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Friction and wear performances of magnesium alloy against steel under lubrication of rapeseed oil with S-containing additive

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Abstract: A S-containing additive, sulfuration modified rapeseed oil (named as SRO), was prepared by chemical modification of rapeseed oil with sulfur compounds. The results indicate that the friction and wear of the magnesium alloy−steel tribomates could be effectively reduced by formulating SRO into rapeseed oil lubricant. The friction coefficients and the wear volumes of magnesium alloy decrease with increasing contents of SRO. The surface lubricated with SRO-doped rapeseed oil was characterized by less wear as compared with that lubricated with neat rapeseed oil. The enhanced anti-wear and friction-reducing abilities of rapeseed oil by SRO in the lubrication of magnesium alloy against steel were ascribed to the formation of a composite boundary lubrication film due to the strong adsorption of SRO and rapeseed oil onto the lubricated surfaces and their tribochemical reactions with magnesium alloy.

Key words: anti-wear; friction-reducing; magnesium alloy−steel tribomate; sulfuration modified rapeseed oil

1 Introduction

In recent decades, magnesium alloys are finding increasing use as structural components in many industrial fields such as aerospace, automobile and electronics [1, 2]. Some of the advantages of the magnesium alloys for industrial applications are their lightweight, high specific strength, good machinability and shock resistance. Despite the growing interest in magnesium alloys, their friction and wear properties are not understood much in detail compared with aluminum alloys [3, 4]. Indeed, friction and wear properties of magnesium alloys are important especially when they are applied for critical industrial applications. While magnesium alloys would normally not be candidates for bearings or gears, there are situations in which their surfaces could come into contact with other materials so as to make their friction and wear behaviors interest. For example, magnesium alloys are subjected to sliding motion in automotive brakes, engine piston and cylinder bores. In addition, friction and wear of magnesium alloys are important considerations in their processing by rolling, extrusion, forging, etc. Tribological study of magnesium alloys is therefore of practical and theoretical significances [5, 6].

Friction and wear of magnesium alloys may normally be reduced by using a lubricant with appropriate anti-wear and friction-reducing additives [7−10]. For the past decades, increasing attention to the environmental issues has driven the lubricant industry to formulate environmentally adopted lubricants with technical characteristics equal or superior to those based on conventional mineral oils [11−14]. Vegetable oils have been proven to be potential candidates for replacement of mineral oils due to their inherent biodegradability, non-toxicity and excellent lubricity. In the present work, the friction and wear behaviors of AZ91D magnesium alloy, one of the leading magnesium alloys used in structural applications, against GCr15 bearing steel under the lubrication of rapeseed oil with a biodegradable S-containing additive were reported. The topographies and chemical species of worn magnesium alloy surfaces were also investigated in an attempt to understand the tribological mechanisms of the S-containing additive in lubrication of magnesium alloy.

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2 Experimental

2.1 Preparation of S-containing additive

S-containing additive was prepared by chemical modification of rapeseed oil with sulfur compounds. A certain amount of rapeseed oil (a well processed, bright and clear oily liquid with kinematic viscosity of 34.8 mm^2/s at 40 °C), was charged into a three-necked flask with a thermometer and a stirrer. S2Cl2 was added in batches and the mixture was refluxed at a fairly low temperature for several hours. The reaction products were centrifugally separated after precipitation with NH4SX and deoxidized iron powder. The supernatant liquids were filtered. A bright amber, transparent, rapeseed oil based sulfur -containing additive, named as SRO, was therefore obtained.

2.2 Friction and wear test

Different mass fractions of SRO, namely, 0.5%, 1.0%, 1.5%, 2.0% and 2.5%, were formulated into rapeseed oil, respectively. The friction and wear behaviors of magnesium alloy against steel were tested on an Optimol SRV reciprocating friction and wear tester lubricated with neat rapeseed oil and the SRO-doped oils, respectively. SRV is a high frequency, linear-oscillation tribotester. The upper test specimen is rubbed against a lower specimen, on which a few milliliters of lubricating oil are placed. In the present test, the upper specimen was a steel ball made of GCr15 bearing steel 12.7 mm in diameter with a hardness of HRC 59−61, while the lower specimen was a disc of mechanically polished AZ91D magnesium alloy (9% Al, 1% Zn, 0.2% Mn and the balance Mg), which is 22.0 mm in diameter and 7.8 mm in height, with surface roughness R_a smaller than 0.6 μm. The friction and wear test was run at frequency of 25 Hz, amplitude of 1 mm, a load of 20 N and test durations of 30 min. For each run, the coefficient of friction was continuously recorded on a chart and the average value was reported. The wear volume of the magnesium alloy was calculated based on the width and the depth of worn scars measured with the aid of a profilometer.

