euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Improvement of an optical fiber stylus for microstructure and surface roughness measurement

Kosuke Uchiyama[1], Hiroshi Murakami[1], Akio Katsuki[2], Takao Sajima[2], Takahiko Yamamoto[3] and Kunitaka Fujiyoshi[4]

[1]*The University of Kitakyushu*
[2]*Kyushu University*
[3]*Inatsuki Science Co., Ltd*
[4]*Fukuoka Industrial Technology Center*

murakami@kitakyu-u.ac.jp

Abstract
In recent years, there has been an increasing demand for measuring the inner diameter of a small diameter hole, such as a TSV, having a diameter of 10 µm or less. Therefore, we have been developing a measurement system using an optical fiber as a stylus to measure microstructures with low measurement force. In this study, a method to design and manufacture an improved two-step stylus that has a small shaft diameter, which can be inserted into a small diameter hole or small groove, and a large diameter of the remaining shaft less susceptible to external influences will be discussed. Furthermore, a method to design and manufacture a two-step plus hinge stylus with a hinge that further helps improve the measurement sensitivity of the two-step stylus, in addition an L-shaped stylus that has a pointed tip and bent shaft in the middle is proposed for surface roughness measurement.

Keywords: Microstructure measurement, stylus, optical fiber, coordinate measurement, surface roughness

1. Introduction

In recent years, with the development of processing micro structures such as micro-molds, various nozzle holes, semiconductor TSV (Through Silicon Via), MEMS (Micro Electro Mechanical Systems), micro-parts such as micro-machines, optical communication equipment, and medical equipment have been manufactured. Accordingly, techniques to measure the 3D parameters of these microstructures are required. Therefore, this study developed a measurement system using an optical fiber as a stylus to measure microstructures with low measurement force. To measure it, we require a stylus with a shaft diameter of 5 µm or less and a tip diameter of 10 µm or less. However, when using a stylus shaft with a diameter of several micrometers or less, the stylus is easily shaken by the influence of external vibration and air flow, which may affect measurement accuracy. Therefore, in this study, we propose the improved styli, such as a two-step, a two-step plus hinge and an L-shaped stylus to solve above mentioned problems.

2. Principle and configuration of measurement system

Figure 1 (a) shows an outline drawing of the stylus used for the developed measurement system. This stylus is made from optical fiber and can measure with low measurement force. As shown in Fig.1(b), the shaft bends when it comes into contact with the measured surface. The contact between the stylus tip and the measured surface is then detected by measuring the displacement of the center of the bending shaft using a semiconductor laser with a wavelength of 405 nm irradiated to the shaft and a dual-element photodiode. Figure 2 shows a cross-sectional view of the stylus and path of the laser beam in the XY plane at the laser irradiation position and illustrates the measurement principle. As shown in Fig.2 (a), condensed lasers irradiated from the XY direction are received by two sets of dual-element photodiodes (PX and PY) on opposite sides of the stylus. The light intensities detected by each photodiode are converted into voltage, which are represented as I_{PX1}, I_{PX2}, I_{PY1}, and I_{PY2} (V). Before the stylus tip comes into contact with the measured surface, the light intensities measured using 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 comes into contact with the measured surface and is displaced, as shown in Fig.1(b), the laser is refracted, as shown in Fig.2(b), by the stylus shaft, which acts as a rod lens. Then, there is a difference of light received on dual-element photodiodes (PX), and $I_{PY1} > I_{PY2}$.

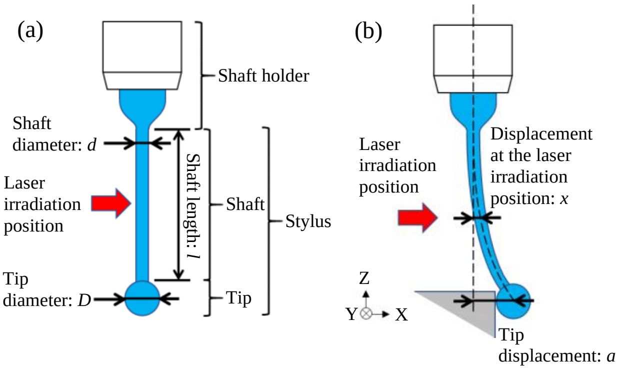


Figure 1. (a) Outline drawing of standard stylus. (b) Relationship between tip displacement and laser irradiation displacement when the stylus tip contacts the surface to be measured.

