1 Introduction

Partially stabilized zirconia (PSZ) is a ceramic material that has been applied extensively in diesel engine fuel system plunger applications [1]. The gradually tightened diesel engine exhaust emission regulations in the past decade have created needs to increase the fuel injection pressure and reduce the sulfur content in diesel fuel. Within the injector, closely matched plungers and barrels with sub-μm precision accuracy are required to generate the high fuel injection pressure and desired combustion performance. The use of PSZ as plunger material eliminates seizure problems, especially in the low sulfur, low lubricity diesel fuel. Compared to other structural ceramics, the thermal expansion coefficient of PSZ has the best match to that of steel, which helps to maintain the tight, 1 μm radial clearance between the steel barrel and PSZ plunger across the engine operating temperature. The high fracture toughness, low coefficient of friction and wear rate, and low density of PSZ also make it suitable for plunger applications.

In addition to performance, cost is another critical plunger material selection criterion. The cost includes both material and machining cost. The shape of plungers for diesel fuel systems has become more complicated. Cost-effective precision form grinding of ceramics becomes an enabling technology to promote the use of PSZ for high-volume automotive applications. Diamond has been the choice of abrasive for efficient grinding of engineering ceramics, including PSZ. Two barriers associated with diamond grinding are: cost of diamond wheels and difficulty of truing diamond wheels to a precise shape for form grinding. Compared to diamond, the cost of SiC abrasive is low. A stationary diamond tool can be used to generate the precise shape on SiC wheels for form grinding [2,3]. This study investigates the use of vitreous bond SiC wheels for grinding of PSZ.

SiC wheels have been tested for grinding ceramics in the past. Typically, high wheel wear rate was a problem. In a series of tests of SiC grinding of PSZ, an exceptionally low wheel wear rate occurred at high infed rates for specially made wheels with fine, 220 ANSI mesh grain size SiC and dense vitreous bond [4]. The fine grain size SiC was selected due to the increase in friability of SiC as the abrasive size is reduced [5]. The G-ratio, which is defined as the volume of work-material removed vs. the volume of wear on the grinding wheel, could be as high as 800 in cylindrical grinding [4]. A higher G-ratio or lower wheel wear rate could be seen at a higher material removal rate. This trend is different from that commonly observed in ceramic grinding. The grinding tests also indicated that the machine stiffness was important to achieve the desired high G-ratio for SiC grinding of PSZ. The goal of this research is to conduct a systematic study on grinding of PSZ using the dense vitreous bond SiC wheel and to investigate the possible reason for such efficient grinding of PSZ.

In this paper, the design and set up of the surface grinding experiment is first discussed. Scanning Electron Microscopy
(SEM) was used to examine the ground surface and debris. The X-ray diffraction method was used to analyze the phase transformation of PSZ debris, ground surface, and original material. A possible grinding mechanism for low wheel wear rate SiC grinding of PSZ is discussed.

2 Grinding Experiment Design and Setup

Grinding experiments were conducted on two instrumented surface grinding machines at Oak Ridge National Laboratory. Surface grinding was selected over the original cylindrical grinding machines manufactured by Harig and Nicco, designated as Machines A and B, respectively, were used. A workpiece fixture and ceramic workpiece and a groove was worn in the middle of the wheel grinding wheel. During grinding, the wheel was wider than the workpiece and a groove was worn in the middle of the wheel surface. To measure the depth of wear, a hard plastic part was used to hold ceramic samples 6.35 mm×20 mm×20 mm in size. Up to five parts, as illustrated in Figs. 1(a) and 1(b), could be held in the fixture. Figure 1(b) also shows the 200 mm diameter, 12 mm wide SiC grinding wheel. During grinding, the wheel was wider than the workpiece and a groove was worn in the middle of the wheel surface. To measure the depth of wear, a hard plastic part was used to produce a replica of the worn wheel surface. A coordinate measurement machine was used to measure the wheel wear on the replica.

