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Multi-objective optimization of process parameters of multi-step shaft formed with cross wedge rolling based on orthogonal test

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Abstract. In order to achieve reasonable process parameters in forming multi-step shaft by cross wedge rolling, the research studied the rolling-forming process multi-step shaft on the DEFORM-3D finite element software. The interactive orthogonal experiment was used to study the effect of the eight parameters, the first section shrinkage rate φ1, the first forming angle α1, the first spreading angle β1, the first spreading length L1, the second section shrinkage rate φ2, the second forming angle α2, the second spreading angle β2 and the second spreading length L2, on the quality of shaft end and the microstructure uniformity. By using the fuzzy mathematics comprehensive evaluation method and the extreme difference analysis, the influence degree of the process parameters on the quality of the multi-step shaft is obtained: β2>φ2>L1>α1>β1>φ1>α2>L2. The results of the study can provide guidance for obtaining multi-stepped shaft with high mechanical properties and achieving near net forming without stub bar in cross wedge rolling.

1. Introduction

Cross wedge rolling is one of new technologies forming of shaft parts, compared with traditional cutting and forging parts, it can form stepped shaft parts that are close to the final shape with a little loss of material. It is an important part of advanced manufacturing technology with the advantages of remarkable lumber and high efficiency in production [1]. In recent years, the transportation industry has been developing rapidly all over the world. As the core part of the driveline, multi-step shafts have high requirements for the macro size accuracy and comprehensive mechanical properties; however, shafts have large deformation and complex metal flow and deformation mechanism during forming process of cross wedge rolling. It is easy to appear the phenomenon of mixed crystal and coarse grain, which affects the mechanical properties of products [2-4]. In order to achieve near net forming and good mechanical properties, it was researched by the finite element method in this paper that process parameters influence the end equality and microstructure uniformity of multi-step shaft. The influence of eight main technological parameters on the concave and microcosmic grain sizes was measured. According to the importance of the measurement index, the measured data were weighted and synthetically judged through the method of combining the orthogonal experiment method and the

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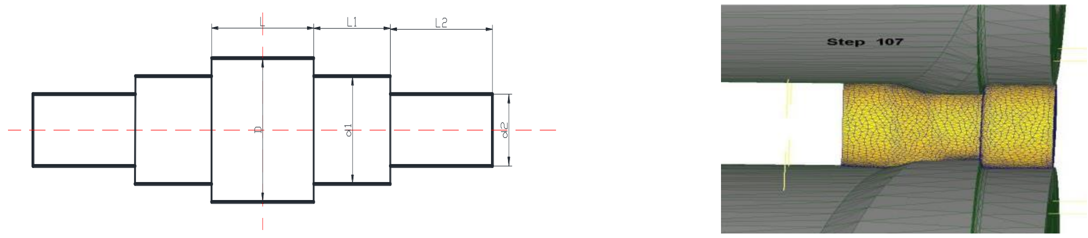
fuzzy mathematics comprehensive evaluation [5,6], the influence degree of different factors and different levels of each factor on the comprehensive value were determined through the range analysis. The best process parameters combination of multi-step shaft was found, which validity was verified. Therefore, the results of this study can provide guidance for the production of high comprehensive cross wedge rolling products with high comprehensive performance.

2. The establishment of the finite element model

The stepped shaft is the main component of the automobile transmission, and it has a high requirement for the forming precision and the mechanical performance. In this paper, the numerical simulation of the cross wedge rolling process is simulated by the DEFORM-3D finite element software, taking the three-step shaft cross wedge rolling as an example. The shape of the part will be as shown in figure 1(a). When the above model is imported to software DEFORM-3D, 1/2 of the model is taken to build the symmetrical shaft and the symmetry constraint is applied to save the computation time, reduce the storage space, and keep the symmetry of the model [7,8]. The rigid plastic finite element model established in this paper will be as shown in figure 1(b). The simulation is meshed by relative meshes, which number is 50000, the rolled material is 42CrMo alloy steel, the billets diameter is 50mm, and the rolling temperature is 1050°C. The heat exchange coefficient is set to be 11 W/(mm^2· K), and the convective heat transfer coefficient with air 0.02 W/(mm^2· K). The initial grain size is set to be 150um in the finite element simulation according to the same experimental result of initial grain size [9,10].



(a) Step-shaft part (b) Finite element model of cross wedge rolling

Figure 1. Step-shaft part and finite element model.

3. Experimental design

3.1. Selection of process parameters

The three-step shaft passes through two times cross wedge rolling plastic forming process, and there are many technological parameters that affect the forming quality. This paper mainly selects 8 model processing parameters as follows: the first section shrinkage rate φ1, the first forming angle α1, the first spreading angle β1, the first spreading length L1, the second section shrinkage rate φ2, the second forming angle α2, the second spreading angle β2 and the second spreading length L2, as shown in figure 2.

