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Technical note

Modeling and machining evaluation of microstructure fabrication by fast tool servo-based diamond machining

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ABSTRACT

A fast-tool servo-machining process is typically utilized to generate sinusoidal microstructures for optical components only when the clearance angle of the cutting tool is greater than the critical value. This paper focuses on the generation characteristics of microstructures for surface texturing applications when the clearance angle of the cutting tool is smaller than this critical angle. A method for calculating the microstructure profile amplitude and wavelength is introduced for the prediction of microstructure generation. Cutting tests were conducted, and the measured results were quite close to the corresponding calculated results, further verifying the capability of the proposed analytical model.

1. Introduction

Ultraprecision microstructured surfaces with microscale or nanoscale resolution are fundamental for enhancing technical surfaces with specific functionalities, such as optical component usage [1], information storage [2], and tribological performance [3]. Optical and electronic methods for fabricating such microstructured surfaces include photolithography, electron beam writing, and focused ion beam machining. Although these methods are effective for fabricating three-dimensional microstructures with a regular configuration, they require a long fabrication period for large-area machining.

Fast-tool servo (FTS)-based diamond machining is an efficient process for producing micro- and nanostructured surfaces on a flat or cylindrical workpiece with a regular array of surface height features and specific functionality [4,5]. The working principle of FTS-based diamond turning on a cylindrical workpiece is shown in Fig. 1. A workpiece is clamped on the spindle; a tool servo is fixed on the slide of the machine and can move in the direction of the *x*-axis (feed rate direction). The cutting tool is translated in and out of the workpiece several times per revolution, in synchronization with the spindle rotation and *x*-axis slide, to obtain the microstructured surface. Depending on its bandwidth, the tool servo can be regarded as a FTS or a slow tool servo (STS) [6]. However, no clear bandwidth boundary exists between them.

FTS-based diamond machining process is used widely for improving the form accuracy of the surface [7] or generating a functional surface on brittle material [8] or for optical components [9,10]. However, these studies only demonstrated the superiority of vibration machining when utilizing FTS to improve the surface form accuracy in ultraprecision manufacturing. Another application is the use of FTS to generate regular sinusoidal microstructures for optical components. Noh et al. [11] designed a voice coil motor (VCM)-assisted FTS to fabricate the micro-lens. Lu and Trumper [12] presented a spindle position estimation technique for effectively improving the form accuracy of one-dimensional (1D) and two-dimensional (2D) sinusoidal surfaces with a peak-to-valley amplitude of 2.041 μm. However, these studies did not discuss the FTS machining conditions in detail when the cutting tool clearance angle is smaller than its critical value.

This paper presents a modeling and manufacturing methodology for microstructures produced by FTS-based diamond machining in large-area surface texturing. The influence of cutting tool geometric parameters (such as clearance angle and nose angle) on microstructure generation is investigated. A method for calculating the microstructure profile amplitude and wavelength is introduced for the prediction of microstructure generation prior to the FTS machining process, especially when the clearance angle of the tool is smaller than the critical value. Finally, a series of cutting tests is carried out, and the experimental results are analyzed and compared with the corresponding calculated values.

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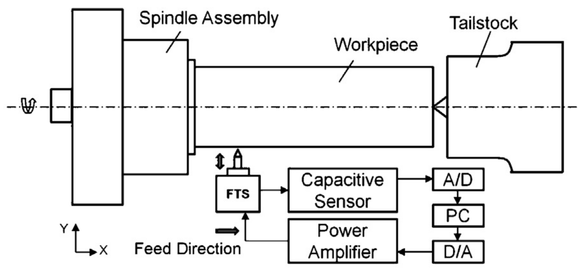

Fig. 1. Working principle of FTS-based diamond turning on a cylindrical workpiece.

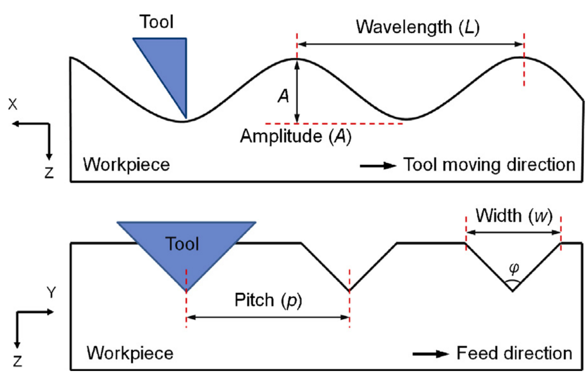

Fig. 2. Schematic diagram of microstructure generation.

