International Journal of Mechanical Sciences 118 (2016) 125–134

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Evaluation for tool flank wear and its influences on surface roughness in ultra-precision raster fly cutting

Guoqing Zhang[a], Suet To[b,c,*], Shaojian Zhang[b]

[a] Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Nan-hai Ave 3688, Shenzhen 518060, Guangdong, PR China
[b] State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, PR China
[c] Shenzhen Research Institute of The Hong Kong Polytechnic University, Shenzhen 518060, Guangdong, PR China

ARTICLE INFO

Keywords:
Diamond tool
Tool wear
Cutting chips
Ultra-precision raster fly cutting
Surface roughness

ABSTRACT

The occurrence of tool flank wear certainly affects the machined surface roughness in ultra-precision machining. The in-process evaluation of tool flank wear and its effects on machined surface roughness is significant, since it helps to find tool flank wear timely and reduce tool wear effect on surface roughness by further actions. However, little attention has been paid to the evaluation of tool flank wear and its effects on machined surface roughness in ultra-precision raster fly-cutting (UPRFC) process especially by using cutting chips. In the present research, evaluation of tool flank wear and its effects on surface roughness is conducted in UPRFC by examination of cutting chip morphologies. Based on the relations between chip morphologies and tool flank wear, a mathematical model was established to identify the width of flank wear land and the theoretical surface roughness under tool flank wear effects. Theoretical and experimental results show that: (1) Tool flank wear occurrence causes the formation of shutter-like structure rather than feather-like structure at the tool entry of cutting chips. (2) Cutting chips are truncated where chip thickness is comparable to the width of wear land. (3) The smooth tool flank wear increase the tool nose radius and therefore reduce the surface toughness theoretically.

1. Introduction

In ultra-precision machining, tool wear affects the surface roughness [1], chip formation [2], cutting force [3], even chatter stability [4] and delamination [5]. Therefore, the in-process evaluation of tool wear and its effects on surface roughness is quite important, since it can detect the poor surface quality caused by tool wear timely, avoid unacceptable cutting and even remedy the surface deterioration. Up to date, research about the evaluation of tool wear has been focused on conventional machining, single point diamond turning, micro milling and conventional drilling process both in direct and indirect methods. Direct tool wear evaluation methods are usually performed by optical inspection. Some typical examples are: Sortino, et al., (2003) adopted a method of statistical filtering for optical detection of tool wear [6]. Wang, et al., (2006) utilized direct optical methods to measure the flank wear of diamond tools [7]. Li, et al., (2013) developed a novel online optical system to inspect and measure tool wear conditions in milling [8]. However, the optical inspection of tool wear is difficult to be realized in-process since diamond tools are covered by chips during cutting process. Therefore, many indirect tool wear evaluation methods were adopted, such as evaluation of tool wear by using cutting force, acoustic emission, power consumption, and even vibration signals. for example, Emel and Kannatey-Asibu, (1989) employed an acoustic emission and force-based sensor fusion system involving pattern recognition analysis to detect tool breakage, chip formation and a threshold level of tool flank wear in turning [9]. Lin, et al., (1995) utilized force signals to achieve on-line drill wear monitoring [10]. Salgado, et al., (2007) presented a tool condition monitoring system (TCMS) for on-line tool wear monitoring in turning by using the feed motor current and the sound signal [11]. Alonso, et al., (2008) developed a reliable tool condition monitoring system (TCMS) based on the analysis of structure of tool vibration signals [12]. The indirect signals can reflect the gradually wear of cutting tools, however there is no accurate indirect tool wear evaluation methods for industrial application.

Surface quality evaluation is another essential topic in ultra-

---

[*] Corresponding author at: State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, PR China.

E-mail address: sandy.to@polyu.edu.hk (S. To).

http://dx.doi.org/10.1016/j.ijmecsci.2016.09.013
Received 18 February 2016; Received in revised form 1 August 2016; Accepted 9 September 2016

precision machining, a significant body of research has been focused on it. For example, Cheung and Lee, (2001) conducted a study about the characterization of nano-surface generation in single-point diamond turning [13]. Their following work focused on the effect of tool interference on surface generation in single-point diamond turning [14]. Quinsat et al., (2008) proposed a 3D surface roughness parameter which can formalize the relative influence of both machining parameters and surface requirements in ball end milling process [15]. Ahn, et al., (2009) presented an elaborate methodology to predict the surface roughness of layered manufacturing processed parts [16]. Also, many attempts were employed to realize online surface quality prediction. For example, Singh, et al.,(2004) revealed a new methodology for predicting surface roughness of engineering surfaces based on the acoustic characterization [17]. Grzesik and Brol, (2009) characterized the surface profiles generated in longitudinal turning operations using continuous wavelet transform [18]. Karayel, (2009) presented a neural network approach for the prediction and control of surface roughness in a computer numerically controlled (CNC) lathe [19]. In addition, Kılıçkap, et al., (2005) conducted a research on the relationship between tool wear and surface roughness in machining of homogenized SiC-p reinforced aluminum metal matrix composite [20]. However, no research was reported on the in-process evaluation of tool wear effects on machined surface quality, especially in ultra-precision raster fly-cutting (UPRFC) process.

