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Study on Surface Roughness in Micro Milling of Single Crystal Materials

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Abstract:
Micro milling is a machining method of high precision and efficiency for micro components and features. In order to study the surface quality of single crystal materials in micro milling, the two-edged cemented carbide tool milling cutter with 0.4 mm diameter was used, and the orthogonal experiment was completed on the micro-milling of single crystal aluminum material. Through the analysis of statistical results, the primary and secondary factor which impacting on surface quality were found as follows: spindle speed, feed rate, milling depth. The ideal combination of optimized process parameters were obtained, when the spindle speed was 36000 r/min, the milling depth was 10 μm, the feed rate was 80 μm/s, which made the milling surface roughness is 0.782 μm and minimal. Single crystal materials removal mechanism were revealed, and the influence of cutting parameters on micro-milling surface were discussed, the reason of tool wear was analyzed. Those provide a certain theoretical and experimental basis for micro milling of single crystal materials.

Keywords: *Surface roughness; Micro milling; Single crystal materials; Orthogonal experiment*

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1. Introduction

Micro milling refers to the cutting technology of precision machining of micro parts with micro milling cutters. The diameter in micro milling cutter is usually less than 1 mm [1].The size of cutter and workpiece are not reduce by macro-size in the process of micro micro-cutting, the cutting edge radius and the cutting depth are in the same order of magnitude. The cutting edge radius of the tool has obvious influence on the minimum cutting thickness, size effect and chip formation. The radius of cutting tool edge has obvious influence on the minimum cutting thickness and chip formation, and the conventional cutting mechanism is no longer applicable in the micro machining [2-4]. Through a lot of test to prove that: The micro-milling mechanism is very different from the traditional milling mechanism in cutting conditions, system stiffness, cutting parameters and so on [5-7]. In order to ensure the surface quality and accuracy of the parts, it is necessary to adopt appropriate milling methods, cutting parameters and machining conditions.

Scholars at home and abroad have studied the micro milling of single crystal silicon, copper and polycrystalline alloys. Sato et al. [8] put forward the scale effect in the micro cutting experiment of aluminum alloy. Lucca et al. [9] found the phenomenon of ploughing and scratching in the small cut depth experiment. Damazo [10] and Schaller [11] put forward the ways to solve the burr in the micro cutting test of copper, stainless steel and cast iron. But it's rarely reported both at home and abroad for micro milling of the single crystal aluminum. Tool geometric parameters, tool wear and tool vibration are many factors that will have an impact on the surface quality and the machining system. In this paper, the micro milling process of single crystal aluminum was studied by means of orthogonal experiment, the reasonable micro milling process was optimized through range and variance analysis, and the mechanism of micro milling and the reasons affecting surface roughness are analyzed.

2. Experiment on micro milling of single crystal aluminum

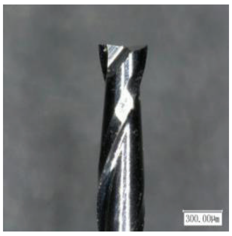
2.1 Experimental condition

As shown in Figure 1(a), The micro milling experiment was carried out on the JX-1 platform, which is equipped with NSK pneumatic spindle, and its working stroke of X axis is 490 mm, Y axis is 490 mm and Z axis is 120 mm respectively. The maximum spindle speed is 60000 r/min, and the radial and axial runout degree of the spindle is less than 0.1 μm and the repeat positioning accuracy is ±0.2 μm; As shown in Figure 1(b), VHX-1000E microscope is used to observe the surface morphology; As shown in Figure 1(c), The surface roughness of the microgroove bottom was measured by STIL laser 3D profile instrument, the measuring accuracy is 0.001 μm, and the measuring range is 0.02-20 μm; As shown in Figure 1(d), the cutter was M.A.FORD uncoated cemented carbide spiral cutter, the cutter diameter is 0.4 mm, the handle diameter is 3 mm, the length of cutter blade is 1.2 mm, and the cutter length is 38 mm.

