Paper:

Fundamental Study on Novel On-Machine Measurement Method of a Cutting Tool Edge Profile with a Fluorescent Confocal Microscopy

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We propose a novel, on-machine method of measuring the profile of the cutting edge of a tool by using the cutting fluid on the tool surface. Despite an environment of on-machine tool profile measurement, it is difficult to measure a cutting edge profile by using conventional optical methods due to interference from the cutting fluid on the tool surface. To overcome this problem, we propose a profile measurement method that uses confocal fluorescent detection from the cutting fluid on the tool surface. Moreover, for precise measurements, a method that corrects for the thickness of the cutting fluid is provided. Fluorescence from the surface of a silicon wafer coated with a fluorescent dye that is set horizontally as well as vertically to the optical axis of a developed fluorescent confocal microscope is detected. As a basic verification, the cutting edge profile of a milling tool with wear is measured using the proposed measuring and correction methods that employ a fluorescent dye. The results confirm that the proposed method can provide detailed measurements of a tool wear profile.

Keywords: on-machine measurement, cutting fluid, fluorescence, tool measurement, confocal microscopy

1. Introduction

The profile of a cutting tool edge greatly affects cutting performance. In general, a cutting tool edge becomes deformed by chipping and wear, repeated processes, etc. [1], and these deformations directly affect the surface quality of a workpiece and the metal removal rate [2–4]. Thus, monitoring the shape of the cutting tool edge is imperative for continued high-accuracy machining. It is possible to observe the cutting edge profile in post process by using image viewing [5, 6], a laser displacement sensor [7], a scanning electron microscope (SEM) [8–10], or a stylus profilometer [11]. However, measuring the tool profile by unloading the tool from the machine has some problems, such as long measurement time and positioning errors that occur upon re-attachment of the tool [6]. In order to solve those problems, an on-machine measuring technique is required. Although a stylus method applying the AFM [12, 13] and optical methods [14, 15] have been proposed as on-machine measurement technologies, these are limited and lack versatility in practical use.

Therefore, we propose a novel, on-machine measuring method that uses the detection of fluorescence from the cutting fluid on the tool surface. The proposed method is a feasible on-machine measuring method of the cutting tool edge because it has the following five advantages:

1. High-speed and non-contact measurement
2. Appropriateness for on-machine environment due to its use of the cutting fluid on the tool surface during machining
3. Possibility to measure vertical or more inclined surface of complex edge shape of a cutting tool
4. Possibility to measure without speckle noise effect caused by light source used to detect incoherent fluorescence.
5. The presence of cutting fluid with fluorescent properties has often been reported to have a wide range of applications for on-machine measurement [16].

In this paper, the principle of the method of measuring the tool cutting edge profile by using confocal microscopy to detect fluorescence from cutting fluid is described. A method of correcting for the thickness of the cutting fluid for precise surface detection is also presented. As a basic experiment, the detection of horizontal and vertical surfaces by means of the proposed method is implemented using, instead of cutting fluid, immersion oil containing a fluorescent dye. Furthermore, the surface profile of a cutting tool is measured by detecting fluorescence from the fluorescent immersion oil.

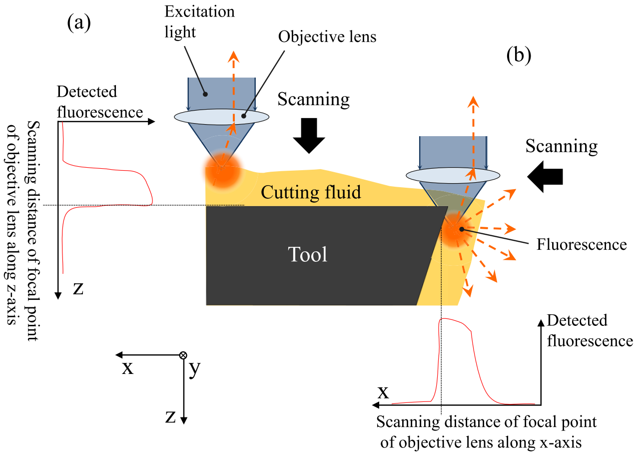

Fig. 1. Measurement principle of the proposed method.