Figure 3 shows a manufactured measurement system. One feature of this device is that the laser beam is irradiated to the stylus at an angle of approximately 60° in the downward direction, and is reflected upward by the prism with the same angle of approximately 60°. With this structure, all the devices can be arranged above the prism, such that the length restriction of the object to be measured in the XY direction can be eliminated.

In this measurement system, the stylus with a constant shaft diameter is used as a standard stylus. However, when using a stylus shaft with a diameter of several micrometers or less and a length-to-diameter (L/D) ratio of 200 or more, the stylus is easily shaken by the influence of external vibration and air flow, which may affect measurement accuracy. Therefore, we have discussed the method to design and manufacture the two-step stylus that has a small shaft diameter, which can be inserted into a small diameter hole or small groove, and a large diameter of remaining shaft less susceptible to external influences. Furthermore, a method to design and manufacture a two-step plus hinge stylus with a hinge that further helps improve the measurement sensitivity of the two-step stylus, in addition an L-shaped stylus that has a pointed tip and bent shaft in the middle for surface roughness measurement is proposed.

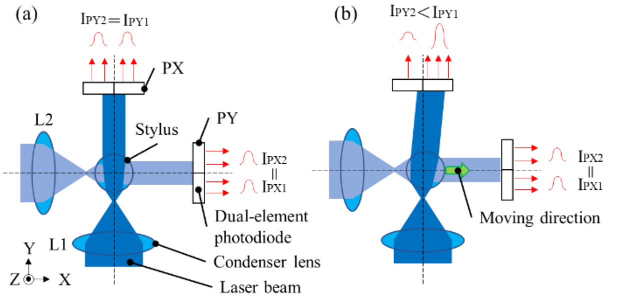


Figure 2. Measurement principle: (a) Initial state, (b) Displacement to the X direction.

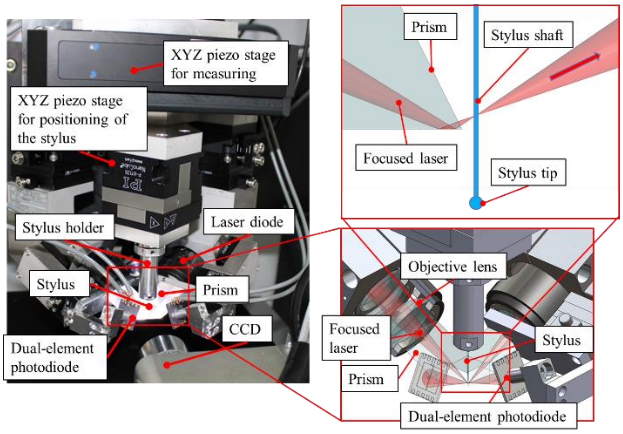


Figure 3. Outline drawing of measurement system.

3. Improvement of stylus

3.1. Standard stylus

Figure 4 shows the method to manufacture a standard stylus, which is shown in Fig.1(a). First, an optical fiber with a diameter of 125µm stripped is soaked in etchant to fabricate the stylus shaft. This etchant can determine the etching amount per unit time by temperature control. Therefore, the shaft diameter can be adjusted using the etching time. Next, the end of the optical fiber whose diameter is reduced by etching is irradiated with CO_2 laser. Thereafter, the end of the optical fiber melts and forms a spherical shape owing of surface tension [1]. The shaft length can be adjusted according to the laser irradiation position. This method enables the manufacturing of a stylus with a shaft diameter of approximately 0.4 µm and tip diameter of approximately 1 µm, as shown in Fig.4(c).

