DEVELOPMENT OF A SYSTEM FOR 3-D MICRO METROLOGY USING AN OPTICAL FIBER PROBE

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INTRODUCTION
In recent years, demand has increased for a method to measure the precision of microstructures of mechanical micro parts, MEMS, micro molds, optical devices, and micro holes, and the like. It is very difficult, however, to precisely measure the shape of microstructures with a large increase of length/diameter (L/D) ratio because of the difficulty of probe fabrication and sensing method with very small measuring force. Many studies have reported microstructure measurement techniques that employ a variety of probes, such as optical probes, vibroscanning probes, vibrating probes, tunneling effect probes, opto-tactile probes, fiber deflection probes, optical trapping probes, diaphragm probes [1–6], among others. This paper presents a system for 3-D microstructure measurement using an optical fiber probe that is available as a kind of displacement measuring probe with low contact force and that has a wide measuring range. It is also easy to fabricate the probe whose stylus tip diameter is smaller than 5 µm with an aspect ratio larger than 200. The stylus of the optical fiber probe was fabricated using an acid etching technique [7]. The shaft of the stylus is not necessarily rigid in order to detect measuring force because its deflection is measured by a non-contact method. In this research, the design parameters of the optical system are determined by using a ray tracing method, and a prototype of the probing system is fabricated on trial to verify the simulation results of the ray tracing method. Also, the utility of this system is confirmed by measuring the shape of a 10 µm diameter micro hole and a 600 µm diameter ruby sphere.

MEASUREMENT PRINCIPLE
Figure 1 shows an illustration of the probing system and a photograph of the stylus shaft and the stylus tip. The fiber probe consists of a stylus shaft (optical fiber) and a stylus tip with diameters of 3 and 5 µm, respectively (Fig. 1(b)). The probing system consists of the fiber stylus, two laser diodes (LDX, LDY), and two dual-element photodiodes (PX, PY) in the X and Y directions. The fiber probe is installed perpendicular to the XY plane between the laser diodes and the dual-element photodiodes (Fig. 1(a)). The stylus shaft is irradiated by two focused laser beams emitted by two laser diodes through condenser lens in the X and Y directions. The dual-element photodiodes, PX and PY, are opposite to the laser diodes, LDX and LDY, with respect to the stylus shaft respectively. Each laser beam, that penetrates the stylus shaft, impinges upon the corresponding dual-element photodiode. The intensities detected by PX and PY are converted into voltage signals and are represented as \( I_{PX1} \), \( I_{PX2} \), \( I_{PY1} \), and \( I_{PY2} \) (V).

(a) Schematic diagram of the probing system

FIGURE 1. Optical measurement system.
Figure 2 shows the principles governing the measurement process. Before the stylus tip contacts the measured plane, the light intensity measured by each element of the dual-element photodiode is equal ($I_{PX1} = I_{PX2}$, $I_{PY1} = I_{PY2}$), as shown in Figure 2(a). When the stylus tip contacts the measured plane in the X direction, the stylus shaft is displaced, and the light intensity of each element of the dual-element photodiode becomes unequal ($I_{PX1} < I_{PX2}$, $I_{PY1} = I_{PY2}$), as shown in Figure 2(b). Additionally, when the stylus tip contacts a measured plane in the Y direction, the stylus shaft is displaced, and the light intensity of each element of the dual-element photodiode becomes unequal ($I_{PX2} > I_{PX1}$, $I_{PY1} = I_{PY2}$), as shown in Figure 2(c). As a result, the contact direction and magnitude of the stylus tip can be ascertained.

The displacement of the fiber stylus is magnified by the probe shaft, which works as a rod lens. The surface of the micro structure is scanned in the XYZ direction using a precision stage, and the accuracy of the micro structure is measured by recording the coordinates of contact points and the displacement of the fiber stylus.

Output signal $I_x$ in the X direction using $I_{PY1}$ and $I_{PY2}$ and output signal $I_y$ in the Y direction using $I_{PX1}$ and $I_{PX2}$ are defined by Equations (1) and (2), respectively.

$$I_x = I_{PY1} - I_{PY2}$$  \hspace{1cm} (1)

$$I_y = I_{PX1} - I_{PX2}$$  \hspace{1cm} (2)

**OPTICAL ANALYSIS AND EVALUATIVE EXPERIMENT**

When the displacement of the fiber stylus is detected, the resolution of the system changes by the distance $L_0$ between the focal position of the condenser lens and the fiber stylus, the distance $L_1$ between the fiber stylus and the dual-element photodiode, and the diameter $D$ of the stylus shaft. In this study, we determine the design parameters of the optical system using a ray tracing method.

First, random numbers with a Gaussian distribution are generated using the Box–Muller method, and rays based on this distribution are radiated from the condenser lens. The radiation intensity distribution of this laser beams is assumed to be the Gaussian distribution. For this simulation of ray tracing method, the intensities detected by each photodiode are defined as relative intensities for all radiation rays and are expressed as $I_x$ (%) and $I_y$ (%). The rays are then traced through the optical system, and the intensity expected at each photodiode is calculated. Table 1 lists the simulation conditions.