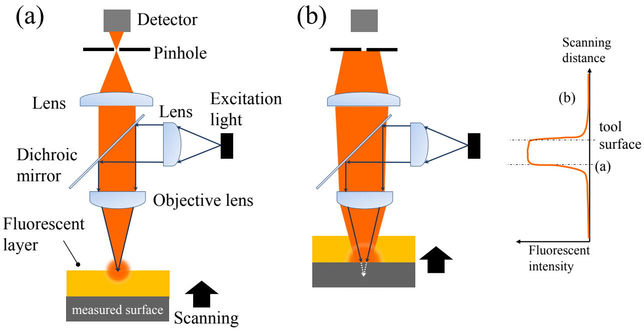

Fig. 2. Optical system of fluorescent confocal microscopy Fluoresce detection: (a) the focal spot is in the fluorescent layer, (b) the focal spot is not in the fluorescent layer.

2. Principle of Measurement

2.1. Measuring the Cutting Tool Edge Profile by Detecting Fluorescence from the Cutting Fluid

As shown in **Fig. 1**, the focal spot of the excitation light of fluorescent confocal microscopy displaces to the tool surface and passes through a cutting fluid layer, which has a fluorescent property, on the tool surface. **Fig. 1(a)** represents horizontal surface detection when a tool surface is on the same plane as the *xy*-plane and scanned along the *z*-axis. **Fig. 1(b)** represents vertical and overhanging surface detection when the tool surface is on the same plane as the *yz*-plane and is scanned along the *x*-axis. When the focal spot of an excitation light is scanned along the *z*-axis and reaches the cutting fluid in the case shown in **Fig. 1(a)**, fluorescence is emitted radially from the cutting fluid by the excitation light. By using fluorescent confocal microscopy, just the fluorescence emitted at the focal spot of the excitation light can be detected as a fluorescence signal. After the focal spot subsequently passes through the layer of cutting fluid and reaches the tool surface, the detected fluorescence signal decreases rapidly because the fluorescent confocal microscopy cannot detect the fluorescence signal when the focal spot is on the tool surface. By detecting the decreasing position of the fluorescence signal in this way, the position of the tool surface can be identified. The profile of the cutting edge of a tool can be measured through the same procedure for different points along the tool surface. It has been reported that fluorescence emits radially in uniform intensity without depending on the irradiation direction of the excitation light [17]. Accordingly, even when the focal spot of the excitation light scans along the *x*-axis and irradiates a vertical surface that has a slope of 90 degrees or more (**Fig. 1(b)**), it is possible to detect the fluorescence signal and measure the surface by detecting the decreasing point of the detected signal. Because this measurement allows for the signal detection by rotating or scanning the tool itself attached to the mother machine, the operating mechanism of the optical system itself is not required. Furthermore, by using confocal microscopy, it is possible to measure the tool surface coordinate with sub-micron precision.

2.2. Surface Detection with Fluorescent Confocal Microscopy

In the proposed method, fluorescent confocal microscopy is utilized. The theoretical resolution is of submicrometer order in the lateral and depth directions [18]. The resolution of the proposed method depends on the resolution of the confocal microscopy. As can be seen in **Fig. 2**, a fluorescent confocal microscope has a pinhole in the front of the detector. This pinhole allows the fluorescence coming just from the focal position of the objective lens to pass through. Consequently, as shown in **Fig. 2(a)**, when the focal spot of the objective lens scans and reaches a fluorescent layer, the fluorescence emitted from the focal spot starts to be detected. In contrast, the fluorescence not emitted from the focal spot is blocked by the pinhole and cannot be detected when the focal spot is not in the fluorescent layer after the spot passes through the measured surface (**Fig. 2(b)**). Since a dichroic mirror reflects the excitation light, just the fluorescence can be detected. Thus, the position of the tool surface can be determined by scanning the fluorescent confocal microscopy and detecting the decreasing point of the fluorescence signal. The focal spot of the excitation light can be utilized as a three dimensional measuring probe [17].

