

Effect of TiB₂ Particles on the Tribological Properties of Stainless Steel Matrix Composites

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Abstract The AISI316L stainless steel composites reinforced with 2, 4, 6, and 8 vol% titanium diboride (TiB₂) particles were sintered by the high pressure-high temperature method. Ball-on-disk method was carried out to study wear behavior of the composites. Tests were carried out at room temperature. The TiB₂ particles improved the hardness and tribological properties of the composites. The friction coefficient of the composites decreased with the increasing content of TiB₂. The reduction of the wear rate with the increasing of the content of TiB₂ particles in the steel matrix was also observed. It is demonstrated that the friction coefficient of composites with the same content of TiB₂ particles depend on the sintering conditions.

KEY WORDS: Metal matrix composites; Titanium diboride; Friction coefficient; Ball-on-disk method

1 Introduction

Metal matrix composites (MMCs) are an important group of the engineering materials due to their enhanced specific properties and their ability to be tailored to suit many different applications. There has been significant research into austenitic stainless steel-based MMCs, because of the excellent corrosion resistance, heat resistance, and workability of steel matrix. The ceramic reinforcement is implemented into steels in order to increase the elastic

modulus and to improve the wear resistance. Therefore, these composites can be used for structural applications in wear industry [1, 2]. Among different ceramic particulates, the titanium diboride (TiB₂) is considered as the best reinforcement for the steel-matrix composites due to its excellent properties such as high hardness, low density, high melting temperature, excellent wear, and corrosion resistance, good wettability and stability in steel matrix [3–5].

In recent years, the researches concerning the influence of the different ceramic particulates (TiB₂, TiC, Al₂O₃, Y₂O₃, SiC etc.) on the tribological properties of the stainless steels were realized [6–12]. Also, an improvement in the wear resistance has been observed when intermetallic particles were used as the reinforcement of the steel-matrix composites [13, 14]. The authors focused mainly on studies of the effect of reinforcing phases on the wear resistance, physical, and mechanical properties and the microstructure of the composites. For example, Pagounis et al. [15] investigated the abrasion wear behavior of the steel-matrix composites reinforced with TiC, Al₂O₃, and Cr₃C₂. They indicated that TiC particles provide the steel matrix with the highest wear resistance followed by Al₂O₃ and Cr₃C₂. The incorporation of the ceramic particles into

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austenitic steel matrices can lead to a dramatic improvement in the abrasive wear resistance. Sliding wear response of the materials depends on a different materials and experimental parameters. Morphology, volume fraction, mode of distribution of various phases, and their properties influence the wear response of materials. Applied pressure, sliding speed, traversal distance, temperature, etc. are the experimental factors influencing the wear characteristics [16–20].

A critical literature analysis reveals few works on wear properties of TiB₂ particle-reinforced steel-matrix composites. Tjong and Lau [21, 22] investigated the properties of the AISI 304 stainless steel and the composites reinforced with various volume fractions of TiB₂ particles. They reported that with increasing TiB₂ content the hardness and tensile strength improved, but dropped the plasticity. It was indicated that the addition of TiB₂ particles was very effective to improve the wear resistance and ductility of austenitic stainless steel. Pin-on-disk abrasive measurements showed that the wear resistance of 304 SS was improved dramatically with the increasing TiB₂ content. Additionally, the volumetric wear of the composite tended to decrease with increasing applied normal loads or with sliding velocity. Recently, Sulima *et al.* [23] studied the influences of 10 and 20 vol% of TiB₂ ceramic on the mechanical and tribological properties of the composites. It was shown that the friction coefficient of the composites decreases with increasing TiB₂ content. The best tribological properties were obtained for the austenitic AISI 316L stainless steel reinforced with 20 vol% TiB₂ ceramics, i.e., the value of the friction coefficient is 0.37.

In the present work, the wear behavior of the 316L stainless steel composites reinforced with various volume fractions of TiB₂ particles has been studied using a ball-on-disk method.

