Pergamon

International Journal of Machine Tools & Manufacture 42 (2002) 1355–1362

INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION

Wire electrical discharge machining of metal bond diamond wheels for ceramic grinding

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Received 11 January 2002; received in revised form 30 April 2002; accepted 1 May 2002

Abstract

The application of cylindrical wire Electrical Discharge Machining (EDM) for profile truing of metal bond diamond wheels is presented. Instead of using the mechanical force to break the diamond and matrix in the grinding wheel, the wire EDM process uses the thermal energy or electrical sparks between the wire and rotating grinding wheel to remove the metal bond and form the wheel. The design and manufacture of a corrosion-resistant, precise spindle with the high-electrical current capability for wire EDM truing of grinding wheel is first introduced. Three truing configurations were designed to study effects of wire EDM process parameters and to investigate the level of form accuracy and corner radii achievable by the wire EDM truing of diamond wheels. Results show that the wire EDM process can efficiently generate the μm-scale precision form on the diamond wheels. The wheel, after truing, was used to grind the silicon nitride workpiece. Grinding forces and wheel wear rate were measured. In the beginning of the grinding, high wheel wear rate was identified. The subsequent wheel wear rate was considerably lower and stabilized. © 2002 Published by Elsevier Science Ltd.

1. Introduction

As applications of engineering ceramics broadened, the shape of these parts has become more complicated and the form tolerance specifications are more stringent [1]. An efficient and cost–effective method to grind a ceramic component with a complicated shape is to generate the desired form on a diamond grinding wheel and then plunge the shaped wheel into the ceramic workpiece. The excess ceramic work-material is removed by the diamond grinding wheel, and the desired form is generated on the workpiece. Based on this approach, the technical challenge has shifted from grinding the workpiece to shaping and conditioning, or truing and dressing, the diamond grinding wheel. This study investigates the wire Electrical Discharge Machining (EDM) of a rotating metal bond diamond wheel for ceramic grinding.

The ceramic work-materials are hard, brittle, and difficult-to-machine. The inherent difficulties arise from the very advantage these materials impart to a wide range of industrial applications: extreme hardness resulting in superior wear resistance during use. As the work-material becomes harder, so should the abrasive used in the grinding wheel to achieve the desired form tolerances and surface integrity on engineering ceramics. Diamond, the hardest material, has become the primary abrasive for ceramic grinding applications.

Traditionally, a stationary or rotary diamond tool is used to true a grinding wheel to generate the desired form. Shih [2] has studied the wear of the rotary diamond tool for truing of a vitreous bond diamond grinding wheel and demonstrated that the wear of diamond tool is significant under a wide range of process parameters. Instead of using the mechanical force to break the diamond, the wire EDM process uses the thermal energy or electrical sparks between a thin, traveling wire and the rotating grinding wheel to remove the metal bond on the grinding wheel surface. Three most popular grinding wheel bonding systems are: metal, resin, and vitreous. The EDM process requires the workpiece, in

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PII: S0890-6955(02)00056-1

this case the diamond grinding wheel, to be electrically conductive. Metal is the bonding system that satisfies such requirement.

The configuration of wire EDM truing is illustrated in Fig. 1(a). The relative motion between the grinding wheel and traveling wire is controlled by X and Y slides in a two-axis wire EDM machine to generate the intricate form on a rotating metal bond diamond wheel. Top view of the trajectory of the wire and the form generated on the wheel is shown in Fig. 1(b). The idea of using the wire EDM to machine cylindrical parts has been reported by Dr. Masuzawa and his colleagues [3–9]. These research activities were focused on manufacturing small-diameter pins, which can be used as a tool for the micro-EDM [10,11]. Qu et al. [12] has studied the use of cylindrical wire EDM for high material removal rate machining of carbide and brass cylindrical parts. Besides the wire EDM, the die-sinking EDM can also be used for truing metal bond diamond wheels [13–18]. The survey found the lack of research to study the level of form accuracy and corner radius achievable by the wire EDM truing of metal bond diamond wheels. The information on EDM process parameters for wire EDM truing of metal bond diamond wheels is not readily available. There is also lacking the wear and grinding performance data of EDM trued metal bond diamond wheels. All these become the objectives of this research.

In this study, the design of a flexible, corrosion resistant, and precise spindle suitable for truing the metal bond grinding wheel is first introduced. The study of the wire EDM truing of metal bond diamond wheel, which includes the adjustment of EDM parameters, form accuracy, and corner radii, are then presented. Results of grinding of silicon nitride ceramics using the EDM trued diamond wheel, which include the wheel wear, grinding forces, and surface finish on ground parts, are discussed.