2.3. Correcting for Cutting Fluid Thickness

In using the proposed method to detect a tool surface, it is necessary to correct the scanning distance when the focal spot of the excitation light passes through the cutting fluid layer. When scanning the focal spot of the excitation light and detecting the fluorescence signal by scanning the focal spot along the *z*-axis, because the refractive index of the cutting fluid is different from that of the atmosphere, the scanning distance is shorter than the actual distance to the surface (**Fig. 3**). An actual scanning distance along *z*-axis d_{actual} is given by the following equation [19]:

$$d_{actual} = nd \quad (1)$$

where n is the refractive index of the cutting fluid and d is the scanning distance passing through the cutting fluid layer. To correct the scanning distance of the focal spot, it is necessary to determine the position of the cutting fluid

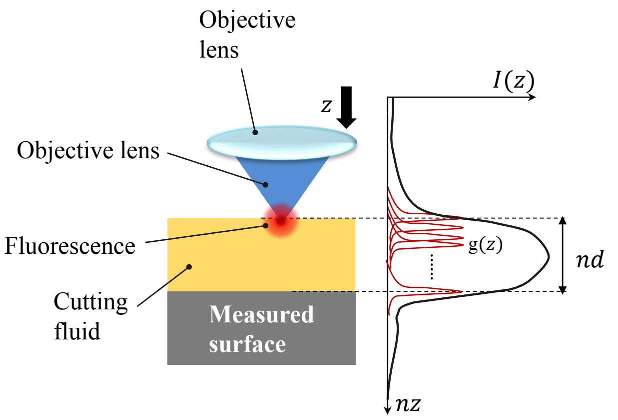

Fig. 3. Scheme of fluorescence signal detection.

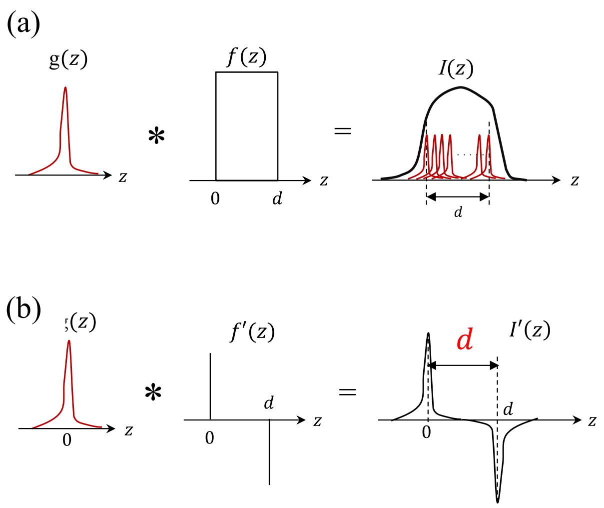

Fig. 4. Principle of surface detection of fluid film and measuring point.

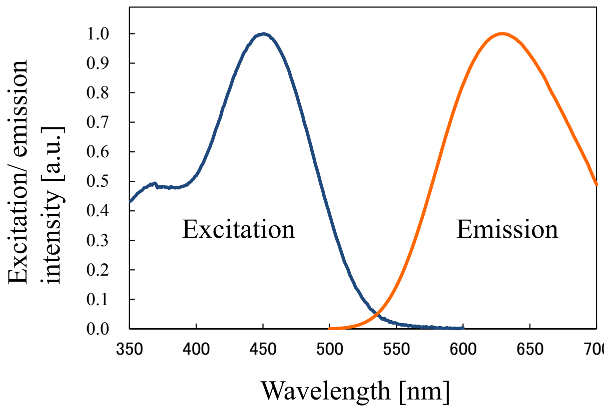

Fig. 5. Fluorescent properties of Fluolid-W-Orange.

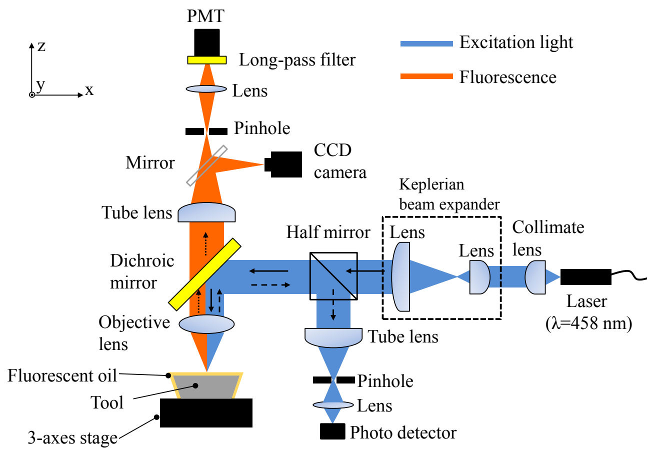

Fig. 6. Schematic of confocal microscopy for fluorescence and reflected excitation light detection.

surface and that of the tool surface based on changes in the fluorescence signal. Therefore, a method of detecting, based on fluorescence signal changes, the surface of the cutting fluid and of the tool itself is described below.

