ELSEVIER

Wear 252 (2002) 644–653

WEAR

www.elsevier.com/locate/wear

Wear mechanism of metal bond diamond wheels trued by wire electrical discharge machining

Brian K. Rhoney [a], Albert J. Shih [a,*], Ronald O. Scattergood [b], Ronald Ott [c], Samuel B. McSpadden [c]

[a] Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, USA
[b] Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC 27695, USA
[c] High Temperature Materials Laboratory, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Received 9 July 2001; received in revised form 15 January 2002; accepted 23 January 2002

Abstract

The stereographic scanning electron microscopy (SEM) imaging was used to investigate the wear mechanism in wire electrical discharge machining (EDM) truing of metal bond diamond wheels for ceramic grinding. A piece of the grinding wheel was removed after truing and grinding to enable the examination of wheel surface and measurement of diamond protrusion heights using a SEM and stereographic imaging software. The stereographic SEM imaging method was calibrated by comparing with the profilometer measurement results. On the wheel surface after wire EDM truing and before grinding, some diamond grain protruding heights were measured in the 32 μm level. Comparing to the 54 μm average size of the diamond grain, this indicated that over half of the diamond was exposed. During the wire EDM process, electrical sparks occur between the metal bond and EDM wire, which leaves the diamond protruded in the gap between the wire electrode and wheel. These protruding diamond grains with weak bond to the wheel were fractured under a light grinding condition. After heavy grinding, the diamond protrusion heights were estimated in the 5–15 μm range above the wear flat. A cavity created by grinding debris erosion wear of the wheel bond could be identified around the diamond grain. © 2002 Published by Elsevier Science B.V.

Keywords: Scanning electron microscopy (SEM); Diamond wheels; Electrical discharge machining (EDM); Grinding wheel wear

1. Introduction

Diamond wheels are used extensively in grinding of engineering ceramics for structural and electronic applications. To achieve the desired form accuracy and surface integrity on ground parts, diamond wheels are usually wear-resistant and difficult to shape or true to the desired geometry [1]. The electrical discharge machining (EDM) process has been applied to generate the precise form on metal bond diamond wheels using either the die-sink [2–7] or wire [8] EDM configurations. At the start of grinding, a high wheel wear rate was observed on metal bond diamond wheels trued by the EDM process. The wheel wear rate was significantly lower in subsequent grinding [8]. The goal of this research is to study the wear mechanism of the wire EDM trued diamond wheels for ceramic grinding.

Advancements in three-dimensional stereo image analysis using the scanning electron microscopy (SEM) have made it an ideal tool to examine the surface topography of metal bond diamond wheels. By applying computer image analysis to a pair of SEM images, a topographic representation of the grinding wheel surface can be obtained. The height of diamond protrusion from the wheel surface after wire EDM truing and after grinding can be quantified using the stereographic SEM imaging analysis. SEM examinations of grinding wheel surfaces and comparison of diamond protrusion heights at different levels of grinding can reveal the wear mechanism for wire EDM trued metal bond diamond wheels.

An early application of stereographic SEM imaging method was presented by Lee and Russ [9] for the metrology of microelectronic devices. Syoji et al. [10] applied the stereographic SEM imaging 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. [11] used the stereographic SEM imaging 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 an electrically conductive metal bond and the non-electrically conductive diamond grain. During the EDM truing, electrical sparks are generated around the diamond to erode the metal bond and cause the whole diamond grain to fall out from the

* Corresponding author. Tel.: +1-919-515-5260; fax: +1-919-515-7968.
E-mail address: ajshih@eos.ncsu.edu (A.J. Shih).

0043-1648/02/$ – see front matter © 2002 Published by Elsevier Science B.V.
PII: S0043-1648(02)00019-4

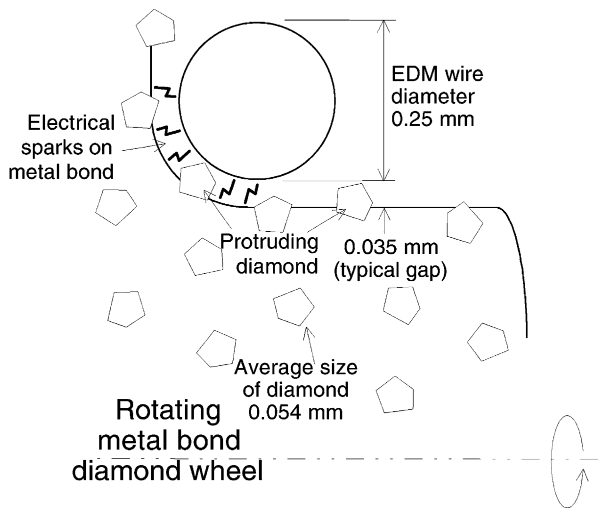

Fig. 1. Schematic illustration of the EDM wire, rotating diamond wheel, the gap between wire and wheel, and the protrusion of the diamond grains on the wheel surface.

wheel surface [8]. During the wire EDM process, as shown in Fig. 1, a gap in the 35 μm level exists between the wire electrode and rotating diamond wheel. The diamond grain protrudes out of the wheel surface by a height close to or slightly less than the gap distance. This theory is examined by using the stereographic SEM imaging to measure the diamond protrusion height on wheel surface.

In this paper, the preparation of the diamond wheel surface with different conditions for SEM study is first introduced. The procedures for using the SEM to generate three-dimensional topographical data and calibrating the stereographic SEM measurement are then presented. Three conditions of the wheel surface:

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

are prepared and quantified using the stereographic SEM imaging method. A wheel wear mechanism was proposed based on the observation.

