Research on Surface Roughness of Supersonic Vibration Auxiliary Side Milling for Titanium Alloy

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Original Article

Keywords: Titanium alloy, Side milling, Axial vibration, Ultrasonic milling, Finite element simulation, Linear regression, Surface roughness

Posted Date: July 28th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-704632/v1

Title page

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ORIGINAL ARTICLE

Research on Surface Roughness of Supersonic Vibration Auxiliary Side Milling for Titanium Alloy

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Abstract: The processed surface contour shape is extracted with the finite element simulation software, and the difference value of contour shape change is used as the parameters of balancing surface roughness to construct the infinitesimal element cutting finite element model of supersonic vibration milling in cutting stability domain. The surface roughness trial scheme is designed in the central composite test design method to analyze the surface roughness test result in the response surface methodology. The surface roughness prediction model is established and optimized. Finally, the finite element simulation model and surface roughness prediction model are verified and analyzed through experiment. The research results show that, compared with the experiment results, the maximum error of finite element simulation model and surface roughness prediction model is 30.9% and12.3%, respectively. So, the model in this paper is accurate and will provide the theoretical basis for optimization study of auxiliary milling process of supersonic vibration.

Keywords: Titanium alloy • Side milling • Axial vibration • Ultrasonic milling • Finite element simulation • Linear regression • Surface roughness

1 Introduction

Nowadays, milling is deemed as one of the most commonly-used processing technologies in manufacturing era. Milling is mainly used for the processing of mould and other free-form surface parts. However, new materials such as high-strength aerospace alloy, etc. confront the following issues in milling: high cutting force, poor surface roughness and rapid cutter abrasion. In order to achieve high precision, and improve the service life of cutter and material removal rate, the scholars at home and abroad constantly explore new technology. Ultrasonic milling technology has developed for many years, in which the supersonic vibration auxiliary milling is a kind of emerging special milling technology. Compared with laser or electrical discharge milling, ultrasonic milling is more environmental-friendly. With the research breakthrough of scholars at home and abroad, the supersonic vibration milling also obtains great progress in the actual application processing field. Currently, it is generally applied in the materials which are difficultly processed, with ideal processing effect.

D.Biermann et al. [1] adopted the ultrasonic milling processing technology in the research on milling of thin-walled workpiece, and analyzed the research results to work out the influence rules and forming reason of vibration milling to workpiece surface roughness. Wang et al. [2] carried out the verification experiment of supersonic vibration auxiliary milling for optical glass K9, which concluded that the subsurface damage of materials is proportional to the change of cutting force and verified the accuracy of prediction model. Shen Xuehui [3] established the tool nose motion trail model based on the change of tool nose motion characteristics after supersonic vibration, and deeply analyzed the relationship between the tool nose motion trial and workpiece's surface quality from the theoretical perspective, and finally through experimental verification concluded that the workpiece's surface quality is related to the ratio between ultrasonic frequency and rotation speed of main shaft, the larger the ratio is, the better the surface quality is.

In recent years, with the gradual development of finite element analysis, it is also widely applied in the cutting field. The dynamic constitutive model [4-6], residual stress of thin-walled parts, prediction precision machining and micro cutting of finite element technology, etc. are researched a lot, with remarkable achievements [7-10]. Moaz H et al. [11] analyzed the influence of feed speed on surface roughness through the finite element simulation in the research on

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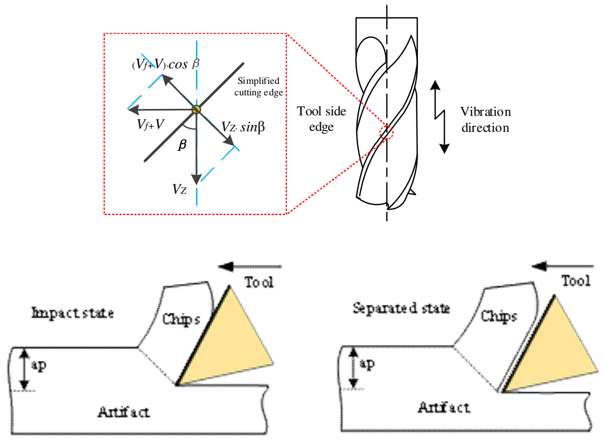
titanium alloy cutting, and concluded that the milling force is consistent with the surface roughness at different feed speeds; Thepsonthi T [12] applied the finite element simulation method and utilized the finite element analysis method in the research on cutter abrasion condition in titanium alloy milling process; Muhammed et al. [13] established the finite element simulation model of 3D ultrasonic milling and traditional milling, and expounded the change of cutting force based on two kinds of processing technologies, and concluded that the vibration milling force reduces due to the increase of actual cutting speed and the continuous cutting of cutter; Sandipl et al. [14] conducted the modeling of 2D simulation model in the auxiliary processing process of rotary supersonic vibration, and in comparison to the traditional milling, concluded that the vibration milling process obviously improves the thermal softening effect of materials and the reduction of strength in clipping region based on finite element simulation of simulation model. The research results of many research scholars at home and abroad indicate that: the finite element analysis is advanced and efficient in the vibration cutting processing field, and is deemed as one of effective and necessary analysis and prediction methods. Finite element simulation analysis can optimize the processing technology parameters and simplify the experiment, especially play an important role in guiding the analysis of the coupling role among multi-factor parameters and the experimental result.

