

Microstructure, Mechanical and Tribological Behaviour of TaC-SiC Composites

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Abstract

Owing to their high hardness and high-temperature strength, tantalum carbide (TaC) ceramics are being developed for cutting tools or anti-wear materials on moving parts. It is worth examining the mechanical strength and intrinsic abrasion resistance of TaC-based composites to promote their tribological applications. In this study, TaC-silicon carbide (SiC) composites with 5–40 vol% SiC were hot-pressed, and their microstructure, mechanical and tribological properties were investigated. The microstructure of the composites was observed with field emission scanning electron spectroscopy (FESEM) and high-resolution transmission electron microscopy (HRTEM). The composition of worn surfaces was analysed by means of X-ray photoelectron spectroscopy (XPS) and Raman spectrometry (Raman). The results showed that compared to pure TaC, the relative densities of the composites were enhanced greatly. With the increasing content of SiC, the hardness of the composites increased gradually, while the bending strength first increased then decreased. The TaC and SiC phases coexisted in the composites, and the interfaces were clean, crystallized, without transition layers. Coupled with SiC, the TaC-SiC composites showed good wear resistance, with wear rates of 10^{-5} mm³/N·m. The main wear mechanisms of the TaC-SiC/SiC pair were abrasion and tribo-chemical reaction.

Keywords: Composites, wear resistance, carbides, wear mechanism

1. Introduction

Tantalum carbide (TaC) is an ultra-high-temperature ceramic with an ultra-high melting point, good corrosion resistance, and strength^{1–4}. TaC is expected to be used for cutting tools, brake blocks, wearing plates, and ultra-high-temperature protective materials. Owing to a strong covalent bond and low self-diffusion coefficient, it is difficult for pure TaC to achieve full density. Numerous investigations have focused on the sintering of TaC with additives^{5–11}, such as various types of C^{5,6}, B₄C^{1,5}, silicon carbide (SiC)^{3,7}, ZrC⁸, B⁹, Si¹⁰, and Si₃N₄¹¹. It has been found that SiC can effectively enhance the densification of TaC and its composites, which is closely related to the glassy pockets present at multi-grain junctions⁷.

TaC and other transition metal carbides are used as reinforcements or anti-wear phases for coatings^{12–15} and bulk materials^{16–18}. As reported by Ren *et al.*, the friction coefficient (CoF) of a TaC@Ta single layer is 0.2, and the specific wear rates (WRs) are as low as 5.6×10^{-7} mm³/N·m¹⁴. The TaC tends to be oxidized into crystallized Ta₂O₅ in air and TaO_x in argon or oxygen at extremely low pressures¹⁹. The results of friction and wear tests show that the tribological behaviour of TaC

has a close relationship with tribo-oxidation¹⁴. The reduced CoF and WRs are due to the existence of lubricious Magnéli phase TaO_x suboxides¹⁴ and TaSiO_x¹⁵ on the tribo-interface. With a higher load, the CoF of the TaC decreases¹⁶.

Adding TaC into the tribo-system is effective in reducing friction and for anti-wear applications. However, owing to the limited volume of its addition, its influence on friction and wear is limited and strongly dependent on specific tribo-systems. The intrinsic tribological characteristics of TaC-based bulk materials have not yet been determined. Therefore, for the tribological application of TaC ceramics, it is significant to identify the friction characteristics of the bulk material itself and clarify the influence of the mechanical properties of the material and the duality and friction conditions on its properties. In this study, based on previous works^{7–11}, TaC-SiC composites with various contents of SiC are hot-pressed. Based on investigation of their microstructure and mechanical properties, the tribological behaviour of the TaC-SiC composites with varied SiC contents is evaluated, and the mechanisms of the TaC-SiC composites are delineated. The results are valuable for tribological applications of TaC-SiC composites.

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II. Experimental

The TaC-SiC composites samples were prepared in a hot pressing process using commercial TaC (D_{50} of 0.9 μm , purity > 99.7 %, O content of 0.22 %, Ningxia Orient Tantalum Industry Co., LTD, China) powder and α -SiC powder (D_{50} of 0.7 μm , purity > 98 %, O content < 1.5 %, Shanghai Yunfu Nano, China) as raw materials. The metal element impurities in the raw powders are shown in Table 1. Carbon impurities in the raw powders were analysed with a Raman spectrometer (Raman, HORIBA JY-LabRAM HR Evolution). The Raman spectra are shown in Fig. 1.

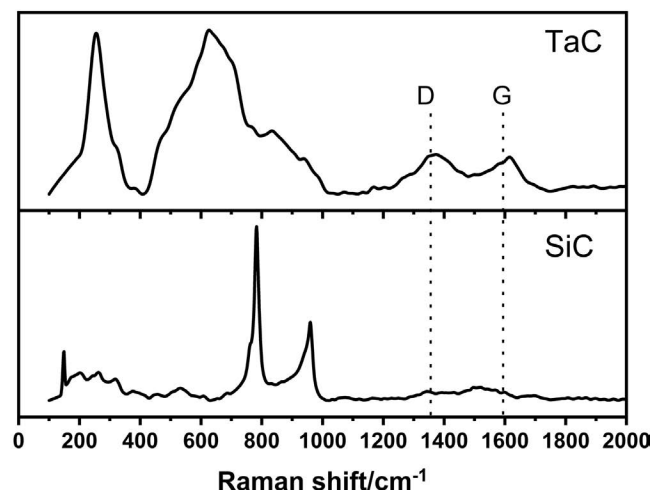


Fig. 1: Raman spectra of TaC and SiC powders.

