

Experimental study on residual stress of milling medical magnesium alloy

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Abstract. Magnesium calcium alloy has the basic condition and potential to improve the specific strength of medical metal materials, has good prospects for development. The residual stress caused by metal cutting has important influence on fatigue performance and corrosion resistance of parts. In this work, the residual stress of milling surface of magnesium alloy was measured by four-factor four-level orthogonal milling experiment, and the trend of residual stress with cutting parameters was analyzed. Furthermore, mathematical model of the relationship between residual stress and cutting speed, feed rate, axial and radial depth of cut was established using orthogonal regression analysis theory on the basis of finished surface residual stress results obtained.

1. Introduction

As a medical implant material, magnesium alloys have a series of advantages. Many methods have been used to improve the corrosion resistance of magnesium alloys, in order to control and prolong the corrosion degradation rate. Magnesium calcium and magnesium calcium based alloys have become one of the important development directions of biomedical implant materials in the future [1, 2].

The influence of cutting process on workpiece surface mainly includes geometric and physical characteristics [3, 4]. The geometric features are mainly surface geometry, and the physical features are mainly the distribution of the residual stress field and the change of the surface structure of the workpiece. These factors have influence on the corrosion resistance of the parts [5, 6].

In the cutting research of magnesium calcium alloy, the domestic and foreign scholars mainly focus on the chip morphology, surface morphology, temperature field distribution and the simulation of residual stress in the process of high speed cutting [7-10]. The effect of the cutting parameters on the residual stress in the machining process is rarely analysed.

2. Experimental Conditions and Measurement of Material Properties

Experimental material was self-made magnesium calcium alloy (MgCa0.8). Milling experiments were processed by YCM-V116B type vertical machining center.

X-ray diffraction method was selected to measure residual stress of milling surface. Elastic modulus and Poisson's ratio are required in the method, so tensile test for material parameters was carried on before the measurement. MgCa0.8 alloy was produced into a proportion sample with the thickness of 1.85mm, width of 13.88mm according to national standard GB/ T228-2002. BF350-6AA type strain gauges with the resistance value of $350 \pm 0.2\Omega$, sensitivity coefficient of $2.11 \pm 1\%$ were pasted on the samples, as shown in Fig. 1. The transverse and longitudinal strain were measured to calculate material properties.



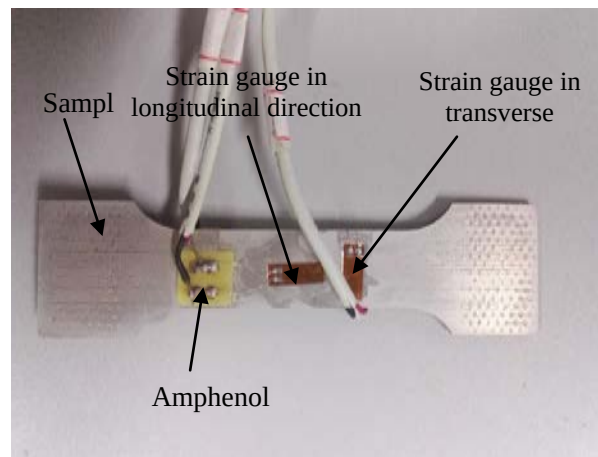


Figure 1. Proportion sample pasted with strain gauge

CMT5305 type electronic universal testing machine shown in Fig. 2 was use to carry on the tensile test. The sample was clamped on tensile tester and stretched at a speed of 0.5 mm/min. The Poisson's ratio of the alloy was 0.327, tensile strength was 212.71MPa, and bending strength was 379.2MPa.



Figure 2. Tensile test

3. Measurement of Residual Stress

X-ray stress analyzer (Xstress 3000 type) manufactured by Stresstech Oy company, Finland, was used to measure residual stress for machined surface of the orthogonal milling experiments. As shown in Fig. 3, it mainly contained the portable host, the goniometer, linear imaging detectors, micro X-ray tube, collimator and other components. The main setting parameters were shown in Table 1.

Measurement results which were the averages of three points measured on each sample surface are listed in Table 2. Fig. 4 was an intuitive analysis chart of residual stress σ_x in the direction of X. It could be seen from the figure that the residual stress σ_x fluctuated greatly with the increase of cutting speed, feed rate and radial depth of cut, but the fluctuation was small with axial depth of cut. The residual stress decreased slightly at the axial depth of cut 4.5mm. However, the residual stress increased when axial depth of cut was bigger than 4.5 mm.

