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Influence of silicon carbide addition on the microstructural development of hot pressed zirconium and titanium diborides

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Abstract

The influences of adding SiC on the microstructure and densification behavior of ZrB_2 and TiB_2 ceramics, hot pressed at 1850 °C for 60 min under 20 MPa, were investigated. The sintered samples were characterized by SEM, EDS and XRD methods. A fully dense TiB_2-based ceramic was obtained by adding 30 vol% SiC. The grain size of ZrB_2 or TiB_2 matrices in the final microstructures decreased with increasing SiC content. The XRD analyses, microstructural characterization as well as thermodynamical calculations proved the in-situ formation of TiC in the SiC reinforced TiB_2-based composites. The interfaces between ZrB_2 and SiC grains in the SiC reinforced ZrB_2-based composites were free of any impurities or tertiary interfacial phases such as ZrC. This result was consistent with the X-ray diffraction pattern and thermodynamics.

Keywords: A. Hot pressing; Microstructure; Zirconium diboride; Titanium diboride; Silicon carbide

1. Introduction

Zirconium and titanium diborides have many superior characteristics such as high melting point, Young's modulus, hardness, corrosion resistance, and thermal/electrical conductivities. Such distinctive traits give ZrB_2 and TiB_2-based ceramics an extensive high temperature structural application domain such as wear-resistant pieces, cutting tools, crucibles, and armor materials. However, due to their strong ionic/covalent bonds and low self-diffusion coefficients, the densification processes of the monolithic ZrB_2 and TiB_2 ceramics are extremely arduous. Hence, when fully dense parts are needed, due to the fact that ultra-high temperatures are required for sintering process, their applications are somewhat limited. In addition, the formed oxide layers (ZrO_2 on the surface of ZrB_2 powder, TiO_2 on the surface of TiB_2 powder, and B_2O_3 on the surface of both powders) are found to be destructive to the densification phenomenon [1–10].

A relative density of ~95% was achieved for TiB_2 ceramic by the pressureless sintering at > 2200 °C [11]. In general, the high temperatures result in exaggerated grain growth which is detrimental to the mechanical properties [12]. In order to decrease the sintering temperature, the hot pressing process was considered as an effective method for fabrication of ZrB_2 and TiB_2 ceramics [11,12]. However, fully dense ZrB_2 ceramics can be fabricated by hot pressing above 2000 °C [13].

The hot pressing temperature and dwell time have great effects on the grain growth of TiB_2. The quick hot pressing at higher temperatures was found as a good sintering method for TiB_2 ceramics [11]. In the hot pressed ZrB_2 ceramics, it was found that the sintering temperature and dwell time were the most consequential factors with respect to density, hardness [14] and final grain size in the microstructure [15].

It was reported that adding SiC to ZrB_2 or TiB_2 changes their microstructure, sinterability and densification mechanism. During the sintering process, SiC reacts with ZrO_2 or TiO_2 impurities on the surface of the starting powders and forms a liquid SiO_2 phase. Hence, the sinterability improvement by adding SiC can be related to the liquid phase sintering mechanism [12,13,16–21].

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The dominant densification mechanisms of ZrB_2–SiC composites were identified at different hot pressing temperatures. For the samples hot pressed at 1700, 1850 and 2000 °C, liquid phase sintering/particle fragmentation/rearrangement, plastic deformation and atomic diffusion were determined as the dominant densification mechanisms, respectively [13,22]. The density of hot pressed TiB_2 ceramic increases rapidly at the initial sintering stage, but raises slowly at the final stage. Hence, the densification mechanisms of TiB_2 ceramics are not the same at different hot pressing stages. The plastic flow and diffusion creep are the dominant densification mechanisms at initial and final sintering stages, respectively [11]. The TiB_2–SiC ceramics with different SiC contents were in-situ synthesized recently by the reactive hot pressing process at 1700 °C under 32 MPa. The amount of SiC and the sintering time were found to have significant influences on the microstructure and mechanical properties of the mentioned composites [23,24]. On the other hand, the applied pressure was identified as the most effective factor on the densification and hardness of hot pressed ZrB_2–SiC composites [25].

In this work, the monolithic ZrB_2 and TiB_2 ceramics as well as ZrB_2–SiC and TiB_2–SiC ceramic composites with different SiC contents (15 vol% and 30 vol%) were densified by the hot pressing process at 1850 °C for 60 min under 20 MPa. The effects of SiC on the microstructure and sinterability of the ceramics were studied. The microstructure and sintering behavior of the hot pressed samples were investigated by scanning electron microscope, energy dispersive spectrometer and X-ray diffractometer.