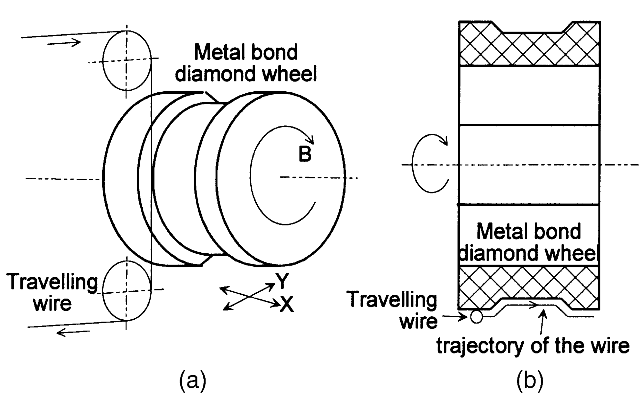

Fig. 1. Wire EDM of metal bond diamond wheel, (a) configuration of the operation, (b) top view of the trajectory of the wire.

2. Spindle design

A spindle, which has the deionized water spraying over it during the EDM, is used to drive the grinding wheel. Pictures of the spindle built for this study and its key components are shown in Fig. 2. This spindle must meet the following design criteria:

1. *Flexibility*: The spindle has to adapt different sizes of grinding wheel. As shown in Fig. 2, the tip of the spindle shaft is ground to have an angle to fit a standard wheel hub, which is used to adopt grinding wheels with different outside diameters and the same bore size.
2. *Corrosion Resistance*: Two deep-groove ball bearings with silicon nitride balls and stainless steel rings were used to support the shaft. All spindle components are made of water corrosion resistant materials, such as the stainless steel, plastic, or aluminum.
3. *Accuracy*: To maintain the consistent gap condition during EDM the grinding wheel, the runout error of the grinding wheel and spindle needs to be small. The angle at the tip of the spindle shaft is ground after the spindle is assembled to minimize the spindle error to less than 1 μm level.
4. *High Current Electrical Connection*: The wire EDM requires the pulsed high-current, high-voltage electrical connections between the rotating grinding wheel and the moving wire electrode. The back-wired carbon electrical brush is required for the electrical connection to the rotating grinding wheel.

The material removal rate in cylindrical wire EDM of metal bond diamond wheel was usually very slow. The motor was constantly running at low speed for a long period of time. An external cooling fan was necessary to enhance the motor heat dissipation. A seal was used on each side of the ball bearing to prevent the EDM debris entering the bearing housing. A round belt and two plastic pulleys were used to transmit power from the motor to spindle. Two spring preloaded carbon brushes with copper wire back wire were installed on each side of the shaft housing. Oxidation of the surfaces between the carbon brushes and shaft was a problem. An electrically conductive grease was applied to the brush contact surface on the shaft, and, periodically, the oxidized layer on the shaft needed to be removed.

3. Wire EDM truing the diamond wheel

The spindle was used to drive a 150 mm diameter, 13 mm wide Norton Scepter metal bond wheel with 325 grit size diamond. This wheel has proven to have outstanding performance [19]. The wheel truing test was conducted on a Mitsubishi Model CX-20 wire EDM machine with 0.25 mm diameter brass wire.

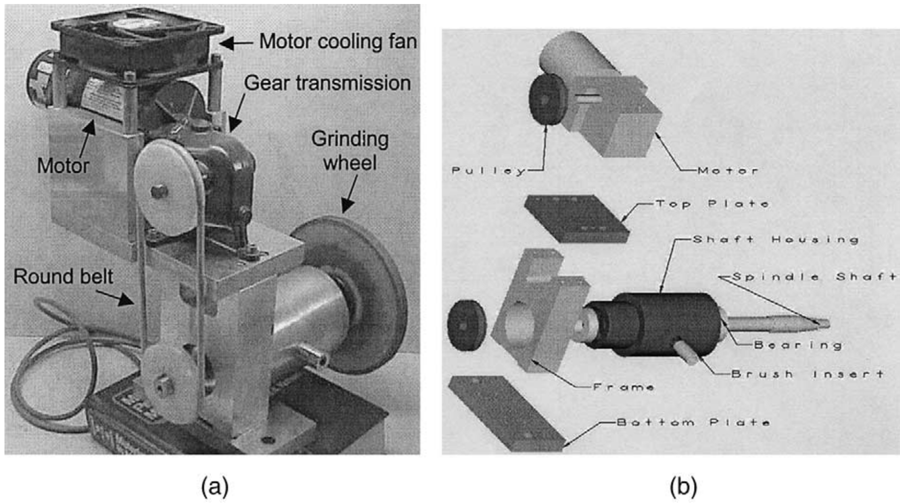

Fig. 2. Spindle design (a) picture of the spindle, (b) components of the spindle.

