Effect of TiC0.4 Addition on Microstructures and Properties of Ti3SiC2 Matrix Composites

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Abstract

TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} composites were manufactured using spark plasma sintering (SPS) at 1400°C for 10 min, with an applied pressure of 40 MPa. The effect of TiC\textsubscript{0.4} additions on microstructures and properties of Ti\textsubscript{3}SiC\textsubscript{2} matrix composites was investigated. The addition of TiC\textsubscript{0.4} induced the formation of TiC\textsubscript{x} (0.4 ≤ x ≤ 1) and promoted the decomposition of Ti\textsubscript{3}SiC\textsubscript{2}, yielding TiC\textsubscript{x} and Ti\textsubscript{5}Si\textsubscript{3}. The mechanical and tribological properties of the TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} composite improved with the TiC\textsubscript{0.4} content due to C vacancy present in TiC\textsubscript{0.4}, although the friction distance in the initial stage of friction test was increased. The 30 vol.% TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} composites exhibited the highest hardness and fracture toughness of 14.87 GPa and 5.45 MPa⋅m\textsuperscript{1/2}. At the same conditions, the wear rate at room temperature reached a minimum value of 4.32×10\textsuperscript{-7}mm\textsuperscript{3}N\textsuperscript{-1}m\textsuperscript{-1}, while the friction coefficient was 0.74. The friction distance in the initial friction stage of 30 vol.% TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} was about 38 m, and the wear mechanism of the composite at room temperature was mainly adhesive wear.

Highlights

1. The effect of C vacancy in TiC\textsubscript{0.4} can not only promote the decomposition of Ti\textsubscript{3}SiC\textsubscript{2} to form hard phases of TiC\textsubscript{x} and Ti\textsubscript{5}Si\textsubscript{3}, but also improve the interface bonding between Ti\textsubscript{3}SiC\textsubscript{2} and TiC\textsubscript{x}.
2. The addition of TiC\textsubscript{0.4} forms the hard phase of TiC\textsubscript{x} and decreases the Ti\textsubscript{3}SiC\textsubscript{2} grain size.
3. The value of bulk density, relative density, hardness and fracture toughness has the same trend of continuous climbing up with the increase of TiC\textsubscript{0.4} adding amount, while that of wear rate exhibits a declining trend. The value of the friction coefficient remains stable initially and then increases.
4. With the increase of TiC\textsubscript{0.4} adding amount, the content of TiC\textsubscript{x} particles in the detached particle increases, resulting in the difficulty of forming the complete lubricating film on the friction surface of TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} composite, and then increases the initial friction distance.
5. The integrity of the lubricating film is improved by the pinning effect of TiC\textsubscript{x} particle, resulting in the decrease of friction coefficient and wear rate.

1 Introduction

Ti\textsubscript{3}SiC\textsubscript{2} ternary ceramic embodies the advantages of both ceramics and metals, such as high Young's modulus (343 GPa) [1], high fracture toughness (7.20 MPa⋅m\textsuperscript{1/2}) [2], high corrosion resistance[3], good thermal and electrical conductivity (43 W/m⋅K and 9.6⋅10\textsuperscript{6} Ω\textsuperscript{-1}m\textsuperscript{-1}) [4], thermal shock resistance [5], etc. Its layered crystal structure is comparable to that of well-known graphite and MoS\textsubscript{2} solid lubricants, implying that it may be an excellent solid lubricant material with a low friction coefficient [6]. Thus, Ti\textsubscript{3}SiC\textsubscript{2} could find potential applications in bearings, turbines, cutting tools, electrical contacts, heat exchangers [7–11], etc. However, this is severely hampered by low hardness (4.54 GPa) and wear resistance (0.21-1.87×10\textsuperscript{-3} mm\textsuperscript{3}/N⋅m) of Ti\textsubscript{3}SiC\textsubscript{2} ceramics [12]. Many reinforcing phases, including
Al\(_2\)O\(_3\), SiC, TiC-TiS\(_2\), and TiC-TiB\(_2\), were applied to improve the hardness and wear resistance of Ti\(_3\)SiC\(_2\) due to the nailing of the softer phase by the hard phase [13–15]. However, we still lack the solution for the weak interfacial bonding between these reinforcing phases and the Ti\(_3\)SiC\(_2\) matrix, limiting the reinforcing phases’ enhancement effect. TiC\(_{0.4}\) is a representative of nonstoichiometric TiC\(_x\) (0.3<x<0.9) compounds, exhibiting a NaCl-type crystal structure [16–18]. It possesses high hardness (24.1-24.8 GPa), and the existence of vacancies improves the interfacial bonding between the reinforcing phase and the matrix [19–21]. Recently, TiC\(_x\) was used to improve the mechanical properties of the Al or Cu matrix composite, showing that the hardness and bending strength were increased by 84.7-116.3 and 80.7-122.4\%, respectively, compared to the Al or Cu matrix composite without TiC\(_x\) [21, 22].