2. Experimental procedure

2.1. Materials and process

Commercially available ZrB_2 powder (particle size ~5 μm, purity >99%, Leung Hi-tech Co., China), TiB_2 powder (particle size ~5 μm, purity >99%, Xuzhou Hongwu Nanometer Material Co., China) and α-SiC powder (particle size ~5 μm, purity >98%, Carborundum Universal Limited, India) were used as raw materials. The powder samples of ZrB_2 and TiB_2 with 0 vol%, 15 vol% and 30 vol% SiC were ball-mixed for 120 min in a polyethylene cup with SiC balls and ethanol as mediums. Then the mixed slurries were dried in a rotating heater and sieved by a 100-mesh sieve. After that, the powder mixtures were put into a graphite die coated with boron nitride and lined with a flexible graphite foil. The hot pressing process was conducted in a graphite resistance-heated furnace (Shenyang Weitai Science & Technology Development Co., Ltd., China) with a vacuum atmosphere of <0.05 Pa, hot pressing temperature of 1850 °C, dwell time of 60 min, and applied pressure of 20 MPa. Each sample was heated at a rate of 15 °C/min up to 1000 °C, then was given a dwell isotherm at 1000 °C for 20 min in order to eliminate volatile gases, and finally was heated again at a rate of 15 °C/min up to 1850 °C. Above 1000 °C, the die temperature was monitored using an infrared thermometer (Dikai IT-6, China) through a sapphire window. Finally, the hot press chamber was cooled down naturally at an average rate of 10 °C/min. Three billets, with a diameter of 24 mm and a thickness of ~5 mm, were fabricated for each composition.

2.2. Characterization

Scanning electronic microscopy (SEM: Mira3 Tescan, Czech Republic), energy dispersive spectroscopy (EDS: DXP-X10P Digital X-Ray Processor) and high resolution X-ray diffraction analysis (HRXRD: Bruker D8 Advance, Germany) were used to evaluate the microstructure, chemical analysis, and phase identification of the hot pressed samples, respectively. The relative density of the samples was calculated as the bulk density was divided by the theoretical density. The bulk density was measured by the Archimedes' method using distilled water as the immersing medium. The theoretical density was estimated by the rule of mixtures assuming the true densities of 6.1 g/cm^3 for ZrB_2, 4.5 g/cm^3 for TiB_2, and 3.2 g/cm^3 for SiC. Image analysis method (ImageJ 1.44p software, Wayne Rasband, National Institute of Health, USA) was used to determine the grain size. In this way, the samples were mechanically polished using diamond abrasive and then thermally etched at 1600 °C for 30 min in vacuum atmosphere (5×10^{-2} Pa). Thermodynamic calculations were performed with the HSC Chemistry software (ver. 5.11, Outokumpu Research Oy, Pori, Finland).

3. Results and discussion

3.1. Densification and grain growth

Fig. 1 shows the relation between the SiC content and relative density of ZrB_2 and TiB_2 based ceramics. Without adding SiC, the relative densities of monolithic ZrB_2 and TiB_2 ceramics after hot pressing at 1850 °C were 94.0 ± 0.2% and 95.2 ± 0.4%, respectively.

The relative density of ZrB_2 ceramic reached 98 ± 0.4% with adding 15 vol% SiC, and 97 ± 0.5% with adding 30 vol% SiC. This observation suggests that SiC can improve the densification of ZrB_2-based ceramics when SiC content is about 15 vol%. However, if the reinforcement content reaches 30 vol%, the relative density decreases slightly, which may be a result of the pores formation caused by excessive SiC. Our group has already reported that the relative density of ZrB_2–SiC composites rose

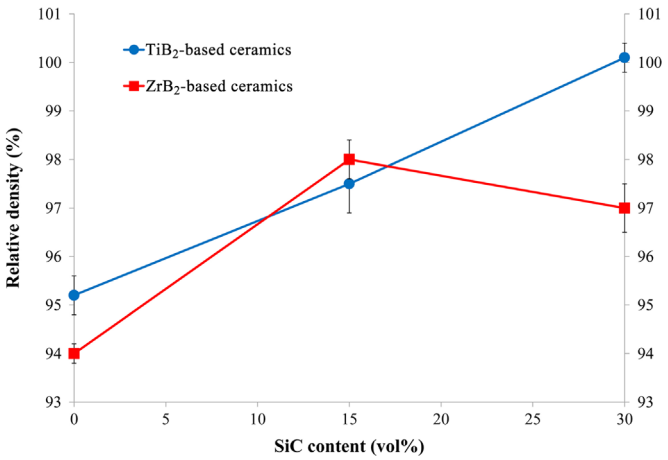

Fig. 1. Relative density of hot pressed ZrB_2 and TiB_2 based ceramics with different SiC additions.

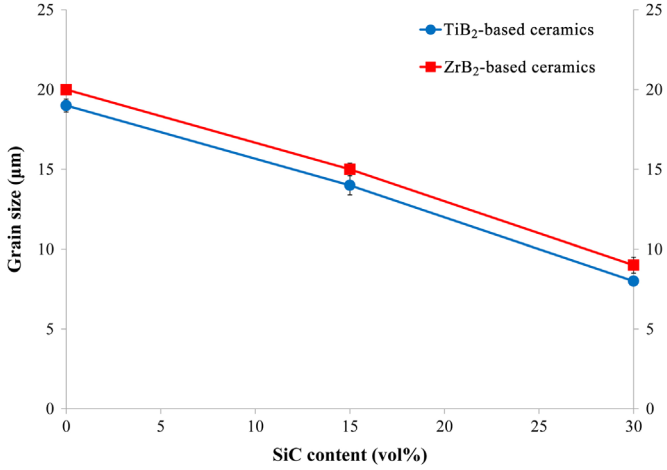

Fig. 2. Average grain size of ZrB_2 and TiB_2 in hot pressed samples with different SiC additions.

with increase in SiC content up to 25 vol%, but decreased with more increase in SiC content to 30 vol% [25].

