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A review of fly cutting applied to surface generation in ultra-precision machining

S.J. Zhang [a,b], S. To [b,*], Z.W. Zhu [b], G.Q. Zhang [b]

[a] Research Institute of Mechanical Manufacturing Engineering, School of Mechatronics Engineering, Nanchang University, Nanchang, Jiangxi, PR China
[b] State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong

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ABSTRACT

Fly cutting in ultra-precision machining (UPM), termed ultra-precision fly cutting (UPFC), is an intermittent cutting process in which a diamond tool is mounted with a spindle to intermittently cut a workpiece. The process offers the high flexibility necessary for fabricating freeform, micro/nano-structural surfaces, as well as hybrid structural surfaces with sub-micrometric form error and nanometric surface roughness, and its constant cutting velocity provides uniform high surface quality. However, in addition to its low machining efficiency, UPFC's intermittent cutting process results in distinctive surface generation mechanisms, covering intermittent tool-workpiece relative motion, tool geometry imprinted into a machined surface, and surface material separation and deformation. General factors, such as cutting conditions, tool geometry, material factors (material property change, material swelling and recovery, and material separation mechanism), kinematic and dynamic errors, assembling errors, cutting strategies, tool path, and workpiece geometry, are individual to UPFC and universal in UPM. Accordingly, this paper focuses on the current investigation of fly cutting applied into surface generation in UPM. Conclusions are reached and the challenges and opportunities for further studies are discussed.

Contents

1. Introduction

Ultra-precision machining (UPM) is a mechanical material removal manufacturing process that involves ultra-precision diamond turning (UPDT), ultra-precision raster milling (UPRM)/fly

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* Corresponding author.
E-mail address: Sandy.To@polyu.edu.hk (S. To).

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cutting (UPFC), ultra-precision grinding (UPG), and ultra-precision polishing (UPP). The achievable form accuracy and surface roughness is one sub-micrometer and several nanometers, respectively [1,2]. In UPM, excellent diamond tools and ultra-precise machines are combined together for the fabrication of such high quality surfaces.

Single crystal diamond is the ideal material for UPM as it has a sub-micrometric tool contour geometry and a nanometric cutting tool edge. In addition, it has many outstanding properties, such as super hardness, high thermal conductivity, a nanometric tool edge, and high wear resistance with low friction [3].

Machine-tool performance determines form error and surface roughness. In UPM, natural granite, polymer concrete or aged cast iron with high stiffness and damping properties are adopted in order to minimize or eliminate vibration and deformation effects on surface generation [4,5]. And, high internal damping [4], aero-/hydro-static slides with low friction [5], laser position feedback with nanometric resolution [6], high thermal stability [7], and nanometric tool positioning [8] have been applied to satisfy the critical demands of UPM. Nowadays, UPM machine tools with nanometric resolution are commercially available.

Typical workpiece materials for UPM are diamond turnable materials such as aluminum alloys, copper alloys, electroless nickel–phosphor plating, and plastics [9–11]. Nowadays, due to the ever-growing demands for specialized products, it is expanded to cut diamond non-turnable materials such as silicon [12] and steel [13]. However, rapid diamond tool wear is still a deterministic drawback.

Miniaturization, specialization, and functionalization have promoted the UPM applications into the fields of optics, medicine, biotechnology, electronics, and communications [14]. Currently, UPM is the fastest and most reliable mainstream technique to cost-efficiently shape high quality complex surfaces. Significantly, UPFC developed from UPDT is highly flexible and therefore suitable for the special fabrication of freeform and structural surfaces, such as v-grooves and pyramids, with uniform surface quality. It is obviously different from UPDT in surface generation mechanisms due to its fly cutting mechanism. Distinctively, in UPFC a diamond tool is mounted with a spindle to cut a workpiece. It also provides the capability of high quality surfaces with sub-micrometric form error and nanometric surface roughness.

This paper surveys the current investigation into fly cutting in UPM (i.e. UPFC) and its applications with a focus on surface generation. Previous key research findings are reported along with related discussions. Challenges and opportunities faced by academia and industry in UPFC are elaborated for future studies with some key conclusions.

