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Auto-tracking single point diamond cutting on non-planar brittle material substrates by a high-rigidity force controlled fast tool servo

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ABSTRACT

This paper presents auto-tracking single point diamond cutting, which can conduct precision cutting on non-planar brittle material substrates without prior knowledge of their surface forms, by utilizing a force controlled fast tool servo (FTS). Differing from traditional force feedback control machining based on a cantilever mechanism such as an atomic force microscope (AFM) that suffers from low-rigidity and limited machining area, the force controlled FTS utilizes a highly-rigid piezoelectric-type force sensor integrated with a tool holder of the FTS system to provide sufficient stiffness and robustness for force-controlled cutting of brittle materials. It is also possible for the system to be integrated with machine tools to deal with the difficulties in the cutting of large area non-planar brittle materials, which requires not only high machining efficiency but also a high stiffness. Experimental setup is developed by integrating the force controlled FTS to a four-axis ultra-precision diamond turning machine. For the verification of the feasibility and effectiveness of the proposed cutting strategy and system, auto-tracking diamond cutting of micro-grooves is conducted on an inclined silicon substrate and a convex BK7 glass lens, while realizing constant depths of cuts under controlled thrust forces.

1. Introduction

Single point diamond cutting is an important technology for precision manufacturing of microstructures with nanometric surface finish and sub-micrometric form accuracy on a variety of materials including not only soft nonferrous metals [1,2], but also brittle materials such as silicon [3], glass [4] and ceramics [5]. Diamond cutting of microstructures is normally realized through position/motion control of a diamond cutting tool with respect to a workpiece surface according to a programmed cutting path qualified by modern ultra-precision multi-axis machine tools [6,7]. A combination of the machine tool with a fast tool servo (FTS), which can position the cutting tool rapidly and accurately along the in-feed direction, is usually employed for generating microstructures with complex shapes and small dimensions [8–10]. For ensuring the form accuracy of fabricated microstructures, surface flattening by precut is a necessary process so that the accuracy of the depth of cut can be guaranteed by assuring the zero depth of cut position [6]. A flattened substrate is also used for fabrication of a product having microstructures on a curved surface, in which the shaping of both the curved surface and the microstructures will be carried out synchronously by diamond cutting based on complicated cutting paths realized by the technique of slow tool servo (STS) [11] or utilizing a long-stroke FTS [12].

Substrate flattening is a relatively easy process when the substrate is a soft nonferrous metal such as copper or aluminum, since a relatively large depth of cut can be applied in the cutting process [6]. However, on the other hand, in the case of a brittle material substrate with a low fracture toughness, substrate flattening becomes a troublesome and time-consuming process since only an extremely small depth of cut of a few tens or hundreds of nanometers can be applied for realizing ductile cutting [13–15]. One of typical examples for this is the mechanical ruling of master diffraction gratings on polished glass substrates based on a ruling engine [16,17]. In the mechanical ruling of grating, a glass substrate is intermittently moved along the cross-feed direction, while a diamond cutter is reciprocated back and forth along the cutting direction to generate a number of equally-spaced parallel grooves on the substrate surface [18]. Deviations of both the period and depth of the grooves in a grating are required to be kept within a few nanometers over the ruled area of larger than 100 mm × 100 mm in order to qualify the performance of the ruled master diffraction grating required for precision positioning [19,20]. However, it is always difficult to align the substrate perfectly with its surface plane coordinates parallel

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to the motion axis of the machine tool, which is so called surface inclination. Excessive machining force due to the surface inclination leads to resultant formation of brittle fractures. To qualify the fabrication accuracy of the glass grating, the substrate inclination must be reduced to several nanometers over the entire substrate surface throughout careful alignment and a surface flattening by precut. This would always take days long and be the most time-consuming process, which influences the fabrication efficiency of diffraction grating by the mechanical ruling. Similar problems can also be found in many other applications of microstructure cutting on brittle material substrates [21–23].

In addition, it is more difficult to carry out diamond cutting directly over curved surfaces of brittle material substrates [24]. For instance, the mechanical ruling is also employed for the fabrication of concave gratings for smart spectrometers, which can realize light dispersion as well as imaging at the same time [25,26]. In the case of mechanical ruling of such a concave grating, differing from cutting of a planar grating, a complicated positioning mechanism for the diamond cutter is needed to realize accurate fabrication of grooves over the curved surface [26]. When such a complicated positioning mechanism is employed, however, tool misalignment becomes unavoidable, resulting in the difficulty of carrying out perfect ruling over the concave substrate surface [26]. It is thus desired to simplify the tool positioning mechanism and enhance the processing efficiency, as well as the machining accuracy in ultra-precision diamond cutting of non-planar substrates.