As shown in Fig. 3, three configurations were used for cylindrical wire EDM truing of metal bond diamond wheel. Each truing configuration had its purpose. The straight truing, as shown in Fig. 3(a), was applied to explore the feasible EDM parameters and generate the wheel profile for the subsequent grinding and wheel wear tests. Fig. 3(b) shows the two half circle arcs used to identify the level of form accuracy achievable by the wire EDM diamond wheels. The ability to generate small and consistent corner radii is an important requirement in form grinding of plungers and shafts for fuel systems. Fig. 3(c) illustrates the test configuration to determine the inner and outer corner radii on a wire EDM trued grinding wheel.

3.1. Adjustment of EDM process parameters

Each wire EDM machine has sets of recommended process parameters for different work-materials and thickness. For cylindrical wire EDM of the metal bond

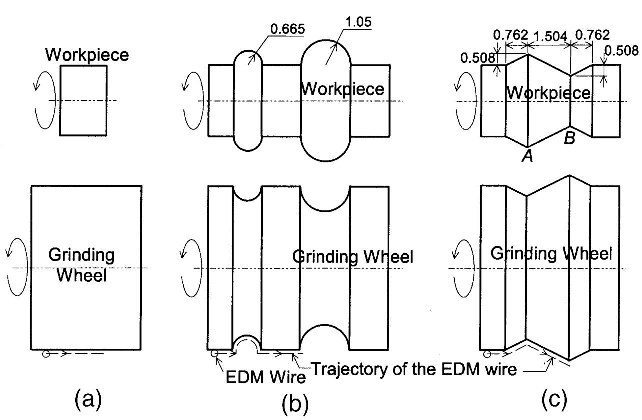

Fig. 3. Configurations used in truing tests (a) straight truing for grinding test, (b) two arcs for truing form accuracy evaluation, and (c) two angles for inner and outer radii evaluation.

diamond wheel, such process parameters are not available for reference. An existing set of wire EDM process parameters used for 6.35 mm thick copper was used as the baseline for modification. Three key process parameters were changed for the wire EDM of metal bond diamond wheel:

1. *Gap Voltage*: The gap voltage was increased from the default 35 to 70 V. By increasing the gap voltage, the distance between the wire and wheel is increased. The larger gap distance avoids the contact between the diamond and wire. If such contact occurs, the diamond, which is not electrically conductive, would abrade the wire.
2. *Spark Cycle Time:* The spark cycle time is the duration of each spark. This has been adjusted from 19 to 32 μs. This allows time for the wire to travel across the EDM area and prevent wire breakage, which was a problem during the wire EDM of metal bond diamond wheel. The pulse on-time, defined as the duration of the pulse in the spark cycle, remained at 12 μs.
3. *Wire Speed:* The wire speed was increased from 12 to 25 mm/s to reduce the possibility of wire breakage. The wire tension was set at 17.6 N.

3.2. Form accuracy of cylindrical wire EDM truing

The two-arc truing configuration shown in Fig. 3(b) was used to quantify the level of achievable form accuracy. The assembly of wheel and hub, after truing, was moved to a grinding machine with the same taper angle on the spindle for grinding tests. A machinable plastic part was ground to copy the form from the wheel to the part. During grinding, the wear of the wheel was negligible. After grinding the machinable plastic part, the same wheel was used to grinding a zirconia ceramic. Both arcs on the machinable plastic and zirconia parts were measured using a Form Talysurf with 0.5 mm ruby ball tip. A best-fit circular arc was used to match these data points. The deviation from the best-fit arc, denoted as W_t, was defined as the form error.

Table 1 summarizes measured profile form errors using either 0.08 or 0.25 mm cutoff length. The cutoff length is defined as the threshold wavelength for which below it the surface roughness data is removed. More data is removed at higher cutoff length, which, in general, generate a lower profile form error. There is no standard for the cutoff length for measuring the wire EDM profile form error. Therefore, two different cutoff lengths were used in this study to investigate their effect on form measurement. The deviation of the measured data from the best-fit circular arc is defined as the profile form error, W_t.

Results in Table 1 show the wire EDM process is capable of generating profile tolerances on the 10 μm-scale level. After grinding, the profile form error was reduced. This could be explained by the wheel wear mechanism [24] that protruded diamond grains on the wire EDM diamond wheel surface were fractured after grinding to restore a more precise form geometry. Results in Table 1 also show that lower form error can be seen at higher cutoff length and smaller arc radius. More study is necessary to optimize the wire EDM process parameters to further improve the form accuracy.