2.1 Grinding Setup. Two computer controlled surface grinding machines manufactured by Harig and Nicco, designated as Machines A and B, respectively, were used. A workpiece fixture device, as shown in Fig. 1(a), was used to hold ceramic samples 6.35 mm×20 mm×20 mm in size. Up to five parts, as illustrated in Figs. 1(a) and 1(b), could be held in the fixture. Figure 1(b) also shows the 200 mm diameter, 12 mm wide SiC grinding wheel. During grinding, the wheel was wider than the workpiece and a groove was worn in the middle of the wheel surface. To measure the depth of wear, a hard plastic part was used to produce a replica of the worn wheel surface. A coordinate measurement machine was used to measure the wheel wear on the replica.

2.2 Experiment Design. The process parameters investigated in this study include:

1. Machines: The static structural stiffness and spindle power of Machines A (Harig) and B (Nicco) are 6140 and 15,600 N/mm and 1.2 and 5.6 kW, respectively. Machine A has low stiffness and spindle power. Fast table speeds and small down feeds are used in Machine A. Machine B is a creep feed grinder with low table speed. A large down feed is typically used in Machine B to achieve the desired material removal rate.

2. Materials: The material used in the baseline grinding test is designated as MgO-PSZ, a 3 wt% (9 mole%) MgO PSZ with 11.8 GPa Knoop hardness under 1000 g load. Other ceramics studied include: (i) Y2O3-PSZ, a 8 wt% Y2O3 PSZ (12.7 GPa hardness), (ii) AD-94, 94% alumina with 4% silica (11.5 GPa hardness), (iii) ZTA, zirconia toughened alumina with 20 wt% zirconia (14.4 GPa hardness), and (iv) ZDY, 9 wt% Y2O3 fully stabilized zirconia (11.0 GPa hardness). All ceramics were made by Coors.

3. Table Speed: Four table speeds, 50.8, 112, 173, and 229 mm/s, were used for Machine A. Five slower table speeds, 0.42, 1.69, 2.54, 3.39 and 6.77 mm/s, were used for Machine B. The range of table speed for Machines A and B does not overlap, i.e., the lowest speed in Machine A is higher than the highest possible speed in Machine B.

4. Down Feed: The down feed is the depth of cut in each grinding pass. Three down feeds, 0.0025, 0.0051, and 0.0127 mm, were used in Machine A. The corresponding specific material removal rates for the 12 grinding tests with the Machine A are shown in Table 1. In Machine B, five down feeds, 0.635, 1.27, 1.91, 2.54, and 3.18 mm, were used. The specific material removal rates of 15 grinding tests in Machine B, as shown in Table 1, overlapped with those in Machine A.

All the other grinding parameters remain the same during the tests. The coolant was water-based Cimtech 500 synthetic coolant at 5% concentration. The wheel surface speed was 39 m/s.

2.3 Analytical Analysis. The applied stress and resulting temperature generated during grinding can transform the metastable cubic and tetragonal phases to the monoclinic phase in MgO-PSZ. X-ray diffraction was used to measure the percentage of the monoclinic phase in PSZ on the original material, ground surface, and debris. A possible grinding mechanism for low wheel wear rate SiC grinding of PSZ is discussed.

![Fig. 1 Setup of the grinding tests, (a) fixture and ceramic workpiece and (b) grinding wheel and workpiece](image_url)

Table 1 The material removal rate of the selected table speeds and down feeds in Machines A and B

<table>
<thead>
<tr>
<th>Table speed (mm/s)</th>
<th>Machine A</th>
<th></th>
<th></th>
<th></th>
<th>Machine B</th>
<th>Table speed (mm/s)</th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Down feed (mm)</td>
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<td>0.0051</td>
<td>0.0127</td>
<td></td>
<td></td>
<td>0.0025</td>
<td>0.0051</td>
<td>0.0127</td>
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</tr>
<tr>
<td>50.8</td>
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<td>0.26</td>
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<td>0.42</td>
<td>0.27</td>
<td>0.54</td>
<td>0.81</td>
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<tr>
<td>112</td>
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<td>0.57</td>
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<td></td>
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<td>1.07</td>
<td>2.15</td>
<td>3.23</td>
<td>4.30</td>
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<tr>
<td>173</td>
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<td></td>
<td>2.54</td>
<td>1.61</td>
<td>3.23</td>
<td>4.84</td>
<td></td>
</tr>
<tr>
<td>229</td>
<td>0.58</td>
<td>1.16</td>
<td>2.90</td>
<td></td>
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<td>2.15</td>
<td>4.30</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>6.77</td>
<td></td>
<td>4.30</td>
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</tbody>
</table>
surface, and grinding debris and to identify the possible grinding mechanism. SEM was used to observe the ground surfaces and debris.