The grinding process for the two raw powders was as follows. According to the ratio of raw powders, the two carbides were weighed and put into a ball grinding tank made of cemented carbide (tungsten carbide, cobalt-bonded, i.e. WC-Co). Cemented carbide balls were used as grinding media. There were two sizes of balls with diameters measuring 5 mm and 3 mm, respectively. The number ratio of the two sizes of balls was 10:1, and the mass ratio of grinding balls and mixing powders was 10:1. Anhydrous ethanol was then added onto the ball grinding tank. The ball grinding tank was placed onto a planetary ball mill and the revolution speed set to 400 rpm. The mill was run for 10 h. The powder mixture was taken out and placed into a vacuum drying oven. The temperature was set to 100 °C, and drying performed for 2 h. After drying, the powder was removed and ground manually for 5 min to break up any caked lumps. The powder was then passed through an 80-mesh sieve.

The mixed powders were put into a graphite die and hot-pressed at 1950 °C, under 30 MPa in argon for 60 min⁷. The samples were sectioned, ground, and polished to a 0.5 μm finish with diamond pastes. For each component of the composites, at least six samples were sintered. Three of these were used for the tribo-test. The rest were machined into a specific dimension for testing of their mechanical properties.

The density of the as-prepared composites was measured in accordance with the Archimedes method. Each sample was measured five times. Their relative density was determined as the percentage fractions of the measured values to

the theoretical ones. The theoretical density of the composites was calculated according to the rule of mixtures, based on the starting composition, assuming no reactions and no impurities in the sintered composite. Further details of the calculation process can be seen in supplementary materials A1. The phase component of the composites was measured by means of X-ray diffraction (XRD, D8 advance, Bruker), using $\text{CuK}\alpha$ radiation. The average grain size of TaC in the composites was measured with the linear intercept method on field emission scanning electron spectroscopy (FESEM, Zeiss, Sigma 300, Germany) micrographs. The morphology and microstructure of the composites were observed with FESEM and high-resolution transmission electron microscopy (HRTEM). The Vickers hardness was measured with the help of a universal indenter using a 98 N load with a 10 s dwell. The average value of ten indentations was reported for each sample. The three-point bending strength was tested using samples measuring 4.0 × 3.0 × 20.0 mm with a 16.0 mm span. The loading rate was 0.5 mm/min.

The friction and wear tests were conducted on a unidirectional ball-on-disk tribometer (HT-1000, Lanzhou Zhongke Kaihua Technology Development Co., Lanzhou). The disks consisted of TaC-SiC composites, and their size was $\varnothing 25 \text{ mm} \times 8 \text{ mm}$. Commercial SiC balls with a radius of 5 mm were used as tribo-pairs. Both balls and disks were cleaned ultrasonically in ethanol and dried before testing. The sliding velocity and load were 0.1 m/s and 5 N, respectively. The rotation radius and duration of the test were 3.00 mm and 60 min, respectively. All of the tests were conducted at room temperature (25 °C), and each test was repeated three times.

The CoF was recorded continuously by a computer during the test. The average CoF was the mean value of the CoF during the steady stage. The wear volume was calculated by measuring the weight loss of the composites after the test. The WR was calculated using worn volume (V), load (F), and sliding distance (L), according to Eq. (1)

$$\text{WR} = V/FL \quad (1)$$

The worn surface of the composites was analysed by means of FESEM. The composition of the as-polished surface and worn tracks of the TaC-SiC disks were analysed with energy disperse spectroscopy (EDS, Aztec X-Max 50, Oxford, UK), X-ray photoelectron spectroscopy (XPS, ThermoFisher 250Xi) and Raman spectrometry. The excitation source of the Raman spectrometer was 514 nm lines of Ar^+ ion laser.

Table 1: Composition of the raw powders (analyzed with ICP)

No.	Main metal elements (wt.%)
TaC	Ta 99.8, Si 0.02, Nd 0.04, Nb 0.03, Fe 0.03
SiC	Si 99.6, Fe 0.09, Na 0.05, Al 0.05, K 0.03, Ca 0.03, Ti 0.02, V 0.02, S 0.02

III. Results and Discussion

(1) Phase composition of the TaC-SiC composites

Fig. 1 shows the Raman spectra of the TaC and SiC powders. It can be seen that there are carbon impurities in the raw materials. Fig. 2 shows the XRD pattern of the as-prepared TaC-SiC composites. It can be seen that well-crystallized cubic TaC phase and SiC phase coexist in the composites, although the peak intensity of the SiC is rather low compared to that of the TaC. Similar patterns are reported by Liu ^{7,20}, Hu ³, and Yu ²¹. In Fig. 2, because of the overlapping of peaks of hexagonal SiC and cubic SiC, it is difficult to identify the type of SiC in the composites. Although the raw materials of SiC are of the Acheson type, mainly 6H polytype (provided by the manufacturer). The type of cubic SiC phase is confirmed by SAED in the following section (Fig. 4f). Although the crystal type of SiC cannot be confirmed, it is certain that, with the exception of TaC and SiC, there are no crystallized materials in the composites, which could be inferred from the XRD pattern.