2. Modeling of microstructure generation

Compared with conventional diamond machining, FTS-based diamond machining offers an indispensable solution for fabricating complicated microstructured surfaces, such as 1D and 2D sinusoidal surfaces [11] and a micro-lens array on a roller [12], without the need for any type of post-processing. A diagram of microstructure generation via FTS-based diamond machining is shown in Fig. 2.

The microstructure profile along the x-axis is generated by tool vibration, while the profile along the y-axis is generated by the shape of the tool. The pitch (p) between two grooves is determined by the feed rate of the cutting tool. The width (w) and angle (φ) of the groove is related to the amplitude of the profile (A) and the nose angle of the cutting tool (α). The wavelength (L) of the profile (along the x-axis) depends mainly on the machining conditions and is given by the following equations:

$$L = V \cdot \frac{1}{f}, \quad \text{for the cutting} \tag{1}$$

$$L = \frac{n}{60} \cdot 2\pi r \cdot \frac{1}{f}, \quad \text{for the turning} \tag{2}$$

where f is the driving frequency of the FTS, V is the cutting speed, n is the spindle speed in rpms, and r is the radius of the workpiece being turned. Above all, the configuration of microstructures is mainly determined by the machining conditions and the shape of the cutting tool.

The tool geometry, which is mainly specified by the tool nose angle, clearance angle (θ), and rake angle, must be selected for a desired microstructure to guarantee form accuracy and microstructure profile generation along the y-axis (in the y–z-plane). FTS-based diamond machining has two primary applications. One is the generation of regular sinusoidal microstructures for optical components. In this application, the clearance angle of the cutting tool plays an important role in ensuring that the cutting process can proceed without interference between the microstructures and the cutting tool. If θ is not large enough, the machined microstructures will be flattened the next time the tool cuts into the bottom of groove, as shown in the shaded portion of Fig. 3(c). Depending on the designed dimensions of the microstructures, the desired value of θ can be calculated from the following equation:

$$\theta > \arctan\left(\frac{2A}{L}\right) \tag{3}$$

where A is the amplitude of the profile. Although this equation is an approximation and only provides an approximate value of θ, it is adequate for microstructure generation with L equal to several hundred micrometers.

For other applications, such as texturing a workpiece surface for improved tribological performance or producing a master roller for roll-to-roll processing, standardized sinusoidal structures are not required, but regular microstructure arrays with L smaller than 100 μm are needed. Hence, a small clearance angle is usually selected for large-area micromachining to ensure the tool lifetime.

Fig. 3 illustrates the generation analysis of a variety of microstructure profiles with increasing L and constant θ. The red line represents the flank edge of the cutting tool. The black solid line is the machined profile, and the black dotted line is the flattened part. The configuration bounded by the black solid line, and the red

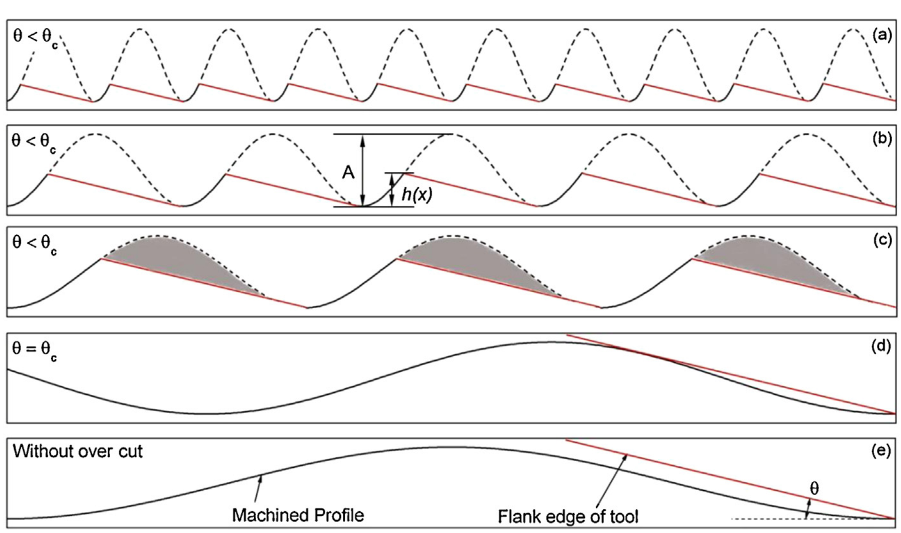

Fig. 3. Generation analysis of a variety of microstructure profiles with increasing L and constant θ.