Currently, the application of finite element simulation method in analysis of supersonic vibration auxiliary milling mostly focuses on the milling force and mises stress, and there is rare research on surface roughness of workpiece obtained through the supersonic vibration auxiliary milling processing in the finite element method. The 3D finite element simulation model of axial supersonic vibration auxiliary cutting titanium alloy is established to analyze the influence on processing surface quality after vibration.

2 Analysis of Finite Element Simulation for Surface Roughness

2.1 Interrupted Cutting Phenomenon Generated by Axial Supersonic Vibration

Since the flat milling cutter's side edge and blade helical angle mainly exert the axial supersonic vibration, in the axial vibration, cutter and workpiece generate the relative radial motion, as shown in Figure 1. The analysis results regarding the relationship between actual cutting speed and indirect cutting show that the cutter and workpiece have intermittent contact in axial supersonic vibration milling. The milling cutter is deemed as single blade milling for the convenience of research. **Error! Reference source not found.**.



A-1 Impact cutting state A-2 Separate cutting state

Figure 1 Relation Drawings of Separation Speed for Cutter Workpiece

Based on the formula (1), cutter's axial vibration velocity and time have the following relationship:

$$V_Z = 2\pi Af \cdot cos\left(2\pi ft\right) \tag{1}$$

Wherein, the A and f refer to the vibration amplitude and vibration frequency, respectively.

The milling processing is here defaulted at stable cutting status, and the main shaft is deemed to have uniform circular motion. So, the milling cutter's cutting speed formula is:

$$V_c = \pi dn / 1000 \tag{2}$$

Wherein, d and n refer to the cutter diameter and rotation speed of main shaft, respectively.

Later, the xoy coordinate system is established in Figure 1, in which the coordinate axis x is established in the direction of cutting edge, and the coordinate axis y perpendicular to cutting edge is established. The cutting speed Vc and cutter's axial vibration speed V_z are decomposed in new coordinate system, then the speed in the direction of y can be decomposed as:

$$V_y = V_c \cos\beta + V_z \sin\beta \tag{3}$$

Cutter moves up and down due to the axial vibration, so the component velocity of V_z in the direction of y changes. When the $Vc\ cos\beta$ and $V_z\ sin\beta$ have the same direction and the resultant velocity in the direction of y constantly increases to the maximum value, the cutter is at the impact state. In order to expound the impact condition of supersonic vibration more intuitively, the acceleration coefficient G is introduced.

$$G = (V_z \sin\beta)' = -(2\pi Af)^2 \cdot \sin(2\pi Af) \cdot \sin\beta \tag{4}$$

In combination with the above analysis results, the cutter has the following shock cutting conditions in the ultrasonic milling processing based on the theoretical analysis:

Cutter is at the shock milling state when G>0;

Cutter is at the critical value of shock milling when G=0;

Cutter is at the non-impact milling state when G<0.

When $V_c \cos\beta$ and $V_z \sin\beta$ have the opposite direction, the resultant velocity direction will point to the direction with larger value, and the cutter and workpiece are separated.

So, in order to expound the separation condition of high-frequency intermittent contact caused by supersonic vibration better, the velocity coefficient *P* is introduced [16].

$$P = \frac{V_z \sin\beta}{V_c \cos\beta} \tag{5}$$

In combination with the above analysis results, the cutter has the following separation conditions for intermittent cutting in the ultrasonic milling processing based on the theoretical analysis:

The processing cutter for supersonic vibration is at the workpiece separation stage when P＞1;

The processing cutter for supersonic vibration is at the critical value of workpiece separation state when P = 1;

The processing cutter for supersonic vibration is at the workpiece contact stage when P＜1.