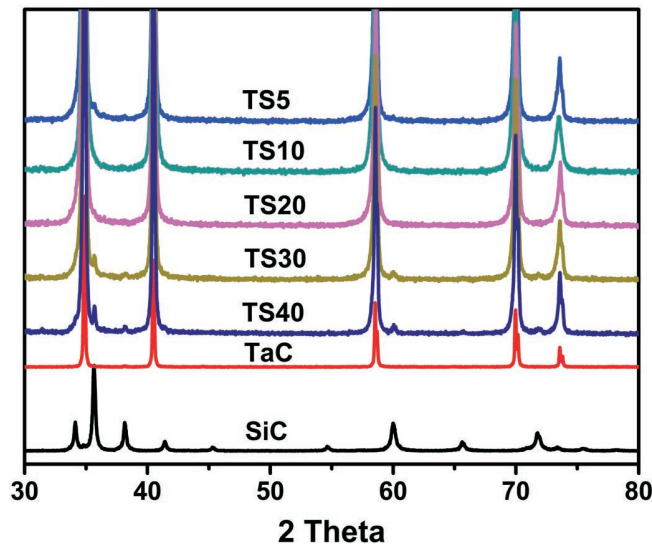


Fig. 2: XRD pattern of the as-prepared TaC-SiC composites.

The calculated lattice parameters of TaC in the composites are shown in Table 2. The *a* of TaC first increases from 4.4543 Å to 4.4619 Å as the SiC content increases from 0 % to 20 %, then decreases to 4.4579 Å as the SiC content in-

creases to 40 %. The corresponding theoretical densities of the composites are calculated according to the lattice parameters. Both the theoretical density and the relative density of the TaC-SiC composites are shown in Table 2. The pure TaC reaches a low density of 78.3 % under the same sintering conditions. With the addition of SiC, the densities of the TaC-SiC composites are enhanced greatly, which are in the range of 98.3 % to 100.0 %. Therefore, the addition of SiC has a good densifying effect. This might be because the addition of SiC can prevent residual pores from being entrapped by inhibiting the fast growth of TaC grains on the basis of physical pinning of the grain boundary ^{7,20}. The carbon impurities in the raw materials can also be a reductant to remove oxides on the outmost surfaces of TaC and SiC.

(2) Microstructure

The fracture surfaces of the TaC-SiC composites are shown in Fig. 3. For the pure TaC, there are many pores in the sintered body (Fig. 3a), which is in line with its low density of 78.3 %. The average grain size of TaC is 0.7 μm (Fig. 3a). For the TaC-SiC composites (Fig. 3b – 3f), it is shown that that matrix-phase TaC disperses continuously while secondary-phase SiC is distributed in the matrix. Many of the SiC grains are located in two-grain or three-grain boundaries of the TaC phase, while some of the SiC grains are embedded inside the TaC grains. With the increase in SiC content, the segregation of SiC particles in boundaries becomes increasingly obvious (Fig. 3b – 3f). For all of the TaC-SiC composites, the dominant fracture mode is intergranular, although there is a small fraction of transgranular fracture. The average grain sizes of TaC in the composites decrease from 3.6 μm to 1.1 μm as the SiC content increases from TS5 to TS40 (Table 3). It can be concluded that, on the whole, a higher content of SiC is beneficial to the refinement of TaC grains ⁷, which may result from SiC particles physically pinning the grain boundaries between TaC particles ³. However, it must be pointed out from TS5 to TS10, the reduction of TaC grain size is 1.8 μm. In contrast, from TS30 to TS40, the reduction is only 0.1 μm, indicating that the grain refining effect caused by the increase of SiC content is not obvious when the SiC content is higher.

Table 2: Composition and the density of the consolidated ceramics and the lattice parameter “*a*” of TaC phase in the composites

No.	Composition	Theoretical density (g/cm ³)	Measured density (g/cm ³)	Relative density (g/cm ³)	<i>a</i> of TaC* (Å)
TaC	TaC-0 vol% SiC	14.47	11.33±0.05	78.27±0.34	4.4543
TS5	TaC-5 vol% SiC	13.91	13.67±0.02	98.30±0.11	4.4567
TS10	TaC-10 vol% SiC	13.34	13.19±0.04	98.86±0.32	4.4590
TS20	TaC-20 vol% SiC	12.22	12.17±0.08	99.56±0.66	4.4619
TS30	TaC-30 vol% SiC	11.09	11.09±0.02	100±0.21	4.4579
TS40	TaC-40 vol% SiC	9.96	9.91±0.02	99.50±0.20	4.4571

* Estimated by means of X-ray diffraction;

