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Parameter Optimization Study of Ultra-High Speed Cutting by DOE Method

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With the increasing demand for high-quality flange, there is a greater need for high-quality and high-speed machining technology. Aiming at difficulty of surface roughness in meeting design requirements and poor machining stability of 7075 aluminum alloy, the classical Design of Experiments (DOE) method is employed to optimize the machining parameters and identify eight pertinent factors. By selecting the feed rate and cutting speed as the two significant factors, a mathematical model of roughness is derived, and the theoretically optimal machining parameters are determined. According to corresponding experimental results, the roughness, the parallelism of the two end faces of the flange, and machining efficiency, in order to further validate the accuracy of the model. The final processing parameters are 0.07 mm.r^{-1} feed rate and 1100 m.min^{-1} cutting speed, which provide reference for actual production.

Keywords: Ultra-precision, DOE, Flange, Optimization study

1 Introduction

Flanges, which are disk-shaped components, are primarily used for connecting tubes and pipes. They find wide applications in equipment manufacturing, ship production, aerospace, national defense construction, automobiles, and other industries [1]. With the development of today's scientific and technological level, the demand for high-quality flanges is increasing. There is a need for flange processing technology that can guarantee both processing efficiency and quality. Therefore, we have designed and implemented ultra-precision processing technology. Ultra-precision machining technology plays a crucial role in elevating a country's machinery manufacturing industry by enhancing product performance, quality, life and research and development of high-tech products [2]. However, ultra-precision machining is a systematic process. In order to achieve consistently high-quality flanges, we utilize the DOE method to optimize the processing parameters and determine the most effective settings. This optimization process serves as a valuable reference for actual processing. The interaction between various influencing factors in the production process can be analyzed to obtain the best parameter combination with reduced testing times, cost, and time [4]. This is a highly practical tool for ensuring quality. In 2018, in order to improve the surface quality of processed fir trees, EmineSedaErdinler and Ender Hazir conducted a 5-factor 2-level experimental design using DOE method, and finally concluded that the wood surface roughness was smaller when the radial feed of sawn wood was 3.58μm and 3.21μm [5]. In 2016, Xiao Changjiang et al. conducted a study where they applied the Design of Experiments (DOE) to cutting. Through an orthogonal experiment, they were able to quickly determine the optimal machining parameters [6].

2 Experimental Conditions

2.1 Processing objects

The experimental flange utilizes 7075 aluminum alloy as the raw material, which possesses the following characteristics: lightweight, corrosion resistance, impact resistance, and excellent mechanical properties [7]. However, due to its high hardness, turning the material becomes challenging, requiring systematic optimization of the processing parameters. Ultimately, the raw embryo needs to be processed into the specific parts depicted in Figure 1.

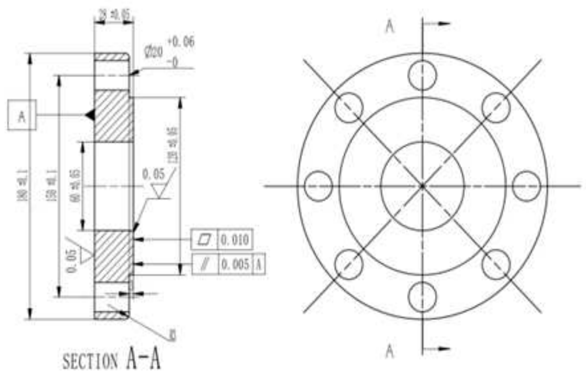


Fig. 1 *Flange parts drawing*

2.2 Processing condition

Mazak's HQR-200MY high precision turning center is selected as the machine tool for processing. In terms of fixture, a vacuum sucker fixture and three-jaw chuck are selected to ensure the parallelizing of both ends of the flange. The cutting tool is Meishangri TPGH080202R/L-S1 ceramic tool. The measuring tool selects Bruker DektakXT probe profile measuring instrument to measure the roughness, and Siri Croma series coordinate measuring instrument to measure the parallelism at both ends of the flange. The processing technology of the flange is designed in three processes, the first is the outer contour processing, and then the finishing end face, and the last is the ultra-precision processing. Flange ultra-precision processing conditions are as follows:

- Machine tool: MazakHQR-200MY series of ultra-high precision lathe
- Tool: TPGH080202R/L-S1
- Fixture: Special fixture (guarantee parallelism)
- Material: 7075 aluminum alloy blank
- Measuring tools: size measuring instrument, surface roughness measuring instrument, parallelism measuring instrument, inner hole air measuring instrument, high precision height gauge.