2.2 Auxiliary Milling Mechanism of Axial Supersonic Vibration

Auxiliary milling device of supersonic vibration mainly includes the ultrasonic power supply, energy converter, ultrasonic handle and milling cutter. When supersonic vibration system starts operation, firstly, the ultrasonic power supply sends out current signal and delivers to energy converter, then energy converter converts the current signal to the sine pulse signal, finally the power amplifier in ultrasonic handle amplifies the vibration amplitude and outputs the vibration information matched with energy converter through the cutter, namely the supersonic vibration auxiliary milling, as shown in Figure 2.

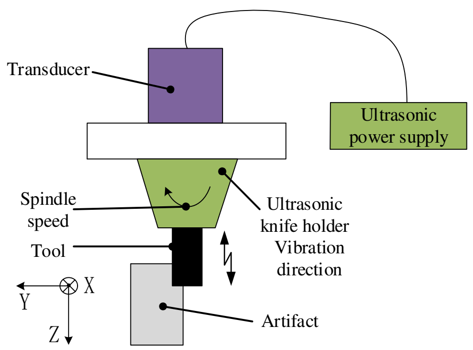


Figure 2 Schematic Diagram of Auxiliary Milling System of Axial Supersonic Vibration

2.3 Establishment of 3D Milling Simulation Model

The milling simulation through finite element software is relatively macro due to less value of surface roughness, so the infinitesimal element simulation is conducted to the milling, and the 3D bevel cutting simulation replaces the 3D milling simulation for the research on surface roughness. The surface roughness is the mean value of infinitesimal displacement variation for contour on the surface of cutting processing workpiece in essence. Since the finite element software doesn't have the module for direct measurement of surface roughness, the simulation measurement could be conducted to the infinitesimal displacement variation of contour on the surface of processed workpiece as the parameters of predicting the surface roughness value. The specific milling parameters are shown in Table 1.

Table 1 Experiment Parameters for Verification of Surface Roughness Empirical Model

Serial number	Spindle speed (r/min)	Feed per tooth (mm/z)	Depth of cut (mm)
1	900	0.08	6
2	1600	0.09	6
3	1700	0.06	9
4	1800	0.07	4

2.3.1 Constitutive Model of Materials

The J-C constitutive model proposed by Jonson et al. is widely applied in the metal cutting field, so the J-C constitutive model is adopted upon establishment of titanium alloy milling finite element simulation model which considers the axial supersonic vibration, as shown in formula (6).

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{6}$$

Wherein, σ, ε and $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ refer to the yield limit of materials, equivalent plastic strain of materials and relative equivalent plastic strain rate, respectively. Reference strain rate $\dot{\varepsilon}_0$ refers to the strain rate of quasi-static compression test; $\dot{\varepsilon}_0 = 0.001 s^{-1}$, C and m refer to the impact index of strain hardening, sensitivity coefficient of logarithmic strain rate and temperature softening coefficient, respectively; For the non-dimensional parameter $T^* = (T - T_r)(T_m - T_r)$, the T refers to the material deformation temperature ($T = T_0 + \Delta T$, the temperature increment ΔT is considered on the basis of original temperature T_0), namely the reference temperature (25°C), the T_m refers to the melting temperature of materials [17].

2.3.2 Material Failure Criteria

In the milling processing process, as the rack face constantly extrudes the materials, the materials are continuously removed to form different shapes of chips. The damage coefficient is deemed as an important parameter which can judge whether materials are invalid in the failure criterion of Johnson-Cook, and is indicated with D (materials are judged to be invalid when D is more than 1) in general [18], with the calculation formula as follows:

$$D = \sum \frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}} \tag{7}$$

Wherein, $\Delta\bar{\varepsilon}^{pl}$ and $\bar{\varepsilon}_f^{pl}$ refer to the equivalent plastic strain increments and the equivalent plastic strain upon unit failure, respectively. Its expression formula is shown in the following formula (8):

$$\bar{\varepsilon}_f^{pl}=\left[d_1+d_2epx(-d_3)\eta\right]\left[1+d_4\ln(\frac{\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_0})\right](1-d_5\theta) \quad (8)$$

The $\bar{\varepsilon}_0$ refers to the reference strain rate; The $\bar{\varepsilon}$ refers to the plastic strain rate; The d_1、d_2、d_3、d_4、d_5 refers to the material failure parameters.

2.3.3 Chips Contact Model

In accordance with the friction model [19] proposed by Zorev, the contact segment between cutter and cutting layer area is divided into the bonded area and slipping area in the established simulation model. In the slipping area, the friction coefficient is a constant and its change scope meets the Coulomb Friction Law, as shown in Formula (9).

$$\tau=\begin{cases}\mu\sigma_n & 0<x<l_p \\ \tau_p & l_p<x<l_c\end{cases} \quad (9)$$

Wherein, σ_n refers to the normal stress; τ_p and μ refer to shear stress and friction coefficient, respectively.

