JMEPEG (2006) 15:242-246
DOI: 10.1361/105994906X95959

1059-9495/$19.00

Surface Grinding of Space Materials Using Specially Formulated Vitrified Grinding Wheels

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(Submitted November 4, 2005; in revised form December 24, 2005)

The quantum leap that is expected in the reliability and safety of machined engineering components over the next 20 years, especially in the space industries, will require improvements in the quality of cutting tools if science-based manufacturing is the goal for manufacturing by 2020. Significant improvements have been made in the past 10 years by understanding the properties of vitrified bonding systems used to bond conventional and superabrasive materials in grinding tools. The nature of the bonding system is of paramount importance if next-generation cutting tools are to be used for aerospace materials, especially if they are dressed using laser beams.

Keywords aerospace materials, grinding, laser dressing, surface coatings, surface engineering

1. Introduction

This paper describes the developments made so far in understanding the interface between the bonding system and abrasive grain and presents challenges to be addressed for processing materials used for next-generation launch vehicles. Methods to specifically engineer the grain-bonding interface for a variety of manufacturing cases will focus on the suppression of mullite formation and the promotion of cristobalite in the vitrified bonding bridge, the dissolution of quartz by combined heat treatment and control of the alkali oxide content within the glass network, boric oxide formation around cubic boron nitride (cBN) crystals, and rutile needle suppression at the interface between the abrasive grain and bonding bridge. The management of this new manufacturing technology will allow next-generation grinding processes to meet the stringent demands made by organizations that are responsible for developing and manufacturing space vehicles.

2. Challenges of the Space Industries

NASA's current focus on advanced manufacturing practices for launch vehicles coincides with developments that have been made in advanced materials. To achieve very precise engineering tolerances for use on uninhabited air vehicles (UAV), high-altitude, long-endurance aircraft (HALE), and hypersonic vehicles, manufacturing processes such as grinding must be understood so that NASA can achieve stringent tolerances and preserve surface integrity of machined components. Composite materials, Ni-base alloys, and exotic Al-Li alloys require manufacturing processes that will not change their mechanical or thermal properties during processing and will not impart undesirable thermal effects on ground components. Three fields of technology that have become established for high-precision grinding are high-speed grinding with cBN grinding wheels; high-speed grinding with aluminum oxide grinding wheels; and grinding with aluminum oxide grinding wheels in conjunction with continuous dressing techniques. Material removal rates have resulted in super-proportional increases in productivity for machining using all three fields of technology in industrial applications. Figure 1 shows the application field for these three grinding regimes, i.e., high-efficiency grinding with cBN abrasives, high-efficiency grinding with aluminum oxide, and continuous-dress grinding (CD grinding). The decision made by manufacturing technology managers on the type of cutting tool used is dependent on the specific material-removal rate required at the specific cutting speed. Clearly, Fig. 1 shows the division and overlap between the types of grinding processes and the appropriate cutting tool needed for each of these processes.

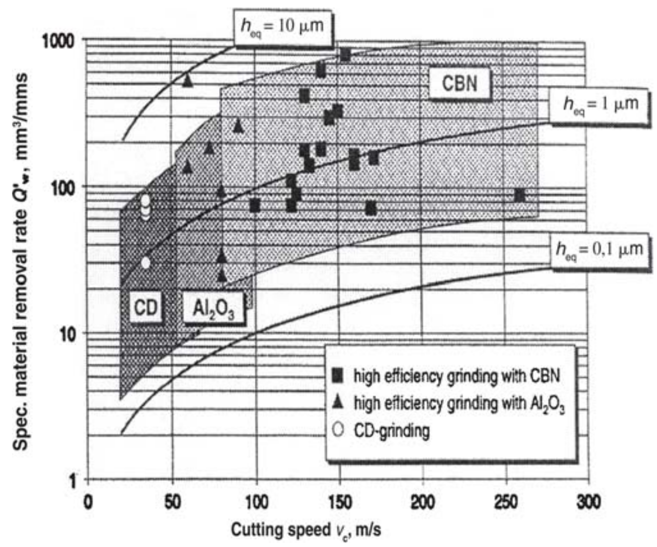

Fig. 1 Main field of applications for high-efficiency precision grinding

This paper was presented at the fourth International Surface Engineering Congress and Exposition held August 1-3, 2005 in St. Paul, MN.

