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ARTICLE

Friction and Wear Performance of in-Situ (TiC+TiB)/Ti6Al4V Composites

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Abstract: (TiC+TiB)/Ti6Al4V composites with different TiC and TiB contents were prepared by in situ synthesis. The influence of load on the dry sliding friction and wear performance of in-situ (TiC+TiB)/Ti6Al4V composites (TMC) was studied by HT-1000 friction and wear testing machine, and the wear behavior of the composites was also investigated by scanning electron microscopy (SEM) and Bruker 3D profilometer. The results show that the wear resistance of TMC is improved by the formation of TiC and TiB phases compared to the Ti6Al4V matrix. For the composites with different volume fractions of reinforcing phases, the wear rate and wear depth increase with the increase of the applied load, and the friction coefficient decreases and fluctuates within a small range. Under low loads, the worn surface is covered with grooves and a small amount of wear debris; under heavy loads, the worn surface is covered with narrow and shallow grooves and a large amount of wear debris. The wear mechanism is abrasive wear and oxidation wear. As the load increases, the size of the debris increases.

Key words: composite; dry sliding friction and wear; wear resistance

Dry sliding wear is one of the most significant behaviors of engineering materials. This behavior has vast implications in industry, including the automotive and aerospace sectors. Titanium and titanium alloys are widely used in various industrial sectors due to their low density, excellent corrosion resistance and mechanical properties. However, titanium and its alloys exhibit poor tribological properties, which limit their usage as structural materials. The addition of hard ceramic particulates is an effective method to improve the mechanical as well as tribological properties of titanium and its alloys [1-4].

Metal Matrix Composites have emerged as an important structural and wear materials primarily because of their superior strength-to-weight and strength-to-cost ratios compared to equivalent commercial alloys. The metal matrix composite properties depend on the matrix metal, reinforcement material and composite fabrication method. In-situ processing offers several advantages over conventional processing techniques, such as finer reinforcement particulates, clean interface between the matrix and the reinforcement, superior thermodynamic stability, and uniform distribution in the matrix. TiC and TiB are expected to be the best reinforcements for titanium-based composites due to their high hardness, excellent wear resistance, high modulus of elasticity, good wettability, and relative stability to titanium matrix. The objective of the two reinforcements is to take advantage of the superior properties of both materials without compromising on their weakness of either [5-8]. Hence, the paper highlights the effect of addition of in situ particulates and tribological parameters on the wear mechanisms of (TiB+TiC)/Ti composites.

1 Experiment

The Ti6Al4V bar (Φ10 mm), the titanium sponge (purity 99.6%) and the B_4C powder (purity 99%) were used as raw materials for (TiC+TiB)/Ti6Al4V in situ composites, and melted in a magnetron tungsten arc furnace. The amount of smelting was about 45 g. In order to make the composition of the sample evenly, each sample was prepared by repeating three times. (TiC+TiB) reinforcements with a theoretical volume fraction of 5%, 10%, 15% and 20% were prepared.

The dry sliding wear test was performed using a high temperature friction and wear tester (model HT-1000, China) in a ball-on-disk contact configuration at room temperature of

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about 25 °C. A Si_3N_4 ball with a diameter of 5 mm was used as the counterface materials. The wear tests were carried out at 5, 10, 15 and 20 N. The sliding speed was 0.167 m/s and the total sliding distance was 310 m. Wear mass loss was measured by an electronic balance with an accuracy of 0.0001 g. The friction coefficient was measured continuously and the corresponding data were recorded. In order to reduce the effect of roughness on the tribological behavior of the sample, the outer surface was polished to remove the prominent ceramic particles by 400#, 600# and then 800# abrasive papers. The discs and the balls were cleaned with acetone to remove stains and other surface contaminates before testing. Microstructure observation of the wear scars and wear debris was carried out by scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS).

