An AFM-based Edge Profile Measuring Instrument for Diamond Cutting Tools

Takemi Asai[1,#], Takenori Motoki[1], Wei Gao[1], Bing-Feng Ju[1] and Satoshi Kiyono[1]

1 Department of Nanomechanics, School of Engineering, Tohoku University, Sendai, Japan
Corresponding Author / E-mail: asai@nano.mech.tohoku.ac.jp, TEL: +81-22-795-6953, FAX: +81-22-795-6953

KEYWORDS: AFM, Edge profile measurement, Diamond cutting tool, Optical sensor, Alignment

This paper describes an atomic force microscope (AFM)-based instrument for measuring the nanoscale cutting edge profiles of diamond cutting tools. The instrument consists of a combined AFM unit and an optical sensor to align the AFM tip with the top of the diamond cutting tool edge over a submicron range. In the optical sensor, a laser beam is emitted from a laser diode along the Y-axis and focused to a small beam spot with a diameter of approximately 10 μm at the beam waist, which is then received by a photodiode. The top of the tool edge is first brought into the center of the beam waist by adjusting it in the X–Z-plane while monitoring the variation in the photodiode output. The cutting tool is then withdrawn and its top edge position at the beam center is recorded. The AFM tip can also be positioned at the beam center in a similar manner to align it with the top of the cutting edge. To reduce electronic noise interference on the photodiode output and thereby enhance the alignment accuracy, a technique is applied that can modulate the photodiode output to an AC signal by driving the laser diode with a sinusoidal current. Alignment experiments and edge profile measurements of a diamond cutting tool were carried out to verify the performance of the proposed system.

Manuscript received: May 1, 2006 / Accepted: January 15, 2007

1. Introduction

Single crystal diamond cutting tools are necessary for machining optical components, such as pickup fresnel lenses for CD and DVD players and light-guiding plates for liquid crystal displays and their molds. The edge of the cutting tool usually has a radius of tens of nanometers, which facilitates the fabrication of high-quality surfaces on the workpieces. The manufacturers supply these tools with regular cutting edges. Since the tools users would like to determine the micro-wear and compensate for it to guarantee the final machining quality, real-time sharpness measurements of the cutting tools are essential. Several new techniques have been proposed to measure the sharpness and nose contours of cutting tools using a scanning electron microscope,[1] a LVDT sensor, [2] and optical scatter.[3] However, these methods cannot produce 3-D images of the cutting edge sharpness with a single measurement.

An atomic force microscope (AFM) has the capability of measuring 3-D surface topography with a high resolution. In this study, we adopted an AFM-based measuring instrument that was set up to measure edge profiles. However, due to the short scanning distance, it was necessary to align the cutting edge to be measured within the scanning area of the AFM; therefore, a modulated optical probe was used [4] through which the cutting tool edge and the AFM tip could be well aligned over a submicron range. An automatic translator was also incorporated into the experimental apparatus to dramatically increase the measuring speed and accuracy.

An alignment experiment was performed in which a diamond cutting tool edge was successfully measured, thereby verifying the performance of this AFM-based measuring instrument.

2. Alignment of the diamond cutting tool with the AFM tip

Figure 1 shows a schematic diagram of the instrument design. It consists of an interrelated alignment unit and AFM, which are capable of aligning the top of the diamond cutting tool edge with the AFM tip so that the 3-D shape of the cutting tool edge can be measured.

