Development of Measurement Method for Shape and Dimension of Micro-Components*

(Modification of the Original Measuring System, Calibration of the Probes and the Results of Dimensional Measurements)

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In order to facilitate the advancement of micromachine technology and to encourage its use across a wider range of industrial fields, a measuring technology appears to be essential. For the development of micromachines and microfabrication technologies, it is necessary to devise a technique to measure both shape and dimensions of micro-components. Some researchs on measurement methods for micro-boreholes in the micrometer range have been reported. However, general-purpose coordinate measuring machine for both shape and dimensional metrology on micro-system components has not been realized yet. To this end, one of the authors attempted to develop a small three-dimensional shape measuring apparatus which has non-contact probe detecting proximity to the object being measured through the tunneling effect, and the results has already been reported. In this study, measurement of not only shape but also of dimensions of micro-components are attempted. A modified device and the calibration technique for micro-probes are explained in detail, and then several measurement results are shown.

Key Words: Measurement, Micro-Components, Profile, Dimension, Micromachine, Coordinate Measuring Machine, Microprobe, Tunneling Effect

1. Introduction

For the development of micromachines and mi-

crofabrication technologies, it is necessary to devise a technique to measure both the profile and dimensions of micro-components. Systematizing of new measuring technologies is strongly demanded because the progress of micro-fabrication technologies requires the advancement of measuring techniques.

As for current techniques used to measure micro-components, a measuring method that enables a wide measurement range in the height direction has been reported^{(1),(2)}. Optical measuring method that enables diameter measurement of approximately 30 μm has been commercialized. Furthermore, measurement methods for optical connector ferrule have been reported^{(3),(4)}. A tactile sensing method based on electrical contacts of an oscillating probe has been reported⁽⁵⁾⁻⁽⁷⁾. Shape measurement, other than that of small holes, using a scanning electron microscope^{(8),(9)} and three-dimensional measuring methods based on a

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confocal laser microscope⁽¹⁰⁾ have been reported.

On the other hand, it is recognized that development of micro-probes is inevitable for profile and dimension measurement of micro-components. Thus, micro-probes such as the laser trapping probe, and a pneumatic ball probe have been developed^{(11)–(14)}.

However, the development of evaluation methods for dimensional accuracy and form accuracy such as, straightness, out of roundness, and squareness that are commonly measured for general machine components is our future goal in the field of micro-fabrication. The general purpose coordinate measuring machine (CMM) that have various measurement functions for micro-system components has not been realized yet. To this end, one of the authors attempted to develop a small three-dimensional form measuring apparatus which has non-contact probe detecting proximity to the object being measured through the tunneling effect, and the results has already been reported⁽¹⁵⁾. Furthermore, we have already reported a micro-probe fabrication method using die-sinking electric discharge machining (EDM)⁽¹⁶⁾.

In this study, the measurement of not only form but also of dimensions of micro-components is attempted. A modified device and the calibration technique for micro-probes are explained in detail, and then several measurement results are shown.

2. Configuration of the Measuring Instrument

In the proposed measuring method, the contact of the probe with the sample surface can be detected by the tunneling current between them⁽¹⁵⁾.

The configuration of the apparatus is shown in Fig. 1. A θ (rotating) stage with a rotary encoder is mounted on a $X - Y$ precision stage with linear encoders of $0.1 \mu\text{m}$ resolution. A small manual $X - Y$ stage for positional adjustments of the specimen is set on the θ stage. A flexure hinge which is movable in the $X - Y - Z$ directions with piezoelectric actuators (PZTs) is set on the Z micro stage. The maximum driving range of the flexure hinge is approximately $10 \mu\text{m}$ along each axis. The displacement of the flexure hinge is measured by strain gauges with 15 nm resolution. The flexure hinge equipped with PZT works not only as the probe over travel protection mechanism but can also be used for precise and high speed mode measurements as described in the following section. Major modifications to the original measuring apparatus consist of the following alterations. As the flexure hinge can move in any direction, the mechanism corresponds to the probe approaching to the measurement sample along any direction. The displacement of the flexure hinge is measured by strain gauges with 15 nm resolution. The displacement measurement of the

flexure hinge by strain gauges greatly enhanced accurate measurement.

