# Cylindrical Wire Electrical Discharge Machining of Metal Bond Diamond Wheels – Part II: Wheel Wear Mechanism

Brian K. Rhoney*, Albert J. Shih*, and Ronald O. Scattergood[+]
*Department of Mechanical and Aerospace Engineering
[+]Department of Materials Science and Engineering
North Carolina State University
Raleigh, NC 27695-7910

Ronald Ott and Samuel B. McSpadden
High Temperature Materials Laboratory
Oak Ridge National Laboratory
Oak Ridge, TN

**Abstract**

The use of stereo scanning Electron Microscopy (SEM) to investigate the wear mechanism of the wire EDM trued metal bond diamond wheel for ceramic grinding is presented. On the grinding wheel, a wedge-shape removal part was machined to enable the examination and measurement of the worn wheel surfaces using the stereo SEM. The stereo SEM was calibrated by comparing results of depth profile of a wear groove with the profilometer measurements. On the surface of the grinding wheel after wire EDM truing and before grinding, the diamond protruding heights were measured in the level of 35 μm, comparing to the 54 μm average size of the diamond in the grinding wheel. The gap between the EDM wire and rotating grinding wheel is estimated to be about 35 to 40 μm. This observation indicates that, during the wire EDM, electrical sparks occur between the metal bond and EDM wire, which leaves the diamond protruding in the gap between the wire and wheel. The protruding diamond is immediately fractured at the start of the grinding process, even under a light grinding condition. After heavy grinding, the grinding wheel surface and the diamond protrusion heights are also investigated using the stereo SEM. The height of diamond protrusion was estimated in the 5 to 15 μm range. This study has demonstrated the use of stereo SEM as a metrology tool to study the grinding wheel surface.

## 1. Introduction

The advancement in three-dimensional stereo image analysis using the Scanning Electron Microscope (SEM) has made it an ideal tool to examine the surface topography of metal bond diamond wheels. By applying the computer image analysis to a pair of SEM images, the topographic measurement of grinding wheel surfaces can be obtained. The diamond protrusion on the wheel surface after the wire EDM truing and after grinding the silicon nitride are quantified using the stereo SEM. The comparison of diamond protrusion heights and SEM examinations of grinding wheel surfaces reveal the wear mechanism for wire EDM trued metal bond diamond wheels.

An early application of the stereo SEM was presented by Lee and Russ [1] for the metrology of microelectronic devices. Katsuo et al. [2] had applied the stereo SEM to measure the protrusion height of abrasive grains on a metal bond diamond wheel and to correlate the measured results to grinding performance. Zhao, et al. [3] used the stereo SEM to study the shape of cutting edges on surfaces of a resinoid bond CBN wheel and to observe the effect of truing parameters on CBN grains.

The diamond wheel used in this study consists of the electrically conductive metal bond and the non-electrically conductive diamond. During the wire EDM truing, as presented in the SEM micrographs of the EDM debris in Part I of this study [4], electrical sparks are generated around the diamond to erode the metal bond and cause the whole diamond grain to fall out from the wheel surface. During the wire EDM process, as shown in Fig. 1, a gap exists between the wire and metal bond diamond wheel. The diamond protrudes out of the grinding wheel surface by a height close to or slightly less than the gap distance. This theory is examined using the stereo SEM to compare the diamond protrusion height from the grinding wheel surface.

In this paper, the preparation of the diamond wheel to make a wedge-shape removal piece on the wheel surface for SEM study is first introduced. The procedure to use the stereo SEM and calibration of the SEM for height measurement are then presented. Three types of grinding wheel surfaces:

1. after wire EDM without grinding,
2. after one pass of grinding with 0.127 mm down feed, and
3. after an extensive, 100 grinding passes heavy grinding with 0.127 mm down feed,

are studied using the stereo SEM to quantify heights of diamond protrusion and to investigate the wheel wear mechanism.

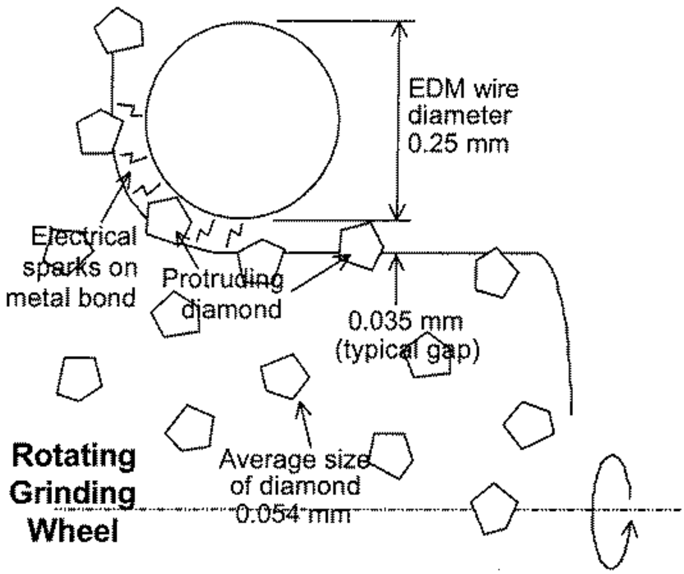



Fig. 1. Schematic illustration of the EDM wire, rotating diamond wheel, the gap between wire and wheel, and the protrusion of the diamond grains on the wheel surface.

**2. Grinding Wheel Preparation**

The 200 mm diameter grinding wheel was too big to be observed using the SEM. A wedge-shape removal piece on the wheel surface, as shown in the front view Fig. 2, was designed to be able to remove from the grinding wheel and to be examined using the SEM. A screw was used to preload and lock this removal piece in place during truing and grinding. The wheel is mechanically balanced using the three-counter-weight method on a balancing stand with two knife edges, as shown in Fig. 3.

