**Article ID:** 1003 - 6326(2005)02 - 0266 - 04

# High-speed friction and wear behaviors of bulk $Ti_3SiC_2$ ①

HUANG Zhen-ying(黄振莺), ZHAI Hong-xiang(翟洪祥),
ZHOU Wei(周 韡), ZHOU Yang(周 洋),
AI Ming-xin(艾明星), ZHANG Zhi-li(张志力), LI Shi-bo(李世波)
(Center of Material Engineering, Beijing Jiaotong University, Beijing 100044, China)

**Abstract:** High-speed friction and wear behaviors of bulk $Ti_3SiC_2$ sliding drily against low carbon steel were investigated. Tests were carried out using a block-on-disk type tester with normal pressures ranging from 0.1 to 0.8 MPa and several sliding speeds from 20 to 60 m/s. The results show that, in the case of sliding speeds of 20 - 40 m/s, the friction coefficient exhibits a decreasing tendency with increasing the normal pressure after an increment in the smaller pressure range, and the worn quantity of $Ti_3SiC_2$ exhibits a nearly linear increase with increasing the normal pressure. However, when the sliding speed is up to 60 m/s, the friction coefficient exhibits a monotonous increase and the worn quantity exhibits a quadric increase with increasing the normal pressure. These speed-dependent and pressure-dependent behaviors are attributed to the antifriction effects of a frictionally generated oxide film covering the friction surface of $Ti_3SiC_2$, and a balance between the generating rate and the removing (wearing) rate of the film.

**Key words:** $Ti_3SiC_2$; tribological behavior; oxide film; antifriction effect; sliding speed; normal pressure
**CLC number:** TB332 **Document code:** A

## 1 INTRODUCTION

The ternary carbide $Ti_3SiC_2$ exhibits a combination of properties, which has been characterized in the last several years[1-9], such as the unusual damage tolerance and thermal shock resistance in ceramics, good oxidation resistance, high elastic modulus and low Vickers hardness, and excellent electrical and thermal conductivities. Such unusual combination suggests that $Ti_3SiC_2$ may be a good material for some tribological applications. We have investigated the friction coefficient and wear behaviors of the bulk $Ti_3SiC_2$ in limited test conditions[10-12]. The result showed that the friction coefficient and the wear rate of a nearly pure $Ti_3SiC_2$ bulk material are 0.25 - 0.35 and $(1.5 - 3.0) \times 10^{-6}\ mm^3/(N \cdot m)$, respectively, when sliding drily against low carbon steel. However, it is remarked that these results are considerably different from the results measured by El-Raghy et al[13, 14]. The friction coefficient is only 1/3 - 2/5 of the result (0.83) measured by El-Raghy et al, and particularly the wear rate is less by three orders of magnitude than the result measured by them. This remarkable difference may limit the appreciation for availability of $Ti_3SiC_2$ as tribological material because the material that has a friction coefficient of 0.83 and a wear rate with order of $\times 10^{-3}\ mm^3/(N \cdot m)$, as reported by El-Raghy et al[13], may not be used as tribological material. However, the friction coefficient of 0.25 - 0.35 and the wear rate of $(1.5 - 3.0) \times 10^{-6}\ mm^3/(N \cdot m)$ may be very good in tribological performance.

This paper exhibits more details of the friction coefficient and wear rate of $Ti_3SiC_2$ bulk material, and discusses the probable mechanism that causes the low friction coefficient and wear rate.

## 2 EXPERIMENTAL

The $Ti_3SiC_2$ samples used in this investigation were prepared by hot-pressing process which is discussed in detail elsewhere[10]. The composition of the resultant products was analyzed by X-ray diffractometry (XRD) with Cu $K_\alpha$ radiation. The content of $Ti_3SiC_2$ was estimated to be greater than or equal to 98% (volume fraction). The density measured by the Archimedes method was 4.31 $g/cm^3$.

