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Fabrication and mechanical properties of ($SiC_w + SiC_{np}$)/SiC layered ceramic composites

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($SiC_w + SiC_{np}$)/SiC layered ceramic composites with different ratios of SiC whiskers and SiC nano-particles were fabricated by tape casting and hot-pressing sintering; the mechanical properties and microstructure of the composites were investigated. The ratio of SiC whiskers and SiC nano-particles significantly influences on relative density and mechanical properties of the composites. The flexural strength and fracture toughness can reach the highest values of 455 MPa and 5.50 MPa·$m^{1/2}$, respectively, with the ratio of 8. The strength/toughness of the composites can be increased by introduction of SiC nano-particles in the layered structure. Crack deflection, crack bridging, and pullouts of whiskers can be observed in the fracture surfaces.

Keywords: layered ceramic composites, SiC whisker, SiC nano-particle, mechanical properties.

Виготовлення та механічні властивості шаруватих керамічних композитів (SiC_w + SiC_{np})/SiC. *Yupeng Xie, Jun Xu*

Шаруваті керамічні композити ($SiC_w + SiC_{np}$)/SiC з різним співвідношенням ниткоподібних кристалів SiC і наночастинок SiC виготовлено методом стрічкового лиття і спікання гарячим пресуванням, досліджено їх механічні властивості і мікроструктуру. Показано, що співвідношення ниткоподібних кристалів SiC і наночастинок SiC істотно впливає на відносну щільність і механічні властивості композитів. Міцність на вигин і в'язкість руйнування можуть досягати найвищого значення 455 МПа і 5,50 МПа·$м^{1/2}$ при співвідношенні 8. Міцність/ударна в'язкість композитів може бути збільшена шляхом введення наночастинок SiC у шарувату структуру. На поверхнях зламу можна спостерігати прогин тріщин, перекриття тріщин і витягування вусів.

Слоистые керамические композиты $SiC_w + SiC_{np}$)/SiC с различным соотношением нитевидных кристаллов SiC и наночастиц SiC изготовлены методом ленточного литья и спекания горячим прессованием; исследованы их механические свойства и микроструктура. Показано, что соотношение нитевидных кристаллов SiC и наночастиц SiC существенно влияет на относительную плотность и механические свойства композитов. Прочность на изгиб и вязкость разрушения могут достигать наивысшего значения 455 МПа и 5,50 МПа·$м^{1/2}$ при соотношении 8. Прочность/ударная вязкость композитов может быть увеличена путем введения наночастиц SiC в слоистую структуру. На поверхностях излома можно наблюдать прогиб трещин, перекрытие трещин и вытягивание усов.

1. Introduction

SiC ceramics have been considered to be a promising candidate for numerous structural applications due to the high thermal and chemical stability, high strength, excellent oxidation, corrosion and wear resistance [1, 2]. However, the low fracture toughness of the SiC ceramics is the main drawback [3, 4]. Many efforts, such as introduction of a second phase, have been made to improve their fracture toughness [5–7]. However, the efforts are limited. SiC_w/SiC and SiC_p/SiC layered ceramic composites are promising for overcoming the brittleness of SiC ceramics due to the different constituents [8, 9]. The whiskers and particles can improve the strength of the matrix, and the layered structure can increase the toughness. Moreover, they can all be combined to improve performance. Although the strength and toughness of the composites have been improved, the material needs further research in order to be practically applied in the military and civilian fields.

In our work, (SiC_w + SiC_{np})/SiC layered ceramic composites with different ratios of SiC whiskers and SiC nano-particles were fabricated by tape casting and hot-pressing sintering. The mechanical properties and microstructures of the composites were investigated. The strengthening/toughening mechanism was studied.

2. Experimental

The β–SiC whiskers with an average length of 18 μm and a diameter of 1.5 μm (Alfa Aesar, MA, USA) and SiC nano-particles with an average diameter of 30 nm (Shuitian Co., China) were used as reinforcements. SiC particles with an average diameter of 1.5 μm (Shuitian Co., China) were used as a matrix.