The truing of the grinding wheel with the wedge-shape removal piece was conducted using a Huffman HS-5100 wire EDM machine. After truing, as shown in the side view in Fig. 2, the wheel was used to grind the sintered silicon nitride (TSN-10 by Toshiba) using a Harig 618 grinding machine. The table speed was 50.8 mm/s, wheel surface speed was 37 m/s, and length of part ground was 21.7 mm. In each grinding pass, the down feed was 0.127 mm and specific material removal rate was 6.46 $mm^2/s$. The middle section of the grinding wheel surface was worn by only a single pass of grinding of Workpiece #1, i.e., $t_1$=0.127 mm in Fig. 1. Workpiece #2 was ground by 100 passes, each with 0.127 mm down feed, to wear the left section of the grinding wheel by heavy grinding.

In summary, three areas on the surface of a single removal piece are generated after truing and grinding. These three areas are: 1. after wire EDM without grinding, 2. after light grinding with one pass of 0.127 mm down feed, and 3. after heavy grinding with 100 passes of 0.127 mm down feed.

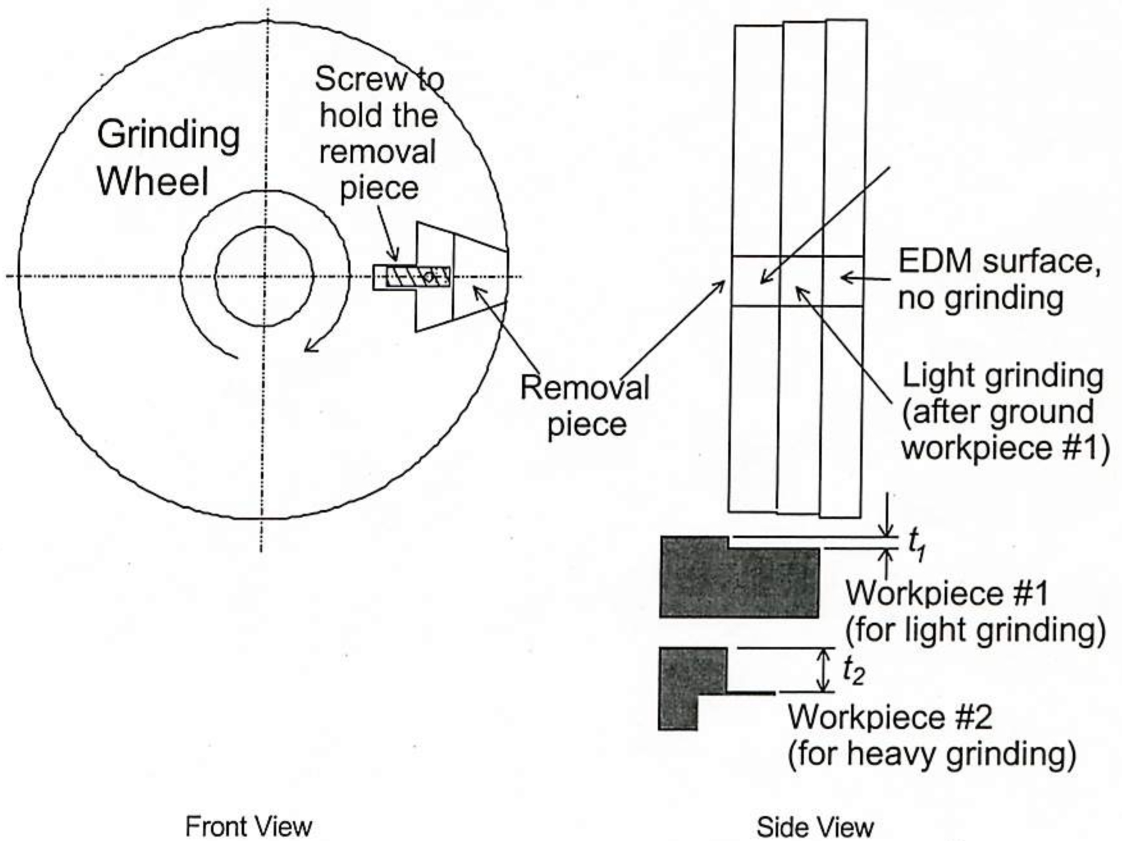



Fig. 2. The wedge-shape removal piece on the grinding wheel surface and the preparation of three areas with different levels of grinding for stereo SEM study.

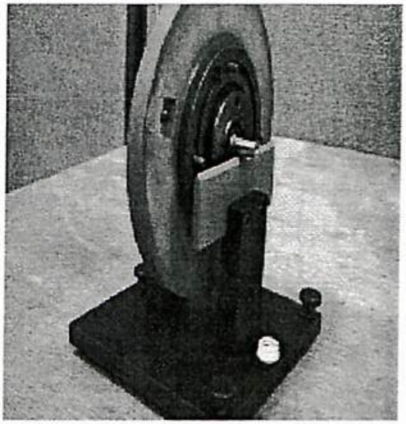


Fig. 3. The grinding wheel on a balancing stand and the wedge-shape removal piece on the wheel.

**3. Stereo Scanning Electron Microscope**

The stereo SEM is a measurement tool used in this study. This section discusses the procedure to generate the surface topography using the stereo SEM and the calibration of this measurement machine.