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To achieve high performance from a grinding wheel, it must stay constantly sharp and have the ability to absorb a high volume of metal chips. Therefore, the grinding wheel must be porous and must be able to withstand the high grinding loads placed on the abrasive grains and on the bonding bridges that hold the grains in position. The nature of the properties of the grinding wheel at the interface between the bonding bridge and the abrasive grains is very important when one considers how forces are transmitted into the bonding bridges through the interfacial layer. Vitrified bonds are typically used for high-performance grinding processes, and in comparison with other types of bonds, vitrified bonds permit easy dressing while at the same time possessing high levels of resistance to wear (Ref 1, 2).

2.1 Wear of Grinding Wheels: Aluminum Oxide

Vitrified grinding wheels wear by four distinct mechanisms: abrasive wear caused by the formation of wear flats; fracture of bond bridges; fracture of abrasive grains caused by mechanical and thermal loads; and fracture at the interfacial layer between abrasive grain and bonding bridge. Economic wear of the grinding wheel is aided by keeping the wheel in an extremely sharp condition, usually by continuous dressing with sharp diamond grains, or by continuously dressing the wheel using a laser beam (Ref 3). The maintenance of a sharp wheel prevents the brittle fracture zone that occurs in the abrasive grain from moving into the interfacial layer and the bonding bridge (Ref 4). When this condition occurs, uneconomic wear of the grinding wheel occurs. To prevent this from occurring, the wheel needs to be continuously dressed and the bonding bridge and interfacial layer must be specifically engineered for a particular grinding operation. In conventional grinding wheels, the formation of various microstructural phases at the interface between abrasive grain and bonding bridge can enhance the wear of the grinding wheel. Figure 2 shows the effect of using two different types of abrasive on interfacial layer activity. The growth of certain phases during sintering has manifested itself as a reduction of economic life of the wheel.

2.2 Wear of Grinding Wheels: Cubic Boron Nitride

The use of cBN in high-performance grinding wheels in high-efficiency grinding operations has significant advantages, not the least of which is economic. Figure 3 shows the effect of the growth of a continuous film at the interface between the abrasive grain and the bonding bridge. The existence of an interfacial layer between cBN and glass was thought to be due to boric oxide (B_2O_3) formation.

As sintering continued, the layer became thicker and tended to strengthen. This is assumed to be the reason why the grinding ratio of the abrasive tool increased as a function of sintering temperature. It was also noted that the size of the cBN grains decreased as the sintering temperature increased until an equilibrium interfacial layer thickness was reached. It was also assumed that, at this point, diffusion of oxygen into the cBN abrasive grain ceases. The fracture surface of the vitrified cBN structure shows that failure is associated with fracture within the bonding bridge rather than fracture at the cBN-bond bridge interface. This tends to imply that the interfacial bonding layer is stronger than the bonding bridge. The bonding bridge has a higher than normal alkali oxide content to suppress the formation of the mullite needle network with the bonding bridge. Mullite tends to reduce fracture resistance in the bridge structure and is replaced with cristobalite and a high proportion of glass containing boric oxide.