Four types of 30 vol.% (SiC_w + SiC_{np})/SiC composites with different ratios of SiC whiskers and SiC nano-particles (SiC_w : SiC_{np} = 10:1, 9:1, and 8:1) were fabricated; these are listed in Table 1. The fabrication processes of the slurry and green tapes were similar to those described in [10]. Al_2O_3 and Y_2O_3 were used as the sintering aids in the slurry, the molar ratio in which was 3:2. The green strips were then stacked one on top of the other until the desired thickness was obtained. The green layered bodies were pressed at room temperature by isostatic pressing. After removing the binder at 500°C for 1 h, the bodies were sintered at 1850°C for 1 h under a pressure of 25 MPa in Ar atmosphere. If the content of the nano-particles is too high, the preparation of the slurry is too difficult, so the composites with a high content of nano-particles have not been prepared. Two kinds of specimens were made from the composites; their dimensions were 3 mm×4 mm×40 mm and 3 mm×5 mm×30 mm, respectively. All the specimens were polished with 800 diamond grit to guarantee the same surface condition for the following tests.

The Archimedes method was used to measure the bulk density of the specimens. The flexural strength of the composites at room temperature (RT) was measured by using specimens of 3 mm×4 mm×36 mm with a span of 30 mm and a crosshead speed of 0.5 mm/min (WDW-10, Jinan Fangyuan Co., Jinan, China). The fracture toughness was determined at room temperature by the Vickers indentation method; specimens of 3 mm×5 mm×30 mm were used for tests

Table. (SiC_w + SiC_{np})/SiC layered ceramic composites

Reinforcement ratio	Only SiC_w	SiC_w : SiC_{np} = 10:1	SiC_w : SiC_{np} = 9:1	SiC_w : SiC_{np} = 8:1
Abbreviation	s-100	s-10	s-9	s-8

Table 2. Properties of (SiC_w + SiC_{np})/SiC layered ceramic composites

Materials	Flexural strength, MPa	Fracture toughness, MPa·m$^{1/2}$	Relative density, %
s-100	427±10	4.95±0.28	95.3
s-10	439±13	5.22±0.33	96.2
s-9	448±9	5.41±0.30	96.6
s-8	455±12	5.50±0.32	97.2

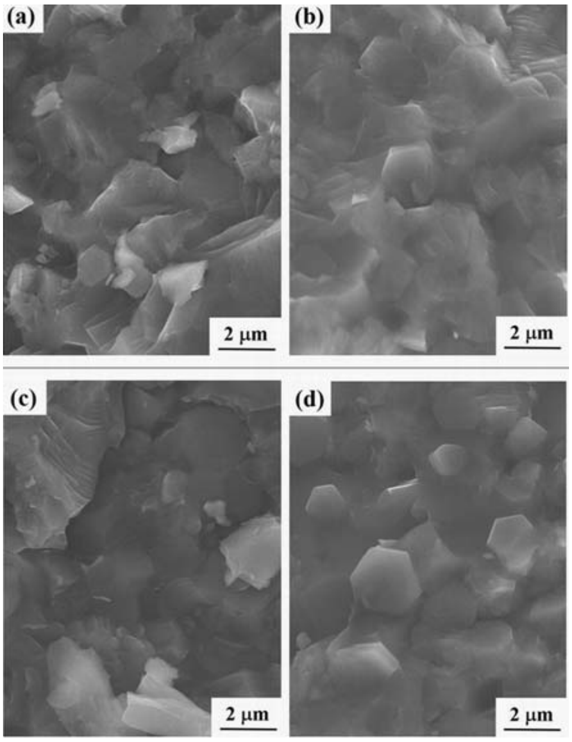

Fig. 1. Fracture morphologies of the composites: (a) S-100; (b) S-10; (c) S-9 and (d) S-8.