A personal computer controls $X - Y - Z$ micro stages through a GP-IB interface. Built-in linear encoders of $0.1 \mu\text{m}$ resolution can enable direct measurement of displacements and, as for the θ stage, a rotary encoder of $3.48''$ resolution measures the angle of rotation. An electrical circuit for applying a voltage between the specimen and probe, detecting the tunneling current, and controlling the PZT, is connected to the computer through an AD/DA converter.

Figure 2 shows the probe over travel protection mechanism consisting of a flexure hinge and three PZT. Strain gauges are attached to the PZT and strain amplifiers measure the displacement of the

Fig. 1 Configuration of measurement apparatus

Fig. 2 Probe over travel protection mechanism

PZT. Figure 3 shows the output signal from the strain amplifiers. The unit of the signal is transformed to the displacement of the PZT. The result shows the electrical noise corresponding to the PZT displacement of less than 15 nm.

Figure 4 explains the operation of the probe over

Fig. 3 Output signal of strain amplifier

Fig. 4 Actions of probe over travel protection mechanism

travel protection mechanism. The probe which approaches the measurement sample along the X axis under the PZT (X) is fully expanded. The PZT contracts when tunneling current is detected to avoid collision with the sample being measured before the X micro-stage stops. The computer issues a command to stop the micro-stage immediately after detecting that the applied voltage to the PZT drops to 0 V. However, due to over travel of the micro-stage, the coordinate values read into the memory of the computer when the micro-stage stops differs from the coordinates of the micro-stage when tunneling current is detected. Thus, the PZT expands until the tunneling current is detected again. The displacement of the PZT when tunneling current is detected is measured by strain gauges, and based on this value, over travel of the micro-stage is compensated. This enhances measurement accuracy. Probe retraction direction can be freely set by computer commands in any movement directions of the X - Y micro-stages.

In this report, the series of measuring procedures using both micro-stages and PZT is called 'stage mode measurement' (Fig. 4; steps ① - ⑤). On the other hand, the measuring procedure using PZTs only is called 'PZT mode measurement' (Fig. 4; steps ④, ⑤). Stage mode measurement has a wider measurement range, however, it requires a longer measurement time, because micro-stages are used to move the probe to the specimen. On the other hand, in PZT mode measurement, even though the measurement range is confined to $10 \times 10 \times 10 \mu\text{m}$ at the moment, high-speed measurement is possible. Thus, PZT mode measurement can be effectively used, for example, for surface roughness measurements of micro portions.

3. Basic Characteristic of the Measuring Instrument and Some Measurement Results

In order to examine the basic characteristics of the measuring instrument, 50 consecutive measurements at the same point on a gauge block are carried out, and the scatter of the data are investigated. Figure 5(a) shows measurement without compensation of PZT displacement by strain gauges in a stage mode measurement, and Fig. 5(b) corresponds to the result with compensation. In Fig. 5(a), scatter of $1 \mu\text{m}$ is observed, and standard deviation of the measurements is $0.25 \mu\text{m}$. The results show that a measurement error of approximately $1 \mu\text{m}$ can be included when encoder counts are used as the measurement. Compensation by strain gauges shown in Fig. 5(b) reduces scattering to approximately $0.4 \mu\text{m}$ and standard deviation to $0.10 \mu\text{m}$. The result shows that compensation by strain gauges is effective from the accuracy point of view.

(a) Without compensation

(b) With compensation by strain gauge

Fig. 5 Measurement results from gauge block

Fig. 6 Result of PZT mode measurement

On the other hand, Fig. 6 shows the result of PZT mode measurement. The same point on a gauge block was subjected to 1 000 measurements, and the scatter of the data is within $0.1 \mu\text{m}$ and standard deviation is $0.025 \mu\text{m}$. However, errors in PZT mode measurement are considerably larger than electrical noise from the strain amplifier shown in Fig. 3. Electrical noise from the sample and hold circuit, which is used when signals from strain amplifiers are transferred to the computer through an A/D converter, is large. Thus, optimal performance of displacement measurement of PZT by strain gauge is not realized.

Figure 7 shows the measurement result of a surface roughness standard specimen for calibration with wavelength $15 \mu\text{m}$ and amplitude $1 \mu\text{m}$. The measurement carried out by positioning the X micro-stage at $0.2 \mu\text{m}$ intervals. For the height direction, the Z PZT is used instead of the Z micro-stage. Good agreement with the measurement result by a stylus instrument shows the validity of PZT mode measurement for surface roughness evaluation of micro-components.