**3.1. Procedure for Stereo SEM**

The Hitachi S-4700 field emission SEM was used in this study. This SEM was selected due to the automated stage positioning and tilting features, which are required for constructing a 3-D topographic image of the surface. First, a SEM image of the surface is taken with the stage set at zero degree tilt. A feature that can be relocated again once the table is tilted is then marked on the image. Once this feature is identified, the stage is tilted by a specific small angle, two degrees in this case. Another SEM image is taken. This image is then translated to bring the original marked feature back to match the original position in the first image. By knowing the work distance and the pixel size, these two images can be combined using the Alicona imaging software to construct a 3-D image of the surface. Several line segments can be drawn on the SEM image and the software will calculate and draw a chart to show the change in height on pixels along these line segments.

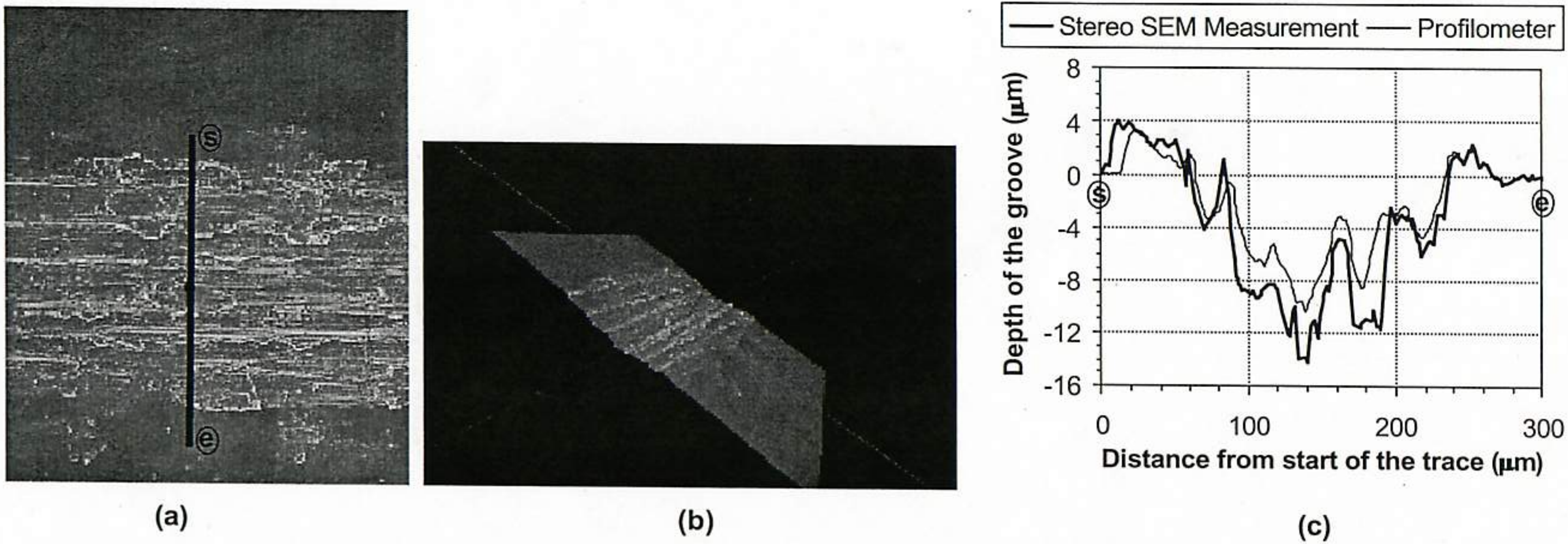



Fig. 4. Calibration of the stereo SEM using a wear groove, (a) SEM micrograph of the wear groove and the starting and ending points of a line segment, (b) stereo representation of the surface, (c) comparison of the wear groove measured using the Talysurf profilometer and stereo SEM.

### 3.2. Calibration

As shown in Fig. 4, a wear groove about 200 µm wide and 6 µm deep was used as a standard sample to calibrate the stereo SEM. The SEM micrograph of the groove and a line segment across the groove are shown in Fig. 4(a). The procedure presented in Sec. 3.1 was applied to generate the stereo representation of the surface, as shown in Fig. 4(b). The same groove was measured using both the Talysurf profilometer contact and the stereo SEM methods. Results of these two measurement methods are shown in Fig. 4(c). These two closely matched measurement traces verified and calibrated the stereo SEM measurement method.

## 4. Diamond Wheel Surface after Wire EDM Truing

The first area to be observed using the stereo SEM is the surface after EDM truing and without grinding. SEM micrographs of the wheel surface are shown in Fig. 5. As shown in the overall view in Fig. 5(c), the surface is rough with sparsely and evenly distributed diamond grains and a significant amount of metal bond material that has been resolidified or recasted to the wheel surface. It is noted that these recasts are strongly bonded to the wheel surface, which was under high pressure jet of deionized water during the wire EDM truing and has been cleaned before examining using the SEM.

Two types of metal resolidification can be identified on the wheel surface. The first type is the recast sphere, which is the molten metal bond that did not escape the gap during EDM spark erosion and was resolidified on the wheel surface. Examples of the recast sphere are indicated in Figs. 5(b), 5(c), and 5(d). The second type is the splashed recast, as shown by examples in Figs. 5(a) and 5(e), which is magnified in Fig. 6(a). This type of recast is possibly due to the collision of the spark eroded molten metal with the diamond and then splashing and resolidifying on the surface close to a diamond grain. Notice in Figs. 5(e) and 6(a) that the splashed recast can occur several times around the diamond. Besides these recasts, diamond exposed out of the wheel surface can also be observed. The height of diamond protrusion is measured using the stereo SEM.