In general, the confocal detected signal can be modeled as the convolution from the response from the minutely thin layer [20]. Thus, the detected signal by the proposed method $I(z)$ can be generated by convoluting $g(z)$ that is a detected signal from a sufficiently thin cutting fluid into $f(z)$ that represents the cutting fluid thickness d (**Fig. 4(a)**). In the proposed method, when the tool surface is displaced along the optical axis, a detected fluorescence signal $I(z)$ has the forms of

$$I = g * f \quad \text{. . . . . (2)}$$

A differentiated fluorescence signal $I(z)$ is given by

$$I = g * f \quad \text{. . . . . (3)}$$

where $f(z)$ is a differentiated function of $f(z)$ that has positively and negatively directed impulse functions at the surface of the cutting fluid and the tool respectively. As a result, $I(z)$ has a form that is placed positive and negative directed $g(z)$ at the cutting fluid surface and the tool surface respectively, as can be seen in **Fig. 4(b)**. Hence, a more precise profile measurement is enabled by identifying the cutting fluid layer and position of the measured surface distance according to those peaks in $I(z)$ and by correcting for it using Eq. (1).

3. Experimental Apparatus

To verify the basic principle of the proposed method, a fluorescent confocal optical system has been developed. As a substitute for cutting fluid, an immersion oil containing dissolved fluorescent dye for which the optical properties are known (hereinafter referred to as “fluorescent oil”) is used. Fluorescent oil is made by dissolving a fluorescent dye (Fluolid-W-Orange; International Science Technology Co., Ltd.) in immersion oil ($n = 1.515$; Nikon Co., Ltd.) until saturation is reached. By using fluorescent oil, the detected fluorescence is more stable and intense than that from cutting fluid. Furthermore, the thickness of the oil film does not change at the time of measurement due to its non-volatile nature. For these reasons, fluorescent oil was chosen in the fundamental experiment. **Fig. 5** shows the excitation and emission spectra of Fluolid-W-Orange. **Fig. 6** is a schematic of the confocal microscopy to detect fluorescence from fluorescent oil and reflected excitation light. The reflected excitation light is detected for basic verification. A diode laser ($\lambda = 458$ nm) used to excite fluorescence travels to the optical system through the optical fiber. The laser is collimated by a collimator lens. A Keplerian beam expander adjusts the beam to the appropriate diameter for an objective lens. The specimen is on a 3-axis stage to displace the focal spot in this system. When the focal spot of the excitation light reaches the layer of fluorescent oil, fluorescence and reflected excitation light are collimated in the objective lens. A dichroic mirror allows the fluorescence to pass through a pinhole and reflects the excitation light reflected from the surface of the fluorescent oil and specimen. The fluorescence emitted from the focal spot of the excitation light passes through a long-pass filter that limits the excitation light, and the fluorescence reaches a detector behind the pinhole (diameter = 20 μm). The fluorescence is weak, so a photo multiplier tube (PMT) is used as the detector. Excitation light reflected at the surface of the fluorescent oil and the specimen is reflected by the dichroic and half mirror. The excitation light reflected at the focal point of the objective lens passes through the pinhole after being reflected at the half mirror and can be detected by a photodiode. A CCD camera installed as a viewing system observes the beam spot on the specimen in order to adjust the optical arrangement. The CCD image can be detected by setting up a mirror between a tube lens and the CCD camera.

4. Results

By using a silicon wafer coated with fluorescent oil as a specimen, fluorescence from the horizontal and vertical surfaces is detected. On the horizontal surface, the excitation light reflected at the surface of the oil and the specimen is detected as is the fluorescence, as a principle verification of the method of correcting the scanning line distance described at section 2.3.

4.1. Fundamental Verifications

As shown in **Fig. 7**, the specimen coated with fluorescent oil is set horizontally. The specimen is scanned 50 μm from the objective lens along the z-axis by driving the stage. Thus, the focal spot of the object lens can pass through the layer of fluorescent oil. Meanwhile, excitation light that is reflected off the surfaces of the oil and the specimen is also detected by the constructed confocal microscopy. **Fig. 8** shows the detected fluorescence signal and the reflected excitation light signal. This data is normalized by the maximum voltage of the signal. A stable fluorescence signal is confirmed from the horizontal surface. Two peaks of reflected excitation light can be detected. A peak of 7.55 μm on the z-axis represents the surface of the fluorescent oil, and the other peak of 20.75 μm represents the surface of the specimen.

