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Preprint

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IN-PROCESS EDM TRUING TO GENERATE COMPLEX CONTOURS ON METAL-BOND, SUPERABRASIVE GRINDING WHEELS FOR PRECISION GRINDING STRUCTURAL CERAMICS

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1. INTRODUCTION

The demand and use of precision grinding of structural ceramics continue to increase as the worldwide advanced ceramic industry surpasses $20 billion in sales [1]. Included in this industry are engineering structural ceramics, electronic ceramics, bioceramics and others. These materials are used in applications such as engine components, casting and extrusion dies, bearings, medical implants, nozzles, thermal insulators, and more. Along with the variety of ceramic applications comes a broad range of precision requirements, which in turn leads to various required processes to accommodate a spectrum of specifications. A process for grinding ceramic components to micrometer tolerances was employed and further developed at Lawrence Livermore National Laboratory for two separate grinding projects.

2. PROCESS DESCRIPTION

The grinding methodology was developed for a variety of ceramic grinding processes including creep-feed and cylindrical grinding. Figure 1 shows a schematic with the major components of the grinding machine used to creep-feed grind flat ceramic components. An in-situ EDM rotating graphite electrode is used to profile metal bond grinding wheels and both the electrode and the grinding wheels are mounted on air-bearing spindles [2]. The rotating electrode has separate truing surfaces, for coarse and fine profiling. In turn, the profile that is imparted onto the grinding wheel may have multiple, complex features for coarse stock removal and finish detailing.

2.1 Creep-Feed Grinding

One application which greatly benefits from adoption of this methodology is creep-feed grinding of precision grooves in flat BeO substrates. Figure 2 shows a photograph of a ground 1 cm x 4 cm x 0.2 cm BeO component. Most tolerances are ± 1 µm, including the periodic spacing among the grooves. In addition to meeting dimensional specifications, it is necessary to maintain surface roughness and sub-surface damage below levels that significantly affect the material properties and component performance [3].

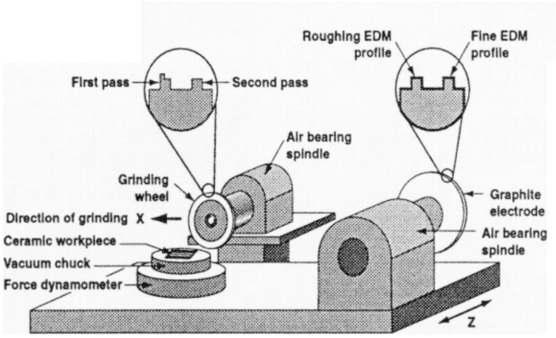

Fig. 1. Creep-feed grinding process schematic with in-situ EDM wheel profiling.

Figure 3(a) shows a close-up photograph of the profiled grinding wheel approaching four BeO workpieces held in a vacuum chuck, which is mounted on a 3-axis, strain-gage force dynamometer. The machine tool is temperature controlled to ± 0.5 C and air-bearing spindles support and drive the grinding wheel and graphite electrode.

Low pressure aqueous grinding fluid is used with the option of applying high pressure fluid to

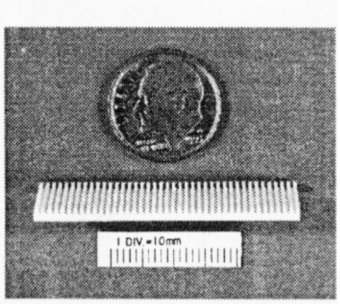

Fig. 2. 4 cm x 1 cm x 0.2 cm BeO substrate

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continuously clean the wheel surface. Figure 3(b) shows the graphite electrode about to profile the metal bond, grinding wheel. For this particular process, a CBN grinding wheel, mounted on the same spindle as the diamond grinding wheel, is used to profile the graphite electrode. Table 1 provides typical process parameters for the creep-feed grinding.

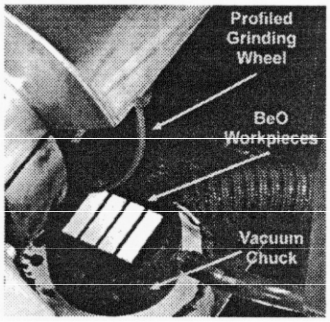

Fig. 3(a). Creep-feed grinding of BeO

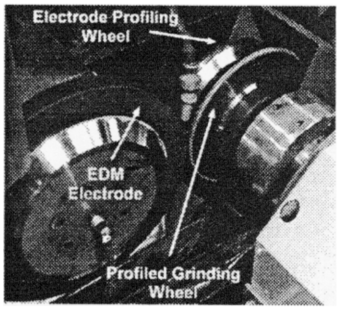

Fig. 3(b). EDM profiling of grinding wheel.

