DESIGN OF AN OPTICAL SYSTEM FOR EVALUATION OF EDGE CONTOUR OF A DIAMOND CUTTING TOOL

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Abstract: (250 Words)

This paper proposes a new optical measurement system for evaluation of a cutting edge profile of a diamond tool. The authors have developed a measurement method of edge contours of diamond tools, in which a micro laser probe scans along the tool edge contour to measure the deviation of the tool edge contour from the scanning path. For further precise tool edge contour measurement with the micro laser probe, the spot diameter of the laser probe needs to be stabilized during the scanning. The proposed optical measurement system includes an optical system for white light scanning interferometer (WLSI) in the laser optical probe system. A rake face of a tool, which normal is set to be parallel to the optical axis of the micro laser probe, is measured by WLSI so that information on both the position of the tool edge with respect to the optical stylus and the scanning path of the optical stylus for tool contour measurement can be acquired. By referring the information acquired by the WLSI, the tool contour would be measured by the optical stylus, while its spot diameter is optimized.

Keywords: Measurement, Cutting tool, Edge contour measurement, White light interferometer

1. INTRODUCTION

In recent, diamond tools are often used for fabricating products having three-dimensional micro structures [1]. Form error of a tool edge is one of the critical factors that affect the quality of the ultra-precision machining, in which nanometric wear on the tool tip could result in a significant surface form error of a product [2]. It is therefore desired to carry out evaluation of the tool edge contour in an on-machine condition. Conventionally, scanning electron microscopes (SEMs) or optical microscopes have often been used for evaluating the tool edge contour [3-4]. However, it is difficult to apply these instruments to the quantitative on-machine tool edge contour measurement.

In responding to the demands described above, an instrument for three-dimensional tool edge measurement based on an atomic force microscope (AFM) was introduced with a combination of a laser probe, which enabled to align a tip of the cutting tool and an AFM probe [5]. A unique alignment sequence was employed so that precise alignment can be carried out in a short time. By using the developed instrument, a three-dimensional tool edge profile with a nose radius of 200 μm to 2 μm was successfully evaluated [6]. Furthermore, a method for tool edge contour measurement by using the laser probe as a measurement probe was also proposed, and its feasibility was verified [7].

To improve the measurement accuracy of the micro laser probe system, a new optical configuration is proposed in this paper. The optical instrument includes a laser probe component and a white light scanning interferometer (WLSI) component. The instrument is designed to make the two optical components share a measuring optical axis. In a static condition, the rake face of a tool, which is set to be vertical to the optical axis, is measured by the WLSI component so that a scanning path for tool contour measurement can be generated from three-dimensional geometric data. By referring the generated scanning path, the tool contour can be scanned by the laser probe with sub-micrometric accuracy. During the scanning, the deviation of light intensity of the laser passed through the tool cutting edge is monitored, and the tool contour can be acquired by using the measured deviation of the light intensity and the scanning path of the optical stylus. A design study of the optical systems and measurement algorithms is discussed.

2. PRINCIPLES OF MEASUREMENT METHOD

2.1 Tool edge contour measurement

Figure 2 shows a schematic of a single point diamond cutting tool. A cutting edge of the tool is determined as an intersection line between a rake face and a clearance face of a tool. A radius of the cutting edge r, which is referred to as a cutting edge radius, is important design parameter for both tool manufacturers and users since the machining performance would strongly be affected by the sharpness. Meanwhile, a radius of a tool edge contour R, which is referred to as a nose radius, is also an important parameter to be controlled since its convolution with a tool path would