2.3 Surface analysis

The microstructures of the worn surfaces of AZ91D magnesium alloy after SRV testing were examined on a AMKAY 1000B scanning electron microscope (SEM) at the voltage of 20 kV. The chemical species of the typical elements on the worn surfaces of the magnesium alloy were analyzed on a PHI−5100 X-ray photoelectron spectroscope (XPS). The binding energy of the tested elements was measured at a pass energy of 29.4 eV and a resolution of ±0.3 eV, with the Mg K_α radiation used as the excitation source and the binding energy of contaminated carbon (C_{1s}: 284.6 eV) as the reference. Prior to the analyses, the specimens were ultrasonically cleaned in ligroin for 10 min.

3 Results and discussion

3.1 Impact of SRO on friction and wear performances of magnesium alloy

The friction coefficients of AZ91D magnesium alloy sliding against GCr15 bearing steel and the wear volumes of the magnesium alloy under the lubrication of rapeseed oil with different contents of SRO are shown in Fig. 1 and Fig. 2, respectively.

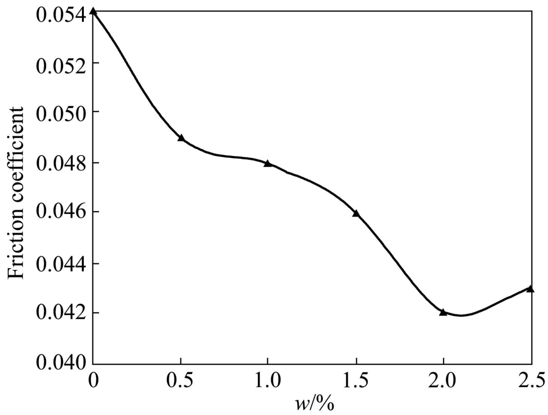

Fig. 1 Variation of friction coefficients with SRO content

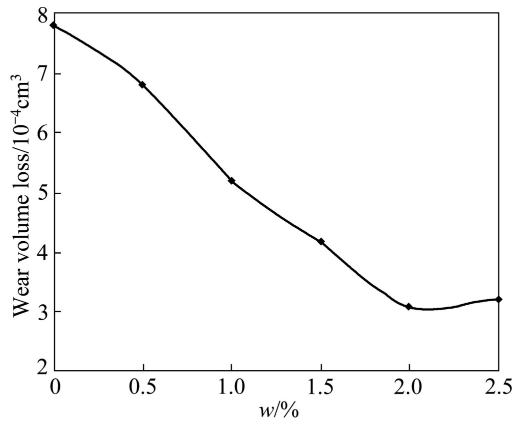

Fig. 2 Variation of wear volume loss with SRO content

It can be seen from Fig. 1 and Fig. 2 that when SRO content is lower than 2.0%, the friction coefficients and the wear volumes decrease markedly with increasing contents of SRO. This indicates that, for AZ91D magnesium alloy−GCr15 bearing steel tribomates lubricated with rapeseed oil, SRO is to a great extent effective in enhancing anti-wear and friction-reducing abilities of rapeseed oil by exhibiting lower friction coefficients and smaller wear volumes when formulated into rapeseed oil, especially at the SRO content of about 2.0%.

3.2 Surface topographies of worn surfaces

Figure 3 shows the SEM images of the worn surfaces of AZ91D magnesium alloy lubricated with net rapeseed oil and the oil formulated with 2.0% of SRO after SRV testing, respectively.

It can be clearly observed from Fig. 3 that the surface lubricated with the SRO-doped oil (Fig. 3(b)) was characterized by milder wear and smoother microstructures than that lubricated with net rapeseed oil (Fig. 3(a)). A careful examination of the surfaces reveals that ploughing wear occurred and some fine wear debris existed on the surface lubricated with net rapeseed oil (Fig. 3(a)), while those on the surface tested with the formulated oil (Fig. 3(b)) were almost unobservable. Thus, SEM observations well demonstrated the ability of SRO in fortifying anti-wear and friction-reducing capabilities of rapeseed oil as reported previously.

3.3 Chemical characteristics of worn surfaces

Figure 4 shows the XPS spectra of some typical elements on the worn surface of AZ91D magnesium alloy lubricated with rapeseed oil doped with 2.0% SRO.

The XPS spectrum of Mg_{1s} (Fig. 4(a)) shows a peak

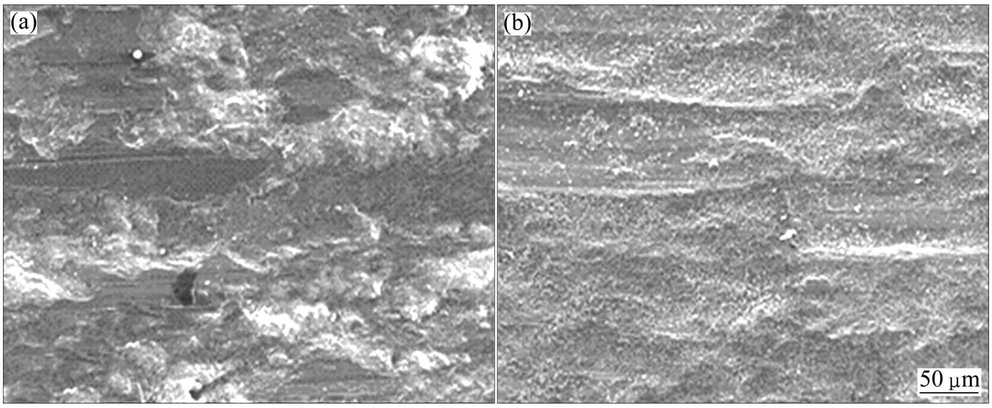

Fig. 3 SEM images of worn surfaces of magnesium alloy: (a) Surface lubricated with rapeseed oil; (b) Surface lubricated with rapeseed oil plus SRO