2 Experimental Procedure

TiB₂ powder (99.9% purity, 2.5–3.5 μm in diameter) and commercial AISI 316L austenitic stainless steel powder (25 μm in diameter, KAMB Import–Export) were used as starting materials. The chemical composition of the AISI 316L steel powder is given in Table 1.

The composites with 2, 4, 6, and 8 vol% TiB₂ were produced by mixing the TiB₂ and AISI 316L steel powders

Table 1 Chemical composition of AISI 316L stainless steel powder (wt%)

C	Cr	Ni	Mo	Mn	Si	S	P	Fe
0.027	17.20	12.32	2.02	0.43	0.89	0.030	0.028	Bal.

in a tubular mixer for 12 h, then the mixtures were formed into disks (15 mm in diameter, 5 mm in thickness) by pressing in a steel matrix under pressure of 200 MPa. The composites were fabricated using the high pressure-high temperature (HP-HT) method. The sintering process was carried out at pressures of 5.0 GPa and (7.0 ± 0.2) GPa and temperatures of 1,000 and 1,300 °C for 60 s. Due to concurrent operation of both pressure and temperature the sintering process proceeds much faster (usually in several minutes) than conventional method which usually takes several hours. The obtained sinters are characterized by high density (almost 100%) and low porosity. Such conditions can also reduce the diffusion of particles and prevent grain growth.

The densities of the composites were measured by Archimedes water immersion method, the uncertainty of measurements was 0.02 g/cm³. Vickers microhardness measurements using a load of 2.94 N, were carried out with an FM-7 microhardness tester.

The surfaces of the investigated composites were prepared according to Ref. [24]. Samples for wear tests were prepared by standard methods of grinding using SiC foil and polishing using 0.4 μm diamond suspension. All the specimen surfaces were cleaned with alcohol and dried. The surface roughness was below 0.2 μm (*R_a*). Tribological tests were carried out using the UMT-2T (CETR, USA) ball-on-disk tribotester under room temperature. Tests were carried out without lubricant according to the ISO 20808:2004(E). For ball-on-disk method, the sliding contact was brought by pushing a Al₂O₃ ball (3.175 mm in

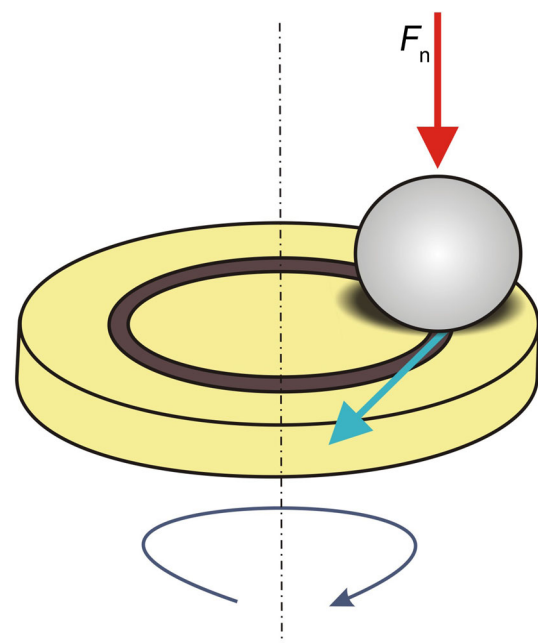


Fig. 1 Schematic of the ball-on-disk wear test system [25]

diameter) on a rotating disk specimen under a constant load F_n of 4 N, as shown in Fig. 1 [25]. The friction track diameter was 4 mm, sliding speed was 0.1 m/s, total sliding distance was 200 m and the test duration was 2,000 s. The friction force was measured continuously during the test using the extensometer. For each test, a new ball is used. Specimens are washed in high purity acetone and dried. After mounting the ball, Specimens were washed in ethyl alcohol and then dried.