2.3.4 Setting of Ultrasonic Motion trial of Shank Cutter

In the established axial supersonic vibration auxiliary milling 3D model, the feeding direction of milling isn't fixed, and the centrode of cutter is a regular wavy curve. In ABAQUS software, the Load function module can control the amplitude value curve by setting up boundary condition or load with the change of time and frequency, thus achieving the simulation condition of non-linear cutter centrode.

The same-cycle amplitude curve is adopted in the model to control the motion mode of cutter, which is calculated in amplitude formula in the setting of parameter process, in which the amplitude's circular frequency has the following calculation formula:

$$\omega=2\pi f t \quad (10)$$

Wherein, ω, f and t refer to the circular frequency, the vibration frequency of cutter and the time step, respectively. The cutter's vibration frequency and time span are 25khz and 0.1s, respectively.

In the amplitude value parameter setting module, in addition to setting up the circular frequency, the size of vibration amplitude shall be set, namely the setup of parameter A and B whose specific relationship as below:

$$u=A_0+A\cos2\pi f+B\sin2\pi f \quad (11)$$

Wherein, u and A_0 refer to the amplitude and the initial amplitude, respectively; A and B refer to amplitude control parameters.

The vibration amplitude needs to be set as 10μm. So if we set the control parameter A of initial amplitude and amplitude as 0, the value of B is equal to the amplitude value. Refer to Figure 3 and Figure 4 for the specific parameter setting of amplitude value.

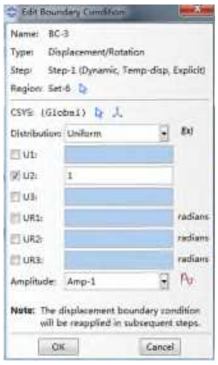


Figure 3 Load Setting

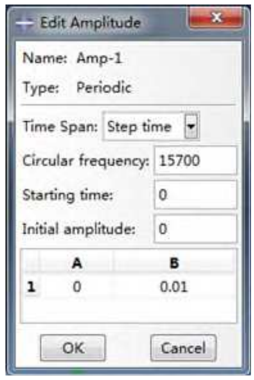


Figure4 Setting of Vibration Amplitude Curve Parameters

2.4 Post-treatment of Finite Simulation Model

The arithmetic average deviation Ra of contour refers to the arithmetic average of surface contour offset absolute value of manufacturing workpiece in the sampling length l, and can accurately and comprehensively reflect the microscopic unevenness of surface [21], as shown in Figure 5, with expression formula as below:

$$\mathrm{Ra}=\frac{1}{n}\sum|y_i| \quad (12)$$

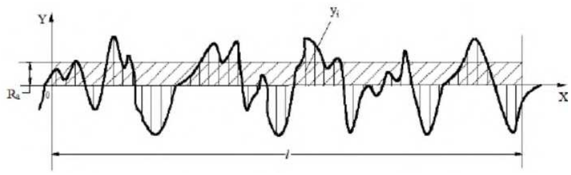


Figure 5 Schematic Diagram of Arithmetic Average Deviation[20]

Wherein, y_i refers to the distance between point and center line on contour.

The Figure 6 is the imitated diagram of surface roughness after simulation processing. When the surface roughness model is predicted through finite element simulation, the infinitesimal element processing is conducted to the auxiliary milling of supersonic vibration, which is replaced with bevel chips.

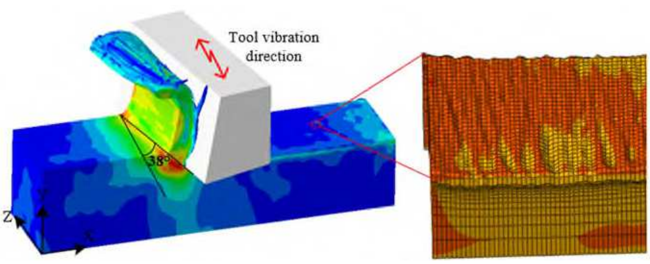


Figure 6 Imitated Diagram of Workpiece Surface Roughness

In order to facilitate the research on simulation result graph of surface roughness, the cutter and chips are hidden, as shown in Figure 7.

