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The relation between chip morphology and tool wear in ultra-precision raster milling

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ABSTRACT

In the field of ultra-precision machining, the study of the relation between chip morphology and tool wear is significant, since tool wear characteristics can be reflected by morphologies of cutting chips. In this research, the relation between chip morphology and tool flank wear is first investigated in UPRM. A cutting experiment was performed to explore chip morphologies under different widths of flank wear land. A geometric model was developed to identify the width of flank wear land based on chip morphology. Theoretical and experimental results reveal that the occurrence of tool flank wear can make the cutting chips truncated at both their cut-in and cut-out sides, and reduce the length of cutting chips in the feed direction. The width of truncation positions of the cutting chip can be measured and used to calculate the width of flank wear land with the help of the mathematical model. The present research is potentially used to detect tool wear and evaluate machined surface quality in intermittent cutting process.

1. Introduction

For decades, ultra-precision machining technology has been widely used in the fabrication of optical products. As a key ultra-precision machining method, single point diamond turning is usually used to fabricate rotational symmetric components. However, for the fabrication of non-rotational symmetric structures or freeform surface, an ultra-precision raster milling (UPRM) is usually employed. Research about UPRM has mainly focused on the theoretical and experimental investigation of surface generation and the factors affecting the surface finish or roughness [1–7]. Recently, Zhang and To conducted a series of investigations on effects of spindle vibration on the surface generation in UPRM [8–9]. However, no research has focused on the relation between chip morphology and tool wear in UPRM.

Cutting chips are directly generated from the material removal processes in metal cutting. Therefore, the occurrence of tool wear can directly affect the chip morphology, and vice versa. The relation between tool wear and cutting chips include two aspects: first, the chip formation in metal cutting has a remarkable effect on tool status and tool life [10]; second, the tribology at the tool–chip interface controls chip formation and tool wear [11]. There is a significant body of research on the relation between chip morphology and tool wear in conventional cutting and single-point diamond turning, for example: Ee et al. presented a methodology for modeling chip-curl in machining with progressively worn grooved tools, which is based on the measurement of cutting forces by using the equivalent tool face model [12]; Kishawy and Wilcox studied the relation between chip morphology and modes of tool wear during machining of hardened steel [13]; Ebrahimi and Moshksar investigated chip characteristics and chip/tool contact length in turning of micro-alloyed and quenched-tempered steels [14]; Bhuiyan et al. introduced a new technique to independently monitor the chip formation effect on the tool state using an acoustic emission method [15]; and SenthilKumar et al. conducted a study on tool wear and chip formation during drilling carbon fiber reinforced polymer (CFRP)/titanium alloy (Ti6Al4V) stacks [16]. However, there has apparently been no research on the relation between chip morphology and tool flank wear in UPRM.

The research that forms the basis of this paper, involved investigation of the relation between chip morphology and tool flank wear in UPRM. A geometric model was developed to present the relation between the width of flank wear land and the captured chip morphology. This model is able to identify the width of flank wear land based on the captured chip morphology. Through a comparison of the identified width of flank wear land with the inspected one, it is found that the measured width of flank wear land agrees well with the identified width of flank wear

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from the cutting chips. The results of this research will help in detection of tool flank wear and the evaluation of machined surface quality in intermittent cutting processes.

2. Experiments

In the experiments, flat cutting was conducted on the Precitech Freeform 705G (Precitech Inc., USA) multi-axes CNC ultra-precision raster milling machine. A round nose diamond tool (Apex Inc.) was employed, whose geometric parameters are: tool radius 0.635 mm, rake angle -2.5°, and clearance angle 15°. The cutting parameters used in this experiment were: feed rate 225 mm/min, depth of cut 0.005 mm, spindle speed 4500 rpm, swing distance 28.35 mm, and step distance 0.025 mm, the cutting strategy is horizontal cutting and the cutting environment is lubricant on. The workpiece material was of brass and the total cutting distance was about 5000 m.

To compare the chip morphologies cut by a fresh tool and a worn tool, cutting chips were collected at the first stage of the cutting experiment and after every 1000 m of flat cutting. The collected chips were then examined by a Hitachi TM3000 scanning electron microscope (SEM) and the inspected results were reordered and used for calculating the width of flank wear. In addition, after every 1000 m of flat cutting, the diamond tool was dismounted and examined by the SEM to measure the width of flank wear land.

