Paper:

Measurement and Compensation of Tool Contour Error Using White Light Interferometry for Ultra-Precision Diamond Turning of Freeform Surfaces

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In ultra-precision diamond turning of freeform optics, it is necessary to obtain submicron-level form accuracy with high efficiency. In this study, we proposed a new method for the quick measurement and compensation of tool contour errors to improve the form accuracy of the workpiece. In this method, the nanometer-scale contour error of a diamond tool is quickly and precisely measured using a white light interferometer and then compensated for, before machining. Results showed that the contour of a diamond tool was measured with an error less than 0.05 μm peak-to-valley (P-V) and the feasibility of error compensation was verified through cutting experiments to create a paraboloid mirror and a microlens array. The form error decreased to 0.2 μm P-V regardless of the contour error of the diamond tools when cutting the paraboloid mirror, and that of the microlens array was reduced to 0.15 μm P-V during a single machining step.

Keywords: freeform surface, ultra-precision cutting, form error compensation, diamond tool, white light interferometry

1. Introduction

In recent years, freeform surfaces have become increasingly useful in the optical industry. Freeform optics can improve the performance of optical systems and downsize system components [1]. Freeform optics are used in fields that require accurate and complex-shaped surfaces, such as photonics, laser systems, aerospace, and biomedical engineering [2, 3]. In recent years, the required machining accuracy has approached the sub-micrometer scale or higher [4, 5].

Among various methods to machine such complex freeform surfaces, ultra-precision diamond turning is an established technology that has seen significant use. Using a slow tool servo (STS) system for diamond turning, the rapid fabrication of complex freeform surfaces has been shown [6]. In STS turning, a tool path is programmed so that a tool contour envelops precisely a designed surface. Since the machined surface is ultimately fabricated by the tool contour, if the tool contour is different from the programed tool contour, it becomes an error factor, causing a form error on the machined surface [7, 8]. Therefore, in ultra-precision turning, it is necessary to measure the tool contour precisely.

Generally, the contour of a commercially available diamond tool used in ultra-precision turning has a submicron scale contour error from the ideal arc shape [9]. However, in previous studies of STS cutting, the tool contour was taken to be an ideal arc shape [10–12]. As a result, the tool contour error causes a submicron scale form error on the machined surface, even after compensating for other errors. With this in mind, the achievable form accuracy in freeform diamond turning is limited by the accuracy of the tool contour.

One possible way to reduce this tool contour-induced form error is feedback compensation using off-machine measurement of the machined surfaces [13, 14]. In this method, the machined surfaces are off-machine measured after machining and the measured form errors are used as feedback for the subsequent machining step. In this way, the tool contour error can be mitigated. However, this method needs multiple machining cycles and workpiece realignment, which decreases productivity and causes tool wear. In addition, applying this method to freeform surface turning is extremely difficult due to a realignment error when remounting a workpiece after the measurement, although the method is usable in conventional symmetric surface turning. Several studies have attempted this method in freeform surface turning; however, the achieved form accuracy was not satisfactory [15, 16].

Another method is feedback compensation using on-machine measurements of workpieces, where a machined workpiece is measured using an on-machine measurement unit [17, 18]. Through this, the remounting of the workpiece is not required, so the realignment error can be suppressed. However, depending on the required measurement accuracy and complexity of workpiece shapes, this method can take a significantly long measurement time [19]. In addition, this method still has difficulties in precision alignment and calibration of the measurement units on a lathe. Therefore, there have been few reports applying this method to freeform surface turning [20], although it has been used in symmetric surface turning [21, 22].

As a contact measurement method, atomic force microscopy (AFM) has been used to measure diamond tool contours [23, 24]. The combination of contact measurement using AFM and non-contact measurement using optical/laser systems were also attempted [25, 26]. However, the measurement is limited to a very narrow range for AFM. Non-contact measurement with optical/laser systems has the limitation that the measurement can only be performed on one target, because the system is specialized for each target [27–29].

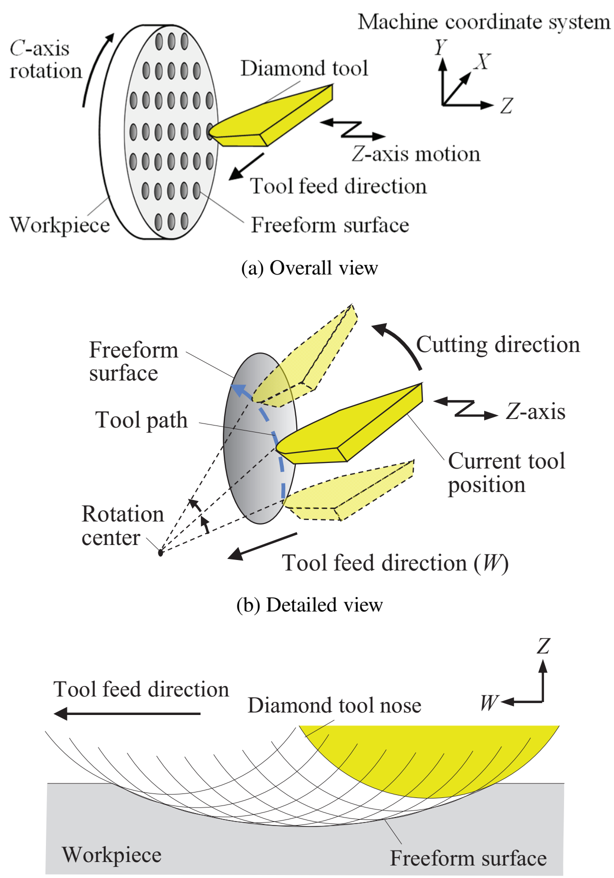
The objective of this study is to develop a quick measurement and feedforward compensation method for the contour error of diamond tools. In this study, a white light interferometer was used to measure the contour of diamond tools. White light interferometry enables measurement of the tool contour over a wide range of sizes, rapidly. Then, the tool contour error was calculated and compensated for in tool path generation before machining. The feasibility of the proposed method was verified by cutting experiments to fabricate a paraboloid mirror and a microlens array. This proposed method will enable the fabrication of freeform surfaces with submicron-scaled accuracy in a single machining step. In addition, this method takes a short machining time regardless of workpiece sizes and shapes, and achieves high form accuracy regardless of the initial contour accuracy of the tool.

