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Scanning tunneling microscopy-based on-machine measurement for diamond fly cutting of micro-structured surfaces

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ABSTRACT

This paper presents a new on-machine measuring system based on scanning tunneling microscope principle, in order to meet the demand for precision form control of fabricated micro-structures. It is compactly established and mounted on a diamond turning machine, capable of on-machine measuring microstructures with steep slopes and size of tens of micrometers, which remains a challenge task to accomplish undistorted measurement even for general off-line metrological methods. Fly cutting with V-tip fly-cutter was first applied in two directions with interval angle of 60° to form the crossed micro V-grooves, and then efficient on-machine measurement was carried out to characterize the machined surface form without ending the proceeding of the subsequent fabrication. By depth compensation of fly cutting in 120° direction through feedback of on-machine measured results, the surface of rectangular pyramid array with diamond-shaped feature was successfully generated. Experimental results demonstrate that the proposed measuring system is of significance in the fabrication process, owing to its efficient on-machine characterization capability for generating accurate micro-structured surfaces.

1. Introduction

Micro-structured surfaces have broad application prospects in optical components, metrology artifacts, biological products, and so on [1,2]. Diamond machining is a well-developed technology to generate precision patterns and surfaces on a micrometer scale [3]. As it develops, various surfaces can be machined by multiple processes such as fast tool servo, slow slide servo, milling and fly cutting [4–6]. In the fly cutting process, the diamond cutter is generally rotated on a rotary spindle at high speed to effectively generate patterned microstructures [7]. V-grooves are micro-structured elements that are frequently machined by fly cutting process, which are widely used in optical technology, fluid engineering, medical science, and so on [8–10]. For example, the micro-pyramid array formed by the intersection of crossed V-grooves is used for the enhancement of light reflection for road signs. The surface of the component is the utmost important for its correct performance [11,12], thus the guarantee of accurately generated surface form is essential.

With the development of the diamond machine, although high precision microstructures can be fabricated by using fly cutting process, the surface form error is inevitably influenced by the drifting of the machine in long term, dynamic motion error of flying cutter, cutting tool form error, tool wear, and so on. Accordingly, accurate on-machine measurement is crucial for form control of the cutting surface. However, traditional scanning probe microscopy utilizes a diamond probe or a ruby ball, and its probe radius is in the range of 2.5–12.5 μm that would greatly influence the measured results [13,14]. Besides, the contact probe probably damages the surface. Optical probing system provides a fast and non-contact means without risk of damage [15–17], but it is not appropriate to image fly cutting microstructures that usually have steep slopes with deep trench like the V-grooves [18]. This is because the slope gradient is large compare to the maximum detectable angle of objective lens that is only around 30° [19]. Besides, the expense and sophisticated system of these methods prevent the practical application to integrate on the manufacturing machine for on-machine measurement. Therefore, on the other hand they fall to general off-line measurement which requires the machined workpiece to be disassembled from the manufacturing machine and moved to a separated measurement room [20,21]. In this case, it blocks the proceeding of subsequent fabrication process due to the relocation error, consequently the surface form is difficult to be guaranteed and the scrap rate may increase.

As we know, scanning tunneling microscope (STM) is a powerful instrument [22], and in recent years it has been tried to shift its application fields to precision engineering for large-area measurement of mechanical machined parts [23–25]. However, they

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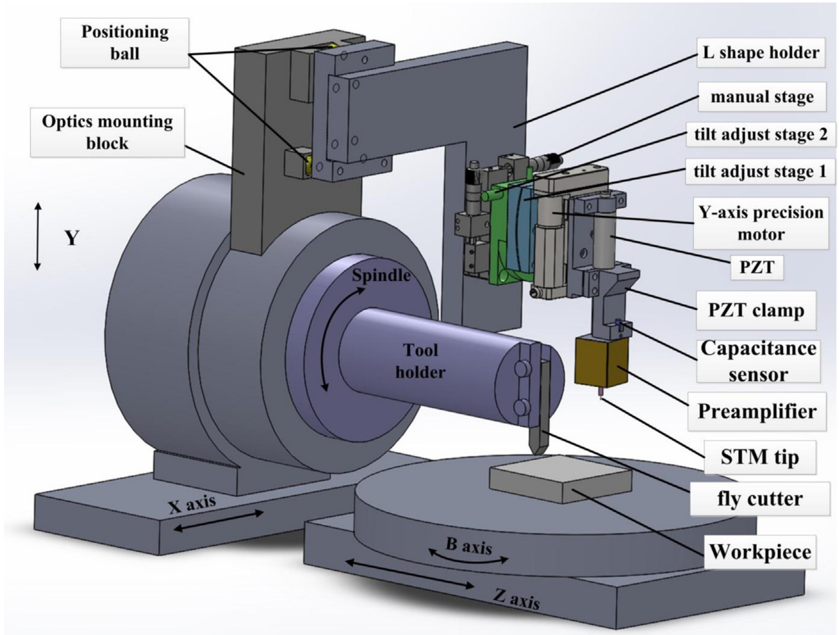

