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Sliding friction and wear performance of Ti_6Al_4V in the presence of surface-capped copper nanoclusters lubricant

Fang Wang[a,b], Qin-Ling Bi[a,*], Xiao-Bo Wang[a], Wei-Min Liu[a]

[a]*State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[b]*Graduate School, Chinese Academy of Sciences, People's Republic of China*

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Abstract

The friction and wear properties of Ti_6Al_4V sliding against AISI52100 steel ball under different lubricative media of surface-capped copper nanoclusters lubricant—Cu nanoparticles capped with *O,O′*-di-*n*-octyldithiophosphate (Cu-DTP), rapeseed oil and rapeseed oil containing 1 wt% Cu-DTP was evaluated using an Optimol SRV oscillating friction and wear tester. The wear mechanism was examined using scanning electron microscopy (SEM) and X-ray photoelectron spectrosmeter (XPS). Results indicate that Cu-DTP can act as the best lubricant for Ti_6Al_4V as compared with rapeseed oil and rapeseed oil containing 1 wt% Cu-DTP. The applied load and sliding frequency obviously affected the friction and wear behavior of Ti_6Al_4V under Cu-DTP lubricating. The frictional experiment of the Ti_6Al_4V sliding against AISI52100 cannot continue under the lubricating condition of rapeseed oil or rapeseed oil containing 1 wt% Cu-DTP when the applied load are over 100 N. Surprisingly, the frictional experiment of Ti_6Al_4V sliding against AISI52100 steel can continue at the applied load of 450 N under Cu-DTP lubricating. The tribochemical reaction film containing S and P is responsible for the good wear resistance and friction reduction of Ti_6Al_4V under Cu-DTP at the low applied load. However, a conjunct effect of Cu nanoparticle deposited film and tribochemical reaction film containing S and P contributes to the good tribological properties of Ti_6Al_4V under Cu-DTP at the high-applied load.

Keywords: Ti_6Al_4V; Cu-DTP lubricant; Friction and wear behavior

1. Introduction

Titanium alloys are a good choice to be used in aerospace and medical devices due to their high specific strength, low density, high ductility, high fatigue strength, high corrosion resistance and excellent biological behavior. For example, Ti_6Al_4V has been used as a light material in engines due to some of these beneficial properties. Tribological studies of titanium alloys focused mainly on the wear behavior led to research on surface treatment [1–4], such as nitriding. Nitriding of titanium and titanium alloys has been investigated for many years and is used effectively for protection against wear. The major types of nitriding are plasma, ion, laser and gas nitriding. Gas nitriding is considered to be a promising method for engineering applications because it can easily form a harder layer on the surface of the materials [5,6]. Recent developments in fabrication techniques of titanium alloys, which greatly lowered the production cost, prompted further interest in exploring the tribological behavior of titanium alloys as bearing materials [7].

The use of inorganic nanoparticles in tribology, especially surface-modified nanoparticles, has received more and more attention recently. The effects of TiO_2 [8], $La(OH)_3$ [9], PbS [10], LaF_3 [11], lanthanum borate [12], titanium borate [13], zinc borate [14], ferric oxide [15], Ni [16] and $CaCO_3$ [17] nanoparticles used as oil additives have been investigated. Results show that these nanoparticles can improve the tribological properties of base oil by means of depositing on the wear surface, but hard microparticles would result in severe abrasive wear. The study of

*Corresponding author. Fax: +86 931 8277088.
E-mail address: qlbi@lzb.ac.cn (Q.-L. Bi).

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Zhou et al. indicates that Cu nanoparticles capped with organic compounds have better friction-reducing and anti-wear abilities than zincdialkyldithiophosphates (ZDDP), especially at high-applied load [18]. In order to broaden the application area of Ti_6Al_4V under liquid sliding condition, the friction and wear performance of Ti_6Al_4V discs sliding against AISI52100 steel ball under various lubricative media of surface-capped copper nanoclusters lubricant (Cu-DTP), rapeseed oil (RO) and RO containing 1 wt% Cu-DTP was evaluated using an Optimol SRV oscillating friction and wear tester in this paper. This study intended to help establish a baseline for further studies on the tribology of titanium alloys under liquid conditions.