3 Grinding Results

3.1 Wheel Wear. Results for the G-ratio are shown in Fig. 2. Relatively high G-ratio, over 110, can be achieved on the low-stiffness Machine A, illustrating the effectiveness of this low cost SiC wheel for form grinding of MgO-PSZ. At the same down feed, high specific material removal rates improve the G-ratio. This trend matches that of previously observed results and is opposite to that seen on Machine B and conventional grinding tests.

At the same specific material removal rate, the G-ratio for Machine A with 0.0025 and 0.0051 mm down feed is higher than that in Machine B, which has higher stiffness and is expected to have lower wheel wear. This can be explained by different grinding configurations of two grinders. The creep feed grinding with high down feed used in Machine B has a much longer arc contact length compared to that of Machine A. Porous vitreous bond wheels are commonly used in creep feed grinding to avoid debris loading in pores on wheel surface. The dense vitreous bond SiC wheel has a low porosity and is not ideal for the large down feed, slow table speed creep feed grinding in Machine B. The G-ratio results in Fig. 2 indicate just that.

3.2 Wheel Wear for Grinding Different Ceramic Materials

A wide variety of ceramics were ground using the dense vitreous bond SiC wheel to understand the cause of high G-ratio in grinding MgO-PSZ. All tests were conducted using Machine A with various materials and down feeds shown in Fig. 3. The G-ratio results are summarized as follows:

1. MgO-PSZ: The G-ratio data for MgO-PSZ, the baseline material, is duplicated from Fig. 2 for mutual comparison.
2. Y2O3-PSZ: Samples were ground at 0.0051 mm down feed and four different table speeds. Slightly better G-ratio, between 100 and 130, was observed.
3. AD-94: This SiC wheel had great difficulty grinding AD-94. Even at the smallest down feed (0.0025 mm) and lowest table speed (50.8 mm/s), the wheel stalled due to the large grinding force. The table speed was raised to 173 mm/s to increase the inertia of the table and the number of samples was reduced from five, as shown in Fig. 1, to just one. As shown in Fig. 3, very low G-ratio, 8, was recorded for grinding AD-94.
4. ZTA: The same problem repeated on SiC grinding of ZTA. Only one sample was ground at 0.0025 mm down feed and 173 mm/s table speed. The G-ratio was 21.

5. ZDY: The fully stabilized zirconia with 2.54 mm in width was ground at three different down feeds. Very high G-ratio of 206 was recorded while grinding at the highest down feed, 0.0127 mm. The high G-ratio at 0.0127 mm down feed may not be comparable to other results because the ZDY samples are thinner than regular samples. However, it is apparent that SiC can grind ZDY efficiently.

Grinding tests were also conducted on sintered silicon nitride with about 16 GPa Knoop hardness, compared to the 25 to 28 GPa Knoop hardness of the green SiC abrasive used in the wheel. The dense vitreous SiC wheel was not effective. The G-ratio results for ZDY indicates that the SiC is effective on both fully and partially stabilized zirconia. The G-ratio results for AD-94 and ZTA show this SiC wheel was not effective for grinding Al2O3-based ceramic. The wheel wear results are further discussed in Sec. 6 to explain a possible grinding mechanism for SiC grinding of PSZ.

3.3 Grinding Forces and Specific Grinding Energy. Figure 4 shows the specific grinding forces vs. specific material removal rate for the 12 baseline tests of SiC grinding of MgO-PSZ in Machine A. The specific grinding forces gradually increase at higher specific material removal rate. Compared to other studies using diamond and CBN grinding of zirconia [6,7], the specific forces for SiC grinding of zirconia are high. This indicates that a

Fig. 2 G-ratio vs. specific material removal rate for grinding tests conducted using Machines A and B

Fig. 3 G-ratio in SiC grinding of different ceramics

Fig. 4 Specific grinding forces for SiC grinding of MgO-PSZ
significant amount of energy, which eventually becomes heat in the abrasive-workpiece contact region, is generated.