3.3. Corner radii generated in cylindrical wire EDM truing

The test configuration shown in Fig. 3(c) was used to find the small comer radii on parts ground by the wire EDM trued diamond wheel. After truing the diamond wheel, a zirconia ceramic part was ground and its two comer radii were measured. The outer comer radius on the part, marked by A in Fig. 3(c), was estimated as 180 μm and the inner comer radius, marked by B in Fig. 3(c), was measured as 82 μm. It is noted that the radius of the EDM wire plus the gap between the wire and workpiece limits the comer radius achievable at A.

Table 1
Form error of the two arcs in cylindrical wire EDM trued metal bond diamond wheel

Form error of arc profile, W_t (μm)			
Cutoff length (mm)		Arc radius (mm)	
		0.665	1.05
0.08	Before grinding	5.45	11.69
	After grinding	1.69	10.45
0.25	Before grinding	3.47	9.16
	After grinding	1.07	6.25

3.4. Analysis of the EDM debris

Fig. 4 shows the Scanning Electron Microscopy (SEM) micrographs of the EDM debris. The spray of deionized water with debris was captured using a container. The debris settled to the bottom of the container and was then dried for SEM examination. The diamond in both SEM micrographs shows the same size as the 325 ANSI mesh or 54 μm average size used in the grinding wheel. This indicates that the EDM spark erosion did not occur on the diamond, which is not electrically conductive. The electrical sparks between the EDM wire and the metal bond surrounding the diamond eroded the bond, weakened the support of the diamond, and made the whole diamond fall out from the grinding wheel. Fig. 4 also shows the ball shape metal debris around the diamond with size ranging from 2 to 30 μm. The metal bond appears to be melted by sparks and then resolidified to form the ball shape.

4. Grinding and wheel wear study

After EDM, grinding tests were performed in an ELB BD10 CNC surface grinding machine to examine the performance of EDM trued diamond wheel. The same grinding wheel was also trued using a conventional stationary single-point diamond tool to benchmark the grinding performance.

4.1. Setup of the grinding test

The grinding experiment setup is shown in Fig. 5. The 200 mm diameter, 13 mm wide diamond wheel was used in a creep feed grinding mode with 3.81 mm down feed and 2.1 mm/s table speed. The spindle speed was 3470 rpm, which corresponded to 36 m/s grinding wheel surface speed, v_s. The work-material was the sintered silicon nitride, Toshiba TSN-10. The width of workpiece is

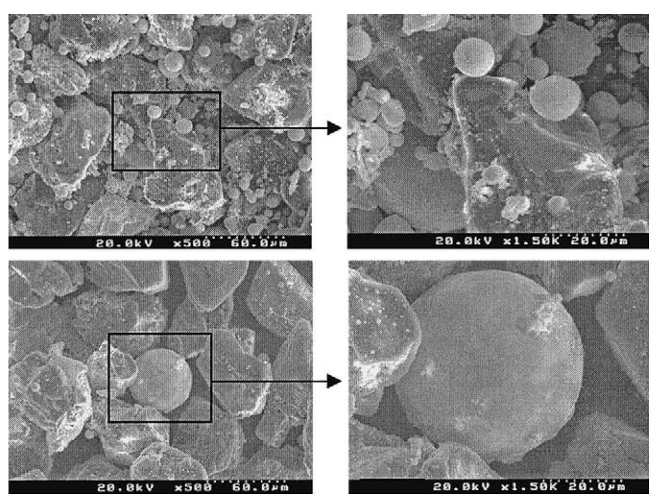

Fig. 4. SEM micrographs of the debris generated in wire EDM of the metal bond diamond wheel with the angular grains diamond and sphere shape debris of metal bond.

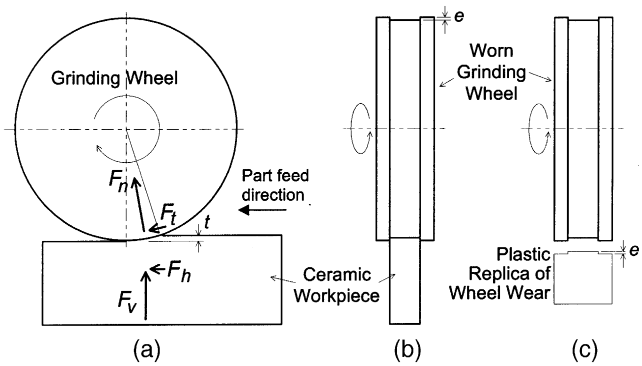

Fig. 5. Grinding test (a) front view and the grinding force components, (b) side view of the grinding and wheal wear measurement using a plastic replica.