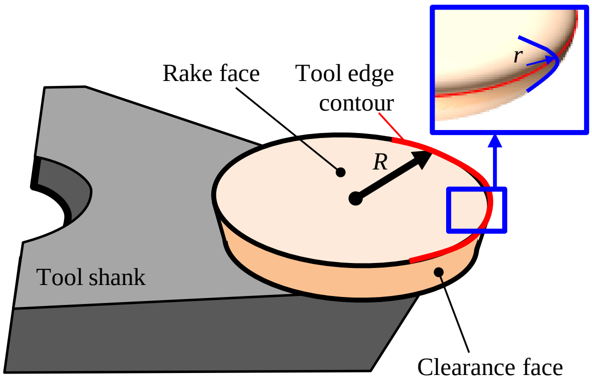


Fig. 1: Single point diamond cutting tool

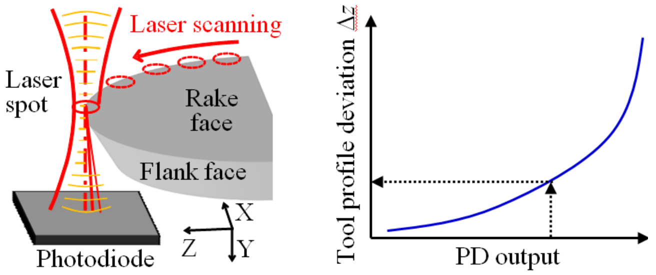


Fig. 2: Tool edge contour measurement by a micro laser probe

directly be transferred to the workpiece surface during machining process. The cutting edge sharpness can be measured by the AFM-based measurement instrument [5-6]. Tool edge contour can also be evaluated by using the acquired AFM image. However, due to the limitation of the measurable area of an AFM system, it is time-consuming task to evaluate tool edge contour over a measurement range of 100 μm×100 μm.

A method for tool contour measurement by using a laser probe has therefore been proposed [7]. Figure 2 shows a schematic of the tool edge contour measurement with the laser probe. In the method, a laser spot with a diameter on the order of micrometres scans the tool edge, while monitoring the intensity of the light which passes through the tool rake face by using a photodiode (PD). The deviation of the light intensity corresponds to the deviation of the cutting edge with respect to a scanning path of the laser spot. A tool edge contour can therefore be evaluated by using a relation curve, which describes the relationship between the PD output and the light spot position with respect to the edge. The relation curve can be acquired in advance of the tool edge contour measurement by a simple procedure [7].

It should be noted that, in the measurement procedure, the accuracy of a scanning path of the laser spot needs to be assured since it directly affects measurement result of a tool edge contour. In addition, during the scanning of the laser spot, deviation of the Z-directional position of the cutting edge with respect to the laser spot needs to be suppressed. Figure 3 shows a measurement error on measured tool edge contour caused by a defocus Δz of the cutting edge. This result means that a tool edge is desired to be positioned at the focal plane of an objective lens in the laser probe unit during the scanning of the laser spot for precise measurement of the tool edge contour.

2.2 Tool rake face measurement

In this paper, an optical configuration for the WLSI component is introduced. Figure 4 shows a schematic image of the setup. To share the optical path with the micro laser probe, the optical configuration having two objective lenses, which is referred to as the Linnik configuration [8], is employed. In the reference arm of the interferometer, a plane mirror is placed at a focal plane of the objective lens, while a cutting tool is placed at a focal plane of another objective lens in the measurement arm. An interference

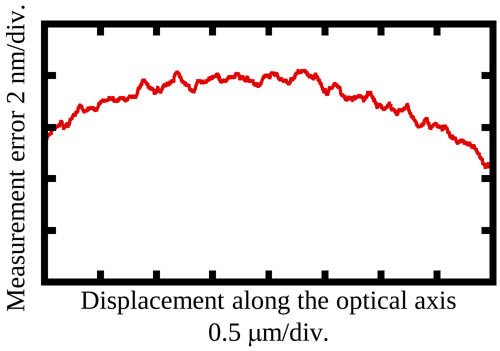


Fig. 3: Measurement error due to defocus

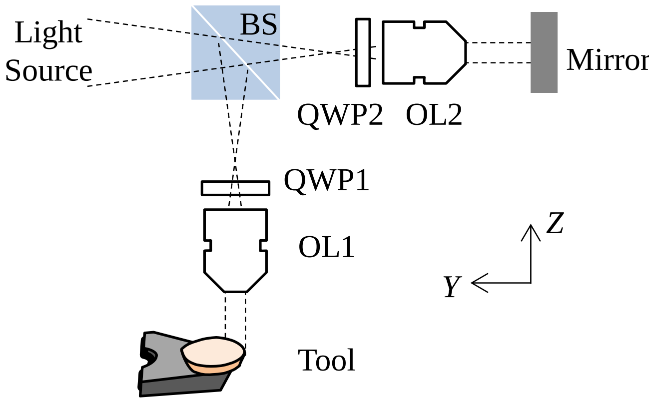


Fig. 4: Tool rake face measurement by a white-light interferometer (Linnik configuration)

fringe can be generated by superimposing the reflected beam from the mirror surface and the tool rake face, respectively.