On the other hand, the relative density of TiB_2 ceramic was $97.5 \pm 0.6\%$ with adding 15 vol% SiC, and $100.1 \pm 0.3\%$ with adding 30 vol% SiC. In accord with the supporting evidences which are described in the next sections (microstructural and XRD analyses as well as thermodynamics), the relative density value of more than 100% can be related to the in-situ formation of TiC. The true density of titanium carbide is 4.9 g/cm^3 [17], higher than those of both TiB_2 and SiC in the starting powder mixture, but was not considered in the relative density estimation by the rule of mixtures.

In general, adding SiC can improve the sinterability of both diborides; however, it seems that higher sintering temperatures [13,28] or finer starting materials (submicron or nano-sized powders [21,26–33]) is required for the ZrB_2-based ceramics to be fully densified.

The mean grain sizes of ZrB_2 and TiB_2 in the hot pressed samples were estimated to study the effect of SiC on the final microstructure. The results show that SiC acted as grain growth inhibitor in both ZrB_2 and TiB_2 matrices (Fig. 2), but discernible grain coarsening occurred in both monolithic ceramics in the absence of SiC. The extreme grain growth not only constricts the densification process, but also decreases the mechanical properties of the samples such as hardness and fracture toughness [34,35]. The oxide impurities of ZrO_2 on the surface of ZrB_2 powder, TiO_2 on the surface of TiB_2 powder, and B_2O_3 on the surface of both powders can promote the occurrence of some detrimental mechanisms such as grain coarsening and evaporation/condensation in the monolithic samples [17]. Wang et al. [11] showed that the increase in sintering temperature and time rises the relative density of TiB_2 ceramics, but leads to the grain growth. Moreover, at higher sintering temperatures, TiB_2 grains grow rapidly and irregularly. They claimed that the rapid hot pressing at high temperature is a good choice for the processing of high-density TiB_2 ceramics with a fine-grained microstructure.

3.2. Microstructure development

The SEM micrographs of the polished and fracture surfaces of the hot pressed ZrB_2-based ceramics are presented in Fig. 3. These images are consistent with the relative density measurements (Fig. 1) which support the fact that the SiC reinforced samples included a small content of porosity ($< 3\%$). The ZrB_2 grains in unreinforced ceramic (Fig. 3a) grew significantly during the sintering process; hence, a mass of large pores remained among the coarsened ZrB_2 grains, which was harmful to the densification progress. By employing the EDS analysis in the hot pressed ceramic matrix composites (not shown here), the light and dark phases in Fig. 3 were clarified as ZrB_2 and SiC, respectively. This figure also demonstrates that adding SiC had a significant influence on the microstructure of the ceramic matrix composites, particularly on the fabrication of the fine-grained ZrB_2 matrices. In the SiC reinforced ceramics, as shown in Fig. 3b and c, SiC grains were distributed uniformly among the ZrB_2 grains. Fewer pores were observed in the composite samples than that of the monolithic ZrB_2 ceramic, which caused the higher relative densities. The interfaces between the ZrB_2 and SiC grains were free of any impurities or interfacial phases. However, the presence of some oxide impurities (white phases in Fig. 3a) in both the polished and fracture surfaces was detected in the monolithic ZrB_2 ceramic.

Fig. 4 shows the SEM micrographs of the polished and fracture surfaces of the hot pressed TiB_2-based ceramics. These images are consistent with the relative density measurements (Fig. 1), as by adding SiC to the TiB_2 matrix, the content of porosity reduces. As it can be clearly seen in Fig. 4a, an extreme growth has occurred for TiB_2 grains in the monolithic ceramic whereas some pores stayed in the microstructure. Similar to the ZrB_2-based ceramics, the presence of SiC had an important effect on the microstructure of the TiB_2-based samples. Based on the fracture surfaces of SiC reinforced samples, few small pores remained in TiB_2–15 vol% SiC ceramic (Fig. 4b), but no porosity was detected in TiB_2–30 vol% SiC ceramic, which is a sign of reaching a fully-dense ceramic matrix composite (Fig. 4c). Unlike the ZrB_2-based ceramics, the interfaces between the TiB_2 and SiC grains in the TiB_2-based composite samples were not free of tertiary phase. By microstructural investigation along with EDS spectra (not shown here) on the polished surface of TiB_2–30 vol% SiC ceramic, three distinct phases were identified in Fig. 4c. These analyses disclosed that the darkgray phase is TiB_2, the dimgray phase belongs to SiC and the lightgray phase located along the grain boundaries can be related to in-situ formed TiC.