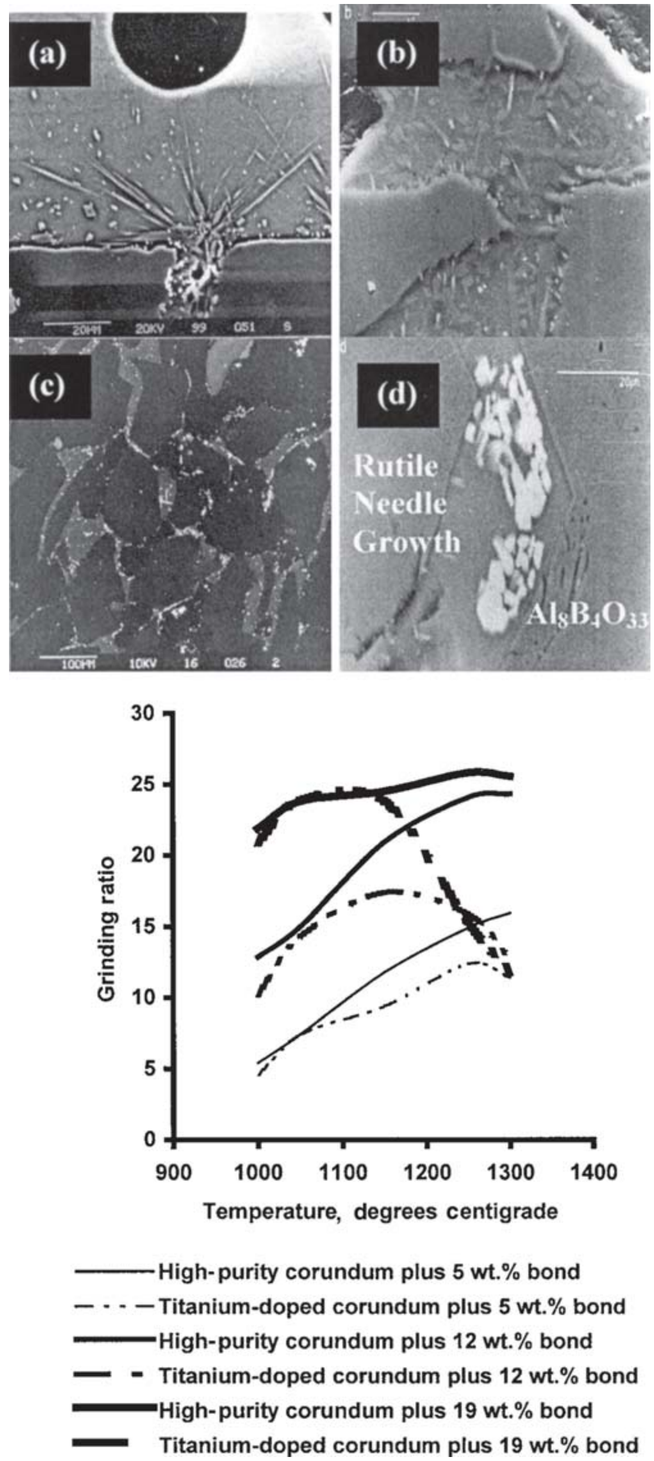

Fig. 2 (a) Titania (TiO_2), in the form of rutile needles, on the surface of the vitrified glass bond; (b) vitrified glass bond shows rutile formation within the glass bonding system; (c) electron backscattered image showing needle growth into the glass bond from the abrasive; (d) devitrified glass bond containing crystals of $Al_{18}B_4O_{33}$ bounded by two abrasive grains. The relationship between the wear parameter (G-ratio), sintering temperature, and abrasive grain composition is on the right-hand side of the figure.

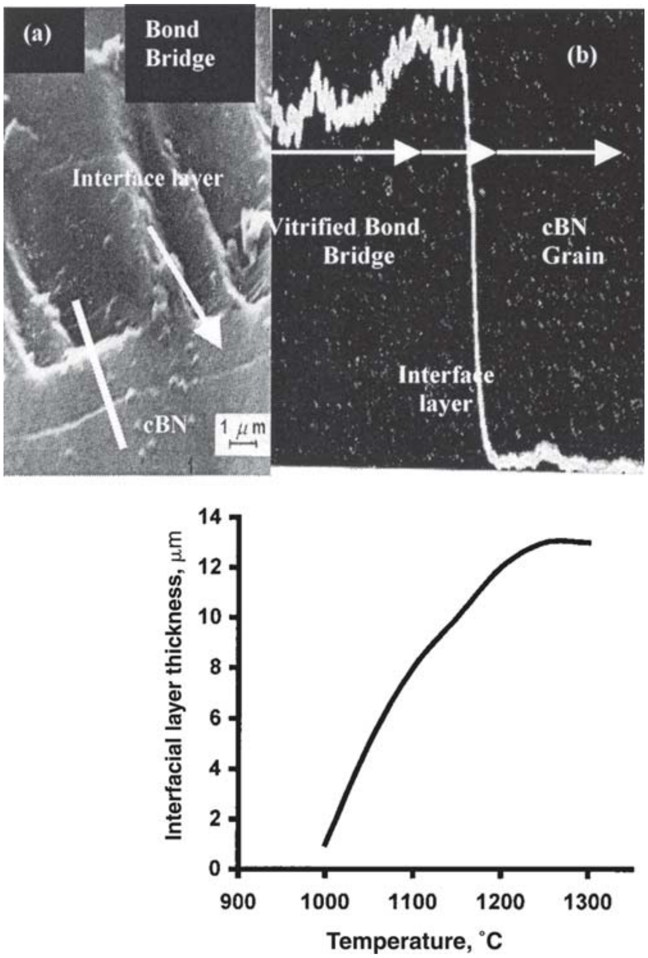

Fig. 3 (a) Polished cross section of cBN abrasive and bond bridge; (b) electron probe microanalysis of oxygen across the line scan shown in (a)