Figure 8(c) shows the measured shape of internal thread, with the major diameter of 1 mm . The

(a) By PZT mode measurement

(b) By Stylus method measurement

Fig. 7 Measurement results from a surface roughness standard specimen for calibration

(a) Specimen for measurement

(b) Probe used for the measurement

(c) 3D expression of the result

Fig. 8 Measurement results from a M1 nut

probe used is a L shaped probe as shown in Fig. 8(b). This is fabricated by micro electro discharge machining⁽¹⁶⁾. The interval is $20 \mu\text{m}$ in the Z direction and $10 \mu\text{m}$ in the Y direction. The pitch and height of the

thread are measured as approximately $250\text{ }\mu\text{m}$ and $100\text{ }\mu\text{m}$, respectively. No other measuring methods are not available at the moment, however the height of the thread is slightly smaller than the value specified in the JIS standard.

Figure 9(a) shows a photograph of a specimen with steps fabricated by a micro-EDM. The photograph is obtained by the long depth of focus micro-

(a) Microscope image of steps fabricated by micro-EDM

(b) 3D expression of the result

Fig. 9 Measurement results from steps

Fig. 10 Master ball and measurement target

scope observation technique⁽¹⁷⁾. The area indicated by the rectangle is measured and showed in Fig. 9(b).

In conventional CMM, the measurement probe can be easily observed by the naked eye. In the proposed measurement, however, even inserting the probe into the region of interest is a tedious process. Thus, as shown in Fig. 10, a micro master ball is used for probe positioning. A steel ball of diameter $0.5 - 1\text{ mm}$ is used for the master ball, and the master ball is set on a palette on to which the specimen is set. The measurement procedure is described as follows.

(1) An optical microscope with a CCD camera measures the distance between the master ball center and the specimens, (a, b, c). Distance 'c' in the Z direction can be measured from the focused image of the microscope.

(2) The master ball is moved underneath the probe, and then the center of the master ball is measured by bringing the probe in contact with more than four points.

(3) Then, micro-stages are moved by distance (a, b, c) which is marked by CCD camera observation.

4. Dimensional Metrology of Micro Components

In general, shape, dimension and surface roughness are important evaluation items for mechanical parts. When several micro components are assembled into a micromachine, the dimensions of the each components must be measured precisely.

4.1 Calibration of probes

In CMM, spherical probes are used. The diameters of the probes are calibrated against a spherical master of known diameter. On the other hand, a different calibration procedure is needed because in the proposed method, probes that have multiple projections are used for the measurements.

If we can know the relative distance between tips of the projections, we can use this measuring method for various dimensional measurements, for example as shown in Fig. 11. In the following, a probe calibration procedure using a master test ball with a known diameter is described. It is assumed that the tip of all projections is spherical as shown in Fig. 12. More than five points on the master test ball are measured by each projection. Using the least squares method, the coordinates of the master ball center corresponding to each projection and each tip radius are measured. Projection i : coordinates of the master ball center (X_i, Y_i, Z_i) , : tip radius of projection r_i : ($i=1, 2, 3, 4, 5$)

Here, as shown in Fig. 13, the center coordinates of the master sphere measured by projections 1 and 2 are equivalent to the center coordinates of projections 1 and 2. Hence, the position vector of the tip of projec-

Fig. 11 Probe shape and measurement functions

Fig. 12 Master ball for probe calibration

Fig. 13 Probe calibration procedure

tion 2 observing from projection 1 is given by,

$$\vec{L}_{12} = (X_2 - X_1, Y_2 - Y_1, Z_2 - Z_1) \quad (1)$$

Hence, the tip positions of all other projections with respect to projection 1 can be expressed as

$$\begin{aligned} \vec{L}_{13} &= (X_3 - X_1, Y_3 - Y_1, Z_3 - Z_1) \\ \vec{L}_{14} &= (X_4 - X_1, Y_4 - Y_1, Z_4 - Z_1) \\ \vec{L}_{15} &= (X_5 - X_1, Y_5 - Y_1, Z_5 - Z_1) \end{aligned} \quad (2)$$

Thus, position vector of all projections with respect to projection 1 can be measured.

