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Research Article

Surface Profile Measurement and Error Compensation of Triangular Microstructures Employing a Stylus Scanning System

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Microstructure-based function components are widely used in precision engineering. Surface profile measurement is an essential tool to verify the manufacturing quality of microstructures and to enhance the working performance of the device employing microstructures as function components. However, highly accurate surface profile measurements are difficult to perform for microstructures owing to their complex surface topographies. In this paper, a measurement system is proposed for the surface profile measurement of microstructures. The main components of the measurement system are a precision displacement stage to move the workpiece, a homemade probing system with a diamond microstylus to sense the surface profile variation of the microstructures on the workpiece, and a vibration isolation table to reduce the disturbance of the measurement environment. In addition, the stability of the measurement was experimentally investigated. Microstructures with shape of equilateral right triangle were employed as the measurement specimen, and the surface profile of triangular microstructures was measured by employing two methods to correct errors caused by the specimen inclination and the radius of the stylus tip. The shape, depth, and period of the measured microstructures were also detected based on the results of the surface profile measurement. Experimental results demonstrate the feasibility of the proposed surface profile measurement for microstructures with complex surface topographies.

1. Introduction

Microstructures are key components that have attracted much attention for wide applications in the field of optical communication, optical storage, and flat panel displays [1–4]. Usually, microstructure-based components/systems have special designed functions, which result from the geometrical characteristics of the employed microstructures [5]. For instance, the backlight module in liquid crystal display panels uses triangular microstructures as the key component to enhance the working performance based on optical properties [4, 6, 7]. Therefore, it is important to precisely measure the surface profiles of microstructures. Typical microstructures have triangular, pyramidal, spherical, and aspherical surfaces with critical dimensions from several microns to several hundred microns, and their maximum local slope is up to 45–90° [8–10]. Because of the surface geometric features, accurate surface profile measurement is difficult to perform using conventional surface profile measurement instruments [4, 11–14].

Commercially available surface profile measurement instruments, such as scanning electron microscopes (SEMs), optical profilers, and atomic force microscopes (AFMs), encounter unsolvable difficulties in the surface profile measurement of microstructures [15–21]. For instance, SEMs can carry out fast measurements with a high horizontal resolution of up to nanometers [17, 18, 22]. However, the result obtained by SEM has limited gray scales to characterize the surface variation in the vertical direction, that is, the vertical measuring scale has a lower resolution and cannot be quantified. An optical microscope is usually used to measure flat-type surfaces [18, 22–24]. During the measurement of microstructures with a slope of 45–90°, the measurement result has large errors in the area with a sharp surface slope because of the effect of light reflection. On the other hand, AFMs have extremely high spatial resolutions both in the

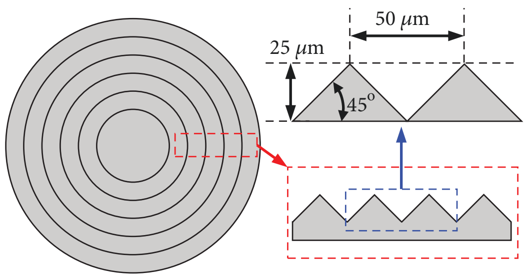

Figure 1: Schematic of the microstructures.

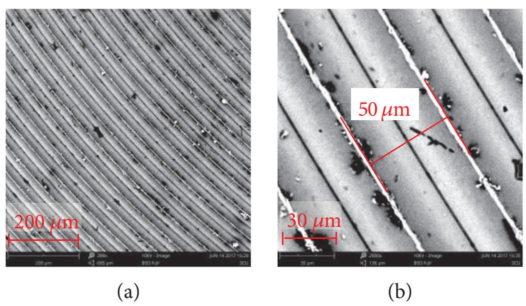

Figure 2: SEM images of the microstructures on the surface of the measured workpiece: (a) SEM image (scale: 200 μm) and (b) details of microstructures (scale: 30 μm).

horizontal and vertical directions and are usually employed for imaging nanoscale surfaces [19–21, 25]. However, its measurement ranges in the horizontal and vertical directions are limited to several microns, and therefore, it cannot effectively measure the surface profiles of microstructures with sizes ranging from several microns to several hundred microns. A stylus profiler, such as the Alpha-Step IQ Surface Profiler of KLA-Tencor, is another kind of powerful instrument that combines a high measurement precision (as low as 0.1 nm) with a large measurement range (up to 2 mm). Commercial stylus profilers employ a design of the leverage structure that leads to nonlinear errors while measuring in the horizontal direction [26]. Commercial stylus profilers are also called step profilers because they are usually used for high measurement precision of the step height of a workpiece.