2 Results and Discussion

2.1 Wear rate and friction coefficient

Fig.1 shows the wear rate of Ti6Al4V alloy with continuously-supplied reinforcements and no reinforcements as a function of the load. With dry sliding without reinforcements, the wear rate of the Ti6Al4V alloy rapidly increased as a function of the load. It is seen that the wear rates of Ti6Al4V alloy undulated slightly under 5~15 N, and then increased above 15 N. In addition, the larger the load was, the faster the wear rate increased under 5~15 N and the wear rate slightly increased above 15 N. With the increase of the (TiC+TiB) reinforcements, the wear rates were observed to be markedly reduced. As observed, there was a similar wear behavior to the Ti6Al4V alloy. With an increase of the load, the wear rate of the (TiC+TiB)/Ti6Al4V composites slightly increased. However, the difference in wear rate of the worn samples is more pronounced at higher loads. The wear rate of the (TiC+TiB)/Ti6Al4V composite with a volume fraction of 20% was noticed to achieve the lowest values throughout the load range. After the test, the wear depths of (TiC+TiB)/ Ti6Al4V composites with a volume fraction of 15% (Fig.2) and samples with different ingredients under 15 N (Fig.3) were measured by a Bruker 3D profilometer. It can be clearly seen that a clear, deep concave wear track is produced under a load of 20 N. The wear rate and wear depth increase as the applied load and the volume fraction of reinforcing phases increase. Hence, TiC and TiB, as a well-known ceramic reinforcements, reduce the wear rate. As the load increases, the wear-reducing effect is gradually enhanced.

The average value of friction coefficients for the Ti6Al4V alloy and (TiC+TiB)/Ti6Al4V in-situ composites under the load of 5, 10, 15 and 20 N is shown in Fig.4. For the composites with different volume fractions of the reinforcing phases, the friction coefficients were decreased with increasing applied load. It is obvious that the wear depth decrease greatly under a load of 10 N. It is noted that the friction coefficient of the in-situ formed (TiC+TiB) reinforced Ti6Al4V composite is less than that of the Ti6Al4V alloy. This may be attributed to the higher hardness of the composite resulting in a lower real area of contact; therefore, a smaller number of junctions form which require less energy to get sheared during sliding as compared to the Ti6Al4V alloy. In addition, TiC and TiB reinforcements have lower friction coefficients and reduce the contact area between the matrix and the counterface, thus minimizing the smearing effect of the composites on the counterface surface.

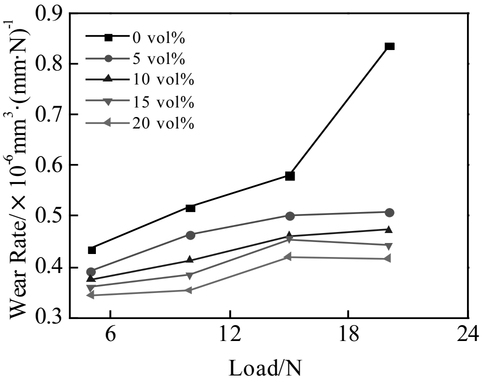


Fig.1 Wear rate of Ti6Al4V alloy and composites as a function of load

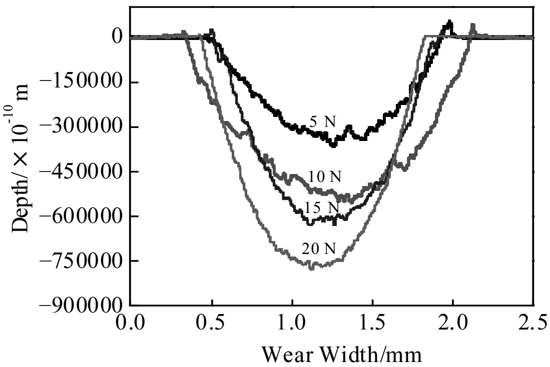


Fig.2 Wear depth of composites with volume fraction of 15% as a function of load

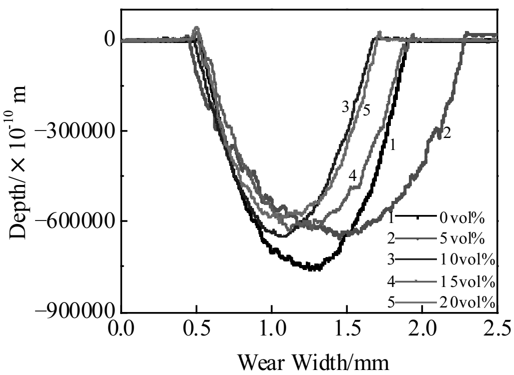


Fig.3 Wear depth of Ti6Al4V alloy and composites with different volume fractions of reinforcing phases under 15 N

