

Study on the surface constitute properties of high-speed end milling aluminum alloy

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Abstract. The physical and mechanical properties of the metal surface will change after the metal cutting processing. The comprehensive study of the influence of machining parameters on surface constitute properties are necessary. A high-speed milling experiment by means of orthogonal method with four factors was conducted for aluminum alloy 7050-T7451. The surface constitutive properties of the Al-Alloy surface were measured using SSM-B4000TM stress-strain microprobe system. Based on all the load-depth curves obtained, the characteristics parameters such as strain hardening exponent n and yield strength σ_y of the milling surface are calculated. The effect of cutting speed, feed rate, and width and depth of cut on n and σ_y was investigated using the ANOVA techniques. The affecting degree of milling parameters on n and σ_y was $v > f_z > a_p > a_e$. The influence of milling parameters on n and σ_y was described and discussed.

1. Introduction

7050-T7451 aluminium alloy has been widely used in aircraft structures due to their perfect strength, fracture toughness, and high stress/density ratio after supersaturated solid solution and prestretching treatment [1, 2]. High-speed milling is one of the most common processes to produce structural parts out of aluminum alloy in the aerospace industry. Under the effect of cutting force, cutting heat and so on, the physical and mechanical properties of metal changed greatly, which was different from the matrix material [3, 4]. The stress-strain state can significantly influence the fatigue strength, creep, and stress-corrosion-cracking resistance of metals. Surface rolling for aeronautical monolithic component distortion correction was a new kind theory and process method [5]. To establish the surface rolling correction analysis model, accurate milling surface constitutive properties and the influence of milling parameters on them were pre-requisite.

Material constitutive model reflects the physical and mechanics behavior, which described the relationship between material flow stress, strain, strain rate and temperature, etc. Many scholars have studied the constitutive relation of 7050 aluminum alloy materials. Wu etc. [6] studied the flow stress and strain characteristics of 7050 aluminum alloy within the scope of the strain rate of 0.01-20s⁻¹ and temperature of 593-743K. In the study, constitutive equations were obtained by isothermal compression experiment and the dynamic analysis, which can be used to predict the stress-strain relationship of higher temperature. Yongzhi, H etc. investigated the strain rate enhancement parameters and thermal softening parameters at room temperature (400-2500 s⁻¹) and strain rate of 2500 s⁻¹ under different temperature by split hopkinson pressure bar (SHPB) experiments [7, 8]. The modified Johnson-Cook constitutive relation model of 7050-T7451 aluminum alloy was established.



The above research can study the constitutive relationship of the basis material at different temperature and strain rate, which reflect the mechanical behavior of the whole materials.

The physical and mechanical properties of aluminum alloy surface will change along the depth direction after the metal cutting processing, and the impact depth was about 0.1mm [9]. It is very critical to predict surface constitutive properties in a high-speed milled aluminium alloy, and a comprehensive study of the influence of machining conditions on surface strain hardening exponent n and yield strength σ_y is necessary. Indentation experiment is one of the effective methods to obtain the metal surface properties, which is a non-destructive testing technology[10,11]. In this article, orthogonal milling test of 7050-T7451 alloy were set up firstly. B4000TM stress-strain microprobe system was used to obtain the load-depth data of aluminum alloy, and the stress strain relations of the milled surface were calculated based on the load-depth data. The mathematical model for milling surface constitutive model was established and the effect of machining parameters on constitutive model was discussed.

2. Experimental setup and procedure

2.1. Work material

The 7050-T7451 aluminum alloy block used in this experiment was manufactured by Kaiser Aluminum and Chemical Corp., USA. The mechanical properties of the material are given in Table 1.

