Development of an optical probe for evaluation of tool edge geometry

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Received 28 February 2014

Abstract
This paper proposes a non-contact and on-machine measurement method for evaluating tool edge geometry. In the proposed method, a focused laser beam having a diameter of several micrometres traces over the tool edge. By utilizing a light intensity of the laser beam passed around the tool rake face, the gap between the centre of the optical axis of the focused laser beam and the tool edge can be obtained. By combining the measured gap and the information on the XY positions of the focused laser beam, the tool edge contour can be evaluated. In the proposed method, stability of the laser power emitted from a light source would affect measurement accuracy of the tool edge contour. A modified optical design was therefore applied to the evaluation system so that a laser power drift and influences of common-mode noise could be compensated in real time. A modified evaluation system consisting of a laser diode, a beam splitter, a pair of lenses and two photodiodes was developed. Experiments were carried out to test the basic performances of the developed evaluation system with the modified optical design. Possible sources of measurement errors in the tool edge contour evaluation were also discussed. Furthermore, computer simulation was carried out to confirm measurement resolution of the developed system along the tool edge contour.

Key words: On-machine measurement, Non-contact measurement, Focused laser beam, Tool edge measurement, Light intensity

1. Introduction

Diamond tools have been used in ultra-precision manufacturing process to fabricate precision surfaces (Ikawa, et al., 1991). With a combination of a diamond tool and a fast-tool servo technology, three-dimensional micro structures can also be fabricated (Cheng and Huo, 2013). Form error of a tool edge is one of the critical factors to be addressed for assuring the quality of the ultra-precision machining. Tool measurements therefore contribute to achieve precise profile manufacturing (Chen, et al., 2009). Conventionally, scanning electron microscopes (SEMs) have been used to evaluate tool edge contours (Drescher, 1993). Although the SEMs have a measurement resolution on the order of nanometres, measurements must be carried out in a vacuum condition. In addition, quantitative analysis from the qualitative results of two-dimensional image costs too much and takes a huge amount of time (Shi, et al, 2010). On the other hand, atomic force microscopes (AFMs) is a candidates for tool edge geometry measurement since they have an excellent resolution in three-dimensional measurement, and can carry out measurements in the air (Lucca, et al., 1993; Zong et al., 2010). However, alignment of an AFM-tip and the target tool was difficult and time-consuming task. In responding to the requirement, an AFM-based instrument including a laser probe system for fast alignment between the AFM-tip and the target tool has been developed, and measurements of micro tool edges have successfully been carried out (Gao, et al., 2009). With the developed instrument, three-dimensional measurement of a tool edge profile not only with a high resolution but also with a high reliability has been achieved. Meanwhile, tool edge measurement by using contact-type instruments has disadvantages; for example, measurement results are influenced by the contact angle or the dissymmetry of a measurement stylus (Odin, et al., 1994). In addition, measurement over a range of millimetres is a time-consuming task for the AFM due to its limited measurement range up to 100 µm. Moreover, AFMs should carry...
out a time-consuming area scanning over a target tool contour, even if only the contour information is required. A new usage of the optical probe, which has been used as an alignment system in the AFM-based instrument (Gao, et al., 2009), has therefore been proposed to measure tool edge contours with a large scale of several millimetres. In principle, lateral measurement resolutions of conventional optical measurement methods such as optical microscopes and white-light interferometers are limited by the diffraction limit of the light (Hocken, et al., 2005). On the other hand, the proposed method would be able to achieve measurement resolution along specific direction beyond the diffraction limit (Jang, et al., 2013). In the proposed method, a focused laser beam traces over the tool edge, while light intensity of the laser beam passed around the tool rake face are monitored. By utilizing the measured light intensity, information of $XY$-coordinate of each point on the tool edge can be calculated.

