INTRODUCTION
Accurate measurement of the wear of diamond tools is of great interest for precision machining. This is often done indirectly using surface finish measurements, combined in some studies with tool force measurements [1]. However, a proper investigation of the tool wear, suitable for the development of wear models, requires the quantitative characterization of the diamond tool edge radius and the flank wear length as a function of the cutting distance for given machining conditions and materials. It is difficult to obtain the sectional curve of the diamond tool edge because the edge radius is on the order of a few tens to hundreds of nanometers and the diamond itself is nonconductive. Up to now, only a few results have been reported for measurement of the edge radius, and these varied due to limitations of the methods. Atomic force microscope (AFM) and AFM combined with nanoindentation were used to map the tool edge topography [2, 3]. The radius of commercially available AFM probe tips is often on the same order of the diamond tool edge radius. Errors arise from the convolution of the probe tip and tool edge profile and the elastic spring back of the indented material.

With the capability of high resolution imaging, the scanning electron microscope (SEM) is desirable for direct imaging of diamond tool edge sharpness. An SEM, which was specially configured with two secondary electron detectors, was used to obtain the profile curve of the diamond tool [4]. The cutting edge profile was determined by comparing the signal differences in two SEM images, which are affected by the convex and the concave shape of the sample surface. Measurement errors come from the reliability of the empirical formula to determine the inclination angle of the diamond tool. Gold thin film coated on the diamond tool surface to eliminate charging will also affect the measurement accuracy. To improve image contrast and obtain quantitative topographic information in direct SEM observation of the diamond tool edge, Drescher developed a simple technique applying the contamination line in a conventional SEM [5]. In this paper, the electron-beam-induced deposition (EBID) method for tool-wear measurements has been further developed and improved using a state-of-the-art SEM instrument. EBID is a phenomenon that is present during SEM observations. The electron beam will crack the hydrocarbon contaminants present in the vacuum column to form a cross-linked polymer [6]. Under proper operating conditions, an EBID line can be deposited across the rake and flank face of an uncoated diamond tool, which allows for direct observation of the tool edge and wear flank geometry.

EXPERIMENT SETUP
A 45° sample holder was used in the experiment to set the diamond tool edge exactly perpendicular to the electron beam. Figure 1a is the side view of the diamond tool on a 45° sample holder. After the SEM electron gun and apertures were aligned and the astigmatism was removed, scan rotation was selected to bring the cutting edge vertical on the SEM CRT screen. The center area of tool edge was located and the scanning mode was switched to line scan. After several seconds, a hydrocarbon EBID line was found to be deposited on the surface (Figure 1b). To get the profile of the EBID line on the edge, the diamond tool edge was tilted 45° towards the detector (Figure 1c). SEM images of the tool edge with the EBID line on it were collected at different magnifications. Figure 1d is a SEM image collected after the 45° tilt operation.
All measurements of the diamond tool edge by EBID method were done using a JEOL JSM-6400F field emission SEM. After careful analysis of the factors involved with the fabrication of EBID in a controlled manner on a non-conductive surface, a small range of SEM conditions were determined to produce satisfactory EBID lines on the diamond tool. A series of experiments were run to determine the optimum conditions from the range considered. The best operating conditions were obtained with a beam energy of 2 keV, a condenser lens setting of 6, and a 30 µm objective aperture. The highest magnification of diamond tool edge obtained using EBID method was 100,000x. During the measurement process, the sample was tilted only once (45° to view the edge profile). Compared to the earlier work at the PEC [5], mechanical rotation of the sample stage was replaced by changing the direction of the electron beam scanning. Since the mechanical change of the sample stage may bring about some error, tilting the diamond tool only once will result in more precise measurement.

FIGURE 1. Illustration of diamond tool position in SEM chamber and measurement steps. (a) Side view of the diamond tool fixed on a 45° sample holder; (b) EBID line deposited across the center of the tool edge; (c) Diamond tool edge is tilted 45° towards the detector; (d) SEM image of diamond tool edge with EBID line collected after 45° tilt operation.

SEM IMAGES OF DIAMOND TOOL EDGE

Figure 2 is the SEM image collection of tool edge for both new and worn diamond tools. Figure 2a, b are the cutting edge images of a new diamond tool with an orthogonal cutting flat nose. Figure 2c, d and Figure 2e, f are the worn tool edge images after cutting 7.5 km of 6061 Al and 15 m of 1215 steel, respectively. EBID lines separated several micrometers away from each other at the tool edge center have exactly the same profile. In the low magnification images, the length of the EBID line is about 7 µm on each side, which would capture the whole profile of interest. In the higher magnification images, the edge sharpness can be observed in better detail. By comparing worn and unworn tool edge images, it is seen that the unworn tool edge profile is much sharper than that of the worn tool. For the worn tool edge images, worn patterns of the tool edge for cutting the two materials are quite different.