4.2 Evaluation of calibration results

After calibration of a probe, the width of a block gauge was measured to examine how accurately the calibration was carried out. The calibration of the probe was carried out using a steel ball of diameter 0.5 mm for the ball bearing. The probe fabricated by micro electro discharge machining is a $X-X$ type probe that has two projections in the horizontal direction. The tip radius of the probe is 1 to 2 μm , sharp enough to be assumed as zero. Calibration of the probe is carried out by stage mode measurements. Five points on the master test ball were measured by each projection. Then the positional relationship between projections 1 and 2 was calculated. Nine points on one side of the 1.5 mm-thick gauge block were measured, and the inclination of the gauge block surface was compensated using a regression surface. Furthermore, nine more points on another side of the gauge block surface were measured to obtain the thickness of the gauge block. Table 1 shows the results of three consecutive measurements through calibration of the probe to the thickness of the gauge block. The results of probe calibration are shown in Table 1, and the position vectors of projection 2 against projection 1 are also shown.

Three experimental results have measurement uncertainties of approximately $\pm 1 \mu\text{m}$ against the width of the gauge block. The X component of the position vector of projection 2 can be seen as the length of the probe, because the gauge block is placed almost parallel to the YZ plane in Fig. 1. The fact that the X components obtained by the experiments are not consistent with the measured width of the gauge block shows that error exists not only in the probe calibration, but also in the measurement of the gauge block.

The cause of error in the probe calibration is considered to be as follows. The radius of the probe

Table 1 Evaluation of the probe calibration method

Experiments	$\vec{L}_{12}$ (μm)	Measured width for gage block (mm)
1	(184.4, -9.8, 10.3)	1.5012
2	(185.7, -9.6, 10.2)	1.4993
3	(183.8, -9.9, 8.5)	1.5007

Fig. 14 Probe with three projections

tip is assumed as zero, however, in practice, it has curvature at some level. Due to the probe shape, the whole of the master sphere cannot be used for calibration. Thus, we have larger error than in the case of calibration of spherical probe of CMM. In CMM, the vertices of a master sphere and four points on the sphere equator can be used for calibration. In order to reach ever higher levels of precision in the width measurement of gauge blocks, the probe over travel protection mechanism consisting of PZT must be modified. This may have been because the PZT motion is slightly on the unstable side when the PZT works to avoid collision with the sample by expansion compared to when it works to avoid collision by shrinking.

4.3 Measurements of micro groove

The shape and dimensions of a micro groove fabricated by micro-EDM as shown in Fig. 15(a) are measured. The probe used for the measurement is an X-Z-X type probe as shown in Fig. 14, and is calibrated by the method described in section 4.2. The measured section is at the inner part, approximately 1 mm from the edge of the specimen. Without changing the orientation of the specimen, upper, side and bottom surfaces are measured continuously. The measurements of the corners of side and bottom surfaces are our future goals, because new types of probes are required to be devised for this purpose.

The measurement results are shown in Table 2. Dimensions are obtained by fitting the least squares line to the measurement results. Measurement results by a laser microscope are also shown for comparison. The calibration results for the probe are expressed as the position vector of projections 1 and 2 with respect to projection 3 (unit: μm).

$$\vec{L}_{31} = (-90.7, -11.0, 100.9)$$

$$\vec{L}_{32} = (52.2, -8.2, 97.2)$$

Table 2 Results of width and height measurements of the grooves

	Width1	Width2	Depth1	Depth2
Proposed method	586.0	218.7	205.9	604.5
Laser microscope	588.9	220.8	203.7	602.0

unit: μm

(a) Grooved surface

(b) Measurement results from a grooved surface

Fig. 15 Dimensional measurements of width and height from grooved surface

5. Conclusions

In this paper, modifications of the original measuring instrument are first described. The major modification of the original design consisted of the accuracy increases in proximity detection between the probe and specimen by measuring the displacement of the PZT for probe over travel protection mechanism by strain gauges. Then, the efficacy of the proposed method is verified by experiments. Furthermore, measurements of not only shape but also of dimensions of micro-components are attempted. The probe calibration procedure, which is inevitable for dimensional measurement, is also described. The results are summarized as follows:

(1) The accuracy of the proposed instrument is

evaluated by measuring the same point of a gauge block surface many times. The accuracy is determined as approximately 0.5 μm for stage mode measurement and 0.1 μm for PZT mode measurement.

(2) It is shown that the PZT mode measurement can be effectively used for surface roughness measurements of micro portions.

(3) The probe that has projections in three directions fabricated by micro-EDM was calibrated using a small steel ball. The width measurement of a gauge block using the probe shows the validity of the probe calibration procedure. Also, the width and depth of micro-grooves can be measured.

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