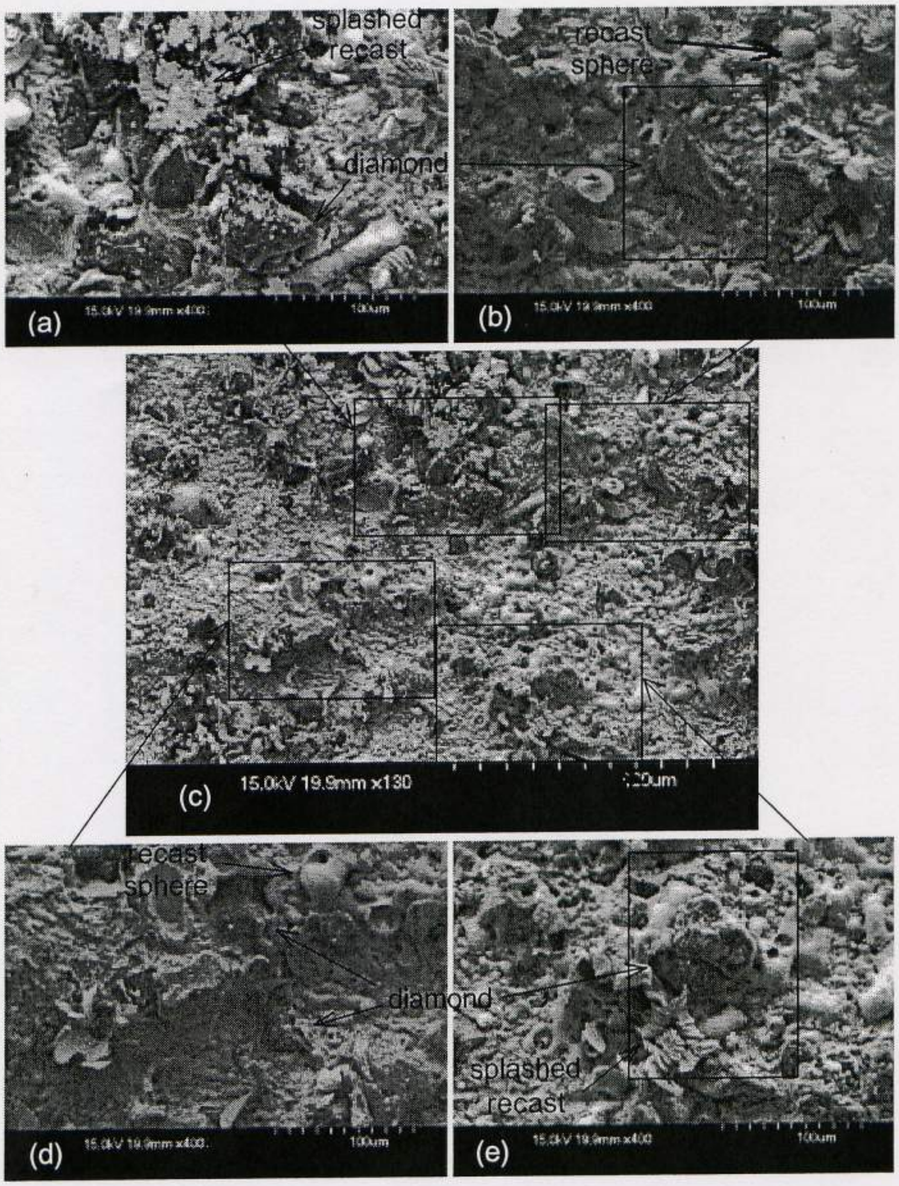



Fig. 5. SEM micrographs of the grinding wheel surface after wire EDM without grinding.