The specific grinding energy, \( u \), was determined from the tangential force and wheel surface speed. In Fig. 5, the dimensionless specific grinding energy \( u/H \), i.e., \( u \) divided by the 11.8 GPa hardness of MgO-PSZ, is plotted against the maximum uncut chip thickness, \( h_m \). \( h_m \) is defined as [5]:

\[
h_m = \left[ \frac{3}{C \tan \theta} \frac{v_w}{v_s} \frac{a}{d_s} \right]^{1/2}
\]

where \( C \) is the number of active cutting grains per \( \text{mm}^2 \), \( \theta \) is the semi-included angle for the undeformed chip cross-section, \( v_w \) is the table speed, \( v_s \) is the wheel surface speed, \( a \) is the down feed, and \( d_s \) is the wheel diameter. In this study, \( C = 35 \text{ mm}^{-2} \) is estimated from SEM micrographs of wheel surface, and \( \theta = 60^\circ \) was used. As shown in Fig. 5, \( u/H \) ranges from 8.4 to 46, which is high compared to that for diamond grinding \( \text{Si}_3\text{N}_4 \) [8]. Figure 5 also shows that high \( u/H \) is generated at small \( h_m \). This follows the same inverse relationship between \( u/H \) and \( h_m \) observed in other grinding studies [8,9].

![Fig. 5 Dimensionless specific grinding energy vs. maximum undeformed chip thickness](image)

| Table speed: 50.8 mm/s | 50.8 mm/s | 229 mm/s |
| Down feed: 0.0025 mm | 0.0127 mm | 0.0025 mm |
| G-ratio: 65 | 56 | 113 |
| MRR (mm²/s): 0.13 | 0.64 | 0.58 |
| Wheel: SiC | SiC | SiC |

(a) (b) (c)

![Fig. 6 SEM micrographs of SiC and diamond-ground MgO-PSZ surfaces. (MRR: Material Removal Rate)](image)

| Table speed: 229 mm/s | 50.8 mm/s | 229 mm/s |
| Down feed: 0.0127 mm | 0.0025 mm | 0.0127 mm |
| G-ratio: 65 | -- | -- |
| MRR (mm²/s): 2.90 | 0.13 | 2.90 |
| Wheel: SiC | Diamond | Diamond |

(d) (e) (f)
where \( C_1 \) and \( C_2 \) are two parameters obtained from regression analysis. As shown in Fig. 5, \( C_1 = 23.8 \, \mu m \) and \( C_2 = -5.76 \).

The \( u \) for SiC grinding of MgO-PSZ ranges from 99 to 547 J/mm\(^3\), which is about 8 to 48 times higher than the 11.5 J/mm\(^3\) required to melt MgO-PSZ. This indicates that a significant amount of redundant energy is required in SiC grinding of MgO-PSZ. Most of the energy is converted into heat in the SiC abrasive and MgO-PSZ workpiece contact region.

4 **SEM Analysis**

A Hitachi S-4700 SEM was used to examine the surface and debris of MgO-PSZ ground by Machine A.

4.1 Ground Surface. Figure 6 shows SEM micrographs of the surface ground by SiC and diamond wheels. The surface ground with the lowest specific material removal rate, i.e., 0.0025 mm down feed and 50.8 mm/s table speed, is shown in Fig. 6(a). The surface is very smooth, about 0.35 \( \mu m \) \( R_a \), and free of

| Table 2  Results of phase analysis on SiC-ground MgO-PSZ surface |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                  | Machine A         |                  | Machine B         |                  |                  |                  |                  |                  |
|                  | Table speed (mm/s)| Down feed (mm)   |                  | Table speed (mm/s)|                  | Down feed (mm)   |                  |                  |
|                  | 0.0025            | 0.0051           | 0.0127           | 0.635            | 1.27             | 1.91             | 2.54             | 3.18             |
| 50.8             | 19.9%             | 18.4%            | 16.1%            | 0.42             | 13.7%            | 14.4%            | 14.6%            | 11.2%            | 12.0% |
| 112              | 20.0%             | 17.9%            | 17.2%            | 1.69             | 14.4%            | 15.1%            | 15.6%            | 14.0%            |
| 112              | 19.0%             | 21.0%            | 17.0%            | 2.54             | 14.7%            | 13.6%            | 12.1%            |                  |
| 229              | 17.0%             | 19.6%            | 16.8%            | 3.39             | 15.1%            | 14.1%            |                  |                  |
|                  |                   |                  |                  | 6.77             | 15.4%            |                  |                  |                  |