The friction coefficient (μ) is calculated as the ratio of the force of friction (F_f) and applied normal load (F_n). Following the wear test, the specific wear rate was calculated. For the wear track on the disk specimen, the cross-sectional profile of the wear track at four places at intervals of 90° using a contact stylus profilometer was measured with accuracy of measurement in the vertical axis of 0.01 μm , in the horizontal axis of 0.1 μm . The cross-sectional area of the wear track was calculated using a specially designed PC program.

Specific wear rate according to wear volume was calculated by

$$W_{\text{disc}} = \frac{V_{\text{disc}}}{F_n L}, \quad (1)$$

where W_{disc} is the specific wear rate of disk, $\text{mm}^3/(\text{N}\cdot\text{m})$; V_{disc} is the wear volume of disk specimen, mm^3 ; L is the sliding distance, m. V_{disc} was calculated by

$$V_{\text{disc}} = \frac{\pi}{2} \times R \times (S_1 + S_2 + S_3 + S_4), \quad (2)$$

where R is the radius of wear track, mm; S_1 , S_2 , S_3 , and S_4 , are the four cross-sectional areas at four different places on the wear track circle, mm^2 .

The cross-sectional microstructure of worn surface was observed using a scanning electron microscope (SEM) JEOL JSM 6610LV. EDS technique (AZtec) was applied to determine the chemical composition of worn surface of the composites.

3 Results and Discussion

Figure 2 presents the evolution of the density with the amount of reinforcement and sintering temperature and pressure. The density of the composites decreases with the amount of reinforcement, due to density of TiB_2 much lower than that of stainless steel. For all composites, very high level of consolidation was obtained (98–100% of theoretical density), even though the duration of sintering was only 30 s. The very high level of consolidation of the composites results from simultaneous effect of high pressure and high temperature during the process. The use of such conditions of sintering allows to limit the diffusion

and to prevent the grains growth. The effect of TiB_2 addition on hardness is illustrated in Fig. 3. The increment of the TiB_2 addition leads to the increase of the hardness of the composites. It is found that the sintering temperature has a significant effect on the hardness of the composites also. It is interesting that the higher value of hardness of the composites were obtained at the lower temperature (1,000 °C). For example, the composites with 8 vol% TiB_2 experience the hardness of 368 $\text{HV}_{0.3}$ and 282 $\text{HV}_{0.3}$ when the sintering temperatures are 1,000 and 1,300 °C (pressure of 5.0 GPa), respectively. Generally, the application of the highest temperature at the same pressure caused the reduction of the hardness of about 28–35%. However, the hardness of the composites appears to increase with increasing pressure of sintering. Figure 4 presents selected