2.3 Experimental scheme design

The software used in the experiment is John's Macintosh Product (JMP), which optimizes the machining parameters of flanges through the classic DOE method in DOE [8-10]. In comparison to traditional optimization methods, the DOE method analysis offers high efficiency, shorter experiment duration, precise results, and requires less technical expertise from operators, making it a cost-effective approach. The DOE method is divided into three steps: partial factorial design, full factorial design, and response surface design. The use of the Department of analysis due to the design of the screening factor, first of all, the ultra-high-speed cutting in the factors affecting surface roughness to analyze, to determine the tool, machine tool, tool walking mode, cooling mode, cutting elements, etc. [11], the impact on its processing, will be generally related to the impact of the factor is listed as follows: cutting speed($m.min^{-1}$), amount of feed($mm.r^{-1}$), Back engagement (mm), Cut-off mode, Cooling mode, Speed type, Cutting direction, Vibration frequency of machine tool. At the beginning of the experiment, all factors are considered to have the potential to impact roughness. Therefore, in the experimental design using factorization analysis, we will assign two levels (high and low) for each parameter, and the specific level settings for each factor are presented in Table 1.

***Tab. 1** Analytic factorization experiment level setting*

Horizontal	Cutting speed ($m.min^{-1}$)	Amount of feed ($mm.r^{-1}$)	Back engagement (mm)	Cut-off mode	Cooling mode	Speed type	Cutting direction	Vibration frequency of machine tool
-	300	0.05	0.001	Intermittent type	Uncooled	Constant speed	Center to edge	500Hz
+	1200	0.19	0.02	Continuous type	Spray type	Constant linear speed	Edge to center of the circle	800Hz

3 DOE Method Design

3.1 Partial causality analysis experimental design

Ignoring the interaction of more than the third order, 2^{8-3}=32 sets of experiments are required, and then JMP software processes it. After the setting is completed, 32 sets of experiments are automatically generated, which are carried out according to the generated sequence of experiments, and then the experimental results are input.

The experimental results are as follows: Table 2 displays the results of observation stepwise regression analysis, while Table 3 presents the results of least square regression analysis.

$$\begin{cases} Y = B_0 + B_1B_1 + B_2B_2 + \cdots + B_mB_m + \varepsilon \\ \varepsilon \in N(0, \sigma^2) \end{cases} \quad (1)$$

In relation (1), Y in equation (1) is the dependent variable, X is the independent variable, B is the regression coefficient, and the constant should follow the normal distribution (0, σ2). Stepwise regression analysis [12]: The regression analysis of the relevant independent variables in the principal component analysis was carried out, and the fitting degree R^2 of the sample points between the dependent variable and the independent variable was calculated respectively. Then, the R^2 corresponding to each independent variable was sorted, and the maximum R^2 variable A_i was selected to establish the regression model, and R_1 and F_1 were calculated. Select the regression model of A_j variable of the second R^2 and calculate R_2, F_2. If $R_1 < R_2$, $F_1 < F_2$, A_i is still significant, then the introduction of A_j makes each variable index better, then A_j is introduced, otherwise A_j is deleted. Repeat the above steps until all principal variables are filtered and the calculation ends.

Least-square method [13]: It is easy to operate and realize, and has become the basis of a general theory. It fits a curve, minimizes the variance and error from each point to the curve, and has higher accuracy than stepwise regression analysis.

The probability values of regression analysis for the feed rate, cutting speed, cutting mode, and machine tool vibration frequency are all less than 0.05, indicating statistical significance. These four factors are determined to be dominant factors, which are related to the surface roughness of the parts [14].