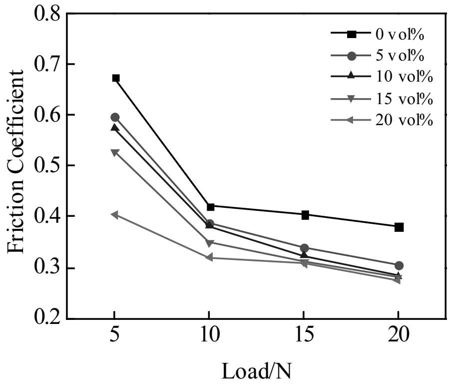


Fig.4 Variation of the friction coefficient for the Ti6Al4V alloy and composites under different loads

Fig.5 illustrates the friction coefficients of (TiC+TiB)/Ti6Al4V composites with a volume fraction of 15% as a function of sliding time under the load of 5, 10, 15 and 20 N. When the external load is 5 N, the friction coefficient always climbed from a plateau after 7 min. In addition, the variable range of the friction coefficient is relatively large. The average friction coefficient is approximately 0.528, as shown in Fig.4. For 10, 15 and 20 N, the friction coefficient rapidly reached a steady stage and fluctuated in a small range. Clearly, the friction coefficient started to decrease and was less than that under the applied load of 5 N. It can also be noted that the friction coefficients increase as the applied load increases.

2.2 Morphology of worn surfaces

Fig.6a~6d show the worn surfaces of (TiC+TiB)/Ti6Al4V composites with a volume fraction of 15% under loads of 5, 10, 15 and 20 N. Wear tracks of composites were mainly a surface damage in the form of longitudinal grooves extending parallel to the sliding direction. As shown in Fig.6a, the worn surface is characterized with fine grooves and wear debris. It indicates that there is a mild wear with fine scratches for the composite. When metallic surfaces are in contact with Si_3N_4 during dry sliding wear, the local temperature at the contact points of the surface is high, and the hardness near these points quickly decreases. As a result, the materials transfer leads to serious material removal from the friction surface in the form of 'thin flake-like' or 'patch-like' wear debris.

The grooves are narrower and shallower, and some are almost unapparent to naked eyes, as shown in Fig.6b~6c. In addition, the number of wear debris gradually increases as the load increases. At the initial stage of sliding, the direct contact of metal-ceramics causes severe wear and generation of debris particles. Some of particles are removed from the sliding

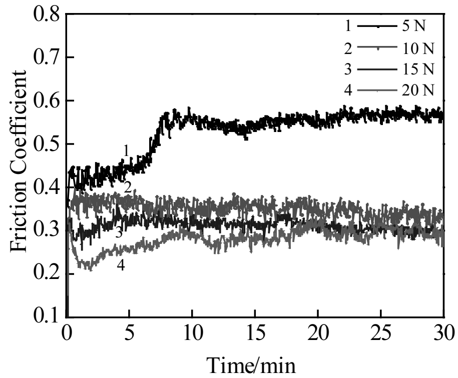


Fig.5 Friction coefficient curves of composites with volume fraction of 15% as a function of sliding time under different loads

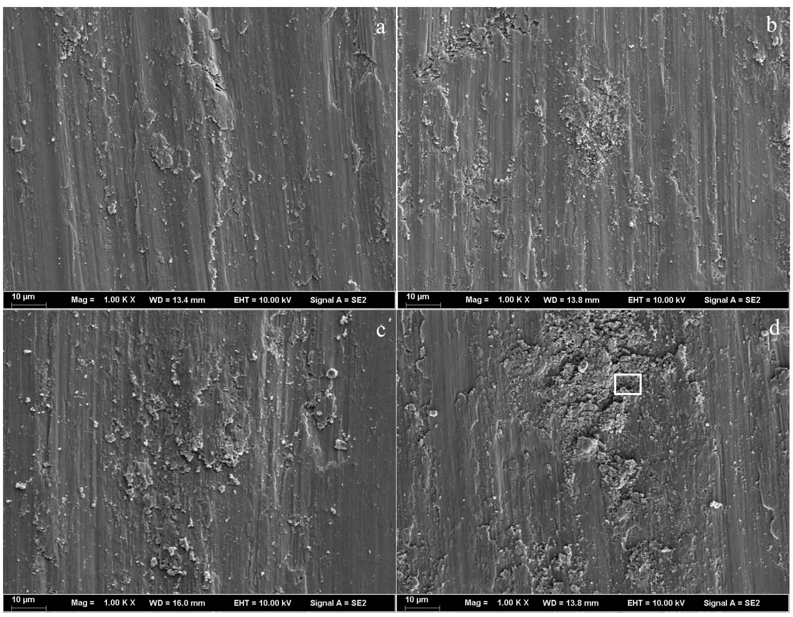


Fig.6 Worn surface morphologies of (TiC+TiB)/Ti6Al4V composites with volume fraction of 15% under different loads: (a) 5 N, (b) 10 N, (c) 15 N and (d) 20 N

