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Orthogonal Test Analysis and Modeling of GCr15 Bearing Steel Machined Surface Residual Stress in Hard Precision Turning

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Orthogonal experimental analysis of GCr15 bearing steel residual stress in machined surface is carried out; Based on 1stOpt software, Using the Marquardt method and universal global optimization algorithm established Multivariate nonlinear prediction model of residual stress in machined surface. There sults of the experiment show that With the increase of cutting speed, the residual tensile stress showed a trend of increasing first and then decreasing; With the increase of feed rate, the residual tensile stress decreases first and then increases, and the residual compressive stress first increases and then decreases; With the increase of cutting depth, residual tensile stress increased slowly (compressive stress decreases); With the increase of the radius, the residual tensile stress increases (compressive stress decreases). The increase of cutting vibration makes the residual tensile stress increase or decrease of the residual compressive stress. Through the test and analysis, the establishment of the prediction model fitting degree is excellent and has statistical significance.

1. Introduction

Hard cutting has the advantages of good machining flexibility, machining efficiency and surface quality, and it has become a new way to hardened aluminium processing. However, control of surface integrity in hard cutting, especially the prediction and modeling of surface residual stress also needs to be studied systematically.

Related scholars have been carried out a lot of researches on the surface residual stress of the machining. Through the hard cutting experiment, Dahlman contrasts the distribution of hard cutting and grinding residual stress. It is indicated that compared with grinding, hard cutting can make the residual stress distributed to a deeper metal layer, the residual stress in the surface layer is greater. With cutting parameters as the influencing factors, Liu M and Barbacki et al. carry out the hard cutting experiments. Through the analysis of the experimental results, it is pointed out that the influence of feed rate on the surface roughness is significant, Increase the feed rate will cause the surface residual compression stress decreases gradually, and finally transformed into tensile stress, and can distribute the residual stress to the distance from the surface. Hua et al. study the influence of cutting tool radius on the residual stress distribution through the hard cutting experiments, through the analysis of the test results, for making the residual compressive stress to distribution in the surface, should choose smaller tip blunt edge of the circular mouth tool guide circle. With the cutting parameters and cutting parameters as the test factors, Thiele et al studies the effect of different factors on the distribution of residual stress. By studying the results of the experiments, they know that, the formation of the surface residual tensile stress is related to the cutting speed and the flank wear of the cutting tool. The cutter parameters have the function of the residual stress in the depth. Professor Chen Ming of Shanghai Jiao Tong University studies the influence of cutting parameters on the surface residual stress; the results show that the influence of the rake angle on the surface residual compressive stress is significant. With taking cutting and cutting tool wear as test factors, Yang Bo carry out the experimental study of high speed milling, The research result is that the cutting speed and cutting depth are significant factors to obtain the surface residual

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compressive stress, When the tool wear is small, we can obtain the surface of the uniform distribution of the residual stress.

Through the orthogonal hard turning test, the surface residual stress is analyzed. based on 1stOpt software, Using the Marquardt method and universal global optimization algorithm to establish a multivariate nonlinear prediction model of Residual stress on machined surface.

2. Hard cutting test

2.1 Test scheme

The orthogonal test was designed with L16 (44) Orthogonal array. The cutting speed v, feed rate f, cutting depth ap, and tool radius rε , as the four test factors, Each of these factors were taken four identical values. A total of 16 sets of experiments were conducted.

2.2 Cutting test condition

The cutting tests are carried out on the CAK4085 numerical control lathe. Figure 1 is a device for cutting tests; in these tests, the GCR15 bearing steel with a geometrical size of Φ110×200mm is chosen. After quenching treatment, the hardness of the material reaches 62~64HRC. The cutting tool is the most basic blade in PCBN7025 negative rake angle Turning Inserts of Sandvik Coromant Company. The cutter bar is CoroTurn RC Rigid clamp DCLNR/L2020K12 conventional tool bar. Table 1 is blade model and its parameters. In the experiment, the vibration acceleration of the cutting tool Ag is measured by the SD1403 piezoelectric acceleration sensor. The vibration signal acquisition and processing is carried out under the Vib'SYS software program, which is in the development of Beijing's pop company.

