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# Effect of $Al_2O_3$ on mechanical properties of $Ti_3SiC_2/Al_2O_3$ composite

H.J. Wang[a,*], Z.H. Jin[a], Y. Miyamoto[b]

[a]*School of Material Science & Engineering, Xi'an Jiaotong University, Xi'an Shaanxi 710049, People's Republic of China*
[b]*Joining and Welding Research Institute, Osaka University, Ibaraki 567, Osaka, Japan*

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**Abstract**

The effect of $Al_2O_3$ on mechanical properties of $Ti_3SiC_2/Al_2O_3$ composite fabricated by SPS was studied systematically. The results show that the hardness of the $Ti_3SiC_2/Al_2O_3$ composite can reach 10.28 GPa, 50% higher than that of pure $Ti_3SiC_2$. However, slight decrease in the other mechanical properties was observed with $Al_2O_3$ addition higher than 5–10 vol.%, which is believed to be due to the agglomeration of $Al_2O_3$ in the composite.


*Keywords:* B. Composites; C. Mechanical properties; D. $Al_2O_3$; $Ti_3SiC_2$; Agglomeration

## 1. Introduction

$Ti_3SiC_2$ is a remarkable material for its combination of properties such as high toughness, high fatigue-crack growth threshold, high Young's modulus, moderate flexural strength, plasticity at high temperature, good electrical conductivity, excellent chemical resistance, high thermal shock resistance, easy machinability, etc. [1–5]. It is expected, therefore, to apply $Ti_3SiC_2$ to various tough components such as commutating brushes for motors, armor, bearing and turbine blades. However, its relatively low hardness (4–5 Gpa) [6,7], leads to poor wear resistance, which limits its application as a structural component.

It has been shown that the addition of $Al_2O_3$ can increase the hardness of some silicon-based composites. This motivated the study in this paper to fabricate the $Ti_3SiC_2/Al_2O_3$ composite directly from raw powders of $Ti/TiC/Si/Al_2O_3$ using the spark plasma sintering (SPS) technique. The mechanical properties of the composites with different $Al_2O_3$ content were compared, assisted with the microstrutural observation on the fracture surface.

## 2. Experimental procedure

High-purity powders of titanium (45 μm, Grade TSPT-350, Sumitomo Sitix of Amagasaki, Inc, Japan), TiC (1.36 μm, New metal Co, Ltd, Japan), Si (purity > 99.99%, 200 mesh, High purity Chemical Co, Ltd, Japan) and $Al_2O_3$ (AKP-30, Sumitomo Chemical Co. Japan) were mixed to yield a final composition with the appropriate stoichiometry, as shown in Table 1.

The powder mixtures were pressed in a graphite die with 30 mm inner diameter. Then the green compacts were hot pressed in the SPS system at 40 MPa in vacuum. The sintering temperature was 1200–1400 °C, with soaking time ranging from 5 to 15 min and a heating rate of 100 K/min.

The surfaces of the sintered samples were machined to remove the layer contaminated by the carbon sheet, using a fine grit, high speed diamond wheel.

X-ray diffraction (XRD) was used to determine the phase composition and relative $Ti_3SiC_2$ content in the composite. The sample density and porosity were measured by Archimedes' method. Samples for Vickers hardness measurement were polished with diamond paste. An Ultra-Micro Indentation System (UMIS-2000) was used for the measurement with 15 s holding time at a load of 98 N.

* Corresponding author. Tel.: +86-29-2667942; fax: +86-29-3237910.
*E-mail address:* hjwang@mail.xjtu.edu.cn (H.J. Wang).

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Table 1
The volume content of $Al_2O_3$ in the designed compositions

| No. | $Ti_3SiC_2$ (vol.%) | $Al_2O_3$ (vol.%) |
|---|---|---|
| 1 | 95 | 5 |
| 2 | 90 | 10 |
| 3 | 80 | 20 |

Specimens for flexural strength and $K_{IC}$ tests were cut and ground. The three-point bending flexural strength was measured on Instron-1195 machine with cross head speed of 0.5 mm/min and span of 18 mm. The fracture toughness measurement was conducted using the single-edge notched beam (SENB) method with the specimen dimensions of 3×4×20 mm. The pre-crack was introduced by indentation in the middle of the specimen on an Instron 1195 machine. The microstructure and fracture surface of selected samples were observed by SEM (Jeol, made in Japan) and EPMA (JXA-8600, made in Japan).