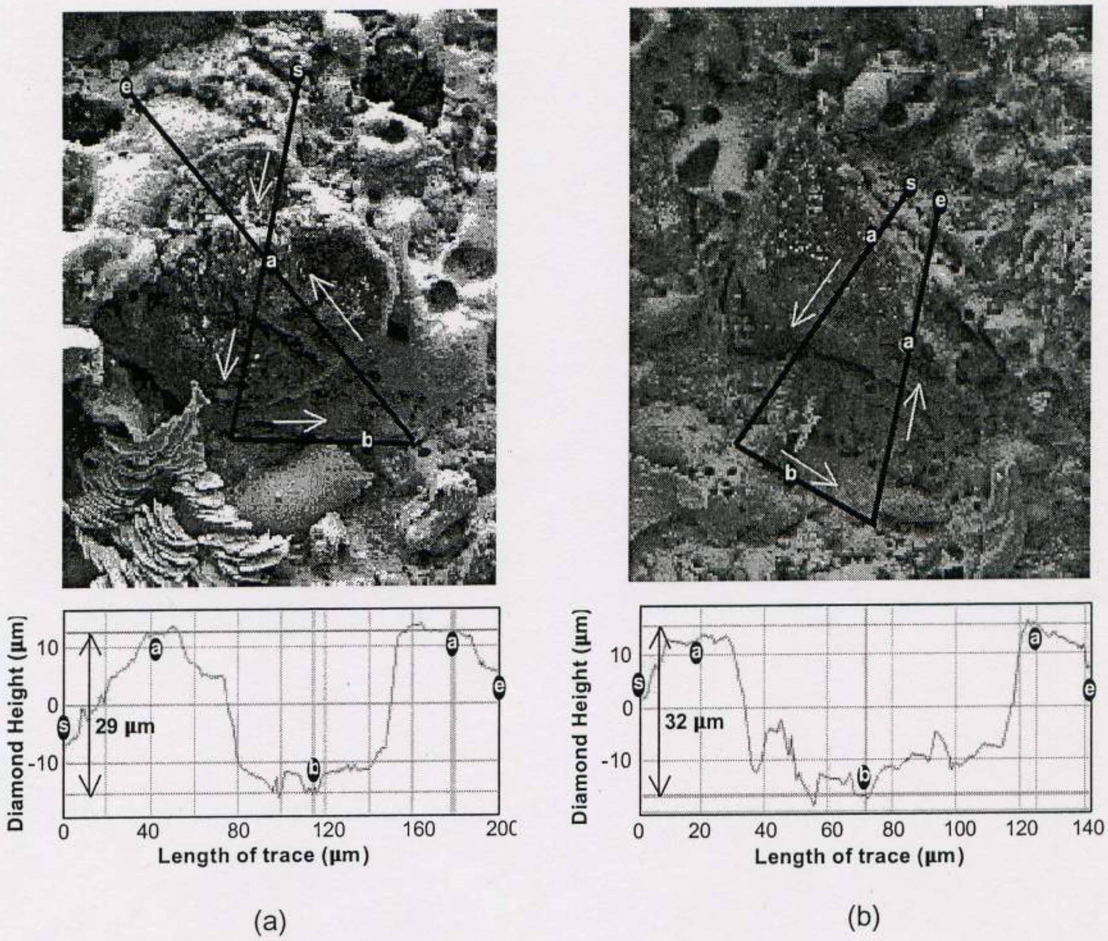
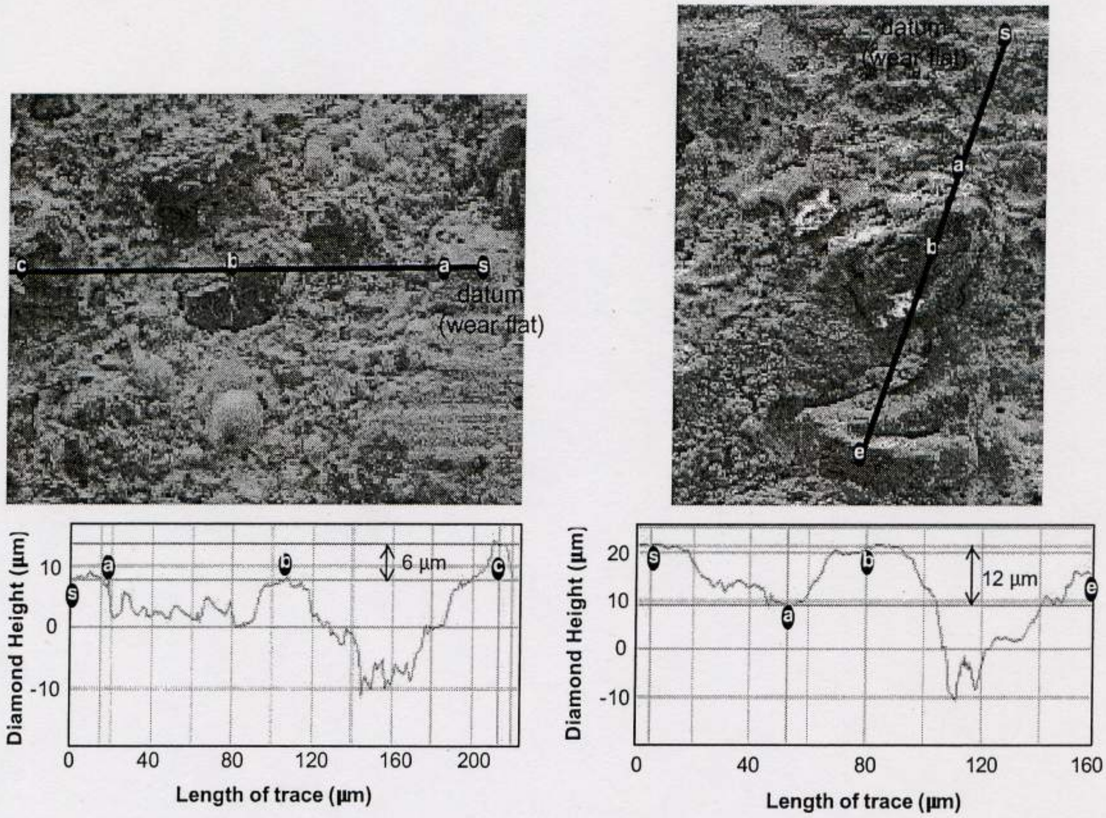



Fig. 6. The height of diamond protrusion on the wire EDM wheel surface without grinding, (a) the diamond in Fig. 5(b) and (b) the diamond in Fig. 5(e).




(a) (b)

Fig. 8. The height of diamond protrusion on the wheel surface after light grinding, (a) the two diamonds in Fig. 7(d) and (b) the diamond in Fig. 7(e).