Figure 1 Experimental Cutting Set-up

Table 1: Model and Parameters of the Blade

Types of Blades	r_ε(mm)	βr	Thickness of Blades S(mm)	The form of Cutting edge	Angle of the Chamfer r_n	b_{rn} (mm)
CNGA120404S01030A	0.4	80	4.76	Negative groove and Fillet	30°	0.10
CNGA120408S01030A	0.8					
CNGA120412S01030A	1.2					
CNGA120416S01030A	1.6					

2.3 Test of Residual Stress

In order to establish the prediction model of residual stress, the residual stress in the surface of the machined surface was measured by X—350A X ray stress measurement system. X ray method is used to testing the residual stress. Basic equation about sin2ψ is as follows:

$$\sigma_\varphi = -\frac{E}{2(v+1)} \cdot \cot\theta_0 \cdot \frac{\partial(2\theta)}{\partial \sin^2\psi} \tag{1}$$

$$K_1 = -\frac{E}{2(v+1)} \cdot \cot\theta_0 \,,\ M = \frac{\partial(2\theta)}{\partial \sin^2\psi} \quad \text{Then} \quad \sigma_\varphi = K_1 \cdot M \tag{2}$$

In the formula; K1—stress constant; M—The slope of 2θ-in2ψ diagram; E—Elastic modulus; v—Poisson ratio; 2θ—Angle between the diffracted rays and the rays; θ—Bragg angle; ψ—Angle between Crystal surface normal that produces diffraction and Material surface normal. Table 4 is orthogonal experiment.

3. The Experiment Results and Analysis

3.1 The Experiment Results

Table 2 are the test data and test results

Table 2: Design and Test Results of Orthogonal Test

	Test parameters				The root mean square value of acceleration	residual stress
	v（m/min）	f（mm/r）	a_p（mm）	r_ε(mm)	A_g（g）	σ_φ（MPa）
1	101	0.03	0.05	0.4	0.02	-1005.98
2	101	0.05	0.1	0.8	0.06	-649.65
3	101	0.08	0.15	1.2	0.03	-229.87
4	101	0.12	0.2	1.6	0.03	49.75
5	202	0.03	0.1	1.2	0.23	109.46
6	202	0.05	0.05	1.6	0.34	-199.82
7	202	0. 08	0.2	0.4	0.02	-106.23
8	202	0.12	0.15	0.8	0.05	90.32
9	301	0.03	0.15	1.6	0.27	300.11
10	301	0.05	0.2	1.2	0.11	350.35
11	301	0.08	0.05	0.8	0.03	-100.28
12	301	0.12	0.1	0.4	0.06	50.43
13	370	0.03	0.2	0.8	0.23	70.64
14	370	0.05	0.15	0.4	0.04	-60.21
15	370	0.08	0.1	1.6	0.31	89.56
16	370	0.12	0.05	1.2	0.03	-200.03

3.2 Range analysis

Table 3 is a table for the analysis of residual stress range.

Table 3: Intuitive Table for the Analysis of Residual Stress Range

	v	f	a_p	r_ε
K_1	-1835.75	-525.77	-1506.11	-1121.99
K_2	-106.27	-559.33	-400.2	-588.97
K_3	600.61	-346.82	100.35	29.91
K_4	-100.04	-9.53	364.51	239.6
k_1	-458.9375	-131.4425	-376.5275	-280.4975
k_2	-26.5675	-139.8325	-100.05	-147.2425
k_3	150.1525	-86.705	25.0875	7.4775
k_4	-25.01	-2.3825	91.1275	59.9
R	609.09	137.45	467.65	340.3975

Table 4 is the Range analysis table about Root mean square of Vibration acceleration

Table 4: The Range Analysis Table about Root Mean Square of Vibration Acceleration

	v	f	a_p	r_ε
K1	0.14	0.75	0.42	0.14
K2	0.46	0.55	0.66	0.37
K3	0.47	0.39	0.39	0.4
K4	0.61	0.17	0.39	0.95
k1	0.035	0.1875	0.14	0.035
k2	0.16	0.1375	0.165	0.0925
k3	0.1175	0.0975	0.0975	0.1
k4	0.1525	0.0425	0.0975	0.2371
R	0.125	0.145	0.0675	0.2021

(1)The influence of cutting speed on the Residual stress and the Vibration of cutting process

As shown in Figure 2, with the increase of cutting speed, the residual tensile stress appears to be increased and then decreased. When the cutting speed is less than 301m/min, the residual tensile stress increases with the increase of cutting speed; When the cutting speed exceeds 301m/min, the residual tensile stress decreases with the increase of cutting speed. When the cutting speed is between 101 and 202m/min, the vibration acceleration increases with the increase of cutting speed. When the cutting speed is between 202 and 301m/min, the vibration acceleration will decrease with the increase of cutting speed; When the cutting speed is between 301 -370 m/min, the vibration acceleration increases with the increase of cutting speed.