6.35 mm and length of grinding is 42.4 mm. As shown in the set up picture in Fig. 6, two ceramic tiles of 21.2×21.2×6.35 mm in size was used in the test. The specific material removal rate during grinding was 8.1 mm^2/s. A Kistler three-axis dynamometer was used to record the horizontal and vertical grinding forces, the F_h and F_v in Fig. 5. A Load Control power sensor was used to measure the grinding wheel spindle power, P. The tangential grinding force, F_t, can be calculated using the following formula.

$$F_t = \frac{P_g - P_i}{v_s} \quad (1)$$

where P_g is the average power during grinding and P_i is the average power of the idling grinding wheel with coolant on.

For the shallow down feed typically used in surface grinding, the vertical and horizontal grinding forces are about the same as the normal and tangential grinding forces, respectively. However, in the large 3.81 mm down feed grinding test, the normal grinding force, F_n, is calculated following the same procedure used by Xu et al. [20] for grinding force analysis. Using the F_h and F_v, measured by the Kistler dynamometer, and F_t, measured using the power sensor, the normal force F_n is derived as:

$$F_n = \sqrt{F_h^2 + F_v^2 - F_t^2}. \quad (2)$$

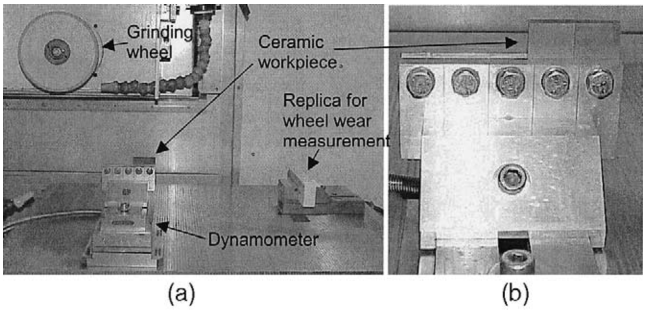

Fig. 6. Metal bond wheel grinding of silicon nitride (a) setup of the test and (b) close-up view of the fixture and the silicon nitride workpiece.

The four grinding forces, F_h, F_v, F_t, and F_n, are further divided by the width of part in contact with grinding wheel (6.35 mm) to calculate the grinding force per unit width or the specific grinding forces, denoted by f_h, f_v, f_t, and f_n. The ratio of normal vs. tangential force, F_n/F_t, can also be calculated to compare to the existing ceramic grinding data.

The method for grinding wheel wear measurement is illustrated in side view in Fig. 5(b) and (c). The 6.35 mm wide ceramic workpiece was positioned in the middle of the 13 mm wide grinding wheel. A groove with average depth, e, was worn on the grinding wheel surface. A machinable plastic part was ground to make a replica of the wheel wear. This plastic part was then measured using the Form Talysurf to quantify the amount of wheel wear, e. A dimensionless parameter, *G-ratio*, is used to represent the wear of the grinding wheel. *G-ratio* is defined as the volume of work-material removed during grinding divided by the volume of wear on the grinding wheel.

4.2. Grinding forces

Figs. 7 and 8 are graphs showing four specific grinding forces, f_h, f_v, f_t, and f_n, for the 33 s duration of the grinding cycle. Two different methods were used to prepare the metal bond diamond wheel before grinding. One

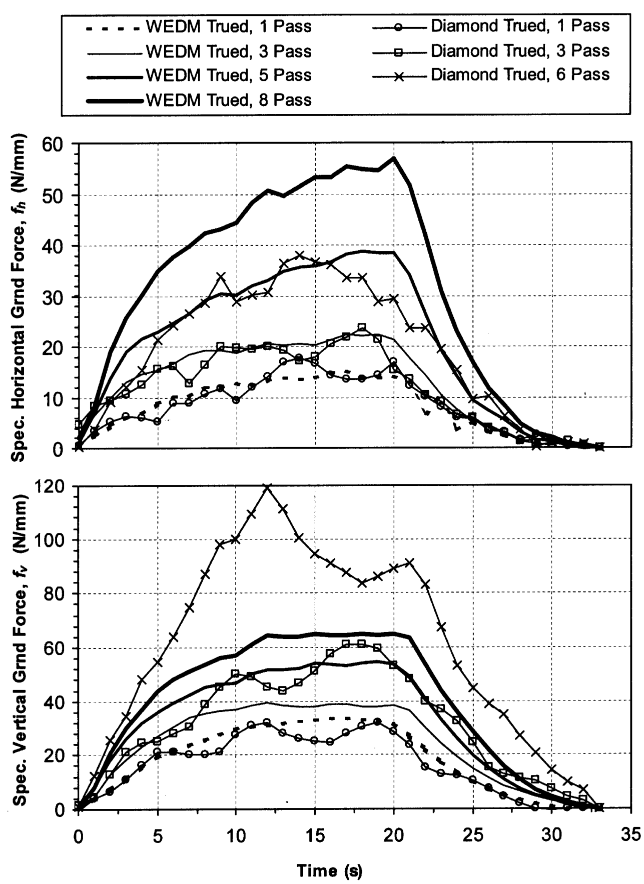

Fig. 7. The measured horizontal and vertical grinding forces.