Surface profile measurement of triangular microstructures not only requires a large measurement range and high measurement resolution but also a high measurement accuracy in both vertical and horizontal directions. Over the years, numerous works have been conducted to resolve this issue. Tian et al. developed a multifunction stylus profiling system employing a special sensing probe [2, 27, 28]. The sensing probe has an electromagnetic force actuator and three precision capacitive sensors, which lead to a slower measurement speed and limited measurement range in the vertical direction (only 10 μm). Fang et al., Claverley and Leach, and Pawlus and Śmieszek studied methods to reduce dynamic errors, which are larger on steeper surfaces [6, 29, 30]. Fang et al., Chen et al., and Ju et al. proposed the sample tilting method for profile measurement of microstructured surfaces using a stylus-based profiler

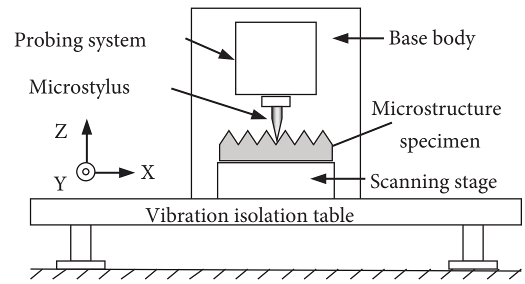

Figure 3: Schematic of the constructed measurement system.

[7, 31, 32]. Schuler et al. and Beutler also proposed a profile measurement method by tilting the sensor heads [14, 15]. The above approaches focused on employing a high-precision hardware, which is expensive and technologically unviable. Therefore, a simple and cost-effective method for surface profile measurement of microstructures is desired in precision engineering.

This paper describes a measurement system specifically designed and constructed for surface profile measurement of triangular microstructures generated on the surface of flat workpieces. Microstructures with shape of equilateral right triangle were employed as the measurement specimen. The surface profile measurement of triangular microstructures was carried out by employing two methods to correct errors caused by the specimen inclination and the radius of the stylus tip. The shape, depth, and period of the measured microstructures were also detected based on the results of surface profile measurement. In addition, the stability of the measurement was experimentally investigated. Experimental results demonstrate the feasibility of the proposed surface profile measurement for microstructures with complex surface topographies.

2. Measurement System for Triangular Microstructures

Figure 1 shows a schematic of the employed workpiece, which is flat and round, with several triangular microstructures fabricated on its surface along the radial direction using a homemade ultraprecision diamond cutting machine tool. The diameter of the workpiece is 20 mm. The nominal height of the microstructure is 25 μm, the period is 50 μm, and the shape is equilateral right triangle.

Figure 2(a) shows the SEM images obtained using an SEM (Phenom™). As can be seen, the workpiece has inerratic periodic microstructures on its surface. Figure 2(b) shows the high-resolution image of the microstructures. The horizontal period of the microstructures was approximately 50 μm. Although the SEM is a powerful tool with a high resolution for imaging subtle features of a workpiece, the vertical features could not be detected, and the shape and height of the microstructures remained unknown even after SEM analysis.

To achieve highly accurate profile measurements of the triangular microstructures, a measurement system has been proposed, as shown in Figure 3. The system mainly consists of a precision scanning stage, a probing system, a microstylus, and a vibration isolation table. In the setup, the workpiece

Table 1: Key parameters of the proposed measurement system.

Probing system	Measurement range	30 mm
	Resolution (linear encoder)	2.5 nm
	Sampling frequency	Up to 20 MHz
	Stability (RMS)	1.6 nm
Microstylus	Tip material	Diamond
	Tip radius	2 μm
	Tip angle	20°
Linear scanning stage	Scanning range	5 mm
	Resolution	7 nm
	Min. incremental motion	50 nm
	Velocity	1 mm/s (max.)

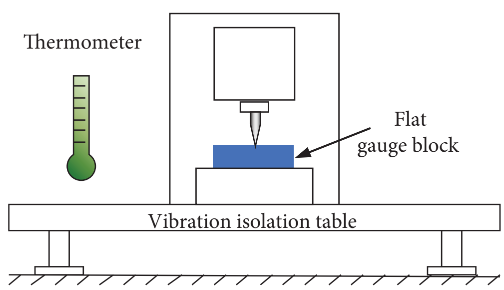

Figure 4: Schematic of the experimental setup for the stability test.

with triangular microstructures was mounted on the surface of the scanning stage, which was horizontally mounted on the vibration isolation table. The probing system was vertically set up and its sensing axis was perpendicular to the surface of the scanning stage. The microstylus, which had a small included angle and a spherical tip, was mounted on the shaft end of the probing system. During measurement, the scanning stage moved the workpiece, and the probing system with a microstylus sensed the vertical variation in the surface profile of the workpiece. The data from the scanning stage and the probing system was employed to reconstruct the surface profile of the measured microstructures.