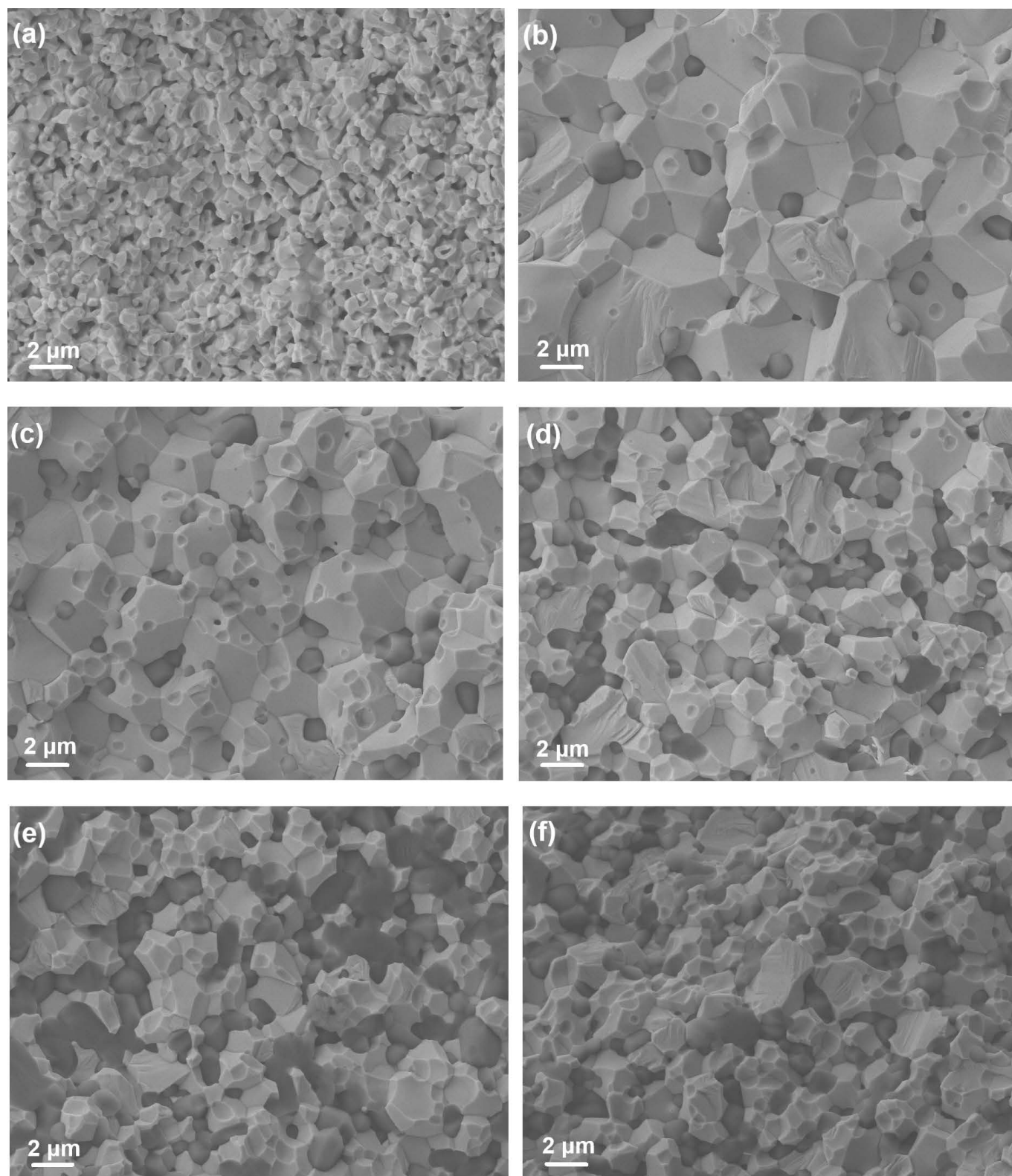


Fig. 3: FESEM images of the fracture surfaces of: (a) TaC, (b) TS5, (c) TS10 (d) TS20, (e) TS30, and (f) TS40.

Fig. 4 shows TEM images and selected area electron diffraction (SAED) patterns of TS30 composite. In Fig. 4a, the continuous dark phase, and the discrete bright phase are TaC and SiC grains, respectively. The agglomeration of SiC grains is clear, which can also be seen from Fig. 3e. In Fig. 4b, the bright triangle area that is surrounded by two TaC grains and one SiC grain is highly crystallized (Fig. 4c). After Fourier transformation (FFT), legible diffraction spots are obtained, the corresponding interplanar spacing of which is 0.2557 nm. Therefore, it could be inferred that the crystal of this area is cubic TaC and its crystal face is (111). The triangular grain boundary in Fig. 4d is enlarged to obtain Fig. 4e. In Fig. 4e, it can be seen that the TaC and SiC phases are highly crystallized (P1, P3, and P4). The interplanar spacing of P1, P3, and P4 are 0.2605 nm, 0.2573 nm, and 0.2519 nm, respectively. Based on these, in Fig. 4f, the corresponding SAED patterns of P1, P3, and P4 are designated to cubic TaC_{[-110][01-1]} and cubic SiC_[01-1], respectively. The connected area of TaC and SiC grain (P2) is crystallized and clear diffraction spots are obtained after FFT. But the area of P2 is too small to obtain reliable diffraction fringe spacing with converse FFT. From Figs. 4c, 4e, and 4f, the phases of grain boundaries of TaC-TaC, TaC-SiC, as well as the three-grain junction areas grains are highly crystallized. There are no glassy layers or other impurities in boundary and three-grain junction areas. This is quite different from the

glassy pockets present at multi-grain junctions reported by Liu *et al.*²⁰ and glassy layers at the boundaries between TaC and SiC reported by Hu *et al.*³. Liu *et al.* found that besides Ta, Si, and C, there are also O, F, and Ca elements in the glass pockets, which presumably are introduced by the impurities in the TaC and SiC starting materials. They believe that glass pockets would be the liquid phase during sintering and wet that SiC, which is the main reason for the enhanced densification. Hu *et al.*³ report a low eutectic liquid phase generated by the oxide on the particle surface to realize relatively low-temperature sintering densification. In this paper, there are no detected impurities as oxides at grain boundaries at the present observation level.

