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Investigation on the surface formation mechanism in micro milling of cemented carbide

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ABSTRACT

Cemented carbide is widely applied in optical glass molding process due to its excellent properties. The surface quality of cemented carbide mold is directly related with the glass element quality, mold life and production cost. In this paper, micro milling experiments were conducted on cemented carbide to investigate the surface formation mechanism. The surface morphology characteristics of different material removal modes were compared. Both the surface formation mechanism and damage behavior during micro milling process were analyzed in detail. The machining parameters selection strategy was suggested to obtain the high material removal rate and smooth surface quality. The surface quality was found to be less affected by the machining parameters when cemented carbide is removed with ductile mode than brittle mode.

1. Introduction

The compression molding technology is widely applied in producing of micro optical glass elements with low cost and high efficiency. Cemented carbide can provide many excellent properties such as high hardness, heat-resistance and wear resistance. It is generally used as mold material in optical glass molding industry to withstand the working environment of high temperature and high pressure [1–3]. Compared with conventional steel mold, cemented carbide presents great advantages both in mold life and product quality. To manufacture cemented carbide mold, various machining methods are used such as mechanical cutting process, electrical discharge machining and electrochemical machining [4–6]. Among these methods, micro cutting with super-hard diamond tool can manufacture miniature parts with complex three dimensional features at low cost, high efficiency and good surface quality [7].

Cemented carbide is very difficult to machine due to the bad surface quality and excessive tool wear. Many researches have been focused on ductile cutting cemented carbide to achieve the surface quality of optical mirror. Liu [8] reported that ductile cutting of cemented carbide is the result of large compressive stress and shear stress in the chip formation zone which can be attained by the small uncut chip thickness. Zhang [9] studied the effects of material properties, cutting parameters and the crystal orientation of diamond tool on the surface quality and tool life in ductile cutting of cemented carbide. Arif [10] developed the theoretical model to predict critical uncut chip thickness for ductile-brittle transition in milling of cemented carbide. Bulla [11] studied the effects of cutting parameters on the critical cutting depth in diamond turning of cemented carbide. Nath [12,13] analyzed the machinability of cemented carbide in ultrasonic elliptical vibration turning with PCD tool and then further investigated the effects of machining parameters and tool tip radius.

Nowadays, diamond turning has been widely studied in machining of cemented carbide. In the aspect of micro milling of cemented carbide, it also attracts more and more attention due to the great application potential. Suzuki [14] machined micro aspheric molds made of cemented carbide by micro milling with the developed SCD micro end mill. Cheng [15] performed the freeform surface milling on cemented carbide with PCD micro ball end mill that fabricated by wire electrical discharge machining. Nakamoto [16] studied the surface quality in micro milling of cemented carbide with PCD tool. The effects of machining parameters on the surface quality and tool wear in micro milling of cemented carbide also were investigated by Zhan [17]. However, these researches mainly are on the exploratory stage, and the essential mechanism researches still are few.

The surface quality of cemented carbide mold is directly related with the optical element quality, mold life and production cost. To achieve high surface quality, this paper presents an experimental investigation on the surface formation mechanism in micro milling of cemented carbide with PCD tool. First, the surface morphology

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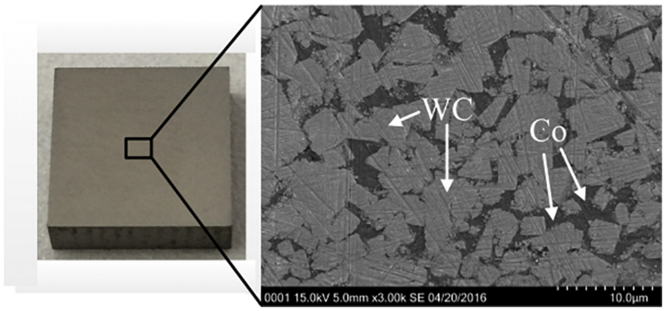

Fig. 1. The raw cemented carbide.

characteristics of different material removal modes were compared and analyzed. Then, both the surface formation and damage mechanisms were studied. The parameter optimization strategy to obtain ductile removal of cemented carbide in micro milling was suggested.

2. Experimental setup and procedure

The used workpiece material was WC-15Co cemented carbide which is composed of 85.0 wt% WC and 15.0 wt% Co. The material is generally used to manufacture optical glass mold that works in high temperature and high pressure environment. As hard and brittle material, it has very high hardness and very poor machinability. The surface morphology of raw cemented carbide is shown in Fig. 1. The WC phase contributes hardness and wear resistance to cemented carbide. The Co phase offers binding action and contributes material toughness. The average grain size of WC particles was measured to be about 4-6 μm. The material properties of raw cemented carbide are listed in Table 1.