2. Measurement and Compensation Methodology

2.1. Tool Contour Error in Freeform Surface Turning

Schematics depicting freeform surface turning are shown in **Fig. 1**, where X-Y-Z is the machine coordinate system. A freeform surface is fabricated by synchronizing Z-axis motion with C-axis rotation as shown in **Fig. 1(a)**. The tool moves in a feed direction toward the spindle rotation center during the spindle rotation, as shown in **Fig. 1(b)**. **Fig. 1(c)** shows a schematic of the surface formation by the tool contour in the tool feed direction. Theoretically, while the tool moves along the feed direction, the tool contour keeps enveloping a designed surface to remove the unwanted material and fabricate the desired structure. **Fig. 2** shows a detailed schematic of the tool contour. A diamond tool usually has a submicron-scaled contour error $r(\theta)$ from an ideal arc shape whose radius is R, where θ is the angle from the tool center.

A schematic of a conventional method of tool path generation is shown in **Fig. 3(a)**, where a tool path is calculated from the ideal tool nose radius R, without considering the contour error $r(\theta)$. In this way, the tool position is given by:



(a) Overall view

(b) Detailed view

(c) Surface formation by tool contour enveloping

Fig. 1. Schematics depicting freeform surface turning.

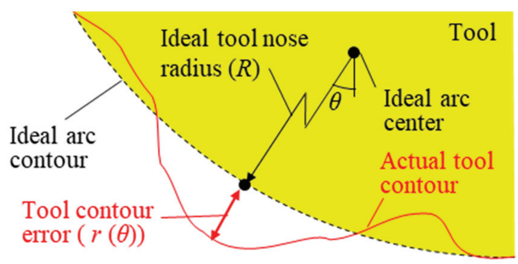


Fig. 2. Schematic depicting contour error of a diamond tool.

$$W_t = W_o - R \sin\theta, \quad (1)$$

$$Z_t = Z_o + R \cos\theta, \quad (2)$$

where (W_t, Z_t) is a programmed tool position and (W_o, Z_o) is the position of a cutting point where the tool contour envelops the designed surface. As a result, the unconsidered contour error causes a deviation between the designed surface and the path of the actual tool contour, as shown in **Fig. 3(b)**, which generates a form error on the machined surface. To solve this problem, feedback compensation is performed after machining, where measuring a workpiece and compensating for the measured tool contour error are performed as per **Fig. 3(c)**.

In this study, we propose a new method for the mea-

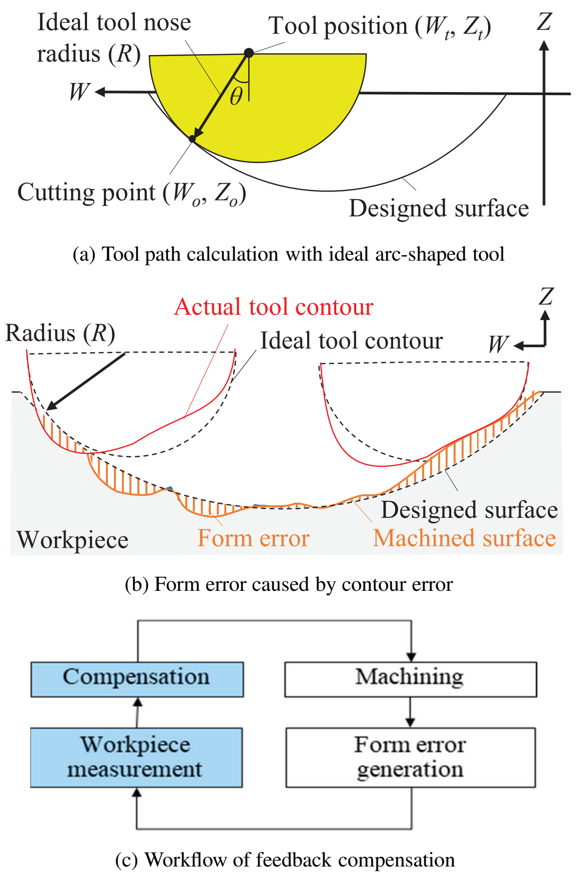


Fig. 3. Tool contour error in freeform surface machining and conventional compensation method.

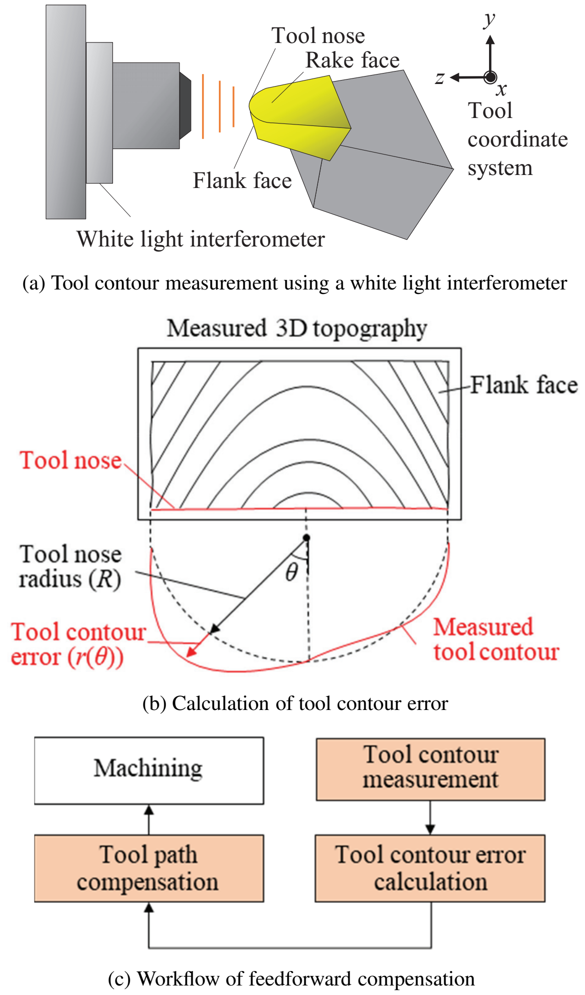


Fig. 4. Proposed workflow for measurement and compensation of tool contour.

surement and compensation of a contour error of the diamond tool as shown in **Fig. 4**. In this method, measurement of the diamond tool nose is performed quickly and precisely before machining using a white light interferometer, as shown in **Fig. 4(a)**, where the tool coordinate system x-y-z is given. Then, the measured raw data is processed to calculate the tool nose radius and contour error as per **Fig. 4(b)**. Finally, the tool path is compensated for by considering the contour error $r(\theta)$, so that the actual tool contour precisely envelops the designed surface, as shown in **Fig. 3(b)**. This method will make it possible to achieve high form accuracy in freeform surface turning without another machining cycle, as shown in **Fig. 4(c)**. In addition, high form accuracy will be obtained regardless of the initial accuracy level of the tool contour, which decreases the production cost of diamond tools greatly.