Flank wear land usually has an angle with the rake face of cutting tools, called the wear land angle. The existence of wear land angle leads to inconformity between the height and width of the flank wear land. Usually, the wear land angle of a cutting tool is different for different workpiece materials that have been cut. To measure the wear land angle, straight cutting was conducted with the worn tool on a thin brass sheet to imprint the wear land angle of the cutting tool. The brass sheet was then examined by the SEM from the side view to obtain the wear land angle. The wear land angle is an important parameter in this investigation.

3. Mathematical model

In the UPRM process, the diamond tool rotates around the spindle axis cutting into and out of the machined surface intermittently. In rotary cutting, chips are generated as a result of three cutting steps: previous step cutting, previous rotary cutting, and current rotary cutting, as shown in Fig. 1. Therefore, cutting chips are enveloped by the initial surface, the surfaces formed by previous rotary cutting, current rotary cutting, and previous step cutting.

Fig. 1 indicates the schematic drawing of cutting mechanisms and chip formations in UPRM. To model the cutting chips, a coordinate system o–xyz is set up at the intersection point of tool holder axis and spindle axis with its x-axis pointing to the feed direction, while its y-axis is along the step direction, as shown in Fig. 1(a). Suppose the cutting chips were enveloped by surface A, surface B, surface C and surface D, the equations of the four surfaces are derived in coordinate system $o-xyz$as follows:

(1) Surface formed by previous rotary cutting (surface A)

$$\left(\sqrt{(x+f)^2+z^2}-w+R\right)^2+y^2=R^2 \tag{1}$$

where f is the feed rate in mm/r, w is the swing distance, and R is the tool nose radius.

(2) Surface formed by current rotary cutting (surface B)

$$\left(\sqrt{x^2+z^2}-w+R\right)^2+y^2=R^2 \tag{2}$$

(3) Surface formed by previous step cutting (surface C)

$$(z-w+R)^2+(y+s)^2=R^2 \tag{3}$$

(4) Initial surface (surface D)

$$z=w-a_p \tag{4}$$

From Fig. 1(b), it is found that the four surfaces form six boundaries, which can be formulated by six equations. The equation for each curve can be derived by solving the same solution of the equations of two neighboring surfaces. Actually, solving the mapping equation of each curve on the x–y plane is more useful for building up the 3D model of cutting chips. The mapping equations for the six curves are derived below:

(1) For curve a, it is the boundary curve of surfaces A and B, combining Eq. (1) and Eq. (2) and eliminating z, yields

$$x=-f/2 \tag{5}$$

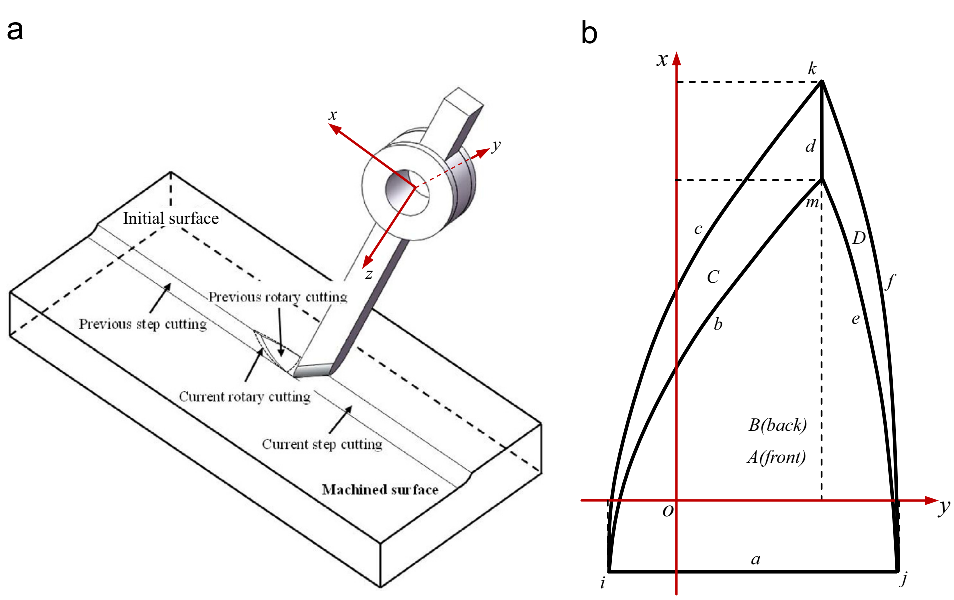

Fig. 1. Schematic illustration of (a) cutting chip generation and (b) chip morphology in UPRM.