Parameter Optimization of Surface Roughness in Ultrasonic Vibration Cutting Process

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Abstract. In order to improve the processing quality of the ultrasonic vibration cutting process and reduce the surface roughness of the workpiece, based on the Response Surface Methodology (RSM), the second-order response model of 45 steel ultrasonic vibration cutting is established. The 45 steel ultrasonic vibration cutting roughness model is fitted by the central composite experiment. The reliability of the model was verified by the significance analysis based on analysis of variance and the validity analysis based on residual graph. Finally, the 3D response surface map of the surface roughness of the workpiece was cut by ultrasonic vibration, and the influence of various process parameters on the surface roughness was analyzed. The suitable cutting amount combination was selected: the spindle speed is 70.95m/min, the cutting speed is 0.11m/min, while the feed rate is 0.95mm/r and the ultrasonic amplitude is 26.80mm.

1. Introduction

Ultrasonic vibration cutting technology refers to the addition of high frequency and low amplitude composite processing method in the cutting process[1]. The advantages of ultrasonic vibration cutting are very prominent, which can improve the service life of the tool, improve the machining accuracy of the workpiece, and low cutting temperature[2].

Workpiece quality is an important indicator for evaluating the processing performance of ultrasonic vibration cutting processes. Ultrasonic vibration cutting workpiece quality is directly related to surface roughness. Under other conditions, the surface roughness is smaller, the workpiece quality is better[3]. At present, the optimization of the parameters of ultrasonic vibration processing has received widespread attention in the industry. For example, Lu Dongxi et al[4] used SPH algorithm for parameter optimization. Chen Haifeng et al[5] used the region approximation algorithm to optimize ultrasonic grinding parameters. The limitation of this method is easy to cause partial optimization. In addition, the use of mathematical statistical methods for ultrasonic vibration processing optimization analysis is also very common, such as Lu Zesheng et al[6] using numerical simulation to optimize precision ultrasonic cutting, Zhang Shengfang et al[7] using numerical fitting method to optimize geometric parameters, etc. Mathematical analysis is very reliable, but does not take into account the effects of interaction. In summary, this paper uses the response surface method (RSM), which is innovative, combines the accuracy of the above experimental methods and mathematical statistics, and reflects the influence of the impact factor on the target value and the parameters interaction[8].

2. Experimental Study on Ultrasonic Vibration Cutting of 45 Steel

2.1 Experimental materials and methods
The experimental material used 45 steel, its main components are shown in Table 1, the basic size is φ50mm×500mm; the test is carried out on the C6201 lathe, the tool material is cemented carbide YNG151C.

| element | Quality score /% | element | Quality score /% |
|---------|------------------|---------|------------------|
| Si      | <0.37            | Cr      | 0.25             |
| Mn      | <0.8             | Ni      | 0.25             |
| P       | 0.035            | Cu      | 0.25             |
| S       | 0.035            | Fe      | 其余              |

The schematic diagram of the experimental device is shown in Fig 1. After the power is turned on, the ultrasonic transducer generates ultrasonic vibration to amplify the amplitude through the horn to achieve ultrasonic vibration cutting. We used the surface roughness (Ra) of the workpiece as the performance evaluation index, measured with a portable surface roughness tester (Mitutoyo SJ-210), observed the change of surface roughness, and analyzed the data.

![Schematic diagram of the experimental device](image)

**Fig 1. Residual normal probability map.**

### 2.2 Experimental scheme and results

The experiment used a central composite experiment (CCD) to determine the level of factors and conduct experimental design. The spindle speed (A), the cutting speed (B), the feed amount (C), and the ultrasonic amplitude (D) were selected as the study variables, and the main parameter for evaluating the workpiece quality: surface roughness (Ra) was determined as the response variable. Through the single factor experiment, the experimental level of determining the processing parameters is divided into: -1 level, 0 level and 1 level, and the specific level coding is shown in Table 2.

| Factor level | -1 | 0  | 1  |
|--------------|----|----|----|
| A / (m/min)  | 60 | 90 | 120|
| B / (mm/min) | 0.1| 0.2| 0.3|
| C / (mm/r)   | 0.2| 0.4| 0.6|
| D / (mm)     | 10 | 20 | 30 |

