XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

FABRICATION OF AN ULTRA-SMALL-DIAMETER OPTICAL FIBER PROBE FOR 3D MICRO METROLOGY

Hiroshi Murakami [1], *Akio Katsuki* [2], *Takao Sajima* [2], *Mitsuyoshi Fukuda* [1]
Masaki Okada [1], *Megumu Nagaura* [1]

[1] The University of Kitakyushu, Fukuoka, Japan, murakami@kitakyu-u.ac.jp
[2] Kyushu University, Fukuoka, Japan

Abstract – This paper presents a system for 3D micro structure measurement using an optical fiber probe. A stylus shaft with a diameter of 0.4 µm was fabricated using an acid-etch technique and the characteristics of the stylus shaft in the process of displacement detection were described. The deformation of the stylus tip caused by the contraction of the ultraviolet curing resin, which was used to glue the stylus shaft to the stylus sphere, was analyzed by a finite element method.

Keywords: Microstructure, Measurement, Optical fiber probe, Laser diode, CMM

1. INTRODUCTION

In recent years, demand has increased for a method that can precisely measure microstructures of mechanical micro parts, micro electro mechanical systems (MEMS), micro molds, optical devices, micro holes, etc. However, it is very difficult to precisely measure the shape of a micro structure with a large length-to-diameter (L/D) ratio because of the difficulty of probe fabrication and sensing methods with very small measuring force. Studies have reported micro structure measurement techniques employing a variety of probes such as optical probes, vibroscanning probes, vibrating probes, tunneling effect probes, opto-tactile probes, fiber deflection probes, optical trapping probes, and diaphragm probes [1-9].

This paper presents a system for 3D microstructure measurement using an optical fiber probe that is available as a kind of displacement measuring probe with low contact force and a wide measuring range. The stylus of the optical fiber probe was fabricated using an acid-etch technique. The shaft of the stylus is not necessarily rigid in order to detect the measuring force because its deflection is measured by a non-contact method. In this study, a stylus shaft with a diameter of 0.4 µm was fabricated using an acid-etch technique. Then, the deformation of the stylus tip caused by the contraction of the ultraviolet curing resin used to glue the stylus shaft to the stylus sphere was analyzed by a finite element method. As a result, a stylus shaft and tip with respective diameters of 0.4 and 1 µm were manufactured. In addition, the finite element method revealed that the maximum elastic deformation volume was about 0.8 nm and that the effect of the adhesive is minimal.

2. MEASUREMENT PRINCIPLE

Figure 1 is a diagram of the optical system. The fiber probe consists of a stylus shaft and a stylus tip. The probing system consists of the fiber stylus, two laser diodes with 375 nm wavelengths (LDX, LDY), and two dual-element photodiodes (PX, PY) in the X- and Y-directions. The stylus shaft is installed between the laser diodes and the dual-element photodiodes, which are oriented orthogonally. The laser diodes are mounted above the stylus tip, and the focused laser beams irradiate along the X- and Y-directions onto the stylus shaft. The two dual-element photodiodes are located opposite the laser diodes, beyond the stylus. The laser beams that pass through the stylus shaft are received by these dual-element photodiodes. The beam intensities detected by the photodiodes are converted into voltages and are identified by the symbols I_{PX1}, I_{PX2}, I_{PY1}, and I_{PY2} (V). A charge-coupled device is employed to monitor the positions of the stylus and test piece during the setting up of the equipment and measurement.

A cross-sectional diagram of the X-Y plane of the optical system shown in Fig.1 is shown in Fig. 2 to illustrate the measurement principle of the optical fiber probe.

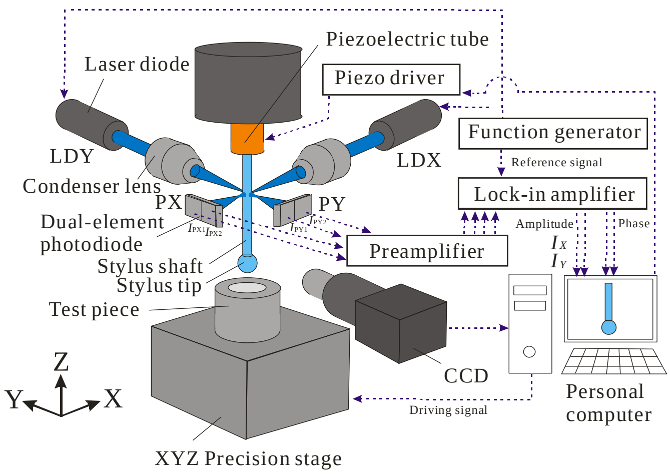

Fig. 1. Measurement system using optical fiber probe.

