STUDY OF NOISE REDUCTION BY OPTIMIZING ULTRA-HIGH SPEED MILLING PARAMETERS BY DOE METHOD

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For the noise problem generated during ultra-high-speed milling electrode machining, the cutting factors are analyzed by Design of Experiments (DOE) method, and the experimental data are analyzed by stepwise regression method and standard least squares fitting method using John's Macintosh Product(JMP) software. By analyzing the mean standard deviation and the feedback of the summary of effects, the significant factors affecting the noise in order of magnitude are tool extension length, back draft, feed, and tool helix angle, while tool diameter and spindle speed are non-significant factors. The single-factor experiment shows that the spindle speed will become louder when the vibration frequency is the same as the machine tool's inherent frequency, and the back draft is directly proportional to the noise level. The DOE method and the single-factor experiments can be used to select cutting parameters for ultra-high-speed milling of electrodes, so as to reduce noise more effectively by optimizing cutting parameters.

Keywords: Ultra-high-speed milling; DOE; Optimization of cutting parameters; Denoise

1. Introduction

The electrodes are mainly used in Electrical Discharge Machining (EDM). EDM is a special type of processing that uses electrical and thermal energy for processing, and the processing form is reverse copy molding processing [1], which is particularly suitable for processing very small holes, deep holes, narrow slits, and cavities with complex shapes. Electrode processing is mainly completed by CNC machine tools. In order to ensure the high precision of the electrode, the main use of ultra-high speed milling technology, and the process of ultra-high speed milling electrode will generate high decibel processing noise, which will cause partial damage to the hearing and brain nerve of the machine tool operators working for a long time. The magnitude of cutting noise is related to the magnitude of vibration caused by cutting forces, and cutting parameters can affect the magnitude of cutting forces, so optimizing cutting parameters can help to

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improve noise hazards. DOE method [2] as a mathematical and statistical method for arranging experiments and analyzing experimental data, is able to establish simulations and predictions based on known data, which can reduce the number of experiments, shorten the experimental period and reduce experimental costs [3]. Therefore, the DOE method is used to optimize the cutting parameters and establish the theoretical model of noise and cutting parameters, which is a guide for the engineers to optimize the parameters.

Huang et al. [4] used the multivariate orthogonal method to conclude that the influence on noise is arranged by axial depth of cut>feed>radial depth of cut>spindle speed. Liu et al. [5] studied the idle noise spectral characteristics and sound pressure variations at different rotational speeds, and found that the chip-tolerant groove area and the front tool face of the insert are the main factors influencing the noise before the pneumatic of the high-speed face milling cutter. Parker and Hargresves [6] found that the noise level generated by the tool during high-speed rotation could reach up to 100-110dB. Sampath et al. [7] found that the pulsating pressure on the surface of the face milling cutter is an important factor in the formation of the noise of the face milling cutter. Among many studies on cutting noise, DOE method design is used to analyze the relationship between cutting parameters and noise magnitude, and it is able to reduce the noise impact by optimizing cutting parameters.

2. Experimental design

2.1 Experimental subjects

Electrodes are mainly used in the processing of irregular deep holes and curved surfaces in injection moulds. The electrode used in EDM is an important guarantee for the precision of deep hole or special curved surface in injection mold, so it has higher requirements for the dimension tolerance, shape tolerance and surface roughness of the electrode. The traditional processing technology requires two processes, milling and grinding, which has low processing efficiency. In order to solve the low processing efficiency and ensure the accuracy of the electrode, Ultra-high speed milling has been widely used in electrode machining. The electrode selected by the experimental object is 159mm long, 53.2mm wide and 90mm high. The section width of each electrode is 1.6mm, the groove width is 7mm and the groove depth is 45mm. The parts of the electrode are shown in Figure 1.

