Mechanical Properties and Microstructure of Al$_2$O$_3$/WC-Co Composites

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Abstract

Alumina and cemented carbides are ceramic materials successfully used for metal cutting tools because they provide strength, hardness and durability. However, alumina has poor toughness and the carbides with a cobalt binder do not allow high speed cutting and can easily deform due to heat generated while cutting. Therefore, a combination of alumina and tungsten carbide-cobalt is of interest. The components of 90wt% alumina and 10wt% of particle reinforcement containing various ratios of tungsten carbide and cobalt were prepared by conventional powder processing. Then, the powder mixtures were pressed and sintered at 1500 and 1600°C for 2 hours in an argon atmosphere. Physical and mechanical properties of the composites, such as density, hardness and fracture toughness including microstructure were investigated. It was found that the composites of 96-98%TD were achieved after sintering at 1600°C. The prepared Al$_2$O$_3$/WC-Co composites provided both hardness and fracture toughness between 17-18 GPa and 5-8 MPa m$^{1/2}$, respectively, which are still appropriate for cutting tool applications.

Key words: Al$_2$O$_3$/WC-Co composites, particulate reinforcements, cutting tools

Introduction

There are many ceramic materials can be used for cutting tool applications e.g. alumina, nitrides and carbides. Alumina (Al$_2$O$_3$) has been commonly used for metals and alloys machining. Apart from its outstanding properties, such as hardness, chemical stability and wear resistance$^{[1-3]}$, it can withstand high temperatures caused by friction while cutting, resulting in higher cutting speed. Tungsten carbide (WC) is another alternative due to comparatively similar hardness, but higher elastic modulus compared to other carbides$^{[4]}$. In general, WC particles are combined with a small amount of cobalt (Co) as a binding agent, so called a tungsten carbide-cobalt composite (WC-Co). Even the WC-Co offers superior toughness, the cemented carbide still has some main drawbacks; it is difficult to sinter and tends to have high temperature deformation during cutting operation. In order to get desirable properties, a composite of Al$_2$O$_3$ matrix containing WC-Co has been introduced. A presence of WC particles in alumina can improve mechanical properties and microstructure by inhibiting grain growth of alumina whereas alumina offers thermal and dimensional stability$^{[5]}$. Several studies have been focused the nature and characteristics of the Al$_2$O$_3$/WC composites as reported elsewhere$^{[1,4,5]}$. However, a combination of Al$_2$O$_3$ and WC-Co are not extensively studied and not clearly understood.

This work covers the mechanical properties of the Al$_2$O$_3$ matrix composites with an existence of WC-Co. Hardness and fracture toughness including phase analysis and microstructure as a function of Co content as well as sintering temperatures are to be determined.

Materials and Experimental Procedures

There were three main powders used; Al$_2$O$_3$ (AKP-30, 99.99%purity, 0.3 µm, Sumitomo, Japan), WC (1.2 µm, ATI Engineered Products, USA) and Co (99.8%purity, 2 µm, Marshall Hard Metals Ltd, Sheffield, U.K.). The Al$_2$O$_3$/WC-Co composites were prepared from the mixture among the three, as shown in Table 1. The chemical composition contained 90wt% Al$_2$O$_3$ and 10wt% of reinforcement, with various ratio of WC to Co powders. Pure Al$_2$O$_3$ and WC-Co specimens were also prepared and used as standard samples. The powders were wet-mixed for 4 hours in ethanol. The blend were then unidirectionally pressed and

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sintered at 1500°C and 1600°C for 2 hours in argon. Density was measured using liquid immersion. Grain size was determined by linear intercept method. Phase content was derived from X-ray diffractometer. Hardness and fracture toughness were determined by Vickers indentation. Finally, microstructures were revealed by thermal etching and observed using scanning electron microscopy.

Table 1. Chemical compositions of the composites.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Powder content (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al2O3</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

Results and Discussion

From XRD pattern of the Al2O3/WC-Co composites sintered at 1500°C and 1600°C in Figure 1, Al2O3 and WC peaks were detected but no interactions between them were determined. Co peaks were not found. This could be caused by two assumptions: (1) there was a very small amount of Co in the powder mixture and (2) the melting point of Co itself. A presence of up to 6wt% Co might not enough to be analyzed by the mean of XRD technique. According to Co, its melting point is approximately 1500°C, Co could be volatile or become liquid while sintering, leaving fine of pores or solidified Co situated along grain boundaries at Al2O3 and WC powders.

Figure 2 presents the microstructure of the monolithic Al2O3 and the composite sintered at 1600°C. The bright particles were WC while the grey background was Al2O3. WC particles homogenously dispersed in the Al2O3 matrix. The addition of WC-Co in the alumina matrix resulted in smaller grain size due to the pinning effect.