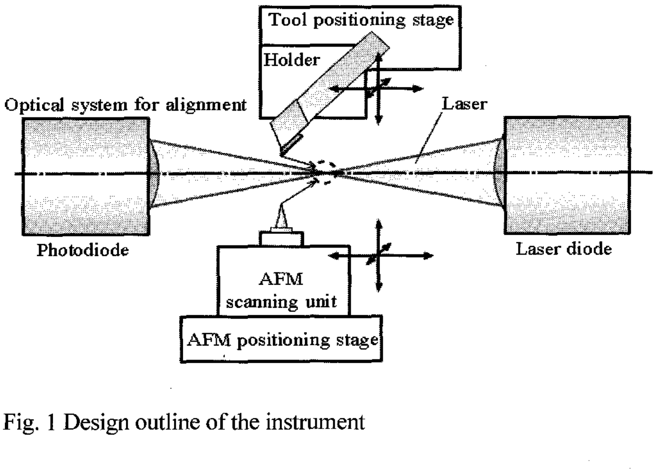


Fig. 1 Design outline of the instrument

2.1 Alignment mechanism

Figure 2 shows a schematic diagram of the optical probe used for the alignment. The laser beam from the laser diode (LD), with a diameter of several millimeters, was condensed to a spot that was tens of microns wide at the focal plane of the condensing lens. The laser passed through the focal plane was condensed to the photodiode (PD) by another lens. This alignment method used the small spot of the laser beam, which may vary from several millimeters to tens of microns in size, depending on its relative position with the focal plane.

The Y-axis was defined as the propagation direction of the laser beam, and the X- and Z-axes were vertical to the Y-axis, as shown in Fig. 2. The cutting tool and AFM tip were originally set at different sides of the optical axis so that the laser beam passed through them. The origin of this coordinate system was the base point of the alignment, which was at the center of the beam spot at the beam waist.