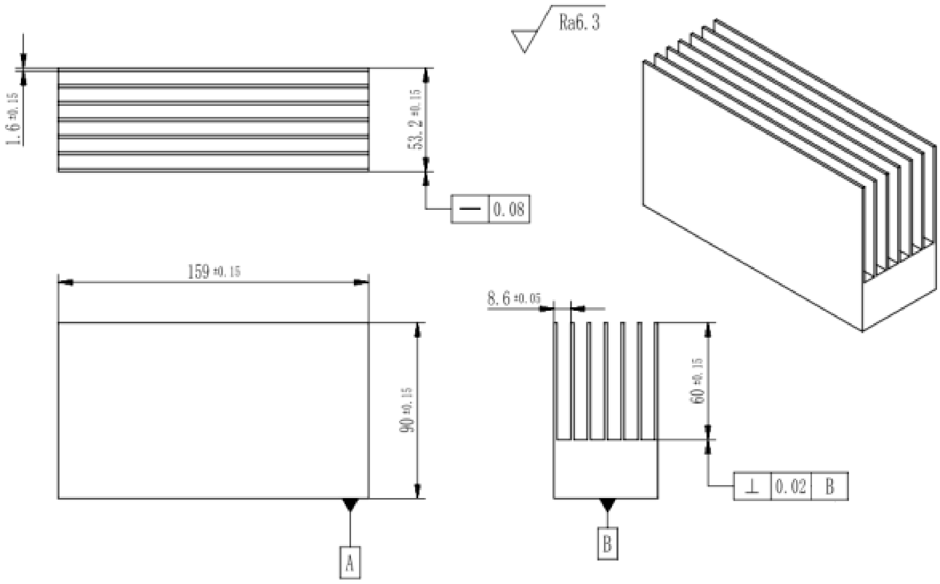

Fig. 1 Electrode parts drawing

2.2 Experimental conditions

During the machining process, the tool is selected from a four-edged tungsten steel milling cutter with a diameter of 6 mm60° and a four-edged tungsten steel milling cutter with a diameter of 4 mm 60°. The machine tool adopts CTS-540 CNC machine tool with spindle speed up to 30000r/min. The fixture is made of Benton BENTDIU's high-precision flat-nose pliers GT7X200, with an accuracy of up to 0.005mm, and the cutting method is smooth milling without cutting fluid [8].

The sound collection system selects the INV3018G 20-channel parallel collector, sound level meter and DASP platform software. INV3018G is a 24-bit high-performance data acquisition instrument with 24-bit AD precision. The maximum sampling frequency of each channel is 102.4KHz, and the dynamic range of each channel is up to 120dB. All channels are parallel without time difference, with high reliability and good anti-vibration performance. The sound collection device is installed at 300mm directly in front of the workpiece according to the requirements of use and better collection of sound pressure, at the same height as the workpiece height center line, in order to prevent the test instrument from being affected by machine tool vibration during machining [9] to ensure that the base of the measurement point does not contact the machine tool. The measurement point arrangement and data acquisition schematic diagram are shown in Figure 2.

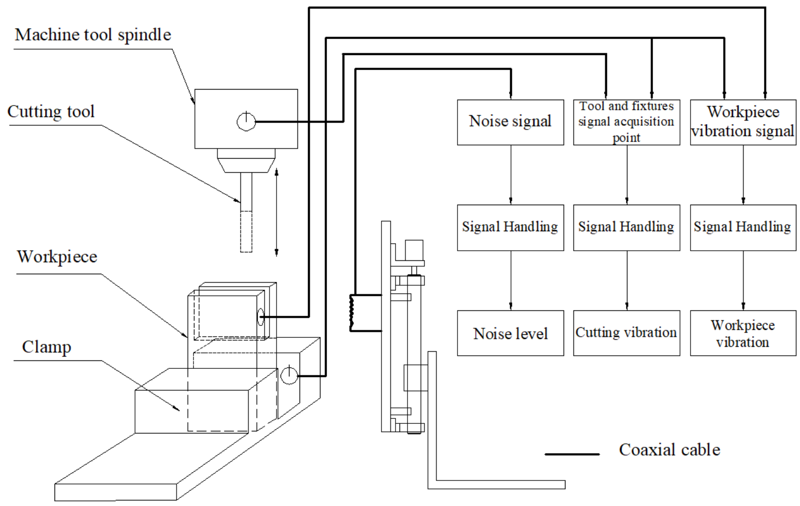

Fig. 2 Monitoring point arrangement

2.3 Theoretical analysis

Sound is a wave generated by air vibration [10]. In the high-speed cutting motion, the workpiece and the tool collide with each other to generate cutting forces that cause the tool and the workpiece and the machine tool to vibrate, and stir up the surrounding air to produce vibration, thus emitting a harsh noise [11]. The magnitude of the cutting force is related to the selection of cutting parameters [12].

