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Ceramics International 34 (2008) 1361–1366
CERAMICS INTERNATIONAL
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Microstructure and mechanical properties of hot-pressed SiC/(W, Ti)C ceramic composites

Deng Jianxin*, Zhao Jinlong, Li Yousheng, Song Wenlong

Department of Mechanical Engineering, Shandong University, Jinan 250061, Shandong Province, PR China

Received 5 May 2006; received in revised form 20 July 2006; accepted 2 March 2007
Available online 8 April 2007

Abstract

SiC/(W, Ti)C ceramic composites with different content of (W, Ti)C solid-solution were produced by hot pressing. The effect of (W, Ti)C content on the microstructure and mechanical properties of SiC/(W, Ti)C ceramic composites has been studied. Densification rates of the SiC/(W, Ti)C ceramic composites were found to be affected by addition of (W, Ti)C. Increasing (W, Ti)C content led to increase the densification rates of the composites. The sintering temperature was lowered from 2100 °C for monolithic SiC to 1900 °C for the SiC/(W, Ti)C composites. Results show that additions of (W, Ti)C to SiC matrix resulted in improved mechanical properties compared to pure SiC ceramic. The fracture toughness and flexural strength continuously increased with increasing (W, Ti)C content up to 60 vol.%, while the hardness decreased with increasing (W, Ti)C content.

Keywords: C. Mechanical properties; D. SiC; (W, Ti)C; Ceramic composites; Microstructure

1. Introduction

Silicon carbide (SiC) is one of the most useful ceramics in modern engineering applications because of its high hardness, high wear resistance, high melting point, good chemical inertness, high Young's modulus and thermal conductivity as well as high thermal shock resistance; that make it promising candidate for wear resistance components. Compared with ceramics such as Si_3N_4, ZrO_2, etc., the strength of monolithic SiC ceramic material is rather lower (about 200–300 MPa), and its fracture toughness is about 2–4 MPa $m^{1/2}$ [1–5]. Moreover, the poor sinterability of SiC limits its application because both high temperature and high pressure are required for a complete densification.

In earlier studies [6–12], some of the SiC-based composites, e.g., SiC/TiC, SiC/TiB_2, SiC/B_4C, SiC/Al_2O_3, SiC/Al, etc., have been developed and used in various applications, mechanical properties and microstructure studies on them are also extensively carried out. It has been shown that the additions of secondary phases to SiC matrix can improve its mechanical properties, i.e. fracture toughness and flexural strength.

In this paper, SiC-based ceramic composites with different content of (W, Ti)C solid-solution were produced by hot pressing. The mechanical properties and the microstructure of these composites have been studied. Particular attention was paid to the effect of (W, Ti)C additions on the mechanical properties and microstructure.

2. Experimental procedure

2.1. Materials and processing

The starting powders used to fabricate the SiC/(W, Ti)C composites are listed in Table 1 with their particle size, purity and manufacturer. SiC was used as the baseline material. (W, Ti)C solid-solution particles were added to SiC matrix. The range of (W, Ti)C additions to the SiC was from 0 to 60 vol.%. The combined powders were prepared by wet ball milling in alcohol for 150 h with cemented carbide balls. Following drying, the final densification of the compacted powder was accomplished by hot pressing with a pressure of 35 MPa in

* Corresponding author. Tel.: +86 531 88392047.
E-mail address: jxdeng@sdu.edu.cn (J. Deng).

0272-8842/$34.00
doi:10.1016/j.ceramint.2007.03.003

Table 1
Particle size, purity and manufacturer of the starting powders

Starting powder	Average particle size (μm)	Purity (%)	Manufacture
SiC	3–5	>98	Beijing Antai Advanced Technology and Materials Co. Ltd.
(W, Ti)C	1–2	>99	Zhuzhou cemented carbide works

argon atmosphere for 30–70 min to produce a ceramic disk. The maximum temperature employed for hot pressing was less than 2100 °C.