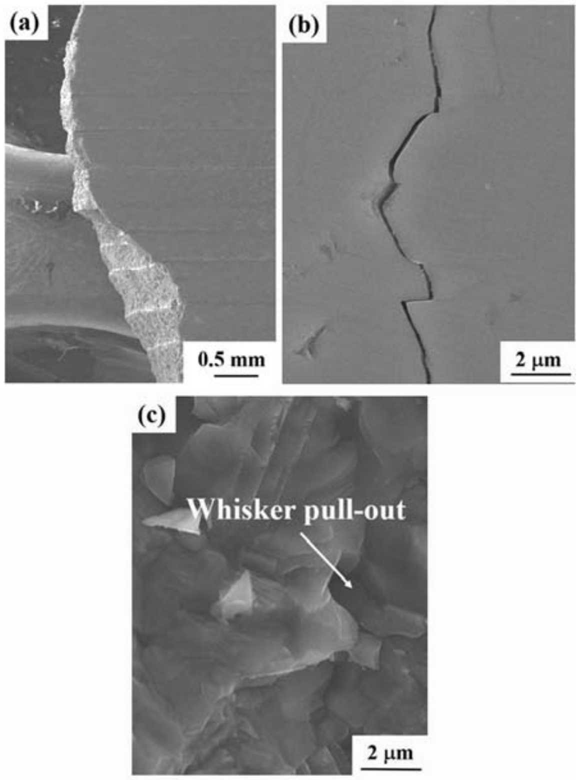

Fig. 2. SEM micrographs of (a) and (b) crack path and (c) fracture surface of $(SiC_w + SiC_{np})/SiC$ composites.

under loads of 98 N for 30 s. The surface morphologies of the composites were investigated by scanning electron microscopy (SEM, S-4700, Hitachi, Japan).

3. Results and discussion

In order to understand the effect of reinforcement of $(SiC_w + SiC_{np})/SiC$ layered ceramic composites, fix contents of reinforcements and changing ratios of SiC whiskers to SiC nano-particles were used. All the results were obtained with a constant reinforcement content of 30 vol.%. The flexural strength, fracture toughness and relative density of the composites are shown in Table 2. Only when reinforced with SiC whiskers do the mechanical properties of $(SiC_w + SiC_{np})/SiC$ composites improve due to a change in the relative content of SiC nanoparticles. The flexural strength and fracture toughness can respectively reach 455 MPa and 5.50 MPa·m$^{1/2}$ as the ratio of SiC_w to SiC_{np} is 8. The relative density of the composites is significantly increased to 97.2 % with the ratio of 8 of SiC nano-particles. Based on above results, the addition of SiC nano-particles can increase the mechanical properties because of densification of the composites.

The morphology of fracture surfaces for the composites with and without nano-particles is shown in Fig. 1. The densification of the composites is improved by introducing SiC nano-particles, and it can be increased gradually with increasing SiC nano-particle content. The results are consistent with Table 2. When the reinforcement is only due to the SiC whiskers, the pores created by whiskers cannot be completely filled by particles; this leads to deterioration in properties. With an increase in the content of SiC nanoparticles and a decrease in the content of SiC whiskers, the whiskers create fewer pores, and they are well filled with SiC particles (nano-particles and micro-particles) during the sintering process [11, 12]. In summary, the increased density is responsible for strengthening/toughening of $(SiC_w + SiC_{np})/SiC$ layered ceramic composites.

In order to understand mechanisms of strengthening/toughening by SiC whiskers and SiC nano-particles, the crack path and fracture surface of the composites were observed by SEM. As shown in Fig. 2, maintain a large length-to-diameter ratio after tape casting and sintering process, which contributes to the strengthening/toughening of the composites. Due to the introduction of SiC nano-particles, the densification of the composites can be increased, resulting in improvement of the strength. The crack deflection can be observed both at the interlayer and at the interfacial surface (Fig. 2a and 2b), which can extend the crack propagation path and increase the energy consumption capacity of the composite [13].

The well-dispersed whiskers and particles in the matrix can also contribute to the crack deflection in the interface as a crack approaches to them [14, 15]. The layered structure with appropriate interlayer bonding strength contributes to crack deflection in the interlayer surface during the fracture process. The longer the crack deflection path, the greater will be the crack propagation resistance. Moreover, crack bridging of the whiskers is observed in Fig. 2b, and pullout of the whiskers can also be observed in the fractures (Fig. 2c); this also helps to improve crack propagation resistance. As a result, the crack propagation resistance increases, which leads to an increase in the toughness of the composite. The strengthening/toughening of (SiC_w + SiC_{np})/SiC layered ceramic composites can be attributed to crack deflection, crack bridging, and pullouts of whiskers.

4. Conclusionы

(SiC_w + SiC_{np})/SiC layered ceramic composites with different ratios of SiC whiskers and SiC nano-particles were fabricated by tape casting and hot-pressing sintering. The properties of the (SiC_w + SiC_{np})/SiC composites are increased by introduction of SiC nano-particles; flexural strength and fracture toughness reach the highest values of 455 MPa and 5.50 $MPa \cdot m^{1/2}$, respectively, with the ratio of 8. The strengthening/toughening mechanism is crack deflection, crack bridging and pullout of whiskers, which contribute to improvement of mechanical properties of the composites.

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