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Study on tool wear for mircomilling of 6061 aluminium alloy

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Abstract. Tool wear is one of the key points of studies on micromilling, which affects tool durability and milling efficiency. In this paper, the two-flute cemented carbide end mills with coating TiAlN are used to conduct the experimental studies on the tool wear in micromilling process for 6061 aluminium alloy material. The wear form and wear mechanism of tools are analyzed. The influence sequence of key parameters on tool wear and the optimized parameters combination are obtained by the orthogonal experiment results analyses. The results show that when micromilling 6061 aluminium alloy, the main wear forms of the tools are coating peeling and tip breakage, and the wear mechanism is adhesive wear. The significance order of key milling parameters for the wear band width of the side edge from large to small is radial depth of cut a_e, feed per tooth f_z and axial depth of cut a_p. The optimized parameters combination which can obtain the minimize tool wear is a_e =300 μm, f_z =1 μm and a_p =150 μm. In actual machining, the tool life can be improved by selecting suitable processing parameters. The results of this study can be used as a reference for the selection of parameters in micromilling.

1. Introduction

With the continuous development of modern science and technology, micro-machining technology has broad application prospects in the fields of national defence industry, aerospace, biomedicine, microelectronics industry and so on[1]. As a kind of micro-machining technology, micromilling has been widely concerned and studied. Compared with the traditional machining method, the micro-machining is more complicated. Tool wear and tool life, machining of small parts, surface quality and so on are the research focus of micromilling technology [2]. Tool wear directly affects the machining quality, cost and processing efficiency of cutting. Wear resistance is one of the most basic and important indicators for measuring the cutting performance of tool materials [3]. Hence, it has great significance to conduct research on tool wear.

   Domestic and foreign scholars have conducted a large amount of researches on tool wear in micromilling. Chen [4] et al has studied the tool wear of diamond tools with radius of 1mm when cutting CaF_2 single crystals. The research findings show that the tool damage models in ultra-precision cutting of CaF2 crystals are grooving damage and notch breakage. The development of the tool damage followed with cutting distance is that the tool damage is extended from the grooving damage in flank face to notch breakage in rake face, and the cutting mode is also changed from the ductile mode cutting to brittle mode cutting. Yang [5] et al has milled lead brass by a TiAlN coated milling cutters with diameter of 0.5mm. The conclusion is that the main failure and wear area of the tool in the micro-machining occurs in the tool tip part. The wear forms include coating peeling and tip breakage. The wear mechanisms include adhesive wear and abrasive wear, and the diffusion wear phenomenon is not obvious. Rahman [6] et al has performed milling experiments on pure copper using end mills

with diameter of 1 mm. A quadratic model of tool life during pure copper micromilling was established by using the response surface method in statistics. It is found that the cutting speed and the amount of back-feeding knife have a significant influence on the tool life, while the influence of the feed rate is not significant. Zhao [7] et al has studied the wear mechanism of the coated and uncoated micro-diameter milling cutters and the mechanical properties during the cutting process. The results show that the coating peeling, diffusion wear and tip breakage are the main wear forms. He [8] has milled stainless steel through cemented carbide end mills and has analyzed the tool mechanism. The main wear forms are abrasive wear, adhesive wear and diffusion wear. The damage forms of the tool are the chipping of the tool tip and the overall fracture. S. De Cristofaro [9] et al has studied the tool wear progression in seven different coatings during micromilling of hardened steel at high-speed under dry cutting conditions. The forms and wear levels of different tool wear are monitored and analyzed. W.Y.Bao [10-11] et al have processed the NAK55 steel with micromilling tools. The cutting force characteristics of micro-end-milling operations with tool run-out were investigated. Then an analytical cutting force model was established and the reliability of the model was confirmed by experiments. The results show that the cutting force can be used to monitor the wear state of the tool and predict the remaining tool life through a reasonable algorithm.

Scholars have done a lot of researches on tool wear in micromilling process for different workpiece materials. Tool wear is mainly discussed based on the wear of the bottom edge of the micromilling cutter, and there is almost no research on the wear of the tool side edge. Therefore, aiming at the tool wear during the micro-machining of 6061 aluminium alloy material, the micromilling parameters experiments have been conducted in this paper. The wear forms and wear mechanisms of the tools are analyzed. Then, the wear band widths of the side edge of the micro-diameter tools are taken as the index, and the significance order of the key parameters and optimized parameters combination are obtained through the orthogonal experiments.