2.2. Material characterization

Densities of the hot-pressed disks were measured by the Archimedes's method. Test pieces of 3 mm × 4 mm × 36 mm were prepared from the disk by cutting and grinding using a diamond wheel and were used to flexural strength, Vickers hardness and fracture toughness tests. Three-point-bending mode was used to measure the flexural strength over a 30 mm span at a crosshead speed of 0.5 mm/min. Fracture toughness measurement was performed using indentation method in a hardness tester (ZWICK3212) using the formula proposed by Cook and Lawn [13]. On the same apparatus the Vickers hardness was measured on polished surface with a load of 98 N. Data for hardness, flexural strength, and fracture toughness were collected on five specimens.

XRD (D/max-2400) analysis was undertaken to identify the crystal phases present after sintering. The microstructures of sintered materials were studied on fracture surfaces and polished section by scanning electron microscopy (HITACHI S-570) and optical microscopy.

3. Results and discussion

3.1. Densification of SiC/(W, Ti)C ceramic composites

Densification rates of the SiC/(W, Ti)C ceramic composites were found to be affected by additions of (W, Ti)C solid-solution. Increasing content of (W, Ti)C led to increase the densification rates of composites relative to monolithic SiC as can be seen in Fig. 1 and Table 2. The relative density of SiC/60 vol.% (W, Ti)C composite reaches 99.3% after sintering at temperature 1900 °C for 40 min; while it is only 96.3% for monolithic SiC ceramic after sintering at temperature 2100 °C for 70 min. The sintering temperature was lowered from 2100 °C for monolithic SiC to 1900 °C for SiC/(W, Ti)C composites.

3.2. Microstructural characterization of SiC/(W, Ti)C ceramic composites

Fig. 2 illustrates the X-ray diffraction analysis of the SiC/60 vol.% (W, Ti)C ceramic composite after sintered at temperature 1900 °C for 40 min. It can be seen that both (W, Ti)C and SiC existed in the sintered specimens.

Fig. 3 shows the SEM micrographs of the fracture surface of monolithic SiC ceramic after sintering at temperature 1700 °C for 60 min, which reveals quite a number of cavities. It is obvious that the monolithic SiC ceramic is porous under these sintering conditions.

The SEM micrographs of the fracture surface of monolithic SiC ceramic after sintering at temperature 2100 °C for 60 min are shown in Fig. 4. The monolithic SiC ceramic clearly exhibited a flat fracture surface, resulting from the transgranular fracture mode, and there are a lot of obvious pores located at the SiC grain boundary. An increase of the grain size (4–10 μm) was observed under these sintering conditions.

Figs. 5–7 show the SEM micrographs of the fracture surface of SiC/60 vol.% (W, Ti)C ceramic composite after sintering at temperature of 1700, 1800, and 1900 °C, respectively. From these SEM micrographs, different morphologies of the

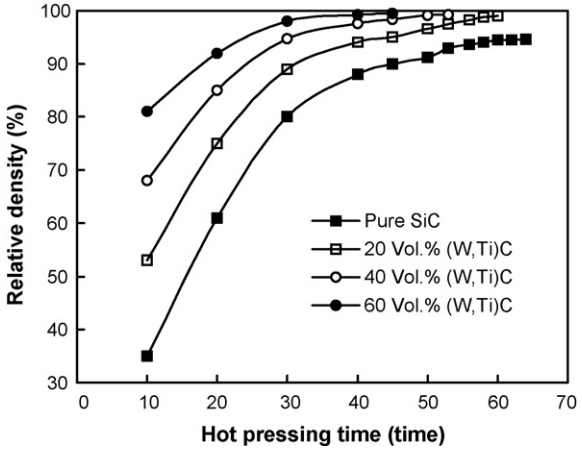

Fig. 1. Densification behavior under hot-pressing conditions of monolithic SiC and SiC/(W, Ti)C ceramic composites (sintering temperature 1900 °C).