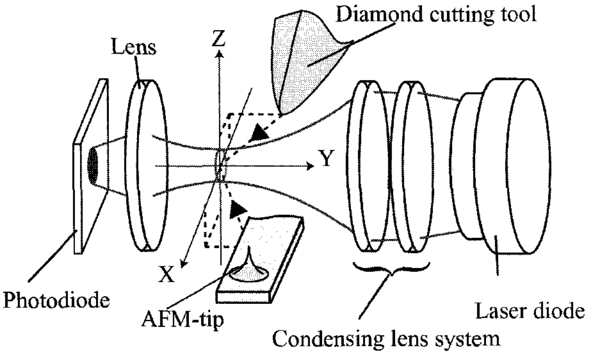


Fig. 2 Schematic illustration of the optical probe

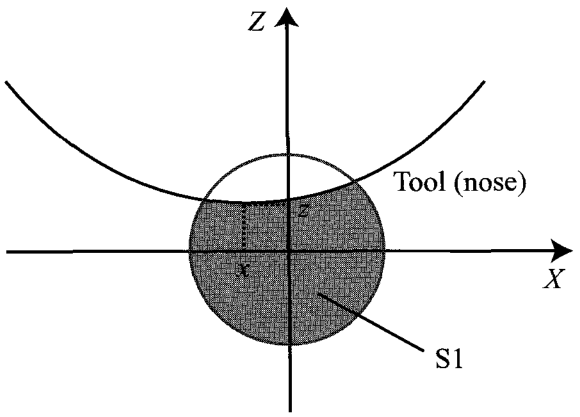


Fig. 3 Bringing the tool edge into the beam spot

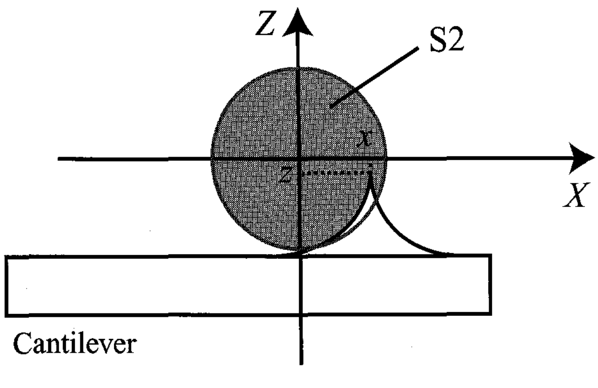


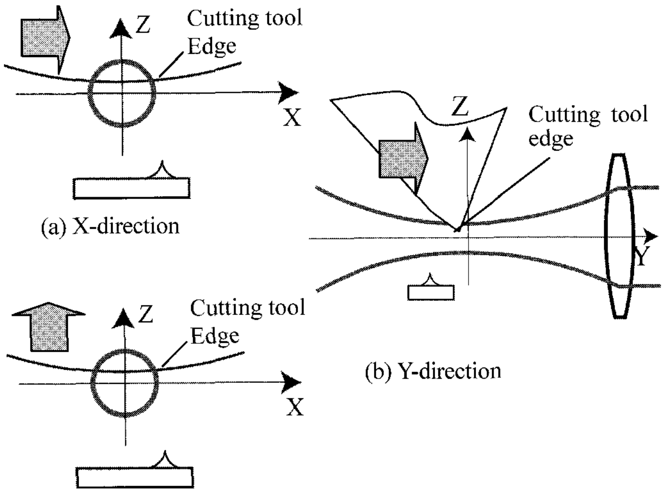
Fig. 4 Bringing the AFM tip into the beam spot

Figures 3 and 4 show the status of the tool edge and AFM tip located in the laser beam. When the tool edge or AFM tip was brought into the laser beam, part of the laser was blocked. The beam intensity detected by the PD was the sum passed through areas S1 and S2. We aligned the AFM tip and the top of the cutting edge to the center of the beam waist using the measured change in the beam intensity.

First, we aligned the cutting tool edge and AFM tip in the X-direction by bringing them into the laser beam, setting Z properly, fixing the Y-direction, and discretely scanning in the X-direction, as shown in Fig. 5(a). We then measured the output of the PD for each position. When the cutting edge or AFM tip reached X = 0 (refer to Fig. 6(a)), the output of the PD was dramatically decreased. The alignment procedure in the Y- and Z-directions was nearly identical (refer to Figs. 5(b) and 5(c)), but when the cutting tool edge or AFM tip reached Y = 0 or Z = 0 (refer to Fig. 6(b)), the output of the PD (or the derivative of the output) had a minimum or maximum value.

2.2 Automatic alignment

Figure 7 shows a block diagram of the alignment system. The motions in the X-, Y-, and Z-directions for both the AFM unit and diamond cutting tool were driven using two sets of 3 DC-servomotor stages (for a total of six motors) that were PC-controlled. When small PD outputs were encountered, which caused a decrease in resolution, the LD intensity output was modulated and a lock-in amplifier, similar to a band-pass filter, was used to reduce the signal noise. The output of the lock-in amplifier was recorded by a PC with an AD converter after every motion, which made it easy to define the minimum or maximum values.