Before the stylus tip contacts the measured surface, the light intensities measured by each element of the dual-element photodiode are equal ($I_{PX1} = I_{PX2}$, $I_{PY1} = I_{PY2}$), as shown in Fig. 2(a). When the stylus tip contacts the measured surface in the X-direction, the stylus shaft is displaced, and the light intensities of each element of the dual-element photodiode are no longer equal to each other ($I_{PX1} = I_{PX2}$, $I_{PY1} > I_{PY2}$), as shown in Fig. 2(b). When the stylus shaft is displaced in the +X-direction, the angle of refraction of the laser beam that passes through the stylus shaft in the Y-direction changes due to a shift in the part of the stylus shaft being irradiated. Additionally, when the stylus tip contacts the measured surface in the Y-direction, the light intensities of each element of the dual-element photodiode are no longer equal to each other ($I_{PX1} < I_{PX2}$, $I_{PY1} = I_{PY2}$), as shown in Fig. 2(c). As a result, the contact direction and magnitude of the displacement of the stylus tip can be obtained from the output signals I_X and I_Y. The noise present in I_X and I_Y is removed by synchronous detection using a lock-in amplifier. The displacement of the stylus is magnified by using it as a rod lens. The surface of the microstructure is measured by recording the displacement of the stylus shaft and the coordinates at which the stylus makes contact with the surface being measured. The output signal I_X in the X direction using I_{PY1} and I_{PY2} and the output signal I_Y in the Y direction using I_{PX1} and I_{PX2} are defined by Equations (1) and (2), respectively.

$$\boldsymbol{I_X = I_{PY1} - I_{PY2}} \quad (1)$$

$$\boldsymbol{I_Y = I_{PX1} - I_{PX2}} \quad (2)$$

3. FABRICATION OF THE OPTICAL FIBER PROBE

The optical fiber probe consists of a stylus shaft and a stylus tip. The fabrication methods of the stylus shaft and tip are described below.

3.1. Stylus shaft

The stylus shaft was fabricated using an acid etch technique. First, the step index multi-mode optical fibers (core diameter: 100 μm, clad diameter: 125 μm) were stripped of their plastic layers. The tips of the fibers were then immersed in a hydrofluoric acid solution, and hydrofluoric acid etching was carried out at room temperature (23 °C). The diameter of the probe shaft was measured with an optical microscope. Figure 3 shows schematics of the stylus shaft at three different stages of the hydrofluoric acid-etch process. After this process, the stylus shaft was rinsed with water and acetone.

Figure 4 shows the experimental result using a 12% hydrofluoric acid solution, with the etching time on the x axis and the resultant diameter of the stylus shaft on the y axis. The etching velocity is 0.45 μm/min during the etching time of 0–60 min and 0.19 μm/min during the etching time of 240–300 min. As the etching time increases, the etching velocity decreases and becomes unstable because of the change in the concentration of the hydrofluoric acid solution caused by the volatilization of solution. Therefore, two-step etching was carried out. First, 46% highly concentrated hydrofluoric acid etching was carried out to fabricate a stylus shaft with a diameter of a few micrometers in a short time. The diameter of the stylus shaft was then measured precisely. Then, 7.7% lower concentrated hydrofluoric acid etching was carried out to fabricate a stylus shaft with a diameter of less than 1 μm.