(a) JX-1 Machine platform

(b) VHX-1000E Microscope

(c) STIL Profilomete



(d) Micro Milling Cutter

Figure 1 Micro milling experimental equipment and cutter

2.2 Experimental scheme

In this experiment, three factors and five levels of orthogonal test are used, namely $L_{25}(5^3)$. Factors set are mainly these cutting parameters which have main effect on cutting quality, namely, the three factors are the spindle speed n, the axial milling depth a_p and the feed rate v. Because the blade diameter of the micro milling cutter is very small, and the maximum speed of machine is 60000 r/min, in order to obtain higher surface accuracy, so the spindle speed was selected in the 12000-48000 r/min equally, that is the spindle speed must be increased; Smaller cutter blade diameter can be easily machined damage, considering the influence of vibration and the minimum cutting thickness, the cutting parameter set strive to smaller, and the milling depth uniform distributed between 5-15 μm, and the feed rate uniform distributed between 20-100 μm /s.

3. Experimental results and analysis

3.1 Experimental data

According to the factors and levels of the orthogonal experiment, the orthogonal experimental table and the corresponding roughness value were established by the micro milling experiment of single crystal aluminum, as shown in table 1.

3.2 Range and Variance analysis

According to the data in table 1, calculating the range R and variance V, the results of data processing were shown in table 2.

The range and variance chart of the surface roughness of single crystal aluminum under three kinds of cutting parameters were shown in Figure 2 We can see from the chart, the spindle speed range was the biggest, the feed rate secondly, and the milling depth is the minimum, thus what can be concluded is that the primary and secondary order was spindle speed> feed rate >milling depth that influenced surface roughness. The optimized combination of process is: when the spindle speed is 36000 r/min, the milling depth is 10 μm, and the feed rate is 80 μm/s, the minimum surface roughness and the best surface quality can be got. The scheme was repeated three times, and the surface roughness value is 0.782μm. By comparing the results, the scheme was the optimal and optimization, and the least roughness.

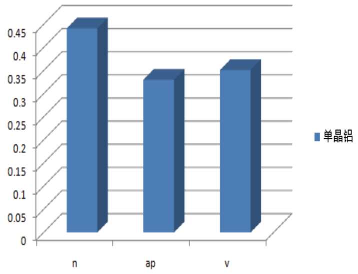
Table 1 Experimental data of the single crystal Al

Experimental Number	n (r/min)	a_p (μm)	v (μm /s)	R_a (μm)
1	12000	5	20	1.03
2	12000	8	40	0.992
3	12000	10	60	0.955
4	12000	12	80	0.962
5	12000	15	100	1.13
6	24000	5	40	1.02
7	24000	8	60	0.954
8	24000	10	80	0.998
9	24000	12	100	0.994
10	24000	15	20	0.946
11	36000	5	60	0.949
12	36000	8	80	0.880
13	36000	10	100	0.800
14	36000	12	20	0.929
15	36000	15	40	1.07
16	42000	5	80	0.863
17	42000	8	100	0.986
18	42000	10	20	1.03
19	42000	12	40	1.05
20	42000	15	60	0.889
21	48000	5	100	0.980
22	48000	8	20	1.01
23	48000	10	40	0.942
24	48000	12	60	1.04
25	48000	15	80	1.02

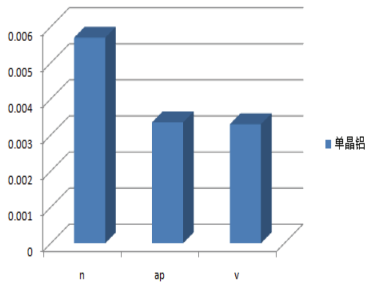
Table 2 Calculated Results of Single Crystal Aluminum Surface Roughness