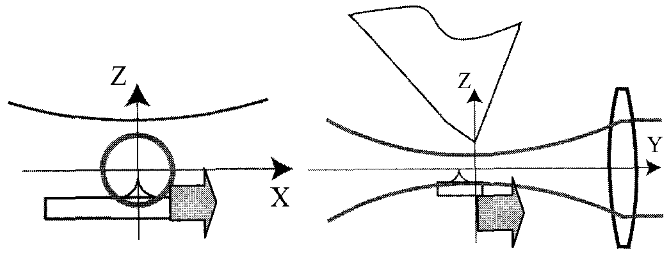


(a) X-direction

(b) Y-direction

(c) Z-direction

Fig. 5 Scanning direction of the diamond cutting tool



(a) X-direction (b) Y-direction

Fig. 6 Scanning direction of the AFM probe

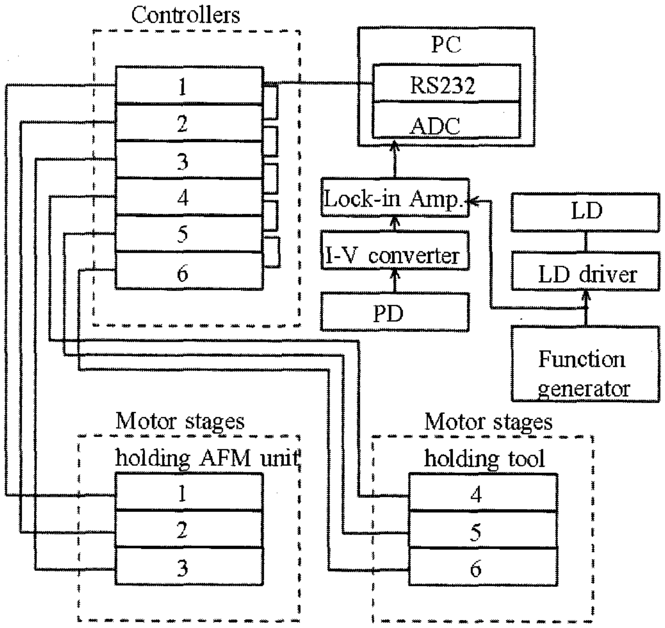


Fig. 7 Block diagram of the alignment system

3. Instrument setup for the edge profile measurement of the diamond cutting tool

Figure 8 shows a schematic diagram of the measurement system in which the AFM scanner was driven by the combination of PZT X- Y- and Z-stages and a capacitive displacement sensor. A piezo controller provided the feedback control for the stages. Table 1 lists the specifications of the stage and the controller. A piezoresistive cantilever acted as a strain gauge in the AFM unit. The strain in the AFM probe due to the deflection corresponding to the interaction force between the tip and the surface was measured using a Wheatstone bridge and a signal amplifier. The force interaction between the tip and the sample surface that caused the cantilever to deflect could be determined by measuring the cantilever deflection from the piezoresistance, which supplied an output voltage proportional to the deflection of the cantilever. At the same time, the PID controller used the output of the force signal to maintain a constant interaction force.

We scanned in the Y-direction and recorded the displacement of the stages in both the Y- and Z-directions using the capacitive displacement sensors to construct a Y–Z cross-sectional edge profile. We then drove the stage in the X-direction and repeated the Y–Z cross-sectional profile measurements to obtain the final 3-D edge profile of the cutting tool.

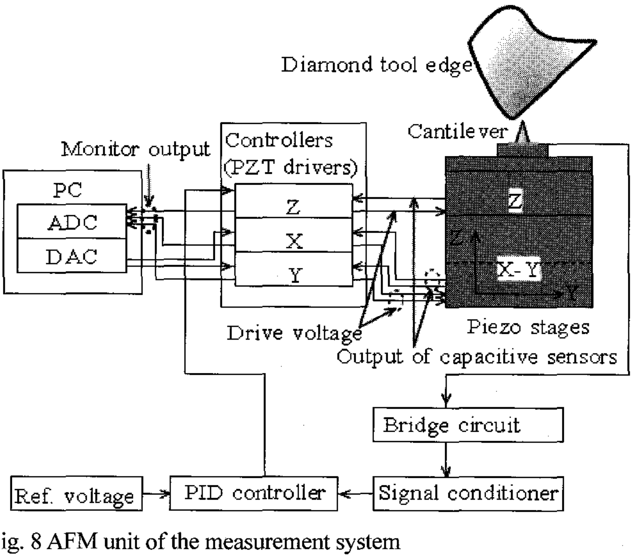


Fig. 8 AFM unit of the measurement system

Table 1 Specifications of the piezo stages and controllers

Name	Manufacturer and Model	Specifications
Nano-Translation Stage	PI P-621.2CD	Active axes: X, Y Closed-loop travel per axis: 100 μm Integrated feedback sensor: Capacitive Typical closed-loop linearity: 0.03%
Nano-Elevation Stage	PI P-621.ZCD	Active axes: Z Min. open-loop travel -20 to 120 V: 120 μm Integrated feedback sensor: Capacitive Typical closed-loop linearity: 0.01%
PZT Servo-Controller	PI E-612.CO	[Amplifier] Accuracy: ±1% Noise: 0.8 mVpp [Sensor Monitor Output] Bandwidth: 1.5 kHz

(We used an analog input instead of a digital input and output to command the controller.)

4. Edge profile measurements of the diamond cutting tool

4.1 Alignment of the diamond cutting tool with the AFM tip

4.1.1 Aligning the tool edge with the beam waist

Referring to the detailed alignment procedures described in Section 2.1, we can estimate the alignment by observing the output of the PD. Figures 9, 10, and 11 show changes to the output of the lock-in amplifier while scanning the cutting tool edge in the X-, Y-, and Z-directions, respectively. A minimum in the output of the lock-in amplifier was obtained in the X- and Y-directions, which we used to align the position accordingly. In the Z-direction, we defined the alignment point from the maximum of the derivative shown in Fig. 11. In the Y-direction, we occasionally obtained a result similar to that shown in Fig. 12, which arose when we scanned over a relative long distance. This did not affect the final alignment since we were only required to observe the minimum value, which occurred in the single valley measured over the entire scanning procedure.