In this study, we prepared the TiC\(_{0.4}\) (10, 20, and 30 vol.%) particles-reinforced Ti\(_3\)SiC\(_2\) matrix composites using SPS. Meanwhile, the effect of TiC\(_{0.4}\) content on the microstructure, mechanical properties, and friction and wear behaviour of the composites was systematically investigated, and the related mechanism was discussed.

### 2 Experimental Details

TiC\(_{0.4}\) powder was synthesized via mechanical alloying (MA) using the production method described in Ref. 19. TiC\(_{0.4}\) (purity 99.6\%, size 180-200 nm) and Ti\(_3\)SiC\(_2\) (purity 99\%, size 30 µm) powders were used as raw materials. The TiC\(_{0.4}\) volume fraction was fixed at 10, 20, and 30 vol.% in the whole raw material, and the corresponding sintered samples were denoted as TC0 (10 vol.% TiC\(_{0.4}\)), TC1 (20 vol.% TiC\(_{0.4}\)), and TC2 (30 vol.% TiC\(_{0.4}\)). These raw materials were well dispersed using the high-energy ball-milling method, and then the mixed powders were sintered using an SPS system (LABOX\(^\text{TM}\)-110, Japan) at a sintering temperature of 1400°C and a holding time of 10 min under a pressure of 40 MPa in a 30 Pa vacuum. The heating rate was set to 100°C/min.

The bulk density of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite was measured by Archimedes' method. The theoretical density of TC0, TC1, and TC2 was 3.78, 4.39, and 4.64 g/cm\(^3\), as calculated using the method described in Ref. 23. The hardness of the Ti\(_3\)SiC\(_2\) matrix composite was measured by a Vicker's hardness instrument (FM-ARS9000, China) with a dwell time of 15 s at a load of 500 gf. Fracture toughness (K\(_{\text{IC}}\)) was determined by the indentation method proposed in Ref. 24 with a load of 5000 g and a holding time of 15 s. Friction and wear tests were carried out using a ball-on-disc system (TRB, Switzerland). A ball sliding on a linear reciprocating athletic flat specimen (5 mm × 15 mm × 5 mm) was adopted. The specimens were cut by electrical discharge method and the test surface was mechanically polished down to 2000# SiC paper. The Si\(_3\)N\(_4\) balls were used as the friction counterparts with a diameter of 4 mm and a hardness of 15 GPa. Disc-specimens and Si\(_3\)N\(_4\) balls were cleaned by acetone solution before frictional wear tests. All tests were carried out under dry sliding conditions at room temperature (25°C) in the air. The wear track diameter was typically 11-13 mm. The tribological tests were performed at an applied load of 5 N, at a sliding speed of 0.1 m/s, and a testing distance of 100 m. The friction coefficient was
continuously measured and automatically recorded by the computer system of the friction tester, while the wear rate was calculated using Archard's equation [25]:

$$W = \frac{V}{P \cdot L}$$

where \(V(\text{mm}^3)\) is the wear volume obtained by measuring the weight loss in a microbalance after ultrasonic cleaning and drying and the measured density, \(P(\text{N})\) is the applied load, and \(L(\text{m})\) is the total sliding distance.