Experiments were carried out by combining the process parameters in the experimental scheme designed by the CCD method, and the test results were measured several times using a surface roughness tester (Mitutoyo SJ-210), and the average value was taken as the final experimental result. The final experimental protocol and experimental results are shown in Table 3.

| code | A / (m/min) | B / (mm/min) | C / (mm/r) | D / (mm) | Ra / (μm) |
|------|-------------|--------------|------------|----------|-----------|
| 1    | 0           | 0            | 0          | 0        | 0.527     |
| 2    | 0           | 0            | 0          | -1       | 0.900     |
| 3    | 0           | 0            | 0          | 0        | 0.503     |
3. Experimental Study on Ultrasonic Vibration Cutting of 45 Steel

3.1 Establishment of mathematical model for ultrasonic vibration cutting

According to the response surface principle\[9\]: If n influence factors $\sigma_1, \sigma_2, \ldots, \sigma_n$ (both natural variables) are included in an experiment, the response model of the input and output is:

$$y = f(\sigma_1, \sigma_2, \ldots, \sigma_n) + \varepsilon$$

Where: $f$ is the target response function; $\varepsilon$ is the error of the large system where the model is located.

If the target response is met:

$$E(y) = E[f(\sigma_1, \sigma_2, \ldots, \sigma_n)] + E(\varepsilon) = f(\sigma_1, \sigma_2, \ldots, \sigma_n) = \eta$$

Then the surface represented by equation (2) is the response surface. To make it easier to study the impact factor, to convert the natural variable into a dimensionless normative variable $x_1, x_2, \ldots, x_n$, the normalized response surface function is:

$$\eta = f(x_1, x_2, \ldots, x_n)$$

Since the functional relationship between the target response and the optimization parameters is unknown, the first step to establish a response surface model is to find a formula that approximates the true function relationship. In general, the response surface is approximated by a high-order polynomial, such as a second-order model:

$$y = \phi_0 + \sum_{i=1}^{n} \phi_i x_i + \sum_{i=1}^{n} \phi_i^2 x_i^2 + \sum_{i} \sum_{j} \phi_{ij} x_i x_j + \varepsilon$$
Where: $\varphi_0, \varphi_1, \varphi_2, \varphi_3$ all are polynomial coefficients estimated by least squares; $\varepsilon$ is a random error.

The response surface model of ultrasonic vibration cutting is: four-factor quadratic response surface model, specifically:

$$y(x) = \varphi_0 + \varphi_1 x_1 + \varphi_2 x_2 + \varphi_3 x_3 + \varphi_4 x_4 + \varphi_{12} x_1 x_2 + \varphi_{13} x_1 x_3 + \varphi_{14} x_1 x_4 + \varphi_{23} x_2 x_3 + \varphi_{24} x_2 x_4 + \varphi_{34} x_3 x_4 + \varphi_{11} x_1^2 + \varphi_{22} x_2^2 + \varphi_{33} x_3^2 + \varphi_{44} x_4^2$$

According to Table 3, the specific second-order model is fitted by least squares method:

$$R_1 = 0.53 - 0.038A + 0.17B - 8.833E-003C - 0.18D - 7.000E-003AB - 5.000E-004AC - 1.375E-003AD + 4.625E-003BC + 0.039BD - 0.010CD + 0.060A^2 - 0.032B^2 + 0.034C^2 + 0.18D^2$$

3.2 Validity test of mathematical model for ultrasonic vibration cutting

In order to verify whether the prediction accuracy of the ultrasonic vibration cutting process parameters and the response variable model is accurate, the Design-Expert software is selected to perform the post-processing analysis on the data in Table 3. Whether a model is suitable or not must first be tested for validity. The residual normal probability map is to determine whether the regression model is valid by analyzing whether the normal probability distribution of the residual follows a straight line [10]. As can be seen from Fig 2, all points are regularly distributed in a straight line, with no signs of violation, which means the model is valid.