$Ti_3SiC_2$ sample was machined into several blocks of 10 mm × 10 mm × 12 mm. A low carbon steel disc with diameter of 300 mm and thickness of 10 mm was used as the friction counterpart. Tests were carried out using a block-on-disk type tester with load-controlling mode, which was shown in

① **Foundation item:** Project(2003AA332080) supported by Hi-tech Research and Development Program; Project(50472045) supported by the National Natural Science Foundation of China; Project(JXJ04008) supported by the Science Developing Fund of Beijing Jiaotong University, China
**Received date:** 2004 - 11 - 20; **Accepted date:** 2005 - 01 - 18
**Correspondence:** ZHAI Hong-xiang, Professor; Tel: +86-10-51687277; E-mail: hxzhai@sina.com

the previous paper[15]. Tests were conducted unlubricatedly under ambient temperature of (20 ±2) ℃ and relative humidity of 25%–28%. The experimental parameters were determined as normal pressures from 0.1 to 0.8 MPa, and several sliding speed ranging from 20 to 60 m/s. Each test process continuously underwent the same sliding distance of 24 000 m. Tests were repeated three times for each given test condition. Whenever the normal pressure was changed, a pre-abrasion was made for reducing the influence of load history on friction surface. The friction coefficient was automatically measured and recorded in real-time by a computer. At the end of each test, the mass loss of $Ti_3SiC_2$ block was measured using an electronic balance with $\pm 10^{-4}$ g accuracy. After wear tests, the worn surface of the $Ti_3SiC_2$ block was analyzed with a scanning electron microscope (SEM, Hitachi, S-3500N).

## 3 RESULTS AND DISCUSSION

Fig. 1 shows the change of friction coefficient as a function of normal pressure at different sliding speeds. Obviously, the friction coefficient is pressure-dependent and speed-dependent. For sliding speeds of 20–40 m/s, the friction coefficient exhibits a decreasing tendency with increase in normal pressure after an increase in the smaller pressure range. It decreases from about 0.35 to 0.27 with the normal pressure increasing from 0.2 MPa to 0.8 MPa at the sliding speed of 20 m/s. For sliding speeds of 30 m/s and 40 m/s, it decreases from about 0.24 to 0.18 and about 0.21 to 0.17 with the pressure increasing from 0.3 MPa to 0.8 MPa and 0.4 MPa to 0.8 MPa, respectively. However, when the sliding speed is up to 60 m/s, instead of exhibiting a descending tendency, the friction coefficient increases monotonously from 0.12 to 0.22 with increase in the pressure from 0.1 MPa to 0.7 MPa. The transition of friction coefficient from increase to decrease could be related with the friction power, which is determined by a product of the sliding speed and the frictional force being proportional directly to the normal pressure. This is reasonable that, because the state of friction surface is always affected by the frictional heat, it has a proportional relationship with the friction power[16].

The mass loss of $Ti_3SiC_2$ blocks which undergo the same sliding distance of 24 000 m under different sliding speeds is shown in Fig. 2 as a function of normal pressure. Irrespective of the sliding speed, the mass loss increases with the normal pressure increasing. For sliding speeds of 20 m/s to 40 m/s, it exhibits a nearly linear relationship with the normal pressure over the entire loading