Figure 9 shows the differential signal of fluorescent intensity in **Fig. 8** with respect to the z-axis. In **Fig. 9**, two peaks, "Peak 1" and "Peak 2," appear at 7.55 μm and 20.6 μm, respectively. The full width at half maximum (FWHM) of Peak 1 is approximately 2.3 μm, and the FWHM of Peak 2 is approximately 1.95 μm. These are about two times wider than the ordinal confocal signal of this system (i.e., 1.2 μm) [17], and these data are noisy.

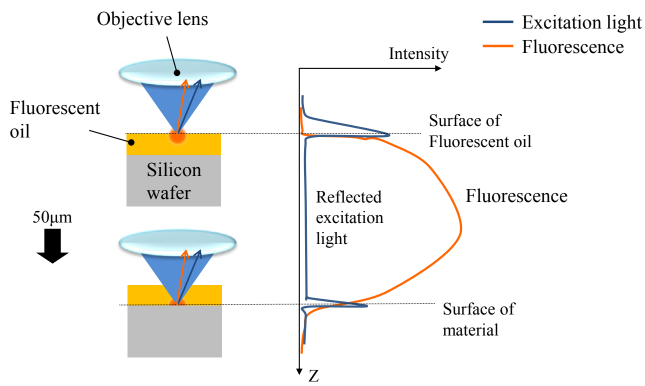

Fig. 7. Method of detecting fluorescence and reflected excitation light from the horizontal surface.

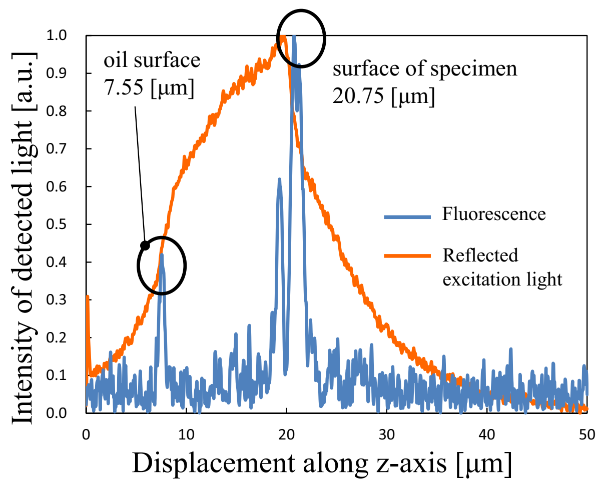

Fig. 8. Detected fluorescence signal and reflected excitation light scanned against horizontal surface.

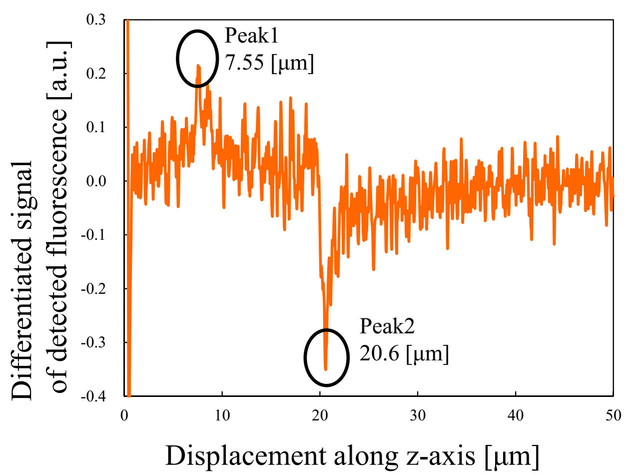

Fig. 9. Differenced detected fluorescence signal scanned against horizontal surface.

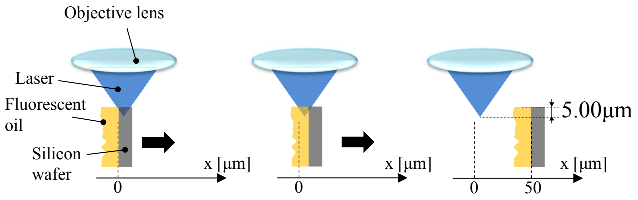

Fig. 10. Detecting method of fluorescence from vertical surface.