Fig. 7 Debris of SiC- and diamond-ground MgO-PSZ
cracks. The original porosity of the MgO-PSZ can be observed. At 0.0127 mm down feed, as seen in Fig. 6(b), a network of surface cracks, possibly due to the thermal stress, becomes apparent. Interestingly, the surface cracks disappear at the highest table speed (229 mm/s) and down feed (0.0127 mm), as shown in Fig. 6(d). Comparing Figs. 6(c) and 6(d), at the same table speed but smaller down feed (0.0025 mm), the ground surface still shows some surface cracking. It is not clear how grinding conditions produce the trend of surface cracking seen in Fig. 6. Further study is required.

SEM micrographs of the MgO-PSZ surface ground in Machine A by a resinoid bond diamond wheel with the same abrasive size (220 ANSI mesh) as in the SiC wheel are shown in Figs. 6(e) and 6(f). These two figures correspond to the SiC-ground surfaces in Figs. 6(a) and 6(d). All diamond-ground surfaces are free of surface cracking.

4.2 Debris. SEM micrographs of collected grinding debris for SiC-ground MgO-PSZ are shown in Fig. 7. The SEM micrographs correspond to the same four sets of process parameters shown in Fig. 6. The size of the debris for all grinding conditions is small, ranging from 2 to 5 μm. Conglomeration of debris was a problem. It is difficult to identify individual grinding chips. At the smallest down feed and lowest table speed, as shown in Fig. 7(a), the debris shows a flat surface on one side and a striated surface on the other. This morphology is similar to metal cutting chips. It could be explained by “ductile regime” grinding [10] in which the brittle material grinds like ductile metals. The other three grinding conditions do not show chip formation as clearly as in Fig. 7(a). Figures 7(e) and 7(f) show debris generated by the diamond wheel. The two sets of process parameters are the same as those in Figs. 7(a) and 7(d). Smaller particles, about 1–2 μm in size, can be seen for diamond grinding.

5 X-ray Diffraction Analysis

At room temperature, the MgO-PSZ base material consists of three phases: monoclinic, cubic, and tetragonal [11]. The cubic and tetragonal are the two meta-stable phases. The metastable tetragonal phase can transform to monoclinic phase under applied stress. A Scintag X-ray diffractometer with a Cu source was used. The percent of monoclinic phase was determined using an analysis described by Garvie and Nicholson [12]. As the peaks on the X-ray scan for cubic and tetragonal phases are too close to separate, the combined cubic and tetragonal phase and the monoclinic phase are calculated and reported. X-ray diffraction results for the base material, ground surface, and debris are presented in this section.

The original surface of the base MgO-PSZ block contains 9.9% of the monoclinic phase. The surface was then polished to remove possible contamination on the surface layer. That surface showed 10.7% of the monoclinic phase. This shows that the base material contains approximately 10% of the monoclinic phase.

Table 2 summarizes the percentage of monoclinic phase on the surface after grinding by the SiC wheel for Machines A and B under various down feeds and table speeds. The percentage of monoclinic phase on all ground surfaces increases beyond the 10% for the original MgO-PSZ due to the stress or temperature generated during grinding. All ground surfaces have therefore experienced some phase transformation. The percentage of the monoclinic phase on Machine A ground surfaces was larger than that for Machine B. This could be explained by previous grinding studies, which show that less heat is transferred to the surface in the creep feed grinding used in Machine B [13,14]. No systematic trend can be seen in Table 2 for the effects of down feed and table speed.

Table 3 summarizes the X-ray diffraction results for the MgO-PSZ debris ground using SiC and diamond wheels at two table speeds and three down feeds. Although the MgO-PSZ debris has undergone large deformation and experienced high temperature, no monoclinic phase (0%) could be found in SiC-ground debris. Based on the MgO-PSZ phase diagram [11], as shown in Fig. 8, one would expect to find significant amounts of monoclinic phase if the temperature remains below 1240°C. However, flash temperature measurements in SiC grinding of MgO-PSZ [15] showed that the SiC-ground chips experienced temperature above 2700°C. At this temperature, all of the monoclinic phase will be absent.