The probing system has a measurement range of 30 mm, resolution of 2.5 nm, and sampling frequency of up to 20 MHz. The stability of the probing system is 1.6 nm. Since the included angle of the stylus tip is 20°, it can be used to measure a steep surface with a slope of up to 80°. The tip radius of the stylus is 2 μm. The linear stage has a scanning range of 5 mm with a resolution of 7 nm. Its minimum incremental motion is 50 nm and its maximum moving velocity is up to 1 mm/s. The parameters of the proposed measurement system are shown in Table 1.

3. Experiments

3.1. Stability Test. Figure 4 shows a schematic of the experimental setup for the stability test of the constructed measurement system. The microstylus of the probing system was made to contact with the surface of a flat gauge block, which

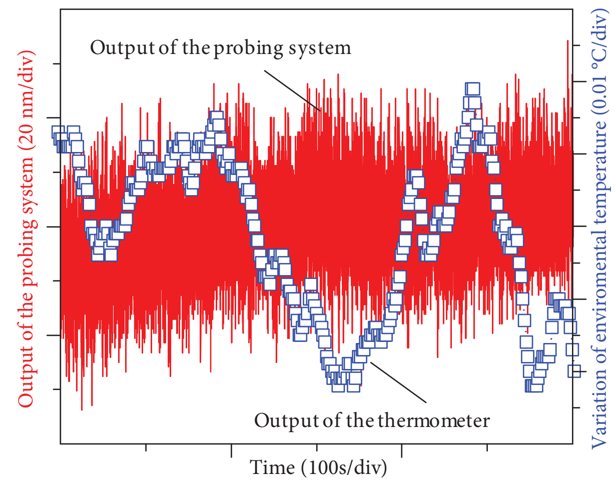

Figure 5: Stability of the constructed measurement system.

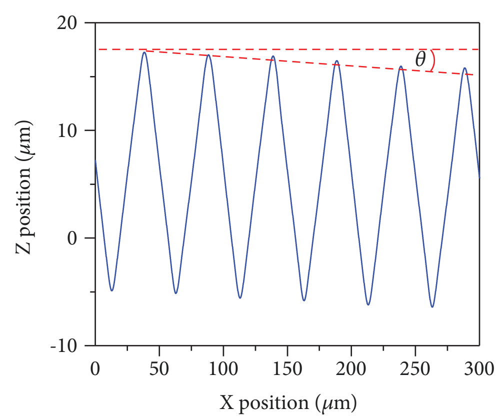

Figure 6: Surface profile measurement results of the microstructures.

was rigidly fixed on the scanning stage surface by screws. A highly accurate thermometer with a resolution of 0.001°C was employed to measure the variation in ambient temperature. The time intervals of data sampling for the probing system and the thermometer were set as 0.1 s and 0.50 s, respectively. The test duration was 300 s.

The acquired results are summarized in Figure 5. The variation in the probing system was ±30 nm, and the temperature variation of the measurement environment is ±0.03°C.

3.2. Surface Profile Measurement. The surface profiles of the triangular microstructures on the surface of the workpiece, whose schematic is shown in Figure 1, were measured by the constructed measurement system. The workpiece was scanned by the linear stage with a speed of 0.3 mm/min. During scanning, the surface profile variation in the vertical direction was traced by the diamond microstylus and detected by a linear encoder inside the probing system. The microstructures were measured in the range of 300 μm and the measurement time was 1 min.

The raw data of the measured profile is plotted in Figure 6, wherein data related to the lower horizontal axis

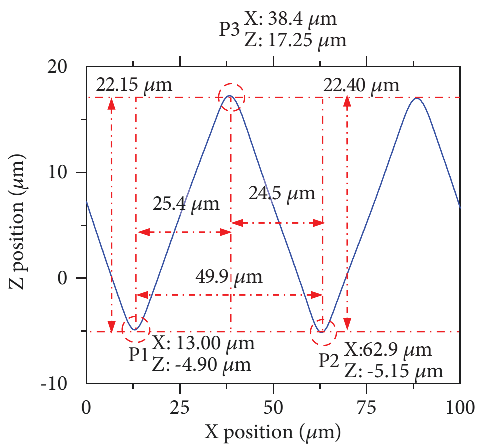

FIGURE 7: Details of the measured surface profile.