2. Principles and applications of UPFC

Although UPFC is developed with fly cutting from UPDT, it is distinctive from UPDT. Firstly, in UPFC the diamond tool rotates with a spindle to remove surface material, i.e. fly cutting, whereas in UPDT a workpiece is mounted with a spindle. Secondly, in UPFC the cutting velocity is constant, whereas in UPDT the cutting velocity changes with the cutting radius distance between tool tip and spindle axis. Thirdly, in UPFC material removal is intermittent, i.e. intermittent cutting, whereas in UPDT it is commonly continuous. Thus, the cutting efficiency of UPFC is lower than that of UPDT.

Regarding surface quality, inconsistent cutting velocity with respect to spindle speed leads to cutting quality inconsistency in UPDT [15]. Secondly, the larger the cutting radius distance in UPDT is, the higher tracking bandwidth is required, which causes tracking bandwidth limitations that induce surface distortions and deterioration [16,17]. Finally, as the sampling number determines the cutting linearization error, azimuth sampling conflicts take place from the outside to the turning center in UPDT [15,18,19].

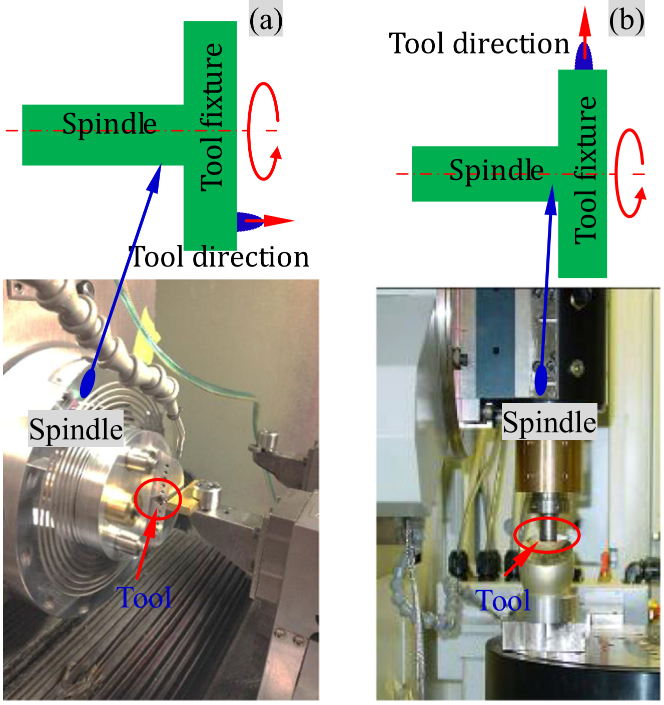

Fig. 1. UPFC: (a) End-UPFC with the tool setup along the spindle axis, and (b) Radial-UPFC (UPRM) with the tool setup along the spindle radial direction.

Fortunately, UPFC does not have the aforementioned disadvantages associated with UPDT, but is capable of deterministically generating a surface of uniform quality with nanometric surface roughness and sub-micrometric form error. However, due to its intermittent cutting process, it is limited by poor cutting efficiency. Therefore, UPFC is more suitable for fabricating special surfaces.

Generally, UPFC includes two cutting types. Fig. 1 shows the setup of diamond tools fixed with a spindle. One type, where the tool direction is parallel to the spindle axis, as shown in Fig. 1(a), is termed end-UPFC, i.e. end fly cutting [20]. The other type, where the tool is mounted with the spindle along the radial direction, as shown in Fig. 1(b), is termed radial-UPFC (UPRM) [21]. Additionally, the spindle can be set up horizontally or vertically. Table 1 presents UPFC classifications.

End-UPFC was originally used to fabricate large flat surfaces with a uniform surface quality. Early, it was designed to fabricate a large flat surface. Montesanti et al. [22] developed a diamond fly cutting machine that could accommodate a 100 kg workpiece with a 490 mm × 490 mm surface. Chen et al. [23,24] also proposed an ultra-precision diamond fly cutting machine for producing a large KDP crystal flat surface at half metric scale. However, recently the fly cutting technique has been implented into UPM with a slow/fast tool servo to fabricate hybrid structural surfaces, such as micro-nano-structural freeform surfaces. The novel method has been

Table 1
UPFC classification.

UPFC	Spindle	Diamond tools
1	Vertical axis	End [22–24]
2		Radial [13,21]
3	Horizontal axis	End [20,25,26]
4		Radial [27]