Tab. 2 *Stepwise regression analysis results*

Argument	Number of participants	Degree of freedom	Sum of squares	F-ratio	Probability >F	Dominant factor
Back engagement(mm)	1	1	0.0087	1.5800	0.2214	
Amount of feed(mm.r^{-1})	1	1	0.2601	46.9937	<.0001	x
Cutting speed(m.min^{-1})	1	1	0.0608	10.9874	0.0030	x
Cut-off mode	1	1	0.0364	6.5734	0.0174	x
Speed type	1	1	0.0003	0.0576	0.8125	
Cooling mode	1	1	0.0010	0.1729	0.6814	
Cutting direction	1	1	0.0034	0.6186	0.4396	
Vibration frequency of machine tool (Hz)	1	1	0.0241	4.3624	0.0480	x

Tab. 3 *Results of least square regression analysis*

Dominant factor	Item	Estimated value	Standard error	t-ratio	Probability >|t|
	Back engagement(mm)	0.0165	0.0132	1.26	0.2214
[x]	Amount of feed(mm.r^{-1})	0.0902	0.0132	6.86	<.0001
[x]	Cutting speed(m.min^{-1})	-0.0436	0.0132	-3.31	0.0030
[x]	Cut-off mode	-0.0337	0.0132	-2.56	0.0174
[x]	Vibration frequency of machine tool (Hz)	-0.0275	0.0132	-2.09	0.0480

3.2 Complete factorial experimental design

The second step is the complete factorial experiment, that is, the further screening of the 4 factors selected by the partial analysis of the factorial experiment [15]. Experiments at 4 factor 2 levels were carried out, and the experimental arrangement and plan were shown in Table 4.

***Tab. 4** Complete factorial experiment 16 groups of experimental arrangement and experimental results*

Mode	Amount of feed(mm.r^{-1})	Cutting speed(m.min^{-1})	Cut-off mode	Vibration frequency of machine tool(Hz)	Surface roughness (Ra)
−−+−	0.05	300	Continuous	500	0.247
−++−	0.05	1200	Continuous	500	0.039
−+−−	0.05	1200	Be interrupted	500	0.039
−−−+	0.05	300	Be interrupted	800	0.311
−+−+	0.05	1200	Be interrupted	800	0.177
+−−+	0.19	300	Be interrupted	800	0.511
−−−−	0.05	300	Be interrupted	500	0.169
−−++	0.05	300	Continuous	800	0.243
+−+−	0.19	300	Continuous	500	0.239
+−++	0.19	300	Continuous	800	0.439
++++	0.19	1200	Continuous	800	0.207
+−−−	0.19	300	Be interrupted	500	0.239
+++−	0.19	1200	Continuous	500	0.171
++−−	0.19	1200	Be interrupted	500	0.257
++−+	0.19	1200	Be interrupted	800	0.167
−+++	0.05	1200	Continuous	800	0.073

3.2.1 Analysis of experimental results

Complete factorial experiments were carried out on the four factors selected by the partial analysis factor design. The results of these experiments are presented in Table 5. It is found that the probability values of "feed rate", "cutting speed" and "machine tool vibration frequency" are <0.05, which proves that they are strongly correlated with surface quality and are dominant factors. The cutting method has less effect.

***Tab. 5** Regression analysis result*

Item	Estimated value	Standard error	t-ratio	Probability >|t|	Dominant factor
Amount of feed(mm.r^{-1})	0.0583	0.0169	3.44	0.0055	x
Cutting speed(m.min^{-1})	-0.0793	0.0169	-4.68	0.0007	x
Cut-off mode	-0.0133	0.0169	-0.78	0.4507	
Vibration frequency of machine tool	0.0455	0.0169	2.69	0.0212	x

3.3 Response surface design

In the third step, we carried out response surface design, and the experiment adopted Box-Behnken design. Different from before, three levels were set for the three factors selected this time, and a total of 15 experiments were required. The experimental plan is shown in Table 6.