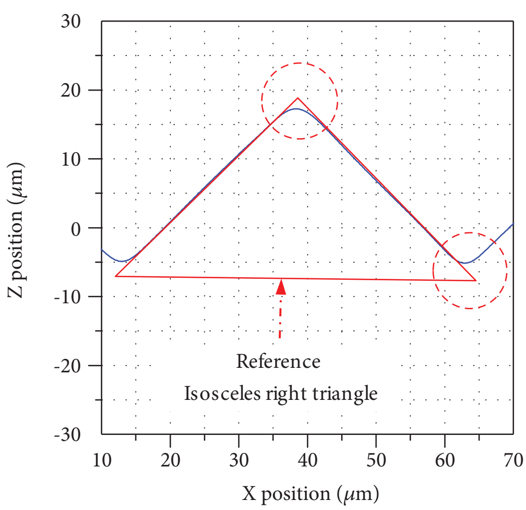

FIGURE 8: Shape comparison of the measured microstructures.

was obtained from the output of the scanning stage, and that related to the vertical axis was obtained from the output of the probing system. The measured microstructures were found to have been fabricated with a highly uniform period. However, the top surface of each period of the microstructures decreased regularly in the vertical direction. This was caused by the mounting process, and the inclination angle is denoted by θ. The error caused by the inclination should be corrected for highly accurate measurements.

To obtain more information from the measurement results, the details of the surface profile were replotted, as shown in Figure 7, and the x-axis range was changed to 100 μm. In this figure, three feature points—P1 and P2 at the surface bottom and P3 at the surface top—were extracted to measure the height and period of the microstructures. As shown in Figure 7, the first period of the measured microstructures was about 49.9 μm, and the heights of the first microstructures in the left and right sides were 22.15 μm and 22.40 μm, respectively.

The surface profile of the first measured microstructure was replotted, as shown in Figure 8, by employing the same

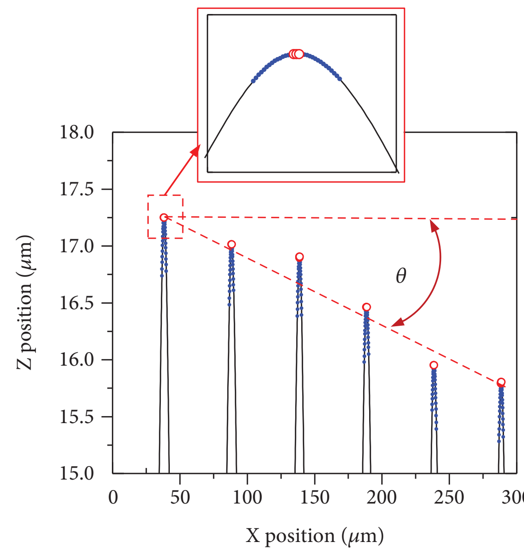

FIGURE 9: Compensation of inclination error.

vertical and horizontal plotting scales. An equilateral right triangle as a reference was used to verify the shape of the measured microstructure. It shows that the shape of the measured microstructure was equilateral right triangle. However, the shapes at the top and bottom were smoother compared to the endpoints of a triangle, which are indicated by two red circles in Figure 8. This error was caused by the stylus tip radius.

4. Error Compensations

4.1. Inclination Error Compensation. In the inclination error compensation, the top surface of the microstructures was used as a reference surface. The compensation process is illustrated in Figure 9. First, the top surface of each microstructure was extracted (blue dots). The top three points of each period (red circles) were fitted to a straight line. Then, the measured surface profile was rotated around the first point of the top three points of the first period. The rotated angle was the inclination angle of the fitted straight line, but the direction was opposite. In this measurement, the inclination angle is -0.36°. Therefore, the measured surface profile was rotated 0.36° along the anticlockwise direction. The results for inclination error compensation are shown in Figure 10.

4.2. Stylus Tip Radius Correction. Although the influence of the inclination error was compensated, the measured data still cannot provide the correct surface profile for the measured microstructures. The raw data of measurement results are a trace of the stylus tip center, which deviate from the real profile of the measured microstructures. Figure 11 schematizes the influence of the stylus tip radius in the surface profile measurement.