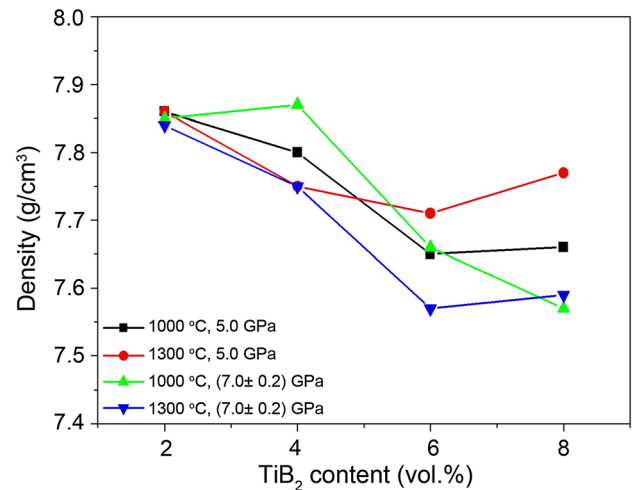


Fig. 2 Variation of the density with TiB_2 contents of the sintered composites

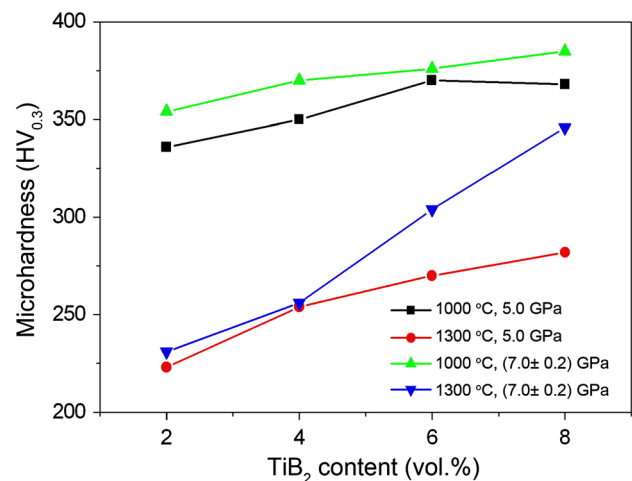


Fig. 3 Results of hardness measurements ($\text{HV}_{0.3}$) for the composites

microstructure of the austenitic stainless steel and the composites containing 8 vol% TiB_2 sintered at 1,300 °C and (7 ± 0.2) GPa. Uniform dispersion of fine TiB_2 particles in austenitic steel matrix was observed in all cases of studied composites. The TiB_2 particles are evident mostly at the grain boundary. No porosity was noticed in the microstructure of the steel and composites, what results in very high densification of the materials.

Figure 5 shows the variation of the friction coefficient for unreinforced steel and tested composites with the test

duration. It shows that the friction coefficient of the composites with the same content of TiB_2 particles depends on the sintering conditions (Fig. 5). The variation of friction coefficient with increasing temperature and pressure had the similar trend for all composites. The best value of friction coefficient of the composites was obtained at the temperature of 1,300 °C and pressure of (7 ± 0.2) GPa. In the case of composites with 2, 4, 6, and 8 vol% TiB_2 , the values of friction coefficient are 0.54, 0.53, 0.52, and 0.50, respectively. Although the variation of friction coefficient

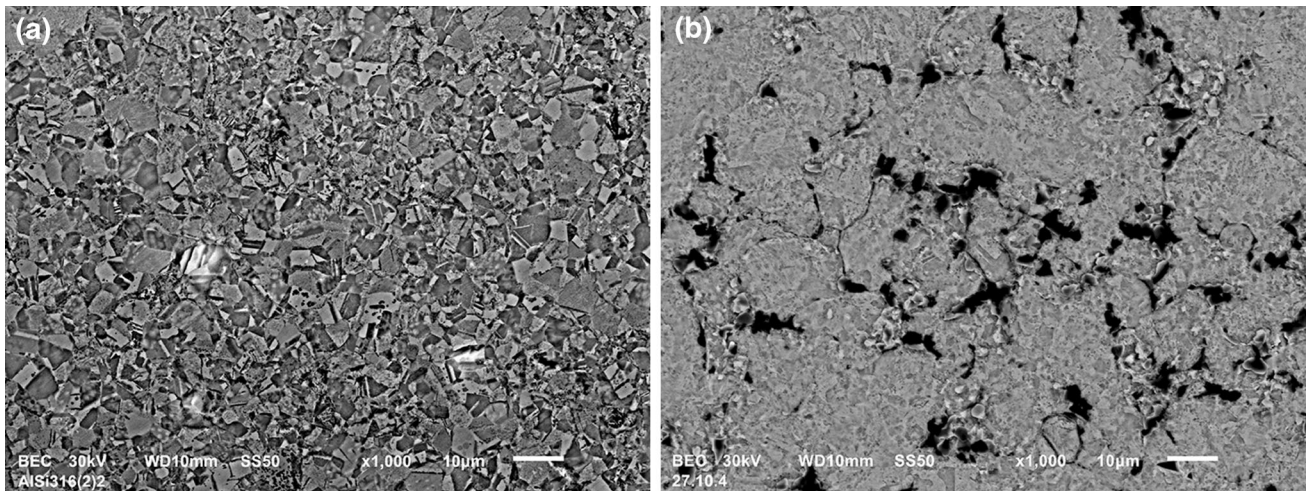


Fig. 4 Typical SEM images of austenitic stainless steel **a**; the composite with 8 vol% TiB_2 which was sintered at a temperature of 1,300 °C and pressure of (7.0 ± 0.2) GPa **b**