Table 1. Material properties of aluminum alloy 7050-T7451

Density (g/cm ³)	Tensile Strength, Ultimate (MPa)	Tensile Strength, Yield (MPa)	Modulus of Elasticity (GPa)	Poisson Ratio
2.83	524	469	71.7	0.33

2.2. Milling experimental design

Experiments based on orthogonal methods were performed to reduce variations in the output response. Factorial design was applied with 4 factors and 4 levels (44 designs), factors consist of cutting speed (v), feed rate (f_z), width of cut (a_p), and depth of cut (a_e). The details are shown in Table 2. Values of cutting speed above 300m/min were chosen so that it falls in the range of high-speed machining.

Table 2. Orthogonal experiment parameters

level	v (m/min)	f_z (mm)	a_p (mm)	a_e (mm)
1	314	0.06	3	6
2	502	0.1	4	8
3	628	0.14	5	10
4	942	0.18	6	12

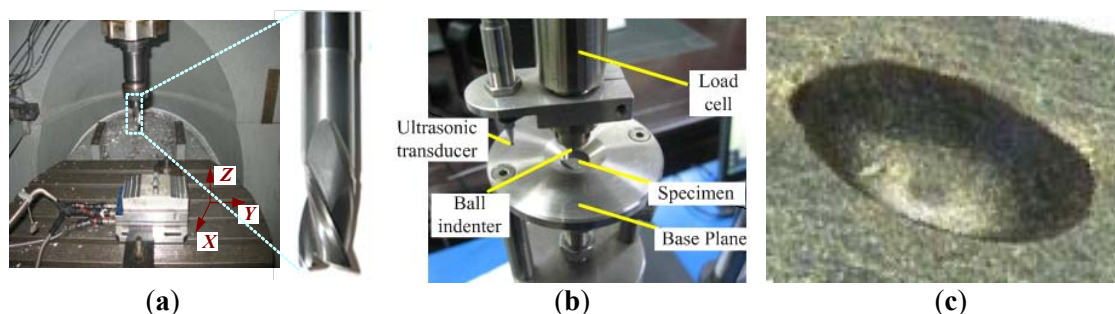


Figure 1. The experiment setup: (a) milling experiment; (b) Indentation experiment; (c) Indentation appearance.

Milling test was performed on a DECKEL MAHO DMU 70V 5-axis universal machining center, and the tool was end mill without coating. Number of teeth was 3; the rake angle was 14°; the relief angle was 12°; the corner radius was 1mm. The experiment setup is shown in Figure 1(a).

2.3. Indentation experiment

B4000TM stress-strain microprobe system was used to obtain the load-depth data of aluminum alloy. Indentation experiment test was conducted at room temperature (18.3°C). The test process contains multiple loading and unloading phase, the test system is shown in Figure 1(b). Spherical indenters made of tungsten carbide were used with diameters 0.45mm. Seven kinds of loading and unloading stages were set up to obtain load-depth curve data respectively. Indenting velocity of ball indenter speed was set at 0.005334 mm/s for a quasi-static state.

Large field depth microscope VHX-600E was used to observe indentation morphology, as shown in Figure 1(c).

3. Surface constitutive model construction

Plastic flow of materials is generally represented by the equation[12]:

$$\sigma_t = K \varepsilon_p^n \quad (1)$$

Where σ_t is the true stress, ε_p is the true plastic strain, n is the strain hardening exponent and K is the strength coefficient.

A computer program is used to solve the following equations to determine the true stress and true strain values. From the plastic depth h_p , the plastic diameter d_p is calculated by iterating the following equation,

$$d_p = \left\{ \frac{2.753P \times D(1/E_{spec} + 1/E_{ind})(4h_p^2 + d_p^2)}{4h_p^2 + d_p^2 - 4h_p D} \right\}^{1/3} \quad (2)$$