## 3. Results and discussion

### 3.1. Effect of $Al_2O_3$ on properties of $Ti_3SiC_2$/ $Al_2O_3$

Fig. 1 shows the density and hardness of the $Ti_3SiC_2$/$Al_2O_3$ composites as a function of the $Al_2O_3$ volume content. All the samples were sintered at 1300 °C for 10 min. The density does not show much variance for $Al_2O_3$ content between 0 and 20 vol.%. However, a significant increase in hardness is observed when the $Al_2O_3$ content exceeds 10%. The $Ti_3SiC_2$/20 vol. % $Al_2O_3$ composite shows a hardness value of 10.29 Gpa, which is 50% higher than that of the pure $Ti_3SiC_2$ (6.69 GPa). Fig. 2 shows the $Ti_3SiC_2$ phase content as a function of $Al_2O_3$ content sintered at 1300°c for 10 min. When the $Al_2O_3$ content increases from 0 to 10 vol.%, the volume content of $Ti_3SiC_2$ also increases from 92 to 96%. The content of $Ti_3SiC_2$ gradually decreases when the $Al_2O_3$ content exceeds 10 vol.%.

Fig. 3 shows the effect of $Al_2O_3$ content on the flexural strength and fracture toughness of the composite sintered at 1300 °C for 10 min under 40 Mpa pressure. A gradual increase in $\sigma_b$ and $K_{IC}$ is observed for $Al_2O_3$ lower than 5–10 vol.%. Further increase of $Al_2O_3$ content slightly decreases the composite strength, yet the toughness almost remains constant.

### 3.2. Microstructure observation

Fig. 4 shows the microstructure of some selected $Ti_3SiC_2$/$Al_2O_3$ specimens sintered at 1200 °C for 5 min. The $Al_2O_3$ grains are uniformly distributed in the grain boundary [Fig. 4(e),(f)]. The pure $Ti_3SiC_2$ sample shows an average grain size of 10 μm. With increasing $Al_2O_3$ content, a finer microstructure is obtained with decreasing grain size. For the $Ti_3SiC_2$/10%$Al_2O_3$ composite, the average grain size is only 1 μm, which could

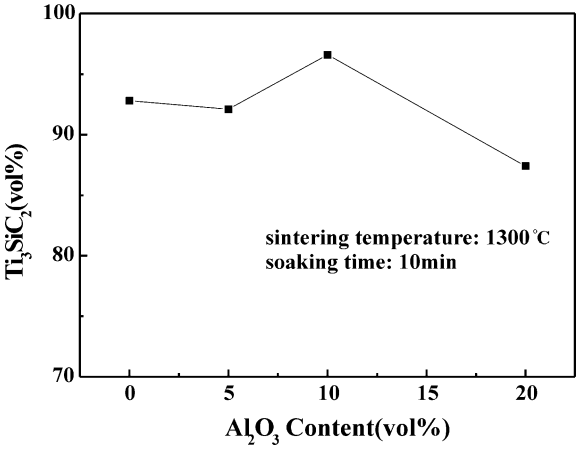



Fig. 2. The effect of $Al_2O_3$ on the $Ti_3SiC_2$ content of $Ti_3SiC_2$/$Al_2O_3$ composite.

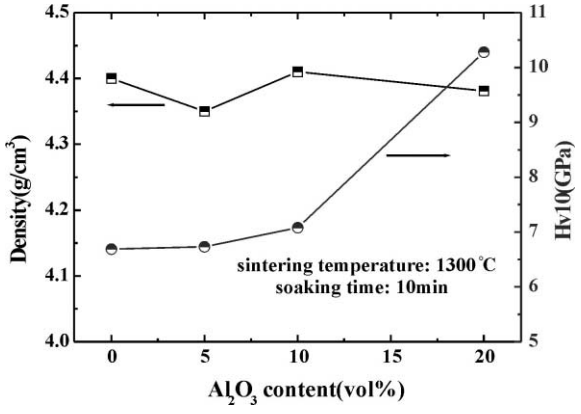



Fig. 1. The effect of $Al_2O_3$ on the density and hardness of $Ti_3SiC_2$/$Al_2O_3$ composite.