(3) Mechanical properties of the TaC-SiC composites

Table 3 shows the hardness and bending strength of the TaC-SiC composites. From TS5 to TS40, the Vickers' hardness of the TaC-SiC composites increases gradually from 1378 to 1660 HV. However, the bending strength of the composites first increases from approximately 330 MPa (TS5) to 360 MPa (TS10 to TS30), then decreases to 320 MPa (TS40). As mentioned in section III(1), the main fracture mode of the composites is intergranular. Since the as-prepared TaC-SiC composites are completely dense materials, the relationship between the mechanical properties and microstructure of the composites is mainly affected by the following factors. The first is the

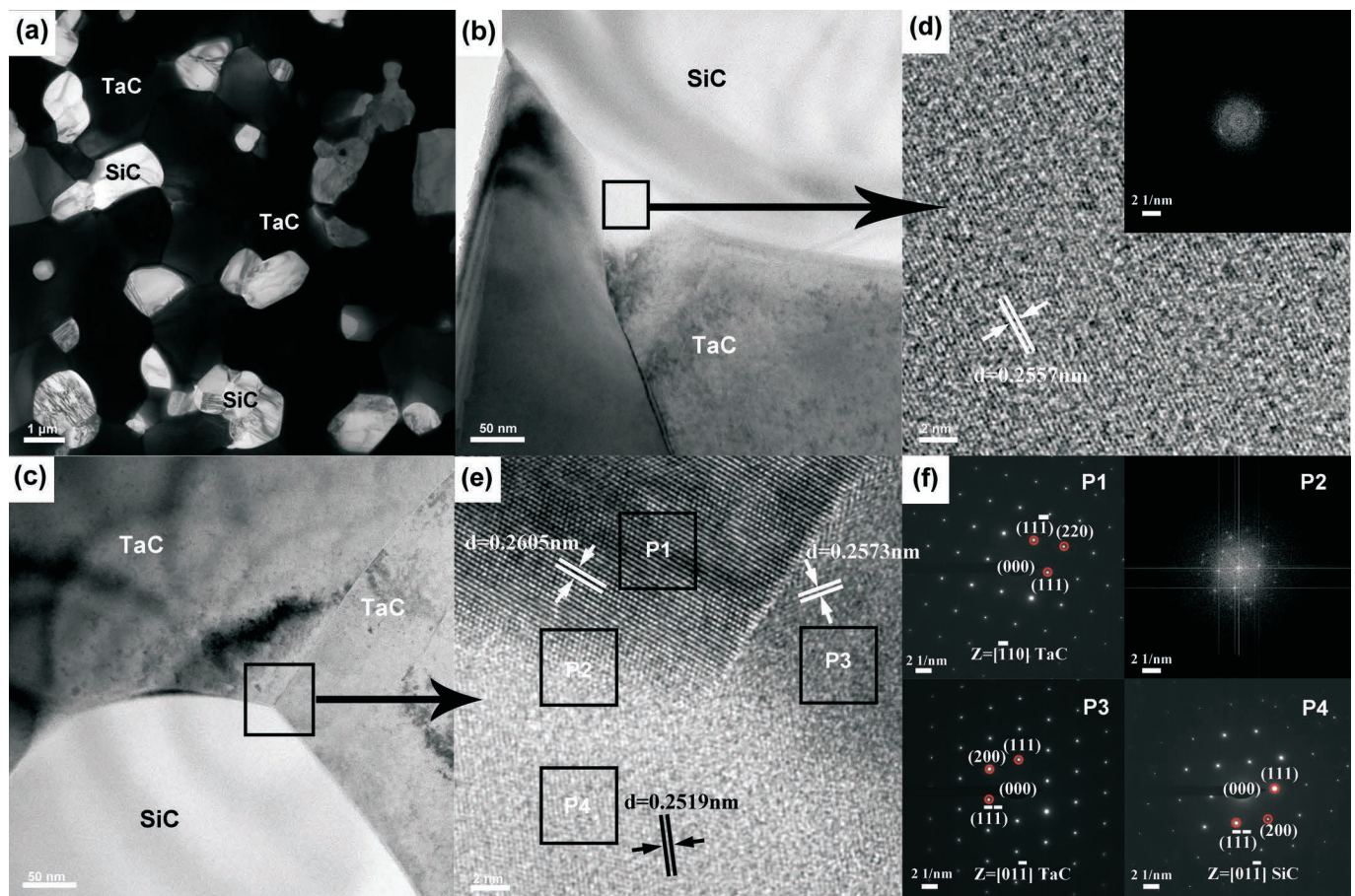


Fig. 4: TEM images of TS30 composites (a), typical three-grain junction area (b), (c) HRTEM image of a selected area in (b), the inset of (c) is the FFT pattern of (c); another typical three-grain junction area (d), (e) the HRTEM image of a selected area in (d); (f) selected area electron diffraction patterns (P1, P3, P4) and FFT pattern (P2) of selected areas in (e).

Table 3: Grain size, hardness, and bending strength of the TaC-SiC composites

No.	Average TaC grain size (μm)	Vickers' hardness (HV)	Three-point bending strength (MPa)
TaC	0.7	—	—
TS5	3.6	1378 $\pm$ 61	331 $\pm$ 3
TS10	1.8	1415 $\pm$ 86	368 $\pm$ 68
TS20	1.6	1478 $\pm$ 37	360 $\pm$ 106
TS30	1.2	1586 $\pm$ 48	357 $\pm$ 28
TS40	1.1	1660 $\pm$ 35	320 $\pm$ 48