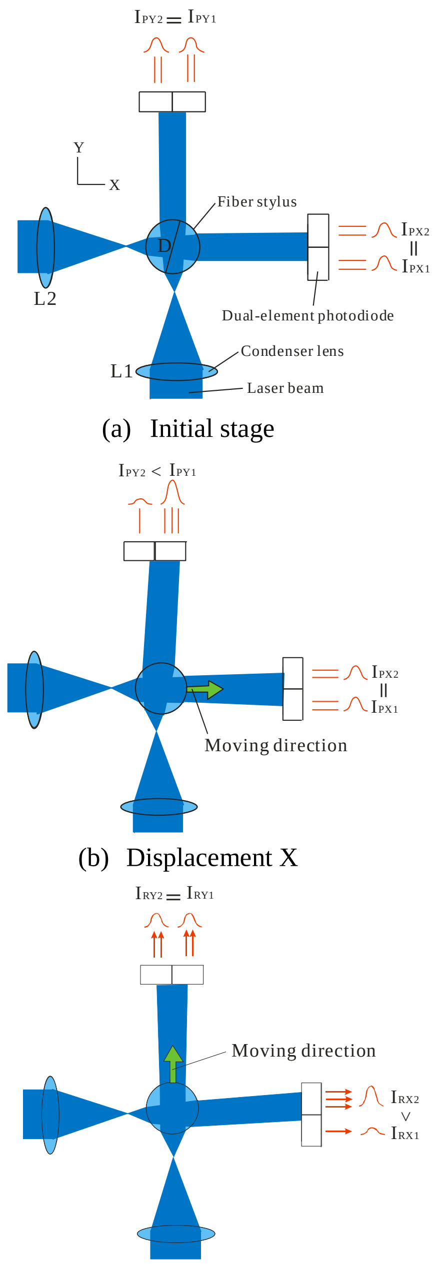

Fig. 2. Principle of measurement.

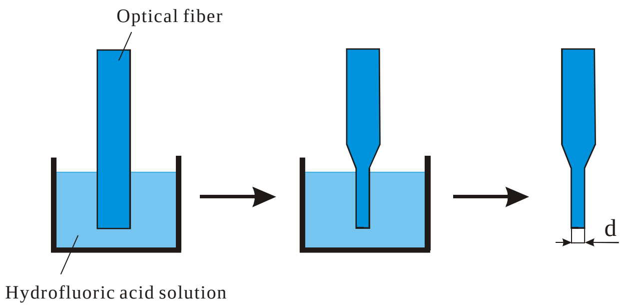

Fig. 3. Stylus shaft during the hydrofluoric acid etching.

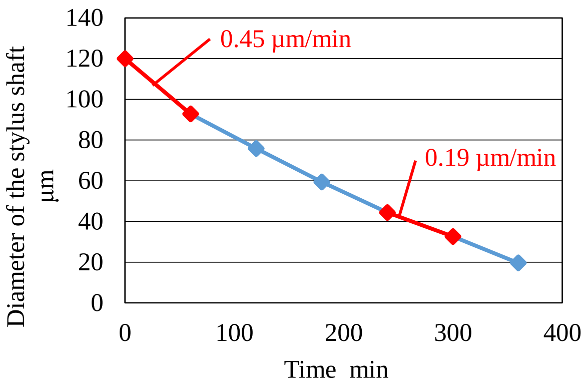

Fig. 4. Relationship between the etching time and diameter of the stylus shaft (12% hydrofluoric acid solution).

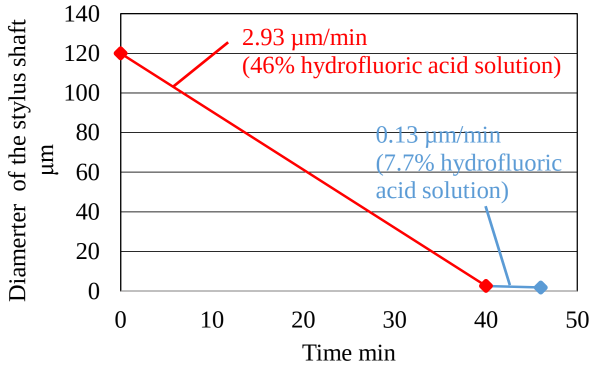

Fig. 5. Relationship between the etching time and diameter of the stylus shaft (46%-7.7% hydrofluoric acid solution).