2. Experimental preparation

2.1. Experimental equipment
The used micromilling machine tool is a self-developed micromilling CNC machine tool that named 3A-S100 [12], as shown in Figure 1. The machine tool is mainly composed of four parts including spindle system, transmission system, control system and machine body. The three motion axes of the machine are driven by linear motors with motion resolution of 0.1 μm. Micromilling machine tool spindle speed is adjustable and the highest speed is 80,000 min^{-1}. Both of axial run out and radial run out are less than 1 μm.

The micro end tools used in experiments are coated cemented carbide double-edged end mill with the diameter of 1mm, as shown in Figure 2. The coating material is TiAlN. The rake angle is 15°, the edge clearance angle is 10°, and the cutting edge radius is 5 μm. The workpiece material is 6061 aluminium alloy, which has excellent processing performance and is widely used in aviation, precision machining, electronics and precision instruments, etc. The workpiece material samples are cuboids with 10mm in length, 10mm, in width and 30mm in height. The chemical constituents of the workpiece materials are shown in Table 1.

Table 1. Chemical composition of 6061aluminium alloy (wt%) .

Cu	Mn	Mg	Zn	Cr	Ti	Si	Fe	Al
0.15-0.4	0.15	0.8-1.2	0.25	0.04-0.35	0.15	0.4-0.8	0.7	96

Figure 1. Micromilling machine tool 3A-S100.
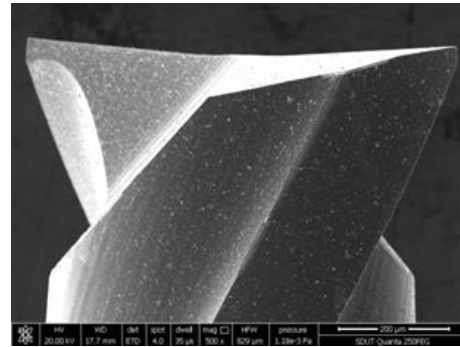
Figure 2. Tool topography.

Before the micromilling experiment, the workpiece is clamped by the fixture and levelled by dial indicator. Then the fixture is fixed on the worktable through attitude adjustment device. The fixture and the experiment process are shown in Figure 3. The good surface finish is pre-milled for each workpiece.
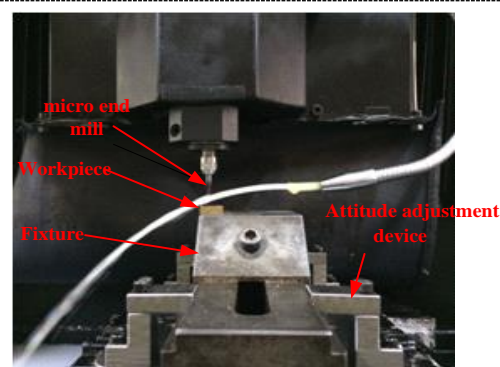
Figure 3. Experimental process.
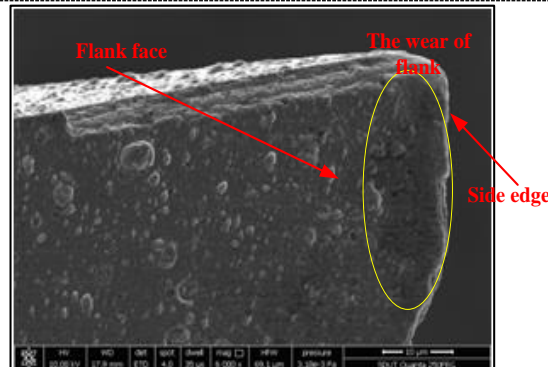
Figure 4. The flank of the side edge after milling.

2.2. Experimental design
In general, the cutting performance of micro end mill is poor in the low-speed cutting processing for machining workpiece, because the wear of the coating will be dominated by brittle fatigue coating peeling with high wear rate under low-speed cutting conditions [13]. The spindle speed of the experiments in this paper is 70,000 min^{-1}. The actual machining length of all experiments is 450 m, and millings are performed on the workpiece by means of a combination of down and up milling.