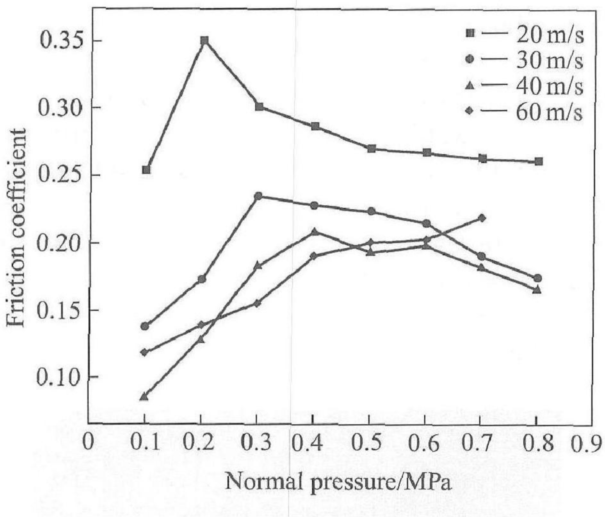


**Fig. 1** Variation of friction coefficient with normal pressure at different sliding speeds

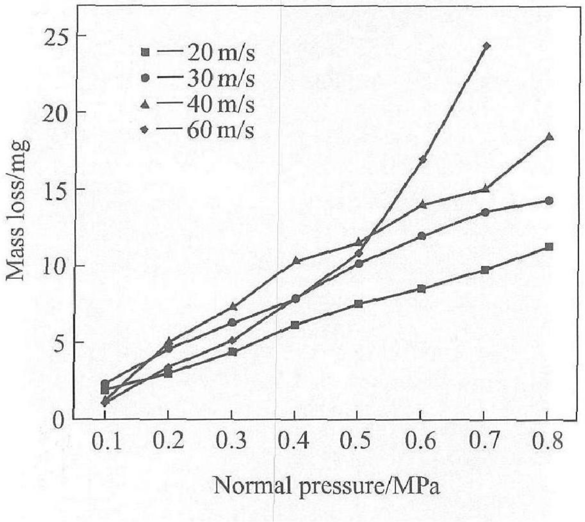


**Fig. 2** Mass loss of $Ti_3SiC_2$ block as function of normal pressure for different sliding speeds

range. While at the sliding speed of 60 m/s, the mass loss follows a quadratic curve law when the normal pressure is less than 0.5 MPa, and it increases abruptly as the normal pressure increases from 0.5 MPa to 0.7 MPa. That is, the mass loss is increased with increase of the friction power for any sliding speed, especially at the case of the sliding speed of 60 m/s; and the pressure is greater than 0.5 MPa, the mass loss increases faster.

Figs. 3(a) and (b) show the typical SEM photographs exhibiting the worn surfaces of $Ti_3SiC_2$ blocks which undergo a sliding distance of 24 000 m under the sliding speed of 20 m/s and the pressures of 0.2 MPa and 0.8 MPa, respectively. It can be seen that both surfaces are covered by a frictionally generated film, though the apparent shapes are different. The film formed at the normal pressure of 0.2 MPa is partially compact so that its surface looks to be relatively rough; while in the case of 0.8 MPa, the film is completely compact and the surface looks to be quite smooth. It is conceivable that the film becomes compacter with increasing the pressure. The previous investigation[10] has shown that the film is composed of a soft and flowable mixture of oxides of titanium, silicon and ferric, which have considerable antifriction effect. As the film becomes compact, the antifriction effect is enhanced, so that the friction coefficient decreases with increase of the pressure. The similar phenomena are also observed in the cases of the sliding speeds of 30 m/s and 40 m/s.

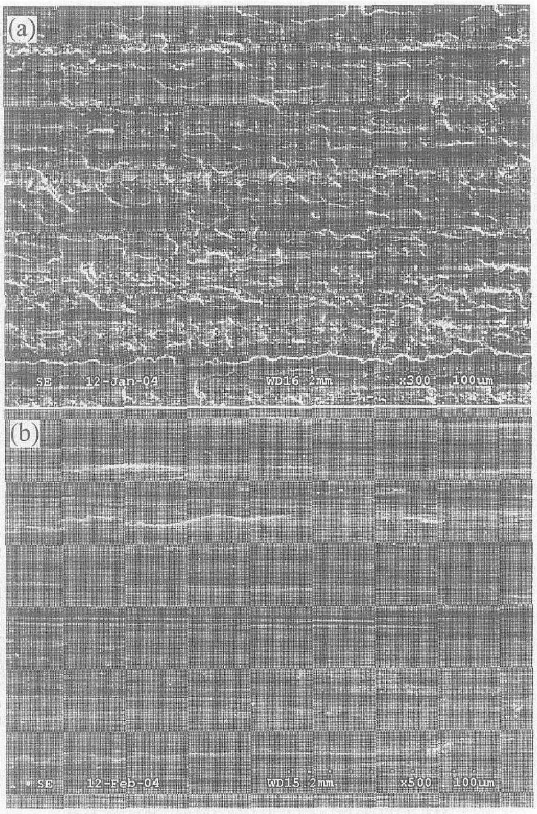


**Fig. 3** SEM photographs exhibiting worn surfaces of $Ti_3SiC_2$ block at sliding speed of 20 m/s
(a) —Normal pressure of 0.2 MPa;
(b) —Normal pressure of 0.8 MPa

Fig. 4 shows SEM photographs of the friction surfaces of $Ti_3SiC_2$ blocks for the sliding speed of 60 m/s and the pressures of 0.2 MPa and 0.7 MPa, respectively. The friction surfaces are also covered with a frictionally generated film. However, the morphology of the film is quite contrary to that in the case of the sliding speed of 20 m/s. The film formed at the normal pressure of 0.2 MPa is thoroughly compact, while in the case of the pressure of 0.7 MPa there is only a partial surface being covered with the oxide film, and the surface becomes considerably rough. It is conceivable that with increasing the pressure, the film changes from compact to uncompacted, and consequently the antifriction effect decreases, so that the friction coefficient increases.