In this study, the prototype of the optical probe for tool edge contour measurement is developed, and its basic performances are verified in experiments. In the previous work (Jang, et al., 2013), feasibility of the proposed method was verified by measuring a straight edge of a cutting tool. Measurement resolution of the developed measurement system along the direction perpendicular to both the normal of the rake face and the tool cutting edge was confirmed to be beyond the diffraction limit of the light. In this paper, a tool contour of a cutting tool with a nose radius of 2 mm was measured to address possible sources of measurement errors in the tool edge contour evaluations with a limited size of a beam spot. Furthermore, measurement resolution of the proposed method along the tool edge contour is also investigated by carrying out computer simulation.

2. Principle of the proposed measurement method

An optical probe is designed for quantitative evaluations of an outline of an edge of a rake face of a diamond tool, which is referred to as a nose contour. Figure 1 shows a principle of the proposed measurement method. A focused laser beam having a diameter on the order of micrometres at the focal point is used as a micro optical probe, which would be located on a tool edge as shown in Fig. 1(a). A part of the laser beam is blocked and reflected by the tool rake face, while the other part would pass around the tool rake face. The intensity of the laser passed around the tool rake face would be obtained by using a photodiode (PD). Fig. 1(b) shows the expanded image of the laser focal point, where the axis of the laser beam is located near the tool edge with a gap of $\delta$ along the $Y$-direction. The laser beam would be scanned along the $X$-direction while monitoring the PD output. The deviation of the light intensity obtained by the PD includes information of the variation of $\delta$. The $XY$-position $(x, y)$ of the focused laser beam is provided by a precision positioning system employed in the developed measurement instruments, and therefore tool edge contour can be derived by using the information of the laser beam position and the variation of $\delta$. A high measurement resolution beyond the diffraction limit of light can be achieved in the direction perpendicular to both the normal of the rake face.

![Fig. 1 Principle of proposed evaluation method for tool edge contour](image)

(a) Schematic of optical probe (b) Expanded
and the tool cutting edge.

In the proposed method, precision alignment of the target cutting edge with respect to the focused laser beam along the axis of the focused laser beam is required since the diameter of the focused laser beam would change in accordance with the positioning error along the Z-direction. In the proposed instrument, fine adjustment for the Z-directional positioning can be carried out by referring the output voltage signal from the PDs (Gao, et al., 2006). A relationship between \( \delta \) and the intensity of the light passed around the tool rake face can be verified by moving the tool in the Y-direction in Fig. 1. By using the acquired relationship curve, deviation of \( \delta \) can be converted into the tool edge contour.

3. Measurement instrument

A prototype optical setup, consisting of a laser diode, a beam splitter (BS), three of lenses and two photodiodes as shown in Fig. 2, was designed to verify the feasibility of the proposed method. In the optical setup, a laser beam was emitted from the laser diode along the Z-axis, and was collimated by a lens. The collimated laser beam was divided by the BS. By using the focusing lens, the transmitted beam was focused on the tool edge so that it could be used as the optical probe. Aspherized achromatic lenses with a numeric aperture (N.A.) of 0.25 were employed as the collimating lens and focusing lens since the diameter of the focused laser beam \( d \) would be determined by the following equation:

\[
d \propto \frac{\lambda}{N.A.}
\]

where \( \lambda \) is a wavelength of the laser beam. In this paper, a blue LD with the wavelength of 405 nm was employed. The intensity of the laser beam passed around the tool rake face of the tool was monitored by the photodiode (PD\(_M\)). Meanwhile, the intensity of the laser beam reflected by the BS was also monitored by another photodiode (PD\(_R\)) so that influences of a drift of the laser power and a common-mode noise affecting PD\(_M\) and PD\(_R\) can be compensated. The two signals from PD\(_M\) and PD\(_R\) were converted into voltage signals, and were recorded by the oscilloscope. The data acquisitions of the PD signals were synchronized with the machining lathe, and the acquired data was utilized to evaluate the variable \( \delta \) at each position on the tool edge. The optical setup was mounted on a spindle case of a machining lathe, which is equipped with a precision XYZ stage system that can realize nanometric translational motions along the XYZ-directions. Two interpolators having a resolution of 0.13 nm were separately employed to detect the X- and Y-directional motions of the stage system. The output voltage signals \( V_M \) and \( V_R \) from PD\(_M\) and PD\(_R\), respectively, can be combined by using the following equation:

\[
V = \frac{V_M}{V_R}
\]
The parameter $q$ can be used as data, in which the influences laser power drift and the common-mode noise is cancelled, that represents the intensity deviation to be used for tool contour evaluation. It should be noted that amplification rates for both $V_M$ and $V_R$ would be adjusted in such a way that the effect of Eq. (2) on the cancellation of the influences laser power drift and the common-mode noise can be maximized (Jang, et al., 2013).

4. Experiment

The sensitivity of the developed instrument is mainly governed by the diameter of the focused laser beam at the focal point. In addition, intensity distribution of the focused laser beam is required to be verified in advance of the tool edge contour measurement. An experiment was therefore carried out to verify both the diameter and intensity distribution of the focused laser beam at the focal point. In the experiment, a knife edge method was employed. A knife edge was mounted on the stage system, and was moved in the $Y$-direction. The measured deviation of the light intensity is shown in Fig. 3. On the assumption that the measured light intensity of the beam spot could be fitted by Fraunhofer diffraction pattern (Hecht, 2002), the diameter of the beam spot was evaluated to be 4.0 $\mu$m.

The stability of the developed optical system was then evaluated. A cutting edge of a diamond tool was aligned with respect to the focused laser beam so that a half of the laser beam would be blocked by a rake face of the diamond
tool. The output voltage signals of both the two PDs were monitored, and \( q \) was obtained by using Eq. (2) as shown in Fig. 4. A peak-to-peak value of the drift in 20 s was found to be 0.005 (\( \delta \)), which corresponds to the deviation \( \delta \) of approximately 20 nm regarding the sensitivity as indicated in the following sentences.

A relationship between a tool displacement corresponding to \( \delta \) and the PD output \( q \), which is referred to as a sensitivity curve of the developed system, was also verified in experiment. As a measurement target, a straight cutting edge of a diamond tool was employed. The cutting edge was aligned to be parallel with the X-axis of the machining lathe within a tolerance of 1 \( \mu \)m with respect to the length of 2 mm in the X-direction so that the influence of the misalignment could be neglected. Figure 5 shows the measured sensitivity curve. Measurements were repeated 5 times. The vertical axis in Fig. 5 indicates \( q \), and horizontal axis indicates \( \delta \) acquired from the Y-directional linear encoder. Deviation of each sensitivity curve with respect to the nominal sensitivity curve was below the noise level of the system during the sensitivity test. The sensitivity curves were curve-fitted by polynomial expressions so that the measured light intensity \( q \) can be converted into the tool contour deviation \( \delta \). The mean sensitivity was calculated to be 0.234 \( /\mu \)m in the range of \( Y \)-directional displacement of 4.28 \( \mu \)m. It should be noted that the measurement resolution would be 7.8 nm when the measurement range of the system is designed to be ±1 \( \mu \)m regarding the diameter of the focused laser beam (4 \( \mu \)m).
Following the experiment confirming the basic performances of the developed measurement system, tool edge contour measurement was carried out. A round-shaped diamond cutting tool with a designed nose radius of 2 mm was employed as a measurement target. Figure 6 shows a flow chart of the tool edge contour measurement carried out in this paper. At first, the focused laser beam scanned the tool edge in clockwise direction as shown in Fig. 6. In the first scan, the optical axis of the focused laser beam was positioned to be on the tool edge. After that, the position of the focused laser beam was shifted in the \( Y \)-direction with an offset of 0.5 \( \mu \)m, followed by the second scanning of the laser beam along the tool edge in the counter-clockwise direction. According to the principle of the proposed method, tool edge contour can be measured regardless of the area size of the beam spot on tool rake face. Experiments were therefore carried out by using two spot paths (S1 and S2) so that the principle of the proposed method can be verified. During the scanning, output voltage signals \( V_M \) and \( V_R \) from PD_M and PD_R, respectively, were measured by using the oscilloscope, whose data acquisition was triggered by a digital signal from the function generator to assure the synchronization between the data acquisition of the measurement instrument and the laser beam scanning. By using the acquired output voltage signals, the parameter \( q \) in Eq. (2) was derived, and was converted into the deviation of the focused laser beam position \( \delta \) with respect to the tool edge contour. By using \( \delta \), data of the tool edge contour was acquired. The center point of the rounded edge was defined by least-squares method considering polar coordinates conversion of the scanning paths and variation \( \delta \). The two results did not show good agreement when the scanning path was deviated from measurement target over the measurement range.