In the case of the interferometer employing an incoherent light such as a white light as a light source, a fringe pattern with maximum contrast can be acquired when the tool rake face is placed at the focal plane of the objective lens; in other word, by using the information of the fringe pattern, the tool edge can be placed on the focal plane of the objective lens. In ideal case, a diameter of the laser probe for tool edge contour measurement is minimized on the focal plane. Furthermore, tilt angles of a tool rake face can also be assured by using a rake face profile measured by the white light interferometer. Measurement condition of the laser probe can thus be optimized by the combination of the WLSI component with the laser probe component.

Figure 5 shows an example of a measurement sequence. At first, by using a function of WLSI, a cutting tool will be positioned at the focal plane of the objective lens. Tilt angles of the rake face with respect to the laser probe will also be adjusted at this stage. Secondly, the tool edge will be positioned precisely with respect to the laser probe by monitoring PD output of the laser probe. After that, scanning path of the laser probe will be generated by using a two-dimensional image of the rake face. Finally, a tool edge will be scanned by the laser probe so that the tool edge contour can be acquired. For measurement in a large area of the tool edge, stitching process will be employed.

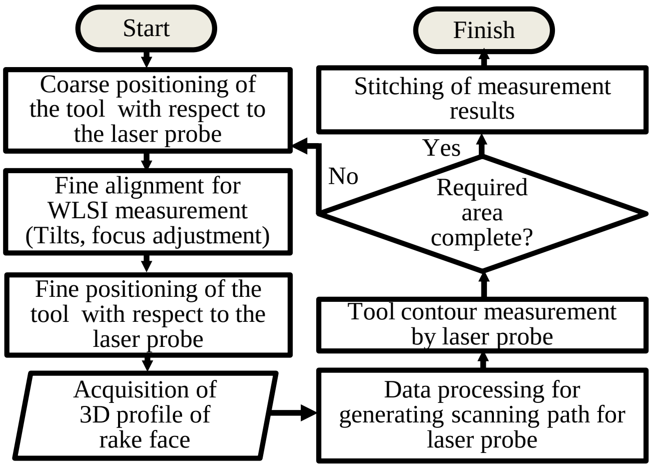


Fig. 5: Measurement procedure

3. DESIGN STUDY OF THE MEASUREMENT INSTRUMENT

3.1 Design of the optical configuration

Figure 6 shows the designed optical configuration of the measurement system. As a light source for the laser probe component and the WLSI component, a laser diode (LD) with a wavelength of 405 nm and a light emitting diode (LED) are employed, respectively. The configuration of the optical system is designed in such a way that the laser probe and the white light scanning interferometer are made to share the same optical axis in the measurement arm. Two objective lenses with a focal length of 10 mm and numerical aperture (NA) of 0.42 are employed in the Linnik configuration. To avoid the interference between the micro laser probe and the WLSI, the LED having a wavelength spectrum from 430 nm to 700 nm is employed. In the setup, the cutting tool is mounted on a precision *XYZ*-stage so that in-plane motion for tool edge contour measurement with the laser probe and the *Z*-directional motion for rake face measurement with the WLSI can be carried out.

3.2Experiments on laser probe component

To confirm the feasibility of the developed measurement system, some experiments were carried out. At first, interference between the laser probe and the WLSI was verified. Figure 7 shows voltage output waveforms of the PDs in the micro laser probe. The laser probe employs two PDs, one is for measurement (PD_M) that monitors deviation of intensity of light passed through a tool rake face, and the other is for reference (PD_R) which monitors deviation of laser power. In Fig. 7, output waveforms of both the PD_M and PD_R are plotted. It was verified that the laser probe was not be affected by the existence of the white light emitted from the LED.