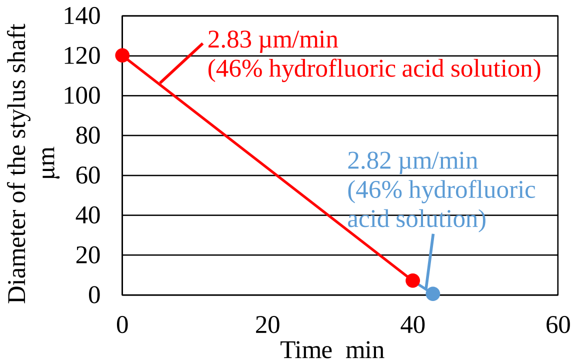

Fig. 6. Relationship between the etching time and diameter of the stylus shaft (46%-46% hydrofluoric acid solution).

Fig. 7. Photograph of the stylus shaft.

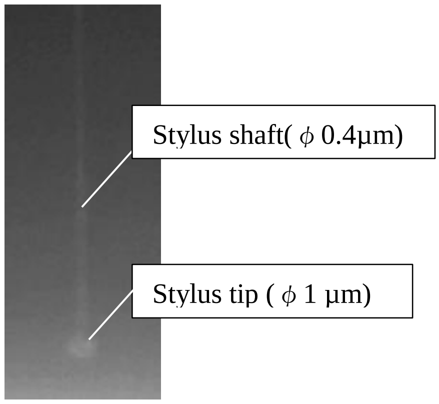

Fig. 8. Photograph of the stylus shaft glued to the stylus tip.

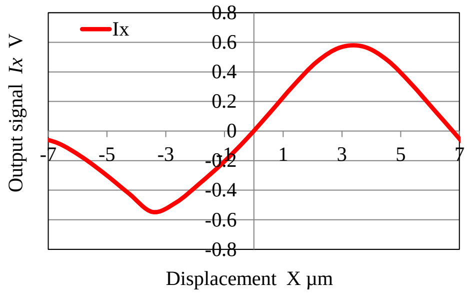

Fig. 9. Output voltage I_X induced by the X-displacement.

Figure 5 shows the experimental results. As is the case with the experimental result using a 12% hydrofluoric acid solution, the etching velocity using a 7.7% hydrofluoric acid solution becomes unstable during the etching time of 40–46 min. Therefore, it is very difficult to manufacture a stylus shaft with a diameter of less than 1 µm. Next, another two-step (46%-46%) etching was carried out. First, 46% highly concentrated hydrofluoric acid etching was carried out to fabricate a stylus shaft with a diameter of a few micrometers in a short time, and then the diameter of the stylus shaft was measured precisely. Then, the remaining etching time was calculated. Last, the same 46% highly concentrated hydrofluoric acid etching was carried out to fabricate a stylus shaft with a diameter of less than 1 µm. Figure 6 shows the experimental results. Because the etching time is less than 3 min, it is difficult to control the etching time, but the etching velocity is stable. As a result, it is confirmed that a stylus shaft with a diameter less than 1 µm could be easily manufactured.

Figure 7 shows a photograph of the tip of the stylus shaft. It is confirmed that the diameter of the thinnest part of the stylus shaft is about 0.4 µm. The length of the etching part is about 1500 µm.

3.2. Stylus tip

After fabricating the probe shaft, the shaft's tip was immersed in ultraviolet curing resin and then moved into contact with the probe sphere, which is made of glass. Next, the probe shaft and sphere were irradiated by ultraviolet rays and glued together. Figure 8 shows a photograph of the stylus shaft glued to a stylus tip, the two parts having diameters of 0.4 µm and 1 µm.

4. STYLUS CHARACTERISTICS

Figure 9 shows the experimental change in output signal I_X when the stylus shaft with a diameter of 0.4 µm was displaced in the ±X-direction. The x axis shows the displacement of the stylus, and the y axis shows the change in output signal I_X. When the stylus shaft is displaced in the X-direction, it can be verified that the fiber probe is available as a displacement sensor, because the rate of change in I_X can be approximated as a straight line within a range of ±3 µm in the X-direction.

An experiment was carried out to evaluate the measurement resolution of the stylus shaft with a diameter of 0.4 µm in the X direction. The change in output signal I_X was investigated when the stylus was displaced by 5 and 10 nm/0.1sec steps in the X direction, with the results shown in Fig. 10. The x axis shows the measurement time, and the y axis shows the change in output signal I_X in the X direction. It is possible to distinguish the 5 nm step, which shows that the resolution of the measurement system using a stylus shaft with a diameter of 0.4 µm is approximately 5 nm.