2. Experimental

2.1. Synthesis of the lubricant

Surface-capped copper nanoclusters lubricant consists of Cu nanoparticles capped with a compound namely *O*, *O*′-di-*n*-octyldithiophosphate (Cu-DTP) is a sticky and red liquid. It was synthesized using a reported method [18,19]. The copper acetate ($Cu(acac)_2 \cdot 2H_2O$) and hydrazine hydrate ($N_2H_4 \cdot H_2O$) are analytically pure reagents (AR), purchased and used without further treatment. The *O*, *O*′-di-*n*-octyldithiophosphoric acid synthesis and characterization were based on Ref. [20]. Deionized water and AR grade benzene were used as solvents. Typical synthesis procedure taking place in air at ambient temperature was as follow procedure. Firstly, a freshly prepared aqueous solution of $N_2H_4 \cdot H_2O$ (500 mL, 0.1 mol/L) was mixed with the solution of $Cu(acac)_2 \cdot 2H_2O$ (500 mL, 10 mmol/L) under vigorous stirring in ambient condition; a brown Cu sol was formed in several minutes. Secondly, 4 mmol *O*, *O*′-di-*n*-octyl dithiophosphoric acid dissolved in 500 mL benzene was added to the sol and further stirred for 3 h, with the gradual transformation of the organic phase into dark red color. Thirdly, the organic phase was separated and evaporated at 80 °C in a rotary evaporator to remove the solvent; a sticky red liquid was obtained, consisting of the expected Cu-DTP nanoparticles lubricant. The diameter of the Cu nanoparticles is in range of 3–7 nm.

2.2. Test of friction and wear properties

A standard Optimol SRV oscillating friction and wear tester was used to evaluate the friction and wear behavior of Ti_6Al_4V disc/AISI52100 steel ball, the details about the tester were given elsewhere [21,22]. Commercially available AISI52100 steel ball (ϕ 10 mm, HRC 59–61) was used as a rider. The Ti_6Al_4V discs were cut to ϕ 24 × 8 mm. Prior to tribo-tests, the surfaces of discs were mechanically polished with 400 and 600 Cw SiC abrasive paper, and then metallographic polishing to a surface roughness of $R_a = 0.2\,\mu m$.

A commercial rapeseed oil (Xi'an Jiali Oil and Grease Factory of China) was used as a base lubricant for the study. For comparison, the RO containing 1 wt% Cu-DTP (1 wt% Cu-DTP/RO) was also investigated.

The test under various condition was carried out in air under load of 20–500 N, sliding frequency of 10–30 Hz, sliding amplitude of 1 mm, and a duration of 30–180 min. The wear volume loss of the lower disc was determined by measuring the area and depth of the wear scar using a profilometer. The wear rate is defined as the total volume loss per unit sliding distance (mm^3/m). The final values quoted for the friction coefficient and wear rate of the specimen were averages of three tests results. The relative errors measured are of the order of $\pm 10\%$.

The wear scars of the discs and counterpart balls were examined by using JSM-5600LV scanning electron microscopy (SEM). The chemical states of the elements in the wear scar on the discs were analyzed using a PHI-5702 X-ray photoelectron spectrometer (XPS).

3. Results and discussion

3.1. Friction and wear properties

The friction coefficient and wear rate with load of Ti_6Al_4V sliding against AISI52100 under RO, Cu-DTP, and 1 wt% Cu-DTP/RO lubricating at sliding frequency of 10 Hz are shown in Fig. 1. It can be seen that Cu-DTP acts as a best lubricant compared with RO and 1 wt% Cu-DTP/RO. The friction coefficient and wear rate of Ti_6Al_4V lubricated with Cu-DTP is much lower than that of RO and 1 wt% Cu-DTP/RO under different applied load. 1 wt% Cu-DTP/RO can decrease the wear rate of the Ti_6Al_4V a small extent compared to rapeseed oil alone, but the friction coefficient was the contrary. In addition, the friction experiment of Ti_6Al_4V sliding against steel ball cannot continue under the lubricating of RO and 1 wt% Cu-DTP/RO when the applied load is over 100 N. The friction coefficient under the lubricating of RO and 1 wt% Cu-DTP/RO decreased with increasing applied load, while the wear rate under the same condition increased with load. The friction coefficient under Cu-DTP lubricating initially decreased with load up to 50 N and then increased with the load increase, while the wear rate under the same condition increased gradually with load increasing.

The influence of load and sliding frequency on the friction and wear behavior of Ti_6Al_4V sliding against AISI52100 under Cu-DTP lubricating was also investigated (see Fig. 2). It can be found that the friction coefficient and wear rate of Ti_6Al_4V under Cu-DTP lubricating at high sliding frequency (20 Hz) is lower than that of at low sliding frequency (10 Hz) under different load. It also can be seen that the friction coefficient of Ti_6Al_4V under Cu-DTP lubricating at 10 Hz decreased rapidly with load at first, and then increased gradually with load in the range of 50–80 N, and increased rapidly with the further increase of applied load. While the friction coefficient at 20 Hz gradually increased with the load in the whole range. The wear rate of Ti_6Al_4V under Cu-DTP