grain size²³. Finer grain size is crucial to the improvement of the mechanical properties of composites. With the increasing content of SiC, the grain size of TaC in TaC-SiC composites decreases gradually. However, when the SiC content is higher than 30 %, the decrease in grain size caused by the increase in SiC content is no longer significant (Table 2). Second, the thermal stress between TaC and SiC can improve the strength of materials within a certain range^{24,25}. The coefficients of thermal expansion of TaC and SiC are $6.3 \times 10^{-6}/\text{K}$ and $4.3 \times 10^{-6}/\text{K}$, respectively²⁶. However, with the increasing content of SiC particles, excessive thermal stress will inevitably lead to the decline of the mechanical properties of the materials. Third, there is no transition layer in the interfaces between TaC-TaC or TaC-SiC grains at the scale of HRTEM in this paper (Fig. 4 and Fig. 5). In other words, the grain boundaries are well crystallized and no impurity is segregated within them (Fig. 4 and Fig. 5), which may endow the composites with good strength at high temperature²⁷. By contrast, at room temperature, the composites are not as strong as those reported by Pienti and Liu *et al.*^{6–9}. Therefore, the improvement in hardness is mainly determined by grain refinement and increasing number of interfaces of TaC-SiC²⁸. From TS5 to TS30, grain refinement is beneficial to strength improvement, but excessive thermal stress between SiC and TaC is detrimental to strength improvement. From TS30 to TS40, the grain size decreases slightly, but excessive thermal stress leads to a decrease in bending strength. Therefore, a range of SiC content from 10 % to 30 % is optimal for the hardness and bending strength of the composites.

(4) Tribological properties of the composites

The average CoFs and WRs of TaC-SiC composites with various SiC contents coupled with SiC are shown in Table 4. For pure TaC, the average CoF is 0.6, and the WRs of TaC disk and SiC ball are $1.2 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$ and $1.7 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. For TaC-SiC composites, the average CoFs are in the range of 0.50 to 0.4, and not sensitive to the change of SiC content in the composites. With the addition of SiC, the WRs of the composite disks decrease one order of magnitude, which is at the order of $10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. For TS5 to TS30, the WRs of the composite disks are in the range of $(1.3–2.8) \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$; For TS40, the WRs increase to $6.6 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. Inversely, the WRs of the SiC balls decrease from $1.7 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ when coupled with TS5 to $6.9 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ when coupled

with TS30, then increase to $1.3 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ when coupled with TS40. In general, the harder the material, the better its wear resistance²⁹. However, although the hardness of the TaC-SiC composites increases with SiC content, its wear resistance decreases. One reason might be that the strength of TaC grains is higher than the bonding strength of TaC and TaC as well as TaC and SiC. Under the action of wear, the removal mechanisms of materials are mainly pull-outs of SiC and TaC grains, and the fracture of TaC grains (which will be discussed in the following section).

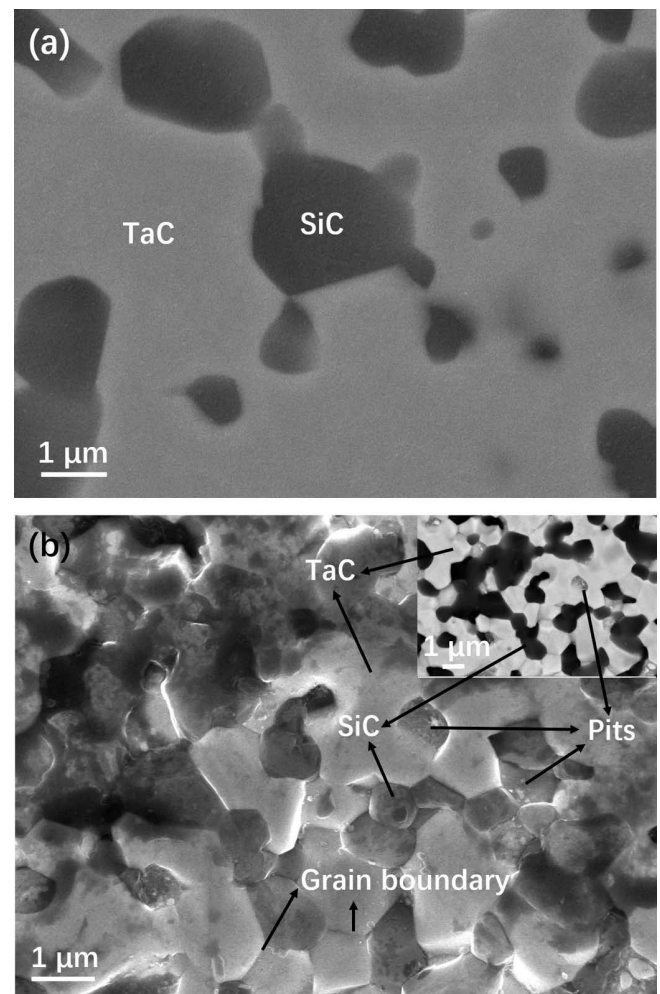


Fig. 5: FESEM secondary electron images of the as-polished (a) and worn surface, (b) of TaC-30%SiC composites. The inlet in (b) is the corresponding backscattered electron image of (b).

Therefore, the wear behaviour of the composites is strongly influenced by a weak interface in the composites. As the SiC content increases, more weak interfaces appear in composites.

What is more, compared to the CoF and WR of a TaC@Ta single layer coupled with Al_2O_3 , which are approximately 0.2 and $10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}^{14}$, respectively, the bulk TaC-SiC composites exhibit greater friction and wear.

The typical morphology of the worn surface of the TaC-SiC composites is shown in Fig. 5. For the as-polished surface (Fig. 5a), it indicates that the SiC particles disperse uniformly in the TaC matrix. The grain boundaries between TaC-TaC, TaC-SiC, and SiC-SiC grains are invisible. In Fig. 5b, there are pits with equivalent size to SiC grains or particles on the worn surface, which are derived from the pull-out of SiC grains and fracture of TaC grains caused by abrasive wear³⁰. There is debris in some of the pits. The grain boundaries of TaC and SiC are obvious, which is different from that on the as-polished surface. From Fig. 5, it could be concluded that under the action of friction, the weak boundaries of TaC-SiC are the source of cracks, which result in the extraction of TaC or SiC.