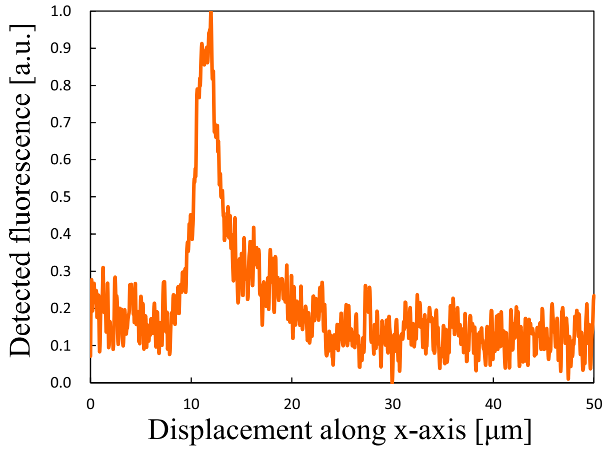

Fig. 11. Detected fluorescence signal scanned against vertical surface.

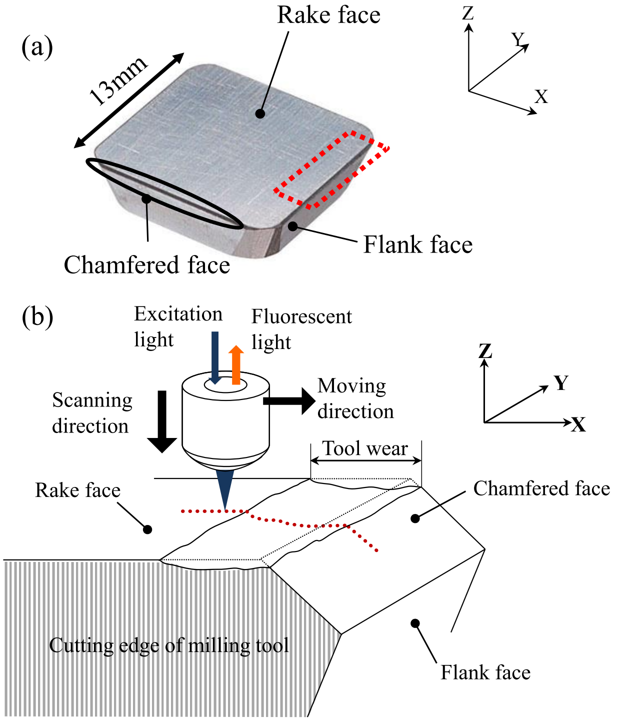

Fig. 12. Measurement method of horizontal surface of cutting edge of milling tool: (a) milling tool to be measured, (b) magnification image of red dotted square in **Fig. 12(a)**.

However, these peak positions correspond well with the positions of surface of the oil and the specimen, respectively. Moreover, the difference in the positions of the peaks between the reflected excitation light signal and the differential fluorescence signal is less than 200 nm. The validity of the proposed method of measuring the thickness of the film of cutting fluid is confirmed.

As can be seen in **Fig. 10**, the specimen coated with fluorescent oil is set vertically. The focal spot is 5.00 μm below the top of specimen. The sample is scanned 50 μm in the x-axis direction in order to allow the focal spot of the excitation light to pass through the layer of fluorescent oil sufficiently. **Fig. 11** shows the detected fluorescence signal. This data is normalized by the maximum voltage of the signal. This fluorescence signal is also considered to successfully detect fluorescence in the oil on the vertical surface to measure, although it is difficult to measure using the conventional optical measurement method. The FWHM of the signal is approximately 2.75 μm. Consequently, the proposed method can measure the position of an edge by scanning its horizontal and vertical surfaces, which are difficult to measure using conventional optical methods in the on-machine environment.