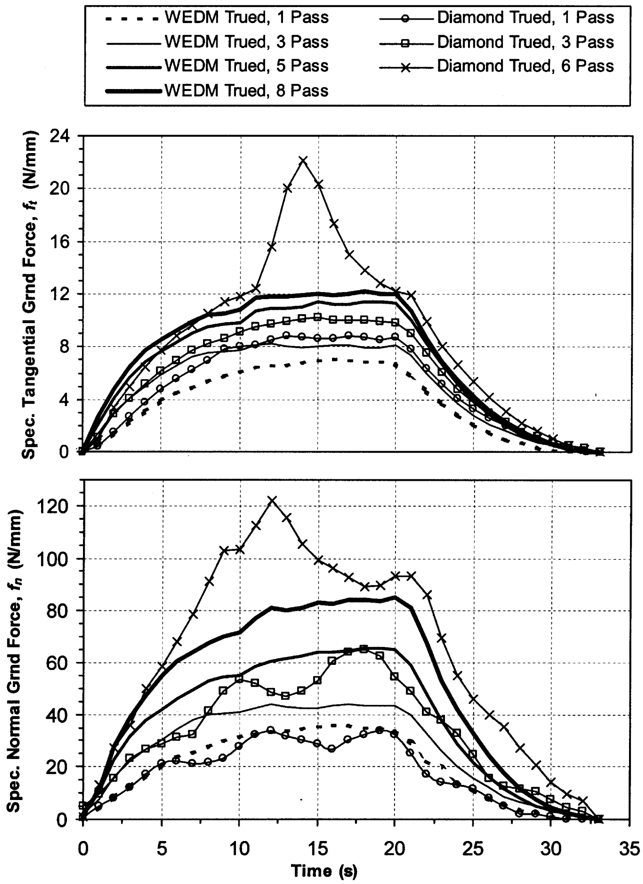

Fig. 8. The measured tangential and calculated normal grinding forces.

is the wire EDM truing method and another is using a stationary single point diamond to traverse across the metal bond diamond wheel. On the single point diamond tool used for truing, significant tool wear was observed. The wheel after truing was used to grind the silicon nitride parts, as shown in Fig. 6. The specific material removed or volume of material removal per unit width was 80.8 mm^2 in each pass. For the grinding wheel trued by the wire EDM, force traces in grinding passes 1, 3, 5, and 8 are presented. For the grinding wheel trued by the single point diamond, force traces in grinding passes 1, 3, and 6 are shown. The forces increase in magnitude as the number of passes increases. This is expected due to the abrasion wear of the diamond.

The specific horizontal grinding forces, f_h, as shown in Fig. 7, are similar for both truing methods. In the first and third grinding pass, the specific horizontal grinding forces peaked at about 14 and 22 N/mm, respectively, for the wheel trued by both methods. Such trend did not repeat on the specific vertical grinding force, f_v. Initially on the first pass, both wheels created the same level of f_v, about 32 N/mm. The single point diamond trued wheel then started to have high peaks of specific vertical grinding force, which reached 120 N/mm in the 6th pass. In comparison, the specific vertical grinding force of the wire EDM trued wheel peaked at about 65 N/mm in the 8th pass. The exact cause for such advantage of wire EDM trued wheel is not known. One of the possible causes is that the metal bond, which supports the diamond grain on the wheel surface, may be damaged during truing using the single point diamond. Very high forces are expected during truing the diamond wheel using a diamond tool [2]. The bond that supports individual diamond grain has to withstand such high impact force and may be damaged. After several grinding passes, the diamond grain with damaged bond was more prone to be pulled out from the wheel surface. This resulted a dull wheel and high vertical grinding forces. On the contrary, the EDM process relies on spark erosion of the bond and very low truing force was generated. The bond that supports the diamond was not damaged during truing and could maintain the performance of grinding wheel for a longer duration.

Fig. 8 shows the measured specific tangential force, f_t. In the first few truing passes, the specific normal force of wire EDM trued wheel was, in general, 20% lower than that of single point diamond trued wheel. This remains the case until the 6th pass, when the single point diamond trued wheel began to break down, which caused the specific tangential grinding force to drastically increase to 22 N/mm.