2. Grinding wheel preparation

The 200 mm diameter grinding wheel was too big to be observed using the SEM. After grinding, a piece on the wheel surface, as shown in the front view Fig. 2, was removed from the wheel and examined using the SEM. The truing of the grinding wheel was conducted using a Brother 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 the 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 $mm^3/mm\,s$. 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 the side view Fig. 2. Workpiece #2 was ground by 99 passes, each with 0.127 mm down feed, to wear the left section of the wheel in the side view by heavy grinding. The t_2 in Fig. 2 was 12.573 mm.

In summary, three areas were generated on the wheel surface. These three areas were: (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.

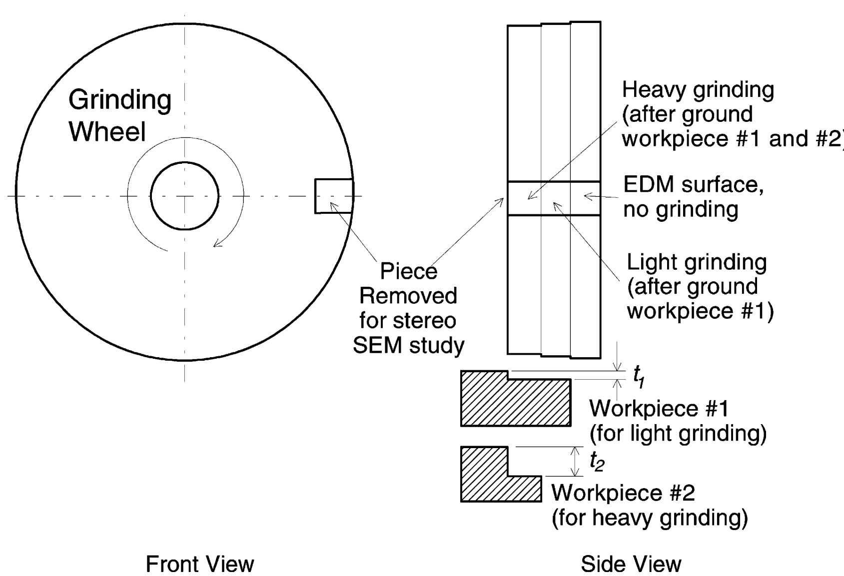

Fig. 2. The grinding wheel surface and the preparation of three areas with different levels of truing and grinding for stereographic SEM imaging study.

3. Stereo scanning electron microscope

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

3.1. Procedure for stereo SEM

A 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 were required for constructing a three-dimensional topographic image of the surface. First, an SEM image of the surface was taken with the stage set at zero degree tilt. A feature that could be relocated again, once the table was tilted, was then marked on the image. Once this feature was identified, the stage was tilted by a specific small angle, two degrees in this case. Another SEM image was taken. This image was 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 could be combined using the Alicona^{TM} imaging software to construct a three-dimensional image of the surface. Several line segments were drawn on the SEM image and the software calculated and created a chart to show the change in height on pixels along these line segments.

3.2. Calibration

As shown in Fig. 3, a wear groove about 200 μm wide and 12 μm deep was used as a standard sample to calibrate the stereographic SEM imaging method. The SEM micrograph of the groove and a line segment across the groove are shown in Fig. 3a. The procedure presented in Section 3.1 was applied to generate the stereo representation of the surface, as shown in Fig. 3b. The same groove was also measured using the Talysurf profilometer with diamond tip contact stylus. Comparisons of these two measurement results are shown in Fig. 3c. The two closely matched traces verified and calibrated the stereographic SEM measurement used in this study.

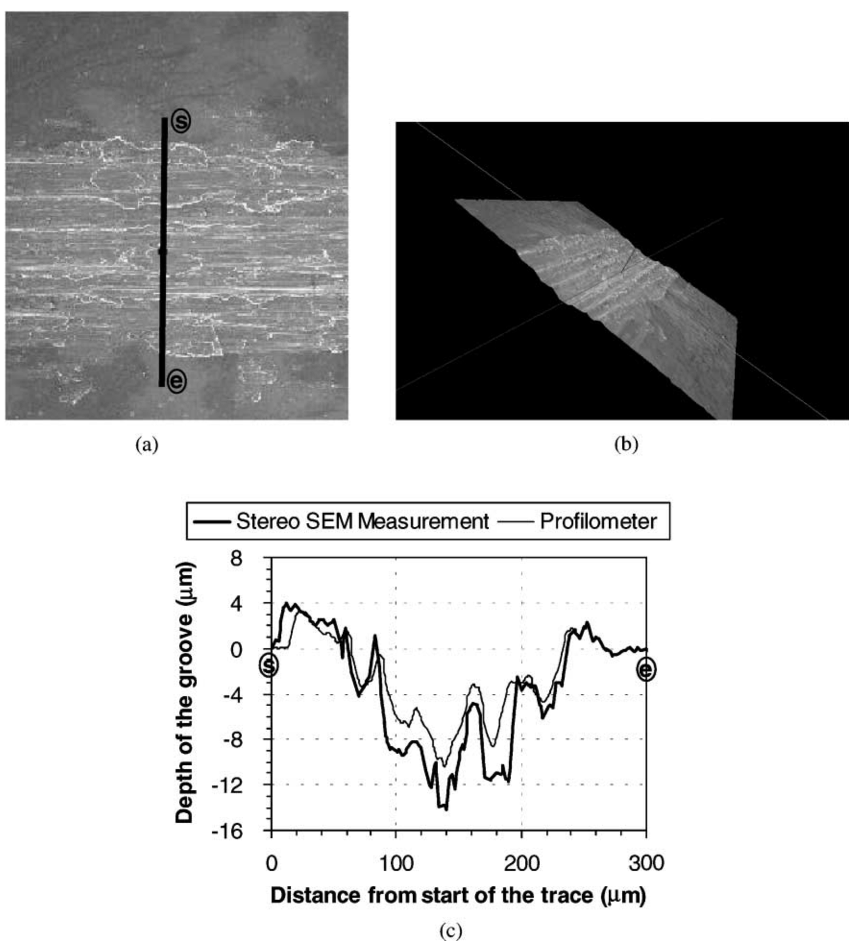

Fig. 3. Calibration of the stereographic SEM measurement method using a wear groove: (a) SEM micrograph of the wear groove and the starting and ending points of a line segment, (b) stereo representation of the surface and (c) comparison of the wear groove measured using the Talysurf profilometer and stereographic SEM imaging methods.