As shown in Fig. 1, the measurement system detects contact by measuring the displacement of the laser irradiation position at the center of the bent stylus shaft by contacting the stylus tip with the measured surface. Therefore, the displacement of the laser irradiation position needs to be determined by comparing with the displacement of the stylus tip. Here, the displacement *x* of the laser irradiation position changes linearly with the tip displacement *a*, as shown in Fig.1 (b). Then, the ratio of *x* to *a* is defined as contact sensitivity *S* and is defined by Equation (1).

$$S = x/a \times 100\,\% \qquad (1)$$

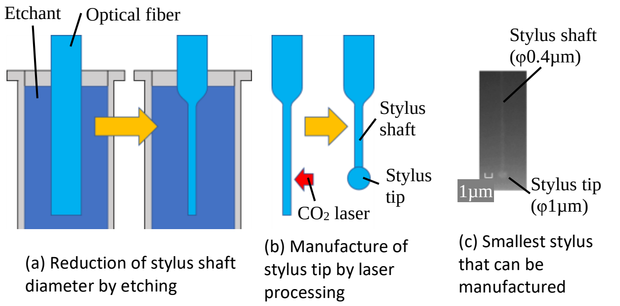


Figure 4. Method to manufacture a standard stylus.

3.1.1. Simulation of standard stylus

Figure 5 shows the standard stylus used in this research. The displacement *x* of the laser irradiation position when the tip displacement *a* is 500 nm was calculated by simulation using a finite element method. Table 1 summarizes the details of dimensions of the standard stylus. The simulation results are listed in Table 2—the displacement *x* of the laser irradiation position is 154 nm, and the contact sensitivity *S* is 31%. And, the natural frequency of this stylus was calculated by the finite element method. As a result, the natural frequency was 1.14Hz.

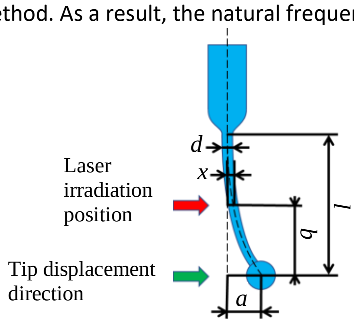


Figure 5. Simulation model and dimensions of standard stylus.

Table 1. Dimensions and simulation conditions of standard stylus.

Shaft diameter: *d*/µm	2
Shaft length: *l*/mm	2
Distance from tip to laser irradiation position: *b*/mm	1
Tip displacement: *a*/nm	500
Stylus material	Quartz glass

Table 2. Simulation results of standard stylus.

Stylus type	Standard
Displacement at the laser irradiation position: x/nm	154
Contact sensitivity: S/%	31

3.1.2. Problems caused by the reducing the diameter of standard stylus shaft

For a standard stylus as shown in Fig. 5, if the shaft diameter is less than several micrometers and the shaft length is 1 mm or more and the natural frequency and stiffness decreased, it is easily shaken by the influence of external vibration and air flow, which may affect the measurement accuracy. In addition, if the shaft diameter at the laser irradiation position is less than several micrometers and the stylus is displaced as shown in Fig.2 (b), the difference of light received on the dual-element photodiode will be small due to the influence of laser diffraction, which may affect the measurement accuracy. Therefore, we proposed the two-step stylus. The shaft diameter of the end of stylus is reduced so that to be inserted into the small diameter hole.

3.2. Two-step stylus

To solve the above mentioned problem, we propose the two-step stylus shown in Fig. 6. The stylus has the first-step shaft that has a diameter of 2 μm such that it can be inserted into a small diameter hole at the end of stylus, and the second-step shaft that has a diameter of 10 μm that is less susceptible to external influences at the root part of stylus. In this stylus, the 2nd-step shaft is irradiated with the laser, so that the diameter of the shaft at the laser irradiation position is larger than that of the standard stylus.