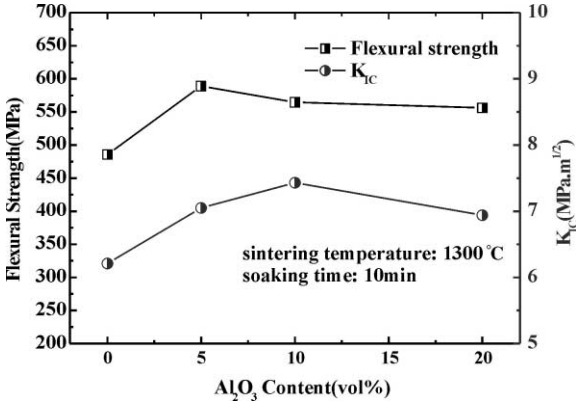
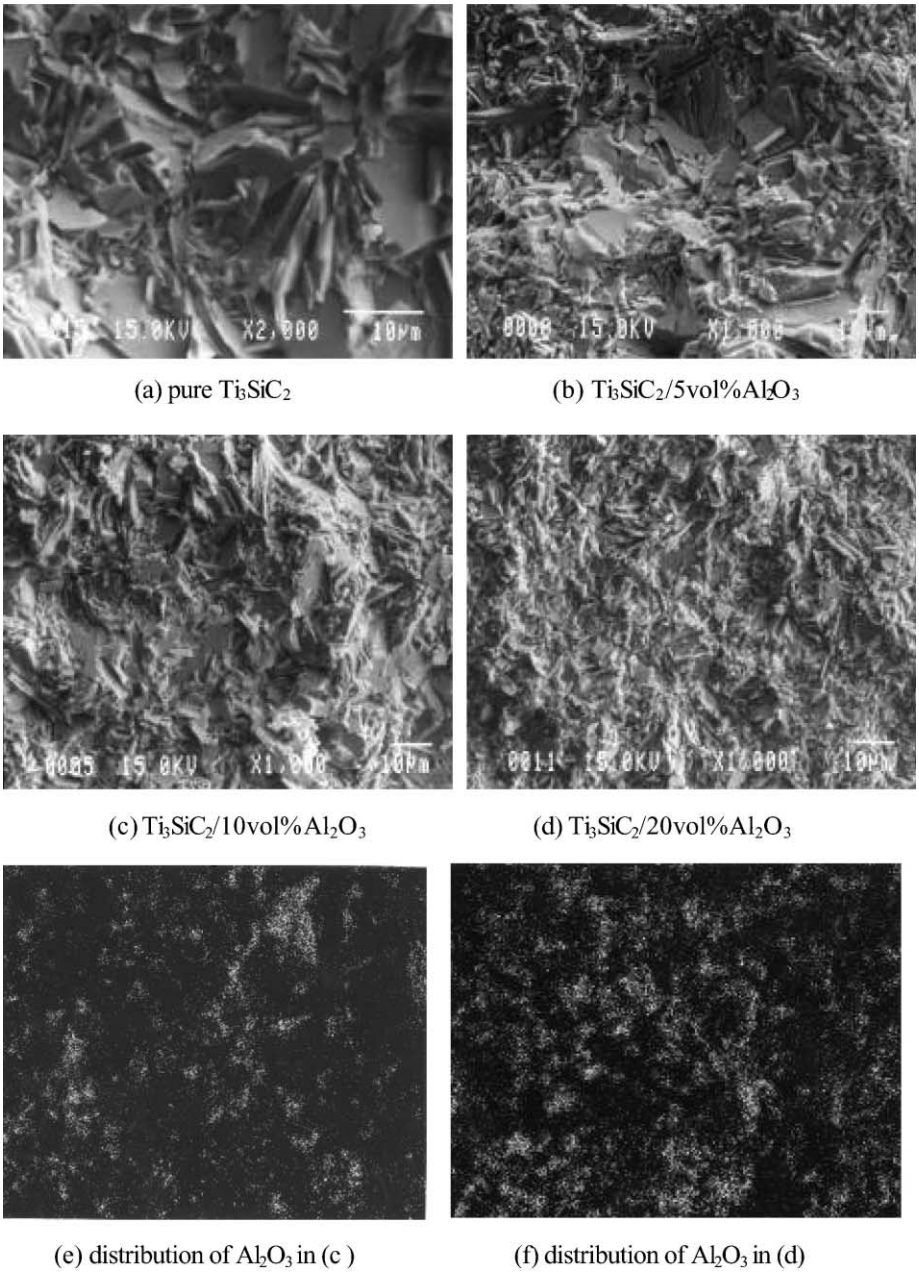