**TABLE 1. Simulation conditions.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser source</td>
<td>Wavelength: 650 nm</td>
</tr>
<tr>
<td>Stylus shaft diameter $D$</td>
<td>3 µm</td>
</tr>
<tr>
<td>Distance between planes 0 and 1 $L_0$</td>
<td>10 µm</td>
</tr>
<tr>
<td>Distance between planes 2 and 3 $L_1$</td>
<td>40 mm</td>
</tr>
<tr>
<td>Numerical aperture of the condenser lens</td>
<td>0.13</td>
</tr>
<tr>
<td>Displacement $X$</td>
<td>$-7.0 \sim 7.0$ µm</td>
</tr>
<tr>
<td>Laser beam diameter $D_s$</td>
<td>10 µm</td>
</tr>
</tbody>
</table>

Figure 3 shows a graphic display of the ray tracing result when the stylus shaft is displaced toward $Y = -0.5$ µm.

Also, Figures 4 and 5 show the overlapping display of ray-tracing simulation and
experimental results in case that the stylus tip displacement from -7 to +7 µm in the X direction. In this graph, the theoretical value is converted into the displacement of the stylus tip. The stylus length is 1 mm and the distance between the stylus tip and the cross section of the stylus shaft irradiated by the laser beam is 0.5 mm. Therefore, the displacement of the stylus tip is magnified to about 3 times that of a diameter of the stylus shaft irradiated by the laser beam when the stylus shaft is regarded as the cantilever beam of rigid support. The theoretical value agrees with the experimental value. Therefore, the utility of this simulation is confirmed.

EVALUATION OF THE MEASUREMENT RESOLUTION
An experiment is carried out to evaluate the measurement resolution of the fiber stylus in the X and Y directions. The changes of an output signal $I_X$ in the X direction are examined when the stylus tip is displaced by 10-nm step in the X direction. Figure 6 shows the output voltage $I_X$ which is induced by the displacement of 10 nm step feeding of the stage toward +X direction. The horizontal axis shows the measurement time, and the vertical axis shows the changes in an output signal $I_X$ in the X direction. The voltage change $I_D$ ($V_{\Delta I}$) is caused by various noises. However, it is possible to distinguish the 10 nm step, which shows that the measurement resolution of this system is 10 nm. In order to improve the measurement resolution, it is necessary to reduce the noise, develop the signal processing method, and use a high-power laser diode.

MEASUREMENT EXAMPLES OF MICRO HOLE (φ10 µm) AND RUBY SPHERE (φ600 µm)
Measuring experiments on a micro hole and a ruby sphere were performed to demonstrate the applicability of the optical fiber probe. Figure 7 shows a photograph of the φ10 µm micro hole while it is measured by a φ5 µm diameter stylus tip. The hole shape was ascertained by scanning the hole wall at contact angle intervals of 10°. The hole wall was displaced in the X and Y directions by the XYZ precision piezoelectric stage to maintain a state in which output signal $I = \sqrt{I_X^2 + I_Y^2}$ was equal to the threshold value; the coordinates of the stage were then recorded, and the hole wall was displaced by 5 µm in the –Z direction. This
operation was repeatedly carried out, to ascertain the shape of the micro hole. The resolution of the stage in X and Y directions is 1 nm. The hole wall fixed by the stage was fed at a rate of 1 µm/s. The measured length was 40 µm. Figure 8 shows the results of form measurement of the micro hole. The maximum value of the hole diameter in the measuring range is 10.45 µm.

Figure 9 shows a photograph of the φ 600 µm ruby sphere while it is measured by a S φ 5 µm diameter stylus tip. The measuring area was 300 × 300 × 100 µm for the X, Y and Z directions. When the stylus tip comes into contact with a measured plane in Z direction, the stylus shaft is buckled and then deflected. This deflection is measured. The ruby sphere was displaced in the +Z direction by the XYZ precision stage to maintain a state in which output signal $l = \sqrt{l_x^2 + l_y^2}$ was equal to the threshold value, the coordinates of the stage were then recorded, and the ruby sphere was moved to the initial position. The resolution of the stage in Z direction is 10 nm. The ruby sphere fixed by the stage was fed at a rate of 1 µm/s in the Z direction. Then, the ruby sphere was displaced by 30 µm in the X or Y direction. This operation was carried out repeatedly, to ascertain the shape of the ruby sphere. The total number of probing points was 100. Figure 10 shows the measurement result. The diameter of the best-fit sphere using the least square method is 598.28 µm.

ACKNOWLEDGMENT
The authors would like to thank Dr. Osamu Ohnishi from the Kyushu University for his technical support in the experiments. This work was supported in part by a Industrial Technology Research Grant Program in 2009 from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

CONCLUSIONS
The system for measuring a 3-D micro structure using an optical fiber probe is developed. The design parameters of this system are determined by ray tracing method. Then, a trial measurement system was fabricated, the measurement accuracy was examined by using basic experimental apparatus. As a result, the following are our result.
1. The design parameters of the optical system are determined by ray tracing method.
2. The resolution of the measurement system is approximately 10 nm.
3. The utility of this system is confirmed by measuring the shape of a 10 µm diameter micro hole and a 600 µm diameter ruby sphere.

REFERENCES