In acoustics, the quantity and optional reference quantity are taken on the order of magnitude of 10 as a common unit of sound size, and its expression formula is [13].

$$L_P = 10lg\frac{P^2}{P_0^2} \tag{1}$$

P-Sound pressure effective value Pa, $P_0 = 2 \times 10^{-5} p_a$

The noise we hear is the total noise level consisting of the target noise and the ambient noise, and we can measure the target noise with the formula:

$$L_{ps} = 10lg[\frac{P^2}{P_0^2} - \frac{p_B^2}{P_0^2}] \tag{2}$$

L_{ps} is the target sound pressure level, p_B is the ambient background sound pressure level.

2.4 Experimental program design

In order to study the influence of cutting parameters on the noise level in the process of ultra-high-speed milling electrode, the DOE method is adopted.

Noise size is measured by sound pressure level. Combined with field processing experience, the main factors affecting noise pressure level in ultra-high speed milling are analyzed. Six factors, including spindle speed, feed, back cutting, tool diameter, tool extension length and tool helix Angle are selected as the influencing factors, and the change of each factor will affect the size of noise pressure level. In the DOE method, we chose the noise sound pressure level as the main measurement parameter. The experimental data are obtained by cutting experiment, and then analyzed by JMP software. The specific steps of DOE method are as follows:

1) Partial factorization experiment is mainly to reduce the number of experiments by screening out the artificially judged experimental factors that have no effect or a relatively small effect on the response factor.

2) The full analysis of the experimental design is to re-screen the factors screened by the partial analysis of the factor design.

3) Response surface design experiments are conducted to analyze the correlation between the screened key factors and the response factors of experiments.

Table 1

Partial analysis of the experimental factors

Horizontal	Speed of main shaft (r/min)	Back engagement(mm)	Feedamount (mm/min)	Knife diameter(mm)	Tool extends in length(mm)	Knife spiral angle
1	14000	0.1	900	4	50	35°
2	26000	0.5	1700	6	70	50°

As shown in Table 1, the six factors (speed of main shaft, back engagement, feedamount, knife diameter, tool extends in length, and knife spiral angle) were selected as the level setting parameters for partial analysis factor experiments, and each parameter was set as high and low levels.

3. Analysis of experimental results

3.1 Principle of model analysis

(1) Stepwise regression method [13]: The influential factors are taken as independent variables, and the independent variables are introduced one by one, and the measurement parameter is taken as dependent variable Y. Each time, the independent variables are imported to select the independent variable that has the most significant influence on Y. The independent variables that have significant influence on the test object are tested one by one, and the independent variables that do not change significantly are removed from the influencing factors one by one.

The variable $x \in \{x_1, x_2 \cdots x_n\}$ establishes n fitted equations for the dependent variable Y, respectively:

$$Y = \beta_i x_i + \varepsilon, \quad i = 1,2,\cdots,n \tag{3}$$

The F (Probability Value) is verified for the n fitting equations, the maximum value of F is found from the n fitting equations, and the corresponding variable x_i is obtained, which is then introduced into the model for recalculation. According to this method, the remaining variable x_i is introduced into the model successively, and the variable x after each introduction is used as the remaining independent variable, which has the greatest impact on Y value. Until all the variables are introduced.

(2) Standard least squares method [14]: Because of the limitation of stepwise regression method, it is necessary to use more accurate "least square" method for regression analysis. The principle of least square method is to measure a set of data $x_i, y_i (i = 1,2\cdots n)$, find an optimal fitting curve such that the sum of squares of the difference between the values of the points on this fitting curve and the measured values is the smallest among all fitting curves. Least square method is also known as curve fitting. The so-called "fitting" means that the curve is not required to pass through all data points completely, but only requires that the obtained curve can reflect the basic trend of data. Curve fitting can be divided into unary linear fitting and multivariate linear fitting.