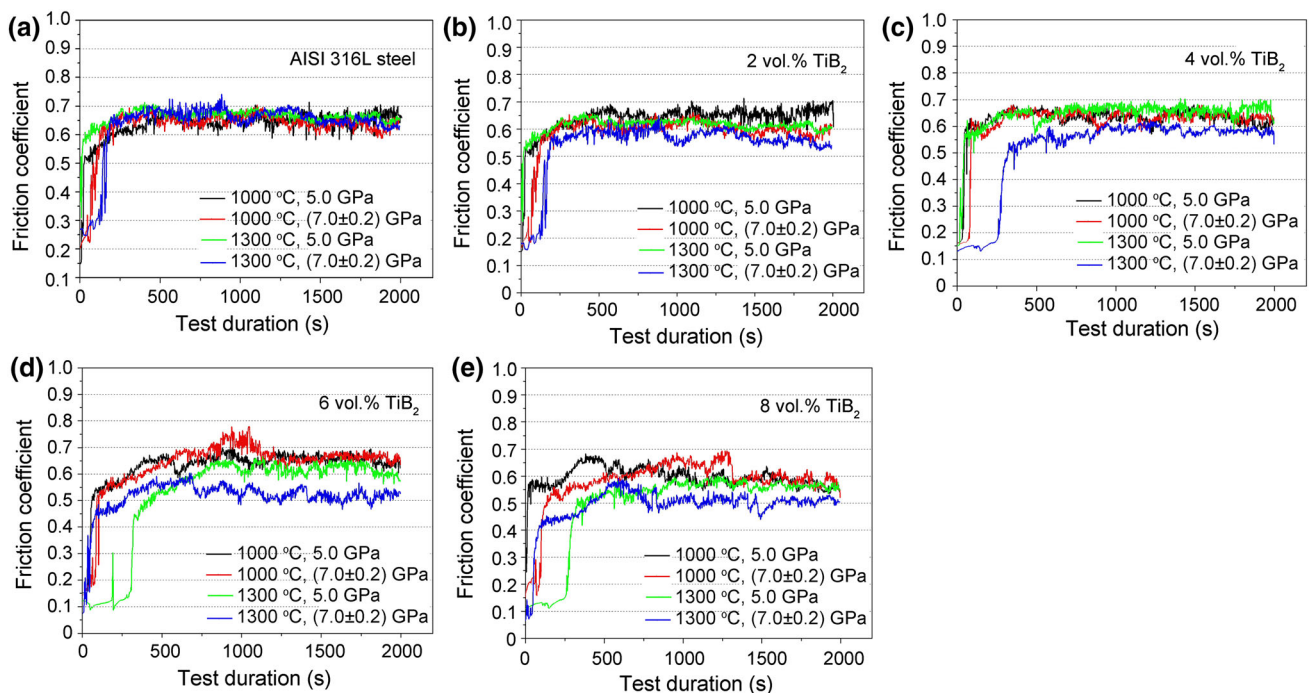


Fig. 5 Typical friction coefficient curves of the materials during testing of unreinforced austenitic stainless steel **a**, composites reinforced with different contents of TiB_2 of 2 vol% **b**, 4 vol% **c**, 6 vol% **d**, 8 vol% **e**

