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Experiments on micro-milling of cemented carbide with extremely sharp diamond micro mills

Yang Wu[1, 2*], Ni Chen[2], Shashwat Kushwaha[1, 3], Ning He[2], Jun Qian[1, 3], Dominiek Reynaerts[1, 3]

[1]*Department of Mechanical Engineering, KU Leuven, Heverlee 3001, Belgium*
[2]*College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, China*
[3]*Member Flanders Make, Belgium*

yang.wu@student.kuleuven.be

Abstract

Cemented carbide is extensively used in molding process of miniature components due to its excellent properties. It is difficult to obtain high-quality machined surface by micro-milling of cemented carbide, due to its high hardness and brittle property. The self-fabricated diamond micro mills with extremely sharp edges have been utilized to carry out the micro-milling experments on cemented carbide. The cutting force was measured and the roughness *R*a of the machined surface was detected. Based on the analyzing of impact of cutting parameters on peak-valley value of feed force and surface roughness *R*a, the feed rate of 0.06 µm/tooth which is the half of cutting edge radius was found to guarantee the occurrence of cutting and shearing instead of ploughing in this condition. Meanwhile the minimal peak-valley (P-V) value of feed force and roughness *R*a can be obtained using the feed rate of 0.06 µm/z in micro-milling of cemented carbide with the self-fabricated diamond micro mills.

Keywords: Cemented carbide, micro-milling, sharp diamond micro mills, size effect

1. Introduction

Micro mold technology is an important production method of numerous miniature components in civil fields. Cemented carbide has been widely applied as mold materials as it offers excellent desired properties such as high hardness, high temperature resistance, and corrosion resistance. More and more molds are made of cemented carbide instead of steel to fulfill the demands of long mold life and high product quality [1].

Micro-milling can produce miniature parts with three-dimensional features such as narrow grooves, microcavities, and aspheric surfaces [2]. Due to the high hardness of cemented carbide, only diamond micro mills can meet the requirements of machining cemented carbide. Suzuki [3] utilized the homemade single crystalline diamond (SCD) micro mills to fabricate the aspheric micro molds made of cemented carbide. Zhan [4] studied the impact of cutting parameters on the surface quality and tool wear in micro-milling of cemented carbide with polycrystalline diamond (PCD) micro mills. Wu [5] analyzed different material removal mechanisms and obtained ductile removal by parameter optimization in micro-milling of cemented carbide.

However, these researches are still on the exploratory stage, and the mechanism study is also limited due to the blunt cutting edge of dimond tools. In this paper, the self-fabricated extremely sharp diamond micro mills (edge radius of 0.12 µm) have been used to study the surface formation mechanism by changing feed per tooth at nanoscale for obtaining better surface quality in micro-milling of cemented carbide.

2. Experimental details

The micro end milling experiments were conducted on a 3-axis milling machine (MMP 2522, Kern, Germany) which is illustrated in Fig. 1(a). It is equipped with three linear axes of X, Y, Z and a high-speed spindle. The maximal rotation speed of the spindle is 40000 r/min and its runout is less than 1 µm. The self-fabricated PCD micro mill [6] with single tooth, rake angle of 0° and relief angle of 12° (γ_1) was utilized in the experiments, as depicted in Fig. 1(b) and (c). The diameter of the micro mill is 400 µm and its cutting edge radius is measured as 0.12 µm with Atomic Force Microscope (AFM). The two edges participating in micro milling are the side edge (Es) formed with rake face (Rf) and flank face 1 (Ff_1), and the end edge (Ee) formed with rake face and flank face 2 (Ff_2). The angle γ_2 is the relief angle of end edge which is designed as 6°, the angle γ_3 is machined to avoid interference. A cuboid block of cermented carbide (WC) was employed as workpiece, which is composed of 85 wt% WC and 15 wt% Co (binder), the average grain size of WC particles was 4-6 µm.

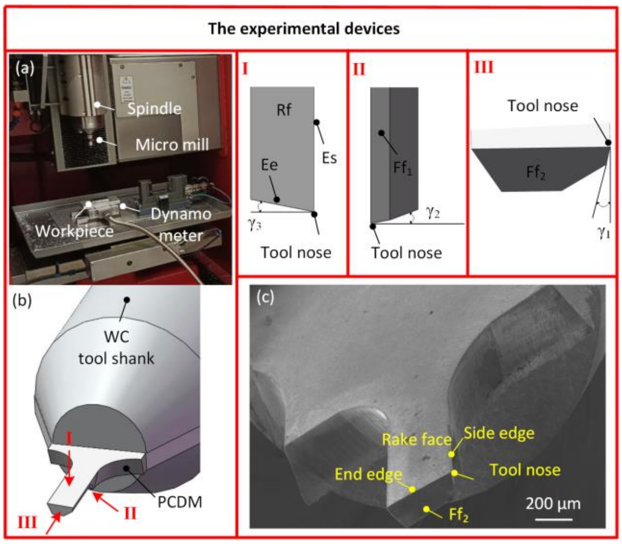

Figure 1. The experimental devices: a) milling machine, b) and c) self-fabricated diamond micro mill.