The calculated specific normal grinding force, f_n, as shown in Fig. 8, was about 20 to 40% lower on the wire EDM trued wheel in the first few passes. On the 6th pass, the specific normal grinding force reached 120 N/mm for single point diamond trued wheel. While on the 8th pass, the wire EDM trued wheel exhibited only 90 N/mm specific normal grinding force. The wheel break down for the wire EDM diamond wheel did not occur until the 15th pass.

Ratios of normal to tangential forces are shown in Fig. 9. For the wire EDM trued wheel, in the first five passes, the grinding force ratio was about 5 to 5.5. In the 8th pass, the grinding force ratio increased to about 7. The

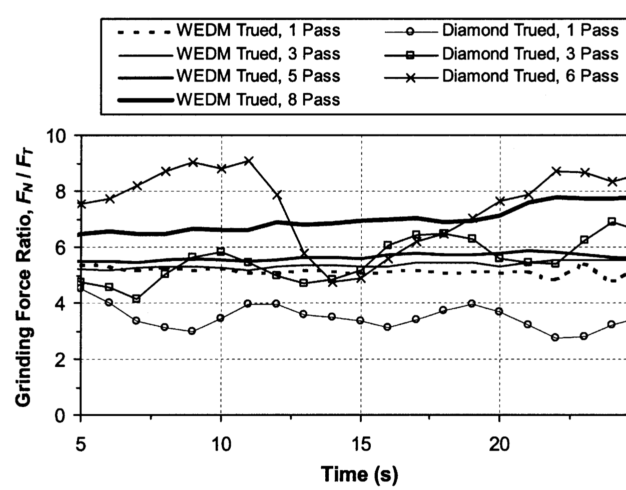

Fig. 9. The ratio of normal vs. tangential grinding force.

grinding force ratio stayed at a nearly constant level throughout all passes for the wheel trued by wire EDM. This level of grinding force ratio was comparable to that reported in [21,22] on CBN grinding of steel and ceramics. For the single point diamond trued wheel, more drastic change of the grinding force ratio throughout all passes could be observed. The same trend of gradually increasing grinding force ratios relative to the number of grinding passes could also be seen.

4.3. Surface roughness

The average and peak-to-valley surface roughness, represented by R_a and R_z, respectively, of the ground silicon nitride parts were measured after each grinding pass. A Talysurf from Rank Taylor Hobson with a standard stylus diamond tip stylus was used. The cutoff length was set at 0.25 mm. Three traces across the grinding direction were measured and the R_a and R_z results were averaged.

Fig. 10 shows the average surface roughness measurement results. The downward trend suggests that both truing methods will produce better surface finish as the number of grinding passes increases. The level of R_a and R_z starts from 0.6 and 5 μm and gradually reduces to 0.4 and 3 μm, respectively. This can be attributed to the increasing attritious wear on the diamond and the wear flat of the metal bond on the wheel surface. The EDM trued wheel created slightly rougher R_a. The R_z values for wheel trued by both methods are about the same.

4.4. Wheel wear

Results of the incremental wheel wear and *G-ratio* of the diamond wheel trued by both methods are presented in Fig. 11. The Form Talysulf with 1 mm diameter ball stylus was used to measure the wheel wear, *e*. In the first grinding pass, a significant wheel wear, about 12 and 6 μm for the wire EDM and single point diamond trued wheel, respectively, was observed. In the subsequent grinding passes, the level of incremental wheel wear dropped to about 1 to 2 μm. Similar trend of high initial wear rate has also been reported during the run-in of new cutting tools [23].

Lower *G-ratio* can be seen on the wire EDM trued wheel. This is caused by the relatively high, 12 μm, wear occurred in the first grinding pass on the wire EDM trued wheel. The cause for this high initial wheel wear has been studied using the stereographic SEM imaging method [24]. Due to the high initial wheel wear, the *G-ratio* was low after the first grinding pass. The *G-ratio* is gradually increasing as more work-material is removed. Although the *G-ratio* results in Fig. 11 shows an upward trend, eventually, it is expected to stabilize and reach a constant level to represent the wear performance of the diamond wheel.