### Table 3 Results of phase analysis on SiC- and diamond-ground MgO-PSZ debris

<table>
<thead>
<tr>
<th>Table speed (mm/s)</th>
<th>SiC Wheel</th>
<th>Diamond Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down feed (mm)</td>
<td>Percentage of Monoclinic Phase</td>
<td>Down feed (mm)</td>
</tr>
<tr>
<td>50.8</td>
<td>0.0025</td>
<td>0.0051</td>
</tr>
<tr>
<td>229</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

*Another test sample recorded 0% monoclinic phase.

---

**Fig. 8** Phase diagram of MgO-PSZ [11]

**Fig. 9** Comparison of thermal conductivity of abrasive and work materials
Cooling from this high temperature would then suppress any further formation of monoclinic phase, assuming that the tetragonal precipitates are sub-critical in size [11]. This appears to be the likely scenario for the absence of monoclinic phase in the grinding chips for the SiC wheel.

In contrast to the SiC-ground debris, the diamond-ground debris contains some monoclinic phase. However, the amount is less than that of base material, which again indicates high temperature. Temperature measurements [15] also showed flash temperatures in the order of 2700°C for diamond grinding of MgO-PSZ. The fact that some monoclinic phase is found in the latter case indicates that the temperature profile is different for SiC- and diamond-ground debris.

6 Discussion

The difference in thermal conductivity of SiC and diamond is likely to be the cause for the change in percentage of monoclinic phase in SiC- and diamond-ground MgO-PSZ debris. As shown in Fig. 9, the thermal conductivity of PSZ is very low, about 2 W/m-K, whereas the thermal conductivity of green SiC and diamond is about 120 and 2300 W/m-K, respectively. The very low thermal conductivity of the PSZ will cause a large fraction of the heat to be retained in the chip, producing high flash temperature for the grinding debris. These high temperatures can also soften the PSZ during chip formation and should be a major contributing factor for high efficiency grinding of PSZ using a SiC wheel.

If the above hypothesis is valid, this will explain why this SiC wheel cannot grind other commercial ceramics. For example, alumina, which has about the same hardness as other zirconia-based work-materials, cannot be ground with the same SiC wheel used for PSZ, as shown in the G-ratio results in Fig. 3. The thermal conductivity of alumina is about 36 W/m-K, much higher than that of PSZ. The flash temperature for the alumina debris is expected to be lower than the PSZ, which would not facilitate grinding as it does for the PSZ.

To further verify this hypothesis, estimating the partitioning of the heat generated in grinding to the workpiece, chip, abrasive, and coolant is necessary. From previous studies on CBN and Al₂O₃ grinding of steel, thermal conductivity of the abrasive has a significant impact on the heat partitioning. The thermal conductivity of CBN, Al₂O₃, and steel are also shown in Fig. 9. Kohli et al. [16] and Guo et al. [17] have measured and calculated that about 60–75% of grinding energy is transported to the steel workpiece as heat with the Al₂O₃ wheels, as compared to only 8–20% with CBN wheels. In diamond grinding of Si₃N₄, Zhu et al. [18] have concluded that 16–24% of the grinding energy is transported as heat to the workpiece in wet grinding. With the very low thermal conductivity of the PSZ, compared to that of steel and Si₃N₄, even less grinding energy is transferred to the workpiece. Thus, an extensive amount of grinding energy generated during SiC grinding of PSZ is likely to become heat and to be retained in the chip.

7 Concluding Remarks

A dense vitreous bond SiC wheel for grinding of various ceramics was studied. Wheel wear results demonstrated that SiC wheels could grind zirconia, both fully and partially stabilized, very effectively. The same wheel was not as effective on other ceramics, including alumina and silicon nitride. X-ray diffraction analysis showed 0% monoclinic phase in MgO-PSZ debris from a SiC wheel. This indicates a possible cause of high G-ratio in SiC grinding of zirconia: the low thermal conductivity of zirconia and SiC, compared to that of diamond, retains the heat in zirconia chips, softens the work-material, and makes efficient grinding possible. Grinding temperature measurements in a companion study [15] supported this hypothesis.

Acknowledgments

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