As shown in Figure 11, the nature of the surface profile measurement employing a contact-type stylus can be modeled as a tangential contact between a sphere and a surface.

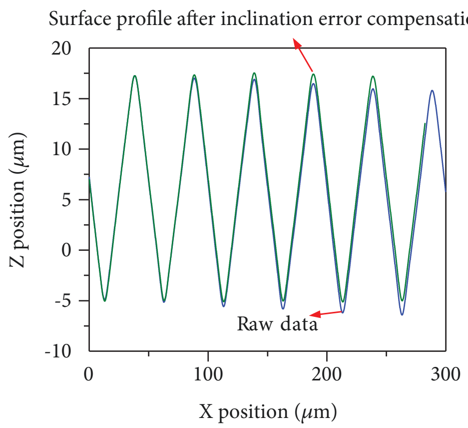

Figure 10: Results for inclination error compensation.

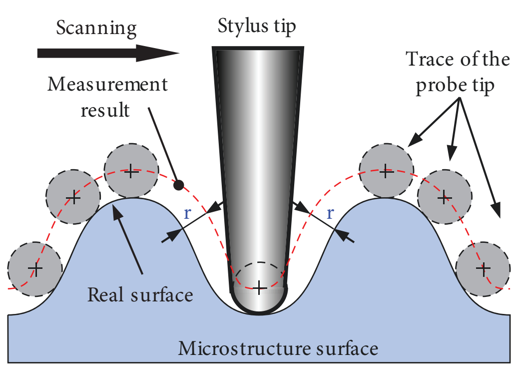

Figure 11: Influence of the stylus tip radius on the measurement result.

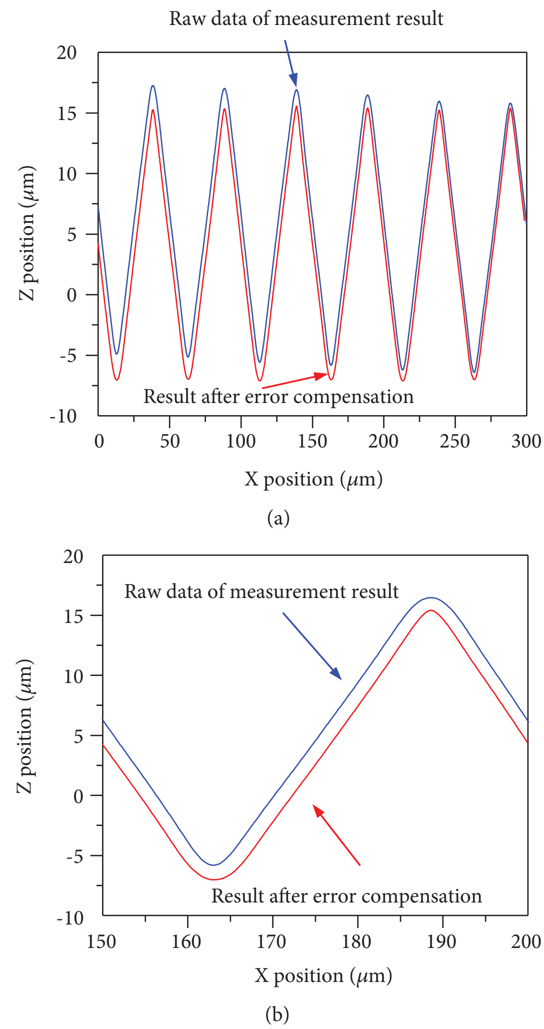

Figure 12: Compensation of the measured surface profile before and after error compensation. (a) Comparison of the raw data and result after error compensation. (b) Details of the surface profile after error compensation.

Therefore, the measurement result (outputs of the probing system and scanning stage) was an envelope curve of the real surface profile of the measured microstructures. One point of the measurement results one contacting point on the real surface. Both points have the same normal vector, and the distance between the two points along the direction of the normal vector is equal to the stylus tip radius. Therefore, the primary task when correcting the probe tip radius is to estimate the normal vector for the points of the measurement result. First-order linear fitting was employed to estimate the normal vector. Each point of the measurement results was first-order linear fitted with two points before and after. The normal vectors of the fitting results and the stylus tip radius were used to calculate the position of the contacting point. The obtained positions of the contacting points were used to reconstruct the surface profile for the measured microstructure. This reconstructed profile was considered the real profile of the measured microstructure with the stylus tip radius error compensated [33].