The element composition of the as-polished surface and worn tracks for TaC-SiC composites are analysed by means of EDS. The element composition of the as-polished surface of TS30 is $\text{Ta}_{21}\text{Si}_{20}\text{C}_{56}\text{O}_3$. The low O content on the composite indicates that mild oxidation naturally occurs during the polishing process³¹. By contrast, the element composition of the worn surface is

$\text{Ta}_{16}\text{Si}_{16}\text{C}_4\text{O}_{64}$. The much higher O content indicates strongly that there is tribo-oxidation during the friction process.

To confirm exact compounds on the as-polished and worn surfaces on the composites, the Raman spectrum (Fig. 6) and binding energy of elements (Fig. 7) are investigated. It can be seen from Fig. 6 that there are TaC³²,

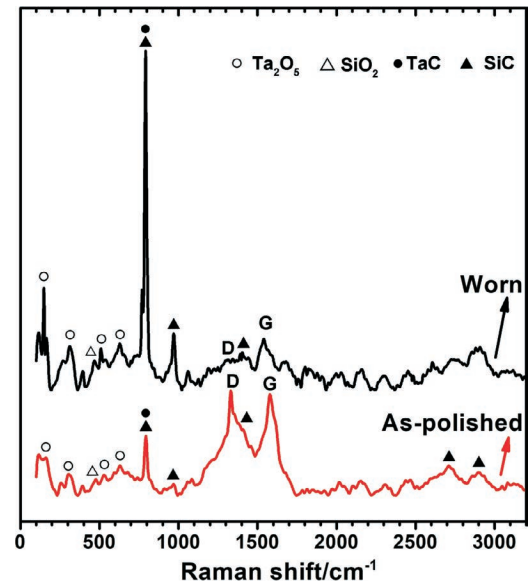


Fig. 6: Raman spectrum of the as-polished surface and worn surface of the TS30 composites.

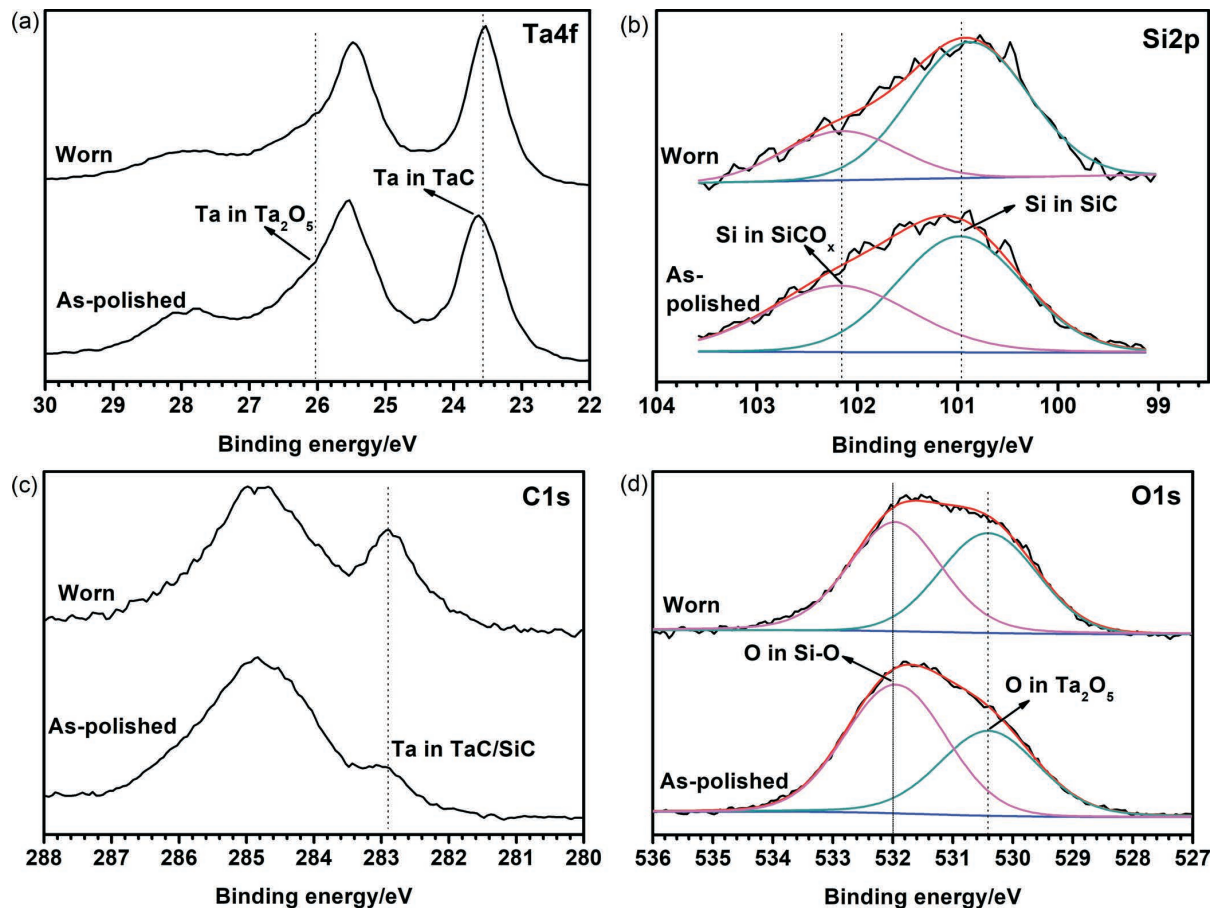


Fig. 7: Binding energy of elements on the as-polished surface and worn surface of the TS30 composites (a) Ta 4f, (b) Si 2p, (c) C 1s, and (d) O 1s.