JMP software is based on the principle of multiple linear fitting to analyze experimental data. In the actual experiment, the JMP software can be used for data analysis to get the calculated results, and the visual regression analysis to get the main impact factors. JMP software will also give specific graphical analysis results according to each factor, the relationship between the predicted value and the actual value of the least square regression analysis, to illustrate the relevance of the regression model.

3.2 Analysis of the results of partial analysis experiments

The partial factorization experiments are conducted with a resolution of 4 to distinguish the main effect factor and the second-order interaction effect factor of these 6 factors in 16 groups as shown in Table 2.

Table 2

Partial factorial experiments

Number	Model	The tool extends in length(mm)	Back engagement (mm)	Amount of feed (mm/min)	Knife spiral angle(°)	Knife diameter (mm)	Speed of main shaft (r/min)	Sound pressure level(Db)
1	++++++	70	0.5	1700	50	6	26000	84.6
2	−−−+++	50	0.1	900	50	6	26000	80.2

3	−+−+−+	50	0.5	900	50	4	26000	81.5
4	+−++−+	70	0.1	1700	50	4	26000	82.7
5	−++−−+	50	0.5	1700	35	4	26000	81.4
6	−−−−−−	50	0.1	900	35	4	14000	80
7	+−−++−	70	0.1	900	50	6	14000	81.8
8	−−+−++	50	0.1	1700	35	6	26000	80.6
9	+−−−−+	70	0.1	900	35	4	26000	81
10	++−+−−	70	0.5	900	50	4	14000	82.7
11	+++−−−	70	0.5	1700	35	4	14000	83.8
12	−−++−−	50	0.1	1700	50	4	14000	81
13	++−−++	70	0.5	900	35	6	26000	83.6
14	−++++−	50	0.5	1700	50	6	14000	83.6
15	+−+−+−	70	0.1	1700	35	6	14000	82.1
16	−+−−+−	50	0.5	900	35	6	14000	80.7

In Table 2, “+” indicates the maximum value of the parameter and “-” indicates the minimum value. The JMP software analysis function is used to fit the model, mainly using the standard least squares model fitting and stepwise regression control model fitting. The results are shown in Table 3 and Table 4.

Table 3

Model results are obtained by the stepwise regression method

Parameter	Degree of free dom	Sum of squares	F-values	Probability>F	P-values	Dominant factor
The tool extends in length	1	11.055625	41.6212	0.0001	0.0012	Y
back Engagement	1	9.765625	9.765625	0.0002	0.0019	Y
Amount of feed	1	4.305625	4.305625	0.0030	0.00299	Y
Knife spiral angle	1	1.500625	1.500625	0.0414	0.04144	Y
Knife diameter	1	0.600625	0.600625	0.1669	0.16691	
Speed of main shaft	1	0.000625	0.000625	0.9624	0.96237	

Table 4

Results of the standard least squares simulation

Term	Estimator	Standard error	T-values	Probability>|t|	Dominant factor
the tool extends in length	0.83125	0.128847	6.45	0.0001*	Y
back engagement	0.78125	0.128847	6.06	0.0002*	Y
amount of feed	0.51875	0.128847	4.03	0.0030*	Y
knife spiral angle	0.30625	0.128847	2.38	0.0414*	Y
knife diameter	0.19375	0.128847	1.50	0.1669	
speed of main shaft	-0.00625	0.128847	-0.05	0.9624	

Among them, the P value is less than 0.05 indicates that the factor is significant, by comparing the F and T-values, it can be concluded that the four significant factors of tool extension length, back engagement, feed, and tool helix angle are high in the experiment.

3.3 Analysis of complete factorial experiment results

After partial factorization experiments, only 4 factors of 6 factors are left, next, a 2×2×2×2 complete factorial experiment with 4 factors is required. The non-significant factor tool diameter is 6mm, the spindle speed is 20000r/min. The experimental data are shown in Table 5, and the key factors are further screened.