3.3. Phase identification and chemical reactions

Fig. 5 shows the phase identification of hot pressed ZrB_2–30 vol% SiC and TiB_2–30 vol% SiC composites by HRXRD. As it can be seen in Fig. 5a, the only detectable crystalline phases in the ZrB_2-based sample are ZrB_2 and SiC. The result of XRD analysis for the TiB_2-based sample is a little different. In

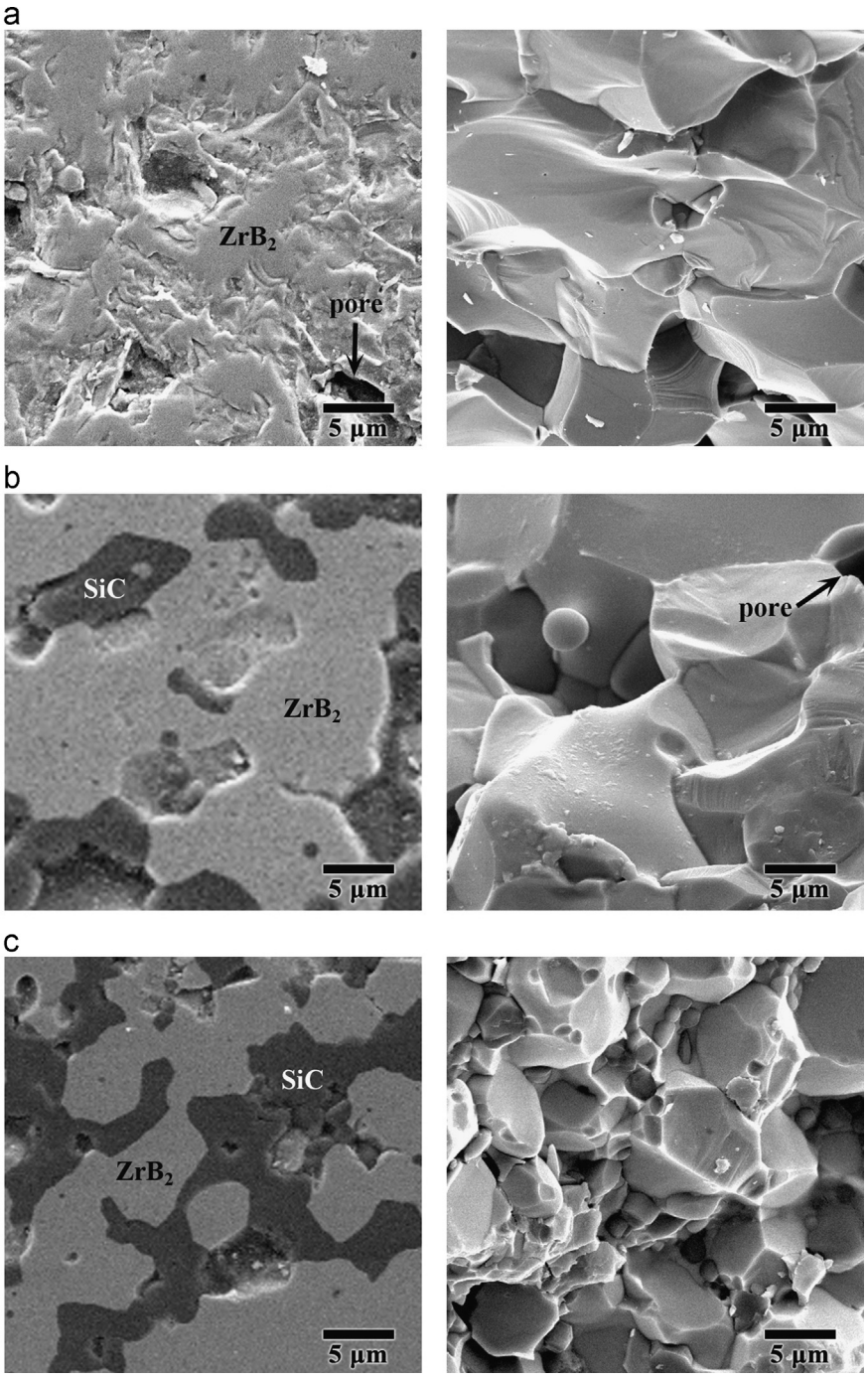

Fig. 3. SEM micrographs of the polished and fracture surfaces of hot pressed (a) ZrB_2, (b) ZrB_2–15 vol% SiC and (c) ZrB_2–30 vol% SiC ceramics.

addition to the anticipated TiB_2 and SiC phases, TiC phase is also detected after hot pressing (Fig. 5b). Titanium carbide was not a part of the starting powders; then, it seems to form during the hot pressing process. The height of TiC peaks is higher than that of SiC which can be attributed to its greater volume fraction than that of SiC in the final microstructure of the hot pressed composite. This outcome is also consistent with the SEM micrograph of the polished surface of TiB_2–30 vol% SiC composite (Fig. 4c).

Torizuka et al. [12] proved that the B_2O_3 surface layer of TiB_2 powder evaporates before the densification, but the TiO_2 surface layer remains in the batch. They showed that the TiO_2 can react with SiC which leads to the formation of TiC and amorphous SiO_2 (Eq. (1)):

$$TiO_2 + SiC = SiO_2 + TiC \quad (1)$$

The phase identification by HRXRD analysis (Fig. 5b) verifies the formation of TiC in the sintered TiB_2–30 vol% SiC composite. This observation indicates that reaction Eq. (1) has occurred. Similar to Eq. (1) for the TiB_2–SiC composites, a hypothetical reaction can be expressed by Eq. (2) for the ZrO_2 surface layer of ZrB_2–SiC composites:

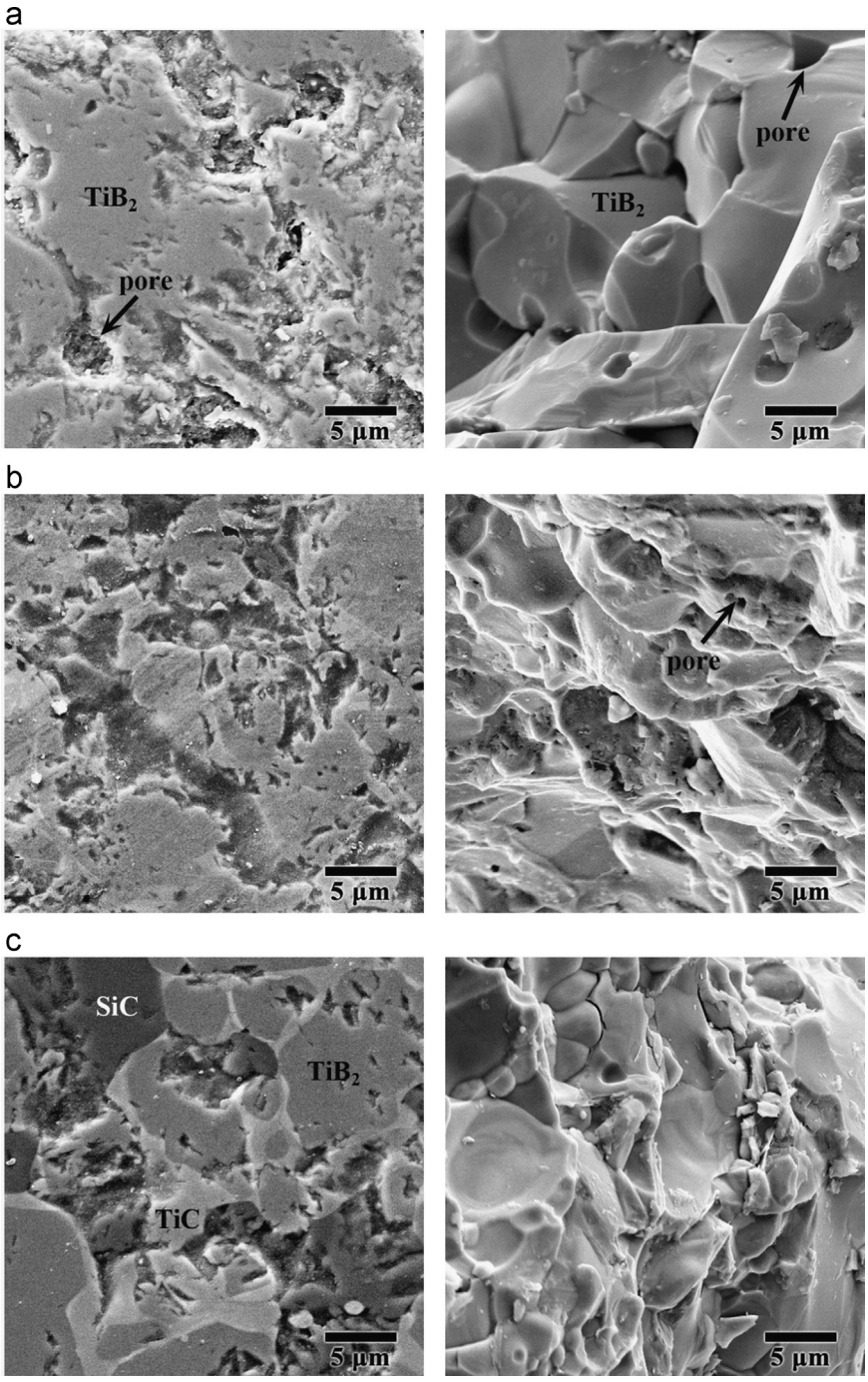

Fig. 4. SEM micrographs of the polished and fracture surfaces of hot pressed (a) TiB_2, (b) TiB_2–15 vol% SiC and (c) TiB_2–30 vol% SiC ceramics.

$$ZrO_2 + SiC = SiO_2 + ZrC \quad (2)$$

On the other hand, the formation of ZrC in the hot pressed ZrB_2–30 vol% SiC ceramic was not detected in its HRXRD pattern (Fig. 5a) which is against the occurrence of Eq. (2). Fig. 6 shows the Gibbs free energy values as a function of temperature which were obtained by the thermodynamic calculations of reactions Eqs. (1) and (2). The Gibbs free energy values of reaction Eqs. (1) and (2) from the room temperature to the sintering temperature are negative and positive, respectively. Hence, regarding the thermodynamics, Eq. (1) occurs during the hot pressing process but Eq. (2) does not happen. However, our group has previously reported the formation of ZrC in the ZrB_2–SiC composites when a tertiary component (such as graphene nano-platelets [36], graphite nano-flakes [37], carbon nanotubes [38], carbon fibers [39] or nano-ZrO_2 [40,41]) was being added to the powder mixture.