UPRFC is a typical intermittent cutting process, the relative complex cutting mechanism of UPRFC makes the in-process evaluation of tool wear and its effect on surface quality difficult, because the diamond tool is rotating in high speed during the UPRFC. Most of research about surface generation in UPRFC has been reported under the consideration of cutting parameters [21,22], cutting strategy [23], kinematics error [24], spindle vibration [25] and workpiece materials [26]. For tool wear characteristics and their effects on machined surface roughness, Yin, et al., (2009) was among the first to investigate the tool wear characteristics in UPRFC [27]. Afterwards, Zhang, et al., (2015) conducted a research to further investigate tool wear characteristics in UPRFC and their effect on cutting force, chip morphology and surface finish [28]. Our previous study focused on the evaluation methods of tool fractures and their effects on surface roughness by using cutting chips [29,30]. Moreover, the relation between tool flank wear and chip morphology was preliminarily investigated [31]. However, surface quality evaluation under the consideration of tool flank wear of diamond tools has not been reported in UPRFC, especially for in-process evaluation and using cutting chips.

In the present research, an in-process evaluation method for tool flank wear and its effects on surface roughness was employed by examining cutting chips. The effective of this method is based on the typical intermittent cutting mechanism of UPRFC. In this method, the cutting chips were collected in a certain interval time. The collected cutting chips were then examined by SEM, the inspected results were used to identify the width of flank wear land. The machined surface roughness under tool wear effect can also be predicted based on the tool flank wear identification. This method can realize the in-process evaluation of tool flank wear and its effects on machined surface roughness. Based on the evaluation, the machined surface quality can be potentially improved by optimizing cutting parameters.

2. Experiments

In this investigation, the cutting experiment was performed on a Precitech 705 G ultra-precision raster fly cutting machine which owns five axes including three translation axes (X, Y, Z) and two rotatable axes (B, C). The experimental setup is shown in Fig. 1. The workpiece material used in the cutting experiment was brass material. Cutting parameters are listed in Table 1. In the experiment, a desired flat cutting and depth cutting were performed. The total cutting distance was about 5000 m. The total cutting time was about 450 h.

Before the flat cutting and after every 1000 m flat cutting, a group of depth cutting was conducted to investigate the effect of wear land on the cutting chips morphology. The cutting depths in the depth cutting were 2 μm, 5 μm, 10 μm and 15 μm respectively. The cutting parameters for flat cutting and depth cutting are listed in the second and third columns of Table 1 respectively.

To compare the morphologies of cutting chips cut by a fresh tool and a worn tool, cutting chips were collected at the first stage of the cutting experiment and at the end of every 1000 m flat cutting and every depth cutting. The collected chips were then examined by Hitachi TM3000 scanning electron microscope (SEM). After finishing every 1000 m of flat cutting, the diamond tool was dismounted and then inspected by the Hitachi TM3000 SEM. After cutting, a Park's XE-70 atomic force microscope (AFM) was used to measure the wear land angle.

3. Results and discussion

In UPRFC, the contact between cutting tool and workpiece in a rotary cutting circle is quite short, which can be proved by the form of the captured cutting force as shown in Fig. 2. The short cutting duration make the cutting tool suffering the effect of cyclical stress. Therefore, the tool wear characteristics in UPRFC are different from that in continuous cutting process.

Fig. 3 shows the tool wear characteristics at different cutting stages. It is found from Fig. 3(a) that fresh diamond tool usually owns sharp cutting edge. After about 1000 m flat cutting, some fractures were found on the cutting edge, the bigger ones of which are marked by F_1 and F_2 in Fig. 3(b). After 2000 m flat cutting, it is found from Fig. 3(c) that the two bigger fractures were flatten a little. Fig. 3(d) shows the tool figure after 3000 m flat cutting. It is found that the cutting edge is not sharp any more, instead, a round cutting edge is formed. In addition, the two bigger fractures are flatten a lot. Fig. 3(e) indicates the diamond tool figures after a 4000 m flat cutting, it is found that a smooth wear land is formed, the width of the wear land is in the range of 0.5–1 μm. Also it is found that the two bigger fractures are flatten and hard to be distinguished. Fig. 3(f) shows the SEM tool wear figure after a 5000 m flat cutting. It is found that the tool wear pattern has no significant difference from that shown in Fig. 3(e), only the width of wear land has a little increase.

The occurrence of tool wear certainly affects the cutting chip morphology. Fig. 4(a) shows the morphology of a cutting chip cut by a fresh tool, it is found that the cutting chip is quite thin at its tool entry, some feather-like structure are formed. While Fig. 4(b) shows the morphology of a cutting chip cut by a tool after 5000 m flat cutting. It is found the cutting chip is truncated, some shutter-like structures are formed at its tool entry side.

The shutter-like structure is caused by the formation of smooth wear land. With the progress of the tool flank wear, as the cutting edge radius of a diamond tool is comparable to the thickness of cutting chips, a macro cutting instead of micro cutting process occurs. This will lead to the formation of some gaps in the lamella structure, so that a shutter-like structure is formed.

Before cutting and after each 1000 m flat cutting, a group depth cutting is performed with the cutting depth of 2 μm, 5 μm, 10 μm, and 15 μm respectively. In each depth cutting, the cutting chips were collected. Fig. 5 shows the figures of cutting chips cut by the fresh tool at different cutting depth, it is found that all the cutting chips can be fully generated at different cutting depth.

Fig. 6 shows the figure of cutting chips cut by a worn tool at different cutting depth. From these figures, it is found that the cutting chips have different morphologies at the different cutting depth. At the cutting depth of 2 μm, the cutting chips can not be formed, only some needle-like structures were found, as is shown in Fig. 6(a). At the cutting depth of 5 μm, some chips were formed, however the chip is truncated on both their tool entry and tool exit sides. The chip