Processing Number	n	a_p	v
K_{1j}	5.069 (1.014)	4.842 (0.968)	4.945 (0.989)
K_{2j}	4.912 (0.982)	4.822 (0.964)	5.074 (1.015)
K_{3j}	4.628 (0.926)	4.725 (0.945)	4.787 (0.957)
K_{4j}	4.878 (0.964)	4.975 (0.995)	4.723 (0.945)
K_{5j}	4.992 (0.998)	5.055 (1.011)	4.890 (0.978)
K_{1j}^2	25.695	23.445	24.453
K_{2j}^2	24.128	23.252	25.745
K_{3j}^2	21.418	22.326	22.915
K_{4j}^2	23.213	24.751	22.301

Processing Number	n	a_p	v
K_{5j}^2	24.920	25.553	23.912
R	0.441	0.330	0.351
T		24.419	
CT		23.852	
SS	0.0228	0.0134	0.0132
V	0.00570	0.00335	0.00330



(a) Range chart



(b) Variance chart

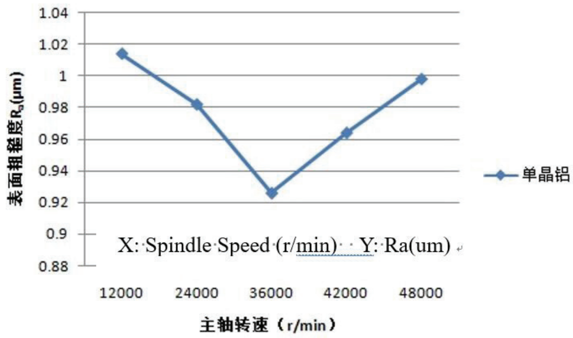
Figure 2 Range and variance chart of the influence of each factor on surface roughness

3.3 The influence of process parameters on the surface roughness

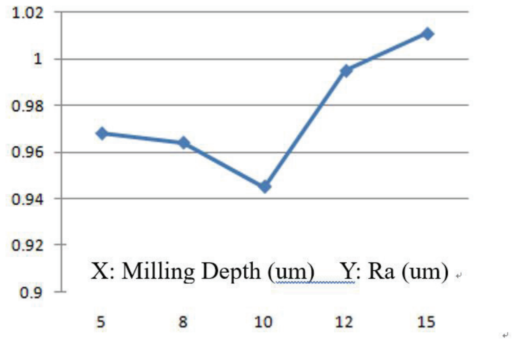
In order to study the influences of various factors on the single crystal aluminum surface roughness, averaged the summation of the data corresponding to each level of each column, as shown in table 2, the broken line graph of the three factors such as spindle speed, milling depth and feed rate that effects on surface roughness were drawn, as shown in Figure 3.

(1) The effect of spindle speed on Ra

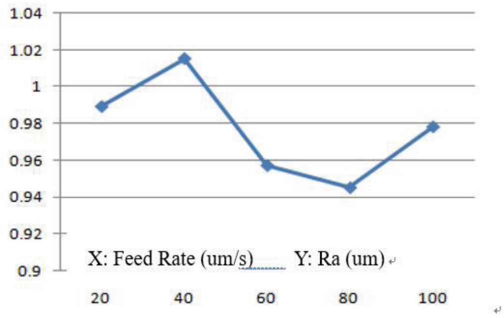
As shown in Figure 3 (a), the surface roughness of micro milling groove was first decreased and then increased with the increase of spindle speed, the turning point was 36000 r/min. When the spindle speed is less than 36000 r/min, the effective friction between the chip and the front tool surface decreases with the increase of the spindle speed, thus the chip deformation time was shortened, and chip was cut from the workpiece instantly. Most cutting heat was taken away by the chip. Small friction reduced cutting force and the possibility of producing tumor, and improved the processing precision of single crystal material. When the spindle speed was greater than 36000 r/min, Due to the lack of rigidity of the system, the spindle produces certain vibration that made the cutter wear with the spindle speed continues to increase. The cutting heat cannot be taken away in time, so that the surface quality would become worse.



