \bigoplus_{i=1}^{2} (\omega_i \bullet r_{ilj})$, $\widetilde{\boldsymbol{R}}_l$ the single-judge index matrix,

$\widetilde{\boldsymbol{R}}_l = \begin{bmatrix} r_{1lj} \\ r_{2lj} \end{bmatrix}$. R_{ls} is the range value of control factor corresponding to comprehensive examined index, $R_{ls} = (b_l)_{\max} - (b_l)_{\min}$. According to above mentioned method, $\boldsymbol{B}_A, \boldsymbol{B}_B, \boldsymbol{B}_C, \boldsymbol{B}_D$ and $R_{As}, R_{Bs}, R_{Cs}, R_{Ds}$ is calculated separately, and the concrete calculation processes are shown as follows

$$\boldsymbol{B}_A = \omega \circ \widetilde{\boldsymbol{R}}_A = (0.8, 0.2) \circ \begin{bmatrix} 0.50 & 0.43 & 0.07 \\ 0.60 & 0.22 & 0.18 \end{bmatrix} = (0.52 \quad 0.39 \quad 0.09)$$

$$R_{As} = 0.43$$

$$\boldsymbol{B}_B = \omega \circ \widetilde{\boldsymbol{R}}_B = (0.8, 0.2) \circ \begin{bmatrix} 0.42 & 0.39 & 0.19 \\ 0.36 & 0.46 & 0.18 \end{bmatrix} = (0.41 \quad 0.40 \quad 0.19)$$

$$R_{Bs} = 0.22$$

$$\boldsymbol{B}_C = \omega \circ \widetilde{\boldsymbol{R}}_C = (0.8, 0.2) \circ \begin{bmatrix} 0.30 & 0.40 & 0.30 \\ 0.38 & 0.22 & 0.56 \end{bmatrix} = (0.32 \quad 0.36 \quad 0.32)$$

$$R_{Cs} = 0.04$$

$$\boldsymbol{B}_D = \omega \circ \widetilde{\boldsymbol{R}}_D = (0.8, 0.2) \circ \begin{bmatrix} 0.40 & 0.25 & 0.35 \\ 0.04 & 0.40 & 0.56 \end{bmatrix} = (0.29 \quad 0.28 \quad 0.43)$$

$$R_{Ds} = 0.15$$

The results indicate that the order of range value is: $A > B > D > C$, namely the sequence of these four processing parameters impacting on the quality of parts is $ABDC$. Fig. 1 shows the relationships between different levels of impact factor and SNR of the examined index. Bigger SNR value shows that real size of parts is closer to theoretical value, namely, higher dimensional accuracy. Therefore, the optimal combination of these four processing parameters is $A_1B_1C_2D_3$.

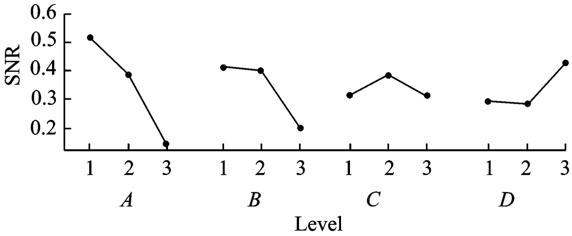

Fig. 1 Effect of different levels on SNR

4 PROCESSING PARAMETER OPTIMIZATION

4.1 Wire-width compensation

For specific solidified wire-width, when the value of wire-width compensation is 1/2 of solidified wire-width, the accuracy of the parts is the highest. That is, the greater the value of the wire-width compensation deflecting 1/2 of the solidified wire-width is, the greater the size error of the parts is. In this experiment the diameter of the nozzle is 0.3 mm, and the theoretical value of the wire-width compensation is in 0.15 mm range vicinity. When wire-width compensation takes the first level, that is 0.17 mm, the value is close to the theory value and SNR is the biggest, so the wire-width compensation checking the first level is the best for size error.

4.2 Extrusion velocity and filling velocity

When no considering interference and random error, the warping deformation increases and SNR decreases correspondingly with the increase of extrusion velocity (v_e) and filling velocity (v_f). Size error affects thread-width through the changes of extrusion velocity and filling velocity. When thread-width matches the wire-width compensation, the dimensional accuracy is the highest.

4.3 Layer thickness

Experimental results indicate that layer thickness has little influence on the size error for rectangular parts, but has great influence on the warpage deformation. The greater the layer thickness is, the smaller the warpage deformation is. This conclusion is coincides with analytical result of the mathematical model established in Ref. [9].

The range values of indexes can be calculated when optimized parameters are obtained. After that, the comprehensive impacts of the processing parameters on dimensional accuracy and warpage deformation are analysized respectively, and then the optimal combination scheme of the processing parameters and their sequence impacting on the quality of parts can be determined. Finding out the major factors impacting the quality of parts and strictly controlling them during the course of fabrication can achieve the purpose of improving the quality of parts.

5 CONCLUSIONS

(1) The significant influence order of the four processing parameters on the dimensional accuracy and warpage deformation is wire-width compensation, extrusion velocity, layer thickness, and filling velocity.

(2) The combinations of processing parameters for improving parts accuracy and reducing warpage deformation are different, which needs to integrally consider indicators of the two indexes to make the processing parameters match the best value.

(3) Under the experimental conditions that wire-width compensation is 0.17 mm, extrusion velocity 20.00 mm/s, filling velocity 30.00 mm/s, and layer thickness 0.25 mm, the dimensional accuracy of the produced block parts reaches ±0.07, meanwhile, the warpage deformation is less.

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基于稳健设计的FDM工艺参数优化

张剑峰[1] 彭安华[2]

(1. 扬州大学机械工程学院，扬州，225009，中国；2. 淮海工学院工程训练中心，连云港，222005，中国)

摘要：在一系列成形试验的基础上，分析了熔融沉积成形(Fused deposition modeling, FDM)工艺对制件精度影响因素，选择线宽补偿、挤出速度、填充速度和层厚4个工艺参数作为控制因子，采用稳健设计和多指标模糊综合评判的方法对FDM工艺参数进行优化。优化结果表明，4个工艺参数对制件精度影响程度不同，不仅每个参数本身需要优化，参数之间的相互匹配也必须满足一定关系，这样才能达到最佳组合，制造出较高精度的零件。

关键词：熔融沉积成形；稳健设计；模糊综合评判；参数优化

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