### 3 Results and Discussion

The TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite is composed of Ti\(_3\)SiC\(_2\) (Fig. 1a, marked as A, D, G, and J in Figs. 1c-f), TiC\(_x\) (Fig. 1a, marked as B, E, and H in Figs. 1c-e) and Ti\(_5\)Si\(_3\) (Fig. 1a, marked as C, F, and I in Figs. 1c-e). Ti\(_3\)SiC\(_2\), TiC\(_x\), and Ti\(_5\)Si\(_3\) particles exhibit lamellar shape, equiaxed grains, and irregular shape, respectively. The relative content of each phase in the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite is semi-quantitatively calculated using the method described in Ref. 26. The relative content of Ti\(_3\)SiC\(_2\) decreases, while the relative contents of TiC\(_x\) and Ti\(_5\)Si\(_3\) increase (Fig. 1b) with the increase of the TiC\(_{0.4}\) amount. The Ti-Si bonds in Ti\(_3\)SiC\(_2\) are weaker than Ti-C bonds [27], so that TiC\(_{0.4}\) can promote the Ti\(_3\)SiC\(_2\) decomposition to form TiC\(_x\) and Ti\(_5\)Si\(_3\) in the environment of C vacancies generated by the TiC\(_{0.4}\) additions [28]. At the same time, TiC\(_{0.4}\) absorbs C atoms from Ti\(_3\)SiC\(_2\) to form TiC\(_x\), which is more stable than TiC\(_{0.4}\), resulting in the small diffraction peak broadening of TiC\(_x\), compared with that of TiC\(_{0.4}\) (Fig. 1a). The Ti\(_3\)SiC\(_2\) decomposition and TiC\(_x\) generation reactions can be described as follows [29]:

\[
\text{Ti}_3\text{SiC}_2 \rightarrow \text{TiC}_x + \text{Si}
\]

\[
5\text{Ti} + 3\text{Si} = \text{Ti}_5\text{Si}_3
\]

\[
\text{TiC}_{0.4} + \text{C} \rightarrow \text{TiC}_x
\]

The Ti\(_3\)SiC\(_2\) grain size decreases from 3.3-6.1 \(\mu\text{m}\) (mean of 5.2 \(\mu\text{m}\)) to 1.4-2.8 \(\mu\text{m}\) (mean of 2.1 \(\mu\text{m}\)) (Figs. 1c-e) because TiC\(_x\) is prone to concentrate around the Ti\(_3\)SiC\(_2\) grain boundaries, hindering the Ti\(_3\)SiC\(_2\) grain growth during the sintering process (Figs. 1c-e). The porosity in the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite gradually decreases with the increase of the TiC\(_{0.4}\) amount (Figs. 1c-e). In addition, the fracture morphology of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite includes transgranular and intergranular fractures (Figs. 1c-e). The crack propagates at the Ti\(_3\)SiC\(_2\) particles of TC2, indicating that the interfacial bonding between Ti\(_3\)SiC\(_2\) and TiC\(_x\) is stronger than the Ti\(_3\)SiC\(_2\) fracture strength (see Fig. 1f). Thus, the interfacial bonding between Ti\(_3\)SiC\(_2\) and TiC\(_x\) is good. The good interfacial bonding between Ti\(_3\)SiC\(_2\) and TiC\(_x\) is attributed to the atomic diffusion of the elements. The reaction layer is about 65-80 \(\mu\text{m}\) in the layered sintered TiC\(_{0.4}\) and Ti\(_3\)SiC\(_2\) composite, indicating a good wettability between TiC\(_{0.4}\) and Ti\(_3\)SiC\(_2\) (Fig. 2). The Si content in the reaction layer is higher than in the Ti\(_3\)SiC\(_2\) region, while the C content is lower than in the Ti\(_3\)SiC\(_2\)
and TiC₀.₄ regions. According to the phase composition of the TiC₀.₄-Ti₃SiC₂ composite (Fig. 1a), Ti₅Si₃ and TiCₓ are formed in the reaction layer. The C vacancies can improve the wettability between TiC₀.₄ and Ti₃SiC₂ by enhancing the atomic diffusion ability of the elements, yielding the formation of TiCₓ and Ti₅Si₃ by the Ti₃SiC₂ decomposition. This can change the interfacial structure between TiC₀.₄ and Ti₃SiC₂ and promote interfacial bonding, enhancing the mechanical and tribological properties of the composite [21, 22].