4.2. Measuring the Horizontal Surface of Cutting Edge of a Milling Tool by Detecting Fluorescence

To examine a potential advantage of the proposed method, an actual profile of a worn cutting tool edge was measured. The wear profile of a used milling cutting tool coated with fluorescent oil was measured using the optical system described in section 3. By comparing the measurements with the results from a stylus profilometer (SE-3500K; Kosaka Lab. Ltd.), the feasibility of the proposed method for measuring actual tool wear was examined. Fluorescent oil was used to measure the cutting edge profile of the milling tool (SEKN42MT; Sumitomo Electric Hardmetal Corp.) with wear was measured (**Fig. 12(a)**). A schematic of the measurement is shown in **Fig. 12(b)**. The cutting edge of the milling tool was coated with fluorescent oil as uniformly as possible. The focal spot of excitation light scanned 100 μm in the z-direction and detected the fluorescence of the fluorescent oil. The stage of the optical system drove the tool one 10-μm step in the x-axis direction to change the measuring point. By performing this process, the profile curve from the rake face to the chamfered face was measured. Two different profiles with different amounts of wear were measured in this way. The same areas were measured using the stylus profilometer, and the two sets of results were compared.

Figure 13(a) shows a typical detected fluorescence signal, and **Fig. 13(b)** shows a differential signal. In **Fig. 13(b)**, two peaks can be confirmed, "peak 1" and "peak 2." In addition, the distance from 0 μm to peak 1 is in the atmosphere, and the distance between peak 1 and peak 2 is in the fluorescent oil. Accordingly, the scanning distance in the oil is corrected by using equation (1). Furthermore, by considering the position of peak 2 as a position of the tool surface, the tool edge profile is given. The red dots in **Fig. 14** represent the results of measurements taken using the proposed method. Black solid lines

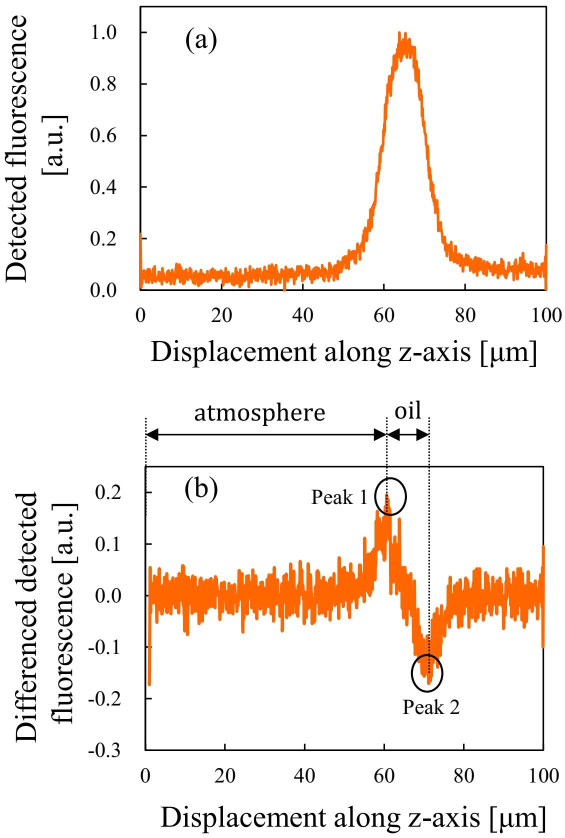

Fig. 13. Typical experimental data: (a) detected fluorescence signal from surface of cutting edge of milling tool, (b) differentiated signal of (a).

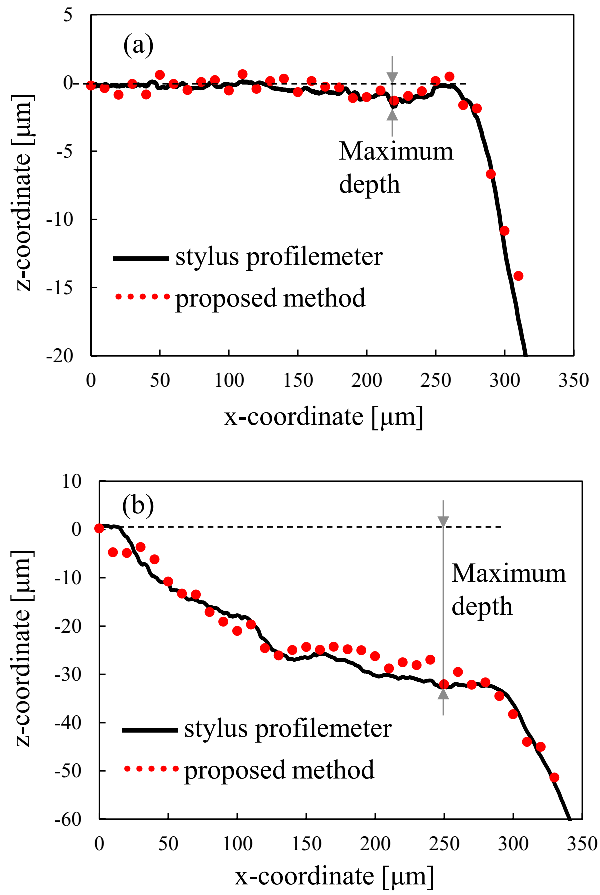

Fig. 14. Measurement results of cutting edge of milling tool by the proposed method and by stylus profilometer. (a) after cutting S53C for 300 m at a cutting speed of 100 m/min, (b) after cutting S53C for 100 m at a cutting speed of 400 m/min.

