Development of a Measuring System for Micro Hole Accuracy Using an Optical Fiber Probe -Evaluation of Measurement Repeatability-

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Abstract:
This paper presents a micro hole measuring system using an optical fiber probe. The probe is deflected when it comes into contact with a hole surface, and this deflection is measured optically. In this research, the accuracy and repeatability of such measurement are examined by measuring a roughness standard specimen and a micro hole. The results clarify that the probe has a resolution of 15 nm and the repeatability error for 10 measurements of a roughness standard specimen is within $\pm 0.1 \mu m$ in touch trigger mode and $\pm 0.03 \mu m$ in scanning mode.

Keywords: micro hole, deep hole, measurement, optical fiber probe, laser diode, accuracy

1. Introduction
In recent years, there has been increasing demand for a method to measure the accuracy of micro holes in fuel injector nozzles, chemical fiber spinning nozzles, optical fiber ferrules, medical devices and so on. However, it is very difficult to precisely measure the shape of a micro hole with a large length/diameter ($L/D$) ratio.

Conventionally, micro holes have been measured using optical microscopes due to the demands of such work. However, this method cannot evaluate the roundness, straightness, cylindricity and surface roughness of the inside of holes because optical microscopes can measure only the shape of a hole’s inlet and outlet. Destructive inspection by cross-sectional observation has been applied to measurement of the internal shape of holes up to now, but this method has the disadvantage of rendering the workpiece unusable after the inspection. Accordingly, non-destructive inspection is essential to assure the quality of the workpiece. A probe with a small diameter, large aspect ratio and low force is necessary to enable precise measurement of micro holes.

Many studies to date have reported on micro hole measurement [1-9] using optical probes, vibroscanning probes, vibrating probes, tunneling effect probes, opto-tactile probes, fiber deflection probes, optical trapping probes, diaphragm probes and so on. This paper presents a micro hole measuring system using an optical fiber probe that is available as a low-force displacement probe and has a wide measuring range.

In addition, it is easy to manufacture the probe with a diameter smaller than 10 µm and a aspect ratio larger than 100. Its shaft does not need rigidity to detect measuring force because the deflection of this fiber probe is measured using a non-contact method. In this research, the accuracy and repeatability of the measuring system are examined by measuring a roughness standard specimen and a micro hole.

2. Measurement Principle
Figure 1 shows an illustration of the optical system and a photograph of the fiber probe. Figure 2 shows the measurement principle. An optical fiber of 30 µm in diameter with a ball of 50 µm in diameter on the end serves as the fiber probe. The system is composed of the fiber probe, two floodlighting fibers (FPX, FPY) and two double-light reception fibers (FX1, FX2, FY1, FY2) in the X and Y directions. The fiber probe is installed between the floodlighting fibers and the light reception probes. The micro hole is placed on an XYZ piezostage. The light from the laser diodes is focused on the fiber probe by a microscope and is detected by the photo diodes. The data is transferred to a personal computer through a CCD.

Figure 1 : Optical system and photograph of the fiber probe
fibers in orthogonal positions. The two floodlighting fibers connected to semiconductor lasers are used for irradiation of the laser beam around the fiber probe. The stem of the probe is irradiated by a laser beam emitted by the two floodlighting fibers in the X and Y directions. The two double-light reception fibers connected to four photo diodes are opposite the floodlighting fibers. The laser beams penetrated the probe are received in the two double-light reception fibers. The intensities detected by the four photo diodes are converted into voltage values, and are defined as $I_{FX1}$, $I_{FX2}$, $I_{FY1}$, and $I_{FY2}$ (V), respectively.

When the fiber probe is not in contact with a hole surface, the light intensity measured by the two double photo diodes is equal ($I_{FX1} = I_{FX2}$, $I_{FY1} = I_{FY2}$), as shown in Figure 2 (a). When it comes into contact with a hole surface (X direction), the probe is displaced and the light intensity of the two double photo diodes becomes unequal ($I_{FX1} = I_{FX2}$, $I_{FY1} > I_{FY2}$), as shown in Figure 2 (b). Additionally, when the fiber probe comes into contact with a hole surface (Y direction), the probe is displaced and the light intensity of the two double photo diodes becomes unequal ($I_{FX1} > I_{FX2}$, $I_{FY1} = I_{FY2}$), as shown in Figure 2 (c). Consequently, the direction of contact can be ascertained.

The displacement of the fiber probe is magnified by using it as a rod lens. The surface of the micro hole is scanned in the Z direction using the precision stage, and the accuracy of the micro hole is measured by recording the contact coordinates and displacement of the fiber probe.

