Tribology International 103 (2016) 228–235

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Low friction properties of Ti_3AlC_2/SiC tribo-pair in sea water environment

Shuai Wang [a,b], Jun Cheng [a], Shengyu Zhu [a], Zhuhui Qiao [a], Jun Yang [a,*]

[a] State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, PR China
[b] University of Chinese Academy of Sciences, Beijing 100039, PR China

ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form
30 June 2016
Accepted 30 June 2016

Keywords:
Ti_3AlC_2
Tribo-film
Lubrication
Sea water

ABSTRACT

In this paper, the tribological property of Ti_3AlC_2/SiC tribo-pair in sea water was investigated. For comparison, the tribological property in deionized water was studied as well. The results revealed that the Ti_3AlC_2/SiC tribo-pair displayed better lubricating effect in the two aqueous liquids. The friction coefficient and wear rate decreased with the increment of reciprocating frequency. Herein, a layer of soft hydrated tribo-film, which was caused by tribo-chemical reaction in aqueous environment, was easily sheared and conceived to be liable for the lubricating effect. The lubrication and wear mechanism were boundary lubrication and tribo-chemical wear, respectively. When the soft hydrated tribo-film was exposed in air, the tribo-film could contract and yield rimose tribo-film on account of the loss of water.

1. Introduction

MAX phases are a class of ternary layered carbides and nitrides possessing the combination of salient properties of metallic and ceramic materials [1,2]. Like ceramics, they exhibit high modulus, good corrosion resistance, excellent oxidation resistance and unusual high temperature tolerance. Additionally, similar to metals, they present exceptional thermal and electrical conductivities, superb machinability, notable thermal shock resistance and high damage tolerance. Hence, MAX phases have been studied intensively in diverse fields since they were discovered, especially for high temperature applications [3–7].

Originally, Barsoum et al. speculated that the Ti_3SiC_2 ceramic was probably self-lubricating on account of no evident burrs after machined by regular high-speed drill without lubrication [8]. Subsequently, Myhra and Crossley found that the layered Ti_3SiC_2 ceramic exhibited ultra-low friction on the basal plane by using lateral force microscopy [9,10]. And coincidentally, MAX phases displayed remarkable laminated structure, which had a hexagonal structure with a space group of P63/mmc, similar to graphite and MoS_2 [2]. On the basis of these evidences, the tribological behavior of MAX phases has attracted considerable attention over the past two decades [6].

To date, for tribological applications, Ti_3SiC_2 and Ti_3AlC_2 were the most extensively studied MAX phases due to the relatively advanced preparation procedures and economically available raw materials [6]. However, only under some special conditions, such as coupling with special counterpart [11], sliding at high speeds [12,13], rubbing under the lower load [14,15], or servicing in certain vacuum environment [16], the two MAX phases could demonstrate satisfactory tribological properties. Moreover, under micro-friction sliding condition, for some other MAX phases under micro-load condition, they could provide lower friction coefficient and wear rate when rubbing against proper counterpart [17]. For the most part, MAX phases could not combat friction and wear well as results of abrasive and adhesive wear [18–20]. At elevated temperatures, the vast majority of MAX phases showed superior wear resistance because of the formation of tribo-oxidation layer on the worn surface, but the layer could hardly reduce friction [19–21].

Nevertheless, the tribological behavior of MAX phases in liquid environments had been less reported. Up to now, to the best of our knowledge, Ti_3SiC_2 was the only MAX phase of which tribological behavior in some solutions had been explored [22–27]. In some alcoholic liquids, Ti_3SiC_2 can provide excellent lubrication when coupled with Si_3N_4 or self-mated [23–25]. The tribo-chemical products in alcoholic liquids were conceived to play an important role for low friction coefficient and wear rates. In addition, a SiO_2 layer generated by chemically corrosive oxidation was believed to be effective lubricant for reducing friction coefficient and wear, when Ti_3SiC_2/Si_3N_4 tribo-pair worked in the concentrated H_2SO_4, HCl and NaOH solutions [26,27].

These novel breakthroughs notwithstanding, for more practically structural applications in marine environments, it is more requisite

* Corresponding author.
E-mail addresses: jyang@lzb.ac.cn, jyang@licp.cas.cn (J. Yang).

http://dx.doi.org/10.1016/j.triboint.2016.06.045
0301-679X/

to investigate the tribological properties of MAX phases in sea water than that in alcoholic liquids or acids solutions. In the previous study, it was found that Ti_3AlC_2/SiC tribo-pair showed outstanding tribological behavior under a load of 20 N and a frequency of 5 Hz in water lubricated environment, compared with that coupled with 316 L stainless steel, Al_2O_3 and Si_3N_4 [28]. In this paper, the tribological properties of Ti_3AlC_2/SiC tribo-pair in deionized water and sea water were systematically studied. In contrast with the previous work, this study focused on the effect of sliding frequency and load on tribological properties of Ti_3AlC_2/SiC tribo-pair. In the two aqueous liquids, Ti_3AlC_2/SiC tribo-pair demonstrated quite lower friction coefficient (0.05 − 0.30) and the wear rate of Ti_3AlC_2 was as low as 1.27×10^{-6} $mm^3 N^{-1} m^{-1}$. Based on these results, the lubricating mechanism was proposed and it was believed that the Ti_3AlC_2/SiC tribo-pair could be employed in sea water environment.