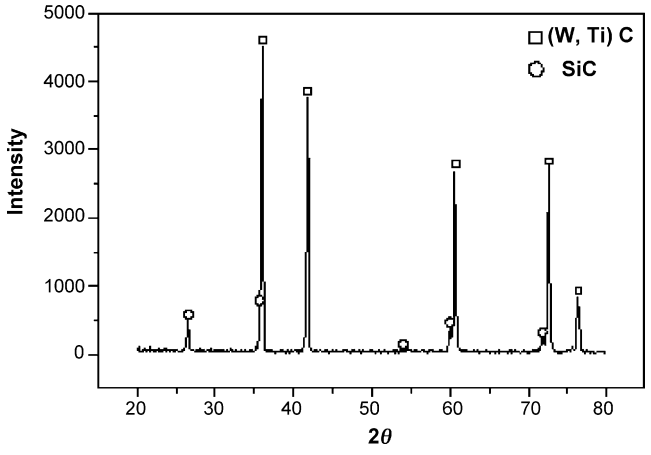

Fig. 2. X-ray diffraction analysis of the SiC/60 vol.% (W, Ti)C ceramic composite after sintered at temperature 1900 °C for 40 min.

Table 2
Sintering parameters, relative densities and grain size of the hot-pressed monolithic SiC and SiC/(W, Ti)C ceramic composites

Sample	Sintering parameter (35 MPa)		Relative density (%)	Grain size (μm)
	Temperature (°C)	Time (min)		
Monolithic SiC	2100	70	96.3	4–10
SiC/20 vol.% (W, Ti)C	1900	60	99.1	3–5
SiC/40 vol.% (W, Ti)C	1900	50	99.2	2–5
SiC/60 vol.% (W, Ti)C	1900	40	99.3	2–4

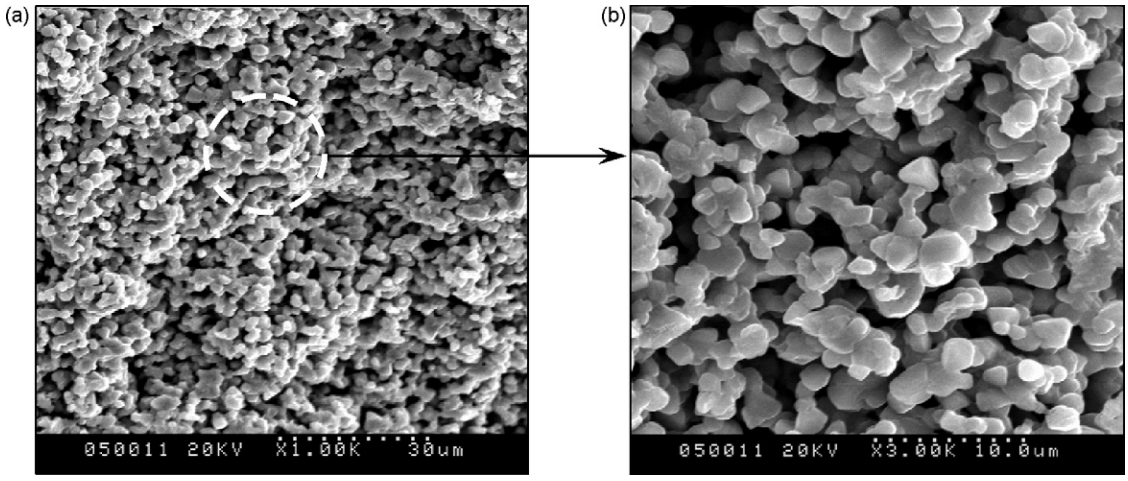

Fig. 3. SEM micrographs of (a) the fracture surfaces of pure SiC after sintering at temperature 1700 °C for 60 min, (b) enlarged SEM micrograph corresponding to (a).

composites can be seen clearly. It is not a dense body, and it shows a lot of incompact powders at the fracture surface when sintered at 1700 °C (see Fig. 5). While the composite sintered at 1900 °C is dense, porosity is virtually absent, and shows an intergranular fracture mode (see Fig. 7). The grain sizes ranged from 2 to 4 μm. The second phase seems to have inhibited the grain growth of SiC by slowing down the grain boundary motion or sliding.