SiC³³, Ta₂O₅¹⁹, and silicon oxides^{34,35} on the as-polished surface of TaC-SiC composites. The compounds on the worn surface are almost the same as on the as-polished surface, except that they are more crystallized, which could be inferred from the shape of the peaks. In Fig. 7, the main compounds on the as-polished surface and worn surface of the composites are TaC and SiC^{14,15,19}, the oxides are Ta₂O₅ (secondary phase)¹⁹ and SiCO_x (main phase)^{14,15,33}. The oxides on the worn surface are beneficial to reducing friction and wear, which has been confirmed by Ren *et al.*¹⁴.

From the above results, it can be seen that with increasing SiC content, the hardness of the as-prepared composites increases gradually, and the bending strength first increases then decreases (Table 2). The friction coefficients of the composites with different content of SiC are in the range of 0.4 to 0.5, and the WRs of the composites increase gradually from $1 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ to $6 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ (Table 4). For the worn morphology of the composites, pits caused by the extraction of TaC and SiC particles are the main worn features. It could be concluded that the weak boundaries of TaC-SiC are the source of cracks, which leads to the removal of TaC or SiC. With the increasing content of SiC, weaker interfaces exist in the composites. This might be the reason why the hardness and strength of the composites increase with SiC content (except TS40), while the wear rates of the composites increase as well.

Compounds like Ta₂O₅ and SiCO_x (Fig. 6 and Fig. 7) on the composites indicate that there is tribo-oxidation during the wearing process. Since the TaC and SiC are typical non-oxides ceramics, they could be oxidized easily during polishing or friction process^{6,15,19}. During the sliding process, the SiC and TaC grains are pulled out of the composites, some of which are trapped in the pits (Fig. 5b) or tribo-oxidized into Ta₂O₅ and SiCO_x. Therefore, the wear mechanism of the TaC-SiC/SiC tribo-pair is mainly mixed wear with abrasion and tribo-chemical reaction.

Table 4: Coefficient of friction and specific wear rates of the TaC-SiC composites coupled with SiC

No.	CoF	Spe- cific wear rates of composites ($10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$)	Specific wear rates of SiC ($10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$)
TaC	0.58±0.04	12.2±2.0	1.74±0.29
TS5	0.50±0.04	1.25±0.59	1.39±0.28
TS10	0.50±0.08	2.38±0.21	1.04±0.35
TS20	0.45±0.04	2.83±0.13	1.04±0.35
TS30	0.40±0.08	2.34±0.37	0.694±0.17
TS40	0.48±0.07	6.64±0.29	1.30±0.22

VI. Conclusions

In this study, fully dense TaC-SiC composites with 5–40 vol% SiC are prepared, and their microstructure, mechanical and tribological properties are investigated. The main findings of this paper are as follows:

a. With the addition of SiC, the densification process of the TaC-SiC composites is enhanced greatly; the hardness increases with SiC content, while the bending strength of the TaC-SiC composites first increases then decreases with SiC content. The range of SiC content of 10 % to 30 % is optimal for the bending strength of the TaC-SiC composites.

b. Cubic TaC and SiC coexist in the composites, and the interface of TaC and SiC is clear, clean, crystallized, without transition layers.

c. Coupled with SiC, the TaC-SiC composites show good wear resistance, with WRs of $10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$. The CoFs of the composites are not sensitive to the change in SiC content. The main wear mechanisms of the TaC-SiC/SiC pair are abrasion and tribo-chemical reaction.

The conclusion of this study is of practical importance for the preparation and application of TaC-SiC composites as wear-resistant materials. However, although the influence of SiC content on the tribological properties of the composites has been studied here, the influence of frictional heat and temperature on the microstructure and composition of the friction surfaces has not been revealed. The structure and composition of friction surfaces are closely related to the properties of TaC composites at high temperatures or high sliding speed. Therefore, the evolution of both the microstructure and composition of the worn surface of TaC composites at high temperatures or high speed should be studied further in the future.

Supplementary materials

A1: Calculation process of theoretical density of the composites

Only the lattice parameter of TaC in the composites is calculated. The theoretical density of SiC is 3.218 g/cm^3 (6H-SiC, pdf: 29–1131).

The basic equations are Equation (1) and (2),

$$2d \sin \theta = \lambda \quad (1)$$

$$d = \frac{a}{\sqrt{H^2 + K^2 + L^2}} \quad (2)$$

The d , θ , and λ in equation (1) are interplanar spacing, grazing angle of a certain crystal surface, wavelength of X-ray produced by the copper target, respectively. In Equation (2), a is the lattice parameter of a crystal, and H , K , and L are indices of interference.

According to Equations (1) and (2), Equation (3) could be inferred.

$$a = \frac{\lambda \sqrt{H^2 + K^2 + L^2}}{2 \sin \theta} \quad (3)$$

Five values of a can be obtained by substituting the corresponding values of θ and H , K , L measured by XRD into Equation (3). The least square method is used to treat the five a , and the more accurate a value is obtained. Then the theoretical density is calculated according to Equation (4),

$$D = \frac{ZM}{N_A V} \quad (4)$$

where D is theoretical density; M is the generalized molar mass of crystal; Z is the number of molecules in the cell, N_A is Avogadro's constant; and V is the cell volume.

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