Table 1. Creep-feed process parameters.

Parameter	**Description**
Grinding wheel	SD1000, N100 M, 18 cm Ø
Workpiece	BeO
EDM electrode	Poco Graphite (1 µm grain size)
Wheel speed	105 m/sec
Feed rate	7.5 cm/min

2.2 Cylindrical Grinding

Another application that utilizes this process methodology is cylindrical grinding of structural ceramic engine components. These multi-featured components have typical tolerances down to a micrometer. Figure 4 shows a photograph of one of the zirconia components.

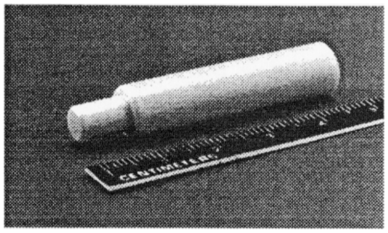

Fig. 4. Ground zirconia component.

Some of the critical features to note regarding this geometry are cylindricity to within 1.5 µm, a specified radius of curvature on the right side of the component, a chamfer edge on the left side and a minimum shoulder internal corner radius.

The process procedure is similar to that for creep-feed grinding except that the workpiece is rotated in a spindle mounted collet, instead of mounted on a traversing table. In this case, in-situ profiling of the EDM electrode is performed using a single-point tool mounted on the machine. The profiled electrode is used to EDM profile the grinding wheel.

Figure 5 shows a photograph of the grinding machine and shown are the grinding wheel spindle and the workpiece spindle that rotates the workpiece and the EDM electrode. Also shown are the ceramic workpiece and the single point tool used to profile the electrode. Table 2 presents the nominal process parameters used in this particular application.

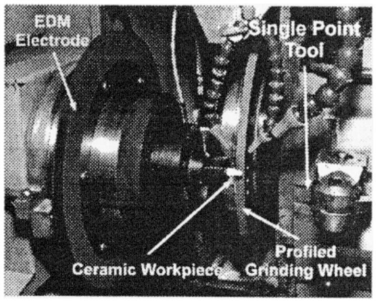

Fig. 5. Cylindrical grinding machine tool.

Table 2. Nominal process parameters for cylindrical grinding using EDM profiled grinding wheels.

Process Parameter	**Description**
Grinding wheel	15-25 µm, cast iron bond, 30 cm Ø
Workpiece	Al_20_3, Si_3N_4 and Al_2ZrO_2
EDM electrode	Poco Graphite (1 µm grain size)
Wheel speed	25 m/sec
Workpiece speed	150 rpm

3. PROCESS ANALYSIS

3.1 Grinding Wheel Wear

Understanding and controlling wheel wear is an essential factor in determining both the level of achievable precision and the economics of the grinding process [4]. To facilitate this understanding, an instantaneous grinding ratio (volumetric material removed/volumetric wheel wear) test procedure was developed to examine the changes in grinding ratio over time. To circumvent the problem of directly measuring small changes in wheel dimensions, measurements of witness grinds were used.

Figure 6 shows a schematic of the instantaneous grinding ratio method using cylindrical grinding. A workpiece is rotated in a spindle and a grinding wheel grinds with only half of the available bond surface, leaving the unused portion intact. Shallow witness grinds, with both the 'unused' and the worn portions of the wheel, are performed on available workpiece areas after each successive grind. This produces a measurable artifact for step height differences between the worn and unused wheel surfaces.

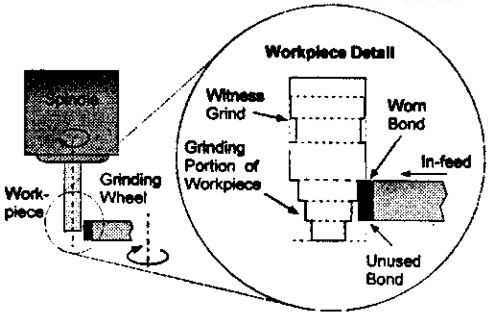

Fig. 6. Instantaneous grinding ratio schematic.

Figure 7 shows an image of a typical ground workpiece from such a test. On the left are shown the grinding steps and on the right is one of the witness grinds used to measure wheel wear. Figure 8 is a plot of data obtained for a particular grinding wheel for different workpiece materials.

3.2 Sub-surface Damage

Investigation of the presence of residual damage, including sub-surface damage (SSD) [5], and its effect on workpiece material properties is being investigated. Transmission electron microscopy (TEM) analysis was used to examine the SSD. Figure 9 shows a typical TEM of a BeO surface using grinding conditions shown in Table 1 and a wheel traverse speed of 5.1 cm/min. This workpiece showed a significant number of cracks between and through grains to depths of 10 μm or more. A sample ground at 0.7 cm/min showed essentially no cracks, but had a larger number of dislocations near the surface. We surmise that the more catastrophic damage of cracks may significantly affect the thermal and mechanical properties of the component.