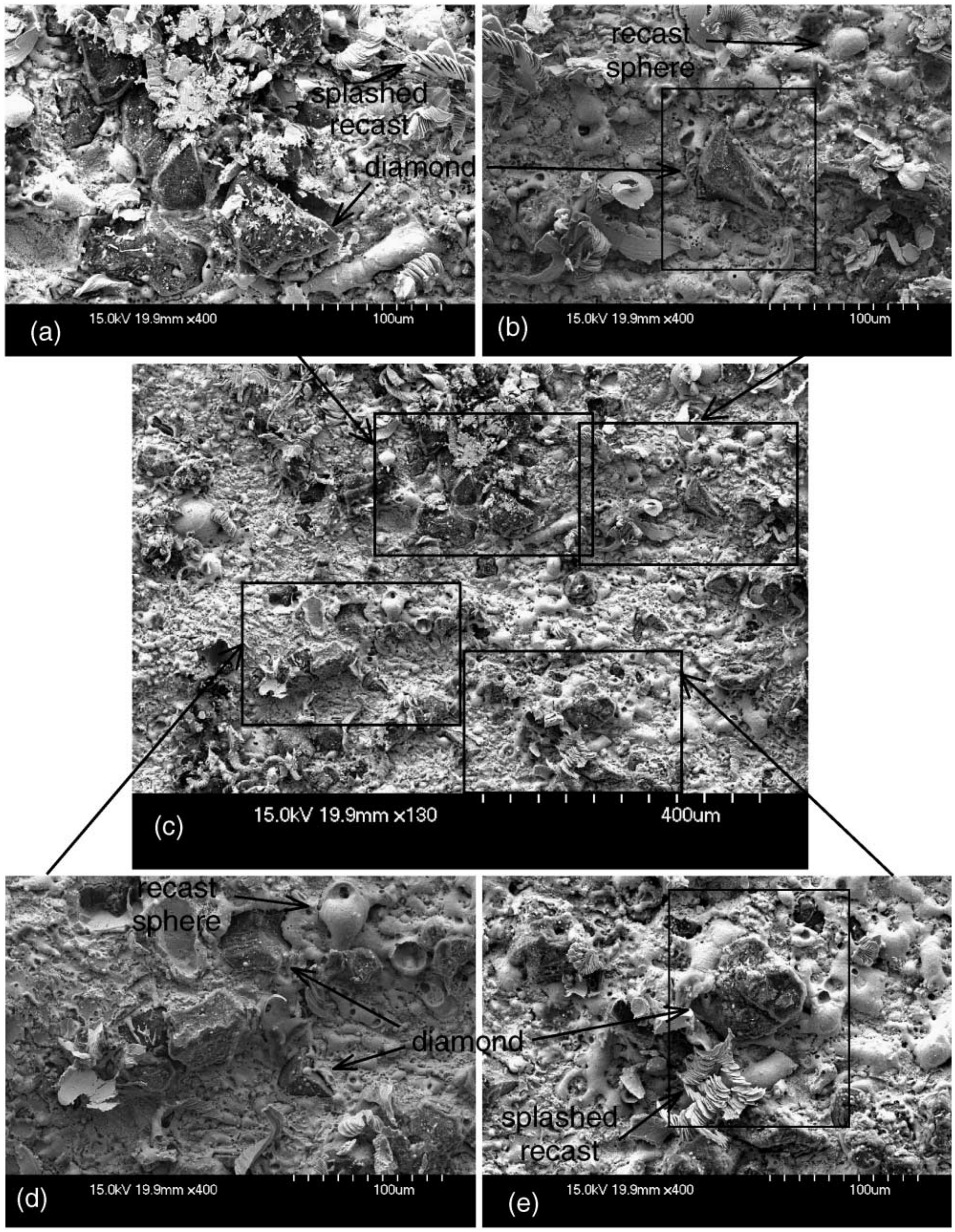

Fig. 4. (a–e) SEM micrographs of the grinding wheel surface after wire EDM without grinding.

4. Diamond wheel surface after wire EDM truing

The first area to be observed using stereographic SEM imaging was the wheel surface after EDM truing without grinding. SEM micrographs of the wheel surface are shown in Fig. 4. As shown in the overall view in Fig. 4c, the surface was rough with sparsely and evenly distributed diamond grains. Some metal bond material has been resolidified or recasted to the wheel surface. It is noted that these recasts are strongly bonded to the wheel surface, despite the use of a high-pressure jet of deionized water during wire EDM truing and the ultrasonic cleaning before examining in 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 Fig. 4b and d. The second type is the splashed recast, as shown by examples in Fig. 4a and e. The splash in Fig. 4e is further magnified in Fig. 5a. This type of recast is possibly due to the collision of the single spark eroded molten metal with the diamond and then splashing and resolidifying layer-by-layer on the surface close to a diamond grain. Figs. 4e and 5a show that several layers of splashed recast can occur. This indicates that the splash occurs at different time during the