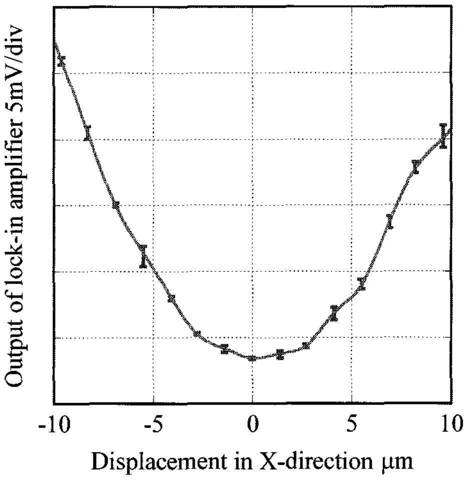


Fig. 9 Tool cutting edge positioning results in the X-direction

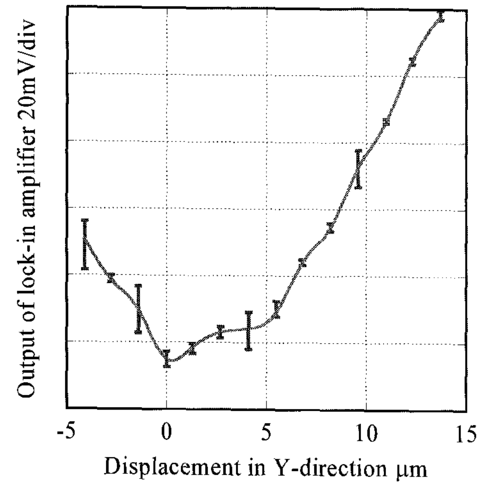


Fig. 10 Tool cutting edge positioning results in the Y-direction

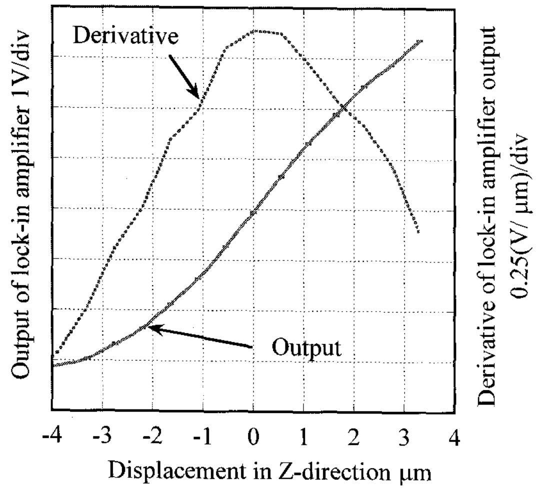


Fig. 11 Tool cutting edge positioning results in the Z-direction

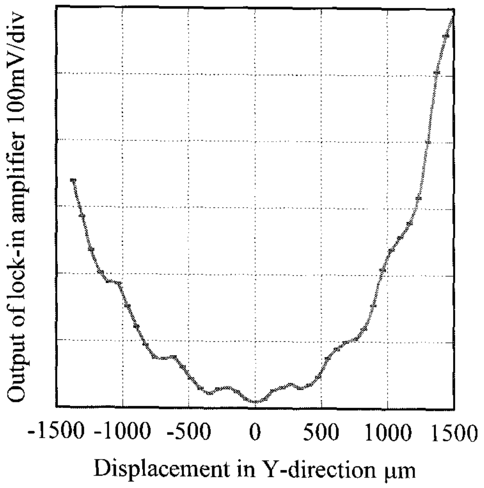


Fig. 12 Tool cutting edge positioning results in the Y-directionafter scanning over a relative long distance

4.1.2 Aligning the AFM tip with the beam waist

After aligning the cutting tool, we recorded its current position and then withdrew it from the laser beam to align the AFM tip. Figures 13 and 14 show the output variations during the AFM tip alignment process in the X- and Y- directions. We could align the tip in the X-direction using the minimum output point. However, in the Y-direction, the output showed several minimum points, which introduced an uncertainty for the appropriate alignment position. To avoid confusion, we chose the position where the output of the lock-in amplifier had the smallest value. The Y-direction alignment could be realized in the same manner.