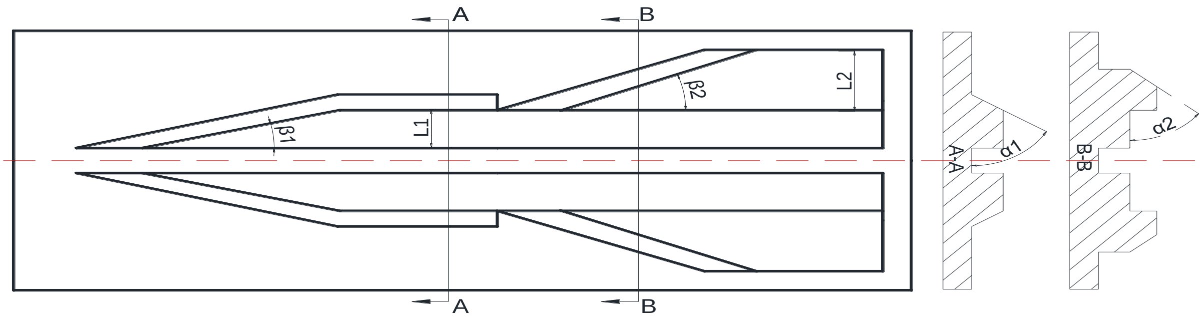


Figure 2. Cross wedge rolling die.

Table 1. Level of the process parameters and factors.

Level	first section shrinkage rate φ1	second section shrinkage rate φ2	the first spreading length L1	second spreading length L2	first forming angle α1	second forming angle α2	the first spreading angle β1	second spreading angle β2
	A	B	C	D	E	F	G	H
1	36	60	20	20	28	24	5	5
2	41	65	30	30	30	26	7	7
3	46.5	70	40	40	32	28	9	9

Table 2. Experimental scheme and experimental result table.

Test number	Influencing factor level setting													test results		
	A	B	A×B (C×D)	B×A	C	E	F	G	D	H	Empty column	Empty column	C×D	Average grain size/um	Concave size/mm	Overall rating
1	2	1	2	1	1	1	3	3	2	3	3	2	3	47.20	17.40	8.44
2	1	3	3	2	1	2	2	1	2	3	3	1	2	46.70	20.64	7.15
3	3	2	1	3	1	3	1	2	2	3	3	3	1	47.50	20.10	7.33
4	1	1	1	1	1	1	1	1	1	1	1	1	1	45.90	20.10	7.64
5	2	3	1	1	2	3	2	1	3	1	3	3	3	27.85	30.71	3.00
6	3	2	1	2	2	1	2	3	2	2	1	1	3	40.00	21.10	7.74
7	2	2	3	2	2	1	3	1	1	3	2	3	1	63.60	22.29	4.17
8	3	3	2	2	1	2	3	2	1	1	1	3	3	45.20	23.72	4.82
9	2	2	3	3	1	3	2	3	1	1	1	2	2	47.00	19.65	7.67
10	3	3	2	3	3	1	2	1	1	2	3	2	1	36.30	24.80	5.45
11	1	1	1	3	2	2	2	2	1	3	2	2	3	46.03	16.78	8.78
12	2	1	2	3	2	2	1	1	2	2	1	3	2	33.10	22.43	7.04
13	1	3	3	3	3	1	1	3	2	1	2	3	3	58.60	28.46	0.31
14	2	3	1	2	1	2	1	3	3	2	2	2	1	29.22	20.86	8.31
15	1	2	2	3	1	3	3	1	3	2	2	1	3	62.00	23.23	3.29
16	1	2	2	1	3	2	2	3	3	3	1	3	1	47.90	17.80	8.22
17	3	1	3	1	1	1	2	2	3	2	2	3	2	44.93	19.22	8.23
18	1	1	1	2	3	3	3	3	1	2	3	3	2	42.80	17.05	9.20
19	3	1	3	2	3	3	1	1	3	3	1	2	3	56.50	16.44	7.29
20	1	3	3	1	2	3	3	2	2	2	1	2	1	40.23	23.20	5.90
21	3	3	2	1	2	3	1	3	1	3	2	1	2	60.00	21.27	5.09
22	2	1	2	2	3	3	2	2	2	1	2	1	1	42.20	22.60	6.25
23	2	3	1	3	3	1	3	2	3	3	1	1	2	33.98	20.52	8.52
24	1	2	2	2	2	1	1	2	3	1	3	2	2	52.00	27.40	1.27
25	3	2	1	1	3	2	3	1	2	1	2	2	2	33.53	24.24	5.36
26	3	1	3	3	2	2	3	3	3	1	3	1	1	37.06	22.30	6.36
27	2	2	3	1	3	2	1	2	1	2	3	1	3	40.00	20.00	8.46

The level of the process parameters and factors are shown in table 1, In the design of orthogonal test, this paper, in addition to the above eight factors, also investigate the interactions between the first section shrinkage rate and the second section shrinkage rate, the first spreading length and the second spreading length. The corresponding experimental design and results are shown in table 2.