Tab. 6 *Experimental arrangement and results of response surface design*

Sequence	Mode	Amount of feed(mm.r-1)	Cutting speed(m.min-1)	Vibration frequency of machine tool(Hz)	Surface roughness (Ra)
1	−0+	0.05	750	800	0.092
2	000	0.12	750	650	0.071
3	0+−	0.12	1200	500	0.037
4	−−0	0.05	300	650	0.213
5	+0−	0.19	750	500	0.206
6	−0−	0.05	750	500	0.049
7	−+0	0.05	1200	800	0.021
8	0−+	0.12	300	800	0.156
9	0−−	0.12	300	500	0.207
10	000	0.12	750	650	0.077
11	0++	0.12	1200	800	0.04
12	++0	0.19	1200	650	0.169
13	000	0.12	750	650	0.074
14	+−0	0.19	300	650	0.292
15	+0+	0.19	750	800Hz	0.135

3.3.1 Analysis of experimental results

In this regression analysis, as shown in Table 7, it can be judged that the vibration frequency of the machine tool is not a dominant factor according to the probability value, and the factors are screened again.

A prediction model was developed by JMP software to evaluate and predict the experimental results of 2-factor and analyze them. With roughness as the output variable and feed and cutting speed as the input variables, the results of the analysis are shown in Figure 2. The prediction plotter of JMP software shows that when the roughness is set to <=Ra0.05μm, the "feed" should be less than 0.078mm/r, and the cutting speed should be more than 812.3 m/min [16].

Tab. 7 *Parameter estimates*

Item	**Estimated value**	**Standard error**	**t-ratio**	**Probability >|t|**	**Dominant factor**
Amount of feed(mm.r-1)	0.0534	0.0149	3.57	0.0044	x
Cutting speed(m.min-1)	-0.0751	0.0149	-5.03	0.0004	x
Vibration frequency of machine tool	-0.0095	0.0149	-0.64	0.5378	

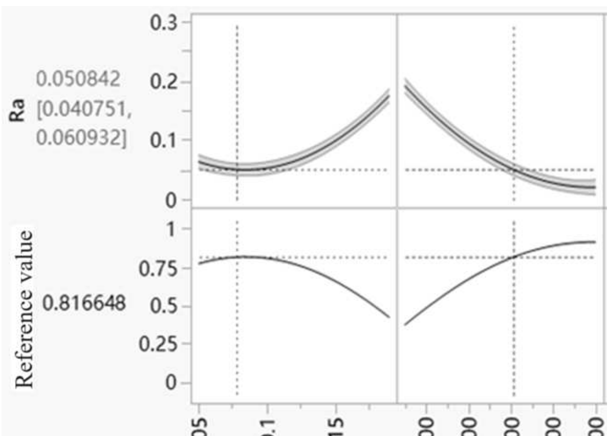


Fig. 2 *Predictive profiler*

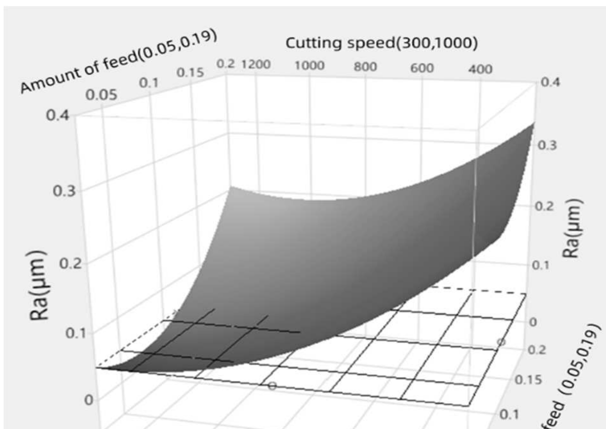


Fig. 3 *Response surface diagram*

Thus, the final mathematical model is obtained, and its mathematical model expression is as follows:

Surface roughness = 0.074 + 0.053375 * (0.07) (: Amount of feed 0.12) / + 0.075125 * ((: cutting speed - 750) / 450) - 0.0095 * ((: machine tool temperature - 30) / 5) + ((: Amount of feed - 0.12) / 0.07) * (((: cutting speed - 750) / 450) * 0.01725) + ((: fAmount of feed 0.12) / 0.07) * (((: machine tool temperature - 30) / 5) * 0.0285) + ((: cutting speed - 750) / 450) * (((: machine tool temperature - 30) / 5) * 0.0135) + ((: Amount of feed 0.12) / 0.07) * (((: Amount of feed 0.12) / 0.07) * 0.055125) + ((: cutting speed - 750) / 450) * (((: cutting speed - 750) / 450) * 0.044625) + ((: machine tool temperature - 30) / 5) * (((: machine tool temperature - 30) / 5) * 0.008625) (2)

3.4 Reliability analysis

The reliability of the experimental results can be assessed by analyzing the variance [17], misfit, and residual plots. Specifically, the variance can be examined in relation to the overall error, as presented in Table 8. The obtained variance value in the results is less than 0.09, indicating a small model error and high accuracy [18].

Tab. 8 *Analysis of variance of prediction model*

The source	Degree of freedom	Sum of squares	Mean square	F-ratio
Model	9	0.0920	0.010226	193.4939
Error	5	0.0003	0.000053	Probability >F
Corrected sum	14	0.0923		<.0001

The disfit mainly reflects the degree of difference between the regression expected value and the mean of the treatment group. As shown in Table 9, the loss of fit R2=0.9998 proves that the model has good fitting results and high reliability.

Tab. 9 *Analysis of disfitting phenomena*

The source	Degree of freedom	Sum of squares	Mean square	F-ratio
Lack of fit	3	0.00024	0.000082	9.1204
Pure error	6	0.00001	0.000009	Probability >F
Total error	9	0.00026		Max.R^2:0.9998

The residual plot can be used to estimate whether the observed or predicted error is consistent with the random error. As shown in Figure 4, the residual also fluctuates roughly around 0. We can judge that the model is accurate and reliable.

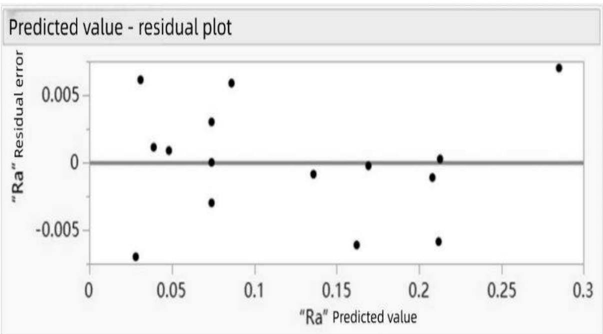


Fig. 4 *Predicted value - residual plot*

4 Cutting Experiment

The final goal is to make the roughness of the flange Ra0.05 and the finished product roughness is stable, the parallelism is high, and the processing efficiency is high. After setting uniform parameters, each experimental group measured the product roughness and parallelism at both ends every 700 meters until the roughness significantly exceeded Ra0.05. The measurement data are collected and made into a table. Finally, the trend of parallelism, roughness and processing efficiency are comprehensively analyzed [19].