2. Experimental details

2.1. Sample preparation

The preparation procedure of Ti_3AlC_2 ceramic can be found elsewhere [8]. In this study, the Ti_3AlC_2 ceramic was synthesized by hot pressing the starting mixture powders of titanium, aluminum and graphite. Herein, commercially available powders of titanium (300 mesh, ≥ 99.2% purity), aluminum (200 mesh, ≥ 99.5% purity) and graphite (400 mesh, ≥ 99.5% purity) were mixed with a stoichiometric molar ratio of 3:1.1:1.8 for 8 h by a planetary ball mill (Fritsch Pulverisette 5, Germany). The hard tungsten carbide jars and balls were chosen in case of the incorporation of other impurities. The rotational velocity was 300 rpm and the weight ratio of ball to powder was 10:1. After homogenizing the starting materials, the mixture was poured into a BN-coated graphite die and cold-pressed at ambient. Subsequently, the graphite die was sintered at 1400 °C in argon atmosphere with a uniaxial pressure of 40 MPa for 2 h in hot pressing sintering furnace. The sintered sample was cut into disks with dimensions of 15 mm × 15 mm × 4 mm for friction and wear tests. Then, the surfaces of disks were polished to about 1 μm roughness on diamond grits.

In the present study, synthetic sea water for laboratory testing was selected to simulate the natural sea water environment, because natural sea water cannot be obtained easily. In the light of ASTM standard D 1141-98, the synthetic sea water was synthesized and the PH was adjusted to 8.2 by 0.1 mol/L NaOH solution [29]. The chemical compositions of synthetic sea water were shown in Table 1.

2.2. Friction and wear tests

During the friction and wear tests, the samples were immersed in the deionized water or sea water. All the friction and wear tests were carried out on a CFT-1 reciprocating friction tester (Zhong Ke Kai Hua Corporation, China) at ambient. The SiC balls with a diameter of 6.35 mm were used to couple with Ti_3AlC_2 disks. Different reciprocating frequency (1 Hz, 5 Hz and 10 Hz) and normal load (20 N, 40 N, 60 N and 80 N) were chosen to investigate the influence of frequency and load on the tribological behavior of Ti_3AlC_2/SiC tribo-pair in the two aqueous liquids. During the sliding, the Ti_3AlC_2 disk was fully immersed in the liquid. The reciprocating stroke was 5 mm. For reliability, every test under the same condition was repeated at least three times and conducted for 30 min. The friction coefficient was read automatically by a computer procedure and the friction coefficient in this paper represented the mean value of friction coefficient in the steady stage in each test. In addition, the wear rate was determined by the following formula: WR=V/(L·D), where WR represented the wear rate ($mm^3 N^{-1} m^{-1}$), V was the final wear volume of Ti_3AlC_2 after test (mm^3), L was the applied normal load (N) and D was the total sliding distance (m). The final wear volume of Ti_3AlC_2 was determined by a 3D surface profiler.

2.3. Material characterizations

An X-ray diffractometer (XRD, D/max-2400 Rigaku, Japan) by Cu Ka radiation was used to detect the phase constituents of the sintered sample. The scan speed was 8°/min and 2θ angle was set form 5° to 80°. It can be established that Ti_3AlC_2 was the dominant phase and no other impurities were detected, as displayed in Fig. 1. Notably, the XRD pattern of the prepared sample exhibited different orientation as compared to that in the previous study.

A JSM-6701F scanning electron microscopy (SEM, Japan) was employed to evaluate the Ti_3AlC_2 worn surfaces after frictional tests. It is well known that the moist or aqueous sample cannot be examined by conventional SEM directly. Hence, the samples after frictional test were dried in air naturally before SEM observation. Energy Dispersive Spectrometer (EDS, England) was utilized to identify the microconstituent of Ti_3AlC_2 worn surfaces as well. However, carbon element cannot be precisely quantified by EDS analysis and here the atomic content of carbon element was designated as "C_x".

3. Results

3.1. Friction coefficient and wear rate

In deionized water, the friction coefficient and wear rate of Ti_3AlC_2 against SiC under different conditions are illustrated in

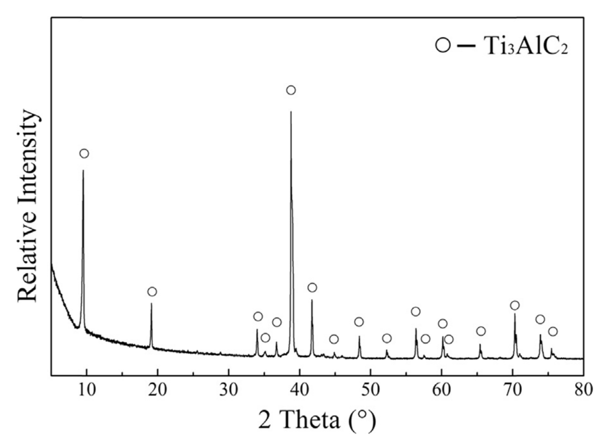

Fig. 1. The XRD pattern of the prepared Ti_3AlC_2 ceramic.

Table 1
Chemical compositions of the sea water.

Compound	NaCl	Na_2SO_4	$MgCl_2$	$CaCl_2$	$SrCl_2$	KCl	$NaHCO_3$	KBr	H_3BO_3
Concentration (g/L)	24.53	4.09	5.20	1.16	0.03	0.70	0.20	0.10	0.03