The experimental variables of the micromilling orthogonal experiments include radial depth of cut a_e, axial depth of cut a_p and feed per tooth f_z. The experiment index is the wear band width of the flank face of the tool side edge. The factor level selection of the orthogonal experiment is shown in Table 2. Regardless of the interaction between the factors, the L$_9$(3^4) orthogonal table is selected based on the number of factors and the number of levels. The orthogonal experiment design and its results are described below.

Table 2. The factor and levels selection.

Experiment level	a_e (μm)	a_p (μm)	f_z (μm/z)
1	100	100	1
2	200	150	2
3	300	200	3

3. Orthogonal experiment results and analysis

3.1. Result analyses

In general, the tool wear index is the wear band width of the bottom flank, and the flank wear band width of the side edge is studied in this paper, as shown in Figure 4. After experiments, the wear band widths at 8 different positions within a certain identical length range are measured for all experimental tools, and the average values are calculated and analyzed in following.

The orthogonal experiment design and results are shown in Table 3.

Table 3. Orthogonal experiment design and results.

| Experiment number	a_e (μm)	Blank column	a_p (μm)	f_z (μm)	Wear band width of Side edge (μm)
1	100	1	100	1	4.650
2	100	2	150	2	4.370
3	100	3	200	3	3.731
4	200	1	150	3	3.924
5	200	2	200	1	3.081
6	200	3	100	2	4.397
7	300	1	200	2	3.925
8	300	2	100	3	3.675
9	300	3	150	1	2.287
K_1	12.751	12.499	12.722	10.018	
K_2	11.402	11.126	10.581	12.692	
K_3	9.887	10.415	10.737	11.330	
k_1	4.250	4.1663	4.240	3.339	
k_2	3.800	3.7086	3.527	4.230	
k_3	3.295	3.4716	3.579	3.776	
R	0.954	0.6946	0.713	0.891	
Factors orders			a_e f_z a_p		
Optimal scheme			a_e=300 μm, a_p=150 μm, f_z=1 μm/z		

Where, K_i in the table indicates the sum of the experiment results corresponding to the horizontal number i (i=1, 2, 3, corresponding number as shown in the factor level table 3) in any column. k_i (k_i=K_i/3) is the arithmetic mean of the experiment results obtained when taking the level i of the factor level on any column. R is range, R=max{K_1,K_2,K_3}-min{K_1,K_2,K_3} or R=max{k_1,k_2,k_3}-min{k_1,k_2,k_3} in any column. The range calculation in table 3 uses the latter. The results of the indicator analyses are shown in table 3 where the blank column is used to verify whether the selected factors are the main influencing factors and whether there are interactions between the selected factors. The range R reflects the influence of factors on the index. According to the size of K_i or k_i under the same factor, the optimal parameter combination is determined.

The influence order of three factors for the wear band width from large to small is radial depth of cut, feed per tooth and axial depth of cut. The final optimization parameters are obtained from the width of the wear band. The smallest wear band width is the best, and the best parameters combination is a_e=300 μm, f_z=1 μm, a_p=150 μm.

3.2 Optimization verification experiment

The optimized parameter combination (a_e=300 μm, f_z=1 μm, a_p=150 μm) obtained in the orthogonal experiment is the same as the best group (Group 9) in the orthogonal experiments. In order to verify the accuracy of the orthogonal experiment, optimization verification experiment is conducted. The tool wear results in the verification experiment are shown in Figure 5. It can be seen intuitively from Figure 6 that after milling a distance of 450 m with optimized parameters, the wear band width of the flank face of the tool side edge is small and there are no tipping and large-area coating peeling off. The

wear width of the tool side edge is 2.294 µm, which has almost no different with the results of Group 9 in the orthogonal experiments. This result not only verifies the accuracy of the orthogonal experiment, but also shows that the tool wear can be effectively reduced by optimal parameters.
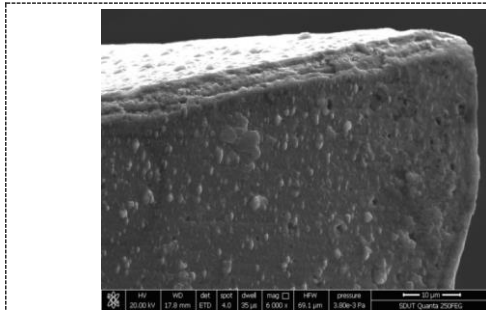
Figure 5. Rake wear under optimal parameters.
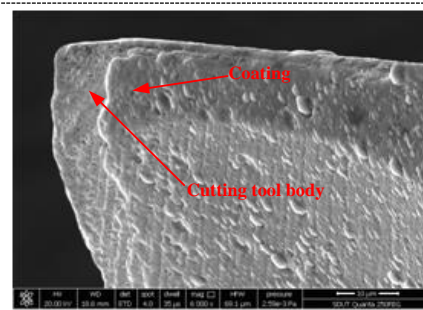
**Figure 6.** Wear characteristics of coating peeling.