5. DEFORMATION OF THE STYLUS TIP

Because ultraviolet curing resin was employed to attach the stylus tip to the stylus shaft, the stylus sphere was deformed by the contraction stress of the resin. Because the shape measured using this system corresponds to the path of the sphere's center of the stylus tip, its shape is different from that of the contact point path of the stylus tip. Therefore, the contact points need to be calculated using the coordinates of the sphere's center measured using this system and the radius of the probe sphere. If the probe sphere is deformed considerably and the distances between the sphere's center and the contact points are different at each contact point, the measurement errors increase. Thus, the sphericity of the probe sphere affects the measured accuracy.

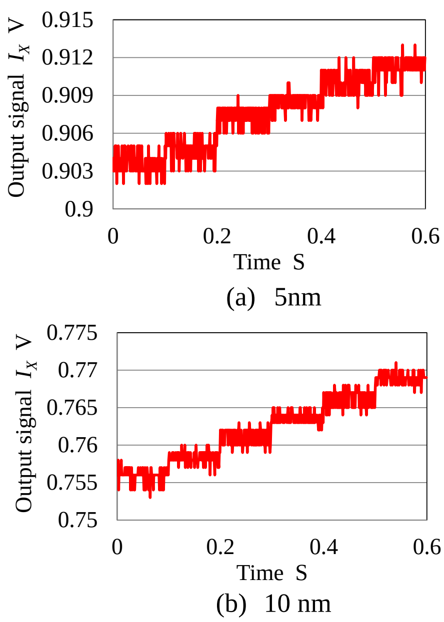

Fig. 10. Variation in output voltage I_X induced by each step feed of (a) 5 nm and (b) 10 nm.

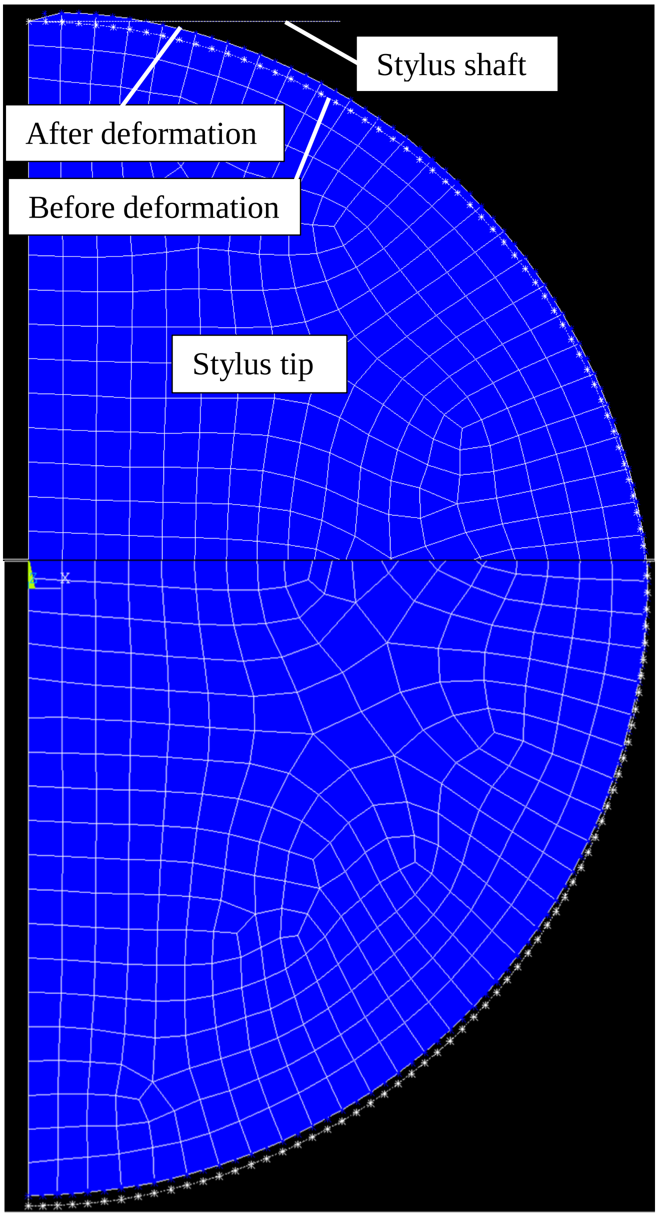

Fig. 11. Analytical result by a finite element method.