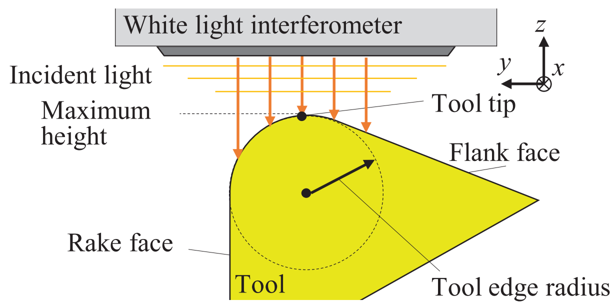


Fig. 5. Schematic of measurement of tool edge.

2.2. Method of Tool Contour Measurement

In the proposed method, the measurement of a tool nose is performed from the tool flank face side, as shown in **Fig. 4(a)**. Since a white light interferometer has a higher resolution (on the order of nanometers) in the light beam direction than in the lateral sampling direction, the measurement from the flank face improves the measurement accuracy of tool contour compared with a measurement from the tool rake face [9]. In this method, the measured raw data of the tool contour is output as a change of height in the light beam direction, as shown in **Fig. 4(b)**.

Generally, as shown in **Fig. 5**, a commercially available diamond tool used in the ultra-precision cutting has a tool edge radius (bluntness) of 50 nm to 100 nm. Since the tool nose contacts the workpiece at the point of maximum height, the profile of the tool contour is extracted from the cross section of the maximum height. Then, the tool nose radius R is calculated, and the function of contour

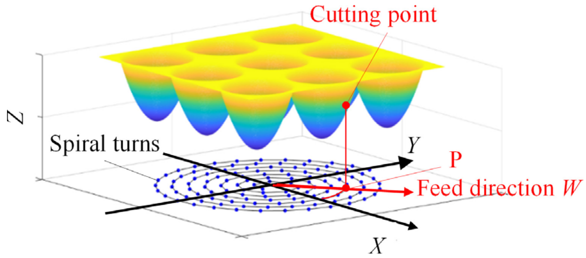


Fig. 6. Tool path generation in freeform surface turning.

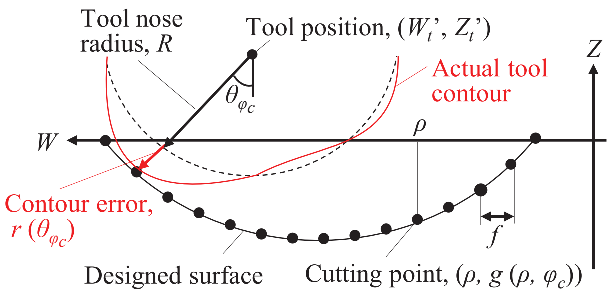


Fig. 7. Tool path compensation considering tool contour error in freeform surface turning.

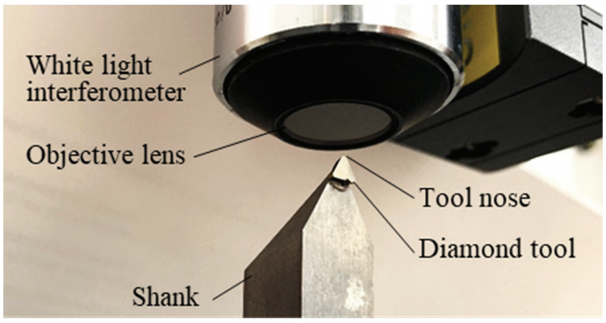


Fig. 8. A snapshot of measurement of tool contour using a white light interferometer.

error $r(\theta)$ can be expressed by the following polynomial.

$$r(\theta) = \sum_{i=0}^{n} \alpha_i \theta^i. \quad (3)$$

2.3. Method of Tool Path Compensation

In freeform surface diamond turning, the tool path is generated by connecting the corresponding cutting points distributed on a designed surface, as shown in **Fig. 6** [30]. In the cross-section of the XY-plane, each cutting point is located on a spiral trajectory. The position of any point P on the spiral trajectory can be defined by an arc-length S, which is the total length of the spiral trajectory from the spindle rotation center to the point P, and an angle φ, which is a total angle from the starting point of spiral turns to point P. The length S is given by the following equation with φ:

$$S = \int \sqrt{\rho^2 + \left(\frac{\mathrm{d}\rho}{\mathrm{d}\varphi}\right)^2}\,\mathrm{d}\varphi$$
$$= \frac{f_r}{2}\left[(2\pi N_t - \varphi)\sqrt{(2\pi N_t - \varphi)^2 + 1} + \ln\left|(2\pi N_t - \varphi) + \sqrt{(2\pi N_t - \varphi)^2 + 1}\right|\right], \quad (4)$$

where ρ is the distance between the origin and point P, f_r is the tool feed rate along the spiral trajectory, N_t is number of spiral turns. Each parameter is also given by:

$$\rho = r_o - f_r r_o, \quad (5)$$
$$f_r = \frac{f}{2\pi}, \quad (6)$$
$$N_t = \frac{r_o}{f}, \quad (7)$$

where r_o is the radius of the workpiece and f is a pitch of the spiral turns, which is equal to a tool feed rate. Finally, a position of cutting point Z can be obtained by substituting the position of point P into a function of a designed surface $g(X)$, as $Z(\rho, g(\rho, \varphi))$.