FIGURE 2. SEM images of diamond cutting tool edge with flat nose. (a), (b) Cutting edge of new diamond tool; (c), (d) Cutting edge of worn diamond tool after cutting 7.5 km of 6061 Al; (e), (f) Cutting edge of worn diamond tool after cutting 15m of 1215 steel. Magnification: 10,000x for (a), (c), (e); 50,000x for (d), (f); 100,000x for (b).

SEM IMAGES ANALYSIS

During the EBID measurement process in the SEM, the diamond tool edge has been tilted 45°, so the tool edge in the SEM images in Figure 2 has the same tilt angle. To get the real edge geometry, the image used for analysis should be stretched 141% (1/cos45°) in the vertical direction to compensate for the other 45° tilt.
Figure 3 show the SEM images stretched using Figure 2b, c and f. Measured from the stretched image of new tool edge, the angle between the EBID line on rake face and flank face is about 84°, which is in agreement with the 6° clearance angle specified by the tool vendor. It can be concluded that the tilt and stretch operation is reliable for obtaining the real diamond tool edge geometry.

To quantitatively analyze the edge radius, a Matlab program was developed to process the digital images. After drawing a set of points along the tip area of the edge, a circle based on a least square method can be fit to the points to describe the tool edge radius. The program will count the pixel value of the circle radius. By comparing the pixel value with that of the scale of the images, the actual value of the edge radius can be obtained. While the circle fitting process is partly subjective, gradually drawing points very close to the tip area of the cutting edge will allow a best-fit circle to be found. To get the edge radius of the new diamond tool, the highest magnification (100,000x) image was used and stretched. Two lines were drawn close to the EBID line to delineate the tool edge. The image was then expanded to better view the tool tip, and points were selected that correspond to the tool edge radius. Note that the circle describing the edge radius needs to be tangent to the rake face and flank face trace lines. Figure 4a shows the best fit circle to describe the edge radius of a new diamond tool before cutting.

The wear pattern for a worn tool is quite different for the two workpiece materials. For the diamond tool cutting 1215 steel, the wear land can be seen clearly and measured directly. Figure 4c shows the fitting result for a worn tool after cutting 1215 steel. For diamond tool cutting 6061 Al, the wear land is not as obvious, and the initial line on the new tool image is needed to make a comparison. First, the initial edge geometry formed by two straight lines on the rake and flank face in the unworn tool image was obtained as the base line. Then, the base line is transferred to the worn tool image. The deviation from the base line is used to describe the flank wear land and to fit a circle to evaluate the edge radius. Figure 4b is the fitting result for a worn tool after cutting 7.5 km of 6061 Al.

WEAR RESULTS FOR 6061 ALUMINUM AND 1215 STEEL
To demonstrate the EBID measurement method for diamond tool wear, two cutting experiments are discussed. Two workpiece materials were used. The diamond cutting tools are flat-nose with 6° clearance angle, which are supplied by Chardon Tool and Supply Company. The orthogonal cutting was performed using the ASG2500 Diamond Turning Machine. Four 6061 Al disks with the total 10 km cutting distance were prepared to study the gradual edge retraction of the diamond tool. The diamond tool was measured using the EBID method after each test. In the case of 1215 steel, a total cutting distance of 20 m was used. Cutting parameters and diamond tool conditions in the two experiments are shown in Table 1.

Table 2 gives the tool wear condition corresponding to Table 1. The edge radius and wear land length increased with the cutting distance. The edge radius of the new diamond tool is about 20 nm, which is the same as the value reported by Asai [4] and much smaller than the value reported by Lucca [2]. Note that the wear rate for 1215 steel is at least two orders of magnitude larger than that for 6061 Al. This is consistent with the chemical wear effect proposed for ferrous metals [7].

**CONCLUSION**

The EBID method was used to measure the diamond tool edge sharpness in a conventional SEM instrument. It is a direct and effective way to obtain tool edge radius and wear land without coating on diamond surface. The edge radius for new commercial diamond tool is around 20 nm, somewhat smaller than values previously reported. Because of the higher magnification of the diamond tool edge images, this method is considered to be the most accurate measurement to date. Based on the measurement results of the edge radius and wear land, the wear volume can be estimated and wear models can be developed. In future work, the EBID method can be further refined to get higher magnification images for improved data fitting.

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**REFERENCES**


