In-situ measurement of curved surfaces on ultraprecision machine tools via chromatic confocal probes

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Ultra-precision machining (UPM) is often used for fabricating optical components due to its extremely high processing accuracy. However, robust surface metrology and form error compensation is necessary for UPM because of errors occurred during the machining process, the measurement process, and from the local environment. In the field of UPM, on-machine measurement systems are getting attention because they can avoid errors caused by repositioning workpieces and also improve measuring efficiency. In this research, we used a chromatic confocal probe for on-machine measurement due to its high measurement accuracy and stability. However, the measurement of highly sloped/curved surfaces is still a challenge because of the significant measurement errors occurring due to the angle of incidence between the probe and workpiece.

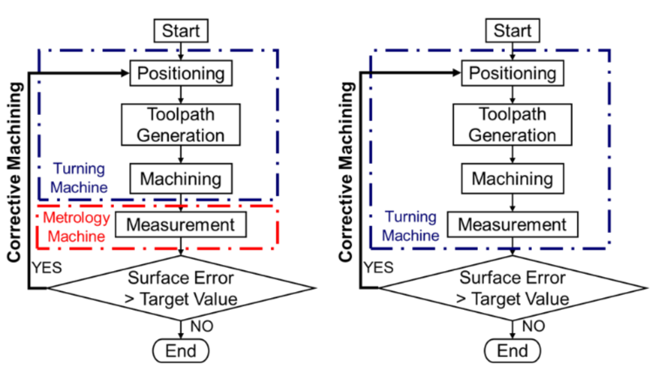
This study investigated the three-dimensional measurement accuracy of a chromatic confocal probe based on-machine measurement system. The chromatic confocal probe used in this research had a 4.5 mm working distance and a 300 μm measuring range. On-machine measurements were performed on multiple reference spheres with varying radii and probe angles to establish the effects that different measurement ranges and surface inclinations have on measurement results. In addition, errors due to the angle of incidence between the probe and workpiece were calculated via the analysis of measurement data from a reference sphere. Measurements were taken at different probe incidence angles on a tilted flat once the center of the probe was aligned with the center of main spindle on the machine tool. By subtracting the computed angle of incidence error from multiple sets of measurement data, a dataset that more accurately reflects the true error in the surface was established, which can be subsequently used for form error compensation on curved surfaces. Throughout the process, the sinusoidal measurement error observed on a tilted flat, caused by probe misalignment with respect to the center of the main spindle was successfully removed.

By measuring a reference sphere, result indicate that measurement error increased as the angle between the probe and surface increased, and that the overall shape of measurement error rotated as the probe was rotated about its main axis. In addition, after error compensation, the range of measurement error was reduced to about 50 nm which is very close to the noise level of the probe. This research has shown an improvement in the measurement accuracy of chromatic confocal probe based on-machine measurement and will contribute to ultra-precision machining.

1. Introduction

Ultraprecision diamond turning process can generate complicated surfaces with submicron level form accuracy and nanometer level surface roughness, which are widely used in various optical devices [1]. However, the machining process induces many errors including geometric, cutting-force related, and fixture-dependent [2]. Therefore, a robust surface measurement and compensation process are essential for better surface accuracy. The flowchart in Fig. 1 illustrates the cutting and measuring process for ultraprecision turning. Conventionally, as illustrated in Fig. 1(a), the surface of workpiece is measured on a metrology instrument after machining. If the measured figure error is larger than the allowed error, a corrective machining process is conducted after remounting the workpiece on the diamond turning machine. Thus, Repositioning the workpiece between machining and metrology platforms generates surface misalignment errors and increases manufacturing time. In this research, as illustrated in Fig. 1(b), an on-machine measurement process is introduced [3]. In this process, both machining and measurement processes are conducted on the same diamond turning machine by adding a metrology device to the machine, and a corrective machining process is performed repeatedly until the required surface form accuracy is achieved. Without the need to remount workpieces between platforms, the on-machine measurement method can avoid the errors caused by repositioning workpieces and improve measuring efficiency.

Because most surface profilometers require a probe tip to contact – and potentially scratch – the surface to be measured, a chromatic confocal probe is an effective, and faster, non-contact a sensor for on-machine measurement, whose principle is illustrated in Fig. 2 [4]. However, measurement error correction is often necessary because the measured error tends to increase when the incidence of angle of the probe axis with respect to the measured surface is large; it is difficult to obtain reflected light back into the probe in this situation. There have been several studies on machining errors on highly inclined surfaces, but most of them are limited to two-dimensional measurements, and a robust method to compensate for measurement errors is not established. This study investigates a process for compensating measurement errors by performing three-dimensional measurements using a reference sphere and will contribute to the improvement of precision and efficiency in ultra-precision machining.