Then, the positional relation between the designed surface and the tool edge can be obtained in the cross section of tool feed direction (W), where $\varphi = \varphi_c$, as shown in **Fig. 7**. In this cross section, the position of the cutting point on the profile of a designed surface is expressed as $(\rho, g(\rho, \varphi_c))$. The compensated tool position (W_t', Z_t') can then be calculated.

$$W_t' = W_o - \left(R + r\theta_{\varphi_c}\right)\sin\theta_{\varphi_c}, \quad (8)$$
$$Z_t' = Z_o + \left(R + r\theta_{\varphi_c}\right)\cos\theta_{\varphi_c}. \quad (9)$$

By calculating the compensated tool position for all φ by substituting $r(\theta)$, the tool path is finally compensated.

3. Experimental Procedures

The white light interferometer used in this study was a CCI-1000 made by AMETEK Taylor Hobson Inc. A 50× objective lens was used for the white light interferometer. As shown in **Fig. 8**, the measurement was performed from the flank face of a diamond tool mounted on a stage. For comparison, two different single-crystal diamond (SCD) tools (tools 1 and 2) with a nose radius of 0.5 mm were used. An SEM image of the nose of tool 1 is shown in **Fig. 9**. The measurement equipment used to obtain reference measurement data was a Form Talysurf PGI with a diamond stylus made by AMETEK Taylor Hobson Inc. The resolutions of the measurement equipment are shown in **Table 1**.

Cutting experiments were carried out on a Nanoform X ultra-precision lathe made by AMETEK Precitech Inc., as shown in **Fig. 10**. As a preliminary cutting experiment, a symmetric paraboloid mirror, the shape of which is shown in **Fig. 11** was cut using both diamond tools. Since the paraboloid has a maximum surface slope of 21°,

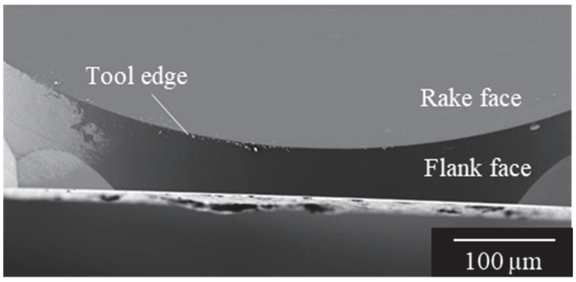


Fig. 9. SEM image of diamond tool nose (tool 1).

Table 1. Resolution of measurement equipment used.

Direction	Resolutions	
	Interferometer	Diamond stylus
Lateral sampling [nm]	350	125
Light beam [nm]	0.1	0.3

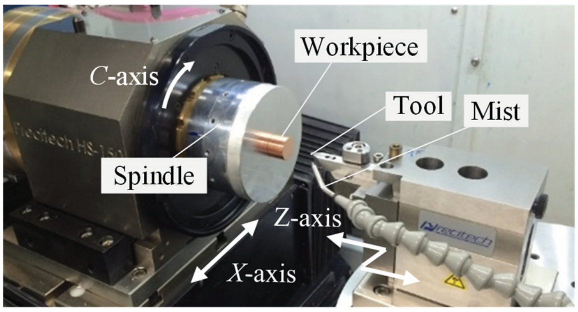


Fig. 10. Photograph of the main section of the ultra-precision lathe used.

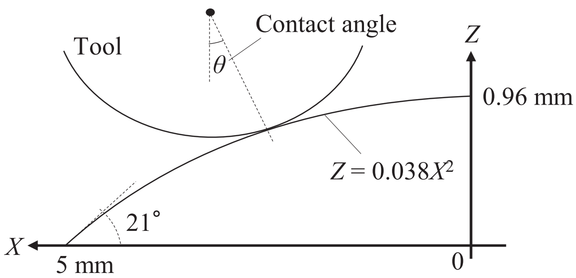


Fig. 11. Design of symmetric surface (paraboloid).

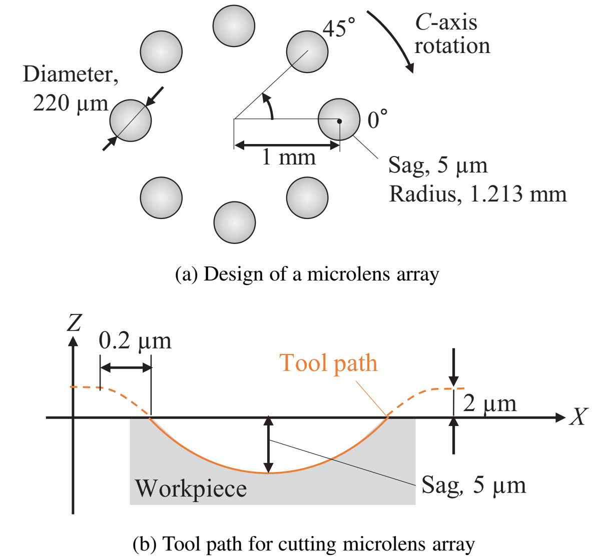


Fig. 12. Design of freeform surface (microlens array).

Table 2. Cutting parameters.

Cutting parameters	Values	
	Symmetric	Freeform
Cutting tool		
Tool 1	SCD, R0.5	
Tool 2	SCD, R0.5	
Workpiece	Oxygen free copper	
Feed rate [μm]	1.0	
Rotation speed [rpm]	1000	15
Depth of cut [μm]	3.0	1.0 ~ 5.0
Cutting atmosphere	Oil mist	

a wide range of the tool contour is used for cutting, making it suitable for verifying the contour error compensation for a tool with a wide window angle. Then, as an example of freeform surface fabrication, a microlens array was machined using tool 2. The design of the microlens array is shown in **Fig. 12**. The microlens has a radius of 1.213 mm, a depth of 5 μm, and a diameter of 220 μm. Microlens arrays are a functional optical element and used in assorted optics [31, 32]. When turning a microlens array, it has been reported that a follow-up error occurs at the lens edge, which makes it difficult to obtain a sharp lens edge [33]. To suppress the influence of the follow-up error, a tool path with an extra curve outside the lens was used so that tool acceleration reduces, as shown in **Fig. 12(b)**. The cutting parameters used are shown in **Table 2**. Oxygen free copper was used as workpiece material and oil mist was used for lubrication. Measurement of the machined workpiece was performed using a white light interferometer (the same as that used for tool measurement) and an ultrahigh accurate 3D profilometer UA3P made by Panasonic Corporation, for comparison.