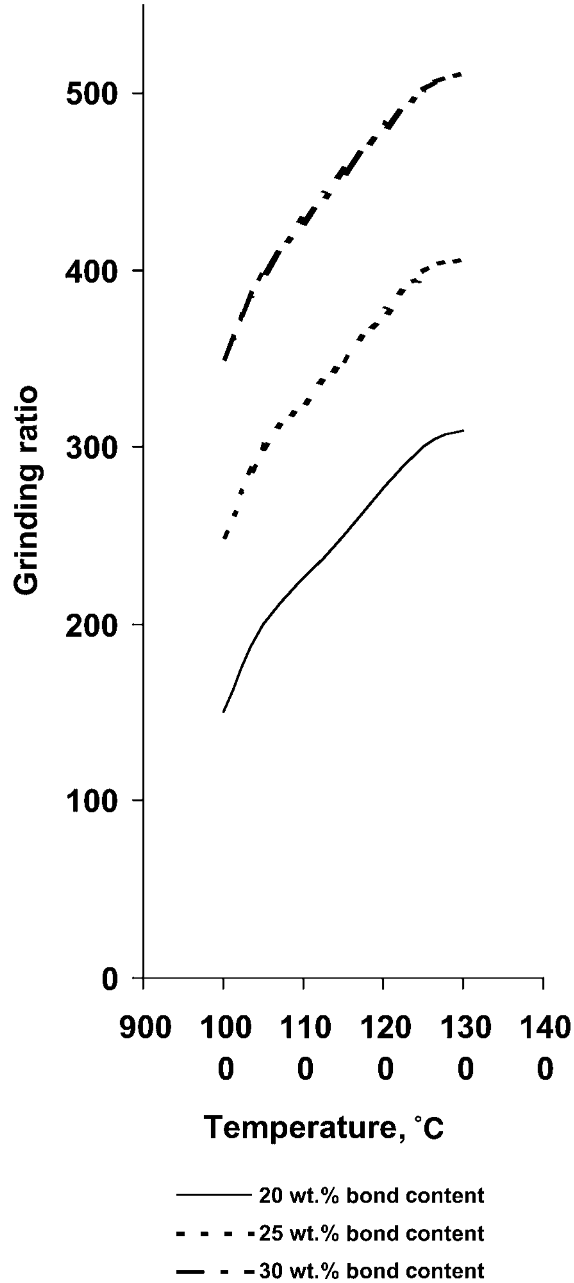

Fig. 4 Relationship between grinding ratio and firing temperature as a function of bond content for vitrified cBN grinding wheel structures

The relationship between the wheel wear parameter, grinding ratio, and the firing temperature for vitrified cBN grinding wheel structures, containing different amounts of bonding content, is shown in Fig. 4. It is shown that grinding ratios are much higher with cBN than with aluminum oxide abrasive materials.

2.3 Laser Dressing of Grinding Wheels

Vitrified bonds are composed of glasses that are formed when clays, ground glass frits, mineral fluxes such as feldspars, and chemical fluxes such as borax melt when the grinding wheel is fired at temperatures in the range of 900 to 1100 °C. With reference to raw material nomenclature, a "frit" is a preground glass with predetermined oxide content. A "flux" is a low melting point siliceous clay that reduces surface tension at the bond bridge-abrasive grain interface. A "pre-fritted" bond is a bond that contains no clay minerals (i.e., clays and fluxes). "Firing" refers to the vitrification heat treatment that consolidates the individual bond constituents. Considering individual bond constituents, mineral fluxes and ground glass frits have little direct effect on the ability to manufacture grinding wheels. However, most clays develop some plasticity in the presence of water (from the binder), which improves the ability to mould the mixture so that the wheel, in its green state, can be mechanically handled. Clays and clay-based fluxes contain an amount of free quartz that has a detrimental effect on the development of strength during vitrification heat treatment. Clays are used to provide vitrified grinding wheels with green strength during the heat treatment process. However, when the glassy material solidifies around the particles of clay and quartz, the displacive transformation of quartz during the cooling stage of vitrification leads to the formation of cracks in the glass around the quartz particle. The strength of the bonding bridge is impaired and leads to the early release of the abrasive particle during the cutting of metal, but more likely during the early stages of dressing. Laser dressing can be performed on a grinding wheel to generate surfaces with sharp cutting edges, either by locally modifying worn-out abrasives, or by dislodging loaded metal chips. Focused laser radiation produces enor-

Table 1 Qualitative comparison for the pole figure analysis at 2θ angles for the undressed and laser-dressed grinding wheels (Ref 5)