On the other hand, differing from CNC machine tool-based diamond cutting, in which the cutting tool is controlled in position, atomic force microscope (AFM)-based machining is possible to carry out nanomachining on non-planar substrates since the tool is controlled in force [27–29]. In the AFM-based nanomachining, grooves with a constant depth are fabricated in such a way that a desired normal force is applied to an AFM probe tip to make it penetrate into the substrate surface, while controlling the tip position along the in-depth direction by a servo actuator so that the force can be kept constant during the scratching over the substrate surface. However, compared with the machine tool-based diamond cutting, the AFM-based nanomachining has some inherent shortcomings. Firstly, the feed mechanism of the probe tip, which is performed by a piezoelectric (PZT) actuator with a limited lateral stroke shorter than 100 μm, is not suitable for large-area machining, since most of the commercial AFM systems are primarily designed for nanometrology and the machining capability is not the major concern of the manufacturers [30]. Secondary, due to the low stiffness of the AFM cantilever, achievable normal force by the AFM-based nanomachining is usually restricted from several nN to several tens of μN, which is only suitable for generating grooves with extremely small depths below several tens of nanometers for soft metal materials and even just several nanometers for brittle materials [31]. The dimensions and forms of the surfaces that can be machined by the AFM-based nanomachining are thus quite limited. Some efforts have been made to improve the applicability of the AFM-based nanomachining techniques by integrating an AFM machining unit into a CNC machine tool [32] or replacing the traditional AFM cantilever to a leaf spring unit for increasing the normal force [33]. However, these kinds of systems still suffer from low robustness and low stiffness, which prohibit such kind of technologies from practical applications in ultra-precision manufacturing.

Meanwhile, on the other hand, piezoelectric force sensors having much higher stiffness and robustness are considered to be more suitable for the integration with ordinary diamond cutting units such as FTS systems and machine tools for practical applications [34]. Piezoelectric force sensors have been widely used for in-process monitoring of diamond machining operations [35]. The authors have once developed a piezoelectric force sensor integrated FTS with hybrid manufacturing and measurement functions for multi applications based on ultra-precision machine tools, including fabrication of microstructures [36], precision tool setting [37], in-process detection of defective microstructures [38] and on-machine measurement of tool edge contours [39], etc. A piezoelectric force sensor integrated diamond tool has also been used for ductile cutting of silicon microstructures with surface inclination measurement and compensation [40]. In the previously proposed method, the force sensor integrated diamond tool is firstly used as a touch-trigger probe to measure the substrate surface inclination, and then the fabrication of microstructure is directly carried out over the inclined silicon substrate surface by compensating the cutting motion axis to be parallel to the surface based on the inclination measurement result [40]. Although this method has been demonstrated as an effective way for accurate cutting on inclined substrates without troublesome pre-adjustment or flattening cutting, it still needs a certain time for carrying out the measurement of substrate inclination. Moreover, it is difficult to use this method when the substrate has a complex curved surface because a large measurement uncertainty would exist in the surface form measurement of the complex curved surface by a discrete probing with the single point diamond tool.

In order to overcome the difficulties in the diamond cutting over large area surfaces of non-planar brittle material substrates which requires not only high-precision, high-efficiency but also a high-stiffness, this paper presents an auto-tracking diamond cutting method, which is capable of conducting ultra-precision ductile cutting on non-planar brittle material substrates without accurate prior knowledge of the surface form by utilizing a high-rigidity force controlled FTS. The force controlled FTS combines the concept of AFM based nanomachining and the body of FTS, which provides much higher stiffness and robustness as well as a longer servo motion stroke than the AFM instruments for the purpose of practical applications with machine tools. In this paper, after a brief introduction of the principles of auto-tracking diamond cutting and the force controlled FTS, experimental results of precision ductile auto-tracking cutting on an inclined silicon substrate and a curved glass substrate, which is carried out to demonstrate the feasibility of the proposed cutting strategy and the developed system, are presented.

2. Principle of auto-tracking cutting by force controlled FTS

A schematic of conventional diamond cutting on an inclined brittle material substrate is shown in Fig. 1. In general, a tool for precut is at first used to remove an inclination component of the substrate after a careful adjustment of workpiece tilts. After that, a fine tool is employed to fabricate desired microstructures on the flattened substrate. During the fabrication, even a small residual inclination component would lead to the appearances of undesired brittle fractures due to the excess of the depth of cut. To overcome the above mentioned shortcoming of the conventional diamond cutting, an auto-tracking cutting is proposed in this paper. Fig. 2 shows a conceptual schematic of the auto-tracking cutting on the inclined brittle material substrate based on the feedback control in machining force. The diamond cutting tool is mounted into a force sensor integrated FTS, which is composed of a piezoelectric actuator for fast positioning of the cutting tool, a displacement sensor for measurement of the tool position, and a force sensor for measurement of the thrust force (normal force) along the in-feed direction (*Z*-direction). Differing from the conventional diamond cutting, in which the tool is set at a pre-determined static position and is moved according to a preset tool path, the tool position and tool path are auto-determined in the cutting process to let the tool tip trace the substrate surface for maintaining a constant thrust force by the feedback control in the proposed auto-tracking