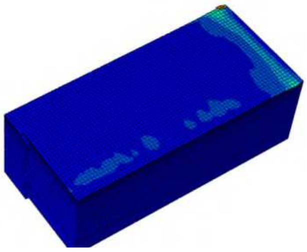


Figure 7 Simulation Result Graph after Concealment of Cutter and Chips

The bevel cutting simulation is conducted to workpiece, then the grid node is selected on the surface of workpiece and is magnified to the maximum degree, and any point around it is selected. The mean value between the workpiece radial coordinate values (coordinate value Y) of extraction point in the actual cutting process and the absolute value of theoretical difference value of workpiece radial coordinate values, is deemed as the workpiece's processing surface contour height Ra. The field output module selects the displacement field output to extract the surface roughness value. 21 points on the processed surface after stable cutting of workpiece are selected, then the absolute value of the 21 groups of the extracted surface roughness parameters is calculated, as shown in Figure 7. The specific value of cutting parameters in Group 2 of Table 1 is shown in Table 2. Finally, the absolute value of y_i in Table 2 is analyzed based on formula (12), and the surface roughness Ra is 0.509. Likewise, the simulation results of milling parameters in Table are processed to work out the surface roughness of each group of processing parameters, as shown in Table 3.

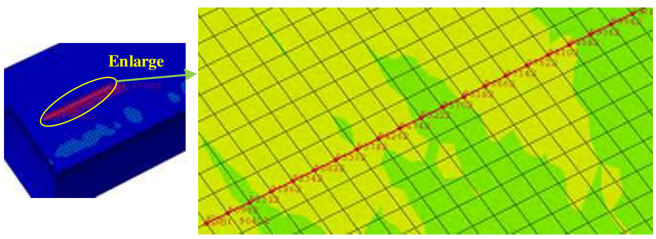


Figure 8 Coordinate Extraction Figure

Table 2 Extraction Data of Surface Roughness

Serial number	y_i(mm)	absolute value of yi (mm)
1	0.0009886	0.000989
2	0.0008354	0.000835
3	0.000145	0.000145
4	5.52E-04	0.000552
5	0.0006107	0.000611
6	0.0006417	0.000642
7	0.0007232	0.000723
8	4.01E-04	0.000401
9	4.60E-04	0.00046
10	0.0006516	0.000652
11	2.24E-04	0.000224
12	0.0001885	0.000189
13	4.35E-04	0.000435
14	5.50E-04	0.00055
15	0.0006506	0.000651
16	0.000647	0.000647
17	4.79E-04	0.000479
18	5.12E-04	0.000512
19	0.0001057	0.000106
20	0.0001678	0.000168
21	2.16E-04	0.000216

Table 3 Surface Roughness Value Obtained through Finite Element Simulation

Serial number	Spindle speed (r/min)	Feed per tooth (mm/z)	Depth of cut (mm)	Ra (μm)
1	900	0.08	6	0.327
2	1600	0.09	6	0.509
3	1700	0.06	9	0.346
4	1800	0.07	4	0.314

3 Empirical Model of Surface Roughness Based on ANOVA

3.1 Construction of Test Platform

The equipment used in the experiment can be divided into the processing center, supersonic vibration system and workpiece. As shown in Figure 9, the experimental machine tool adopts the VDL-1000E three-axis milling machine, the workpiece materials adopt titanium alloy, the ultrasonic power frequency is 25khz, and the cutter adopts the 4-blade φ10 cemented carbide flat milling cutter, with the specific parameters shown in Table 4. Workpiece connects its machine tool workbench, and the ultrasonic handle connects the main shaft.

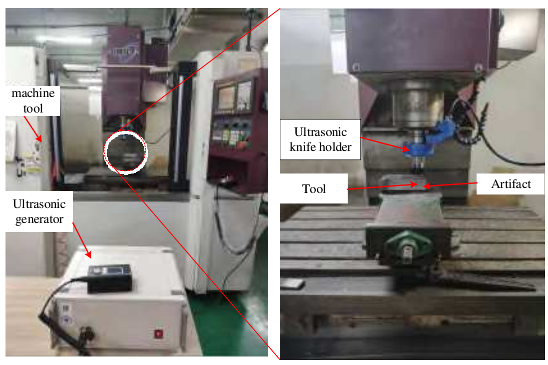


Figure 9 Test Platform

Table 4 Cutter Parmeters

parameter	Parameter value
material	Hard alloy
Helix angle	38°

Front angle	8°
Back angle	9°
Interdental angle	90°

3.2 Orthogonal Test Design and Specific Test Parameters

The test study adopts the orthogonal test method which is a kind of commonly-used research method of inquiring the multifactor variables at present. The orthogonal test can reduce the times of test as far as possible, rapidly obtain the representative test data, improve the test progress and guarantee the reliability of test results. The specific test parameters are shown in Table 5.