Fig. 8 shows typical optical micrographs from the polished surface of hot-pressed SiC/(W, Ti)C ceramic composites after sintering at temperature 1900 °C for 40 min. The gray (black) areas as identified by EDX analysis are SiC and the white areas are (W, Ti)C phases. It can be seen that (W, Ti)C particles are quite uniformly distributed throughout the microstructure. It is apparent from these SEM micrographs that the (W, Ti)C particles were well-distributed in the SiC matrix.

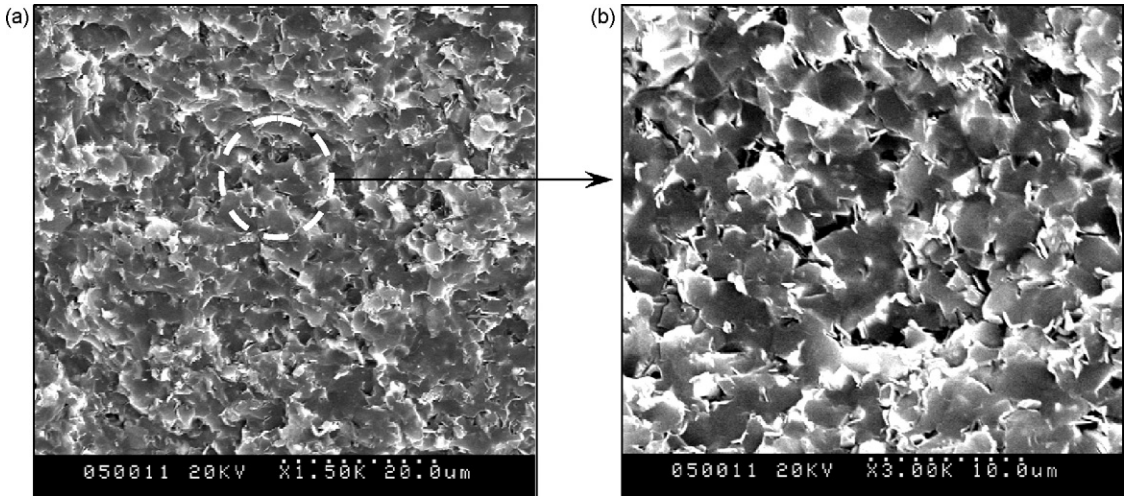

Fig. 4. SEM micrographs of (a) the fracture surfaces of pure SiC after sintering at temperature 2100 °C for 60 min, (b) enlarged SEM micrograph corresponding to (a).