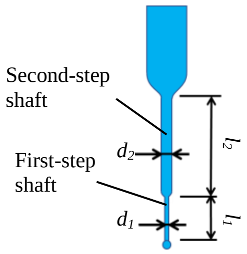


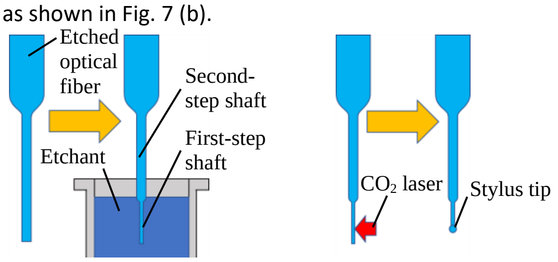
Figure 6. Simulation model of two-step stylus.

Table 3. Dimensions of two-step stylus.

First-step shaft diameter: d_1/μm	2
Second-step shaft diameter: d_2/μm	10
First-step shaft length: l_1/mm	0.2
Second-step shaft length: l_2/mm	1.8

3.2.1. Manufacture method of two-step stylus

Figure 7 shows the method to manufacture the two-step stylus. First, the second-step shaft with a diameter of 10μm is manufactured by etching similar to standard stylus as shown in Fig.4 (a). Next, as shown in Fig. 7 (a), only the part at the end of the stylus is re-etched to manufacture a first-step shaft with a diameter of 2 μm. Finally, the stylus tip is manufactured by CO_2 laser as shown in Fig. 7 (b).



(a) Manufacture of first-step shaft and second-step shaft by etching

(b) Manufacture of stylus tip by laser processing

Figure 7. Manufacture method of two-step stylus.

3.2.2. Simulation of two-step stylus

The displacement *x* of the laser irradiation position at the second-step shaft when the same displacement *a* of 500 nm as that of the standard stylus was applied to the tip of the two-step stylus shown in Fig. 6 was calculated by simulation using the finite element method. Table 3 summarizes the details of dimensions of the two-step stylus. The distance *b* from tip to the laser irradiation position is 1 mm. The simulation results are listed in Table 4—the displacement x of the laser irradiation position of the two-step stylus was 100 nm and the contact sensitivity S was 20 %. And, the natural frequency of this stylus was calculated to be 6.42 Hz by the finite element method. These results indicate, the contact sensitivity *S* of the two-step stylus was 11 % smaller than that of the standard stylus, and the contact sensitivity deteriorated. However, the natural frequency of the two-step stylus was about 5.6 times larger than that of the standard stylus. Therefore, the two-step stylus is hardly affected by the environment, such as vibration and the current of air. Therefore, we manufactured a stylus with a hinge on the top of shaft to improve sensitivity.

Table 4. Simulation results of two-step stylus.

Stylus type	Two-step
Displacement at the laser irradiation position: x/nm	100
Contact sensitivity: S/%	20

3.3. Two-step plus hinge stylus

The two-step stylus has a higher natural frequency than the standard stylus, but has the problem of low contact sensitivity. Therefore, in order to improve the sensitivity, the two-step stylus provided with a hinge on the upper part of the second-step shaft is proposed. Figure 8 shows a model of two-step plus hinge stylus. In this stylus, the second-step shaft is irradiated with the laser, so that the diameter of the shaft at the laser irradiation position is larger than that of the standard stylus.

3.3.1. Manufacture method of two-step plus hinge stylus

Figure 9 shows the method to manufacture the two-step plus hinge stylus. First, a second-step shaft with a diameter of 10μm is manufactured by etching similar to standard stylus, as shown in Fig. 4 (a). Next, as shown in Fig. 9 (a), masking paste is applied to a shaft, excluding the hinge, and the hinge with a diameter of 4 μm is manufactured by etching. Then, after removing the masking paste, the end of shaft is re-etched, as shown in Fig. 9 (b) to manufacture the first-step shaft with a diameter of 2μm. Finally, as shown in Fig. 9 (c), the stylus tip is manufactured by laser processing.