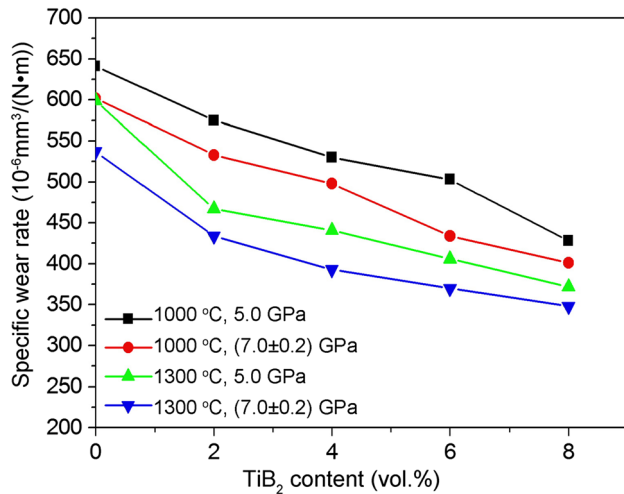


Fig. 6 Variation of specific wear rate with TiB₂ content of the composites sintered at different temperatures and pressures

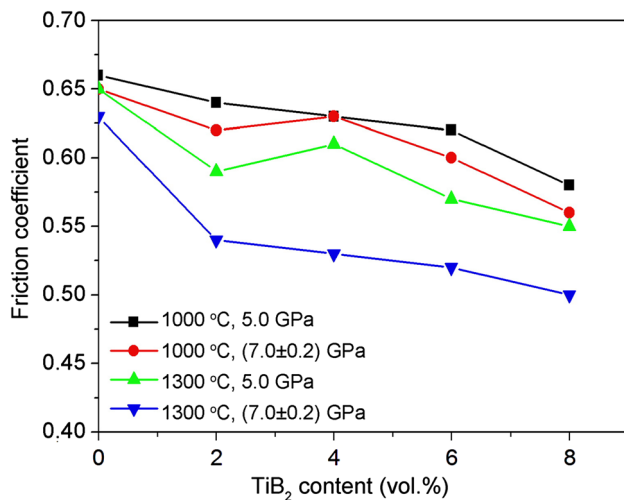


Fig. 7 Variation of the friction coefficients with TiB₂ content of the composites sintered at different temperatures and pressures

is not large, it tends to reduce the wear rate when the temperature and pressure of sintering increase (Fig. 6). Moreover, the friction coefficient depends on the content of TiB₂ particles (Fig. 7). In the case of the composites with 2 and 4 vol% TiB₂, the values of the friction coefficient are very similar, and are placed in the range of 0.6–0.64 for temperature of 1,000 °C [pressures of 5.0 and (7 ± 0.2) GPa] and 1,300 °C (pressure of 5 GPa). Although variation of the friction coefficient is not very significant, it tends to reduce the friction coefficient when TiB₂ are added. The examinations show that the friction coefficient of the composite with 8 vol% TiB₂ is 0.50, which is the smallest. For comparison, the value of the friction coefficient for the austenitic stainless steel is in the range 0.66–0.68 (Fig. 5a). It is evident that TiB₂ additions cause the improvement of

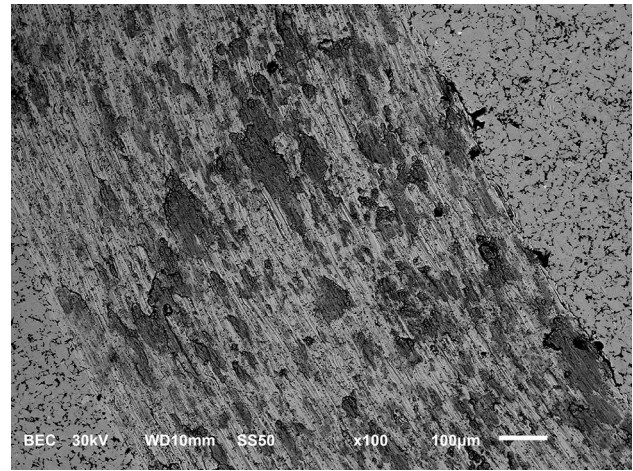


Fig. 8 SEM micrograph of the worn track on the surface of the composites with 8 vol% TiB₂ sintered at temperatures of 1,300 °C and pressure of (7.0 ± 0.2) GPa