**Figure 3.** Xstress 3000 type X-ray stress analyzer**Table 1.** Main setting parameters of stress analyzer

Parameters	values	Parameters	values
Measure method	fixed Ψ and swing method	Material	MgCa0.8
Target material	CrKa	Elastic modulus/MPa	4.52×10^4
Start scanning angle/ $^\circ$	132	Poisson's ratio	0.327
End scanning angle/ $^\circ$	126	Exposure time/s	12
Scanning step/ $^\circ$	0.10	Diffraction angle / $^\circ$	145
X-ray pressure/kV	29.3	Current / mA	6.75

Table 2. Residual stress results

Experiment No.	$v_c / \text{m} \cdot \text{min}^{-1}$	$f_z / \text{mm} \cdot \text{z}^{-1}$	a_p / mm	a_e / mm	σ_x / MPa	σ_y / MPa
1	500	0.05	3	6	-19.70	-32.43
2	500	0.13	4.5	15	14.60	-94.30
3	500	0.21	6	9	19.13	-72.10
4	500	0.29	7.5	12	47.47	-21.20
5	650	0.05	4.5	12	27.47	-23.45
6	650	0.13	3	9	25.67	-60.73
7	650	0.21	7.5	15	22.97	22.97
8	650	0.29	6	6	75.97	-56.90
9	800	0.05	6	15	-42.07	-14.30
10	800	0.13	7.5	6	55.63	-111.37
11	800	0.21	3	12	16.40	-47.10
12	800	0.29	4.5	9	-20.80	-22.23
13	950	0.05	7.5	9	21.83	30.40
14	950	0.13	6	12	33.47	-50.00
15	950	0.21	4.5	6	17.93	71.60
16	950	0.29	3	15	37.17	66.97

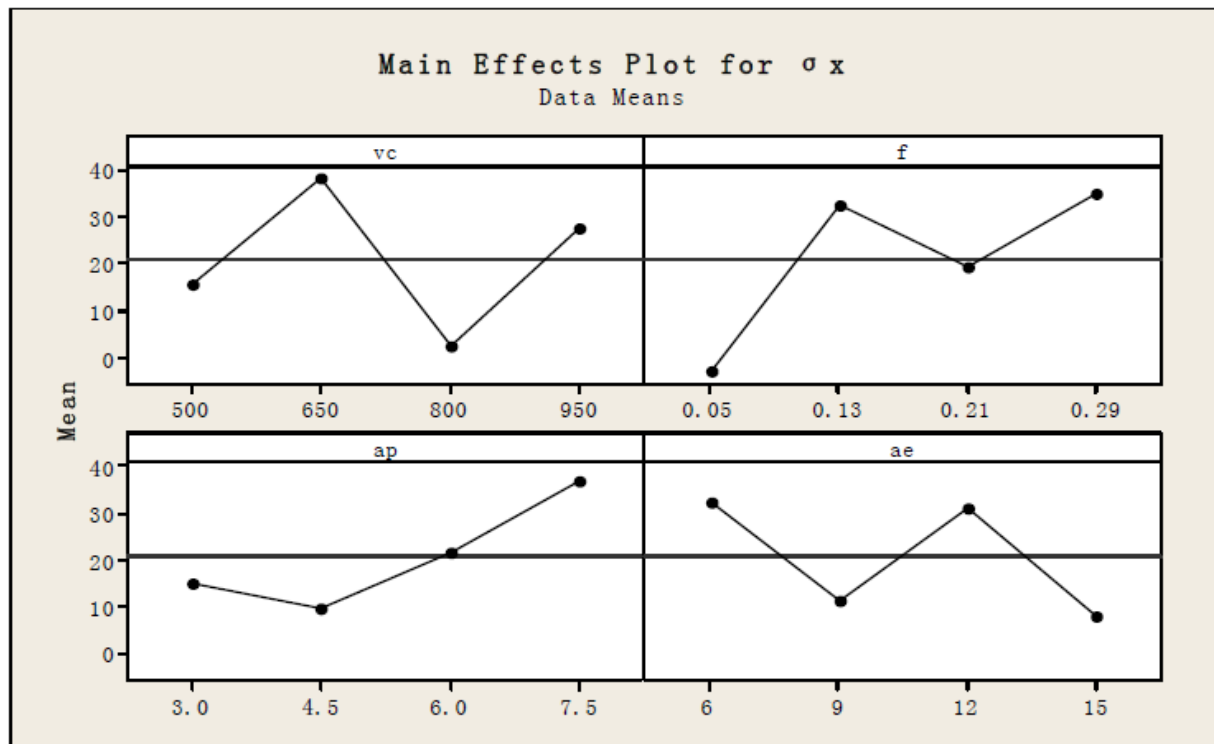


Figure 4. Intuitive analysis of the effect of cutting parameters on residual stress σ_x