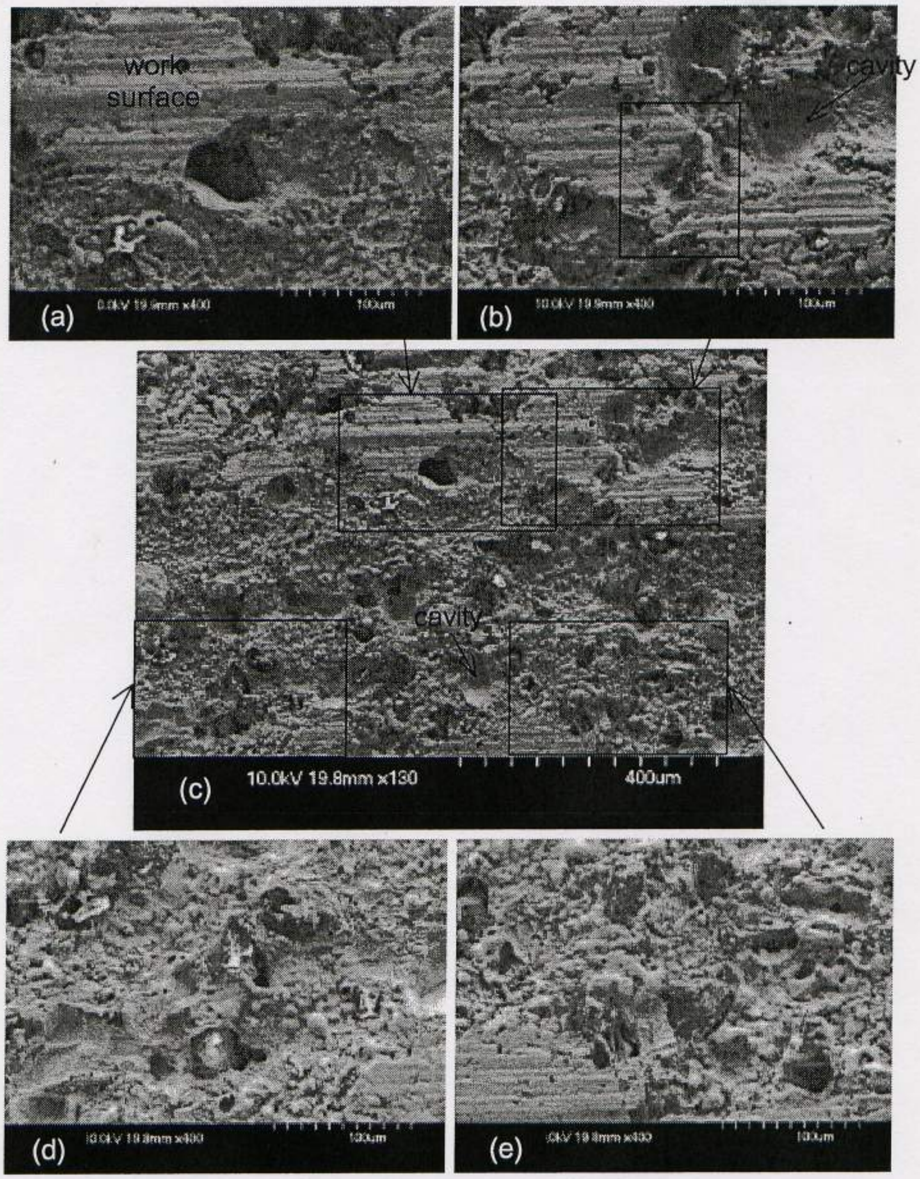



Fig. 9. SEM micrographs of the wheel surface after heavy grinding.

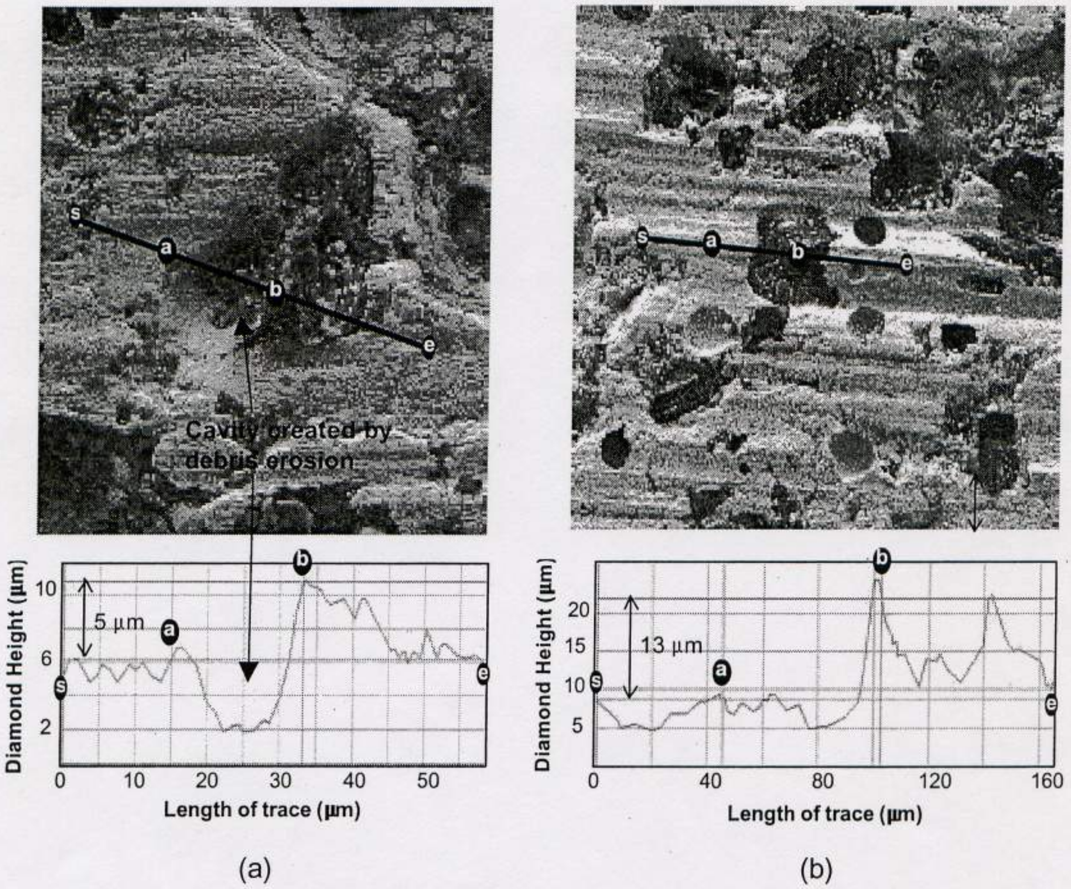



Fig. 10. The height of diamond protrusion on the wheel surface after heavy grinding, (a) the diamond in Fig. 9(b) and (b) a diamond protruded from the wear flat.