interfaces, but most of the particles are remained in pits or grooves. Under the action of load, the remained particles undergo comminution, agglomeration and solidification. Simultaneously, the presence of wear debris acts as an in situ solid lubricant and reduces the overall friction coefficient of the composites. It can be recognized that the presence of large amounts of wear debris and many wear scars indicate an abrasive wear mechanism in dry sliding.

According to Fig.6d, the morphology of the worn surface under the load of 20 N is different from that under the load of 5 N. There are a large amount of wear debris (white spots in the micrograph) in Fig.6d while a small amount of wear debris and many wear grooves in Fig.6a. The composition of debris particles (Fig.7a) was analyzed by EDS, as shown in Fig.7b, to further analyze the wear mechanism. It can be seen that the composition of the white spots observed in Fig.6d is mainly Ti, Al, O and Si elements, as shown in Fig.7b. Hence, EDS analysis confirms that these white particles are debris accumulation. In addition, the Si element is transferred from the ground material Si_3N_4, and the presence of the O element shows a certain degree of oxidation. Results above indicate that as the load increases, the wear of the composites becomes more severe and consistent with the results of the wear rate.

The wear debris of (TiC+TiB)/Ti6Al4V composites under loads of 5, 10, 15 and 20 N in Fig.6a~6d are given in Fig.8a~8d. It reveals a large amount of sponge. It is noted that the wear particles increase gradually as the load increases. Accordingly, the composite also shows the largest wear rate under a load of 20 N. The composition of debris particles in Fig.8a has also been investigated by chemical analysis, as shown in Fig.9. It is noted that the components of the wear particles are mainly Ti, Al, O and V elements, as shown in Fig.9. However, the presence of a large amount of wear particles also indicates an abrasive wear in dry sliding.

Fig.10 shows the micro-morphology and EDS analysis of Si_3N_4 ball of (TiC+TiB)/Ti6Al4V composite with a volume fraction of 15% under 20 N. It can be seen that the composition of the A region observed in Fig.10 is all Si element. And the composition of the B region is mainly Ti, Al and Si elements, as shown in Fig.10. In addition, EDS analysis confirms that the material of the B region is mainly from the wear debris.

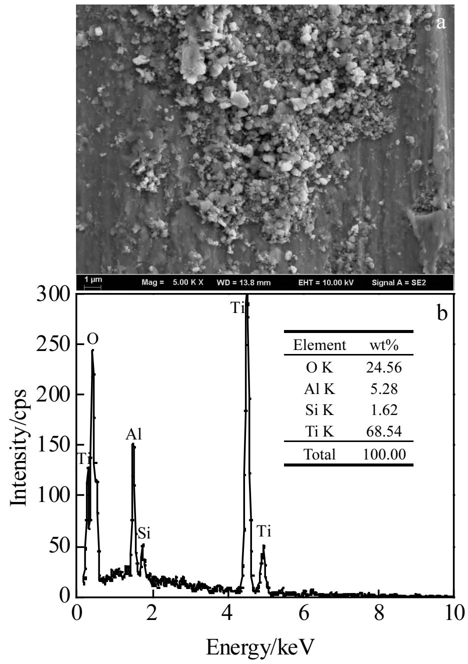


Fig.7 Worn surface morphologies (a) and corresponding EDS analysis (b) for (TiC+TiB)/Ti6Al4V composite with volume fraction of 15% under the load of 20 N