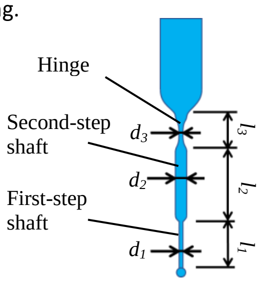


Figure 8. Simulation model of two-step plus hinge stylus.

Table 5. Dimensions of two-step plus hinge stylus.

First-step shaft diameter: d_1/μm	2
Second-step shaft diameter: d_2/μm	10
Hinge diameter: d_3/μm	4
First-step shaft length: l_1/mm	0.2
Second-step shaft length: l_2/mm	1.3
Hinge length: l_3/mm	0.5

3.3.2. Simulation of two-step plus hinge stylus

The displacement *x* of the laser irradiation position at the second-step shaft when the same displacement *a* of 500 nm as that of the standard stylus was applied to the tip of the two-step plus hinge stylus shown in Fig. 8 was calculated by simulation using the finite element method. Table 5 summarizes the details of dimensions of the two-step plus hinge stylus. The distance *b* from tip to the laser irradiation position is 1 mm. The simulation results are listed in Table 6—the displacement x of the laser irradiation position of the two-step plus hinge stylus was 196 nm and the contact sensitivity S was 39 %. And, the natural frequency of this stylus was calculated to be 0.97 Hz by the finite element method. These results indicate, the contact sensitivity *S* of the two-step plus hinge stylus was 8 % larger than that of the standard stylus, and the contact sensitivity was improved. However, the natural frequency deteriorated 0.85 times comparing with the standard stylus. Figure 10 shows a manufactured two-step plus hinge stylus.

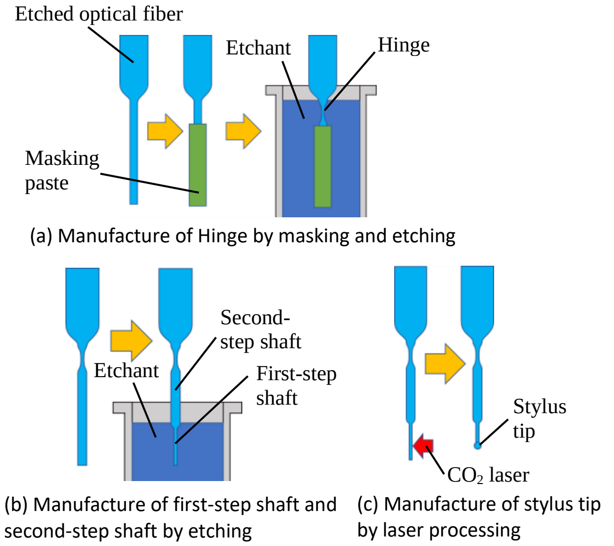


Figure 9. Manufacture method of two-step plus hinge stylus.

Table 6. Simulation results of two-step plus hinge stylus.

Stylus type	Two-step plus hinge
Displacement at the laser irradiation position: x/nm	196
Contact sensitivity: S/%	39

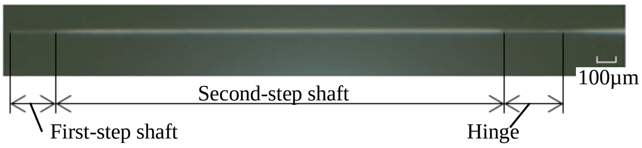


Figure 10. Photograph of manufactured two-step plus hinge stylus.

3.4. L-shaped stylus

The standard stylus is used to measure the outer and inner diameter of a hole and other parts that comes into contact with the object from the XY direction, and the measurement of steps and grooves that come into contact with the object from the Z direction. However, it is difficult to measure the surface roughness of the inner hole wall. Therefore, we propose the L-shaped stylus as shown in Fig. 11. The stylus has the pointed tip and the middle of the shaft is bent 90° to trace the inner wall of the hole and to measure surface roughness.