The amorphous SiO_2 melts during the hot pressing at 1850 °C; therefore, it improves the sinterability of TiB_2 particles by the liquid phase sintering mechanism which also results in the rearrangement of particles. However, Torizuka et al. [12] observed that only the liquid phase sintering is not enough to

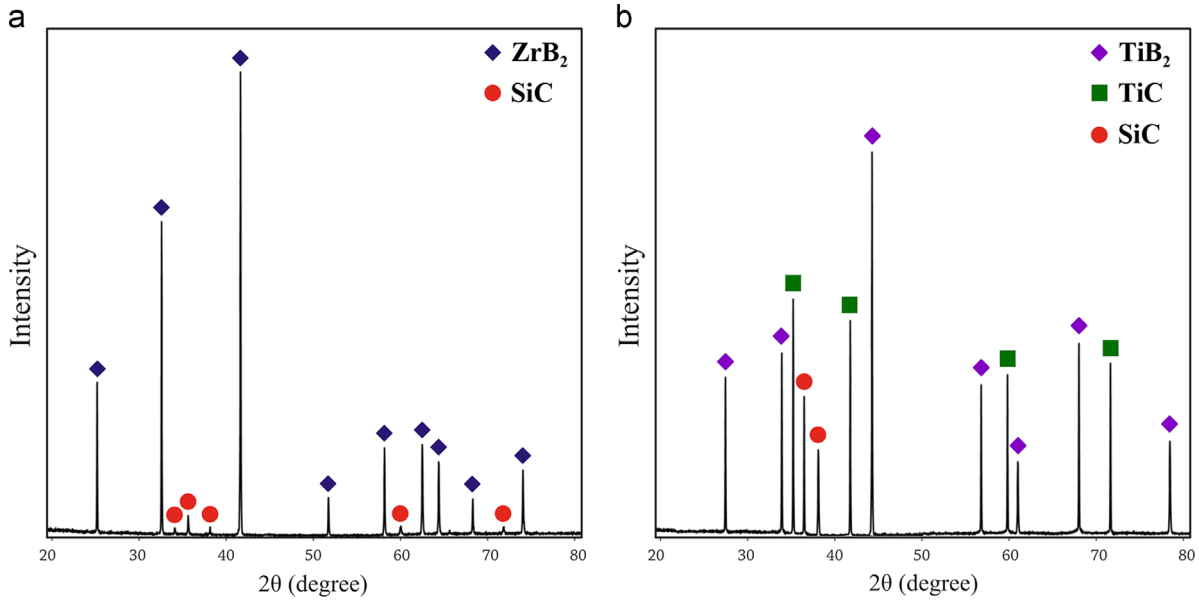

Fig. 5. Phase identification by high resolution X-ray diffraction of (a) ZrB_2–30 vol% SiC and (b) TiB_2–30 vol% SiC ceramics after hot pressing.

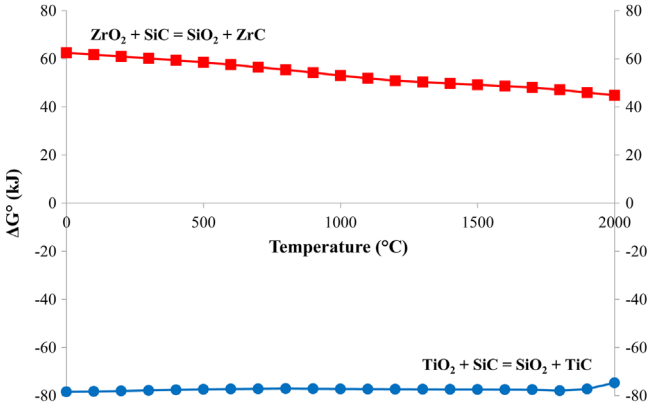

Fig. 6. Gibbs free energy of reactions (Eqs. (1) and (2)) obtained by HSC Chemistry, a software for thermodynamic calculation.

fabricate a fully-dense TiB_2–SiC ceramic; hence, applying an external pressure seems to be necessary.

4. Conclusion

In this study, the microstructural development during hot pressing of monolithic ZrB_2 and TiB_2 ceramics as well as ZrB_2–SiC and TiB_2–SiC composites at 1850 °C for 60 min under 20 MPa were investigated based on SEM, EDS and XRD analyses and thermodynamical estimations. The microstructures and densification processes of both ZrB_2 and TiB_2-based ceramics were significantly affected by adding SiC. The presence of SiC was found to prevent the grain growth of ZrB_2 and TiB_2 matrices during the sintering process. In-situ formed tertiary TiC phase was identified in the TiB_2–SiC composites by means of EDS spectra and XRD pattern, which was consistent with the thermodynamics. No interfacial phase (e.g. ZrC) was detected between ZrB_2 and SiC grains in the ZrB_2–SiC composites according to the phase and microstructural characterizations as well as thermodynamical predictions.

