Development of a System for Measuring Micro Hole Accuracy Using an Optical Fiber Probe*

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Abstract

This paper presents a system for measuring micro holes that makes use of an optical fiber probe. The optical fiber probe is deflected when it comes into contact with a hole surface, and this deflection is measured optically. For this research, the optical fiber probe is fabricated by using an acid etch technique and its characteristics in the process of displacement detection are described. The effects of surface force are then evaluated. The diameter of the optical fiber probe sphere at the tip of the probe is calibrated by using a 1mm gage block, and the effect of the probe sphere diameter is compensated for measurement of the roughness standard specimen. As a result, it is confirmed that the accuracy after compensation of the roughness standard specimen as measured by the measuring system corresponds well to that of the surface roughness tester in both shape and value, demonstrating the utility of this means of calibration.

Key words: Micro Hole, Deep Hole, Measurement, Optical Fiber Probe, Laser Diode, Accuracy

1. Introduction

In recent years, there has been an 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 the like. It is very difficult, however, to precisely measure the shape of a micro hole that has a large length/diameter (L/D) ratio.

Micro holes have conventionally been measured using optical microscopes due to the demands of the process. This method, however, 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. Cross-sectional observation allied to a destructive mode of inspection has been used to measure the internal shape of holes, but this method has the disadvantage of rendering the workpiece unusable after inspection. A means of non-destructive inspection is therefore needed not to scratch the surface of the workpiece. A probe with a small diameter, large aspect ratio and low force is necessary to make possible the precise measurement of micro holes.

Many studies have been reported on micro hole 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 [1-15], among others. This paper presents a system of micro hole measurement using an optical fiber probe that is available as a low-force displacement probe and has a wide measuring range [16]. It is also easy to fabricate a probe with a diameter smaller than 10 μm and an aspect ratio larger than 100. The shaft of such a probe is not necessary to be rigid in order to detect measuring force because its deflection is measured by a non-contact method. In this research, the optical fiber probe is fabricated by using an acid etch technique and the probe's characteristics in the process of displacement detection are described. The effects of surface force are then evaluated. The diameter of a probe sphere is calibrated using a 1mm gage block, and the effect of the probe sphere diameter is corrected for measurement of the roughness standard specimen.

2. Principles of Measurement

Figure 1 shows an illustration of the optical system and a photograph of the fiber probe. The fiber probe consists of a probe shaft (optical fiber) and probe sphere with diameters of 30 and 50 μm , respectively. 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 fibers in orthogonal positions. The two floodlighting fibers, which are connected to laser diode, 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 that are connected to four photo diodes are opposite to the floodlighting fibers. The laser beams that penetrate the probe are received in the two double-light reception fibers. The intensities detected by the four photo diodes are converted into voltage values that are defined as I_{FX1} , I_{FX2} , I_{FY1} , and I_{FY2} (V).

Figure 1 : Optical system and photograph of the fiber probe

Figure 2 shows the principles that govern the measurement process. When the probe sphere 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 the probe sphere comes into contact with a hole surface (X direction), the probe shaft 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 probe sphere comes into contact with a

hole surface (Y direction), the probe shaft 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). As a result, 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 the 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.

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

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

Figure 2 : Measurement principle

3. Fabrication of the Optical Fiber Probe

3.1 Probe shaft

The optical fiber probe 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 fibers were then immersed in a 25% hydrofluoric acid solution, and hydrofluoric acid etching was carried out at room temperature (27 degrees). The diameter of

the probe shaft was measured with an optical microscope (magnification $50\times$). Figure 3 shows schematics of the probe shaft at three different stages of the hydrofluoric acid etching process. After hydrofluoric acid etching, the probe shaft was rinsed with water and acetone. Figure 4 shows the experimental results. The horizontal axis shows the etching time, and the vertical axis shows the diameter of the probe shaft.