Table 5 Multi-factorial Test Parameter Table

Vibration frequency (khz)	25	amplitude (μm)	8
factor	Level		
	I	II	III
A- Spindle speed (r/min)	1000	1500	2000
B- Feed per tooth (mm/z)	0.05	0.07	0.09
C- Depth of cut (mm)	3	6	9

The test aims to research the surface roughness, the multi-factorial test which involves four factors and three levels and also considers the mutual influence among each factor, is designed. The header design of test scheme is shown in the Table 6:

Table 6 Multi-factor Header Design

NO	A	B	(A*B)1	(A*B)2	C	(A*C)1	(A*C)2	(B*C)1	(B*C)2
	1	2	3	4	5	6	7	8	9

3.3 Test Results and Analysis of Surface Roughness Based on ANOVA

The single-factor analysis results of workpiece surface roughness in the last section show that the rotation speed and feed speed of main shaft are the main causes of influencing the surface roughness of processed workpiece. But in actual milling process, their influence on surface roughness of workpiece is mutually influenced. Based on that issue, the response surface methodology will be utilized to analyze the influence of interaction among three cutting factors on surface roughness to seek the optimal milling parameter combination. The test result is shown in Table 7.

Table 7 Experimental result

NO	A	B	(A*B)1	(A*B)2	C	(A*C)1	(A*C)2	(B*C)1	(B*C)2	Ra
1	I	I	I	I	I	I	I	I	I	0.275
2	I	I	I	I	II	II	II	II	II	0.326
3	I	I	I	I	III	III	III	III	III	0.403
4	I	II	II	II	I	I	I	II	III	0.553
5	I	II	II	II	II	II	II	III	I	0.564
6	I	II	II	II	III	III	III	I	II	0.864
7	I	III	III	III	I	I	I	III	II	1.130
8	I	III	III	III	II	II	II	I	III	1.231
9	I	III	III	III	III	III	III	II	I	1.310
10	II	I	II	III	I	II	III	I	I	0.225
11	II	I	II	III	II	III	I	II	II	0.255
12	II	I	II	III	III	I	II	III	III	0.317
13	II	II	III	I	I	II	III	II	III	0.374
14	II	II	III	I	II	III	I	III	I	0.420
15	II	II	III	I	III	I	II	I	II	0.452
16	II	III	I	II	I	II	III	III	II	0.742
17	II	III	I	II	II	III	I	I	III	0.745
18	II	III	I	II	III	I	II	II	I	0.957
19	III	I	III	II	I	III	II	I	I	0.234

20	III	I	III	II	II	I	III	II	II	0.300
21	III	I	III	II	III	II	I	III	III	0.321

3.4 Surface Roughness Modeling Based on RSM

The variance method is adopted to analyze the rule of influence of milling parameters on the surface roughness of processed workpiece, but the interaction among each milling parameter in actual cutting processing is great. Hence, response surface methodology shall be utilized to further analyze the optimization results. Such analysis method considers the interaction effect and secondary effect among every process parameters, with the expression formula as follows:

$$\mathrm{Y} = R\mathrm{a} - \varepsilon = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x + \sum_{i=1}^{k} \beta_{ij} x_i^2 \qquad (13)$$

Wherein, the Y refer to the response value of surface roughness x_i and x_j refer to the independent variable, The Ra and refer to the surface roughness and the error, respectively; β_0, β_i, β_{ij} and β_{ii} refer to the regression coefficient of each item.

Based on the Design-Expert 8.0.6 software, the stepwise regression analysis method is utilized for the repeated optimization processing of test data in Table 7 in order to process platform. The stepwise regression analysis is conducted to the test data in Table 7 through Design-Expert 8.0.6 software, and the repeated consequent selection and reverse removal are conducted to the test data to work out the Level-II response surface analysis model equation of titanium alloy surface roughness based on three cutting factors:

$$\begin{aligned} Ra &= 0.49 - 0.15A + 0.32B + 0.088C - 0.082A*B \\ &-0.064A*C + 0.027B*C + 0.14A^2 + 0.046B^2 + 0.025C^2 \end{aligned} \qquad (14)$$

Wherein, the A, B and C refer to the rotation speed of main shaft, feed speed and cutting depth, respectively.

3.5 Optimization and Inspection of Surface Roughness Regression Model

In order to improve the accuracy of established regression model of surface roughness, the Design-Expert 8.0.6 software is adopted for significance analysis of all independent variables in model. If the value P of the tested objects among analysis results is no more than 0.05, such object is significant, otherwise it is non-significant.