shown in **Fig. 14** are results of measurements taken using the stylus profilometer. **Fig. 14(a)** shows the profile of the milling tool edge after cutting 300 m of S53C carbon steel at a cutting speed of 100 m/min. **Fig. 14(b)** shows the profile of the milling tool edge after cutting 100 m of S53C at a cutting speed of 400 m/min. Results from **Fig. 14** show that the features of the milling tool edge profiles measured using the proposed method are in good agreement with the feature of profiles measured using the stylus profilometer. According to measurements taken with the stylus profilometer in **Fig. 14(a)**, the maximum crater wear is about 2.0 μm deep, while the maximum crater wear measured using the proposed method is about 1.4 μm deep. In **Fig. 14(b)**, the maximum crater wear is about 32.7 μm deep, while the maximum crater wear measured using the proposed method is about 32.1 μm deep. These results show that the proposed method makes it possible to measure the tool wear within a crater several μm crater deep. Both results show that the proposed method can evaluate the features of cutting tool edge wear precisely. In **Fig. 14(b)**, there are profile differences between the measurements taken with the profilometer and those taken using the proposed method i.e., depth differences of roughly ± 5 μm. Those differences are larger than the differences shown in **Fig. 14(a)**. According to the four measured profiles produced using the profilometer, the differences between them are about ± 5 μm in depth for a deep crater and about ± 2 μm for a shallow crater. It can therefore be said that the surface profiles with deep craters are rougher than those with shallow craters. When the measured profile created using the proposed method is not in just the same position as that created using the profilometer, the differences shown in **Fig. 14(b)** are subject to the surface roughness of the deep crater.

5. Conclusions

In this paper, we have proposed a novel, on-machine cutting tool edge profile measurement method that detects fluorescence emitted from cutting fluid adhering to the surface of a tool. For precise measurements using the proposed method, a method of correcting for cutting fluid thickness by means of signal differentiation was established.

To verify the principles of the measurement and correction methods, fluorescent confocal microscopy was constructed. As results, fluorescence signals from the horizontal and vertical surface of a silicon wafer were successfully detected by using fluorescent oil. Moreover, the proposed correction method was shown to be theoretically valid. The proposed method enables the signal from the vertical surface to be detected, something that is difficult to do using conventional optical methods. Therefore, this method might be used to measure cutting tool edge profiles that have complex structures, such as vertical surfaces.

As a basic verification of the proposed measuring and correction methods, cutting edge profiles of a milling tool with wear were measured using the proposed measuring and correction methods. The results of the cutting tool edge profile were in a good agreement with the measurements taken using a stylus profilometer.

Therefore, it has been found that the proposed method has the potential to measure a detailed tool wear profile in the on-machine environment.

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Main Works:

• Y. Takaya, M. Michihata, T. Hayashi, and T. Washitani, “Dimensional measurement of microform with high aspect ratio using an optically controlled particle with standing wave scale sensing,” Annals of the CIRP, Vol.61, Issue 1, pp. 479-482, 2012.
• Y. Takaya, M. Michihata, T. Hayashi, R. Murai, and K. Kano, “Surface analysis of the chemical polishing process using a fullerenol slurry by Raman spectroscopy under surface plasmon excitation,” Annals of the CIRP, Vol.62, Issue 1, pp. 571-574, 2013.

Membership in Academic Societies:

• Japan Society for Die and Mould Technology (JSDMT), Vice president
• Japan Society of Precision Engineering (JSPE)
• Japan Society of Mechanical Engineers (JSME)
• American Society for Precision Engineering (ASPE)
• Japan Society for Abrasive Technology (JSAT)
• International Measurement Confederation (IMEKO) TC14, Chair
• International Academy of Production Engineering (CIRP), Fellow