3.3 Significance test of mathematical model of ultrasonic vibration cutting machining

In order to study the influence degree of each process parameter on the roughness in the ultrasonic vibration cutting process, the response surface model also needs to be tested for significance. The significance of the model is also an important criterion for judging the prediction accuracy of the model. Therefore, the variance analysis of the experimental results is required. Judging its significance, the analysis results are shown in Table 4. The p value was used to analyze the significance of the object. If $P < 0.0001$, it means that the response model reached a very significant level. If $p < 0.05$, it means that the response model reached a more significant level. If $p > 0.1$, it means that the response model is not significant [11].

| Source of variance | square sum | degree of freedom | mean square value | F statistic | P value |
|--------------------|------------|-------------------|------------------|------------|---------|
| model              | 1.52       | 14                | 0.11             | 159.51     | <0.0001 | Significant |
| A                  | 0.027      | 1                 | 0.027            | 39.02      | <0.0001 |
| B                  | 0.52       | 1                 | 0.52             | 765.26     | <0.0001 |
It can be seen from Table 4 that the influence of the model is significant, which indicates that the prediction accuracy of the model is high. In addition, it can be judged from the P value that for the linear effect, the spindle speed A, the cutting speed B, and the ultrasonic amplitude D on the surface roughness is extremely significant (p<0.0001), and the influence of the feed amount C on the surface roughness is not significant (p>0.1). Comparing the magnitudes of the mean square values, the main order of linear effects affecting surface roughness is: D>B>A>C; for secondary effect, the effect of D$^2$ on surface roughness is extremely significant (p<0.0001); the effect of A$^2$ on surface roughness is also more significant (p<0.05); B$^2$, C$^2$ effect on surface roughness is not significant (p>0.1), compared with the mean square value, the order of secondary effects affecting surface roughness is: D$^2$>A$^2$>C$^2$>B$^2$. For interaction, the effect of BD on surface roughness is extremely significant (p<0.0001), and the influence of other factors is less significant (p>0.1). Comparing the magnitude of the mean square value, the order of interaction affecting the surface roughness is: BD>CD>AB>BC>AD>AC. The p value of the lack of fit in the table is not significant, which proves that the model has good reliability.

3.4 Parameter Optimization Based on Response Surface Method

3.4.1 Analysis of response surfaces
Since the surface roughness of the ultrasonic vibration cutting process product is affected by multiple factors, there is still interaction between the various factors. Therefore, the surface roughness model can be fitted by the response surface method to analyze the influence law. The response surface is shown in Fig 3.

![Fig 3. Response surface map of B and D affecting surface roughness.](image)

For the optimized response target surface roughness, the interaction between the cutting speed B and the ultrasonic amplitude D is significant from the significance test analysis. Fig 3 is a response
surface diagram of the cutting speed and the ultrasonic amplitude (BD), which is obtained by the graph: the surface roughness gradually decreases as the cutting speed decreases and the ultrasonic amplitude increases.

3.4.2 Parameter Optimization and Verification of Ultrasonic Vibration Cutting Process

In the Design-Expert software, the second-order response regression prediction model equation of the ultrasonic vibration cutting process is analyzed. The optimization function of the optimization module is used to optimize the extreme points of the surface roughness. The optimal process parameter combination is: The spindle speed (A) is 70.95 m/min, the cutting speed (B) is 0.11 mm/min, the feed rate (C) is 0.95 mm/r, and the ultrasonic amplitude (D) is 26.80 mm. The surface roughness at this time is 0.302μm. According to the optimized parameter combination, the ultrasonic vibration cutting experiment was carried out again to verify that the surface roughness was 0.356μm, and the calculated relative error was only 1.5%, which indicated that the response surface optimization method used was accurate and reliable.

4. Conclusions

(1) Using the response surface method, a second-order response model with high prediction accuracy is established, the validity test and significance test are carried out. From the residual probability analysis and variance analysis, the order of influence of surface roughness linear effect, secondary effect and interaction effect is obtained.

(2) In the ultrasonic vibration cutting process, when the spindle speed (A) is 70.95 m/min, the cutting speed (B) is 0.11 mm/min, the feed rate (C) is 0.95 mm/r, and the ultrasonic amplitude (D) is 26.80 mm, the surface roughness is the smallest, it is 0.302μm. The results show that the suitable ultrasonic vibration cutting parameters are more conducive to improve the cutting quality, and provide a theoretical basis for the selection of process parameters in ultrasonic vibration processing.

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