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Large-area profile measurement of sinusoidal freeform surfaces using a new prototype scanning tunneling microscopy

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ABSTRACT

This paper presents large-area profile measurement of ultra-precision diamond turned sinusoidal surfaces by using a specially developed scanning tunneling microscopy (STM). The new prototype of STM system employs a long stroke PZT servo actuator as the *Z*-directional scanner, an integrated capacitance displacement sensor to accurately measure the *Z*-directional profile height, a motorized stage with long traveling stroke for carrying out large-area scanning. A simple method for self-calibration of the inevitable sample tilt is proposed in order to achieve large-area measurement without tip-crashing or losing of tip-sample interaction. Several types of ultra-precision machined sinusoidal freeform surfaces with different geometrical parameters are measured by the new STM system over large scanning areas at the scale of millimeters. Specially, a sinusoidal surface with peak-valley amplitude of 22 μm and periodical wavelength of 550 μm is successfully measured and imaged by the STM system. The measurement repeatability error, repeatability standard deviation and measured profile deviation are also evaluated. It is confirmed that the new STM system is capable of carrying out large-area as well as large-amplitude measurement of the ultra-precision machined sinusoidal surfaces.

1. Introduction

Freeform surfaces, defined as surfaces with no axis of rotational invariance, normally have arbitrary or periodical shapes, and regular or irregular surface structures [1–4]. They are now widely used in engineering optics, biological products, metrology artifacts, data storage and so on [5–7]. In most of the applications, the freeform surfaces are required to be with sub micrometer form accuracy and nanometer surface finish [8]. Sinusoidal surfaces are ones of the typical shapes of freeform, with a key application for positioning of multi-axis precision motion stages [9]. Ultra-precision sinusoidal surfaces are found to be quite effectively fabricated by diamond turning through applying the technique of fast tool servo (FTS), comparing to multiple processes such as grinding, lapping and polishing [10,11]. Based on the optimization of the machining parameters and elimination of the cutting interference, ultra-precision sinusoidal surfaces are successfully fabricated over large areas by the FTS technique [12,13].

In sinusoidal surfaces, several featured parameters including amplitudes, periodical wavelengths and surface forms would mainly dominate the performance of the components [13]. Thus it is desired to precisely measure the three-dimensional (3D) profiles of the machined sinusoidal surfaces in order to guarantee their functions and quality [14]. Normally, the machined sinusoidal surface is composed of periodical micro-features over an area larger than several square millimeters with amplitudes from sub-micrometers to several tens of micrometers and wavelengths from several tens micrometers to several hundreds of micrometers. In this case, the metrology instruments for measuring such type of surfaces are required to have large-area scanning capability as well as high measurement resolution. Scanning probe microscopes (SPMs), which are typically represented by scanning tunneling microscopy (STM) and atomic force microscopy (AFM), are the powerful instruments for the micro/nano topography measurement [15–17]. However, the conventional SPMs are always with limited scanning range, which is typically below 100 μm in the lateral direction and below 10 μm in the vertical direction, therefore they are not suitable for the special application of large-area metrology of such ultra-precision machined sinusoidal surfaces. Although metrological long range SPMs have been designed and built in some national standard institutes for the establishment of traceability [18–21], the measuring systems are too expensive and complicated for practical uses.

In this study, with the motivation of measuring the ultra-precision machined sinusoidal freeform surfaces, a prototype of STM system with large-area scanning capability is specially

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developed. A bi-directional motorized driven stage is used for performing large-area raster scanning of surface profiles, a tilt-adjustment stage is employed to adjust the probe-sample relative angle to compensate the inevitable non-parallel effects, a PZT actuator with long stroke is used as a servo scanner in the vertical direction for tracking the profiles with large amplitudes. Several types of ultra-precision machined sinusoidal freeform surfaces with different geometrical parameters are successfully measured by the new STM system. Specially, for testing the large-amplitude measuring and analyzing capability of the system, an ultra-precision machined sinusoidal surface with peak-valley amplitude of 22 μm and periodical wavelength of 550 μm is measured over a large area of 2 mm × 2 mm. 3D measurement results of the surface profiles, measurement repeatability errors, repeatability standard deviations and measured form accuracy of the ultra-precision surfaces are also analyzed.