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References

[1] W.G. Fahrenholtz, G.E. Hilmas, I.G. Talmy, J.A. Zaykoski, Refractory diborides of zirconium and hafnium, J. Am. Ceram. Soc. 90 (2007) 1347–1364.
[2] Z. Balak, M. Zakeri, Effect of HfB_2 on microstructure and mechanical properties of ZrB_2–SiC-based composites, Int. J. Refract. Met. Hard Mater. 54 (2016) 127–137.
[3] M. Shahedi Asl, B. Nayebi, Z. Ahmadi, P. Pirmohammadi, M. Ghassemi Kakroudi, Fractographical characterization of hot pressed and pressureless sintered SiAlON-doped ZrB_2–SiC composites, Mater. Charact. 102 (2015) 137–145.
[4] T. Csanádi, S. Grasso, A. Kovalčíková, J. Dusza, M. Reece, Nanohardness and elastic anisotropy of ZrB_2 crystals, J. Eur. Ceram. Soc. 36 (2016) 239–242.
[5] T.S. Srivatsan, G. Guruprasad, D. Black, R. Radhakrishnan, T. S. Sudarshan, Influence of TiB_2 content on microstructure and hardness of TiB_2–B_4C composite, Powder Technol. 159 (2005) 161–167.
[6] T. Csanádi, P. Szommer, N.Q. Chinh, S. Grasso, J. Dusza, M. Reece, Plasticity in ZrB_2 micropillars induced by anomalous slip activation, J. Eur. Ceram. Soc. 36 (2016) 389–394.
[7] T.S. Srivatsan, G. Guruprasad, D. Black, M. Petraroli, R. Radhakrishnan, T.S. Sudarshan, Microstructural development and hardness of TiB_2–B_4C composite samples: influence of consolidation temperature, J. Alloy. Compd. 413 (2006) 63–72.
[8] Z. Ahmadi, B. Nayebi, M. Shahedi Asl, M. Ghassemi Kakroudi, Fractographical characterization of hot pressed and pressureless sintered AlN-doped ZrB_2–SiC composites, Mater. Charact. 110 (2015) 77–85.
[9] M. Khoeini, A. Nemati, M. Zakeri, M. Tamizifar, H. Samadi, Comprehensive study on the effect of SiC and carbon additives on the pressureless sintering and microstructural and mechanical characteristics of new ultra-high temperature ZrB_2 ceramics, Ceram. Int. 41 (2015) 11456–11463.