Output signal $I_X$ in the X direction using $I_{FY1}$ and $I_{FY2}$ and output signal $I_Y$ in the Y direction using $I_{FX1}$ and $I_{FX2}$ are defined by Equations (1) and (2), respectively.

$$I_X = I_{FY1} - I_{FY2} \quad (1)$$

$$I_Y = I_{FX1} - I_{FX2} \quad (2)$$

### 3. Fundamental Experiment

#### 3.1 Contact Force and Resonant Frequency of the Fiber Probe

A low-force probe is necessary in order to prevent scratching and deformation during the measurement of micro holes. Figure 3 shows the contact force calculated by assuming that the optical fiber probe measuring 50 µm in diameter and 5mm in length is equal to the cantilever of the fixed support. The horizontal axis shows the displacement of the feeler (probe tip), and the vertical axis shows the contact force of the fiber probe. When the
displacement of the feeler is several µm, the probe maintains a low contact force of within several µN.

The resonant frequency calculated by assuming that the optical fiber probe measuring 50 µm in diameter and 5mm in length is equal to the cantilever of the fixed support is 926Hz.

3.2 Evaluation of Measurement Resolution

Output signals $I_x$ and $I_y$ change when the fiber probe is displaced. However, for the same amount of probe displacement, these signals differ in terms of the amount of change depending on the contact azimuth angle between the contact sphere of the probe and the measured surface. An experiment was therefore carried out to evaluate the measurement resolution of the fiber probe by changing the contact azimuth angle.

The amounts of change $\Delta I_x$ and $\Delta I_y$ in output signals $I_x$ and $I_y$ were examined when the probe was displaced by 15, 30 and 50 nm in the contact direction $\theta$ (15° pitch), as shown in Figure 4. Figure 5 shows the experimental apparatus used to evaluate the measurement resolution. The probe was displaced in the contact direction $\theta$ by the hole wall of the jig fixed by the precision piezoelectric stage (P600.3S, PI Co., Ltd.). The amount of change of the output signal in the contact direction $\theta$ is defined as $\Delta I = \sqrt{\Delta I_x^2 + \Delta I_y^2}$.
Figures 6, 7 and 8 show the output voltage $\Delta I$ induced by the displacement of step feeding by 15, 30 and 50 nm, respectively. The horizontal axis shows the measurement time, and the vertical axis shows the amount of change in the output signal $\Delta I$. The voltage variation caused by various noises is defined as $I_D(V_{p-p})$. $I_D$ is shown in Figure 6. It is possible to distinguish the 15 nm step from Figure 6, and, it is confirmed that the measurement resolution of the optical fiber probe is about 15 nm.

Figure 9 shows the experimental results. The horizontal axis shows the contact azimuth angle $\theta$, and the vertical axis shows the resolution. The measurement resolution of this fiber probe is approximately 15 nm over the measuring range of 360°. In order to improve this resolution, it is necessary to reduce noise, develop the signal processing method and use a high-power laser diode.

4. Measuring Experiment

4.1 Roughness Standard Specimen

Next, a measuring experiment using a roughness standard specimen ($Ra = 2.94 \mu m$, $Rz = 9.3 \mu m$) was performed to evaluate measurement accuracy and repeatability. The experiment was conducted using touch trigger mode and scanning mode. The precision XYZ piezo stage was controlled to maintain a state in which output signals $I_X$ and $I_Y$ were equal to the threshold value; the coordinates of the stage were then recorded, and the shape of the measuring sample was ascertained using its coordinates in touch trigger mode. In scanning mode, on the other hand, the measuring sample was scanned in one direction (e.g., the Z direction), and the shape of the measuring sample was then ascertained by measuring the probe deflection (using output signals $I_X$ and $I_Y$).

4.1.1 Touch trigger mode

Figure 10 shows the experimental apparatus used to measure the roughness standard specimen in touch trigger mode. The specimen was displaced in the –X direction by the XYZ precision piezoelectric stage to maintain a state in which output signal $I_X$ or $I_Y$ was equal to the threshold value (0.015V); the coordinates of the stage were then recorded, and the roughness standard specimen was displaced by 1 µm in the –Z direction. This operation was repeatedly carried out, to ascertain the shape of the roughness standard specimen. The specimen fixed by the stage was fed at a rate of about 10 µm/s, and measuring data were acquired at sampling intervals of 1 µm in the –Z direction. The measured length was 100 µm due to the limitations of the stage’s range of movement.