The surface profile after stylus tip radius compensation is shown in Figure 12(a). Note that the errors of both, inclination and stylus tip radius, were compensated for the final measurement results. More detail of the compensation result is shown in Figure 12(b).

5. Depth and Period Measurements

The depth and period, which are two most important features of manufacturing, were evaluated based on the well-measured surface profile of the measured microstructures. As shown in Figure 13, the period of the microstructures was evaluated by the peak-to-peak difference in the x-direction. The depth of the microstructures was evaluated by the peak-to-valley difference along the z-direction.

Figure 14 shows the evaluation result of the period of the measured microstructures. The mean value of each period was 50.065 μm, and the maximum variation was from $-0.360\,\mu$m to 0.425 μm. The standard deviation of periods was 0.291 μm.

Figure 15 shows the evaluation result of the depth of the measured microstructures. The mean depth for each case was 22.408 μm, and the maximum variation was from $-0.093\,\mu$m to 0.240 μm. The standard deviation of periods was 0.126 μm.

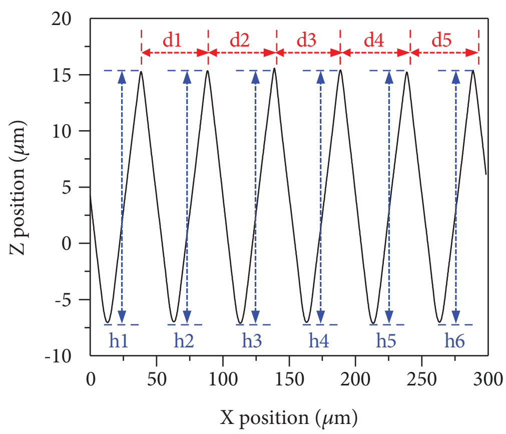

FIGURE 13: Evaluation of the period and depth.

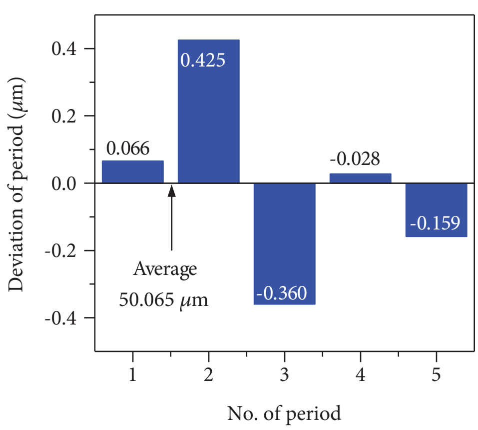

FIGURE 14: Evaluation result of the period of microstructures.

6. Conclusions

A measurement system, which employs a probing system with a microstylus and a linear scanning precision stage, is proposed in this paper. Surface profile measurement of the triangular microstructures was carried out to verify the performance of the developed system. Two methods were employed to correct the measurement errors caused by the specimen inclination and the radius of the stylus tip. The shape, depth, and period of the measured microstructures were also detected based on the results of surface profile measurement. The variation of the probing system was ±30 nm. The shape of the measured microstructures was an equilateral right triangle. The period of the measured microstructures was 50.065 μm, with a standard deviation of 0.291 μm. The depth of the measured microstructures was 22.408 μm with a standard deviation of 0.126 μm. Experimental results demonstrate the feasibility of the proposed surface profile measurement for microstructures with complex surface topography.

The proposed method can potentially measure the surface of more types of microstructures, and the measurement uncertainty can be evaluated by standard samples of the

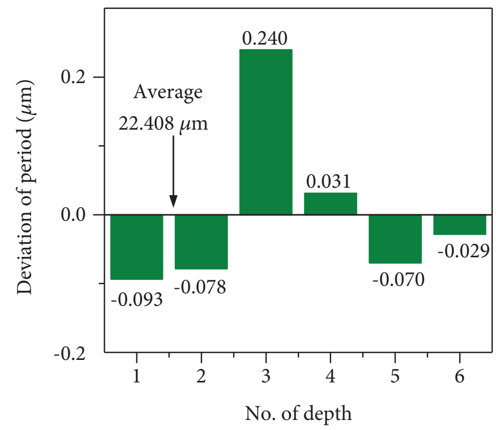

FIGURE 15: Evaluation result of the depth of microstructures.

microstructure with highly geometrical accuracy; these can constitute future work.

Data Availability

1. The (SEM image) data used to support the findings of this study are included within the article. 2. The (measurement result obtained by the proposed system) data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no competing interests.

Acknowledgments

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