Since the uncertainty usually occurred in the Y-direction, the imperfection of the optical system this direction was also evaluated. Figure 15 shows a photo captured by a laser camera that shows the distribution of the laser beam intensity passing through the condensing lens system. Since we applied a condensing lens with a large aperture, this could have introduced nonuniformities to the condensed laser beam, which appeared as wrinkles in the circled region shown in Fig. 15.

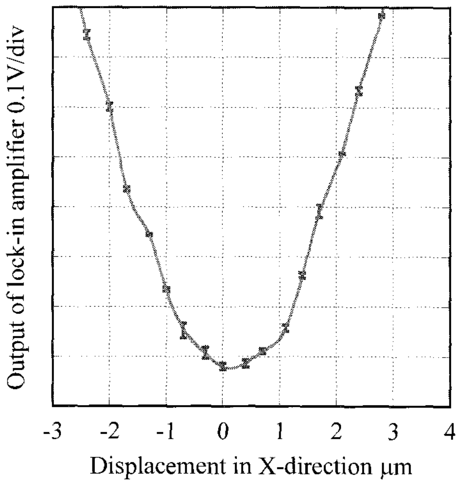


Fig. 13 AFM probe positioning results in the X-direction

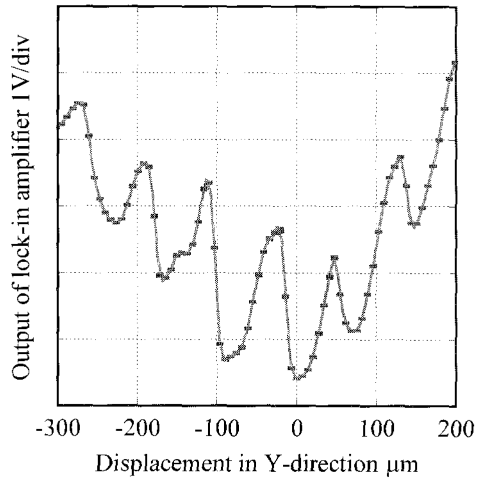


Fig. 14 AFM probe positioning results in the Y-direction

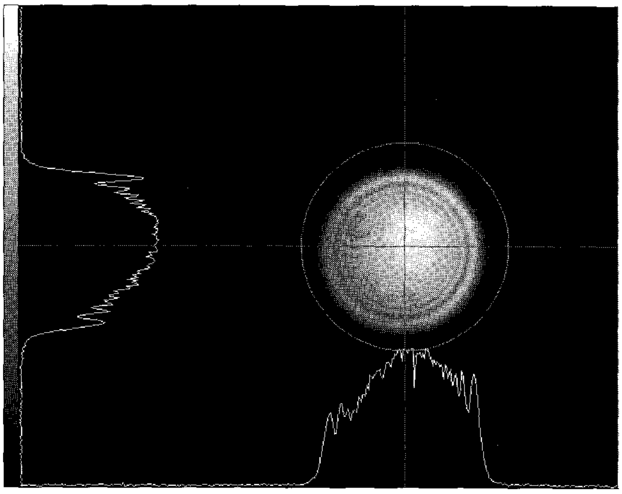


Fig. 15 Cross section of the laser beam intensity distribution

4.2 Edge profile measurements of a diamond cutting tool

After the alignment procedure, we made actual contact between the AFM tip and the cutting tool surface. This was achieved using the typical AFM mechanism, *i.e.*, by detecting the repulsive force between the AFM tip and the tool surface. Figure 16 shows a representative repulsive force curve.