Where P is the measured load, D is the indenter diameter, E_{spec} and E_{ind} are the elastic modulus of the specimen and indenter (6.41×10^5 MPa), respectively. The true stress and plastic strain values are then calculated using the following equations,

$$\varepsilon_p = 0.2d_p/D \quad (3)$$

$$\sigma_t = 4P/\pi d_p^2 \delta \quad (4)$$

Where δ is a constant related to the constraint effect for plastic deformation. δ is calculated by iterating the following set of equations:

$$\delta = \begin{cases} 1.12 & \Phi \leq 1 \\ 1.12 + \tau \ln \Phi & 1 < \Phi \leq 27 \\ 2.87\alpha_m & \Phi > 27 \end{cases} \quad (5)$$

Where $\tau = (2.87\alpha_m - 1.12)/\ln(27)$, $\Phi = \varepsilon_p E_{spec} / 0.43\sigma_t$. The α_m parameter is material dependent and is held at a constant value of 1.0 for 7050-T7451 alloy [13].

Values of n and K are determined by regression analysis of the data fitted to equation (1). Data points from all loading cycles are fit by linear regression analysis to the following relationship:

$$P/d_t^2 = A(d_t/D)^{m-2} \quad (6)$$

Where d_t is the total indentation diameter, m is the Meyer's coefficient and A is a material parameter obtained from the regression analysis.

For each loading cycle, the total penetration depth (h_t) is measured while the load is applied and the depth is converted to a total indentation diameter (d_t) using the following equation:

$$d_t = 2(h_t D - h_t^2)^{1/2} \quad (7)$$

The yield strength (σ_y) is calculated from the expression:

$$\sigma_y = \beta_m A \quad (8)$$

Where β_m is a constant (0.219) for 7050-T7451 alloy[14].

4. Results and discussion

4.1. Regression equation and ANOVA significance testing

The profile of load-depth curve was obtained by B4000TM stress-strain microprobe system. The maximum indentation depth was 0.1mm. Figure 2 represents a typical load-depth curve obtained for a cutting speed of 628m/min, feed rate of 0.06mm/z, and depth of cut and width of cut were 5mm and 12mm. The yield strength analysis is carried out by taking into account simultaneous occurrence of yielding and strain hardening of the material under conditions of multiaxial compression. There were seven consecutive processes of work hardening of surface materials.

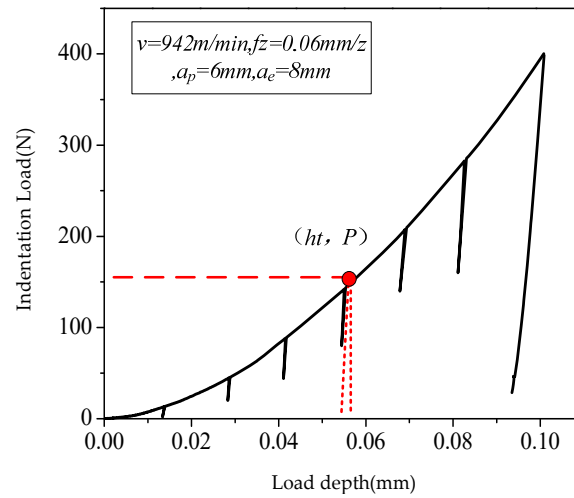


Figure 2. Typical load-depth curves

Table 3 shows the orthogonal experiment schemes and experiment results. It can be found that there is a complex relationship between cutting parameters and surface constitutive model in the milling process. Under the conditions of the present experiment, the yield strength of 7050-T7451 surface layer changed from 351MPa to 533MPa, and the strain hardening exponent changed from 1.12 to 1.67. It is important to put the relation between cutting parameters and surface constitutive model in a mathematical form by the obtained results. Therefore, a mathematical model between machining parameters and n , σ_y was as follows:

$$\begin{aligned} n &= C_1 v^{b_1} f_z^{b_2} a_p^{b_3} a_e^{b_4} \\ \sigma_y &= C_2 v^{b_5} f_z^{b_6} a_p^{b_7} a_e^{b_8} \end{aligned} \quad (9)$$