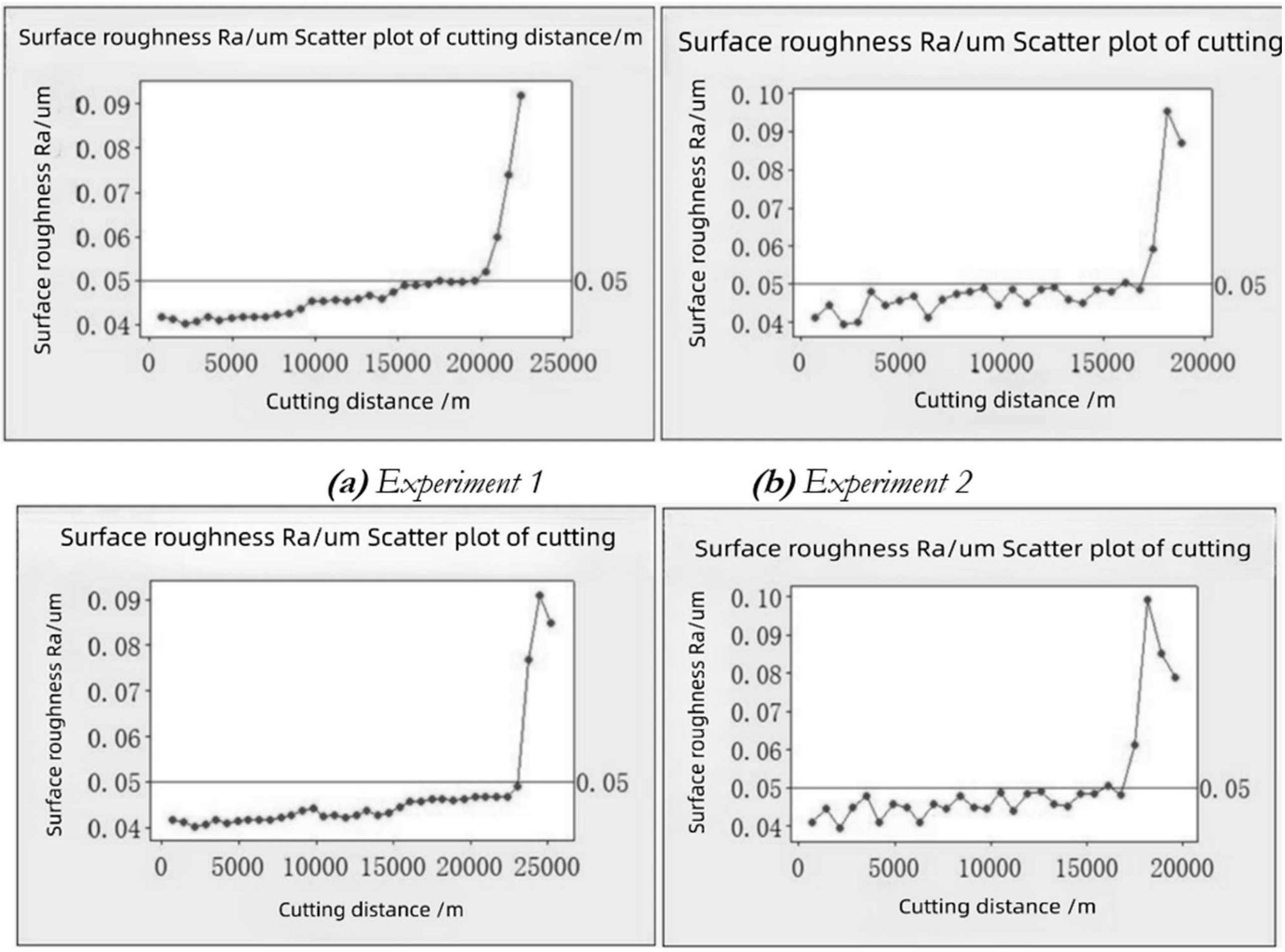
The cutting experiment is carried out according to the processing conditions, and the experiment of different level groups is tested by changing the numerical control program. The specific test plan is shown in Table 10 and Table 11.

Tab. 10 *Ultra-precision experimental parameter setting*

Experimental group	Amount of feed(mm.r^{-1})	Cutting speed(m.min^{-1})
Experiment 1	0.07	860
Experiment 2	0.04	860
Experiment 3	0.07	1100
Experiment 4	0.04	1100

Tab. 11 *Other parameter Settings*

Other parameter items	Numerical value
Back engagement(mm)	0.01
Cut-off mode	Be interrupted
Cooling mode	Non-use
Speed type	Constant speed
Cutting direction	Center to edge
Vibration frequency of machine tool	Random