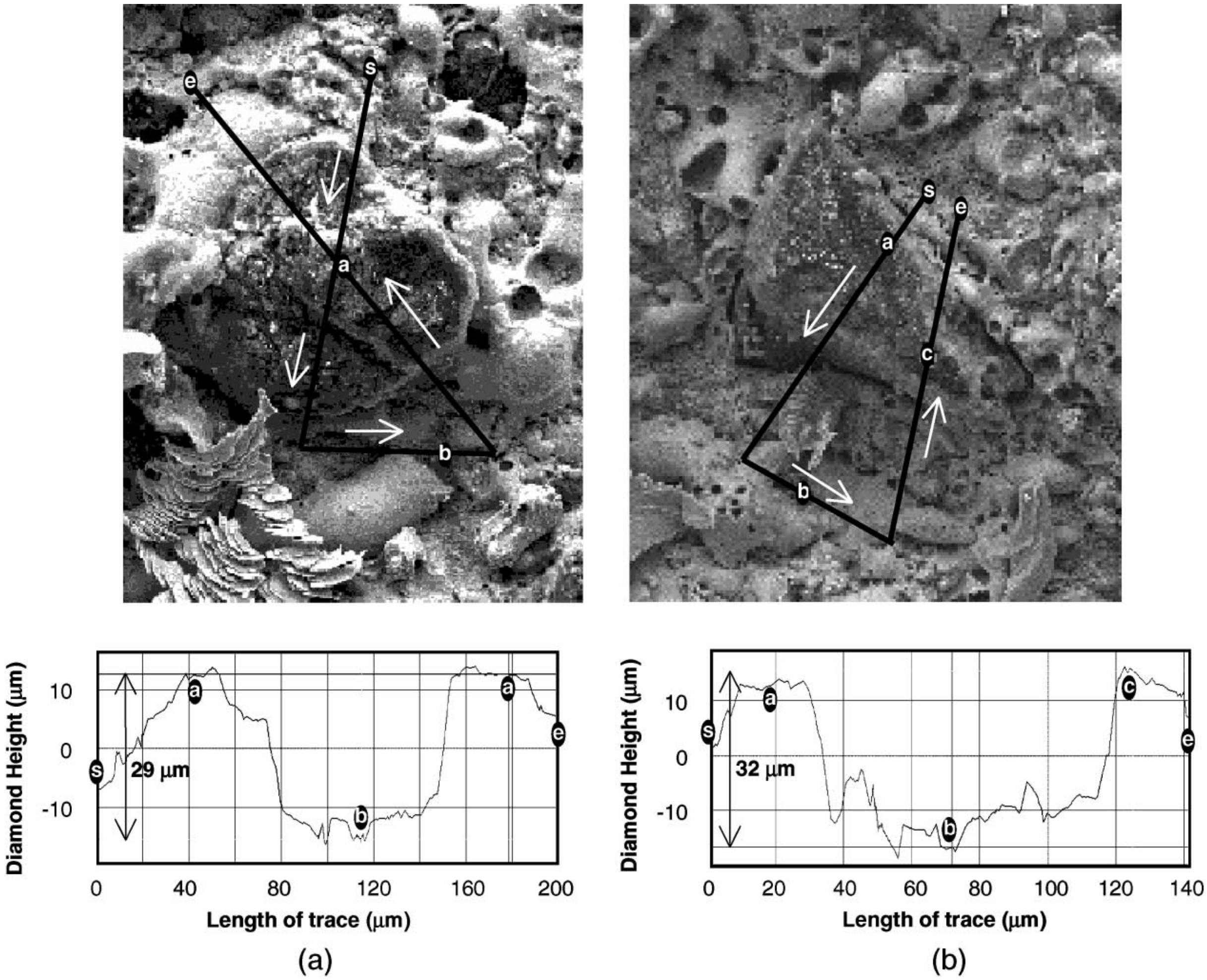

Fig. 5. The height of diamond protrusion on the wire EDM wheel surface without grinding: (a) the diamond grain in Fig. 4e and (b) the diamond grain in Fig. 4b.

wire EDM truing. Besides these recasts, diamond grains exposed out of the wheel surface can also be observed. The protrusion height of these diamond grains is measured using the stereographic SEM imaging method.

Fig. 5a shows the enlarged view of the diamond grain in Fig. 4e. Three line segments were selected on the SEM image to measure the protrusion height of the diamond grain. The Alicona^{TM} three-dimensional imaging software was used to construct a stereo image of this surface and to calculate the variation of height along pixels on these three line segments. The measurement trace starts from a point marked by s and ends at the point e. Two or three other points, marked by a–c, are used as the intermediate markers to link the position on measured height trace to the point on SEM image.

Results of the height variation are shown in the trace below SEM micrographs. The diamond grain in Fig. 5a protrudes over the surrounding metal matrix by about 29 μm. Fig. 5b shows another diamond grain, the one boxed in Fig. 4b, protruding out of the surrounding surface by about 32 μm.

The average size of the 325 ANSI mesh diamond grain in the wheel is about 54 μm. Results in Fig. 5 indicate that after wire EDM truing, many diamond grains on wheel surface have exposed over half of their size outside the surrounding metal bond. Section 5 will show that these over-protruded diamond grains are expected to fracture or pull out of the wheel surface after light grinding. It is noted that not all the diamond grains are protruding in the 30 μm level. Other diamond protrusion heights, in the range of 6–20 μm, have been measured. Some of these diamond grains may not be fractured and become active for material removal during grinding.

The hypothesis of the fracture of over-protruded diamond grains after light grinding can support the wear measurement results presented in the wheel wear study [8]. The initially high wear rate on the wire EDM trued metal bond diamond wheel surface can be caused by the fracture of over-protruding diamond grains. Fig. 5a and b also demonstrate the advantage of using the stereographic SEM as a metrology tool to quantify the diamond protrusion height on grinding wheel surface.