4. Results and Discussion

4.1. Measurement of Tool Contour Error

Figure 13 shows a 3D topography of the nose of tool 1 measured using the white light interferometer. **Fig. 14** shows the tool contours extracted from the measured raw data and calculated contour errors of tools 1 and 2. The tool nose radius is calculated to be 471.98 μm for tool 1 and 512.80 μm for tool 2. Tool 1 has a contour error of 3.517 μm peak-to-valley (P-V) and 0.802 μm root-mean-square (RMS), whereas tool 2 has a smaller contour error of 0.426 μm P-V (0.086 μm RMS). To verify

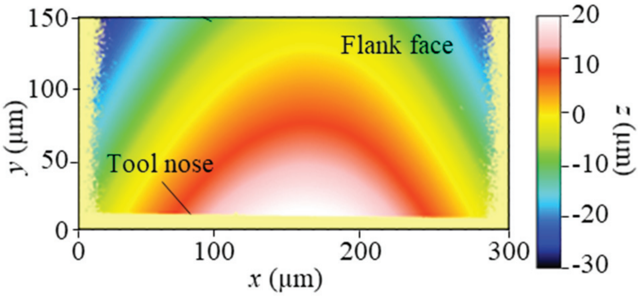


Fig. 13. 3D topography of a measured tool nose.

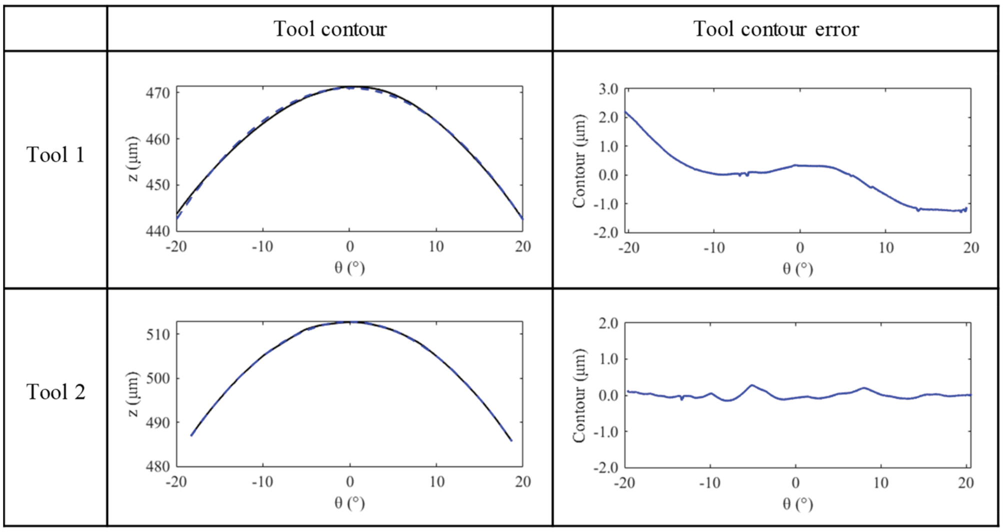


Fig. 14. Profiles of tool contour and tool contour error measured by white light interferometry.

the accuracy of the measurement, the measured contour error of tool 1 was compared with that measured using a diamond stylus. The calculated deviations are shown in **Fig. 15**. The difference between the two results is 19 nm RMS (92 nm P-V) in the window angle range of $\pm 20°$. It can be seen that the deviation is larger at a larger θ. This is thought to be because the measurement accuracy of a white light interferometer is significantly affected by the surface slope. A white light interferometer measures a surface by detecting light reflected from the surface. If the slope of the surface increases, the intensity of the reflected light decreases, which results in a decrease in measurement accuracy. The accuracy of non-contact measurement of a tool edge decreases when the slope of a sample surface is larger than 8° [9].

In this study, the achieved measurement accuracy is comparable with that of previous studies, which was approximately 200 nm P-V using laser-based non-contact measurement [27, 28]. In addition, the measurement takes only 4 min, including the subsequent calculation, which is shorter than that reported in previous studies ($\sim$30 min) [9, 25]. Therefore, it can be seen that the measurement of tool contour errors using a white light interferometer is precise and quick.

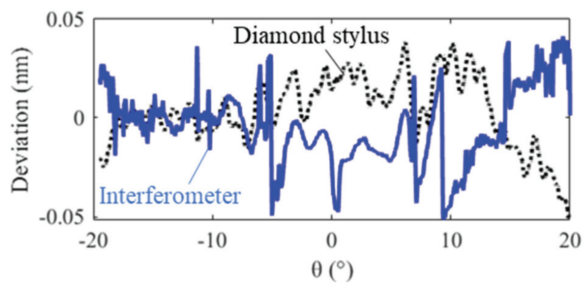


Fig. 15. Comparison of measurement results of tool contours obtained using a white light interferometer and contact measurement using a diamond stylus.

4.2. Cutting of Paraboloid Mirror

A cutting test of a paraboloid mirror is performed while compensating for the measured tool contour error. Based on the measurement results, $r(\theta)$ is calculated for tools 1 and 2 using a polynomial of the 20th degree shown in Eq. (3). **Fig. 16** shows an optical image of the machined paraboloid mirror. **Fig. 17** shows profiles of the form errors of workpieces machined with tools 1 and 2, with and without compensation, respectively. The measurement was performed along the cross section passing through the