Table 5

2×2×2×2Complete factorial experiments

	Model	The tool extends in length	Back engagement	Amount of feed	Knife spiral angle	Sound pressure level
1	+−−−	70	0.1	900	35	80.6
2	+−++	70	0.1	1700	50	82.5
3	+−−+	70	0.1	900	50	80.6
4	−−−−	50	0.1	900	35	79.4
5	−−+−	50	0.1	1700	35	80
6	+−+−	70	0.1	1700	35	81.9
7	−−++	50	0.1	1700	50	80.7
8	−+−+	50	0.5	900	50	81.2
9	−−−+	50	0.1	900	50	79.6
10	++++	70	0.5	1700	50	83.5
11	−+++	50	0.5	1700	50	82
12	−+−−	50	0.5	900	35	80.2
13	+++−	70	0.5	1700	35	83.1
14	−++−	50	0.5	1700	35	81.5
15	++−−	70	0.5	900	35	81.8
16	++−+	70	0.5	900	50	82.4

Stepwise regression control and standard least squares model fitting are performed. The results are shown in Table 6, Table 7.

Table 6

Model results are obtained by the stepwise regression method

Parameter	Degree of freedom	Sum of squares	F-values	Probability>F	Dominant factor
the tool extends in length	1	8.7025000	151.3478	<.0001*	Y
back engagement	1	6.7600000	117.5652	<.0001*	Y
amount of feed	1	5.5225000	96.0435	<.0001*	Y
knife spiral angle	1	1.0000000	17.3913	0.0016*	Y

Table 7

Standard least squares model fitting results

Term	Estimator	Standard error	T-values	Probability>|t|	Key factor
the tool extends in length	0.7375	0.059948	12.30	<.0001*	Y
back engagement	0.65	0.059948	10.84	<.0001*	Y
amount of feed	0.5875	0.059948	9.80	<.0001*	Y
knife spiral angle	0.25	0.059948	4.17	0.0016*	

According to the estimated values in Table 7, the influence sequence from the largest to the bottom is the length of the tool, back engagement, the feed amount and the spiral angle of the tool. The spiral angle of the tool has less influence than the other three factors, so the influence factor of the spiral angle of the tool can be screened out.

3.4 Analysis of response surface experimental results

The complete factorization experiment selects the tool extension length, back engagement, and the feed amount as the key factors, and then selects the response surface design and the design type of Box-Behnken in the experiment in the JMP menu bar. The experiments are shown in Table 8.

Table 8

Combination and results of the 16 experiments

	Model	The tool extends in length	Back engagement	Amount of feed	Sound pressure level
1	000	60	0.3	1300	82.2
2	0−+	60	0.1	1700	80
3	−+0	50	0.5	1300	81.4
4	++0	70	0.5	1300	83
5	+0+	70	0.3	1700	82.5
6	0+−	60	0.5	900	81.7
7	−0+	50	0.3	1700	80.4
8	+−0	70	0.1	1300	80
9	+0−	70	0.3	900	82
10	000	60	0.3	1300	80.2
11	−−0	50	0.1	1300	78
12	0−−	60	0.1	900	79.4
13	−0−	50	0.3	900	79
14	0++	60	0.5	1700	82.3
15	000	60	0.3	1300	80.2

The results obtained by model fitting are shown in Table 9.

Table 9

Response analysis results

Term	Estimator	Standard error	T-values	Probability>|t|	Key factor
Intercept	80.82	0.154851	521.92	<.0001*	
The tool extends in length	1.0875	0.212038	5.13	0.0003*	Y
Back engagement	1.375	0.212038	6.48	<.0001*	Y
Amount of feed	0.3875	0.212038	1.83	0.0949	

The complete factorial experiment was analyzed, and the JMP software gave the analysis results through multiple linear fitting. In Table 9, "tool extension length" and "back cutting amount" were the key factors.DOE method mainly analyzes the key factors, from the analysis of variance, whether the disfitting phenomenon is serious in the analysis of variance, the significance of each effect, as well as the residual diagnosis and fitting of the selected model, to obtain the prediction experimental model and mathematical model expression:

Sound pressure level = 80.82 + 1.0875 * ((:tool extension length - 60) / 10) + 1.375 * ((:back engagement - 0.3) / 0.2)+ 0.38749999999999999 * ((:Feed - 1300) / 400)

3.5 Analysis and prediction of comprehensive experimental results

Predictive descriptors: In addition to the mathematical model, JMP software will draw some visual picture modules for intuitive observation of the relationship between factors and output items. The prediction model is established by JMP software, and the experimental results of the three factors are evaluated and predicted. As shown in Figure 3, it can be obtained that the extension length of the tool is <=60, and Back engagement is <=0.3425455. Amount of feed <=1700.

Based on the above three experiments, the optimal processing parameters of the 6 factors predicted during the processing of ultra-high-speed milling electrodes can be obtained, as shown in Table 10.

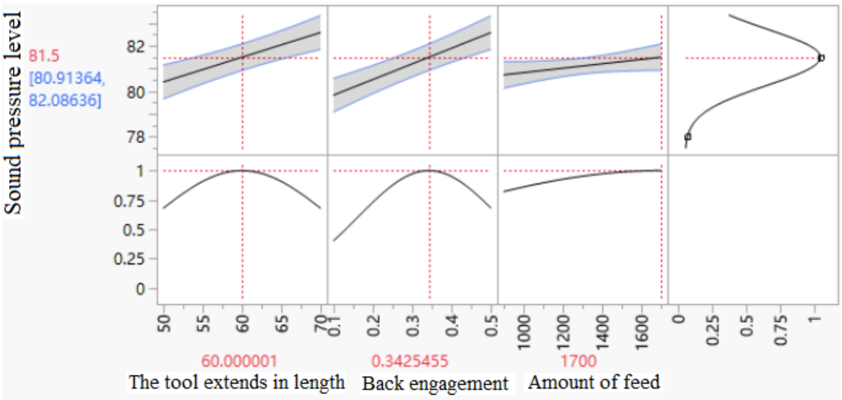

Fig. 3 Predictive descriptors

Table 10

Optimal parameter combination

Factor	Processing parameters	Figure
Key factor	The tool extends in length	<=60
The dominant factor	Back engagement	<=0.3425455
The dominant factor	Amount of feed	<=1700
Significant factors	Knife spiral angle	50
Non-significant factors	Knife diameter	4~6
Non-significant factors	Speed of main shaft	14000~26000

4. Verified by one-factor experiments

4.1 Cutting speed-noise single-factor experiment

Experimental steps:
(1) Set the experimental conditions, under the conditions of tool clamping height of 110mm, back engagement of 0.05mmand feed of 1000mm/min, by setting the spindle speed to 10000r/min, 12000r/min, 14000r/min, 16000r/min, 18000r/min, 20000r/min for experiments and collecting the data of cutting noise.
(2) Processing the background noise during cutting.
(3) Establish the numerical relationship between cutting speed and cutting noise, and perform the related image analysis.

The results of the analytical experiment are shown in Figure 4.

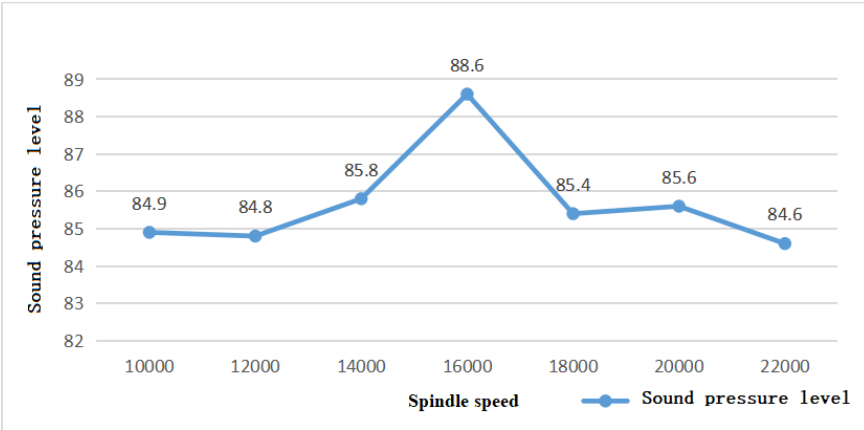

Fig. 4 Cutting Speed-Noise Map

It can be seen from the line chart that in addition to the speed of 16000r/min, the change in spindle speed has little effect on the noise sound pressure level, so in general, the impact of spindle speed on cutting noise is not a large non-significant factor, only when the spindle speed causes the spindle vibration frequency to resonate with the natural frequency of the bed at the same time, the noise will be increased [15].