As shown in Table 8, the B of primary item is extremely significant, the A2 of primary item, interaction item and quadratic term is significant, the B2 and C2 of interaction item and quadratic term are not significant.

Table 8 Significance Analysis of Surface Roughness Regression Model

So	sum of	Degree of	Mea	F value	P value
A	0.17	1	0.17	41.84	0.0009
B	0.84	1	0.84	208.97	≤0.000
C	0.059	1	0.05	14.86	0.0130
AB	0.028	1	0.028	7.01	0.0331
AC	0.017	1	0.017	4.12	0.0818
BC	3.042E-	1	3.042	0.76	0.4790
A^2	0.057	1	0.057	14.30	0.0071
B^2	1.980E-	1	1.980	0.49	0.3.53
C^2	1.698E-	1	1.698	0.042	0.5100

In order to obtain the optimal surface roughness model, the optimal principle of regression equation is utilized to eliminate the non-significant value in significant analysis module and to optimize the established model. The response surface analysis model of titanium alloy surface roughness is:

$$Ra = 0.49 - 0.15\mathrm{A} + 0.32B + 0.088C - 0.082A*B + 0.14A^2 \quad (15)$$

In order to verify the accuracy of optimized model, the significance analysis is needed for model to judge the reliability of model, as shown in Table 9. The smaller lack of fit of established model indicates good model fitting degree; $(P = 0.2137 > 0.05)$ The value P corresponding to the model regression item is far less than *, which indicates the excellent significance of established regression model. $0.05(P < 0.0001)$

Table 9 Significance Verification of Surface Roughness Regression Model

Source of Variance	sum of square	Degree of freedom	Mean square	F value	P value
Regression model	1.27	9	0.14	25.99	≤0.0001
Residual	0.038	7	5.441 E-003		
Lack of fit	0.024	3	8.100 E-003	2.35	0.2137
Pure error	0.014	4	3.447 E-003		
sum	1.31	16			

3.6 Optimization of Auxiliary Milling Auxiliary Titanium Alloy Process Parameters for Supersonic Vibration

The visual processing analysis is conducted to the optimized surface roughness regression model through Design-Expert 8.0.6 software. Based on fixed parameter, the rule of influence of interaction between any two milling parameters on titanium alloy surface roughness is shown, the optimal value of surface roughness Ra=0.277μm, and the corresponding milling process parameters A=1403.29r/min, B=319.75mm/min、and C=3.1mm, as shown in Figure 10.

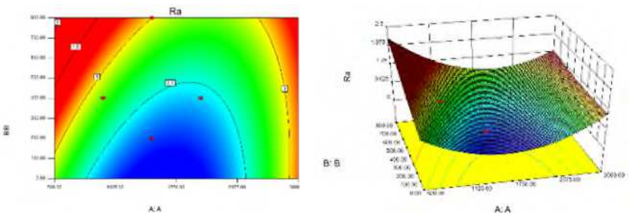


Figure 10 3D Response Surface Figure of Surface Roughness Regression Equation(Response surface and contour of A and B)

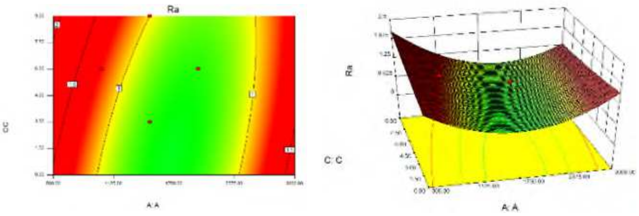


Figure 11 3D Response Surface Figure of Surface Roughness Regression Equation(Response surface and contour of A and C)

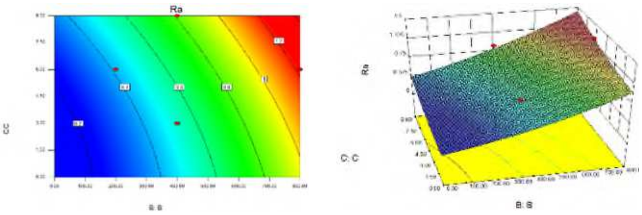


Figure 12 3D Response Surface Figure of Surface Roughness Regression Equation(Response surface and contour of B and C)

As shown in Figure 10,the surface roughness changes a little with the increase of rotation speed of main shaft; surface roughness would rapidly increase with the increase of feed rate of every gear. The feed rate of every gear becomes the most critical factor of influencing surface roughness of workpiece, because the remaining height of processing surface is mainly controlled by tool nose's radius and feed rate. When the radius of tool nose is fixed, the remaining height of processing surface will increase with the increase of feed rate of every gear.