2θ, deg	Plane	Undressed sample	Dressed sample, laser intensity 500, W	750, W	1000, W
25.57	(012)	S	CC	CC	CC
57.50	(116)	CC	S	S	S
37.76	(110)	S	CC	CC	CC
66.50	(214)	S	R	R	R
35.15	(104)	S	CC	CC	CC

Note: S, scattered; CC, concentrated about the center in a symmetric way; R, poles are arranged in a concentric ring about the center

mous power densities in a very small region of the wheel surface, and thus, can cause a localized modification either of the exposed grain or of the bond. Some of the major advantages of the use of a laser for dressing operation are:

- Spot size control
- Fast process
- Ease of beam delivery to the work piece via an optical fiber cable
- Selective removal of the clogged material alone is possible
- Consistent dressing conditions especially on difficult-to-grind materials

Jackson et al. (Ref 3, 5) describe the process of laser dressing conventional vitrified grinding wheels. A 2.5 kW Hobart continuous-wave Nd:YAG laser equipped with a fiber-optic beam delivery system was used for dressing a vitrified grinding wheel. A laser beam was focused at a height of 0.5 mm above the surface of the wheel. The lenses within the output-coupling module of the fiber optic delivery system were configured to provide 3.5 mm × 600 μm rectangular beam in spatial distribution onto the sample surface. Such a configuration provides rapid processing speed and limits the overlap between the laser passes to <20%. Laser power intensities of 500, 750, and 1000 W were used. Dressing of the entire surface was done by scanning the laser beam in parallel tracks at a linear speed of 50 cm/min on the surface. X-ray diffraction (XRD) methods were used to characterize the effects of dressing. A Philips Norelco x-ray diffractometer with Cu Kα radiation operated at 40 kV and 15 mA was used to characterize the dressed wheel surface in terms of the phases present. Furthermore, pole figure measurements were performed for possible texture, using a Philips X'Pert (Philips, Sunnyvale, CA) analytical diffractometer. The instrument was operated at 45 kV and 40 mA, using Cu Kα radiation through a point source. The reflection method was used for pole figure analysis with ϕ varying between 0 and 360° and ψ between 0 and 85°. Planes with higher relative intensity in the normal XRD (2θ versus intensity) plots were analyzed for their pole figures. XRD analysis of undressed grinding wheels as well as the laser dressed samples, showed corundum (α-Al_2O_3) present as a primary phase; however, the intensity of a few individual peaks was significantly higher than that of others in the laser-dressed samples, indicating preferential orientation. Pole figure analysis was done for selective 2θ angles chosen from the XRD plots, corresponding to the peaks with higher relative intensity. Table 1 indicates the poles and their corresponding planes, which were analyzed. Also, it

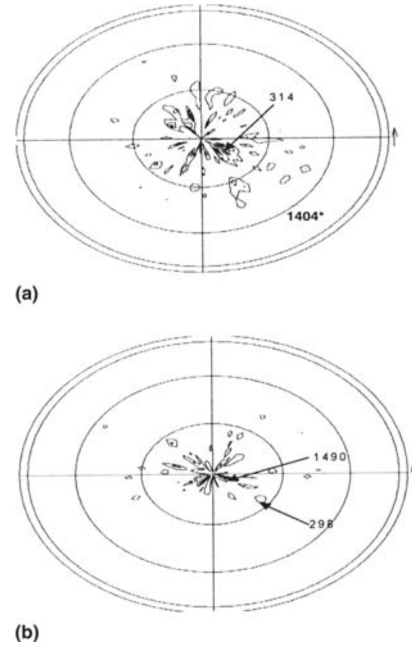

Fig. 5 Pole figure for the (012) plane in (a) undressed sample and (b) laser-dressed sample. *Denotes intensity on an arbitrary scale (Ref 5)

qualitatively compares the nature of pole figures obtained for these poles at different laser powers as well as in the undressed grinding wheel.

The scattered peaks in the pole figure indicate absence of any preferential orientation, whereas if the peaks are concentrated symmetrically about the center then the sample has a preferential orientation for that plane. For the planes analyzed during the experiments, the (012), (104), and (110) planes were scattered in the undressed sample, whereas after laser dressing, they were concentrated about the center. Figure 5 is an example of this. The labels on the pole figures indicate the intensity of the line profiles of the peaks on an arbitrary scale. The (116) plane, which was the most prominent peak in the undressed sample, was reduced in intensity in the laser-dressed material. For this plane, the corresponding pole figure after laser dressing had all of the poles scattered. For the (214) plane, the poles were scattered in the undressed condition, but after dressing, most of them were arranged in a concentric ring about the center (Fig. 6), indicating orientation of the peaks at an angle to the sample surface. The (110) plane, which was almost in the background in the undressed sample, became the plane with the highest intensity after laser dressing.

