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An edge reversal method for precision measurement of cutting edge radius of single point diamond tools

Yuan-Liu Chen, Yindi Cai, Malu Xu, Yuki Shimizu*, So Ito, Wei Gao

Department of Finemechanics, Tohoku University Sendai 980-8579 Japan

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ABSTRACT

A method, which is referred to as the edge reversal method, is proposed for precision measurement of the cutting edge radius of single point diamond tools. An indentation mark of the cutting edge which replicates the cutting edge geometry is firstly made on a soft metal substrate surface. The cutting edge of the diamond tool and its indentation mark, which is regarded as the reversal cutting edge, are then measured by utilizing an atomic force microscopy (AFM), respectively. The cutting edge radius can be accurately evaluated through removing the influence of the AFM probe tip radius, which is comparable to the cutting edge radius, based on the two measured data without characterization of the AFM probe tip radius. The results of measurement experiments and uncertainty analysis are presented to demonstrate the feasibility of the proposed method.

1. Introduction

Single point diamond tools with sharp cutting edges are widely used for ultra-precision diamond cutting of optical components such as prism arrays [1], freeform lenses [2–4] and diffraction optical elements (DOE) [5–7]. The tool cutting edge radius is one of the primary factors that determine the quality of the machined surfaces [8–10]. Differing from the tools used for conventional metal cutting, such as high speed steel tools or carbide tools, a diamond tool used for ultra-precision cutting can have a cutting edge radius down to tens of nanometers [11]. A less sharp cutting edge would cause more energy dissipation and decreases the cutting accuracy. Therefore, it is important to carry out precision measurement of the cutting edge radius not only for qualifying the precision in manufacturing of diamond tools, but also for the quality control in ultra-precision cutting with the tools. The measurement uncertainty of tool edge radius is desired to be on the order of 5 nm because the tool edge radius of a diamond cutting tool used in ultra-precision cutting is on the order of tens of nanometers.

Taking into consideration the nanometric scale of the cutting edge radius of a single point diamond tool, surface measuring instruments with nanometric resolutions in both lateral and vertical directions are necessary for the measurement. Although optical methods provide fast and non-contact measurement [12,13], their lateral resolutions are not sufficient for measuring nanometric cutting edges due to the light diffraction phenomena. A scanning electron microscopy (SEM) has a large depth of field and a nanometric lateral resolution [14]. However, it is typically used for observation of the state of the tool cutting edge instead of the quantitative evaluation of a cutting edge radius because the SEM image is basically a two dimensional projection of the three dimensional (3D) cutting edge and its imaging accuracy is also limited by the charging effect associated with diamond materials [8]. On the other hand, atomic force microscopy (AFM) is powerful for measurement of 3D microstructures with subnanometric resolutions [15,16]. It has been successfully applied for quantitative measurement of the cutting edge radius as well as the 3D cutting edge profiles of diamond tools [11,17]. Indirect cutting edge radius measurement has also been conducted by using an AFM to measure an indentation mark of the cutting edge of a diamond tool on the surface of a copper specimen [18].

However, both the direct and indirect measurements of tool cutting edge radius by AFM suffer from the same shortcoming that the measurement accuracy is inevitably influenced by the finite size of the AFM probe tip although typically the AFM probe tip radius is smaller than that of the diamond tool cutting edge. Taking into consideration the tip radius of an AFM probe is on the order of 10 nm, it is thus necessary to characterize the AFM probe tip radius and to remove its influence on the measurement result of the cutting edge radius for achieving the required 5 nm measurement uncertainty. The AFM probe tip radius is usually estimated by using the AFM to scan a reference sample with a geometrically well-defined

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* Corresponding author.
E-mail address: yuki.shimizu@nano.mech.tohoku.ac.jp (Y. Shimizu).

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structure which is called a tip characterizer [19]. The estimation accuracy by such a method depends on the knowledge on the geometry of the tip characterizer. A tip characterizer is often observed by SEM or TEM (Transmission Electron Microscopy) before it is used for tip characterization. However, it is difficult to make accurate quantitative determination of the nanometric geometry of the tip characterizer [19] since the geometry of the tip characterizer can also be changed due to contamination or wear during the tip characterization process. Although blind reconstruction algorithms have been developed for AFM tip characterization without a priori knowledge of the actual structure of the sample [20], it is difficult to guarantee the effectiveness and accuracy of such a method in practical applications because the tip reconstruction result, which is dependent on the convergence of an iteration process, significantly varies with the selection of the initial input parameters and there are no clear guidelines for the parameter selections [20]. Because many of the commercial AFMs are now equipped with full closed-loop controlled scanners in both lateral and vertical axes and can accomplish 3D positioning of the AFM probe with nanometric or even sub-nanometric accuracies in certain measurement ranges, the uncompensated tip radius of AFM probe has become the largest error source for preventing the accurate measurement of cutting edge radius of a single point diamond tool with a measurement uncertainty of 5 nm.

In order to improve the measurement accuracy of cutting edge radius, this paper proposes a new method, which is referred to as the edge reversal method, for precision measurement of the cutting edge radius of a single point diamond tool based on AFM with a target measurement uncertainty of 5 nm through compensating for the influence of the AFM probe tip radius. The tool cutting edge and its indentation mark on a substrate, which is regarded as the reversal cutting edge, are scanned by using an AFM probe tip, respectively. The influence of the AFM probe tip radius on the measurement result of the cutting edge radius can be directly removed by using the two AFM images without time-consuming characterization or complicated blind reconstruction. As the first step of research, measurement experiments are carried out to verify the feasibility of the proposed method. After a description of the measurement principle, results of the experiments and uncertainty analysis are presented.