Figure 17 gives the 3-D edge profile of a diamond cutting tool obtained using the AFM-based measuring system. The diamond cutting tool with a nose radius of 0.2 mm was provided by Tokyo Diamond Tools Mfg. Co., Ltd. The scanning area was approximately 60 μm × 3.05 μm, and the total measuring time was 4.5 min. Figure 18 shows one cross-sectional image of the cutting tool edge. Although noise occurred on the rake face, the outline of edge area between the rake face and flank face could be clearly recognized.

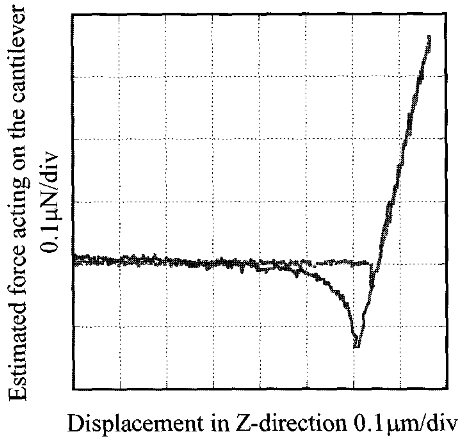


Fig. 16 Repulsive force curve

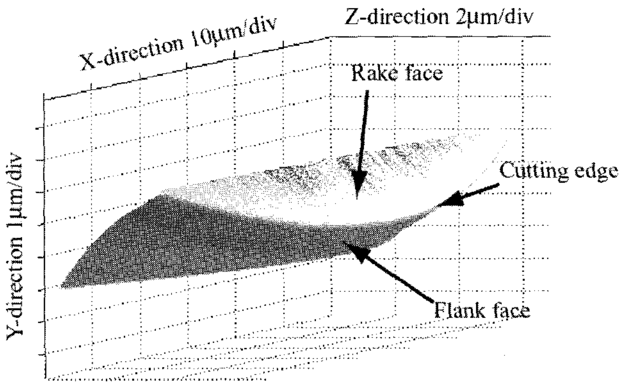


Fig. 17 Three-dimensional profile of the diamond cutting tool (nose radius 0.2 mm)

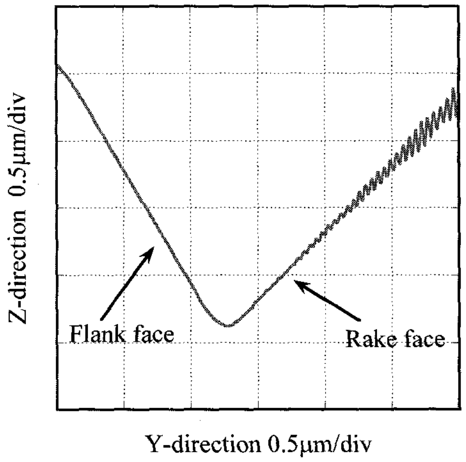


Fig. 18 Cross-sectional view of the cutting edge

5. Conclusions

We developed an AFM-based instrument to measure nanoscale tool edge profiles. The instrument consisted of an interrelated alignment unit and AFM, which were capable of aligning the AFM tip with the top edge of a diamond cutting tool as well as measuring the three-dimensional shape of the cutting tool edge. The performance of this AFM-based instrument was verified by obtaining 3-D edge profile measurements of a diamond cutting tool.

ACKNOWLEDGMENT

This study was supported by a grant from JSPS (No. 18206016). We thank Tokyo Diamond Tools Manufacturing Company for help setting up the instrument.

REFERENCES

1. Asai, S., Taguchi, Y., Horio, K. and Kasai, T., "Measuring the very small cutting edge radius for a diamond cutting tool using a new type of SEM having two detectors," CIRP Annals, Vol. 39, pp. 85–88, 1990.

2. Born, D. K., "An empirical survey on the influence of machining parameters on tool wear in diamond turning of large single-crystal silicon optics," Precision Engineering, Vol. 25, pp. 247–257, 2001.

3. Soares, S., "Nanometer edge and surface imaging using optical scatter," Precision Engineering, Vol. 27, pp. 99–102, 2003.

4. Gao, W., Motoki, T. and Kiyono, S., "Nanometer edge profile measurement of diamond cutting tools by atomic force microscope with optical alignment sensor," Precision Engineering, Vol. 30, pp.396-405, 2006.