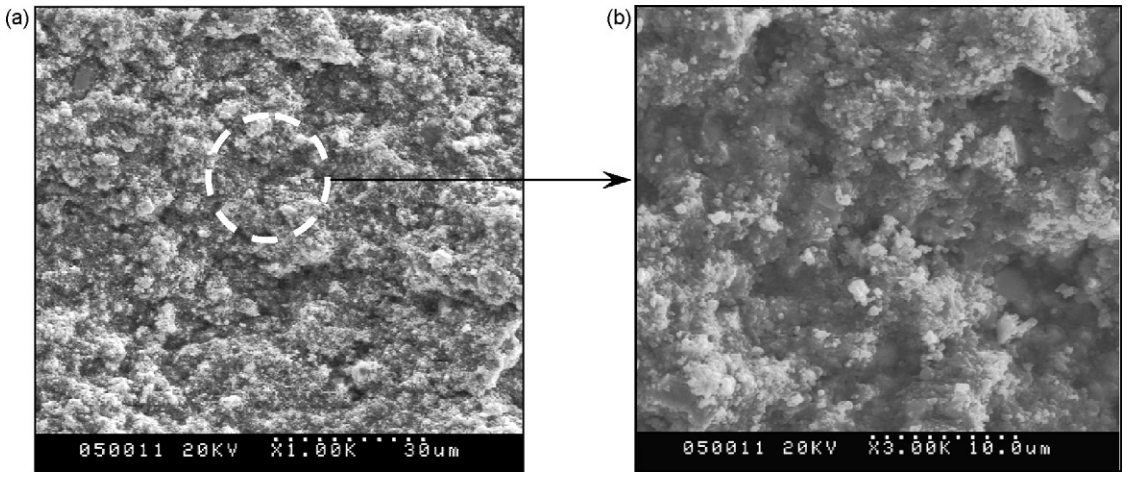

Fig. 5. SEM micrographs of (a) the fracture surfaces of SiC/60 vol.% (W, Ti)C composite after sintering at temperature 1700 °C for 40 min, (b) enlarged SEM micrograph corresponding to (a).

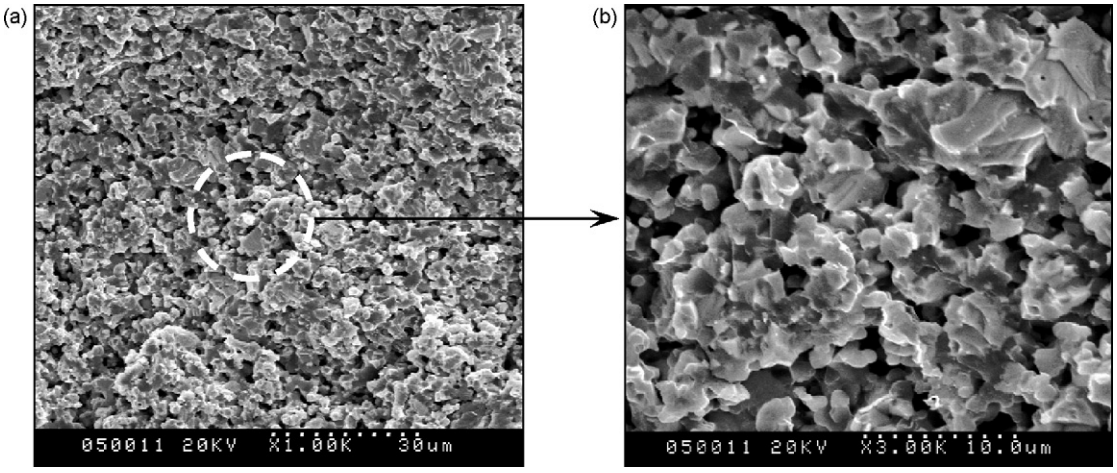

Fig. 6. SEM micrographs of (a) the fracture surfaces of SiC/60 vol.% (W, Ti)C composite after sintering at temperature 1800 °C for 40 min, (b) enlarged SEM micrograph corresponding to (a).