the wear resistance of austenitic stainless steel due to the high hardness of TiB₂ particles which can reach 3400 HV [26] and the slow wear of reinforcement. Therefore, unreinforced 316L stainless steel exhibits the higher wear rate of $553 \times 10^{-6} \text{ mm}^3/(\text{N m})$, while with only 2 vol% TiB₂ addition, wear rate of composites reduced to $434 \times 10^{-6} \text{ mm}^3/(\text{N m})$. As it can be concluded from Fig. 7, the wear rate decreases with the content of TiB₂ particles increase. The TiB₂ particles protect the steel matrix during sliding. Additionally, the homogeneous distribution of fine reinforcement is favorable for the further improvement of the wear resistance [27]. Therefore, for composites with lower content of TiB₂ of 2 and 4 vol%, the Al₂O₃ ball can penetrate easily the steel matrix during sliding, resulting in excessive material removal from the worn surface. In the composites with 8 vol% TiB₂, the material removal is delayed most probably due to an accumulation of TiB₂ particles on the surface after the austenitic stainless steel is removed during the abrasion.

Tjong and Lau [22] showed that the wear resistance of 304 stainless steel increases with the increasing TiB₂ content. It was indicated that the hardness of the composites tends to increase with increasing the TiB₂ content, thus the abrasive wear resistance of the composites improves considerably with increasing TiB₂ content. It is consistent with the well-known Archard's law for sliding wear [28]. The discussed results also confirm the dependence of wear resistance on the hardness for the same sintering conditions (Fig. 3, 6). It was noticed that this dependence is not always true, when taking the influence of sintering conditions into consideration. The rise in pressure causes the increase of the hardness and the wear resistance at the same temperature. This is especially visible for composites with 8 vol% TiB₂ obtained at the sintering temperature of