As shown in Figure 11,the surface roughness value changes a little with the increase of cutting depth, and the surface roughness decreases before increasing with the increase of rotation speed of main shaft. The surface roughness reduces mainly because the increase of rotation speed of main shaft improves the contact rate between cutter and workpiece and reduces the surface roughness Ra; later, with the promotion of rotation speed of main shaft, the strengths of vibration milling reduce, and secondary "ironing" becomes poor, causing the surface roughness becomes poor.

As shown in Figure 12,with the increase of the feed rate of every gear, the growth trend of surface roughness isn't obvious, which indicates that the interaction between the feed rate of every gear and the cutting depth doesn't generate significant influence on surface roughness.

3.7 Experimental Verification of Regression Model and Optimal Milling Parameters

In order to verify whether the milling parameter corresponding to the optimal value of workpiece surface roughness through model analysis is accurate, the optimal combination of supersonic vibration milling process parameters is adopted for the milling process of titanium alloy. The number of terms and the times of independent variables contained in the surface roughness empirical model can be adjusted sharply, and the model precision can be improved by increasing the number of high-order terms. **Error! Reference source not found.**. So, the established surface roughness empirical model has good progress, and the specific milling parameters are shown in Table 1.

As shown in Figure 13, the predicted error range of the surface roughness model of workpiece and the finite element simulation model is 4.4%~12.3% and 27.5%~30.9%, respectively, and the surface roughness empirical model has higher fitting precision. The comparison results between predicted value and experiment value show that experiment value is larger than predicted value, and the error is mainly generated due to the following causes:

(1) Simulation aspect: Firstly, the processing environment in simulation process is ideal and doesn't consider the vibration of machine tool in the actual processing process, the error between cutter and workpiece clamping, etc.; Secondly, the measurement error also exists upon milling process and milling force measurement; Finally, with the constant cutting of cutter in the process of cutting simulation calculation, the grid cell on workpiece has distortion, which will influence the simulation results.

(2) Empirical model aspect: On the one hand, the influence of cutter abrasion on surface roughness isn't considered in the test process; on the other hand, the vibration of machine tool in processing process and the inherent processing features of materials cause the smaller predicted value of model.

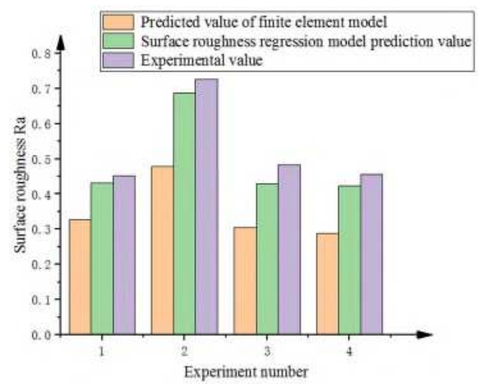


Figure 13 Comparison Diagram of Surface Roughness

4 Conclusions

The auxiliary milling surface roughness of axial supersonic vibration is researched in the finite element simulation and test method, with main conclusions below:

(1) The finite element software is applied for simulation of infinitesimal displacement variation for contour on the surface of processed workpiece, and the surface roughness of finite element simulation model is verified through experiment, with error range of 4.4%~12.3%, further concluding the established model is accurate. The experimental results of multifactor experiments are analyzed through response surface methodology to work out the empirical model of predicted surface roughness with error range between 27.5%~30.9%.

(2) Under the premise of not considering the influence of cutter abrasion on the surface roughness, the predicted value of the surface roughness empirical model obtained in test method is more accurate than that of surface roughness through finite element simulation, mainly because the processing environment of finite element simulation is relatively ideal, and the test method is more suitable for the actual process in comparison to the finite element simulation method.

5 Declaration

Acknowledgements

The authors sincerely thanks to Mr. CaiXu Yue, Mr. XianLi Liu and Mr. DeSheng. Hu of Harbin University of Science and Technology for their opinions on the revision of this paper. Mr. YunPeng Ding of Suzhou Vocational Institute of Industrial Technology and Mr. Steven Y. Liang of Georgia Institute of Technology for their formatting references, preparing figures and making corrections during manuscript preparation.

Funding

This research was funded by Projects of Outstanding Youth Fund of Heilongjiang Province (Grant Number YQ2019E029) and International Cooperation and Exchanges NSFC (Grant Number 51720105009) and National Key Research and Development Project (Grant Number 2019YFB1704800).

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' Contributions

XW and CY were in charge of the whole trial; XW and CY wrote the manuscript; DH and XL assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

Competing Interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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