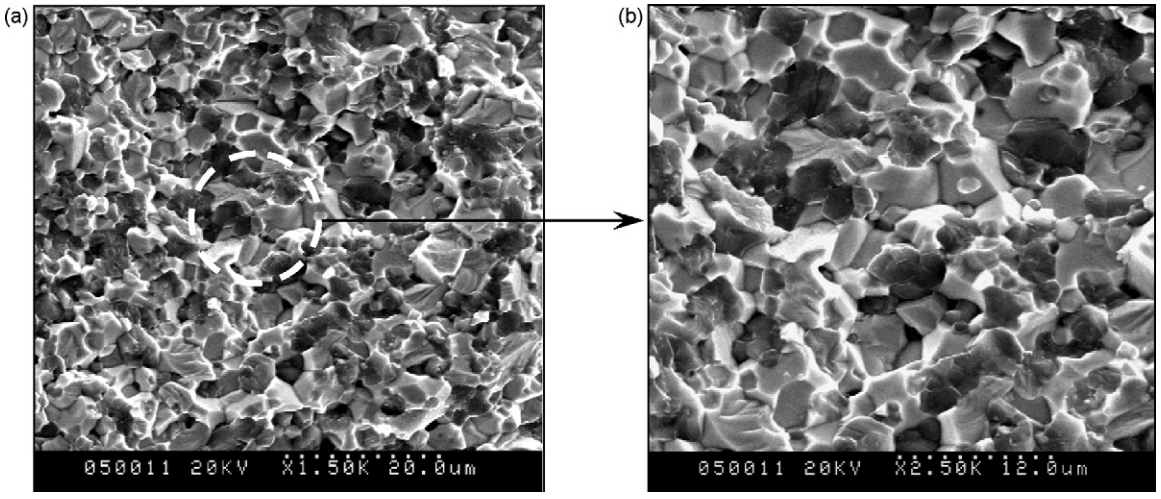

Fig. 7. SEM micrographs of (a) the fracture surfaces of SiC/60 vol.% (W, Ti)C composite after sintering at temperature 1900 °C for 40 min, (b) enlarged SEM micrograph corresponding to (a).

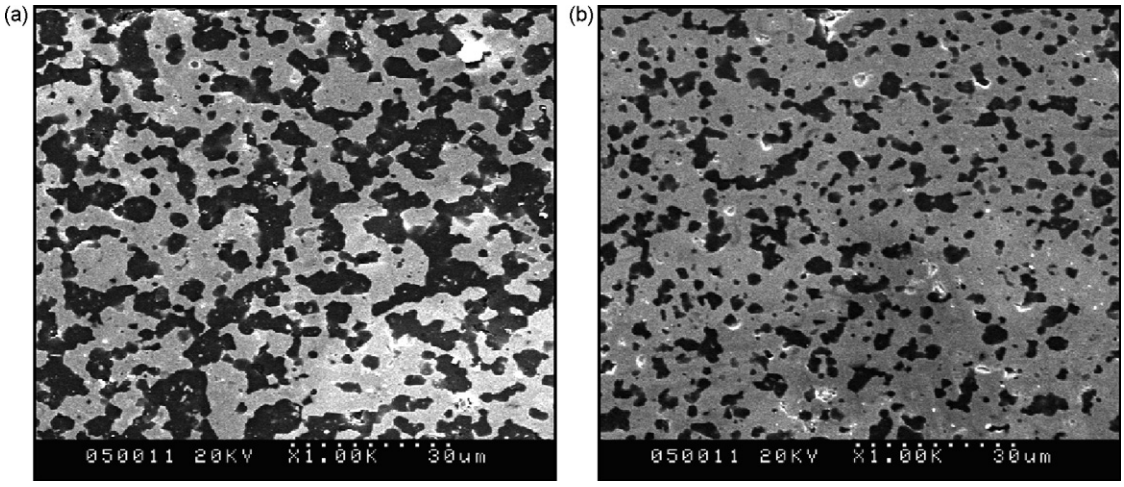

Fig. 8. Typical optical micrographs of the polished surface of hot-pressed: (a) SiC/20 vol.% (W, Ti)C and (b) SiC/60 vol.% (W, Ti)C composites after sintering at temperature 1900 °C for 40 min.

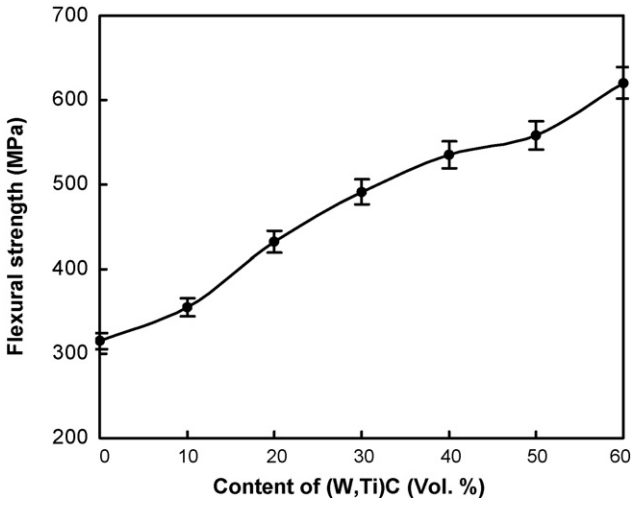

Fig. 9. Variation of composite flexural strength with (W, Ti)C additions (sintering temperature 1950 °C, holding time 40 min).