![Fig. 7 Tool edge contour evaluated by the measurement algorithm in Fig. 6. \( r_{S1} \) and \( r_{S2} \) correspond to the nose radii evaluated in S1 and S2, respectively.](image)

![Fig. 8 (a) A schematic image of a diamond cutting edge and (b) the profile of the clearance face measured by the white-light interferometer](image)
Figure 7 shows a measured tool edge contour. In Fig. 7, the results acquired in both the first scan (S1 in Fig. 6) and the second scan (S2 in Fig. 6) are plotted. The radius of the tool edge contour was evaluated to be 1.9615 mm and 1.9613 mm in the first scan and the second scan, respectively. As can be seen in Fig. 7, good measurement repeatability was confirmed in terms of the evaluation of tool nose radius. Meanwhile, relatively large difference of the tool edge contour up to several-hundred nm was found in the angular position ranging from -20° to -5°. In principle, these measurement results should coincide with each other. One of the possible reasons of this large difference can be explained by the sensitivity of the developed measurement system. In the second scan, from the value of \( q \), it was confirmed that the different region of the sensitivity curve in Fig. 5 was utilized to convert the measured \( q \) into \( \delta \) in the angular position. As can be seen in Fig. 5, the sensitivity curve had nonlinear components. The difference of the sensitivity used in each case of the measurement was considered to result in the large difference of the acquired tool edge contour.

The measurement result could also be influenced by the profile of the clearance surface in the case of measurement of cutting tool with a small clearance angle. According to the geometric optics, the laser beam passed around the tool rake face of the cutting tool could be affected by the clearance face of the cutting tool, especially when the focused laser beam is shifted along the \( Y \)-direction as the case of the second scan in the experiment. Uplifted surface profile of the tool clearance face has therefore a possibility to interfere with the laser probe passed around the tool rake face, resulting in measurement error in the tool edge contour. Figure 8 shows the three-dimensional profile of the clearance face of the tool, which tool edge contour was evaluated in Fig. 7, measured by a white-light interferometer (Zygo NewView 7300). As can be seen in Fig. 8, a large defect with a height of approximately 150 nm was found on the tool clearance face. The defect was located at the position of 15 \( \mu \)m from the tool rake face, and could have an influence on the tool edge contour measurement. To avoid the influence of the profile of tool clearance face, the optical system of the measurement instrument should be designed to have the focusing lens with a smaller number of the numerical aperture. On the other hand, however, the smaller N.A. would lead to a larger diameter of the focused laser beam as predicted by Eq. (1), resulting in the degradation of the measurement resolution of the tool edge contour. The optical system in the measurement instruments should be designed in such a way that paying attention not only to the diameter of the focused laser beam but also to the geometric relationship between the laser probe and the tool tip profile.