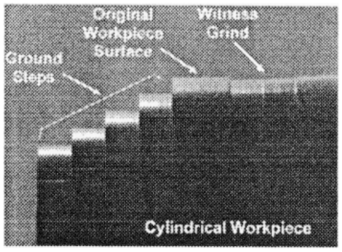

Fig. 7. A typical workpiece ground during an instantaneous grinding ratio test.

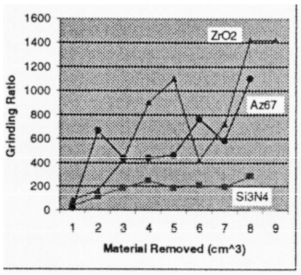

Fig. 8. Instantaneous grinding ratio data for various materials. Wheel: 15-25 μm, cast iron bond.

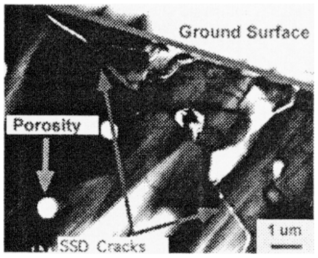

Fig. 9. TEM image of a ground BeO surface with wheel traverse speed of 5.1cm/min.

Another type of grinding test was conducted to investigate the effect of residual damage on the modulus of rupture (MOR) values of zirconia-alumina (ZrO_2-Al_2O_3) bars. Three groups of bars were machined, then tested in a 4-point flexure [6]. The first group was loose abrasive polished (0.5 μm diamond), the second was ground with a 25 μm diamond abrasive, bronze bond wheel, and the third was ground with a 100 μm diamond abrasive, bronze bond wheel. Figure 10 shows a plot of the

MOR values for the three cases and indicates that the polished and the fine ground parts had statistically similar MOR values, while the coarse ground parts exhibited a reduction of MOR by a factor of approximately 3.

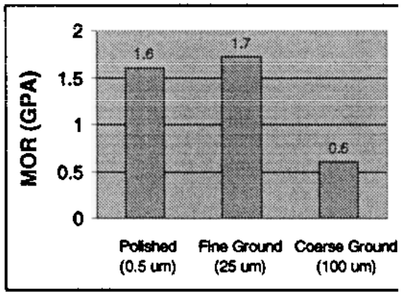

Fig. 10. MOR values as a function of grit size. ZrO_2-Al_2O_3 MOR bars.

4. DISCUSSION

The economic advantages of instituting an on-machine EDM profiling process for precision grinding can be substantial for a number of reasons. Integrating the entire process on one machine reduces operator set-up and tear-down times over multiple-machine procedures. Using a single machine tool reduces capital equipment expense and decreases required floor space. However, one of the largest economic incentives of such a procedure is that performing all the machining and grinding on one machine can significantly improve part accuracy leading to improved yield. Equally important is the versatility to generate complex profiles in grinding wheels, which can reduce the number of passes required to grind a given component.

Control of wheel wear is essential to controlling the accuracy of the grinding process. Traditional grinding ratio tests typically require substantial grinding, with a single 'integrated' grinding ratio value as the result. The instantaneous grinding ratio tests discussed here allow the user to capture wheel wear information throughout the life of the wheel. The data shown in Figure 8 all show a sharp increase in grinding ratio after the first few grinding steps. The initial low grinding ratios are the result of the softer, recast layer generated on the wheel surface during EDM profiling, which wear quickly relative to the bulk bond matrix. To maintain dimensional accuracy, the user must be aware of how the wheel wears over time and optimize the wheel profile and EDM parameters to account for the recast layer.

The residual SSD imparted in the ceramic workpiece is often as important to the customer as is compliance with geometric specifications. As higher performance demands are placed on ceramic components, changes of 10 – 15% in mechanical properties can become crucial. In one test, we noted a 3 times decrease in modulus of rupture values for coarse ground parts over polished or fine ground parts. This has significant implications regarding component reliability and time between failures. Further research will continue at LLNL to investigate the thermal and mechanical SSD effects on ground ceramic components.

5. SUMMARY

A generalized precision grinding process is under development at Lawrence Livermore National Laboratory to use EDM profiled, metal-bond, superabrasive grinding wheels to economically fabricate ceramic components. The two applications reported here include creep-feed grinding of 0.5 mm wide grooves in BeO substrates and cylindrical grinding of various ceramic components with micrometer tolerances. Resultant sub-surface damage and grinding ratios were investigated to optimize grinding conditions for maximum yield and wheel life.

6. REFERENCES

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