3.2. Measurement indicators
In this paper, the effect of different process parameters on the end quality and microstructure uniformity during the cross wedge rolling process is mainly investigated. For the end quality, it is mainly measured by the axial length of the concave, and the microstructure uniformity is mainly measured by the average grain size.

3.2.1. Calculation method of concave value. As one of the measuring indexes, the concave directly reflects the quality of the end of the workpiece, so it is particularly important to measure the size of the concave effectively. This article takes the mean value measured by multiple measurements as a measure, specific methods as shown in figure 3: 25 nodes are evenly selected on the outermost ring of the end section of the end of the rolling piece. Then the central point of the concave and 24 points evenly distributed on the circular boundary which takes the central point as a centre point and approximately 0.2 mm as a radius are selected. The value of the single side concave of the rolled piece is the average axial coordinate value of the 25 nodes of the outer ring of the workpiece minus the average axial coordinates of the 25 nodes of the central region. The calculation formula is as follows:

$$Y = \frac{1}{25}\sum_{i=1}^{25} Si - \frac{1}{25}\sum_{i=1}^{25} Sj \tag{1}$$

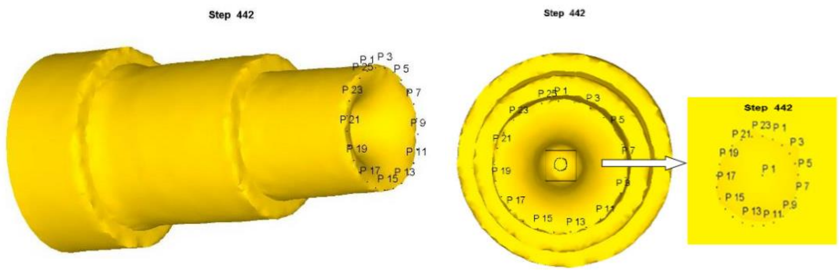


Figure 3. distribution of feature points.

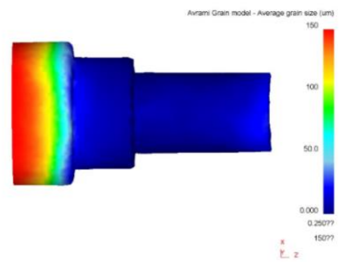


Figure 4. The microcosmic average grain size.

3.2.2. Microstructure uniformity. The uniformity of microstructure mainly includes the uniformity of grain distribution and the size of grain size [11]. The grain refinement in the process of multi-step rolling is mainly concentrated in the forming area. The microcosmic average grain size of the step shaft is shown in figure 4. minimum grain size of second-steps and third-steps metal of shaft after rolling process are 0.2 μm, and the first-step metal of shaft has not been rolled, although due to the axial deformation of penetration, part of the grain was refined, but the overall grain size is still maintained at more than 140 μm. Based on the above microcosmic grain distribution characteristics and taking into account the measurability, we choose the average grain size as a measure of microstructure uniformity.

3.3. Data processing
In the simulation experiments, the two selected indicators have great difference in dimension, and they also have different emphasis on the importance of products. It is impossible to directly superimpose the two sets of data as an evaluation index. Therefore, according to the industry standard and the actual production experience, four indexes intervals are divided combined with the statistical method of fuzzy mathematics as shown in table 3, The index values of each interval are mapped to the [0,1] numerical interval respectively through the mapping function of the S type distribution, according to the difference of the important degree of each factor, the weighted comprehensive score is used for the

mapping values of each index. In this paper, the weighted values of the size of the concave and the average grain are b1=7, b2=3, respectively, as shown in formulas (2) and (3).

Table 3. Value of each parameter of the function.

measuring indexes.	Index values		
	a	b	c
Average grain size/um	63.5	45	31.8
Concave size/mm	30	23	16

S type mapping function
$$Y_{ij}=\begin{cases}1 & x_{ij}<c\\ 1-2\left(\dfrac{x_{ij}-c}{a-c}\right)^2 & c\le x_{ij}<b\\ 2\left(\dfrac{x_{ij}-a}{a-c}\right)^2 & b\le x_{ij}<a\\ 0 & x_{ij}\ge a\end{cases} \tag{2}$$

the weighted comprehensive score
$$Y=b_1Y_{i1}+b_2Y_{i2} \tag{3}$$

In the formula: i is the test number, j is the number of measuring indexes.