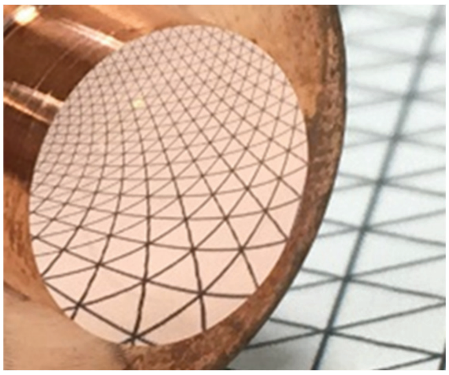
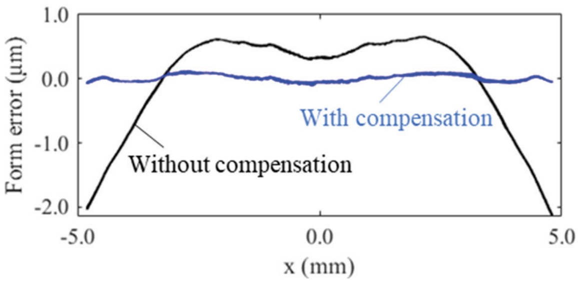
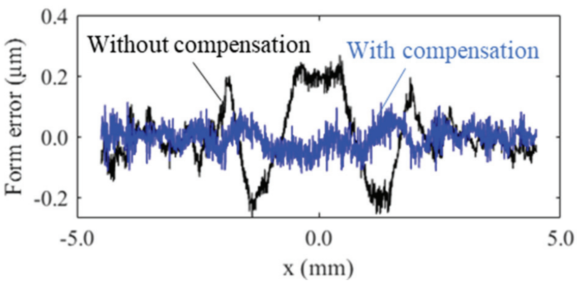


Fig. 16. Optical image of a machined paraboloid mirror.



(a) Machined using tool 1



(b) Machined using tool 2

Fig. 17. Form errors in a paraboloid mirror machined by different cutting tools with and without compensation.

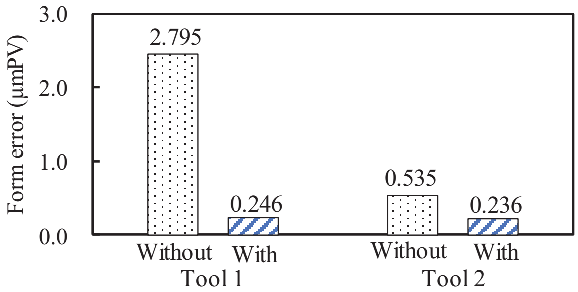


Fig. 18. Comparison of form error between different tools, with and without compensation.

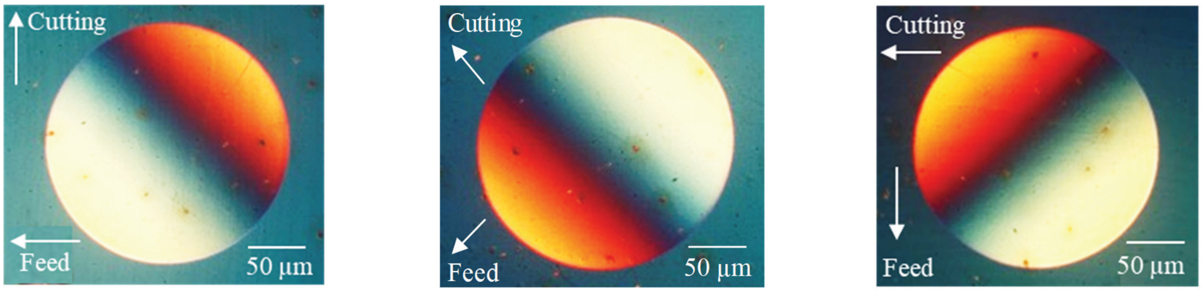
workpiece center. For both tools 1 and 2, the form errors have significant perturbation due to contour errors. By compensating for the tool contour errors, the amount of form errors is seen to significantly reduce. The amount of form errors with and without compensation are compared in **Fig. 18**. For tool 1, a large form error of 2.795 μm P-V is seen without the compensation of tool contour error, whereas the form error is reduced to 0.246 μm P-V after the compensation. For tool 2, the form error is smaller (0.535 μm P-V) than that of tool 1, even without the compensation. This result agrees with the tool contour measurement result, where the contour error of tool 2 is significantly smaller than that of tool 1. After compensation for tool 2, the form error was reduced to 0.236 μm P-V, which is the same as that of tool 1. This indicates that without compensation of tool contour error, the form accuracy is significantly influenced by the initial accuracy of the tool contour. However, by compensating for the tool contour error, it is possible to achieve the same level of form accuracy regardless of the initial accuracy of tool contour. This may significantly reduce the production cost of diamond tools.

4.3. Cutting of a Microlens Array

The fabrication of a microlens array is attempted using tool 2. **Fig. 19** shows the optical microscopy images of machined microlenses at different locations on the workpiece. Precise circular shapes are identified without burrs and edge distortion, indicating the tool path used in the experiment is effectively suppressing follow-up errors. **Fig. 20** shows 3D topographies and calculated form errors of the lens located at 0° machined with and without tool contour compensation, respectively. Before the compensation, a form error of 292 nm P-V is measured, whereas the form error is reduced to 153 nm P-V after the compensation. **Fig. 21** shows profiles of the form errors in the cross-section of the lens center. In the cutting direction, a form error of approximately 50 nm P-V is observed, which is smaller than that in the feed direction. This is because the change in contact angle of the tool edge is smaller in the cutting direction, resulting in a smaller magnitude of contour error affecting form error generation. In the feed direction, the influence of tool contour error and its compensation is more apparent. In this study, the form accuracy for a microlens array is seen to be 153 nm P-V, which is high enough for practical use as an industrial optical lens [33, 34]. This form accuracy is higher than previous studies where a conventional feedback compensation was used [15, 16, 20].

4.4. Factors for Further Improvement of Form Accuracy

In the cutting tests of the paraboloid mirror and the microlens array, it is seen that although the tool contour error compensation improved the form accuracy of the machined surface, a small amount of form error is observed (**Figs. 17** and **21**). One possible reason for this error might be the measurement error of the tool contour. To confirm this, the form error caused by tool contour measurement error is calculated based on the measurement error shown in **Fig. 15**. A comparison of profiles of the calculated form error and the measured form error of the machined surface



(a) 0°　　(b) 45°　　(c) 90°

Fig. 19. Microscopic images of a machined microlens array.