For the purpose of studying the impact of cutting parameters on the machined surface quality and cutting force, the micro-milling experiments were designed as shown in Table 1. The micro slots were macnined with these parameters to analyze their effect on cutting force and machined surface quality. The feed rate was mainly focused due to its vital impact on size effect, the parameters of feed rate were chosen according to different ratios of cutting edge radius (0.25~1 of 0.12 μm). The cutting force was measured by a dynamometer (Kistler, 9119AA1, Switzerland) with the threshold of 2 mN. The force signals were recorded with the sampling frequency of 30 kHz and processed by second-order high-pass filter with cut-off frequency of 1875.38 Hz to remove the noise. The morphology of the machined grooves were observed by using a surface profilometer (S neox, Sensofar, Spain) and it was also used to obtain the roughness value Ra of the machined groove surface.

Table 1 The detailed cutting parameters in the experiments

Depth of cut a_p(μm)	Spindle speed n (10^4 r/min)	Feed rate f (μm/tooth)
2	2	0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.1, 0.12
4	2	0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.1, 0.12

3. Results and discussion

In the micro-milling experiments, three dimensional cutting force was measured by the dynamometer with different cutting parameters. In this study, the impact of feed per tooth on cutting force and surface formation mechanism was mainly focused, and the feed force and cross-feed force showed the same trend with the variation of feed rate. To avoid redundant description, only the feed force was analyzed. Moreover, since the feed force exists in two exact opposite directions, the positive and negative values were both recorded. In order to better describe the variation of feed force and to compare its values under different cutting parameters, the peak-valley (P-V) value of feed force was calculated to do the characterization. The P-V value was reffered to the amplitude between the maximal and minimal values within a spindle rotation, and in this study, it was averaged over 200 rotation.

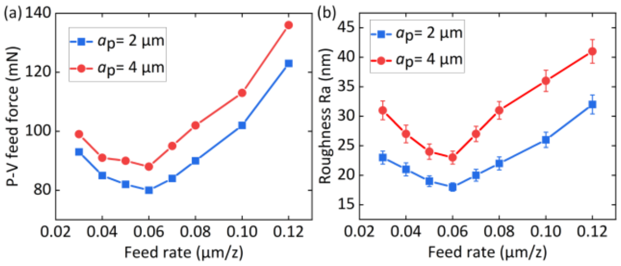

Figure 2. Impact of feed rate on (a) P-V feed force and (b) machined surface roughness Ra.

It can be seen from Fig. 2, both of the two curves have local minimal values of P-V feed force with the feed rate of 0.06 μm/z, which is the half of the cutting edge radius. The reason is that size effect occurs when the feed rate is below 0.06 μm/z, under this circumstance, the cutting thickness is too small to guarantee the occurrence of cutting behavior. The cutting edge keeps ploughing and squeezing the material rather then cutting off the material, in this way the material cannot be removed smoothly leading to the increment of P-V feed force. As the feed is increased the ploughing effect decreases and vanishes until 0.06 μm/z, at this moment, the real cutting behavior occurs and chips are generated, thus the minimum value of P-V feed force is formed. Subsequently, the P-V feed force continues to increase due to the growth of chip thickness.

The topology of machined micro grooves was observed and the roughness value *R*a of these machined surface was also detected along the line profile shown in Fig. 3 by the profiler. It can be seen from Fig. 3a, convex contours and unremoved material formed on the machined surface, indicating that the ploughing effect dominated during machining with feed rate of 0.03 μm/z. Thus the machined surface has a relatively larger *R*a. When the feed rate increased to 0.06 μm/z which is the half of cutting edge radius, the tool path on the machined surface is clearly visible as shown in Fig. 3c. The shearing effect replaced ploughing effect and the material was removed by cutting off under this condition, so the roughness *R*a decreased to a local minimal value as depicted in Fig. 4. However, as the feed rate continued to increase, the surface quality decreased due to the enlargement of cutting thickness, meanwhile, the roughness *R*a also increased.

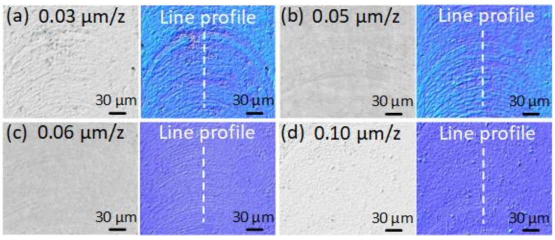

Figure 3. The morphology and outline topography of machined surface with feed rate of a) 0.03 μm/z, b) 0.05 μm/z, c) 0.06 μm/z and d) 0.10 μm/z.

4. Conclusions

Micro-milling experiments on cemented carbide with extremely sharp diamond mills have been conducted and the cutting force as well as the machined surface roughness *R*a have been also measured. By analyzing the variation of P-V feed force and roughness *R*a along with the cutting parameters, the feed rate of 0.06 μm/tooth which is the half of cutting edge radius was recommended due to the occurrence of cutting and shearing instead of ploughing in this condition. Meanwhile the minimal P-V feed force and roughness *R*a can be obtained in this way. Further research is to study the surface formation mechanism in ploughing, shearing and brittle machining of cemented carbide.

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