Figure 3 shows a comparisons of properties of alumina-matrix composites compared to alumina and WC-Co materials. The density values of all 90wt% alumina and 10wt%WC-Co composites sintered at 1500°C were less than those sintered at 1600°C due to incomplete densification. The densities of the 90wt% Al2O3 and 10wt%WC-Co (composition 2 to 5) were achieved up to 98%TD when sintered at 1600°C, regardless to Co content.
Figure 3. Characteristics of the 90wt% alumina and 10wt%WC-Co composites at various conditions.

Sintering temperatures had slightly effect on hardness, the values of which sintered at 1500°C and 1600°C were comparatively similar. In this work, the 90wt% Al₂O₃ and 10wt% WC-Co composites provided the hardness values - falling between 17-18 GPa. However, sintering temperatures may influence more on the fracture toughness. The values of fracture toughness of the 90wt% Al₂O₃ and 10wt%WC-Co sintered at 1500°C were less than those sintered at 1600°C. As for the WC-Co samples, no crack lines were found because the material was relatively tough according to Co content, this could be inferred that WC-Co offered high toughness but the toughness cannot be determined by the mean of Vickers indentation.

Table 2 shows the comparisons of physical and mechanical properties of the Al₂O₃/WC-Co composites. The density values of all composites Al₂O₃/WC-Co up to 98%TD were obtained. The Al₂O₃/WC-Co composites sintered at 1600°C provided hardness which were in the range of 17-18 GPa. This values suggested that the Al₂O₃/WC-Co system were suitable to be used as cutting tools, which generally tall between 17-22.5 GPa.⁵

The fracture toughness tended to rise with higher Co content. This may be explained from the assumptions mentioned earlier. If Co itself melted and settled along the grain boundaries of Al₂O₃ and WC, Co could partially absorb stress at crack tips. Alternatively, if Co volatiled and left very fine pores in the structure, these fine pores can relieve stress as well. However, the pores or intergranular phase of Co were not much affected to strength due to its very small amount. Both actions eventually inhibited crack propagation and may slightly rise fracture toughness when determined from Vickers indentation technique.

Table 2. Properties of the Al₂O₃/WC-Co composites at various compositions sintered at 1600 °C

<table>
<thead>
<tr>
<th>composition</th>
<th>Powder content (wt%)</th>
<th>Density (%TD)</th>
<th>Hardness (GPa)</th>
<th>Toughness (MPa m¹/₂)</th>
<th>Strength (MPa)</th>
<th>average grain size [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure Al₂O₃</td>
<td>99.2 ± 0.2</td>
<td>16.9± 0.8</td>
<td>3.8± 0.8</td>
<td>202± 32</td>
<td>3.5±0.6</td>
</tr>
<tr>
<td>2</td>
<td>90 wt% Al₂O₃ +10 wt% WC +0 wt% Co</td>
<td>97.0± 0.3</td>
<td>18.0± 0.4</td>
<td>4.7± 0.6</td>
<td>336± 45</td>
<td>1.3±0.1</td>
</tr>
<tr>
<td>3</td>
<td>90 wt% Al₂O₃ +9.4 wt% WC +0.6 wt% Co</td>
<td>96.9± 0.2</td>
<td>17.1± 0.5</td>
<td>5.7± 0.6</td>
<td>349± 38</td>
<td>1.05±0.4</td>
</tr>
<tr>
<td>4</td>
<td>90 wt% Al₂O₃ +9 wt% WC +1.0 wt% Co</td>
<td>96.7± 0.3</td>
<td>18.1± 0.7</td>
<td>5.5± 0.4</td>
<td>353± 14</td>
<td>1.29±0.6</td>
</tr>
<tr>
<td>5</td>
<td>90 wt% Al₂O₃ +7 wt% WC +3.0 wt% Co</td>
<td>98.7± 0.1</td>
<td>17.6± 0.5</td>
<td>8.0±0.6</td>
<td>374± 61</td>
<td>1.34±0.4</td>
</tr>
<tr>
<td>6</td>
<td>94 wt% WC +6 wt% Co</td>
<td>96.1± 0.7</td>
<td>16.7± 0.7</td>
<td>no crack lines</td>
<td>125± 122</td>
<td>-</td>
</tr>
</tbody>
</table>
Conclusions

1) The additions of WC and Co particles to pure Al$_2$O$_3$ increased the fracture toughness from 3.8 to 10.3 MPa m$^{1/2}$
2) No Co phase could be detected neither by XRD nor by EDS techniques.
3) Sintering temperatures increased density as well as fracture toughness but it affected slightly on hardness.
4) Al$_2$O$_3$/WC-Co composites have hardness of 17-18 GPa. However, hardness were not very sensitive to chemical composition between WC and Co in the reinforced particles.
5) Fracture toughness were between 5-8 MPa m$^{1/2}$ and slightly increased with Co content.
6) The Al$_2$O$_3$/WC-Co composites provide hardness fracture toughness as well as strength while are appropriate to use as cutting tools materials.

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References