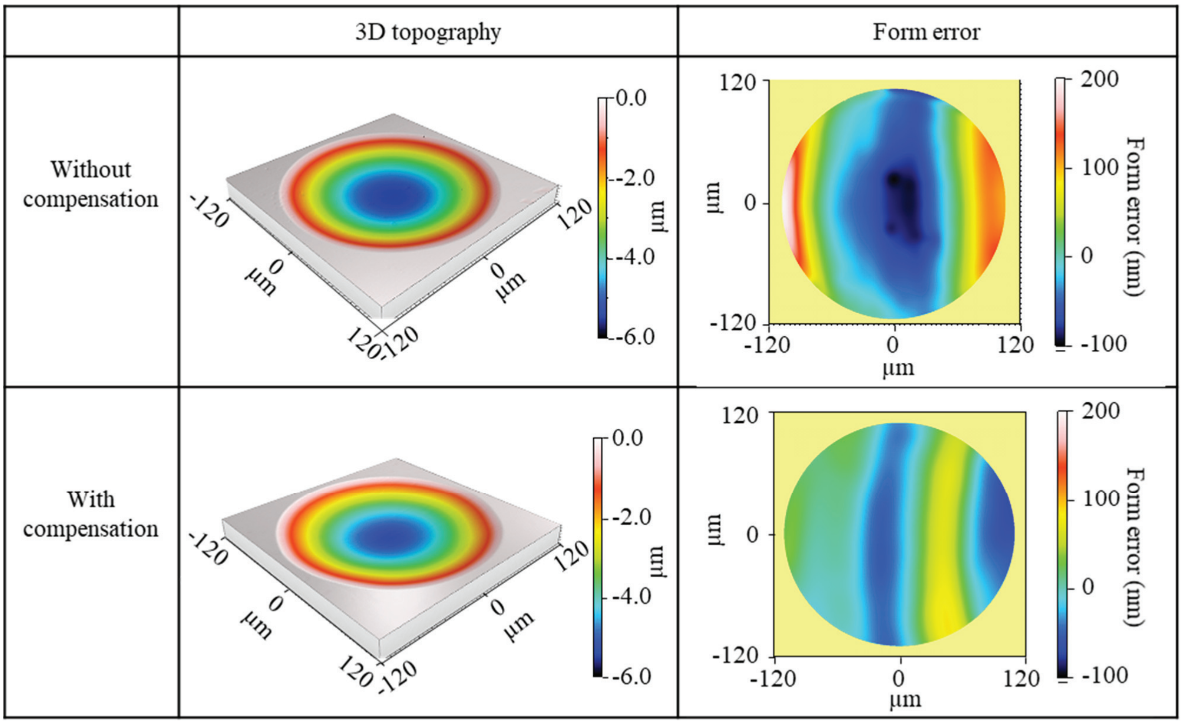
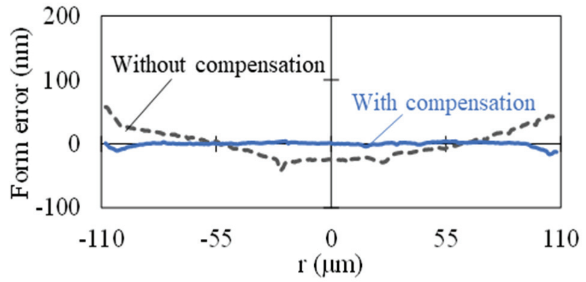


Fig. 20. 3D topographies and form errors of a microlens array machined with/without compensation of tool contour error.

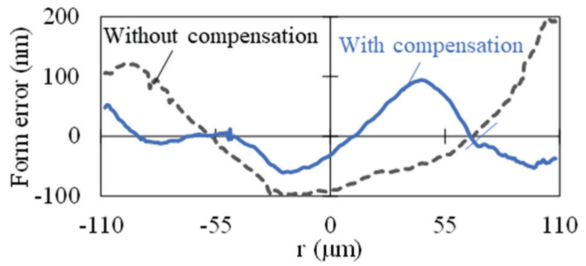
is shown in **Fig. 22**. The calculated result agrees well with the measured result and demonstrates that the remaining form error was mainly caused by the measurement error of the tool contour.

Another factor resulting in form error is the realignment error of a diamond tool. As shown in **Fig. 23**, when measuring a tool, the tool is aligned on a stage aslant with angles $\theta_{x,m}$ and $\theta_{y,m}$ in x- and y-axes, respectively. Then, after measurement, the tool is mounted on a lathe aslant with angles $\theta_{x,c}$ and $\theta_{y,c}$. If these angular positions in the measurement and machining have errors ($\Delta\theta_x$ and $\Delta\theta_y$), a compensation error will occur. In the experiment, the alignment errors $\Delta\theta_x$ and $\Delta\theta_y$ are experimentally measured as 0.013° and 0.0047°, respectively, using a ruby probe. The influences of both aslant errors $\Delta\theta_y$ and $\Delta\theta_x$ on form error generation are analyzed in **Figs. 24** and **25**, respectively. As shown in **Fig. 24(a)**, $\Delta\theta_y$ shifts the tool contour in contact with the workpiece along the cutting edge. Namely, it shifts the profile of tool contour error calculated in **Fig. 14** parallel to the θ-axis. Therefore, a form error caused by $\Delta\theta_y$ is calculated by comparing the measured profile and the profile shifted by $\Delta\theta_y$ in the θ-axis. **Fig. 24(b)** shows the calculated error. The error is approximately 1 nm RMS, which is significantly smaller than tool measurement error.

Moreover, $\Delta\theta_x$ shifts a tool contour contacting with a workpiece along the tool flank face, as shown in **Fig. 25(a)**. Since $\Delta\theta_x$ is small in this experiment, and the tool face shift insignificant, the effect of tool edge radius is more significant, as shown in **Fig. 25(b)**. When the tool position rotates by $\Delta\theta_x$, a tool contour is deviated by Δd in the z-direction. Therefore, the tool contour used in machining can be obtained from the 3D topography of the tool nose (**Fig. 13**) by shifting the contour from the highest point by a distance of Δd in the z-direction. By comparing both contours, the influence of $\Delta\theta_x$ on the form error can be calculated. Since the tool used in this experiment has a tool edge radius of approximately 100 nm,



(a) In cutting direction



(b) In tool feed direction

Fig. 21. Cross-sectional form error profile on a machined microlens array measured along different directions.