5. Wear of the diamond wheel surface after light grinding

SEM micrographs of the wheel surface after one pass grinding of silicon nitride with 0.127 mm down feed are shown in Fig. 6. The spherical and splashed recasts, which originally bonded to the wheel surface after EDM truing, were mostly disappeared. Some diamond grains had been pulled out and left a cavity on the wheel surface, as indicated in Fig. 6c and e. Some of the diamond grains exhibited fractured surfaces, such as those marked in Fig. 6a and b. Wear flat areas on the metal bond, such as those shown in Fig. 6a and c–e, were created after light grinding. These wear flats were used as the datum for stereographic SEM measurement of diamond protrusion heights.

Fig. 7 shows results of two diamond protrusion height measurements. The starting point of the line, marked by s, was located on a wear flat, which was set as the datum for measurement. The straight-line segment in Fig. 7a crossed the two diamond grains shown in Fig. 6d. The first diamond grain, marked by b, had about the same height as the wear flat. The second diamond grain, marked by c, was about

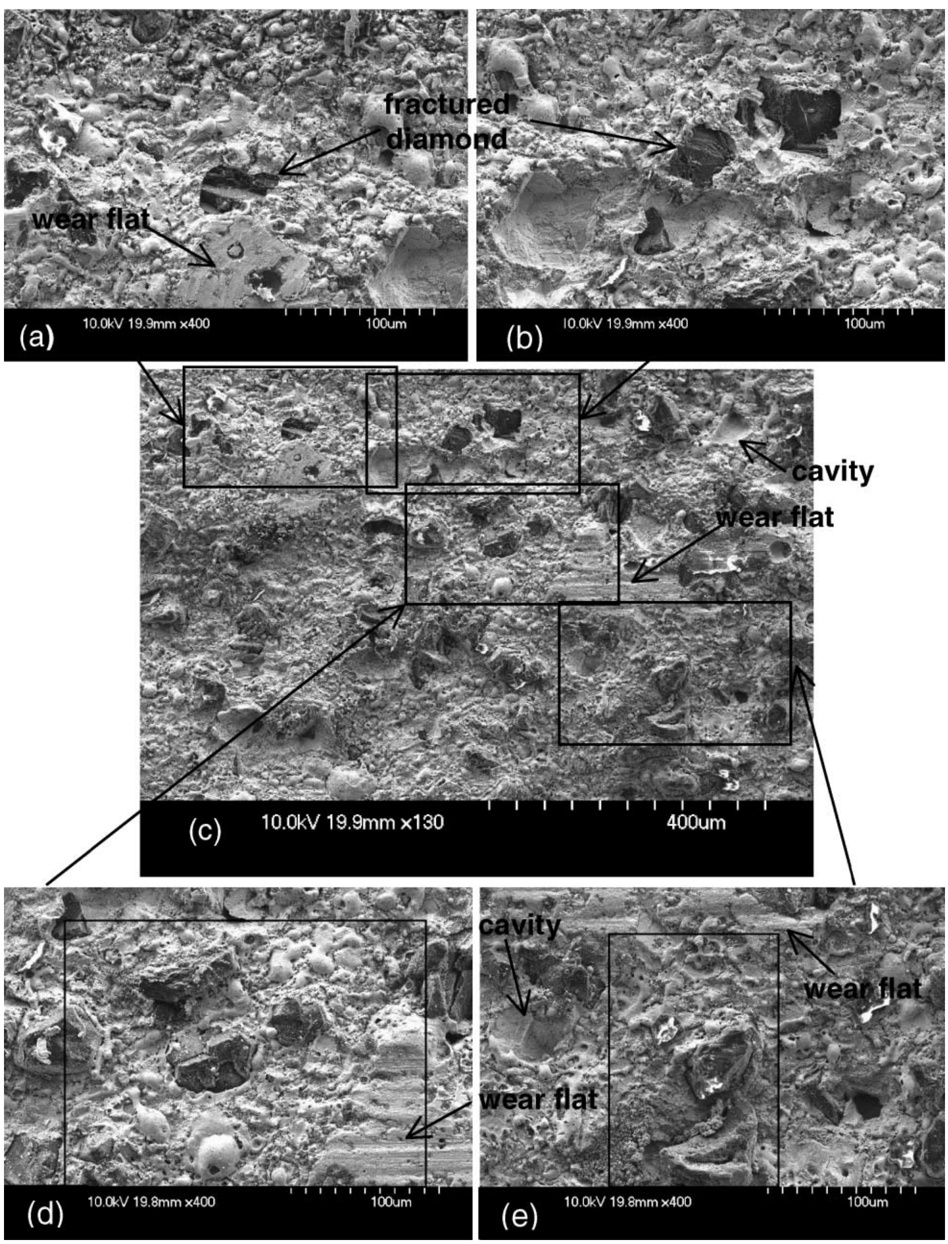

Fig. 6. (a–e) SEM micrographs of the wheel surface after light grinding.