The bulk density, relative density, hardness, fracture toughness, friction coefficient, and wear rate of TiC₀.₄-Ti₃SiC₂ composites are in the range of 3.7-4.63 g/cm³, 98.1-99.7%, 4-14.87 GPa, 3.6-5.45 MPa·m¹/², 0.63-0.74, and (4.32-6.49)×10⁻⁷mm³N⁻¹m⁻¹, respectively (Figs. 3a, b, and f). The indentations of hardness and fracture cover the whole phases of the TiC₀.₄-Ti₃SiC₂ composites at the optical microscope so that the values of hardness and fracture toughness of the TiC₀.₄-Ti₃SiC₂ composites measured by indentation method are accurate (Figs. 3c and d). The values of bulk density, relative density, hardness, and fracture toughness exhibit the same trend of a continuous increase with the TiC₀.₄ amount, while the wear rate exhibits a declining trend. The value of the friction coefficient remains stable initially and then increases. With a 30 vol.% TiC₀.₄ addition, the bulk density, relative density, hardness and fracture toughness of the TiC₀.₄-Ti₃SiC₂ composites reach maximum values of 4.63 g/cm³, 99.7%, 14.87 GPa, and 5.45 MPa·m¹/², respectively, while the wear rate reaches a minimum value of 4.32×10⁻⁷mm³N⁻¹m⁻¹. With a 20 wt.% TiC₀.₄ addition, the friction coefficient of the TiC₀.₄-Ti₃SiC₂ composites reaches a minimum value of 0.63. The behaviour of bulk density, hardness, and fracture toughness values with the TiC₀.₄ amount originates from the contribution of three factors. Firstly, the relative contents of TiCₓ (4.46-4.86 g/cm³ and 18-32 GPa [20, 30]) and Ti₅Si₃ (4.32 g/cm³ and 9.5 GPa) phases increase with the increase of the TiC₀.₄ amount, while the relative content of the Ti₃SiC₂ matrix (4.53 g/cm³ and 4 GPa) decrease, yielding a higher bulk density and hardness of TiC₀.₄-Ti₃SiC₂ composites (Figs. 1a-b). Secondly, the TiC₀.₄ addition can improve the interfacial bonding of Ti₃SiC₂ and TiCₓ so that it is conducive to the stress transfer from the Ti₃SiC₂ matrix to TiCₓ at high pressure and impeding the grain boundary sliding, which increases the resistance of dislocation movement (Figs. 1c-f). It yields an improvement in density, hardness and fracture toughness of the TiC₀.₄-Ti₃SiC₂ composites. Finally, hardness and fracture toughness are directly related to the grain size [31]. The Ti₃SiC₂ particle size decreases with increase with the increase of the TiC₀.₄ amount, causing an increase in the grain boundaries of TiC₀.₄-Ti₃SiC₂ composites and resulting in higher hardness and fracture toughness (Figs. 1c-e) [32, 33]. Although the fracture toughness of the TiC₀.₄-Ti₃SiC₂ composites is close to the mean value reported in the previous studies [7, 14, 30, 34–39], the TiC₀.₄-Ti₃SiC₂ composites exhibit an unprecedentedly high hardness of ~14.87 GPa (Fig. 3e). TiCₓ particles can effectively pin the Ti₃SiC₂ matrix to prevent the Ti₃SiC₂ detaching during the friction process due to the high hardness and strong interfacial bonding between TiCₓ and Ti₃SiC₂ (Fig. 1) [14]. In addition, the decrease of grain size lowers the wear rate due to the mitigation of multiple risks caused by plastic deformation, fracture,
fragmentation, and oxidation of grains \[40\]. The detached particles partly form a lubricating film on the friction surface of TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite, while others yield wear debris, which is later removed \[32\]. As the TiC\(_{0.4}\) addition increases from 20 to 30 vol.\%, the friction coefficient increases although the wear rate decreases, implying that the excessive TiC\(_x\) particles destroy the continuity of the lubrication film formed by the Ti\(_3\)SiC\(_2\) matrix (Fig. 4b-d). It is worth noting that TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites show a wear rate as low as 4.32-6.49×10\(^{-7}\)mm\(^3\)N m\(^{-1}\), which is much lower than the values reported for pure Ti\(_3\)SiC\(_2\) and other Ti\(_3\)SiC\(_2\)-based ceramics \[14, 37, 41–46\].