Figure 3 : Probe shaft during the hydrofluoric acid etching

Figure 4 : Relationship between the etching time and diameter of the probe shaft

3.2 Probe sphere

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 are irradiated by ultraviolet rays and glued together. Figure 5 shows a photograph of the fiber probe. Figure 5 (a) shows a probe shaft of $30\text{ }\mu\text{m}$ in diameter with a probe sphere of $50\text{ }\mu\text{m}$ in diameter. This fiber probe is used in the later experiments. Figure 5 (b) shows a probe shaft of about $3\text{ }\mu\text{m}$ in diameter with a probe sphere of $5\text{ }\mu\text{m}$ in diameter.

(a) Probe shaft $\phi 30\text{ }\mu\text{m}$ and sphere $\phi 50$

(b) Probe shaft $\phi 3\text{ }\mu\text{m}$ and sphere $\phi 5\text{ }\mu\text{m}$

Figure 5 : Photograph of the fiber probe

4. Characteristics of the Probe during Displacement Detection

Figure 6 shows the changes in I_X and I_Y when the probe sphere was displaced in the $\pm X$ direction. I_X and I_Y were experimentally obtained. The horizontal axis shows the displacement of the fiber probe, and the vertical axis shows the changes in I_X and I_Y . It was confirmed that I_Y only changes slightly when the probe sphere is displaced in the X direction, and that the fiber probe is available as a displacement sensor because the rate of change of I_X can approximate a straight line within a range of $\pm 4 \mu\text{m}$ in the X direction.

Figure 6 : Output voltage I_X , I_Y induced by the X-displacement

5. Effects of Surface Force

In general, when the particle size is less than several $10 \mu\text{m}$, the effects of surface force due to the intermolecular force, electrostatic force and liquid bridge force are strengthened and become greater than the force of gravity [17]. Because we used a fiber probe with a $50 \mu\text{m}$ diameter sphere on its tip, we found that the measured surface draws the probe sphere closer when the probe sphere approaches it and the distance between the probe and the surface is less than the regular displacement. When the probe and the measured surface contact each other, the probe adheres to the measured surface and they cannot be separated. There is no reproducibility in the adhesion, which is influenced by the environment (e.g., humidity, temperature) and surface roughness of the measured plane.

Another experiment was then carried out to investigate the effect of the adhesion force. Figure 7 shows the experimental apparatus that was used to evaluate the adhesion force. The change of an output signal I_X in the X direction was measured when the measured surface approached the probe in the +X direction and was separated from the probe in the -X direction (reciprocating motion).

Figure 8 shows the results of these measurements, which are as follows. ①The output voltage does not change when the distance d between the probe sphere and the measured surface is more than the displacement of $0.1 \mu\text{m}$. ②The probe sphere is drawn and adhered to the measured surface, when the former approaches latter and the distance d is less than $0.1 \mu\text{m}$. The output voltage I_X expresses a negative value because the probe sphere is displaced in the -X direction. ③Next, the output voltage I_X returns to the initial state when distance d is 0. ④Then, output voltage I_X increases because the probe sphere is displaced keeping contact with the measured surface. Because the effect of the surface force is not negligible in the measurement of a microstructure, we need a method of measurement that takes surface force into consideration. However, a force greater than the surface force is required to separate the probe sphere which adheres to a measured surface from that surface (⑥).

Figure 7 : Experimental apparatus for examining the adhesion force

Figure 8 : Output voltage I_x induced by the X-displacement (reciprocating motion)

6. Calibration of Probe Sphere

6.1 Probe sphere diameter

The probe sphere is made from glass and its diameter is about $50 \mu\text{m}$ (NIST traceable mean diameter : $49.9 \pm 3.0 \mu\text{m}$). However the diameter is calibrated using a 1mm gage block for its precise measurement. The tilt of the gage block is compensated for by measuring the several points on both sides of the gage block. The difference of the measured length and the gage block length gives the diameter of the probe sphere in the X direction. The measured diameter of the probe sphere was $50.56 \mu\text{m}$.