4.2 Back engagement-noise single factor experiment

Experimental steps:
(1) Set the experimental conditions, under the conditions of tool clamping height of 110mm, spindle speed of 12000r/min, feed amount of 1000mm/min, by setting back engagement is 0.05mm, 0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm, 0.35mm for experiments and collect cutting noise data.

(2) Deal with the background noise during cutting.
(3) Establish the numerical relationship between the back engagement and cutting noise and perform the related image analysis.

The results obtained by analyzing the experiments are shown in Figure 5.

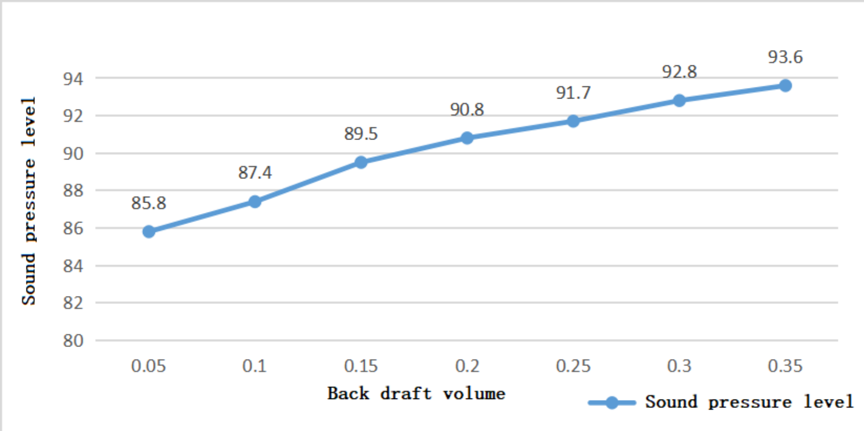

Fig. 5 Back engagement quantity-noise diagram

Through the data analysis of the collection, it can be observed that back engagement is proportional to the cutting noise, and as back engagement increases, the cutting noise also increases. Therefore, the back engagement is the key factor.

5. Conclusion

Taking the copper electrode of the radiator part as the research object, the six cutting factors preliminarily determined in the ultra-high-speed milling process are analyzed by means of DOE method design of experiments. The key factors affecting the noise are obtained by fitting the JMP software model and then screening the factors step by step. And the reliability of the conclusions is verified by single-factor experiments. Based on the analysis of experimental data, the following conclusions can be obtained:

(1) In the ultra-high-speed cutting electrode, the factors that affect the noise are, in descending order, length of the tool, back engagement, the feed amount and the helix angle. Among them, the length of the tool, back engagement and feed amount are significant factors. The tool diameter and spindle speed are non-significant factors, which have almost no effect on the magnitude of the noise generated by cutting.

(2) The influence of spindle speed on noise is mainly related to frequency. Under normal circumstances, the spindle speed of the machine tool has little influence on the noise level, but only when the spindle vibration frequency is the same as the machine tool inherent frequency and the two resonate, the noise will

increase sharply. As for the amount of back eating knife, it is concluded through experiments that the cutting noise increases with the increase of the amount of back eating knife. The experimental results of both verify the accuracy of the analysis of the DOE method.

(3) In the ultra-high-speed milling electrode processing, not only copper electrodes but also other materials such as graphite, tungsten and iron exist, and subsequent noise studies can be carried out on electrodes of materials other than copper. Due to the different characteristics of the materials, there should be a variety of variations in the cutting parameters. The research results can provide reference for ultra-high-speed machining technicians to reasonably select cutting parameters and reduce cutting noise.

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