The relationship between friction coefficient and friction distance of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites can be divided into two stages, i.e., initial friction and stable friction (Fig. 4a). The friction distance of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites in the stable friction stage is from the end of the initial friction stage to the end of the friction process (Fig. 4a). The friction distance of TC0, TC1, and TC2 is about 4, 26, and 38 m in the initial friction stage. Detached particles gradually form the lubricating film on the friction surface of TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites during the friction process in the initial friction stage \[38\]. Since the more lubricating film is formed than lost through the wear debris formation, the friction coefficient gradually increases and fluctuates significantly in the initial friction stage. As the friction distance increases, the formed lubricating film covers the complete friction surface of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite, yielding the stage of stable friction. Consequently, the lubricating film production of TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites is in dynamic balance with its loss during the friction process, and the friction coefficient curve becomes smooth \[48\].

The content of TiC\(_x\) particles in the detached particles increases with the increase of the TiC\(_{0.4}\) amount, hampering the formation of the complete lubricating film on the friction surface of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composite so that the friction distance of the initial friction increases. The friction surface of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites mainly exhibits abrasive debris (Figs. 4b-d), indicating that the wear mechanism of the TiC\(_{0.4}\)-Ti\(_3\)SiC\(_2\) composites is adhesive wear. The abrasive debris on the friction surface decreases with the increase of the TiC\(_{0.4}\) amount. The C content in the smooth regions (L, N, and O points in Figs. 4b-d and Table 1) is lower than in the abrasive areas (K and M points in Figs. 4b-c and Table 1), unlike the O content. In addition, the O content in the smooth regions decreases with the increase of the TiC\(_{0.4}\) amount, while the C content increases in the smooth regions. Conclusively, the formation of abrasive debris is caused by the shedding of the lubricating film, which is inhibited by the TiC\(_{0.4}\) amount, decreasing the wear rate.
Table 1
The EDS elemental analysis (wt.%) of the regions marked in Figs. 4b-d

| EDS measured points | Ti  | Si  | O   | Fe  | C   |
|---------------------|-----|-----|-----|-----|-----|
| K                   | 33.23 | 12.58 | 35.11 | 1.08 | 18  |
| L                   | 37.34 | 14.15 | 26   | 1.23 | 21.28 |
| M                   | 32.78 | 14.34 | 24.29 | 0.85 | 25.74 |
| N                   | 35.91 | 15.01 | 20   | 1.97 | 27.11 |
| O                   | 31.06 | 13.33 | 22.11 | 1.14 | 32.36 |

The C vacancies in TiC<sub>0.4</sub> promote the Ti<sub>3</sub>SiC<sub>2</sub> decomposition, and thus, the formation of TiC<sub>x</sub> and Ti<sub>5</sub>Si<sub>3</sub> hard phases (Figs. 1a-b) and also improve the interfacial bonding between Ti<sub>3</sub>SiC<sub>2</sub> and TiC<sub>x</sub> (Figs. 1c-f and Fig. 2). In addition, the TiC<sub>0.4</sub> addition causes the formation of the hard TiC<sub>x</sub> phase around the Ti<sub>3</sub>SiC<sub>2</sub> grain boundaries, decreasing the Ti<sub>3</sub>SiC<sub>2</sub> grain size (Figs. 1c-e). The synergistic effect of these factors improves the mechanical and tribological properties of the TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites (Figs. 3). However, it affects the tribological properties mainly through the formation of the lubricating film on the surface of the TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites. As the formation of the lubricating film is in a dynamic balance with its loss during the friction process, the lubricating film is formed on the entire friction surface of the TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites, stabilizing the friction coefficient (Fig. 4 and Table 1). The lubricating film integrity is improved by the pinning effect of TiC particles, decreasing the friction coefficient and wear rate. Still, the pinning effect of TiC particles is limited by the continuity of the lubricating film. If TiC<sub>x</sub> particles in the TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites are present in excess, the continuity of lubricating film will decrease although the pinning effect of TiC particles is improved, yielding an increase of friction coefficient (Fig. 3d, Fig. 4, and Table 1).