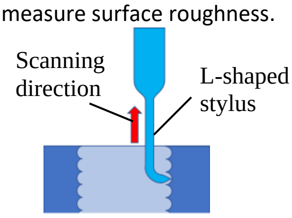


Figure 11. Outline drawing of L-shaped stylus.

3.4.1. Manufacture method of L-shaped stylus

Figure 12 shows the method to manufacture an L-shaped stylus. First, the shaft is manufactured by etching similar to standard stylus as shown in Fig. 4 (a). Next, as shown in Fig. 12 (a), only the shaft end face is soaked in the etchant. Then, the etchant surface is pulled up to the side surface of the stylus by the surface tension as shown in Fig. 12 (b). Further, owing to the effect of volatilization on the etchant surface, the etchant concentration is thin on the surface and thick inside. Owing to this concentration gradient, the etching amount on the etchant surface decreases, and the etching amount increases toward the inside. This method demonstrates that the stylus has a pointed tip. Finally, as shown in Fig. 12 (c), a low-output CO_2 laser is irradiated on the shaft above the pointed tip from the orthogonal direction. Then, a temperature gradient is generated inside the shaft as shown in Fig. 12 (d). Owing to this temperature gradient, only the high-temperature part irradiated with the laser melts, and the surface tension acts. Then, that part contracts, and the shaft can be bent toward that direction. Figure 12 (e) shows the manufactured L-shaped stylus.

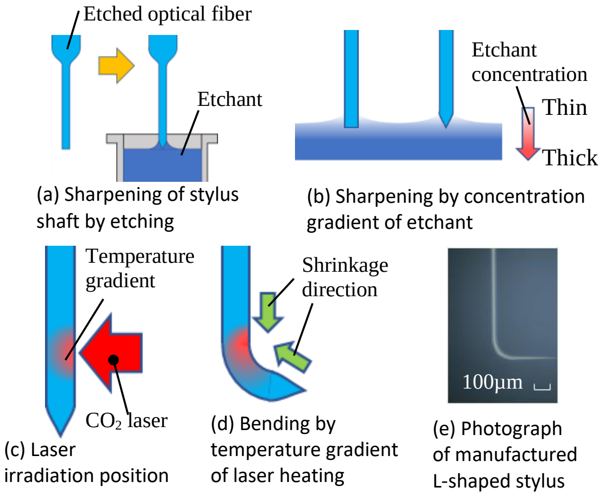


Figure 12. Manufacture method of L-shaped stylus.

Table 7. Performance comparison for each stylus type.

Stylus type	**Displacement at the laser irradiation position: x/nm**	**Contact sensitivity: S/%**	**Natural frequency: Hz**
Standard	154	31	1.14
Two-step	100	20	6.42
Two-step plus hinge	196	39	0.97

4. Conclusion

In this research, we proposed the two-step stylus, the two-step plus hinge stylus, and the L-shaped stylus to improve their performance. The design parameters of these styluses were simulated by the finite element method, and the results of the actual examination are summarized in Table 7 and below.

(1) The two-step stylus with a small shaft diameter only at the part to be inserted into a small diameter hole can reduce the influence of exterior because the natural frequency is improved to 6.42 Hz, but the contact sensitivity has been reduced to 20%.

(2) The two-step plus hinge stylus with a hinge on the upper part of the two-step stylus has improved contact sensitivity to 39%, but the natural frequency is 0.97 Hz so that is susceptible to external influences. However, since the shaft diameter at the laser irradiation position has increased, there is no concern that the measurement accuracy will decrease.

(3) The L-shaped stylus can be manufactured by the concentration gradient of the etchant surface and temperature gradient of the laser irradiation position to measure the surface roughness of the inner wall of the hole

In the future, we plan to conduct a stylus performance evaluation experiment using these styluses.

References

[1] Hiroshi M, Akio K, Takao S and Kosuke U 2017 *Int. J. of Automation Technology Vol.* ***11*** *No. 5 699-706*