Figure 6(a) shows ~~the close view~~ of the diamond in Fig. 5(e). The splashed recast near the diamond and some small spherical recast can be seen more closely. Three line segments were selected on the SEM image to measure the protrusion height of the diamond. The Alicona 3-D imaging software was used to construct a 3-D image of the surface and to calculate the variation of height along these three line segments. Results of the height variation were shown in the trace below the SEM picture. The starting and ending points of the trace were marked by s and e. Two other points, a and b, were marked both along the line and on the trace of the height measurement. Figure 6(a) showed the diamond protrudes over the surrounding matrix by about 29 µm. The diamond boxed in Fig. 5(b) was also analyzed using the stereo SEM. Results of the height variation along the three line segments were shown in Fig. 6(b). This diamond was also protruding out of the surrounding surface by about 32 µm. The advantage of using the stereo SEM as a metrology tool to quantify the diamond protrusion height was illustrated by these two examples.

The average size of the 325 ANSI mesh diamond wheel is about 54 µm. Results in Fig. 6 indicate that over half of the size of diamond is exposed outside the surrounding metal matrix. The next section will show that these over-protruded diamond grains are expected to fracture or pull out of the wheel surface immediately at the start of grinding, even under very light grinding condition. It is noted that not all the diamond grains are protruding in the 30 µm level. Some other heights of diamond protrusion, in the range of 6 to 20 µm, have been measured on the wheel surface. These will be the active diamond grains during grinding.

The hypothesis of the immediate fracture of those over-protruding diamond at the start of the grinding can also support the observation of relatively high wheel wear. This being the 12 µm wheel wear measured on the machinable plastic replica of the EDM trued wheel surface after the first grinding. During grinding of the machinable plastic part, the protruded diamonds are subjected to very small forces and are not likely to fracture. Therefore, after just one grinding pass of the silicon nitride, a step of 12 µm was measured in the middle section of the wheel, which was subjected to contact with the ceramic part.

## 5. Wear of the Diamond Wheel Surface After Light Grinding

SEM micrographs of the grinding wheel surface after one pass grinding of silicon nitride with 0.127 mm down feed are shown in Fig. 7. The spherical and splashed recasts, which are weakly bonded to the surface, mostly disappeared. Some diamonds have been pulled out and leave a cavity on the surface, such as those indicated in Fig. 7(c) and 7(e). Some of the diamonds exhibit fractured surface, such as those marked in Figs. 7(a) and 7(b). Wear flat areas, such as those shown in Figs. 7(a), 7(c), and 7(d), are created after the light grinding. These wear flats are used as the datum for the measurement of the diamond protrusion height.

Figure 8 shows two examples of the measurement of diamond protruding height relative to the wear flat datum using the stereo SEM. The starting point of the line, marked by s, was located on a wear flat and set as the datum for measurement. The straight line segment in Fig. 8(a) crossed the two diamonds shown in Fig. 7(d). The first diamond, marked by b, had about the same height as the datum. The second diamond, marked by c, was about 6 μm over the datum surface. Both diamonds showed rub marks on the surface and appeared to be active in grinding. Another example in Fig. 8(b) showed the active diamond (also seen in Fig. 7(e)) has about the same height as the datum. The chip clearance around this diamond was measured about 12 μm.

## 6. Wear of the Diamond Wheel Surface After Heavy Grinding

The wheel surface after extensive grinding, 100 grinding passes with 0.127 mm down feed or 100 times more work-material removed than the light grinding presented in the previous section, was studied using the stereo SEM. Comparing to Fig. 7(c), relatively larger areas of wear flat could be seen in Fig. 9(c). The cavity created by diamond pull out could also be observed, as indicated in Figs. 9(b) and 9(c).

The diamond located in the middle of a large wear flat area in Fig. 8(b) was studied using the stereo SEM. Figure 10(a) showed a line starting and ending both on the wear flat. The diamond, indicated by b, was protruding about 5 μm over the wear flat. A cavity in front of the diamond, about 4 μm deep, could be observed. As illustrated in Fig. 11, this cavity was created by the erosion of silicon nitride debris during grinding. Similar observation has been reported in superabrasive grinding [5]. Another diamond, not shown in Fig. 9(c), was studied using the stereo SEM. As shown in Fig. 10(b), this diamond, marked by b, is protruding over the wear flat by about 13 μm.

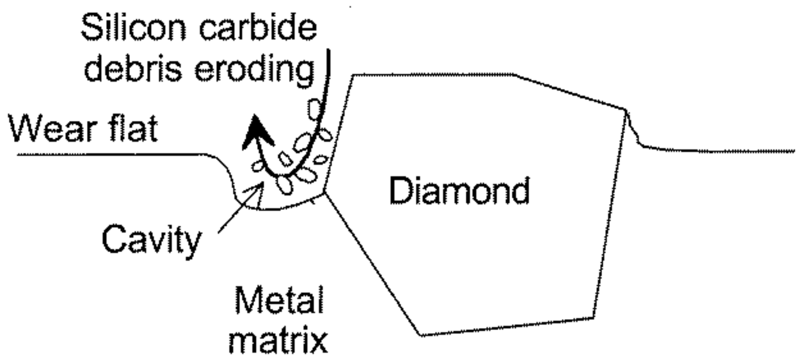



Fig. 11. The erosion of debris in front of the diamond to creative a cavity.