6.2 Compensation for the shape of the probe sphere

Because the shape measured using this system corresponds to the path of the ball's center, its shape is different from that of the contact point path. A measurement experiment using a roughness standard specimen ($Ra = 2.94 \mu\text{m}$, $Rz = 9.3 \mu\text{m}$) was therefore performed to investigate the effect of the shape of the probe sphere. To make a comparison, the roughness standard specimen was measured by using both this measuring system and a commercial surface roughness tester (CS-5000, Mitutoyo).

Figure 9 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 so that 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 $1 \mu\text{m}$ step in the $-Z$ direction. This operation was carried out repeatedly, to ascertain the shape of the roughness standard specimen. Considering the effect of the surface force, as mentioned above, the specimen fixed by the stage was fed at a rate of about $10 \mu\text{m/s}$ in the $-Z$ direction. If the specimen was fed in the X and Y directions, the probe shaft would be deflected by the surface force and the measurement accuracy

Figure 9: Experimental apparatus used to measure the roughness standard specimen

Figure 10: Comparison of the cross-sectional shapes of the roughness standard specimen measured by a surface roughness tester and the measuring system (Before probe-radius compensation)

would decrease greatly. The measuring data were acquired at a sampling interval of $1\ \mu\text{m}$. The measured length was $100\ \mu\text{m}$ due to the limitations of the stage's range of movement.

Figure 10 shows the measurement results for the roughness standard specimen as measured using both the measuring system and a surface roughness tester.

The shapes of the concave and convex parts are slightly different from the shape of the roughness standard specimen because the diameter of the probe sphere used with the surface roughness tester (radius = $5\ \mu\text{m}$) was different from that used with the measuring system (radius = $25\ \mu\text{m}$) shown in Figure 11. When the diameter of the probe sphere is large, the tilt angle of the roughness curve in the shape of convex parts decreases and the angle in the shape of the concave parts increases. Thus, since the diameter of the probe sphere affects the measured shapes, it must be compensated in order to obtain precise measurement results.

Therefore, as shown in Figure 12, the regression line was calculated using the measuring coordinate $P_i(x_i, y_i, z_i)$, the front coordinate $P_{i-2}(x_{i-2}, y_{i-2}, z_{i-2})$, $P_{i-1}(x_{i-1}, y_{i-1}, z_{i-1})$ and the rear

coordinate $P_{i+1}(x_{i+1}, y_{i+1}, z_{i+1})$, $P_{i+2}(x_{i+2}, y_{i+2}, z_{i+2})$. The normal vector of the regression line was then calculated. Next, the measuring coordinate $P_i(x_i, y_i, z_i)$ was moved from the ball center point to the contact point in the direction of the normal vector (moving distance = calibrated radius of the probe sphere: $50.56/Z \mu\text{m}$). As a result, compensated values are determined.

Figure 13 shows the measurement results for the roughness standard specimen measured using both a surface roughness tester and the measuring system after the diameter of the probe sphere is compensated. Though it is not possible to accurately compare these measurement results since the same part of the roughness standard specimen was not measured, their shapes, wavelengths, and crest values correspond well with each other. The shape of the concave part is slightly different from that of the roughness standard specimen, perhaps because the shape of the probe sphere cannot be compensated well due to the rugged shape of the concave part, as shown Figure 10.

Figure 11: Schematic diagrams of roughness shapes measured by probe sphere of 50 and 10 μm in diameter

Figure 12: Schematic diagram of the correction method of the effect of the probe sphere diameter

Figure 13: Comparison of the cross-sectional shapes of the roughness standard specimen measured by a surface roughness tester and the measuring system (After probe-radius compensation)

7. Conclusion

We have developed a system for measuring micro hole accuracy using an optical fiber probe. A prototype of the system was fabricated on trial. The optical fiber probe was fabricated using an acid etch technique, and the characteristics of the probe in the process of displacement detection were then described. The effects of the surface force were then evaluated. The diameter of the probe sphere was calibrated using a 1mm gage block, and the effect of the probe sphere diameter was corrected for measurement of the roughness standard specimen.

As a result, it was confirmed that the accuracy after correction of the roughness standard specimen measured by the measuring system corresponds well to that of the surface roughness tester in both shape and value, demonstrating the utility of the calibration.

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