Fig. 3. The effect of $Al_2O_3$ on the flexural strength and fracture toughness of $Ti_3SiC_2$/$Al_2O_3$ composite.

be responsible for the slight increase in $\sigma_b$ and $K_{IC}$. Such microstructural evolution can be understood if it is postulated that the $Al_2O_3$ grains inhibit grain growth and the grain-boundary mobilities. But when the $Al_2O_3$ content exceeds 10vol%, the agglomeration of the $Al_2O_3$ grains is observed [Fig. 4(f)], lead to the decrease in $\sigma_b$ and $K_{IC}$.

Fig. 5 shows the microstructure evolution of $Ti_3SiC_2$/10 vol.%$Al_2O_3$ sintered at 1400 °C for 5 min. Compared with Fig. 4(c), higher sintering temperatures results in coarser-grained microstructure. Fig. 5(b) shows the dispersion of $Al_2O_3$ in the composite. Compared with Fig. 4(e), the agglomeration of $Al_2O_3$ can be seen more obviously in the 1400 °C sintered sample, which consists of partially sintered $Al_2O_3$. When the temperature reaches 1400 °C, the grain size becomes larger, which may be the reason for the decrease of $\sigma_b$. But because of the card-frame structure is unaffected at this temperature, the fracture toughness does not change obviously [8].

In conclusion, this study has shown the improvement of the hardness of $Ti_3SiC_2$ material with addition of

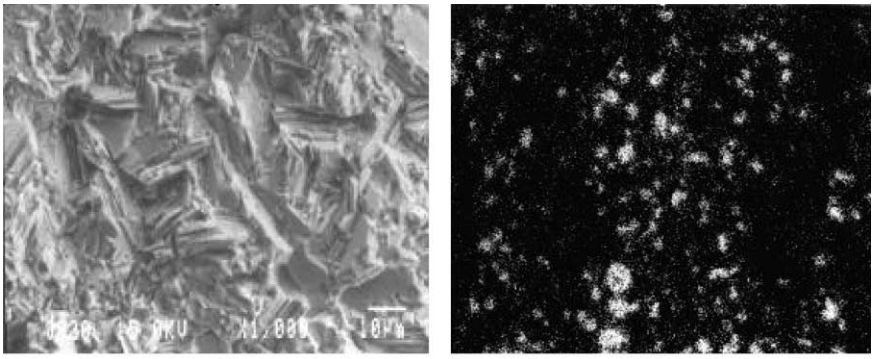


(a) pure $Ti_3SiC_2$ (b) $Ti_3SiC_2$/5vol%$Al_2O_3$

(c) $Ti_3SiC_2$/10vol%$Al_2O_3$ (d) $Ti_3SiC_2$/20vol%$Al_2O_3$

(e) distribution of $Al_2O_3$ in (c ) (f) distribution of $Al_2O_3$ in (d)

Fig. 4. Fracture surface and distribution of $Al_2O_3$.



(a) fracture surface (b) distribution of $Al_2O_3$

Fig. 5. Fracture surface and distribution of $Al_2O_3$ of $Ti_3SiC_2$/10 vol.%$Al_2O_3$ sintered at 1400 °C.

$Al_2O_3$. Suitable $Al_2O_3$ content is about 10–20 vol.%. The sintering temperature should not exceed 1350°C; otherwise the agglomeration of $Al_2O_3$ occurs and decreases the composite strength and toughness.

## 4. Conclusion

1. $Al_2O_3$ is an effective dopant to increase the hardness of $Ti_3SiC_2$. The $Ti_3SiC_2$/20vol%$Al_2O_3$ composite shows hardness of about 10.28 GPa, which is 50% higher than that of pure $Ti_3SiC_2$.
2. The addition of $Al_2O_3$ slightly decreases the other properties, such as $Ti_3SiC_2$ content, strength and fracture toughness, of composite.
3. It is viable to add some $Al_2O_3$ to $Ti_3SiC_2$ in order to increase its wearability, and the appropriate content is about 10–20 vol.%.

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