Single flute PCD micro end mill which is pre-formed by WEDM and then further sharpened by grinding was used for the experiments, as shown in Fig. 2. The PCD material was produced by Element Six Group Company. The tool diameter was 0.7 mm. The tool tip radius was 8 μm. The bottom cutting edge presented inclination angle of 10°, rake angle of 0° and flank angle of 10°. The cutting edge radius was inspected to be about 3 μm.

The experiments were performed on the self-developed micro milling machine. The machine is specifically designed for micro milling of miniature parts. It can provide positional accuracy of ± 1 μm. The cemented carbide workpieces were polished before experiments to ensure flatness and then mounted on the machine worktable, as shown in Fig. 3. The stereo microscope was applied for tool setting and monitoring.

In the experiments, the spindle speed n was fixed, and different values were set for the cutting depth a_p and the feed per tooth f_z, as listed in Table 2. A set of grooves were milled with the specified machining parameters. The machined surface was cleaned by ultrasonic cleaning machine and the surface roughness was measured in the feed direction. The surface morphology was observed with scanning electron microscope.

Table 1
Cemented carbide properties.

Properties	Value
Density (g/cm^3)	13.9
Hardness (HV$_{10}$)	1607
Elastic modulus (GPa)	498
Fracture toughness (MPa·m$^{1/2}$)	9.1

3. Results and discussion

3.1. Surface morphology characteristics

In the traditional cutting mechanism, the cutting tool usually is assumed to be perfectly sharp. Actually the cutting tool has a circular arc both at the tool tip and cutting edge [18,19]. In micro milling, they have significant effect and can not be ignored due to the small machining parameters. As shown in Fig. 4a, the cutting depth a_p in micro milling usually is less than the tool tip radius γ_ε. Just small segment of cutting edge at the bottom of tool tip arc participates in cutting workpiece material. The geometric characteristics of cutting section are changed and different from traditional milling. The actual uncut chip thickness is no longer equal to the feed per tooth. It is gradually increasing from the bottom of tool tip arc and reaches the maximum value at the intersection point of cutting edge and workpiece surface. The maximum uncut chip thickness h_{max} can be calculated with the following formula:

$$h_{max} = \gamma_\varepsilon - \sqrt{\gamma_\varepsilon^2 + f_z^2 - 2f_z\sqrt{2\gamma_\varepsilon a_p - a_p^2}} \tag{1}$$

where γ_ε is the tool tip radius, f_z is the feed per tooth, a_p is the cutting depth. It is indicated that the maximum uncut chip thickness h_{max} is greatly related with both the milling parameters and tool geometry. In addition, the uncut chip thickness h_c in micro milling usually is less than the cutting edge radius γ_β, as shown in Fig. 4b. The nominal rake face is invalid. The cutting edge arc becomes the actual rake face. It leads to the effective rake angle is large negative [20].

Cemented carbide is hard and brittle material and generally removed with brittle fracture in traditional cutting. This may induce brittle cracks and pits on the machined surface and result in poor surface quality. However, it is found that brittle material also can be removed with plastic deformation to avoid brittle fracture defects when the uncut chip thickness is very small [21]. From the previous researches, the critical uncut chip thickness d_c of ductile cutting is calculated with the following formula:

$$d_c = u\left(\frac{E}{H}\right)\left(\frac{K_{IC}}{H}\right)^2 \tag{2}$$

where u is the material coefficient, H is the material hardness, E is the elastic modulus, K_{IC} is the fracture toughness. Based on the raw material properties in Table 1, the critical uncut chip thickness d_c of cemented carbide is 1.49 μm.

The surface morphology of different material removal modes is shown in Fig. 5. When the maximum uncut chip thickness is far larger than the critical value d_c, cemented carbide is removed with brittle fracture. It is seen that the machined surface is very rough and filled with micro cracks, pits and material fragments that induced by brittle fracture. These defects are the main reasons that cause the poor surface quality in cutting of cemented carbide. Since the maximum uncut chip thickness is lower than the critical value, cemented carbide is removed with plastic deformation. The cutting textures are fine and continuous. The machined surface is very smooth without brittle fracture defects.

Except the cutting textures, some micro burrs also are observed on the machined surface of ductile cutting. The enlarged view is shown in Fig. 6. These micro burrs are extruded to thin and flat. From the feed direction, they mainly are distributed on the backside of feed marks. The micro burrs are generated by material plastic side flow at the bottom cutting edge. It is also confirmed that cemented carbide material has occurred plastic deformation.

In micro milling, the cutting edge arc is the actual rake face. The cutting process is with large negative rake angle. The cutting edge arc severely extrudes workpiece material. When cemented carbide occur plastic deformation, the most material flow out along the rake face to form chips. But a small amount of material flow through the cutting edge arc to the flank face due to severe extrusion. Subsequently, they