Fig. 1. Structural configuration of the STM-based on-machine measuring system.

focused more on large-area or long-range scanning, rather than on-machine measurement aimed at fabricating accurate surfaces. Previously, we had developed the etching process to fabricate ultra-sharp probes with high aspect ratio 450:1 that is rather difficult to reach for the cantilever probe in the atomic force microscope [26], and achieved the off-line observation of highly oriented pyrolytic graphite (HOPG) as well as diamond machined sinusoidal freeform surfaces [27,28]. In this work, with the motivation of improving fabricated surface accuracy and reducing scrap rates, a new on-machine measuring system based on STM was developed on the diamond turning machine to apply in the fly cutting process for on-machine surface form characterization and assist the precision fabrication of rectangular pyramid array with slope angle of 45° and height of 15 μm.

2. STM-based on-machine measuring system

2.1. Structural configuration

Fig. 1 shows the structural configuration of the proposed STM-based on-machine measuring system and Fig. 2 is the photograph of the integrated system on the diamond turning machine. The overall system is installed in a temperature-controlled room that maintains the temperature of 21.0 ± 0.1 °C. As we know that, the optics mounting block is originally designed for mounting the optical tool setting system while tool alignment is needed. To achieve the kinetic mounting mechanism, position balls and L-shaped holder are used to mount the measuring system on the optics mounting block. During fabrication process, the optical tool setting system is removed, and our self-developed on-machine measuring system can be loaded. The compact scanning head consists of a piezoelectric transducer (PZT) with long stroke of 80 μm, a PZT clamp, a STM tip, a preamplifier and a capacitance sensor. The two tilt adjust stages are specially employed for the adjustment of scanning head to compensate the scanner's tilt error. *Y*-axis precision motor (M122, PI, Germany) is served to auto-approach the scanning probe tip to the machined workpiece before measuring.

The control diagram of the STM-based on-machine measuring system is shown in Fig. 3. The bias voltage, which origins from the bias voltage regulator shown in Fig. 2, is applied to the machined workpiece for generating tunneling current when the STM probe tip approaches the surface. The feedback tunneling current goes through the probe towards the preamplifier (*I*–*V* converter with bandwidth of 10 kHz). After the signal conditioning, the amplified signal is compared with a set-point value, and the difference is transferred to a PID controller and PZT driver. The output drives PZT with the probe tip to minimize the difference between detected current and the set-point value, so that the probe tip can follow the surface variations of the machined microstructure at a constant distance. The capacitance sensor is to record the displacement of the driven PZT which corresponds to the surface profile of the microstructure.

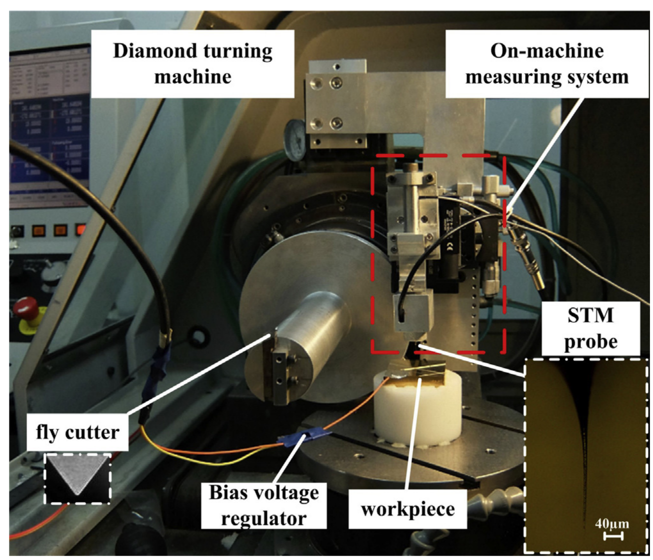

Fig. 2. Photograph of the integrated system on the diamond turning machine.

2.2. Performance evaluation

In order to achieve a nanoscale resolution with millimeters' traveling range, high precision motion stages are used by the diamond