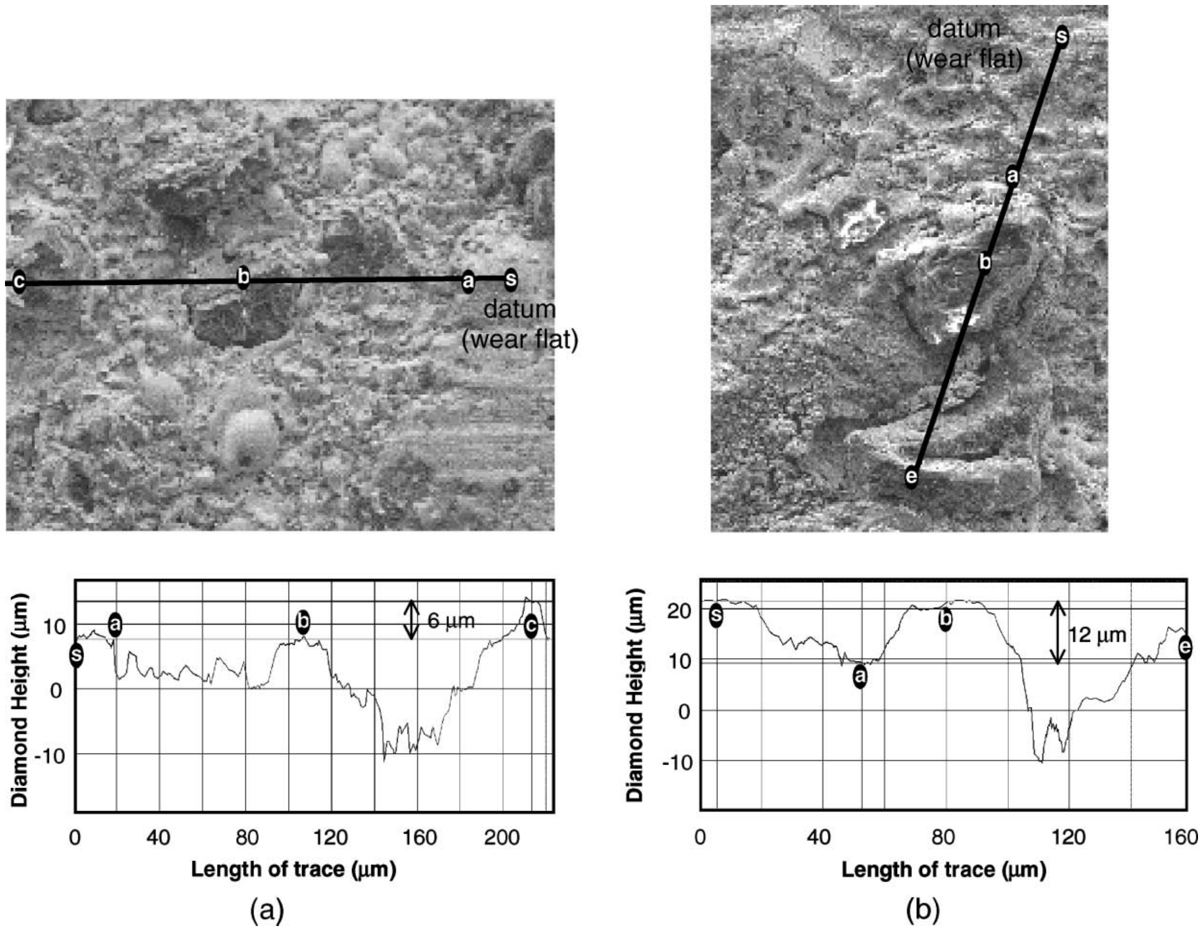

Fig. 7. The height of diamond protrusion on the wheel surface after light grinding: (a) the two diamond grains in Fig. 6d and (b) the diamond grain in Fig. 6e.

6 μm above the wear flat. Both diamond grains showed rub marks on the surface and appeared to be active in grinding. Another example illustrated the active diamond grain in Fig. 6e, which is marked as point b in Fig. 7b, had about the same height as the datum wear flat surface. Fig. 7 and other measurement traces on the wheel surface after light grinding concluded diamond grains protruding above the wear flat by about 6–12 μm after light grinding.

6. Wear of the diamond wheel surface after heavy grinding

The wheel surface after 100 grinding passes of 0.127 mm down feed, or 100 times more work-material removed than the light grinding presented in Section 5, was studied. SEM micrographs of the wheel surface after such heavy grinding are shown in Fig. 8. Comparing to Fig. 6c, relatively larger wear flat areas could be seen in Fig. 8c. The cavity created by diamond grain pull out, as indicated in Fig. 8b and c, could be identified.

The diamond grain located in the middle of a large wear flat area shown in Fig. 8b was studied using the stereographic SEM imaging method. Fig. 9a showed a line starting and ending both on the wear flat. The diamond grain, indicated by b, was protruding about 5 μm over the wear flat. A cavity in front of the diamond grain, about 4 μm deep, could be observed. As illustrated in Fig. 10, the grinding debris eroded the bond in front of the diamond grain during grinding and generated a cavity. For grinding ceramics, the use of debris for erosion wear of the wheel bond in front of diamond grain has been reported [12]. This is a technology to self-dress or self-sharpen of wheels for efficient grinding of ceramics.

Another diamond grain, not shown in Fig. 8, was studied using the stereographic SEM imaging method. As shown in Fig. 9b, this diamond grain, marked by b, is protruding over the wear flat by about 13 μm. A cavity in front of this diamond grain could also be identified in Fig. 9b. Fig. 9 and other measurements showed diamond grains are protruding about 5–15 μm above the wear flat after heavy grinding.