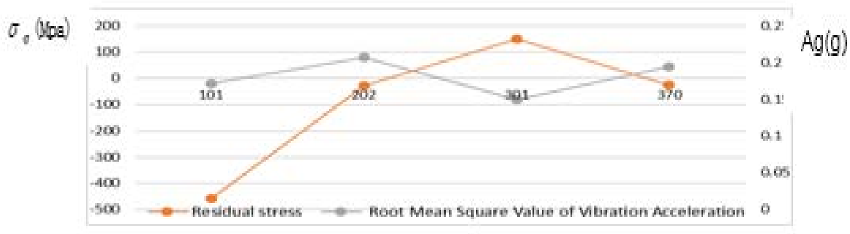


Figure 2: The Influence of cutting speed on the Residual Stress and the Vibration Acceleration of Cutting Process

(2) The influence of feed rate on the residual stress and the vibration of cutting
As shown in Figure 3, with the increase of feed rate, the residual tensile stress appears to be decreased and then increased. When the feed rate is less than 0.05 mm/r, the residual tensile stress decreases with the increase of the feed rate; When the feed rate is greater than 0.05 mm/r, the residual tensile stress increases with the increase of the feed rate. The vibration acceleration of the cutting process gradually decreases with the increase of the feed rate.

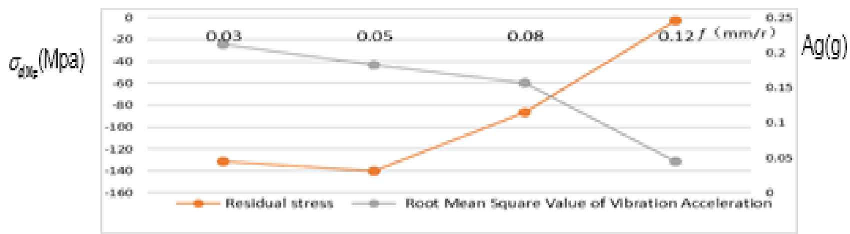


Figure 3 : The Influence of Feed Rate on the Residual Stress and the Vibration Acceleration of Cutting Process

(3)The influence of the cutting depth on the Residual stress and Vibration of cutting process
As shown in Figure 4, with the increase of the cutting depth, Residual tensile stress appears to be slowly increasing; (Residual compressive stress appears to decrease); However, the vibration acceleration of the cutting process firstly increases and then decreases. When the cutting depth is less than 0.1mm, the vibration acceleration will increase with the increase of cutting depth. When the engagement was between 0.1 and 0.15mm, the cutting depth will increase the vibration acceleration decrease, when the cutting depth is more than 0.15mm, the vibration acceleration will no longer change.

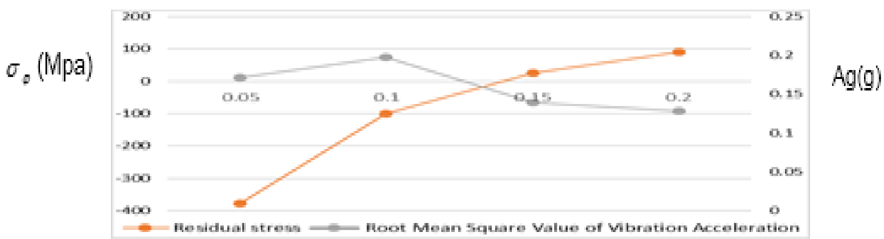


Figure 4: The influence of the cutting depth on the Residual stress and Vibration Acceleration of cutting process

(4) The influence of corner radius on the Residual stress and Vibration of cutting process

As shown in figure 5, with the increase of the corner radius, the Residual tensile stress and Vibration of cutting process gradually increases; however when the corner radius is between 0.8 and 1.2mm, the Vibration acceleration increases slowly.

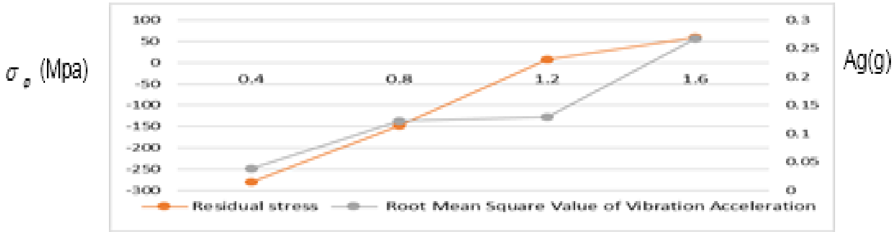


Figure 5: The Influence of the Corner Radius on the Residual Stress and Vibration Acceleration of Cutting Process

4. Modeling and Analysis of Residual Stress

According to the test results of Table 2, A prediction model of residual stress in machined surface is established by using the method of Marquardt, widely used in 1stOpt software and General global optimization algorithm.