(a) *Experiment 1* **(b)** *Experiment 2*

(c) *Experiment 3* **(d)***Experiment 4*

Fig. 5 *Surface roughness variation trend chart*

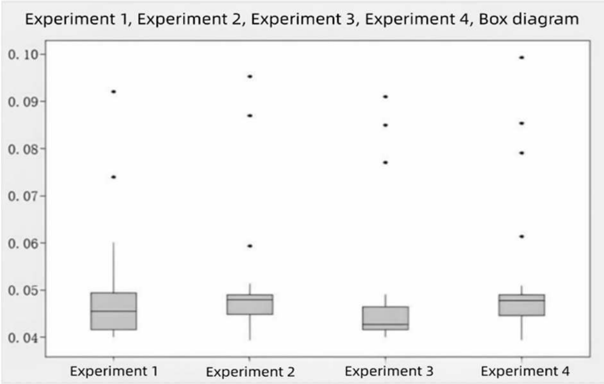
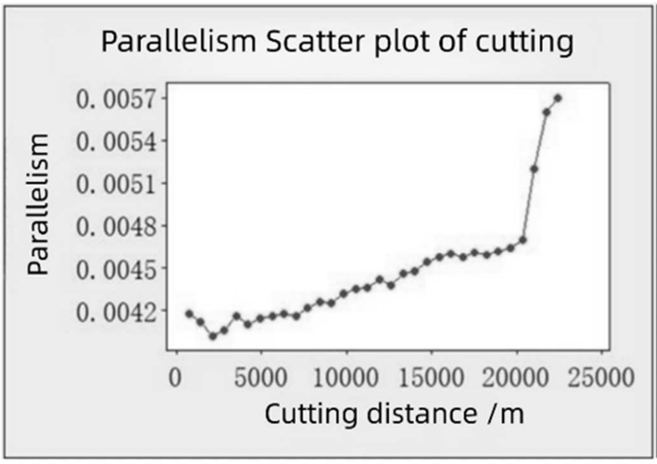
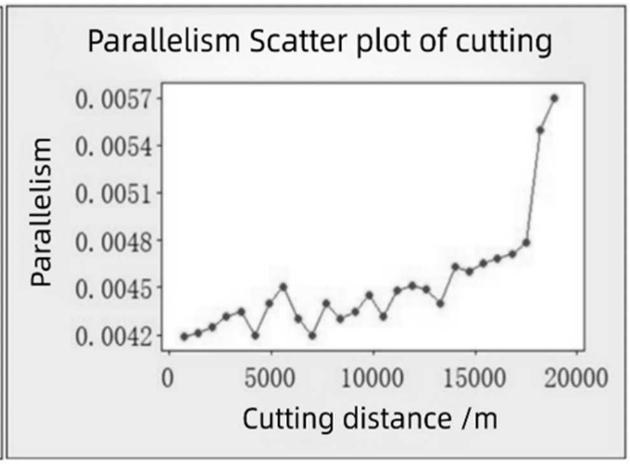


Fig. 6 *Four groups of experimental surface roughness box diagrams*

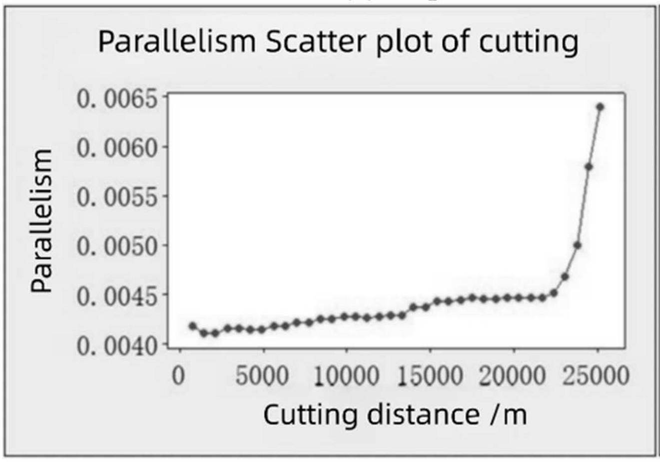
Through the analysis of the surface roughness change trend chart in Figure. 5, it can be seen that the cutting distance of the experimental group 3 is the longest when the roughness changes rapidly, which is about 24,000 meters, and the surface roughness change amplitude is stable before 24,000 meters. Through the analysis of the surface roughness boxplot in Fig. 6, it is evident that the data of experimental group 3 consistently exhibit lower values compared to the other groups. This observation provides evidence that the majority of roughness values in experimental group 3 are at a low level. It can be seen that the flange surface quality is the best when the feed rate is 0.07mm.r^{-1} and the cutting speed is 1100m.min^{-1}.