4. Establishment of Residual Stress Predicting Model

Cutting parameters had important influence on residual stress, which could be expressed by a complex exponential relationship. A general model of orthogonal design could be established using mathematical statistical method.

$$\sigma = C_0 v_c^{b_1} f_z^{b_2} a_p^{b_3} a_e^{b_4} \quad (1)$$

Exponential predicting model of residual stress was established after logarithmic transform and least-square regression.

$$\sigma_x = 5.302 v_c^{0.219} f_z^{0.097} a_p^{0.549} a_e^{-0.205} \quad R^2 = 0.222 \quad (2)$$

$$\sigma_y = 289.166 v_c^{0.084} f_z^{0.280} a_p^{-0.337} a_e^{-0.602} \quad R^2 = 0.260 \quad (3)$$

However, the linear correlation coefficients R of the two exponential equations were smaller than the critical linear correlation coefficient of 0.821. Table 3 was significance test for exponential equations, from which it could be seen that the value of F was less than $F_{0.01}(4, 15) = 4.89$, meaning the equations was not significant enough. So the multivariate nonlinear regression equation was established for the residual stress data. The equation was as follows:

$$\begin{aligned} \sigma_x = & -122.459 + 0.081 v_c - 989.856 f_z + 0.045 a_p + 26.280 a_e - 0.359 v_c f_z \\ & + 0.023 v_c a_p + 227.492 f_z a_p + 17.452 f_z a_e - 4.983 a_p a_e \quad R^2 = 0.746 \end{aligned} \quad (4)$$

$$\begin{aligned} \sigma_x = & -271.970 + 0.766 v_c + 142.713 f_z + 56.956 a_p - 39.017 a_e + 0.425 v_c f_z \\ & - 0.128 v_c a_p - 188.941 f_z a_p + 36.980 f_z a_e + 6.583 a_p a_e \quad R^2 = 0.696 \end{aligned} \quad (5)$$

Table 3. Significance test of exponential equations

	Source	SS	df	MS	F	Sig.
σ_x	Regression	0.755	4	0.189	0.785	0.558
	Residual	2.642	11	0.240		
	Total	3.396	15			
σ_y	Regression	1.453	4	0.363	0.968	0.463
	Residual	4.125	11	0.375		
	Total	5.578	15			

Table 4. Significance test of multivariate nonlinear regression equations

	Source	SS	df	MS	F	Sig.
σ_x	Regression	9584.736	10	958.474	1.466	0.353
	Residual	3269.490	5	653.898		
	Total	12854.226	15			
σ_y	Regression	28702.687	10	2870.269	1.146	0.468
	Residual	12526.363	5	2505.273		
	Total	41229.050	15			

The significance results of the multivariate nonlinear equations are shown in Table 4, from which it could be seen that the linear correlation coefficients R and F of the multivariate nonlinear equation had some increase compared with the exponential model. It means the multivariate nonlinear equation was more suitable for the residual stress prediction. But the values F and R were still below the critical values, indicating that the nonlinear equation was inadequate in the prediction of residual stress.

5. Summary

The residual stress model of the milling surface was established and tested in this paper, the conclusions are as follows:

(1) Mathematical model of the relationship between residual stress and cutting speed, feed rate, axial and radial depth of cut was established using orthogonal regression analysis theory on the basis of finished surface residual stress results obtained in the orthogonal milling experiments.

(2) It could be seen that the correlation coefficients R and F were smaller than the critical values in significance test results of the exponential equations, indicating that the exponential prediction model was not significant. Then multivariate nonlinear regression equations were established for supplement, whose linear correlation coefficients had some increase but were still smaller than the critical values. So, more perfect prediction model was needed to predict residual stress.

(3) Workpiece material, tool geometry and material also had influence on residual stress except cutting parameters cutting speed, feed rate, axial depth of cut and radial depth of cut. But whether the exponential model or multiple nonlinear regression equations did not take into account factors other than cutting parameters, which lead to not enough significance of models.

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