In order to get the relationship between the various factors and the comprehensive index, to find out the influence laws and trends of the factors on the quality of the rolled pieces, the data were analysed by range analysis. Through range analysis of experimental data, the greater the range value, the greater the impact of the factor on the comprehensive index, the more critical the factor, and vice versa. The range values and effects of various factors are shown in table 4.

Table 4. Range analysis table.

projects	A	B	A×B (D×C)	B×A	C	E	F	G	D	H	C×D		
T1	51.7	69.2	65.88	60.34	62.8	51.7	52.7	50.3	61.2	42.6	59.63	64.8	60.4
T2	61.8	53.5	49.86	56.19	49.3	64.4	62.4	59.5	55.5	63.6	59.51	49.7	58.4
T3	57.6	48.5	55.53	54.74	59.0	55.0	56.0	61.3	54.4	64.9	52.13	56.6	52.3
t1	5.8	7.7	7.3	6.7	7.0	5.8	5.9	5.6	6.8	4.7	6.6	7.2	6.7
t2	6.9	6.0	5.5	6.2	5.5	7.2	6.9	6.6	6.2	7.1	6.6	5.5	6.5
t3	6.4	5.4	6.2	6.1	6.6	6.1	6.2	6.8	6.1	7.2	5.8	6.3	5.8
Excellent level	2	1	1	1	1	2	2	3	1	3	1	1	1
R	10.1	20.7	10.8		13.5	12.7	9.7	10.9	6.8	22.3	11.7	15.0	8.2
The order of primary and secondary					H>B>C>E> C×D>G>A×B>A>F>D								

3.4. Result analysis

According to the range analysis, it can be clearly seen that the second spreading angle H and the second section shrinkage rate B have great influence on the comprehensive index. the second spreading length D and the second forming angle F have little influence on the comprehensive index. The important influence degree of each factor from large to small is H>B>C>E>C×D>G>A×B>A>F>D, The combination of the best factor level of the model is A2B1C1D1E2F2G3H3. From the horizontal impact trend diagram of figure 5, it can be seen that the changing trend of H is bigger, and the changing ranges of D and F are relatively small. The horizontal combination of the maximum values are the best process parameters. There is no corresponding combination in the test scheme of table 2, so it must be tested by experiments.

Through DEFORM-3D finite element numerical simulation, under the optimized process level condition, namelyA2B1C1D1E2F2G3H3, the average grain size is 34.5 µm, the average concave value is 17.79 μm, the comprehensive score is 9.724. In comparison with table 2, it is known that the scheme is the best process plan.

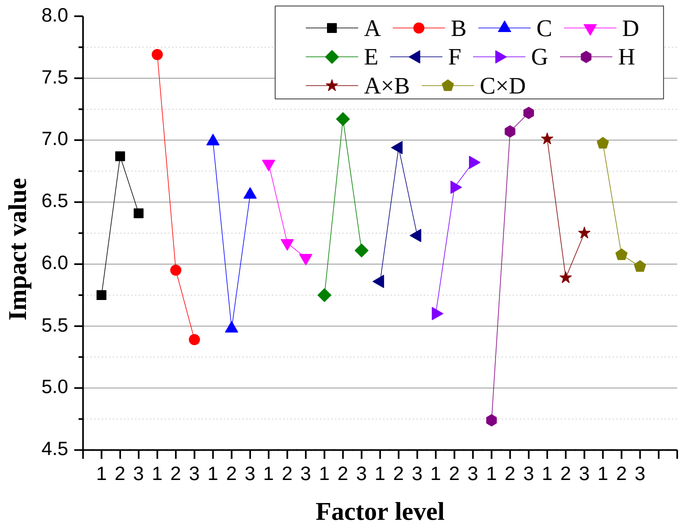


Figure 5. Tendency chart of various factors at different levels.

4. Conclusion

- Process parameters are the key factors affecting the quality of cross wedge rolling products. Through the reasonable design of the technological parameters of the cross wedge rolling die, the end quality and microstructure uniformity of the rolled piece will be improved effectively, thus the comprehensive performance of the product has be improved.
- With the comprehensive index as the evaluation standard, the main and secondary relationship between the factors of the process parameters and the rolling quality of the multi- stepped shaft is in turn as follows: the second spreading angle H, the second section shrinkage rate B, the first spreading length C, the first forming angle E, the first spreading angle G, the first section shrinkage rate A, the second forming angle F, the second spreading length D, namely $\beta 2>\varphi 2>L1>\alpha 1>\beta 1>\varphi 1>\alpha 2>L2$, the best combination is A2B1C1D1E2F2G3H3.

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