**7. Discussion and Concluding Remarks**

The stereo SEM was used as a measurement tool to examine the surface of metal bond diamond wheel. A wedge-shape removal part was cut on the grinding wheel. Grinding tests were conducted to create three distinct conditions: 1. after the wire EDM truing before grinding, 2. after a single pass light grinding of the silicon nitride, and 3. after 100 passes of heavy grinding the silicon nitride, on this removal part. The stereo SEM, which had been calibrated by measuring a wear grove and validated the results by comparing with profilometer measurements, was used to measure the height of diamond protrusion in these three conditions.

The stereo SEM measurement results showed that, after the wire EDM, some diamonds were protruding a large distance, about 30 μm, above the surrounding metal bond. Such diamond height is over half of the 54 μm average size of the diamond grain. These over-protruded diamond grains have weak bonds to the wheel, and are expected to fracture immediately at the start of the light grinding of ceramics. The fracture of these diamond grains create high initial wheel wear. The advantage of wire EDM truing of metal bond diamond wheel is the capability to generate intricate and precise profiles on the wheel surface for form grinding. It is possible that, during the wire EDM truing process, the desired form was preserved on the metal bond, slightly below the tip of the over-protruding diamond grains. This is especially important for form grinding of miniature features. More studies are required to conclude this hypothesis.

Benefits of using the stereo SEM as a measurement tool is demonstrated in this study. The profiles presented in this study are very difficult to quantify using the contact profilometer method. The stereo SEM method can be applied to other research areas to study the topography of rough surfaces that are difficult to quantify by the stylus contact probing method.


**Acknowledgements**

The authors gratefully acknowledge the support by National Science Foundation Grant #9983582 (Dr. K. P. Rajurkar, Program Director). Portion of this research was sponsored by the User program of the High Temperature Material Lab, Oak Ridge National Lab.


**References:**


1. J. H. Lee and J. C. Russ, Metrology of microelectronic devices by stereo SEM, J Comput Assisted Microsc. v 1 n 1 Mar 1989, p 79-90.
2. K. Syoji, L. Zhou, and S. Matsui, Studies on truing and dressing of diamond wheels (1st report). The measurement of protrusion height of abrasive grains by using a stereo pair and the influence of protrusion height on grinding performance, Bull Jpn Soc Precis Eng. v 24 n 2 Jun 1990, p 124-129.
3. X. Zhao, K. Syoji, T. Kuriyagawa, and L. Zhou, Truing of resinoid-bonded CBN wheels (1st report, cutting edge shape after truing), Transactions of the Japan Society of Mechanical Engineers, Part C. v 62 n 601 (1996) 3725-3730.
4. B. K. Rhoney, A. J. Shih, R. O. Scattergood, R. Ott, and S. B. McSpadden, Cylindrical wire electrical discharge machining of metal bond diamond wheels – part I: truing, grinding, and wear measurement, Wear (submitted).

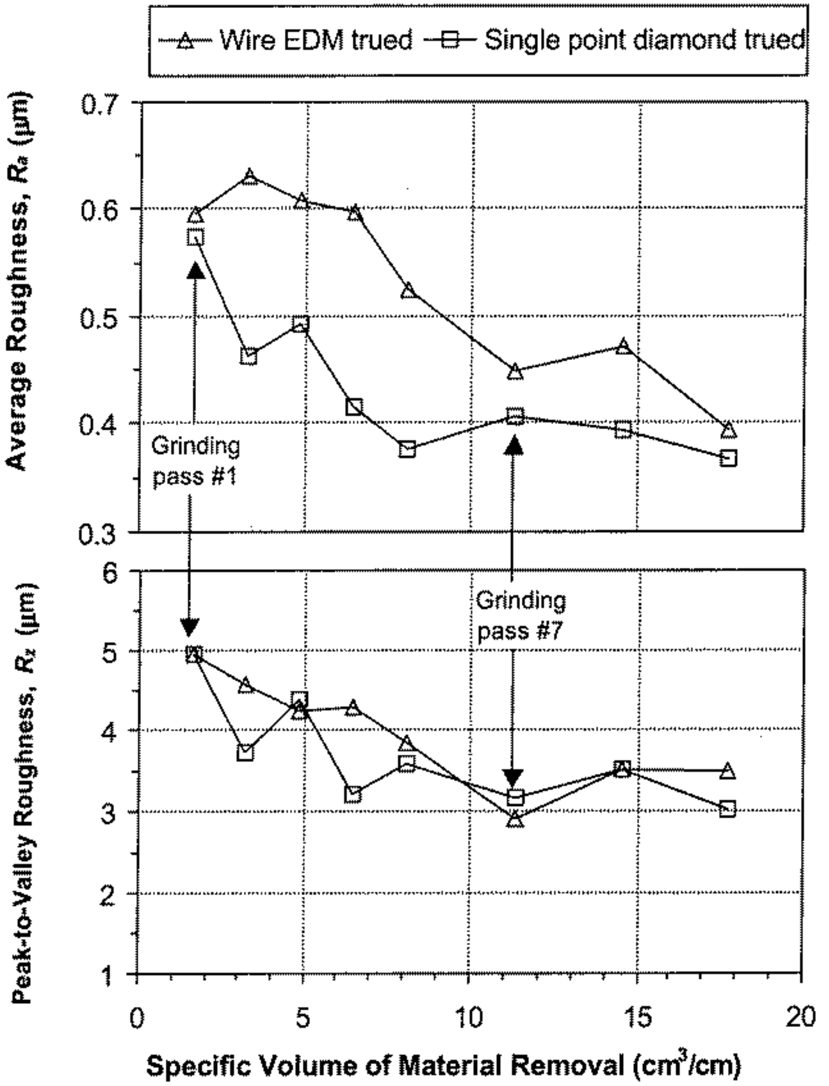



Fig. 10. Average and peak-to-valley surface roughness of ground silicon nitride samples.