Where C is a coefficient factor depending on workpiece material, machine tool, and cutting condition; b_1 to b_8 are exponents of v , f_z , a_p , a_e , respectively. The empirical equations of surface strain hardening exponent n and yield strength σ_y could be achieved based on multiple linear regression analysis, as shown (10).

$$\begin{aligned} n &= 8.35 v^{-0.221} f_z^{0.359} a_p^{0.112} a_e^{0.151} \\ \sigma_y &= 3870 v^{-0.307} f_z^{0.268} a_p^{0.141} a_e^{0.098} \end{aligned} \quad (10)$$

An analysis of variance (ANOVA) for surface constitutive models was shown in Table 4. The ANOVA results indicated that the most significant factor was cutting speed. The F value were 38.5 and 31.1 for n and σ_y at the level of 0.05. The affecting degree of the parameters was described as $v > f_z > a_p > a_e$ in order.

Table 3. Orthogonal experiment schemes and experiment results

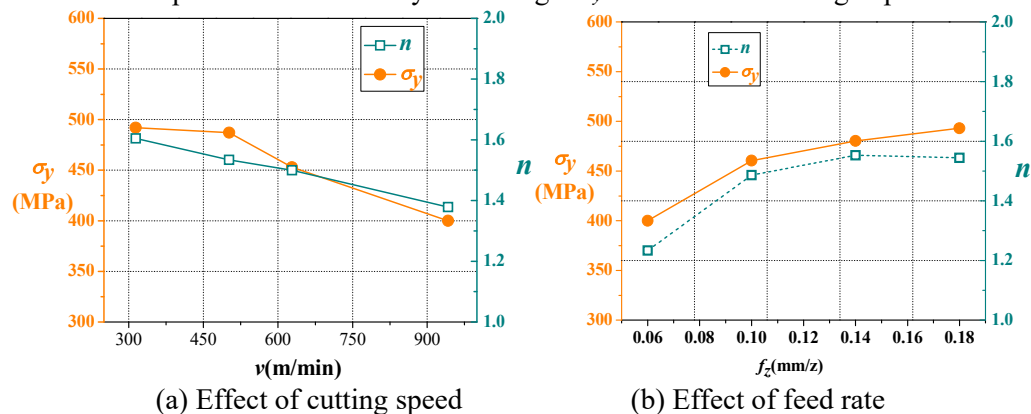
No	v (m/min)	f_z (mm)	a_p (mm)	a_e (mm)	σ_y (MPa)	n
1	942	0.06	6	8	351.25	1.12
2	942	0.1	5	6	381.63	1.26
3	942	0.14	4	12	433.21	1.54
4	942	0.18	3	10	437.08	1.59
5	628	0.06	5	12	403.47	1.27
6	628	0.1	6	10	466.29	1.52
7	628	0.14	3	8	452.74	1.53
8	628	0.18	4	6	490.29	1.66
9	502	0.06	4	10	411.36	1.27
10	502	0.1	3	12	461.15	1.52
11	502	0.14	6	6	519.86	1.67
12	502	0.18	5	8	517.50	1.67
13	314	0.06	3	6	433.89	1.26
14	314	0.1	4	8	533.00	1.63
15	314	0.14	5	10	515.27	1.46
16	314	0.18	6	12	487.48	1.25

Table 4: Significance testing of the machining parameters on n and σ_y

Factors	Sum of squares		DF	Mean of squares		F		Major-minor order of factors
	n	σ_y		n	σ_y	n	σ_y	
v	19.2	428.6	3	23.1	435.9	38.5	31.12	$v > f_z > a_p > a_e$
f_z	10.4	182.5	3	13.1	196.9	20.24	15.37	
a_p	2.89	56.4	3	2.8	63.5	6.39	7.72	
a_e	1.6	39.6	3	1.2	42.4	3.48	2.53	
Error	9.4	65.3	3	10.1	56.7			
Total	43.5	772.4	15					

4.2. Influence of the machining parameters on n and σ_y

Figure 3 shows the influence of machining parameters on the n and σ_y values by the range analysis taking into account the four parameters reported above. It is possible to describe how the n and σ_y are affected by the cutting parameters. The horizontal axis represents the cutting parameters, and the left and right vertical axis represents the surface yield strength σ_y and strain hardening exponent n .