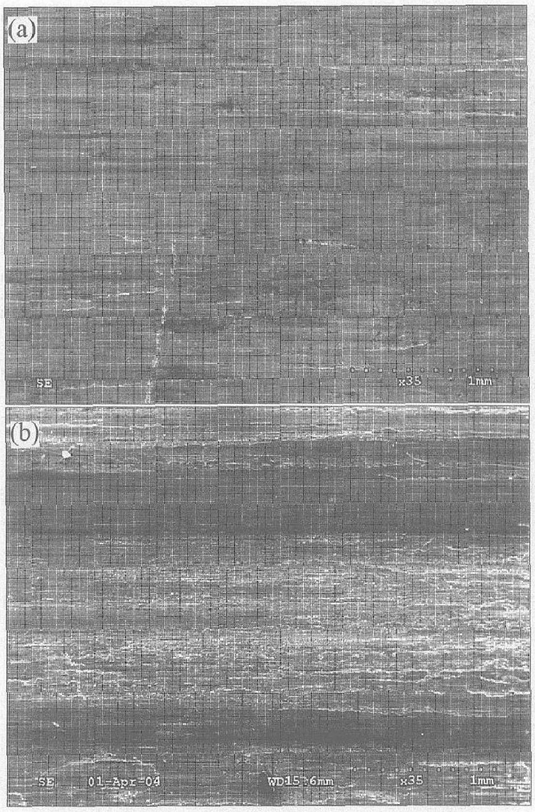


**Fig. 4** SEM photographs exhibiting worn surfaces of $Ti_3SiC_2$ block at sliding speed of 60 m/s
(a) —Normal pressure of 0.2 MPa;
(b) —Normal pressure of 0.7 MPa

Barsoum et al[8] have shown that $Ti_3SiC_2$ can be oxidized at high temperature in air, forming a dense, adhesive and layered scale consisting of $SiO_2$ and $TiO_2$ on the surface of $Ti_3SiC_2$ and the thickness of oxidation layers increases with the temperature rising. It is conceivable that, in the present cases, when the pressure is large and/or the sliding speed is high, the frictional heat will be enough to cause oxidizing behavior to occur on the friction surface of $Ti_3SiC_2$, and generate the same oxides as that formed in air. However, the normal pressure and the sliding speed may have two different and reversal effects. On one hand, with the increase of the normal pressure and/or the sliding speed, the frictional heat increases, and it accelerates the generation of the oxide film. On the other hand, the increase of the normal pressure and/or the sliding speed leads to the increase of the worn quantity, as shown in Fig. 2, that is, the consumption of the oxide film formed is accelerated (the oxide film is removed from the friction surface). When the generating rate of the oxide film is larger than or equal to the consumption rate, the oxide film will become compacter, hence the friction coefficient reduces. Reversely, the oxide film will be uncompacted or even disappear, and consequently the friction coefficient increases. There could be a balance point for the existence of the oxide film, where the generation rate and the consumption rate of the oxide film keep a dynamic balance. In that case, the compactness or the thickness of the oxide film will hold a constant, and correspondingly the friction coefficient and the wear rate will not change. It is conceivable that, in the sliding speeds ranging from 20 m/s to 40 m/s, the generation rate of the oxide film is faster than the consumption rate, with increasing the pressure, so that the friction coefficient exhibits a decreasing tendency. When the sliding speed is up to 60 m/s, the worn quantity exhibits an abrupt increment when the pressure is larger than 0.5 MPa, as shown in Fig. 2, which means that the consumption rate is larger than the generation rate. In such case, as shown in Fig. 4(b), the compactness of the oxide film descends significantly, and correspondingly the friction coefficient increases.

## 4 CONCLUSIONS

The tribological behaviors of bulk $Ti_3SiC_2$ sliding dryly against low carbon steel were investigated by varying normal pressures and sliding speeds. In terms of the present work, the following conclusions can be drawn.

1) In the sliding speed range of 20 − 40 m/s, the friction coefficient exhibits a decreasing tendency with increasing the normal pressure, and the worn quantity of $Ti_3SiC_2$ exhibits a nearly linear relationship with the normal pressure. The decreasing behavior in friction coefficient is attributed to the antifriction effect of a frictionally generated oxide film covering the friction surface of $Ti_3SiC_2$.

2) In the case of the sliding speed of 60 m/s, the film becomes uncompacted with increasing the normal pressure. Correspondingly, the friction coefficient increases monotonously, and the worn quantity of $Ti_3SiC_2$ exhibits an abruptly increasing tendency when the normal pressure is larger than 0.5 MPa.

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(Edited by YANG Bing)