(a) Conventional Method (b) On-machine measurement

Fig. 1 Flowchart of cutting and measuring process for ultraprecision turning

2. Methodology

2.1 Machining and metrology platforms

This study used a chromatic confocal probe (CHRocodile 2 S PRECITEC Co., Ltd.) mounted to an ultraprecision lathe (Nanoform X AMETEK Precitech Co., Ltd.). It was a 5-axis machine (XYZBC). The Precitec probe had a 4.5 mm working distance, a 300 µm measuring range, and was fixed to the stage of the Precitech lathe along the Z-axis direction. Three-dimensional measurements were performed using the X, Y, and Z axes on the Precitech lathe.

This study conducted two on-machine measurement experiments. PV (Peak to Valley) value and RMS (Root Mean Square) value were used to evaluate measurement accuracy.

2.2 On-machine measurements with different measurement ranges and surface inclinations

On-machine measurements were performed on multiple reference spheres with varying radii and probe incidence angles to establish the effects of different measurement ranges and surface inclinations on measurement results. Fig. 3 shows outline drawing and Table 1 illustrates probe parameters.

2.3 Error compensation on curved surfaces

A reference sphere was measured and the data was used to correct for measurement error caused by the probe angle of incidence with respect to the measured surface, outlined in Fig. 4. First, a reference sphere was measured in the incidence angle range of 0° to 30°, and the

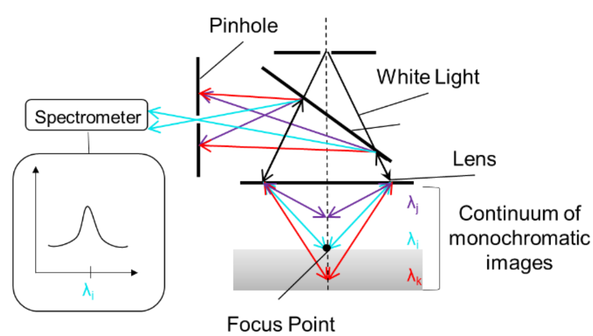


Fig. 2 Measurement principle of chromatic confocal probe

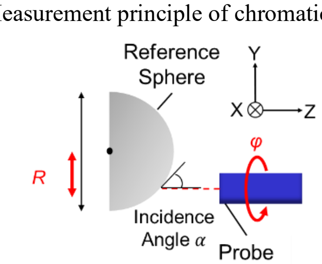


Fig. 3 Outline drawing for the first experiment

Table 1. Probe parameters

Feedrate f [mm/min]	100
Scan rate V [Hz]	1000
Measurement range R [mm]	2.5, 6
Probe angle φ [°]	0, 90, 180, 270

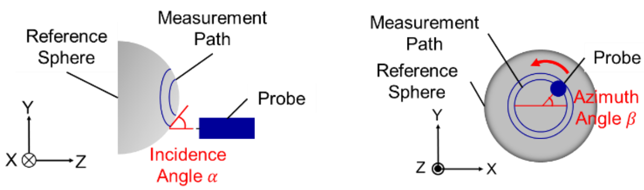


Fig. 4 Outline drawing for the second experiment

measurement error due to the incidence angle was calculated for each azimuth angle. Subsequently, measurements on a tilted flat with an incidence angle of 11.21° were taken at different probe incidence angles. The incidence angle of the tilted flat was selected between the range of measurement angle. Since the center of the probe was aligned with the center of main spindle of the machine tool, the probe reading should have been zero, but was not zero due to errors caused by the probe's angle of incidence. By subtracting the computed angle of incidence error from multiple sets of measurement data, a dataset that more accurately reflects the true error in the surface was established, which can be subsequently used for form error compensation on curved surfaces. Throughout the process, the sinusoidal measurement error observed on a tilted flat, caused by probe misalignment with respect to the center of the main spindle was observed and then removed. These experiments were conducted 5 times.

3. Results and discussion

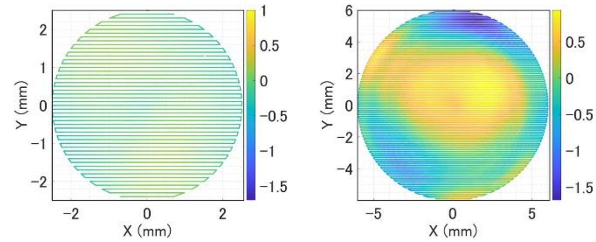
3.1 On-machine measurements with different measurement ranges

Fig. 5 shows the results of two on-machine, X-axis raster measurements of a sphere of known radius constrained inside circles of radius 2.5 mm and 6 mm. Both the PV and RMS values decreased as the measurement radius was reduced and the measurement range was narrowed. This indicates that the further away from the center of the reference sphere – and thus the larger the probe angle of incidence with respect to the measured surface – the greater the error in the measurement results.

As shown in Fig. 2, detecting reflected light in the probe's sensor becomes more difficult as its angle of incidence with respect to the measured surface increases. Since the slope of the surface of a sphere increases further from the center, the measurement error also increases further from center, where the measurement range is larger.