Thus, the (110) plane appeared to have the highest preferential orientation after dressing. The faceted structure on the surface of particles is possibly a result of such preferred orientation. This gives an indication of texture formation on the surface as a result of laser dressing. Identification of planar textures due to laser dressing is important because the (atomic) planar density is expected to influence the grinding characteristics, grinding performance, and the lifetime of these grinding surfaces. It is shown that laser dressing of vitrified grinding wheels produce less mechanical damage than conventional diamond dressing procedures. This reduces the wear experienced by the grinding wheel during grinding operations, and the process can be designed to clean the wheel, dress the wheel, and restructure the wheel during a grinding process. The economic

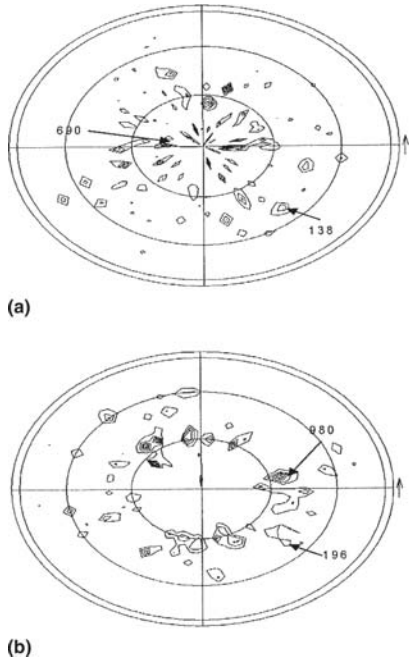

Fig. 6 Pole figure for (214) plane in (a) undressed sample and (b) laser-dressed sample (Ref 5)

benefits gained by using a laser beam to clean and dress the grinding wheel are clearly desirable. However, vitrified bonding systems are required that will allow the laser beam to selectively clean and dress the grinding wheel without damaging the abrasive grains and the vitrified bonding system.

3. Conclusions

The challenges presented to the space industries for next generation launch vehicles and spacecraft will require advanced manufacturing processes that will maintain the integrity of the material. For the grinding wheel manufacturer, this will require wheels that are extremely porous, that possess strong bonding systems that can be dressed using noncontact profiling techniques, and that are wear resistant. The use of lasers to dress and clean grinding wheels will aid in the maintenance of wheel sharpness and will render the wheel economically fit for purpose without damaging, or changing, the characteristics of the material. Manufacturing technology managers should be aware of the effects of changing or using the three types of grinding procedures for processing aerospace materials. As shown in Fig. 1, the type of process selected has a significant effect on the type of cutting tool required by the process. It is essential that manufacturing technology managers understand the differences between the processes and cutting tools required for each process. The interfacial bonding between abrasive grain and bonding system appears to be the key to the success of the grinding process.

References

1. M.J. Jackson, C.J. Davis, M.P. Hitchiner, and B. Mills, High-Speed Grinding with cBN Grinding Wheels—Applications and Future Developments, *J. Mater. Process. Technol.,* 2001, **110,** p 78-88
2. M.J. Jackson, N. Barlow, and K.K.B. Hon, Computer Aided Design of High-Performance Grinding Tools, *Proc. Inst. Mech. Eng. (London), Part B—J. Eng. Manuf.,* 2001, **215,** p 583-588
3. M.J. Jackson, G.M. Robinson, N.B. Dahotre, A. Khangar, and R. Moss, Laser Dressing of Vitrified Aluminum Oxide Grinding Wheels, *J. Inst. Mater., Minerals, Mining, Br. Ceram. Trans.,* 2003, **102,** p 237-245
4. M.J. Jackson, Fracture Dominated Wear of Sharp Abrasive Grains and Grinding Wheels, *Proc. Inst. Mech. Eng. (London), Part J–J. Eng. Tribol.,* 2004, **218,** p 225-235
5. M.J. Jackson, G.M. Robinson, A. Khangar, and N.B. Dahotre, Laser Dressing of Alumina Grinding Wheels, *Proceedings of the 22nd Heat Treating Society Conference and the 2nd International Surface Engineering Congress,* Indianapolis, IN, ASM International, 2003, p 423-426