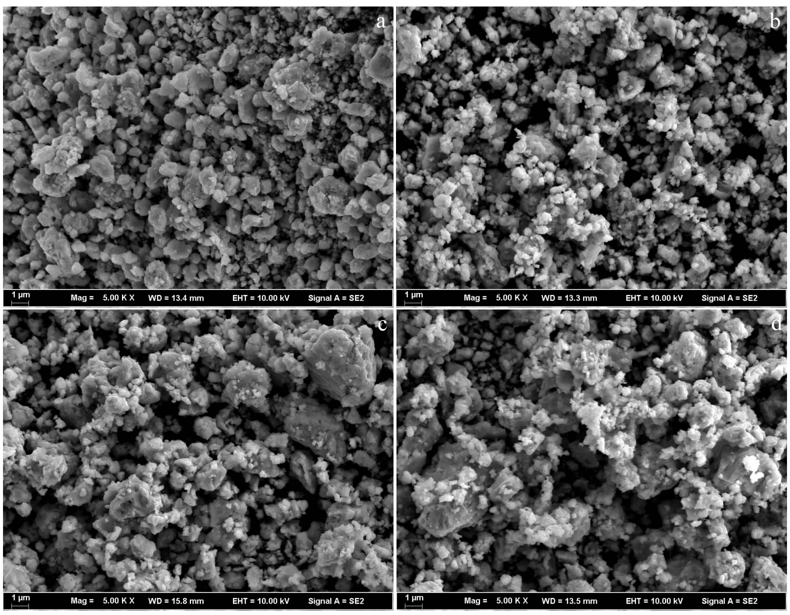


Fig.8 Wear debris of (TiC+TiB)/Ti6Al4V composites with volume fraction of 15% under different loads: (a) 5 N, (b) 10 N, (c) 15 N, and (d) 20 N

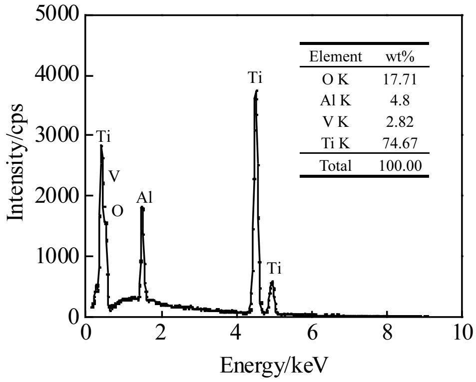
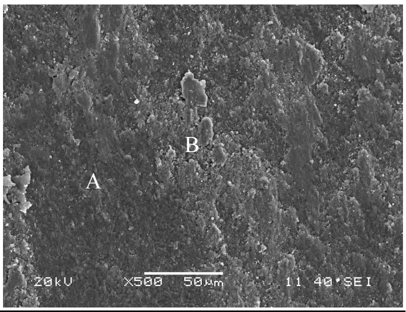


Fig.9 EDS analysis of the wear debris in Fig.8a



Position	Element	Content/wt%
A	Si	100
B	Si	3.07
	Al	4.47
	Ti	92.46

Fig.10 SEM morphology and EDS analysis of Si_3N_4 ball of (TiC+TiB)/Ti6Al4V composite with volume fraction of 15% under 20 N

3 Conclusions

1) The wear rate and friction coefficient of the (TiC+TiB)/Ti6Al4V composites are less than those of the Ti6Al4V alloy. The friction and wear of the Ti6Al4V alloy are improved because of the formation of TiC and TiB.

2) For the composites with different volume fractions of reinforcing phases, the wear rate and wear depth increase with increasing applied load, and the friction coefficient decreases and fluctuates within a small range.

3) There is a mild wear with grooves and a small amount of wear debris for the composites under low loads. The grooves are narrower and shallower, and the amount and size of wear debris gradually increase as the load increases. The wear of the composites become more severe as the load increases. The wear mechanism is abrasive wear and oxidation wear.

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原位自生(TiC+TiB)/Ti6Al4V 复合材料摩擦磨损性能研究

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摘　要：利用原位反应法制备了不同 TiC 和 TiB 增强相含量的(TiC+TiB)/Ti6Al4V 复合材料（TMC），用 HT-1000 型摩擦磨损试验机研究了外加载荷对原位(TiC+TiB)/Ti6Al4V 复合材料干滑动摩擦磨损性能的影响，并利用扫描电镜及布鲁克三维形貌仪观察其磨损行为。结果显示，与 Ti6Al4V 基体相比，TiC+TiB 增强相的生成提高了复合材料的耐磨性。对于含不同体积分数增强相的复合材料，随着外加载荷的增加，材料的磨损率和磨损深度增加，摩擦系数减小且在小范围内波动。在小负载下，磨损的表面覆盖有一些沟槽和少量磨屑；在大负载下，磨损的表面覆盖有一些浅沟槽和大量磨屑。磨损机制为磨粒磨损和氧化磨损。随着负荷增加，碎屑的尺寸增加，磨损加剧。

关键词：复合材料；干滑动摩擦磨损；耐磨性

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