[10] S.Q. Guo, Densification of ZrB_2-based composites and their mechanical and physical properties: a review, J. Eur. Ceram. Soc. 29 (2009) 995–1011.
[11] W. Wang, Z. Fu, H. Wang, R. Yuan, Influence of hot pressing sintering temperature and time on microstructure and mechanical properties of TiB_2 ceramics, J. Eur. Ceram. Soc. 22 (2002) 1045–1049.
[12] S. Torizuka, K. Sato, H. Nishio, T. Kishi, Effect of SiC on interfacial reaction and sintering mechanism of TiB_2, J. Am. Ceram. Soc. 78 (1995) 1606–1610.
[13] M. Shahedi Asl, M. Ghassemi Kakroudi, Fractographical assessment of densification mechanisms in hot pressed ZrB_2–SiC composites, Ceram. Int. 40 (2014) 15273–15281.
[14] M. Shahedi Asl, M. Ghassemi Kakroudi, B. Nayebi, H. Nasiri, Taguchi analysis on the effect of hot pressing parameters on density and hardness of zirconium diboride, Int. J. Refract. Met. Hard Mater. 50 (2015) 313–320.
[15] M. Shahedi Asl, M. Ghassemi Kakroudi, M. Rezvani, F. Golestani-Fard, Significance of hot pressing parameters on the microstructure and densification behavior of zirconium diboride, Int. J. Refract. Met. Hard Mater. 50 (2015) 140–145.
[16] M. Mashhadi, H. Khaksari, S. Safi, Pressureless sintering behavior and mechanical properties of ZrB_2–SiC composites: effect of SiC content and particle size, J. Mater. Res. Technol. 4 (2015) 416–422.
[17] A. Sabahi Namini, S.N. Seyed Gogani, M. Shahedi Asl, K. Farhadi, M. Ghassemi Kakroudi, A. Mohammadzadeh, Microstructural development and mechanical properties of hot pressed SiC reinforced TiB_2 based composite, Int. J. Refract. Met. Hard Mater. 51 (2015) 169–179.
[18] D.S. King, W.G. Fahrenholtz, G.E. Hilmas, Silicon carbide–titanium diboride ceramic composites, J. Eur. Ceram. Soc. 33 (2013) 2943–2951.
[19] M. Jaberi Zamharir, M. Shahedi Asl, M. Ghassemi Kakroudi, N. Pourmohammadie Vafa, M. Jaberi Zamharir, Significance of hot pressing parameters and reinforcement size on sinterability and mechanical properties of ZrB_2–25 vol% SiC UHTCs, Ceram. Int. 41 (2015) 9628–9636.
[20] M. Mallik, S. Roy, K.K. Raya, R. Mitra, Effect of SiC content, additives and process parameters on densification and structure–property relations of pressureless sintered ZrB_2–SiC composites, Ceram. Int. 39 (2013) 2915–2932.
[21] M. Jaberi Zamharir, M. Shahedi Asl, N. Pourmohammadie Vafa, M. Ghassemi Kakroudi, Significance of hot pressing parameters and reinforcement size on densification behavior of ZrB_2–25 vol% SiC UHTCs, Ceram. Int. 41 (2015) 6439–6447.
[22] B. Nayebi, M. Shahedi Asl, M. Ghassemi Kakroudi, M. Shokouhimehr, Temperature dependence of microstructure evolution during hot pressing of ZrB_2–30 vol% SiC composites, Int. J. Refract. Met. Hard Mater. 54 (2016) 7–13.
[23] G. Zhao, C. Huang, H. Liu, B. Zou, H. Zhu, J. Wang, A study on in-situ synthesis of TiB_2–SiC ceramic composites by reactive hot pressing, Ceram. Int. 40 (2014) 2305–2313.
[24] G. Zhao, C. Huang, H. Liu, B. Zou, H. Zhu, J. Wang, Microstructure and mechanical properties of TiB_2–SiC ceramic composites by reactive hot pressing, Int. J. Refract. Met. Hard Mater. 42 (2014) 36–41.
[25] M. Shahedi Asl, M. Ghassemi Kakroudi, F. Golestani-Fard, H. Nasiri, A Taguchi approach to the influence of hot pressing parameters and SiC content on the sinterability of ZrB_2-based composites, Int. J. Refract. Met. Hard Mater. 51 (2015) 81–90.
[26] M. Shahedi Asl, M. Ghassemi Kakroudi, B. Nayebi, A fractographical approach to the sintering process in porous ZrB_2–B_4C binary composites, Ceram. Int. 41 (2015) 379–387.
[27] M. Gu, C. Huang, S. Xiao, H. Liu, Improvements in mechanical properties of TiB_2 ceramics tool materials by the dispersion of Al_2O_3 particles, Mater. Sci. Eng. A 486 (2008) 167–170.
[28] M. Shahedi Asl, M. Ghassemi Kakroudi, A processing–microstructure correlation in ZrB_2–SiC composites hot-pressed under a load of 10 MPa, Univers. J. Mater. Sci. 3 (2015) 14–21.
[29] R. He, R. Zhang, Y. Pe, D. Fang, Two-step hot pressing of bimodal micron/nano-ZrB_2 ceramic with improved mechanical properties and thermal shock resistance, Int. J. Refract. Met. Hard Mater. 46 (2014) 65–70.
[30] Q. Liu, W. Han, J. Han, Influence of SiC_{np} content on the microstructure and mechanical properties of ZrB_2–SiC nanocomposite, Scr. Mater. 63 (2010) 581–584.
[31] M. Shahedi Asl, M. Ghassemi Kakroudi, A. Farzaneh, B. Nayebi, Influence of nano-SiC participation on densification and mechanical properties of ZrB_2, in: Proceedings of the 10th Nanoscience and Nanotechnology Conference of Turkey (NanoTR10), Istanbul, 2014.
[32] S. Zhu, W.G. Fahrenholtz, G.E. Hilmas, Influence of silicon carbide particle size on the microstructure and mechanical properties of zirconium diboride–silicon carbide ceramics, J. Eur. Ceram. Soc. 27 (2007) 2077–2083.
[33] F. Monteverde, Beneficial effects of an ultrafine α-SiC incorporation on the sinterability and mechanical properties of ZrB_2, Appl. Phys. A 82 (2006) 329–337.
[34] Z. Balak, M. Zakeri, M.R. Rahimipur, E. Salahi, H. Nasiri, Effect of open porosity on flexural strength and hardness of ZrB_2-based composites, Ceram. Int. 41 (2015) 8312–8319.
[35] M. Shahedi Asl, M. Ghassemi Kakroudi, S. Noori, Hardness and toughness of hot pressed ZrB_2–SiC composites consolidated under relatively low pressure, J. Alloy. Compd. 619 (2015) 481–487.
[36] M. Shahedi Asl, M. Ghassemi Kakroudi, Characterization of hot-pressed graphene reinforced ZrB_2–SiC composite, Mater. Sci. Eng. A 625 (2015) 385–392.
[37] M. Shahedi Asl, M. Ghassemi Kakroudi, R. Abedi Kondolaji, H. Nasiri, Influence of graphite nano-flakes on densification and mechanical properties of hot-pressed ZrB_2–SiC composite, Ceram. Int. 41 (2015) 5843–5851.
[38] M. Shahedi Asl, I. Farahbakhsh, B. Nayebi, Characteristics of multi-walled carbon nanotube toughened ZrB_2–SiC ceramic composite prepared by hot pressing, Ceram. Int. 42 (2016) 1950–1958.
[39] M. Shahedi Asl, F. Golmohammadi, M. Ghassemi Kakroudi, M. Shokouhimehr, Synergetic effects of SiC and C_{sf} in ZrB_2-based ceramic composites. Part I: densification behavior, Ceram. Int. 42 (2016) 4498–4506.
[40] N. Pourmohammadie Vafa, M. Shahedi Asl, M. Jaberi Zamharir, M. Ghassemi Kakroudi, Reactive hot pressing of ZrB_2-based composites with changes in ZrO_2/SiC ratio and sintering conditions. Part I: densification behavior, Ceram. Int. 41 (2015) 8388–8396.
[41] N. Pourmohammadie Vafa, B. Nayebi, M. Shahedi Asl, M. Jaberi Zamharir, M. Ghassemi Kakroudi, Reactive hot pressing of ZrB_2-based composites with changes in ZrO_2/SiC ratio and sintering conditions. Part II: mechanical behavior, Ceram. Int. 42 (2016) 2724–2733.