## 4. Tool wear and mechanism analyses

4.1. Tool wear form
The tool wear forms in this paper are coating peeling and tip breakage.

4.1.1. Coating peeling. In the experiments, the coating peeling on the rake face, as shown in Figure 6. The thermal expansion coefficient of the coating material and the tool base are different [14].During high-speed milling, frequent temperature changes occur in the contact area between the tool and the workpiece due to mechanical and thermal stresses, plus adhesive wear occurs. Under these effects, the coating and the cutter body are loosened to separate them and the coating peeling phenomenon occurs. As the tool usage time and the number of cutting cycles increases, the coating peeling phenomenon becomes more and more obvious [15].

4.1.2. Tool tip breakage. The wear and tear in micromilling cutter mainly occurs near the tool tip. As shown in Figure 7, the corners of the tool tip are clearly rounded, and the tool nose radius is larger. As the cutting material increases, the wear of the tool increases, and the radius of the tool tip radius becomes larger. As shown in Figure 8, the tip of the tool is chipped showing a typical tip breakage. The possible reason may rely in that the tip of the tool is subjected to complex mechanical and thermal coupling loads. The pressure between the tip and the workpiece is large and the stress concentration is significant. At the same time, due to cyclic changes in cutting and air-cutting during milling, mechanical fatigue is applied to the tool tip. Therefore, the tool wear is accelerated and the probability of tip breakage is increased obviously [5].
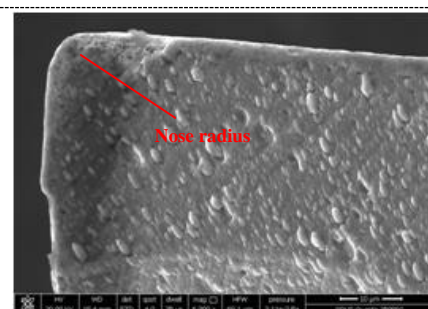
**Figure 7.** Photo of tool wear.
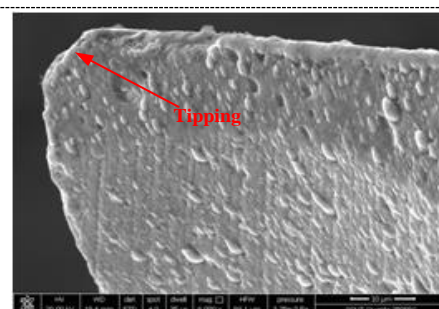
**Figure 8.** SEM morphology of breakage near edge nose.

4.2. Wear mechanism

The wear mechanism in this paper is adhesive wear. Adhesive wear is cold welding wear. Under the action of high temperature and high pressure, the material properties of the tool surface layer changes. When the workpiece and the tool move in opposite directions, the adhesive particles of the tool material are taken away and the adhesive wear is formed [16].