4. Conclusions

TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites composed of Ti<sub>3</sub>SiC<sub>2</sub>, Ti<sub>5</sub>Si<sub>3</sub>, and TiC<sub>x</sub> were manufactured using SPS at 1400°C for 10 min. The relative content of Ti<sub>3</sub>SiC<sub>2</sub> decreased, while the relative contents of TiC<sub>x</sub> and Ti<sub>5</sub>Si<sub>3</sub> increased with the increase of the TiC<sub>0.4</sub> amount. TiC<sub>x</sub> was concentrated around the grain boundaries of Ti<sub>3</sub>SiC<sub>2</sub>. The TiC<sub>0.4</sub> addition improved the mechanical and tribological properties of the TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composites due to the presence of C vacancies in TiC<sub>0.4</sub>. The Ti<sub>3</sub>SiC<sub>2</sub> composite with 30 vol.% TiC<sub>0.4</sub> exhibited better comprehensive properties than other composites. The bulk density, relative density, hardness, fracture toughness, friction coefficient, and wear rate of the 30 vol.% TiC<sub>0.4</sub>-Ti<sub>3</sub>SiC<sub>2</sub> composite were 4.63 g/cm<sup>3</sup>, 99.7%, 14.87 GPa, 5.45 MPa·m<sup>1/2</sup>, 0.74, and 4.32×10<sup>-7</sup>mm<sup>3</sup>N<sup>-1</sup>m<sup>-1</sup>, respectively.
This work provides a theoretical basis for studying other materials enhanced by the addition of nonstoichiometric compounds and broadens the application spectra of the Ti$_3$SiC$_2$ matrix composites under severe environments.

Declarations

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Figures

Figure 1
(a) XRD patterns of TiC$_{0.4}$ and the TiC$_{0.4}$-Ti$_3$SiC$_2$ composites; (b) relative content of each phase in the TiC$_{0.4}$-Ti$_3$SiC$_2$ composites; FESEM micrographs of the cross-sectional microstructures of the TiC$_{0.4}$-Ti$_3$SiC$_2$ composites: (c) 10 vol.% TiC$_{0.4}$-Ti$_3$SiC$_2$, (d) 20 vol.% TiC$_{0.4}$-Ti$_3$SiC$_2$, and (e) 30 vol.% TiC$_{0.4}$-Ti$_3$SiC$_2$; (f) Crack propagation in the 30 vol.%TiC$_{0.4}$-Ti$_3$SiC$_2$ composite.

Figure 2

FESEM micrograph and the EDS line-scan analysis of the layered interface between TiC$_{0.4}$ and Ti$_3$SiC$_2$ sintered at 1400 °C.

Figure 3

Mechanical and tribological properties of the TiC$_{0.4}$-Ti$_3$SiC$_2$ composites. (a) density, (b) hardness and fracture toughness, (c) an optical micrograph of the Vickers indentation at load of 500gf, (d) an optical micrograph of the Fractures indentation at a load of 5000gf, (e) friction coefficient and wear rate; (f) the comparison of the hardness and fracture toughness values between the TiC$_{0.4}$-Ti$_3$SiC$_2$ composites and other Ti$_3$SiC$_2$ matrix composites reported in the literature.
Figure 4

Tribological properties of the TiC\textsubscript{0.4}-Ti\textsubscript{3}SiC\textsubscript{2} composites. (a) the relationship of friction coefficient and friction distance; FESEM micrographs of the friction surface of (b) TC0, (c) TC1 and (d) TC2.