4.1 The establishment of nonlinear model of residual stress.

The established prediction model is shown in the following formula:

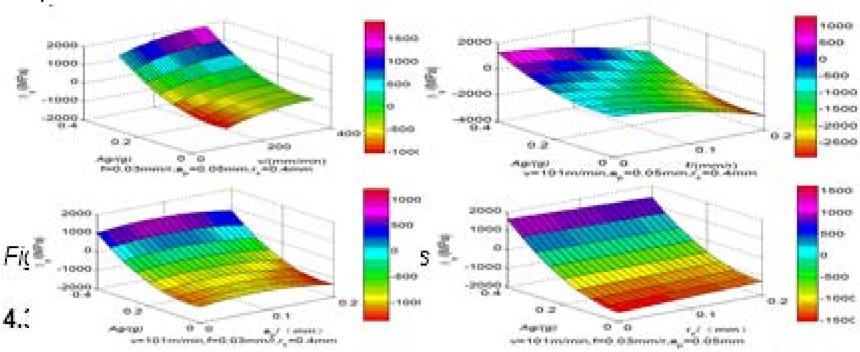
$$\sigma_{\varphi} = p1+p2*x1^2+p3*x2^2+p4*x3^2+p5*x5^2+p6*x1+p7*x2+p8*x4+p9*x5+p10*x1*x2+p11*x3*x4+p12*x4*x5+p13*x2*x3+p14*x2*x4 \quad (3)$$

Using 1stOpt software to fit the above model:

$$\sigma_{\varphi} = -2134.746+7.919v-7774.413f+1609.562r_{\varepsilon}+1038.642A_g+26.911v_f+1207.950a_p r_{\varepsilon}-139.502r\varepsilon A_g+126570.896f_{ap}-10801.238fr_{\varepsilon}-0.013v^2-35895.264f^2-6105.159a_p^2+17111.474A_g^2 \quad (4)$$

4.2 Prediction of model simulation

Figure 6 is a model simulation for predicting the residual stress, through the analysis of the pictures we learn that, the increase of cutting vibration makes the residual tensile stress increase or decrease of the residual compressive stress.



Through the forecast error table 5, we can see Maximum error is4.57%, Minimum error is -0.03%, Mean error is 0.01%, Forecast model has higher precision. Error analysis of the residual stress prediction model, as shown in Table 6, coefficient of determination is0.999979134, which shows that the fitting is good; Chi square coefficient is 0.145762, which shows that the deviation degree of theoretical inference and practical observation is very small; F Statistical value is 670928.2, which shows that the above models have statistical significance.

Table 5: Error of Residual Stress Prediction

Serial number	experimental values	predictive value	residual	errors
1	-1005.98	-1004.76	-1.21878	0.12%
2	-649.65	-651.523	1.873171	-0.29%
3	-229.87	-227.461	-2.4088	1.05%
4	49.75	47.4754	2.274595	4.57%
5	109.46	109.0422	0.41782	0.38%
6	-199.82	-200.649	0.829464	-0.42%
7	-106.23	-106.878	0.648187	-0.61%
8	90.32	93.89815	-3.57815	-3.96%
9	300.11	300.2061	-0.09613	-0.03%
10	350.35	350.4396	-0.08961	-0.03%
11	-100.28	-100.554	0.273729	-0.27%
12	50.43	48.44903	1.980968	3.93%
13	70.64	71.29634	-0.65634	-0.93%
14	-60.21	-60.9258	0.715753	-1.19%
15	89.56	90.40327	-0.84327	-0.94%
16	-200.03	-199.907	-0.12262	0.06%

Table 6: Error Analysis of Residual Stress Prediction Model

Mean Square Deviation	Residual Sum of Squares	Squared Correlation Coefficient (R^2)	Coefficient of Determination	Chi Square Coefficient	F Statistics
1.4946111	35.741797	0.9999791	0.999979134	0.145762	670928.2

5. Conclusion

Orthogonal experimental analysis of GCr15 bearing steel residual stress in machined surface is carried out. With the increase of cutting speed, the residual tensile stress showed a trend of increasing first and then decreasing. With the increase of feed rate, the residual tensile stress decreases first and then increases, while the residual compressive stress first increases and then decreases; With the increase of cutting depth, residual tensile stress increased slowly (compressive stress decreases); With the increase of the radius, the residual tensile stress increases (compressive stress decreases). The increase of cutting vibration makes the residual tensile stress increase or the residual compressive stress decrease.

Establish a multiple linear regression model about the residual stress In the process of precision cutting of hardened steel; After examination and analysis, It is proved that the forecasting model has good fitting degree, and it has statistical significance.

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