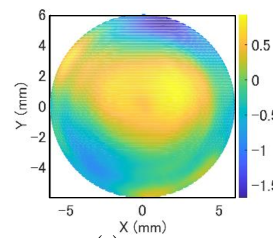
3.2 On-machine measurements with different probe clocking angles

Fig. 6 shows the results of four on-machine measurements with the probe clocked about its axis for $\varphi = 0°$, 90°, 180°, and 270°. The probe was rotated about its axis between each measurement as shown in Fig. 3. It can be seen that the form of the measurement error also rotates with the probe rotation. The standard deviations of the PV and RMS values at different probe clocking angles are 90.4 nm and 17.1 nm, respectively These results confirm that the change in measurement error corresponds to the change in probe clocking angle, and that the



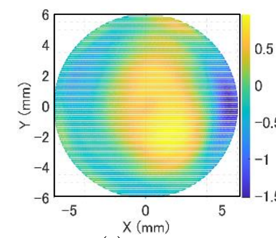
(a) R=2.5 mm (b) R=6 mm

Fig. 5 Results of on-machine measurements with different measurement ranges



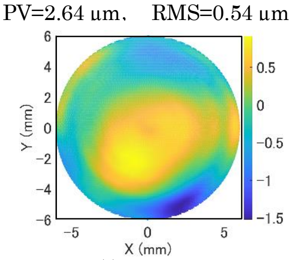
(a) $\varphi = 0°$

PV=2.64 um, RMS=0.54 um



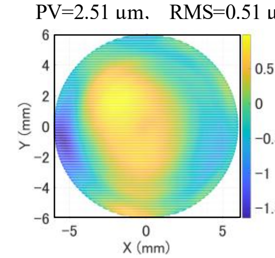
(b) $\varphi = 90°$

PV=2.51 um, RMS=0.51 um



(c) $\varphi = 180°$

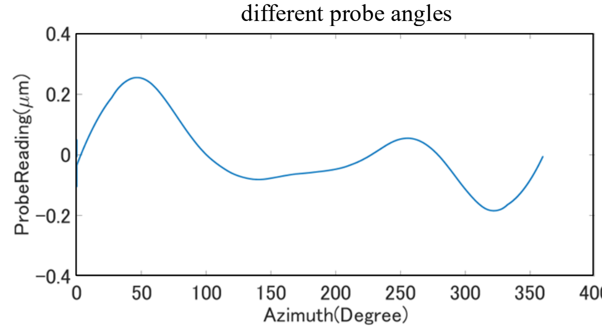
PV=2.45 um, RMS=0.50 um



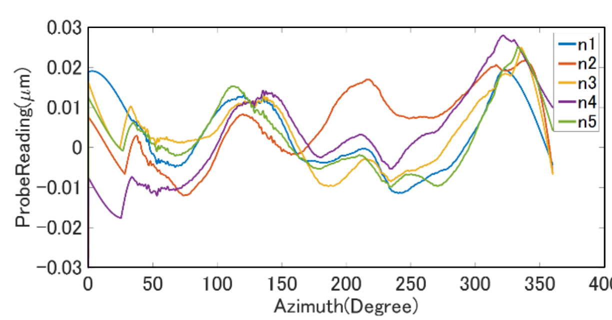
(d) $\varphi = 270°$

PV=2.62 um, RMS=0.52 um

Fig. 6 Results of on-machine measurements with different probe angles



(a) The measurement result of the tilted flat



(b) The results of the correction

Fig. 7 The measurement result before and after correction measurement error originates from an error inside the probe and not on the surface being measured.

3.3 Error compensation on curved surfaces

Fig. 7(a) shows the measurement result, smoothed with a Savitzky-Golay filter, for one rotation of a tilted flat, where the horizontal axis indicates the azimuth angle as viewed from the probe. Before correction, the range of measurement error was 0.44 μm Then, angle of incidence error was calculated for incidence angle of 11.21° by taking the error of 11° and 12° which were calculated from the reference sphere measurement data. The calculated data was used to subtract from the measurement data of the tilted flat. Even after correction, the readings did not follow a straight line, but rather a sinusoidal curve, which was considered to be due to probe misalignment. Therefore, a sine curve was fitted to the corrected data and subtracted. These calibration processes were conducted in the all 5 experiments. Fig. 7(b) shows the results of the correction for 5 times. After correction, the range of measurement error decreased to about 50 nm which is very close to the noise level of the probe.

4. Conclusion

By performing on-machine measurements on a reference sphere using two methods with a chromatic confocal probe, the following conclusions were reached.

(1) When measuring a reference sphere with chromatic confocal probe, ~~result indicate that~~ measurement error increased as the angle between the probe and surface increased.

(2) The measurement error due to the angle of incidence was confirmed to be caused by the probe itself.

(3) The error due to probe angle of incidence is repeatable, and it is therefore possible to compensate for it. The range of measurement error after compensation was reduced to about 50 nm which is very close to the noise level of the probe.

This research has shown an improvement in the measurement accuracy of chromatic confocal probe based on-machine measurement and will contribute to the improvement of precision and efficiency in ultra-precision machining.

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