As described in the principle, the measurement resolution of the developed measurement system along the direction perpendicular to both the normal of the rake face and the tool cutting edge is beyond the diffraction limit of
the light. Meanwhile, the measurement resolution along the tool edge contour would be limited by the diffraction limit of the light. As can be seen in Fig. 9, features on the tool cutting edge smaller than the diameter of the focused laser beam cannot be measured by the developed method. Measurement results by the proposed method would therefore include measurement error in the region where the tool edge has small features whose sizes are comparable to (or small compared with) the diameter of the focused laser beam. In this paper, computer simulation was carried out to investigate the relationship between the diameter of the focused laser beam and the sizes of the features on the tool edge contour to be measured by the laser beam. Figure 10 shows a schematic of the simulation model of the tool edge contour measurement. In the model, an object having sinusoidal patterns on its straight edge was assumed to be scanned by a focused laser beam having a radius of $r_{\text{spot}}$ at the focal plane. The intensity distribution of the focused

![Fig. 11 Simulation results for investigation of lateral resolution of the proposed method when the tool edge has features (a) Feature pitch: from $0.1 \times r_{\text{spot}}$ to $3.0 \times r_{\text{spot}}$ (b) Feature pitch: from $1.1 \times r_{\text{spot}}$ to $1.5 \times r_{\text{spot}}$.]

![Fig. 12 Transmission coefficients of damped amplitude against the pitches of simulation objects]
Fig. 13 Measured tool edge contour of a fresh diamond tool with a straight cutting edge

A laser beam was assumed to be the Fraunhofer diffraction pattern as shown in Fig. 10. The radius $r_{\text{spot}}$ was defined by 13.5% of maximum value of the light intensity. The amplitude of the sinusoidal patterns on the tool edge was fixed to be $r_{\text{spot}}$, while its wavelength was set to be from $0.1 r_{\text{spot}}$ to $100 r_{\text{spot}}$. As can be seen in Fig. 10, the sum of the unblocked light intensity was treated as a measurement signal $q$. Figure 11(a) shows the results. The sinusoidal patterns on the object were confirmed to be measured when its pitch was set to be larger than $3.0 r_{\text{spot}}$. Figure 11(b) shows the simulation results in the cases of the pitches set to be from $1.1 r_{\text{spot}}$ to $1.5 r_{\text{spot}}$. The amplitude of a measurement signal $q$ was found to decrease with the shrinkage of the pitch size. Fig. 12 summarizes the transmission coefficients of the damped amplitude calculated in terms of the pattern pitch. From the simulation result, it was verified that the focused laser beam diameter is required to be as small as possible for higher measurement resolution along the tool edge contour direction.

Throughout the discussion described above, it can be concluded that the proposed method is suitable for the verification of the edge contours of unused or fresh cutting tools. In addition, the proposed method is expected to be applied for measurement of slight wear on tool edge contours in the order of nanometres, which cannot be measured by conventional inspection methods. Figure 13 shows a measured tool edge contour of an unused diamond tool. Measurements were repeated four times. From the results, good measurement repeatability was confirmed. The out-of-straightness of the tool edge contour was evaluated to be 30 nm. In the area 1 and area 2 in Fig. 13, small features with pitches of approximately 4.9 $\mu$m and 14.3 $\mu$m, respectively, were successfully distinguished, although those amplitudes were considered to be damped due to the influence of the transmission coefficient shown in Fig. 12.

5. Conclusion

A prototype of the optical probe, which had a focused laser beam with a diameter of 4 $\mu$m, was developed for evaluation of tool edge contour. The stability of the optical probe was improved by applying a modified optical setup to the optical probe, in which influences of both a laser power drift and a common-mode noise in output voltage signals from photodiodes could be cancelled. With the combination use of the modified optical setup and a precision positioning system in a machining lathe, a measurement resolution of approximately 8 nm along the direction perpendicular to both the normal of the rake face and the tool cutting edge was achieved. Following verification test of the basic performances of the developed optical probe, tool edge contour measurements were carried out by using the developed measurement. As possible sources of measurement errors in the tool edge contour evaluation, influences of the nonlinear component in the sensitivity curve of the optical probe system and a profile of the tool clearance face
were discussed. Furthermore, computer simulation was carried out to verify the measurement resolution of the developed optical probe along the tool edge contour direction. Regarding both the experiment results and simulation results, it was concluded that the proposed method is suitable for the verification of the edge contours of unused or fresh cutting tools.

Acknowledgement

This project was supported by Japan Society for the Promotion and Science (JSPS) and JST (A-step).

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