Figures 11 (a) and (b) show the measurement results for the roughness standard specimen measured using a surface roughness tester and the measuring system, respectively. Though it is not possible to compare these measurement results accurately since the diameter of the surface roughness tester’s feeler (radius = 5 µm) was different from that of the measuring system (radius = 25 µm), their shapes, wavelengths and crest values correspond well with each other. The shapes of the
concave and convex parts are a little different from the shape of the roughness standard specimen because the diameter of the feeler for the surface roughness tester was different from that for the measuring system shown in Figure 12. When the diameter of the feeler is large, undulations in the shape of convex parts vary slightly and those in the shape of concave parts vary significantly. Figure 11 (c) shows the values for 10 measurements of the roughness standard specimen obtained using the measuring system and superimposed, and Figure 11 (d) shows the deviation from the average of the 10 measurements superimposed. The repeatability error for these measurements is within ±0.1 µm.

4.1.2 Scanning mode

The roughness standard specimen was scanned in the Z direction (the stage is not controlled in the X and Y directions), and the shape of the measuring sample was then ascertained by measuring the probe deflection (using output signals \( I_x \) and \( I_y \)) in scanning mode. Because the measuring range (the range of the fiber tip’s deflection) of the fiber probe is about ±4 µm, it is impossible to measure the shape of all concave and convex parts. Accordingly, measurement of parts with a convex shape was carried out. The roughness standard specimen fixed by the stage was fed at a rate of 20 µm/s, and the shape of the specimen was ascertained by scanning the wall at sampling intervals of 1 µm in the -Z direction. The measured length was 50 µm.

Figures 13 (a) and (b) show the measurement results for the roughness standard specimen measured using a surface roughness tester and the measuring system, respectively. In the same way as outlined above, since the diameter of the surface roughness tester’s feeler is different from that of the measuring system, and moreover parts with a convex shape were measured, the shape and crest values are different from the measured values of the surface roughness tester shown in Figure 14. When the diameter of the feeler is large, undulations in the shape of convex parts vary slightly and the measured values are small. Figure 13 (c) shows the values for 10 measurements of the roughness standard specimen taken by the measuring system and superimposed, and Figure 13 (d) shows the deviation from the average of the 10 measurements superimposed. The repeatability error for these measurements is within ±0.03 µm. Accordingly, it is confirmed that repeatability in scanning mode is higher than that in touch trigger mode.

4.2 Micro Hole (\( \phi \)100 µm)

A measuring experiment on a micro hole was performed to demonstrate the applicability of the optical fiber probe. The micro hole used here was made in acrylic using a \( \phi \)100 µm drill. Figure 15 shows a photograph of the hole and the optical fiber probe taken using a microscope, and also includes a schematic diagram of the measuring experiment.

The measured depth was about 70 µm due to the limitations of the stage’s range of movement. The hole shape was ascertained by scanning the hole wall at contact

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**Figure 13**: Comparison of the cross-sectional shape of the roughness standard specimen ascertained using a surface roughness tester and the measuring system (scanning mode)

**Figure 14**: Schematic diagram of differences in measurement shape using feelers of 50 µm and 10 µm in diameter

**Figure 15**: Photograph and schematic diagram of the measuring experiment
angle intervals of 15° in the Z direction. The hole wall fixed by the stage was fed at a rate of 20 µm/s in scanning mode, and the shape of the roughness standard specimen was ascertained by scanning the wall at sampling intervals of 1 µm in the +Z direction.

Figure 16 shows the results of measuring the straightness of the micro hole (+X direction). Figure 17 shows the deviation from the average of the 10 measurements superimposed. The repeatability error for these measurements is within ±0.03 µm.

Figure 18 shows the results of form measurement of the micro hole. It is confirmed that the hole expands in the +Z direction. The maximum value of the hole diameter in the measuring range is 105.53 µm.

5. Conclusion
We developed a measuring system for micro holes using an optical fiber probe. A prototype of the system was manufactured, and its measuring accuracy and repeatability were examined. The results obtained are as follows:
1. The measurement resolution of the fiber probe is approximately 15 nm over the measuring range of 360°.
2. A measuring experiment on a micro hole was performed to demonstrate the applicability of the optical fiber probe. The results show that it can be used to evaluate micro hole accuracy.
3. The accuracy of a roughness standard specimen measured using the system corresponds well to that of a surface roughness tester in terms of both shape and value.
4. The repeatability error for 10 measurements of the roughness standard specimen is within ±0.1 µm in touch trigger mode and ±0.03 µm in scanning mode.

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