Sensitivity of the laser probe for tool edge contour measurement was also evaluated in experiment. Figure 8 shows the relationship between the *Z*-directional tool displacement and the laser probe output. According to the noise level of the laser probe (0.03% of the normalized PD

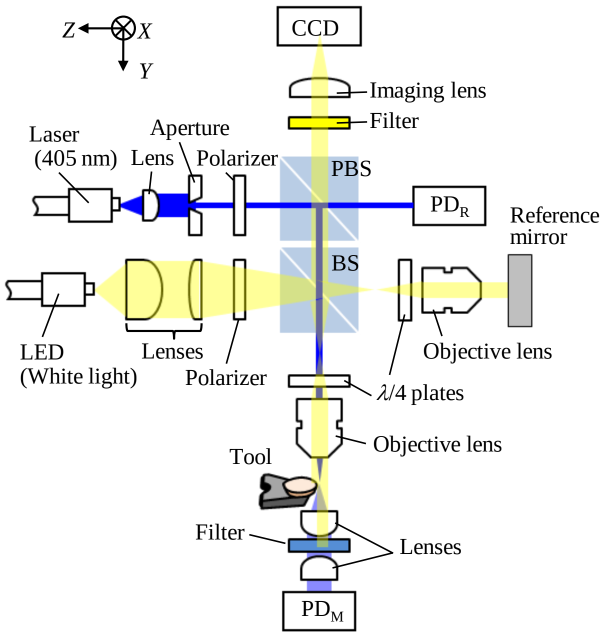


Fig. 6: Optical configuration of the designed system

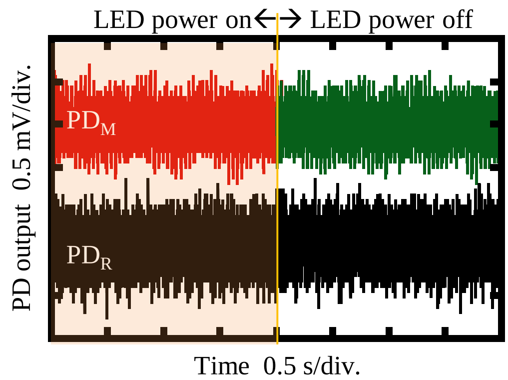


Fig. 7: Voltage output waveforms of photodiodes

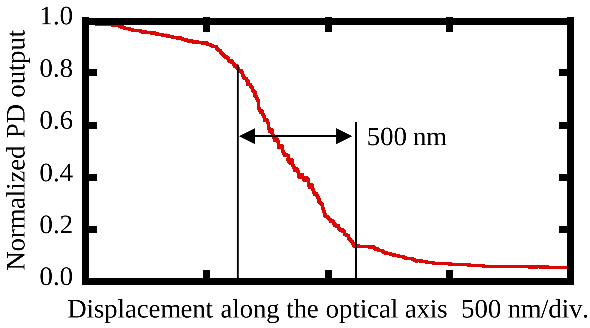


Fig. 8: Sensitivity of the micro laser probe component

output), it was verified that the laser probe has a resolution of less than 1 nm for tool edge contour measurement.

3.3 Experiments on WLSI component

Figure 9 shows the spectrum of the light intensity of the LED used in the WLSI component. By referring the spectrum, the interference signal $I(\zeta)$ was simulated based on the following equations:

$$I(\zeta)=\sum_{\lambda=0}^{\infty}U(\lambda)G(\lambda,\zeta) \quad (1)$$

$$G(\lambda,\zeta)=I_1(\lambda)+I_2(\lambda)+2\sqrt{I_1(\lambda)I_2(\lambda)}\cos[(f-\zeta)K(\lambda)] \quad (2)$$