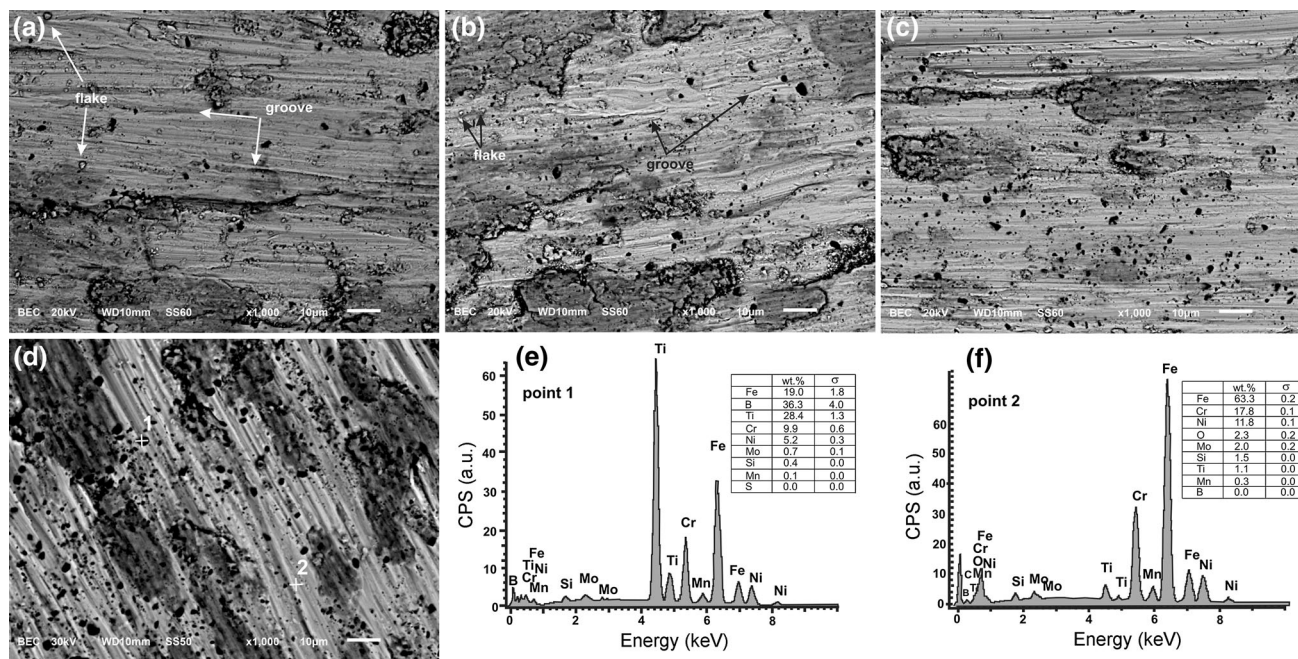


Fig. 9 SEM micrographs of the worn surface of composites sintered at temperatures of 1,300 °C and pressure of (7.0 ± 0.2) GPa that with 2 vol% **a**, 4 vol% **b**, 6 vol% **c**, 8 vol% **d** TiB₂ additions and the corresponding EDS analyses of the selected point **e**, point **f** in **d**

1,300 °C. In this case, for pressure of 5.0 GPa and (7.0 ± 0.2) GPa, the hardness are 282 HV_{0.3} and 346 HV_{0.3} and friction coefficients are 0.55 and 0.50, respectively. However, it is noted that this relationship is not verified when the effect of the temperature at constant pressure. It is interesting that with increasing temperature of sintering the hardness drops, nevertheless improving the wear resistance. For example, the hardness of the composites with 6 vol% TiB₂ are 376 HV_{0.3} and 304 HV_{0.3} when the sintering temperature are 1,000 and 1,300 °C under (7.0 ± 0.2) GPa, respectively. However, the friction coefficients are 0.60 and 0.52, respectively.

Figure 8 shows that the SEM micrograph of the surface of composites with wear track. Figure 9 presents the worn surfaces of the composites with different content of TiB₂ particles, which were sintered at temperature of 1,300 °C and pressure of (7.0 ± 0.2) GPa. Abrasive wear mechanism is operation in all composites, which is characterized by the scratches on the surface. The worn surface topographies indicate the dominant wear mechanism is plowing. This is consistent with the behavior that has been observed in other composite materials [6, 10, 29]. The surface of investigated composites exhibits grooving, most probably produced as a result of plowing by the hard Al₂O₃ ball, because the hardness of Al₂O₃ (2,000 HV) is higher than that of the sintered austenitic stainless steel matrix. Also, the flake formation was observed locally in Fig. 9a, b. Additionally, no cracking can be seen in the worn surface. It can be seen from Fig. 9c, d that the exposed TiB₂

particles appear in the plastic plowing on the worn surfaces. The reinforcing particles reside on the top surface of the composite after sliding. Fine TiB₂ particles were not removed from the steel matrix during sliding. It is evident that the TiB₂ particles effectively cover the steel matrix and restrict the metal removal by the abrasive particles in the case of the composite. Such worn surface is characteristic especially for composites with 8 vol% TiB₂. EDS results confirm further only the presence of TiB₂ particles on the top surface of the composite after sliding, as the black particles in Fig. 9d–f indicated.

4 Conclusions

Four austenitic steel-TiB₂ composites were obtained by HP-HT method. The addition of TiB₂ particles has a positive effect on the hardness and tribological properties of composites. The wear rate of the composites decreases with the increasing TiB₂ content, indicating that the addition of hard TiB₂ improves wear resistance of the composites. The friction coefficients of all materials are in the range from 0.50 to 0.64.

The sintering temperature and pressure have significant effect on the densification, hardness, and the wear resistance of the composites. The composites with 8 vol% TiB₂ obtained at temperature of 1,300 °C and pressure of (7.0 ± 0.2) GPa exhibit good combination of properties such as hardness (346 HV_{0.3}) and friction coefficient (0.50).

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