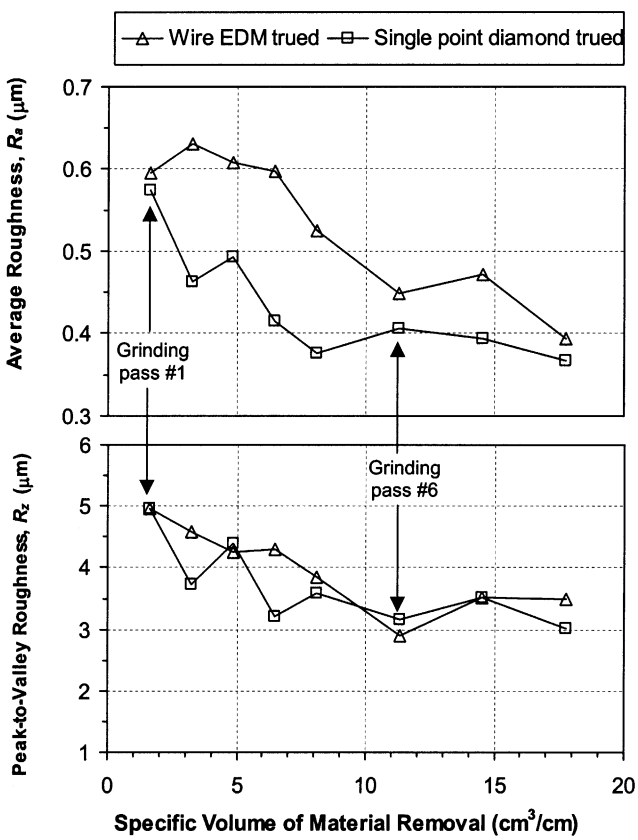

Fig. 10. Average and peak-to-valley surface roughness of ground silicon nitride samples.

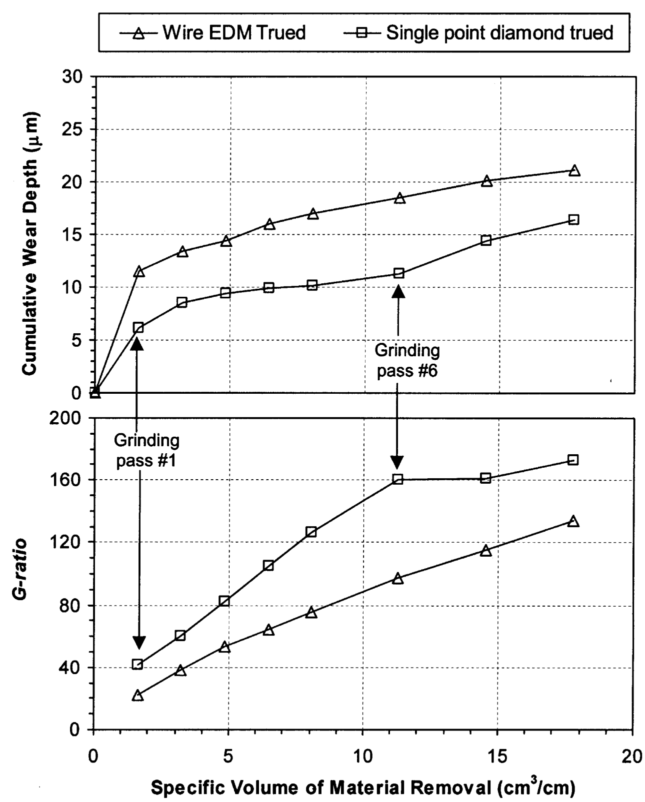

Fig. 11. Cumulative wear of the diamond wheel and *G-ratio* during grinding.

5. Concluding remarks

This study presented the use of cylindrical wire EDM method for truing a metal bond diamond wheel for precision grinding of ceramics. A flexible, corrosion-resistant, and precise spindle was first built to enable the wire EDM truing of metal bond diamond wheels. Several key wire EDM process parameters, including the gap voltage, spark cycle time, and wire speed, were altered in order to EDM the rotating metal bond diamond wheel. The profile form accuracy and corner radii of wire EDM diamond wheel for ceramic grinding was quantified.

The same grinding wheel was trued by the wire EDM and single point diamond methods. The EDM trued diamond wheel showed a 20–40% lower grinding force than that of the same wheel trued by the single point diamond. The EDM trued wheel also lasted longer. The drastic increase of grinding force due to diamond pull out occurred much earlier on the single point diamond trued wheel. However, the EDM trued wheel had a significant high wheel wear rate in the first grinding pass. Results presented in this study represented the diamond wheel trued by specific mechanical and EDM truing conditions. The wear rate of diamond wheel will change under different truing conditions.

This study has demonstrated the feasibility of using the wire EDM process to generate precise profiles on a rotating metal bond diamond wheel and to use the profiled wheel for form grinding of ceramics. More studies to investigate the EDM process parameters to achieve either the maximum material removal rate or miniature features in truing the metal bond diamond wheel and to understand the limit on the diamond grain size in both truing and grinding are necessary to promote this method for production grinding of ceramics and other advanced engineering materials.

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.

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