2. Principle and analysis

A schematic of the edge reversal method proposed for measurement of the cutting edge radius of a single point diamond tool is shown in Fig. 1. The diamond tool cutting edge is formed by the intersection of a flat rake face and a cylindrical flank face. The cutting edge radius of the single point diamond tool is denoted by R_{tool}. An AFM is employed for the measurement of R_{tool}. The AFM probe tip radius is denoted by R_{probe}, which is assumed to be smaller than R_{tool}. The AFM probe tip is also assumed to have a round and symmetrical shape, which can fit most cases of the AFM probes. However, there are some exceptional cases, for instance, a possible AFM probe tip wear or damage can make the AFM probe tip with an irregular shape which cannot be assumed to be a round shape. It should be noted that these exceptional cases are not considered in this paper. To remove the influence of R_{probe} on the measurement of R_{tool}, the following four consecutive steps are carried out:

STEP 1: Replication of the cutting edge is firstly made by indenting the tool cutting edge into the surface of a substrate, by which the cutting edge geometry can be transferred to the indentation mark, which is regarded as the reversal cutting edge. The material chosen for the substrate can be a soft non-ferrous metal such as copper or aluminium so that the indentation process will not damage the cutting edge. The non-ferrous metal substrate is also easy to be diamond turned or polished to obtain a mirror-finish surface so that the influence of the surface roughness on the precision of the cutting edge replication can be eliminated. Denote the radius of the indentation mark of the cutting edge by $R_{\text{r\_tool}}$. For an ideal case, assume that the geometry of the cutting edge is well transferred to its indentation mark and thus $R_{\text{r\_tool}}$ is equal to R_{tool}.

STEP 2: The diamond tool cutting edge is scanned by using the AFM probe tip after carefully aligning the cutting edge area of interest with the AFM probe tip. As shown in Fig. 1, since the measured sectional profile of the cutting edge is the convolution of the probe tip geometry and the tool cutting edge, the apex radius $R_{\text{m\_T}}$ of the measured sectional profile of the tool cutting edge is the sum of the tool cutting edge radius R_{tool} and the AFM probe tip radius R_{probe}:

$$R_{\text{m\_T}} = R_{\text{tool}} + R_{\text{probe}} \tag{1}$$

STEP 3: The indentation mark of the cutting edge on the substrate surface is also scanned by utilizing the same AFM probe without changing the orientation of the probe tip. Because of the concave shape of the indentation mark of the cutting edge, as shown in the figure, the bottom apex radius $R_{\text{m\_R}}$ of the measured sectional profile is the difference between the indentation mark radius $R_{\text{r\_tool}}$ (=R_{tool}) and the AFM probe tip radius R_{probe}:

$$R_{\text{m\_R}} = R_{\text{tool}} - R_{\text{probe}} \tag{2}$$

It should be noted that the bottom of the indentation mark can be touched by the AFM probe tip because R_{probe} is assumed to be smaller than R_{tool}.

STEP 4: By combining Eqs. (1)–(2), the cutting edge radius R_{tool} can be obtained as follows:

$$R_{\text{tool}} = \frac{R_{\text{m\_T}} + R_{\text{m\_R}}}{2} \tag{3}$$

It can be seen that the influence of R_{probe} has been removed from the measurement of R_{tool} in Eq. (3). Since all of the STEPs can be operated at a temperature controlled room, thermal deformation of the indentation mark should not be an influencing factor. However, in real situation, as shown in Fig. 2, possible difference can still exist between $R_{\text{r\_tool}}$ and R_{tool} due to the elastic recovery of the substrate material when the tool is retracted back after making the indentation mark. Taking into consideration the effect of elastic recovery, $R_{\text{r\_tool}}$ can be expressed by:

$$R_{\text{r\_tool}} = (1 - \sigma) \cdot R_{\text{tool}} \tag{4}$$

where σ is a coefficient less than 1 associated with the elastic recovery of the substrate material. The larger the Young's modulus the substrate material has, the lower the elastic recovery effect will be and the less the value of the coefficient σ is. Eq. (3) can thus be rewritten as:

$$R_{\text{tool}} = \frac{R_{\text{m\_T}} + R_{\text{m\_R}}}{2 - \sigma} \tag{5}$$

From Eq. (5), it can be seen that in addition to the performance the AFM instrument itself, the achievable accuracy of this method is dependent on the coefficient σ. Estimation of σ is thus an important prerequisite for qualification of this measurement method. Considering the nanometric scale of the indentation depth in the cutting edge replication process, molecular dynamics (MD) analysis method is employed for estimation of σ based on the Large-scale Atomic Molecular Massively Parallel Simulator (LAMMPS) code [21]. Three-dimensional simulation is conducted and Fig. 3 shows a plane-view of the results of the MD analysis. In the MD analysis, a diamond tool cutting edge is modelled by carbon atoms and shaped to be with a cutting edge radius of 20 nm, which is very close to that of an actual single point diamond tool. A substrate is modelled by a total of 119,940 copper atoms which are divided into three layers of atoms, namely, boundary atoms, thermostat atoms and Newton

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