3.3. Mechanical properties of SiC/(W, Ti)C ceramic composites

Fig. 9 shows the effect of (W, Ti)C addition on the flexural strength of SiC. It was found that the flexural strength continuously increased with increasing of (W, Ti)C content up to 60 vol.%, and rose from 315.0 MPa for hot-pressed monolithic SiC to 620.0 MPa for SiC/60 vol.% (W, Ti)C composite, representing a maximum strengthening increase of 305.0 MPa. The flexural strength of the composite is greatly improved with respect to the SiC matrix when the composite are nearly fully dense and with finer microstructure (see Table 2). So strong grain refinement, higher density, more uniform microstructure associated with the reduction of porosity may be the direct causes of the higher strength of the composites.

Fracture toughness measurement was performed using indentation method in a hardness tester using the formula proposed by Cook and Lawn [13]. Fig. 10(a) shows path of a crack produced by Vickers indentation on the polished surface of

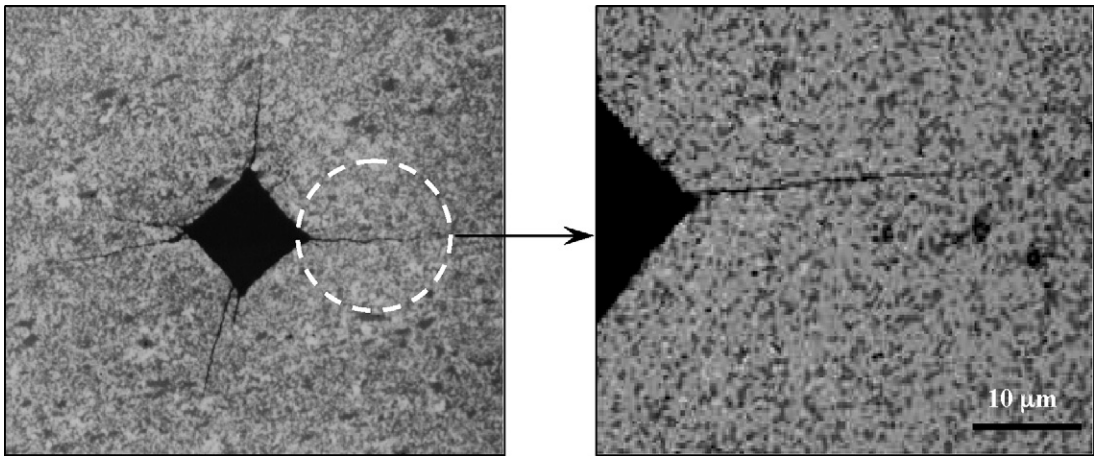

Fig. 10. Crack path produced by Vickers indentation on the polished surface of (a) hot-pressed SiC/60 vol.% (W, Ti)C composite, (b) enlarged photo corresponding to (a).