The energy spectrum analysis for spot 1 (Figure 9) is shown in Figure 10. Comparing the energy spectrum of the new tool before cutting (Figure 11), it is found that the spot 1 contains a large amount of Al element, and there are also the existence of Mg, Zn and Si. The larger amount of Al element existed in the spot 1 indicates that a amount of workpiece material is bonded to the tool and the adhesive phenomenon occurs. The presence of W and C indicates that the coating material is partially peeled off and the body material is exposed.
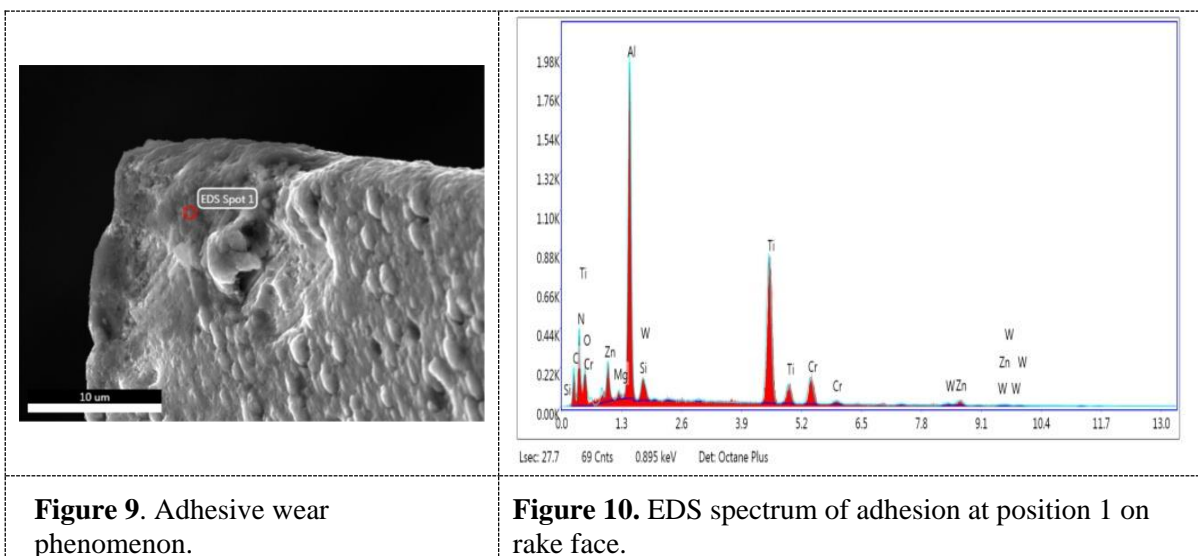
Figure 9. Adhesive wear phenomenon.

Figure 10. EDS spectrum of adhesion at position 1 on rake face.
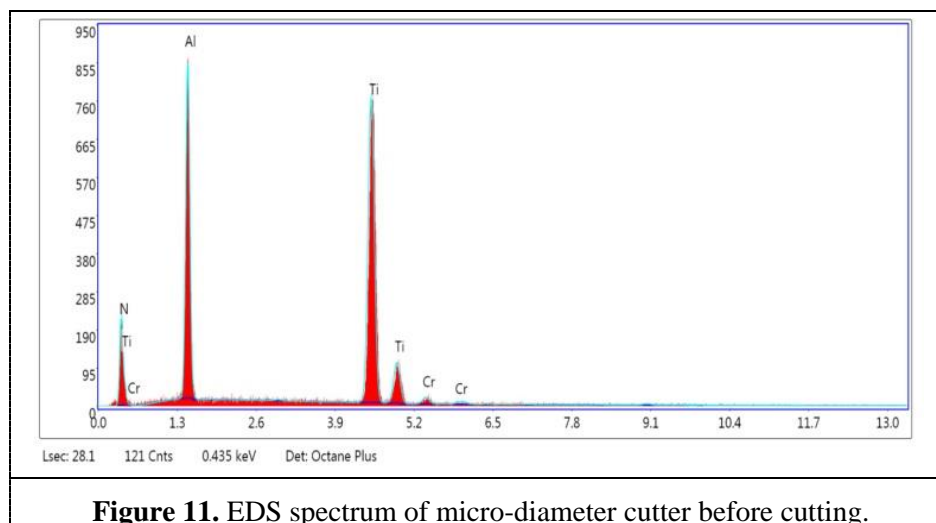
Figure 11. EDS spectrum of micro-diameter cutter before cutting.

5. Conclusions

In this paper, the parameter experiments are carried out concerning the tool wear during micromilling 6061 aluminium alloy material. The significance order of the key parameters and the optimal parameter combination are obtained. The wear form and wear mechanism of the tool during the micromilling 6061 aluminium alloy are also analyzed. The results of orthogonal optimization

experiments show that the significance order of key parameters for the wear band width is ae, fz and ap. The optimal parameter combination obtained is ae=300μm, fz=1μm, ap=150μm. When micromilling 6061 aluminium alloy material, the main wear forms are coating peeling and tool tip breakage, and the wear mechanism is adhesive abrasion. In this paper, the wear mechanism and optimization parameters are studied and the results can provide theoretical guidance and experimental basis to increase the durability of the tool, improve the milling efficiency and ensure the processing quality for actual machining.

Acknowledgement

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