(a) Influence of Spindle Speed on Ra



(b) Influence of Milling Depth on Ra



(c) Influence of Feed Rate on Ra

Figure 3 Influence of each factor on surface roughness

(2) The effect of milling depth on Ra

As shown in Figure 3 (b), the surface roughness of micro milling groove decreased first and then increased with the increase of milling depth, and the turning point is 10 μm, the roughness is the minimum. When the milling depth was lesser, the milling process was not easy to produce cutting, the cutter produced squeeze and slippage, and thereby the surface roughness was degraded. When the milling depth was greater than 10 μm, the amplitude of the cutting force increased with the increase of the milling depth, which resulting in deformation and cutting vibration of workpiece and tool, and causing a significant increase in surface roughness.

(3) The effect of feed rate on Ra

As shown in Figure 3(c), the surface roughness of micro milling groove increased first and then decreased and then increased with the increase of feed rate. Due to the exist of minimum chip thickness, when the feed rate is less than 40 μm/s, the feed per tooth is less than the minimum cutting thickness, and the milled surface was mainly caused extrusion and ploughing, and thereby the milling force was increased and surface roughness was became bigger. When the feed per tooth is greater than the minimum cutting thickness, the surface roughness decreases at first and then increases. When the feed is greater than 80 μm/s, increasing the feed rate can improve the machining efficiency, increase the residual area height, and directly lead to the increase of surface roughness.

4. Micro Milling Cutter Wear

Single crystal aluminum belongs to the plastic removal material. Through 25 groups of micro milling experiments and observed by superfield depth microscope, the micro-milling blade used in the experiment has a certain amount of wear and tear, by the observation of microscope with super field depth, as shown in Figure 4, the cutting edge radius was 0.97 μm before processing, and the cutting edge radius was 2.65 μm after wearing. It can be seen that the wear of cutter nose and grooves in the cut deep direction were the main forms of failure. In the micro milling process, a lot of heat and shear stress were generated in the deformation zone, and the cutter was easy to cause failure because of the adhesive softening, blade deformation and hot tearing. In milling process, with the increase of cutter wear, the cutter edge radius would increase sharply, and the milling force and the friction coefficient increases, and the machine trembled, thus degrading the surface roughness. Therefore, in the milling of difficult machining materials, cutting tools should be replaced in time to reduce the influence of tool wear on workpiece quality.

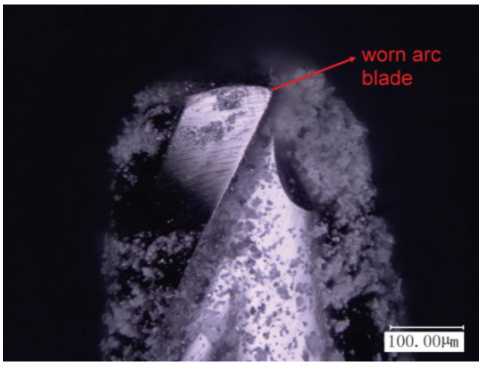


Figure 4 Worn Cutter

5. Conclusions

(1) The cemented carbide micro milling cutter with 0.4mm diameter was used for the micro milling of the single crystal aluminum by three factors and five levels orthogonal experiment. The primary and secondary factors that affect the processing surface roughness were as follows: spindle speed, feed rate, milling depth.

(2) Through the range and variance analysis and the optimized process scheme, when the spindle speed was 36000 r/min, the milling depth was 10 μm, the feed rate was 80 μm/s, the minimum surface roughness can be obtained and its value is 0.782 μm.

(3) Because of the low stiffness of the micro milling cutter, the worn cutter had a certain effect on the micro milling surface roughness. Under appropriate conditions, the cutters should be replaced to ensure the processing quality of parts.

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