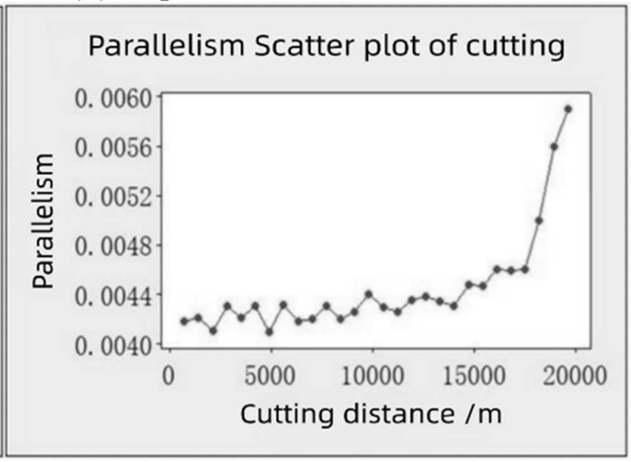
(a) *Experiment 1*



(b) *Experiment 2*



(c) *Experiment 3*



(d)*Experiment 4*

Fig. 7 *Parallelism trend chart*

Through the analysis of Figure 7, the relationship between parallelism and cutting distance of both sides of the flange is learned, which is similar to the curve of roughness trend in Figure 5. The mean value of parallelism in experiment 3 is lower than that of the other three groups, and the stability is higher than that of the other three groups, which once again proves the correctness of the mathematical model.

In terms of processing efficiency comparison, experiment 1 is 40 seconds, experiment 2 is 44 seconds, experiment 3 is 35 seconds, experiment 4 is 43 seconds, hence experiment 3 has the fastest processing speed and the highest processing efficiency.

The cutting speed of 1100m.min^{-1} and the feed rate of 0.07mm.r^{-1} are determined as the final processing parameters of the flange. Compared with the values of feed rate ≤0.078mm.r^{-1} and cutting speed ≥812.3m.min^{-1} obtained by the theoretical model, the difference between the experimental and theoretical values is not large, and it is within the allowable range.

5 Conclusion

The study focuses on the surface roughness of the flange and aims to optimize the machining parameters using the classical DOE method for ultra-precision machining, and the mathematical model was obtained, so that the surface roughness of flange was controlled within Ra0.05. Finally, through the actual cutting experiment, the roughness, parallelism of two end faces and machining efficiency are comprehensively analyzed, and the final actual machining parameters are obtained. Based on the experimental results, the final machining parameters are determined, and the following conclusions are drawn.

(1)Optimization of processing parameters using DOE method, DOE method is a systematic design of experiments program, can be developed in accordance with the predetermined objectives of the appropriate experimental program [20], in order to facilitate the effective statistical analysis of the experimental results of the mathematical principles and implementation of the method, through the experimental validation of the method, the method can be fast and more accurate to give the processing program.

(2) Among the 8 factors affecting surface roughness, cutting speed and feed rate are dominant factors, which have the greatest influence on surface roughness. In the obtained mathematical model, it can be seen that in order to make the roughness less than Ra0.05, the feed rate should be ≤0.074mm.r^{-1}, and the cutting speed should be ≥812.3m.min^{-1}.

(3) In the actual cutting experiment, experiment 3, the feed rate of 0.07mm.r^{-1} and the cutting speed of 1100m.min^{-1} were used to carry out the experiment, and it was concluded that the average value of surface roughness and parallelism was low, the stability was high, and the processing efficiency was high. Therefore, the feed rate of 0.07mm.r^{-1} and the cutting speed of 1100m.min^{-1} are the optimal processing parameters of the flange.

Acknowledgement

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