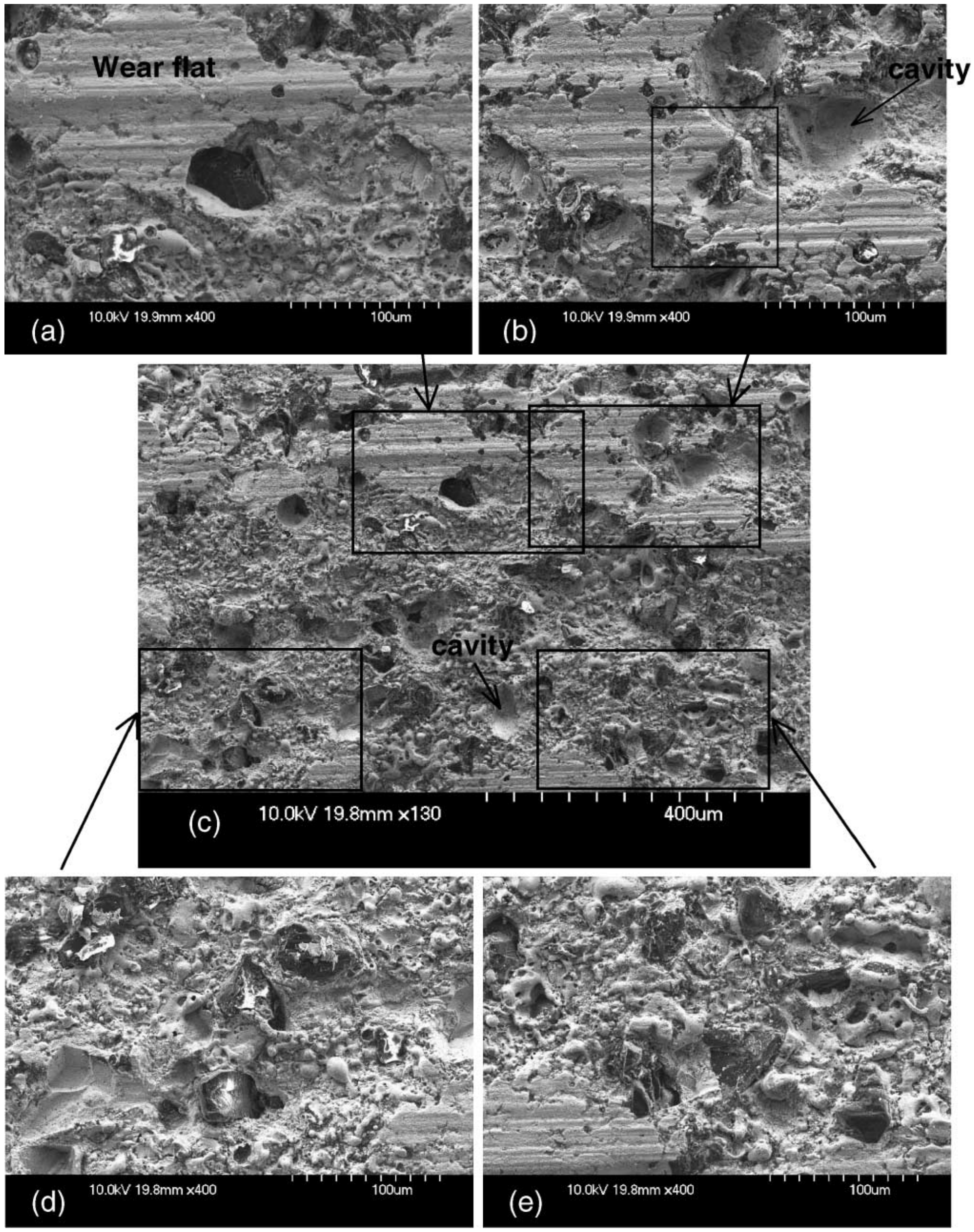

Fig. 8. (a–e) SEM micrographs of the wheel surface after heavy grinding.

7. Discussion and concluding remarks

The stereographic SEM imaging method was used as a measurement tool to examine the surface of a metal bond diamond wheel. Grinding tests were conducted to create three distinct conditions: (1) after wire EDM truing before grinding, (2) after a single pass of light grinding of the silicon nitride and (3) after 100 passes of heavy grinding the silicon nitride, on the diamond wheel surface. The stereographic SEM imaging method, which had been calibrated by validating with profilometer measurements, was used to study the diamond grain protrusion heights in these three conditions.

The stereographic SEM imaging measurement results showed that, after the wire EDM process, some diamond grains were protruding extensively, 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 do not bond strongly to the wheel and are fractured under the light grinding condition. The fracture of these diamond grains creates the initial high wheel wear rate [8]. The advantage of wire EDM truing of metal bond diamond wheel is the capability to generate intricate and precise profiles for form grinding. It is possible that, during the wire EDM truing process, the desired form is preserved on the metal bond, slightly