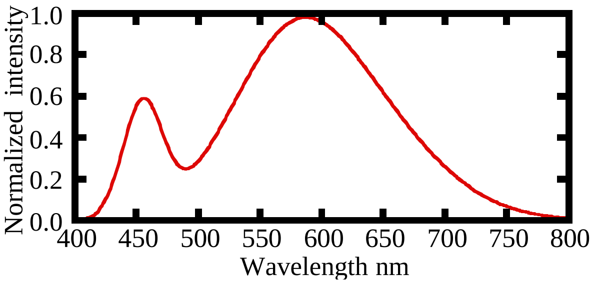
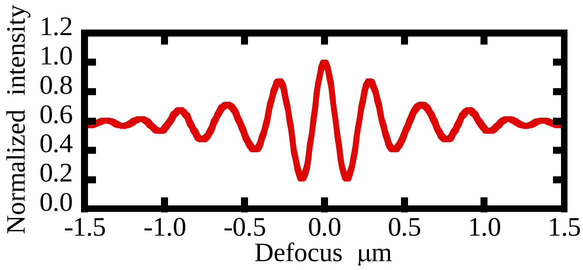
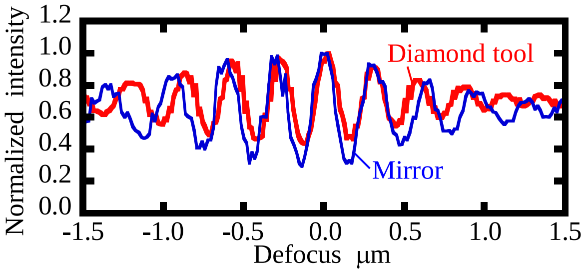


Fig. 9: Spectrum of the light intensity of the LED



(a) Simulation

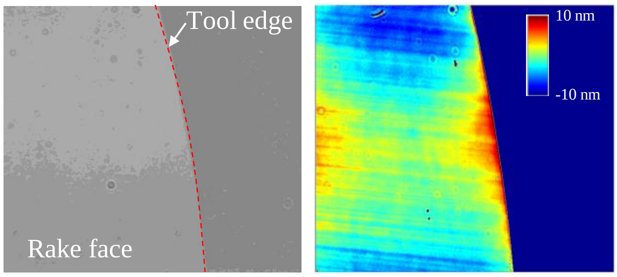


(b) Measured results

Fig. 10: Interference signal

where λ is a light wavelength, f is a focal length of the objective lens, $I_1(\lambda)$ and $I_2(\lambda)$ are the intensities of the light reflected from a measuring target surface and a reference mirror, respectively, and ζ is a distance from the focal plane. The simulated variation of the light intensity with respect to the *Y*-directional displacement of the measuring target surface is plotted in Fig. 10(a). In the figure, the intensity of a practical case ($I_1 > I_2$) is plotted. After that, the variation of the light intensity of the developed WLSI was verified by using a plane mirror and a diamond tool as measuring targets. Figure 10(b) shows variations of light intensities detected at a certain cell on the CCD camera used in WLSI component. The period of the variation of the measured interference signal was approximately 300 nm, and a good agreement was found between the simulation result and the experimental results. A coherence length observed in the experiments was slightly longer than that in the simulation result. In the optical path of the WLSI, two filters are employed; one is beneath the measuring target, the other is in front of the imaging lens and the CCD camera. Filters in the system made the spectrum bandwidth narrow, resulting in longer coherence length.

Figure 11 shows the tool rake face measured by the developed WLSI component. Slight scratches on the rake face, which were generated during the tool fabrication process, were successfully observed. Development of the algorithm for generating a scanning path of the laser probe for tool edge contour measurement, verification of the effect



(a)CCD image (b) Measured profile

Fig. 11: Tool rake face measured by WLSI component in the developed instrument

of the WLSI on the optimization of the condition of the tool edge contour measurement by using the micro laser probe and a large-area measurement of both a tool edge contour and a tool rake face will be carried out as future work.

4. CONCLUSIONS

An optical measurement instrument for tool edge contour and tool rake face was proposed, and its design study was carried out. An optical configuration, in which a laser probe and a white light scanning interferometer (WLSI) shares the same optical axis for measurement, was designed, and its feasibility was tested in experiments. It was verified that there was no interference between the laser probe and WLSI. Furthermore, feasibility of the developed laser probe component and the WLSI component were also verified.

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