The deformation of the stylus tip caused by the contraction of the ultraviolet curing resin gluing the stylus shaft and stylus sphere together was analyzed by a finite element method. There are 1778 nodes after finite element discretization. The diameters of the stylus shaft and sphere are 2.5 and 5 µm, respectively. By considering the coefficient of contraction of the ultraviolet curing resin and the ratio of the Young's modulus of the ultraviolet curing resin to the Young's modulus of the silica stylus sphere, the displacement magnitude of each node in contact with the ultraviolet curing resin is calculated.

Figure 11 shows the analytical result. The white broken line shows the stylus tip after deformation. It was shown by a finite element method that the maximum elastic deformation volume was about 0.8 nm in the Y direction. The elastic deformation volume in the X direction is much smaller than that in the Y direction. The elastic deformation volume in the Y direction is smaller than the measurement resolution of this system. Therefore, the effect of the contraction of the ultraviolet curing resin is minimal.

6. CONCLUSIONS

This paper describes a system for measuring 3D microstructures using an optical fiber probe. For this research, a stylus shaft and stylus tip were fabricated by using an acid-etch technique and gluing the stylus shaft and sphere together using ultraviolet curing resin. The characteristics of the stylus shaft in the process of displacement detection were described. Then, the deformation of the stylus tip caused by the contraction of the ultraviolet curing resin, which was used to glue the stylus shaft and sphere together, was analyzed by a finite element method. As a result, a stylus shaft and tip with respective diameters of 0.4 and 1 µm were manufactured, and the resolution of the measurement system using this shaft was found to be approximately 5 nm. In addition, using the finite element method, it was revealed that the maximum elastic deformation volume was about 0.8 nm and the effect of the contraction of the ultraviolet curing resin is minimal.

ACKNOWLEDGMENTS

This study was partly supported by a research grant from the Mitutoyo Association for Science and Technology and by JSPS KAKENHI Grant Number 26420392.

REFERENCES

[1] T. Masuzawa, Y. Hamasaki and M. Fujino, Vibroscanning Method for Nondestructive Measurement of Small Holes, CIRP Annals, Vol.42, No.1, (1993) pp.589-592.

[2] K. Hidaka, A. Saito and S. Koga, Study of a Micro-roughness Probe with Ultrasonic Sensor, CIRP Annals—Manufacturing Technology, Vol.57, (2008) pp.489-492.

[3] M. B. Bauza, R. J. Hocken, S. T. Smith and S. C. Woody, Development of a Virtual Probe Tip with an Application to High Aspect Ratio Microscale Features, Review of Scientific Instruments, Vol.76, (2005) pp.095112-1-095112-8.

[4] J. D. Claverley and R. K. Leach, A Vibrating Micro-scale CMM Probe for Measuring High Aspect Ratio Structures, Microsystem Technologies, Vol.16, (2010) pp.1507-1512.

[5] T. Shiramatsu, K. Kitano, M. Kawata and K. Mitsui, Development of a Measuring Method for Shape and Dimension of Micro-components—Modification to the Original Measuring System, Calibration of the Probes and the Results of Dimensional Measurements—, Journal of the Japan Society of Mechanical Engineers, Series C, Vol.68, No.683, (2002) pp.267-274 (in Japanese).

[6] H. Schwenke, F. Wäldele, C. Weiskrich and H. Kunzmann, Opto-Tactile Sensor for 2D and 3D Measurement of Small Structures on Coordinate Measuring Machines, CIRP Annals, Vol.50, No.1, (2001) pp.361-364.

[7] B. Muralikrishnan, J. A. Stone, and J. R. Stoup, Fiber Deflection Probe for Small Hole Metrology, Precision Engineering, Vol.30, (2006) pp.154-164.

[8] M. Michihata, Y. Takaya and T. Hayashi, Development of the Nano-probe System based on the Laser-trapping Technique, CIRP Annals, Vol.57, (2008) pp.493-496.

[9] T. Liebrich and W. Knapp, New Concept of a 3D-probing System for Micro-components, CIRP Annals, Vol.59, (2010) pp.513-516.