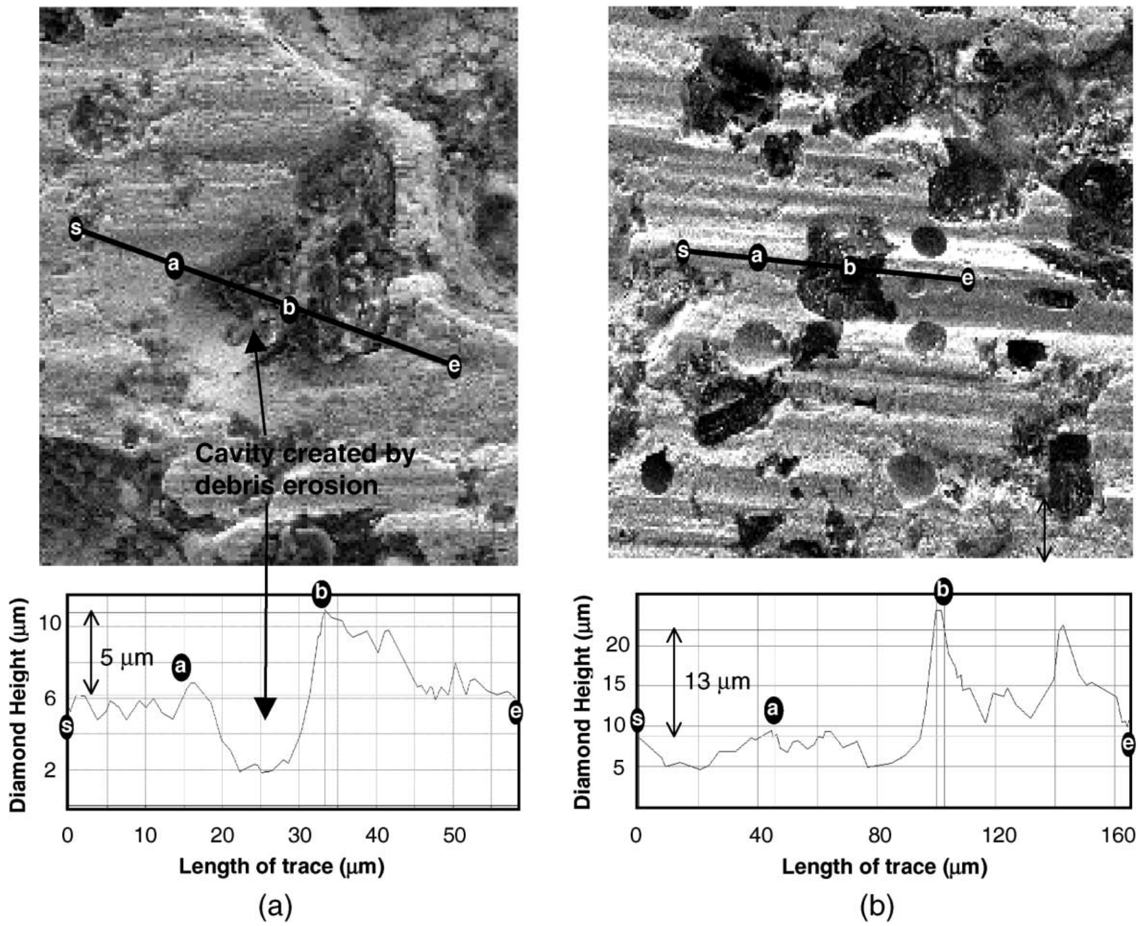

Fig. 9. The height of diamond protrusion on the wheel surface after heavy grinding: (a) the diamond grain in Fig. 8b and (b) a diamond grain protruded from the wear flat.

below the tip of over-protruding diamond grains. This is especially important for the precision form grinding using EDM trued diamond wheels. More studies are required to further validate this hypothesis.

Benefits of using the stereographic SEM imaging as a measurement tool have been demonstrated in this study. Heights of diamond protrusion are very difficult to quantify using the contact profilometer method. The stereographic SEM imaging method can be applied to other research areas to study the topography of rough surfaces that are either too small or difficult to be measured using the stylus contact probing method.

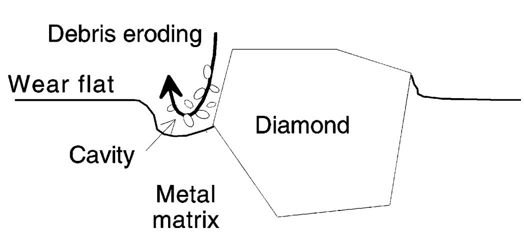

Fig. 10. The grinding debris erosion of a cavity in front of the diamond grain.

Acknowledgements

The authors gratefully acknowledge the support by National Science Foundation Grant #9983582 (Dr. K.P. Rajurkar, Program Director). Support for this research was also provided by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the High Temperature Materials Laboratory User Program, Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the US Department of Energy under Contract no. DE-AC05-00OR22725.

References

[1] A.J. Shih, Rotary truing of the vitreous bond diamond grinding wheels using metal bond diamond disks, Machining Sci. Technol. 2 (1998) 13–28.

[2] K. Suzuki, T. Uematsu, T. Nakagawa, On-machine truing/dressing of metal bond diamond grinding wheels by electro-discharge machining, Ann. CIRP 36 (1) (1987) 115–118.

[3] K. Suzuki, T. Uematsu, T. Yanase, T. Nakagawa, On-machine electro-discharge truing for metal bond diamond grinding wheels for ceramics, in: S. Jahanmir (Ed.), Proceedings of the International

Conference on Machining of Advanced Materials, NIST Special Publication 847, Gaithersburg, MD, 20–22 July 1993, pp. 83–88.
[4] X. Wang, B. Ying, W. Liu, EDM dressing of fine grain super abrasive grinding wheel, J. Mater. Process. Technol. 62 (1996) 299–302.
[5] K. Sato, T. Yokoyama, K. Suzuki, Production of electrodeposited diamond wheels and grinding performance for hard metals and ceramics, J. Mater. Process. Technol. 62 (1996) 303–308.
[6] J. Qian, W. Li, H. Ohmori, Precision internal grinding with a metal-bonded diamond grinding wheel, J. Mater. Process. Technol. 105 (2000) 80–86.
[7] C. Zhang, H. Ohmori, W. Li, Small-hole machining of ceramic material with electrolytic interval-dressing (ELID-II) grinding, J. Mater. Process. Technol. 105 (2000) 284–289.
[8] B.K. Rhoney, A.J. Shih, R.O. Scattergood, J.L. Akemon, D.J. Gust, M.B. Grant, Cylindrical wire electrical discharge machining of metal bond diamond wheels, Int. J. Machine Tool Manufac., in press.
[9] J.H. Lee, J.C. Russ, Metrology of microelectronic devices by stereo SEM, J. Comput. Assisted Microsc. 1 (1) (1989) 79–90.
[10] K. Syoji, L. Zhou, 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. 24 (2) (1990) 124–129.
[11] X. Zhao, K. Syoji, T. Kuriyagawa, L. Zhou, Truing of resinoid-bonded CBN wheels (1st report, cutting edge shape after truing), Trans. Jpn. Soc. Mech. Eng. Part C 62 (601) (1996) 3725–3730.
[12] A.J. Shih, T.M. Yonushonis, High infeed rate method for grinding ceramic workpiece with silicon carbide grinding wheels, US Patent 6,030,277 (2000).