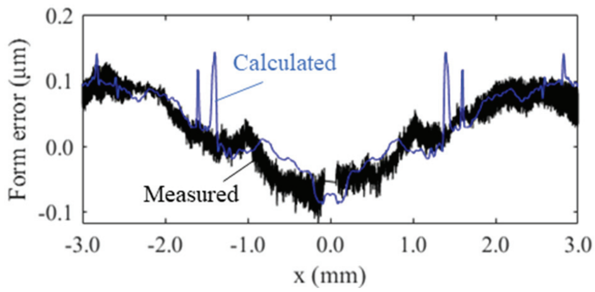
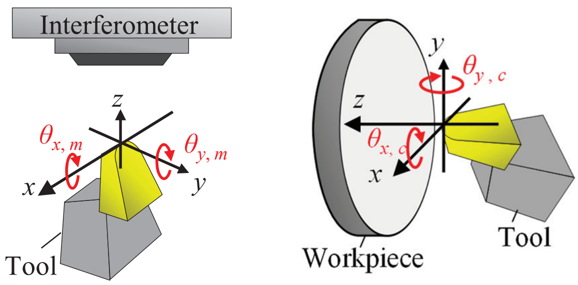
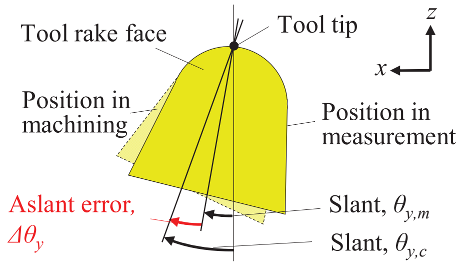


Fig. 22. Comparison of measured form error with result calculated from tool contour error.

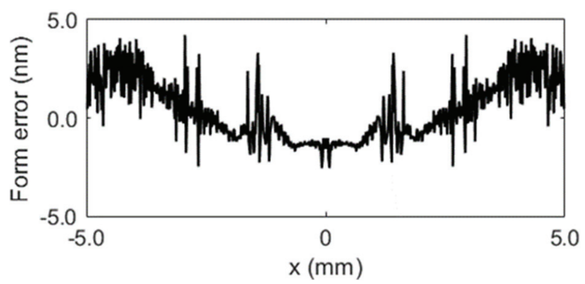


(a) In measurement (b) In cutting

Fig. 23. Slant of tool in measurement and in cutting.



(a) Schematic of aslant error in y-axis ($\Delta\theta_y$)



(b) Calculation result of form error caused by aslant error in y-axis ($\Delta\theta_y$)

Fig. 24. Cross-sectional form error profile on a machined microlens array measured along different directions.

Δd is 2.3 nm. **Fig. 25(c)** shows the calculation of form error caused by $\Delta\theta_x$. The error is calculated to be approximately 1 nm RMS, which is comparable to that caused by $\Delta\theta_y$.

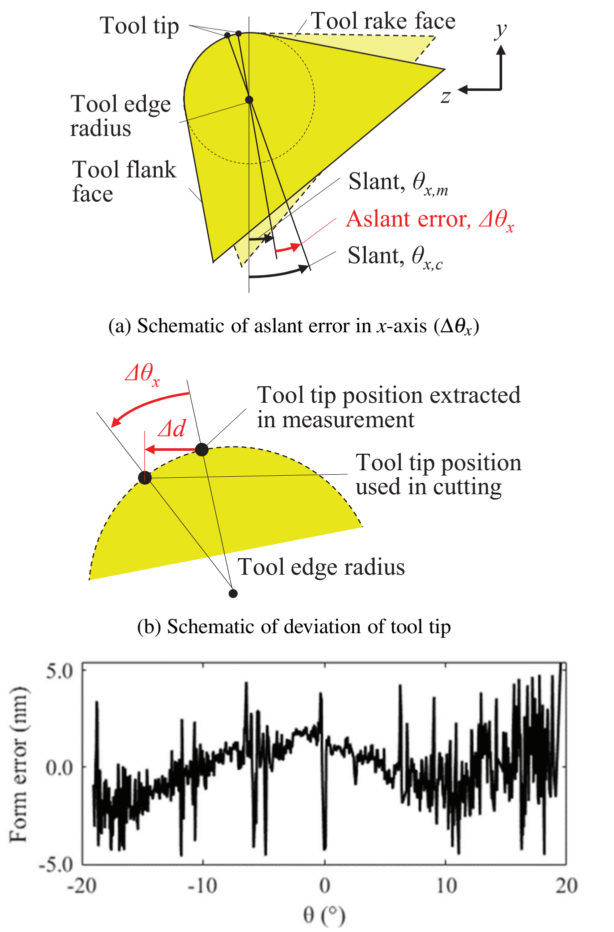
In summary, the tool contour measurement error is a dominant factor limiting the achievable form accuracy of workpiece in the proposed measurement and compensation method. The accuracy of tool contour measurement might be improved by using a higher-magnification objective lens for the white light interferometer. Another solution is to reduce the noise of scanning interferometry for surface topography [35]. Furthermore, the microscopic tool tip vibration caused by the machine tool dynamics [36] should be suppressed in order to improve the tool measurement stability and accuracy. These issues will be considered in the future work of this study. The continuous research and development in this area will extend the accuracy level to nanometer scale which will greatly contribute to the manufacturing of high value-added products with extreme precision [37].

5. Conclusions

In this study, the possibility of measuring and compensating contour errors of diamond tools by using white light interferometry for ultra-precision turning of freeform surfaces was investigated. The following conclusions were obtained.

(1) The contour of diamond tools was measured using a white light interferometer with a deviation of 19 nm RMS as compared to a diamond stylus contact-measurement over a wide range of 40°. The measurement time was 4 min, which was shorter than previous contact measurement methods.

(2) By measurement and compensation of tool contour error, workpiece form error was decreased to 0.236 μm P-V in the turning of a paraboloid mirror. The same level of form accuracy was achieved regardless of the accuracy of the diamond tool contour.



(a) Schematic of aslant error in x-axis ($\Delta\theta_x$)

(b) Schematic of deviation of tool tip

(c) Calculation result of form error caused by aslant error in x-axis ($\Delta\theta_x$)

Fig. 25. Form error caused by the slant of tool in x-axis.

(3) A microlens array was successfully machined with a form error of 0.153 μm P-V in one-step machining using the proposed compensation.

(4) Compensation accuracy of the proposed method depends on the measurement accuracy of the tool contour, and increasing the measurement accuracy will directly improve the form accuracy after the compensation.

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