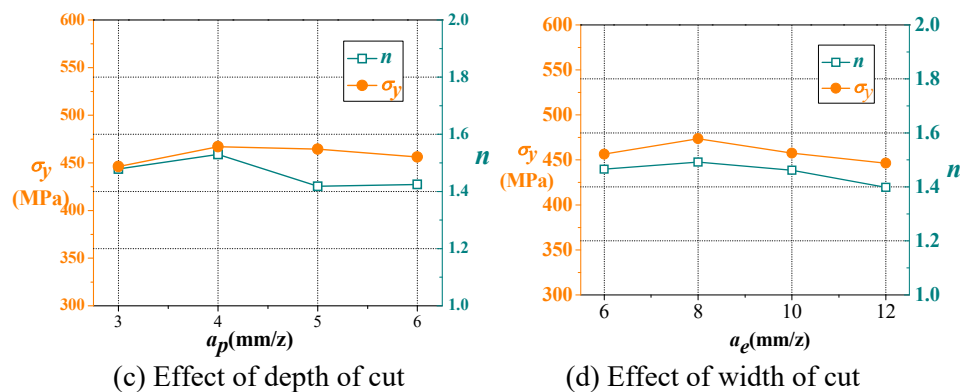


Figure 3. Range analysis of n and σ_y

Figure 3(a) shows that the increase of the cutting speed from $v=314\text{m/min}$ to $v=628\text{m/min}$ causes a consecutive reduction of the compressive residual stresses. The surface constitutive properties were associated with the previous milling plastic deformation. The observed effect may be explained by an understanding of the material strain rate of cutting that determines the nature of plastic deformation in the machining. At the lowest cutting speed of 314m/min , the chips stay in the machining zone for a relatively longer duration and less heat dissipates into the machined surface, which leads to increase of σ_y and n on the machined surface.

As seen in Figure 3(b), an increase of the feed rate f_z from 0.06mm/tooth to 0.1mm/tooth leads to a pronounced effect on the surface constitutive properties. But, further increase in the feed rate to 0.18mm/tooth shows a less pronounced increase of σ_y and n . The increased cutting force and more plastic deformation were generated with the increasing of the feed rate.

Figure 3(c) shows that a slight change of σ_y and n was observed when the depth of cut increased from 3mm to 6mm . Further, the chart of Figure 3(d) shows that the width of cut does not present an obvious influence on the surface constitutive properties. A variation of the cutting depth and width causes a direct proportional increase of the forces. At the same time, cutting temperature increases with more cutting heat. It is envisaged that the effect of cutting force goes hand-in-hand with the cutting temperature change, which offsets the influence on the 7050-T7451 alloy milling surface plastic deformation.

5. Conclusions

The influence of machining parameters on the surface constitutive properties of 7050-T7451 aluminum alloy was investigated by orthogonal cutting and indentation experiment. The important conclusion drawn from the present research was summarized as follows.

(1) Plastic deformation caused by milling will change the surface constitutive properties of 7050-T7451 alloy. Under the conditions of the present experiment, the yield strength of 7050-T7451 surface layer changed from 351MPa to 533MPa , and the strain hardening exponent changed from 1.12 to 1.67 .

(2) The surface stresses could be predicted effectively by applying cutting speed, feed rate, depth of cut, width of cut, and their interactions in multiple regression exponent models. Their affecting degree diminishes in order, described as $v > f_z > a_p > a_e$ based on the ANOVA analysis of orthogonal experiment.

(3) It has been shown that the decrease of the cutting speed and the increase of the feed rate lead to significant increase of the yield strength and strain hardening exponent on 7050-T7451 finished surface.

Acknowledgments

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