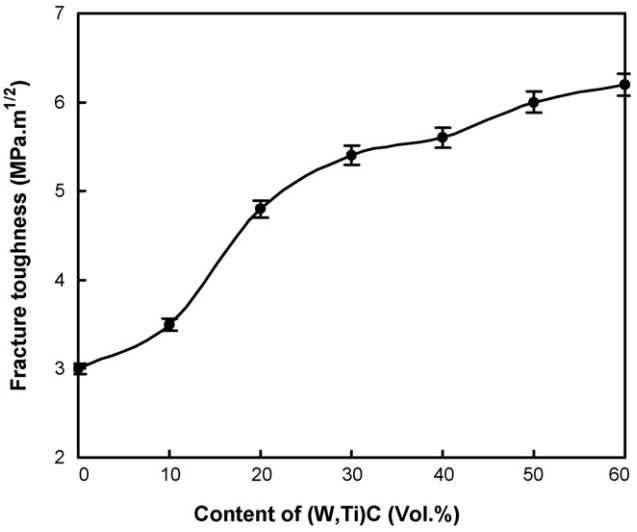

Fig. 11. Variation of composite fracture toughness with (W, Ti)C additions (sintering temperature 1950 °C, holding time 40 min).

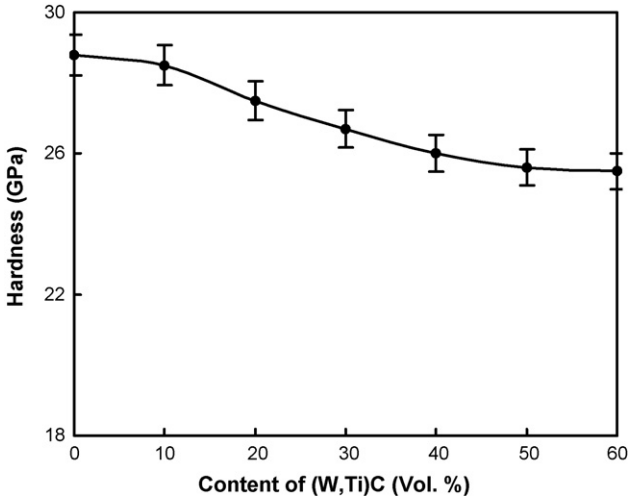

Fig. 12. Variation of composite hardness with (W, Ti)C additions (sintering temperature 1950 °C, holding time 40 min).

hot-pressed SiC/60 vol.% (W, Ti)C. Fig. 10(b) is a portion of (a) at higher magnification. Fig. 11 shows the variation of fracture toughness with (W, Ti)C content, exhibiting a maximum value of 6.2 MPa m$^{1/2}$ for 60 vol.% (W, Ti)C composite. The trend of the fracture toughness is the same as that of the flexural strength. The fracture toughness continuously increased with increasing of (W, Ti)C content up to 60 vol.%, and rose from 3.0 MPa m$^{1/2}$ for hot-pressed monolithic SiC to 6.2 MPa m$^{1/2}$ for SiC/60 vol.% (W, Ti)C composite, representing a maximum toughening increase of 3.2 MPa m$^{1/2}$.

The hardness of SiC/(W, Ti)C composite was found to decrease with increasing (W, Ti)C content as it can be seen in Fig. 12. As the (W, Ti)C is less hard than SiC, the hardness of the composite decreased with increasing (W, Ti)C content.

4. Conclusions

SiC/(W, Ti)C ceramic composites with different content of (W, Ti)C solid-solution were produced by hot pressing. Results shows that additions of (W, Ti)C to SiC matrix resulted in improved mechanical properties compared to pure SiC ceramic. The densification rates of the SiC/(W, Ti)C ceramic composites were found to be affected by additions of (W, Ti)C. Increasing content of (W, Ti)C led to increase the densification rates of the composites. The sintering temperature was lowered from 2100 °C for monolithic SiC to 1900 °C for SiC/(W, Ti)C composites. The fracture toughness and flexural strength continuously increased with increasing (W, Ti)C content up to 60 vol.%, while the hardness decreased with increasing (W, Ti)C content.

Acknowledgements

This work was supported by ‘‘the National Natural Science Foundation of China (50475133, 50675120)’’, ‘‘the Natural Science Foundation of Shandong Province (Y2004F08)’’, ‘‘the Program for New Century Excellent Talents in University (NCET-04-0622)’’, ‘‘the Taishan Scholar Program of Shandong Province’’.

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