2. Materials and methods

2.1. Setup of the newly prototype STM system

Fig. 1 shows a schematic of the new STM system. The system is constructed onto a marble base, which has high stability and low thermal expansion coefficient. Instead of using traditional lateral PZT scanner whose scanning range is limited, long range sample-scanning is performed in this system by a DC motor-driven stage (M-112, PI, Germany) with a resolution of 30 nm and a straightness of approximately 4 μm over the whole traveling range of 25 mm in both *X* and *Y* directions. A tilt-adjustment stage is specially mounted onto the scanning stage for compensating the sample-tilt error, which inevitably occurs due to the inconformity of the specimen amplitude and the manufacturing deviation of the sample holder. The vertical servo probing unit is separated from the sample-scanning stage with the purpose of eliminating the coupling effect among *XYZ*-directions, a PZT actuator with long stroke of 60 μm is employed as the *Z*-scanner for carrying out tracking motions on sinusoidal surfaces, a capacitance displacement sensor with high resolution is integrated inside the PZT actuator to measure the tracking displacement. The PZT actuator is mounted on a motorized stage, which acts as a coarse adjustment mechanism for the positioning of the STM probe with respect to the sample surface in *Z*-direction. The STM sensor unit that is composed of a tunneling current preamplifier and a probe tip is attached at the end of the PZT actuator for probing the surface microstructures. High aspect ratio STM probes with small apex cone angle, which are self-fabricated previously by the technique of electrochemical polishing [22,23], have also been integrated in this measuring system for reducing the probe-sample convolution effect.

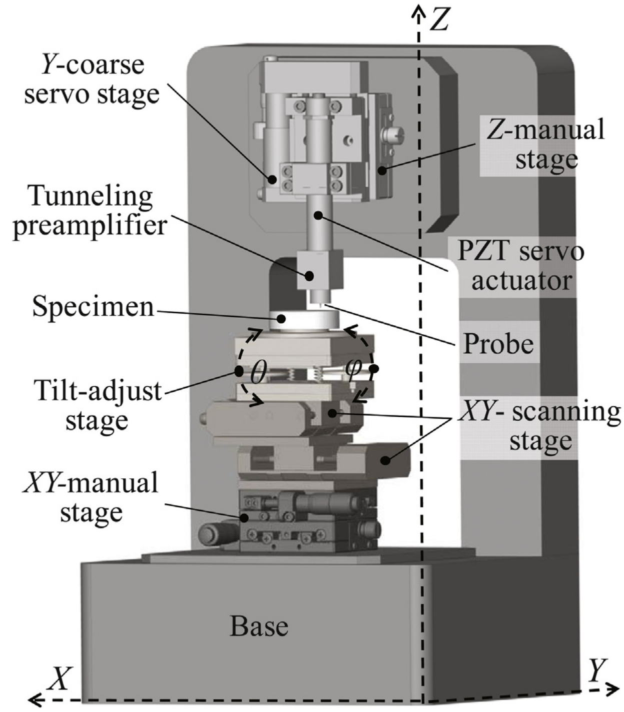

Fig. 1. Schematic of the new prototype of STM system with long stroke PZT servo actuator and tilt-adjustment sample stage.

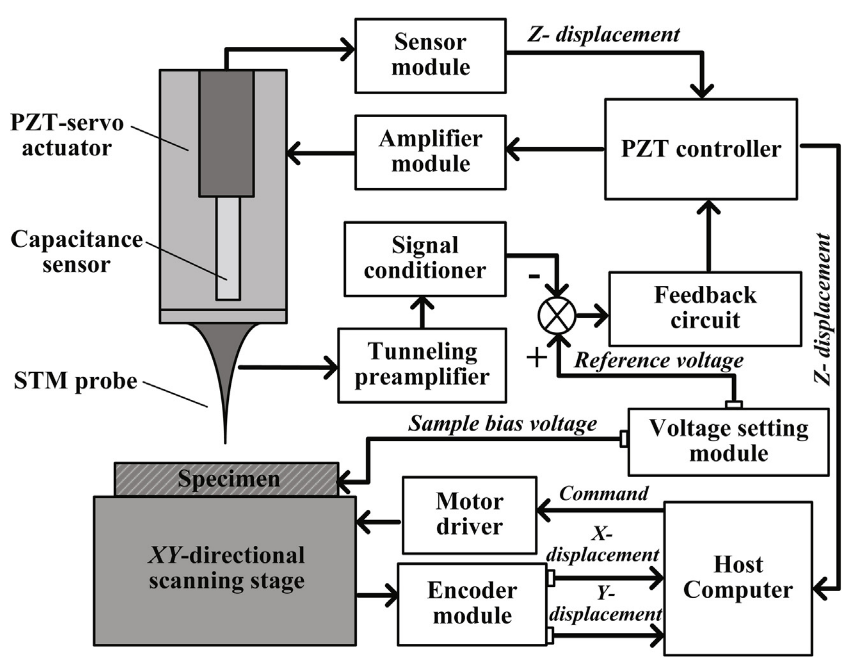

Fig. 2. Diagram of the control system for the new STM system.