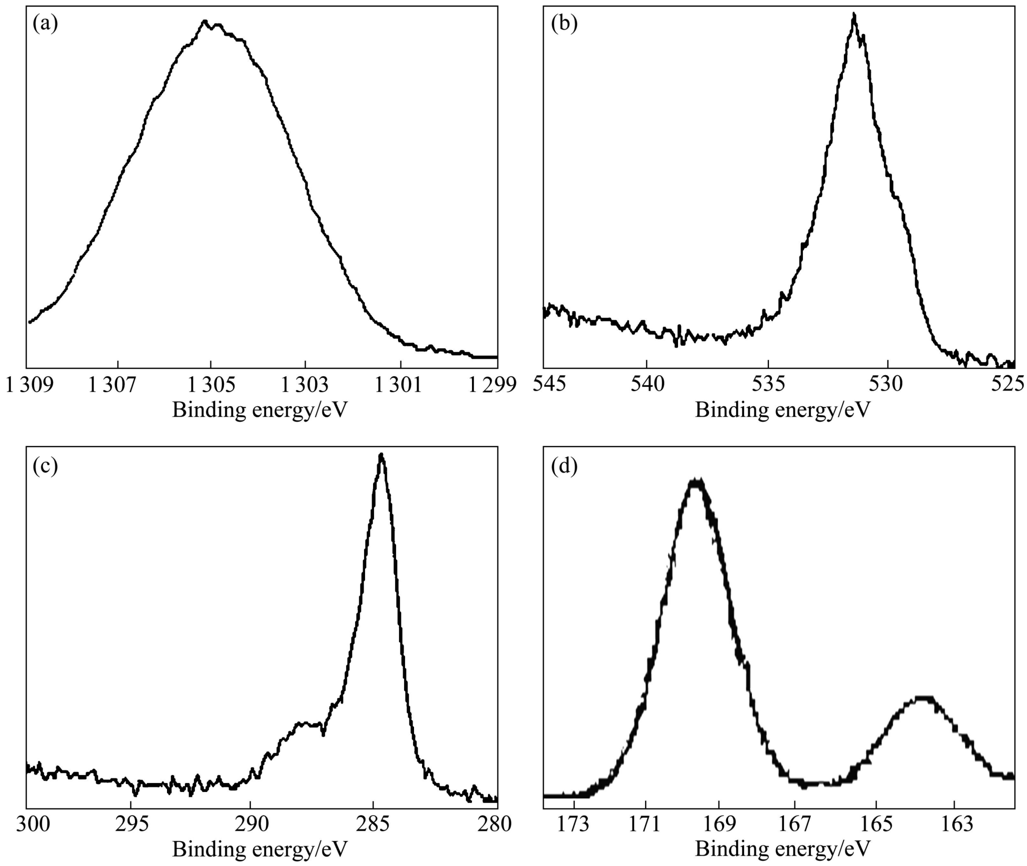

Fig. 4 XPS spectra of typical elements on worn magnesium alloy surfaces: (a) Mg 1s; (b) O 1s; (c) C 1s; (d) S 2p

at the binding energy of 1 305.10 eV, which was assigned to the chemical state of metallic magnesium. The peak of O 1s (Fig. 4(b)) at the binding energy of 531.5 eV was attributed to the chemical state of oxygen in the glyceride of SRO and rapeseed oil and indicated that the molecules of SRO and rapeseed oil adsorbed on the friction surfaces, in combination with the binding energy of C 1s in the binding energy range of 284.6−288.8 eV (Fig. 4(c)), which were assigned to the chemical species of C—H, —C—C— or —O—C═O. In the spectrum of S 2p (Fig. 4(d)), the peak at binding energy of 169.80 eV corresponded to the species of MgS, which demonstrated that tribochemical reactions were also involved between magnesium alloy and SRO [15].

As we know, the triglyceride structure of vegetable oils provides qualities desirable in a lubricant. Vegetable oils are particularly effective as boundary lubricants when the high polarity of the entire base oil allows strong interactions with the lubricated surfaces. Boundary lubrication performance is affected by attraction of the lubricant molecules to the surface and also by possible reaction with the surface. Thus, based on the XPS analysis in the present study, the SRO additive, in the molecules of which sulfur was chemically bonded into the triglyceride structure of rapeseed oil, could also strongly adsorb onto the friction surfaces due to the long and polar molecular origin of rapeseed oil. In addition, the adsorption of SRO on the surfaces provided more sulfur contents in the surface phase than in the bulk phase, promoting tribochemical reactions between SRO and the magnesium alloy substrate as a result. Thus, the contribution of SRO in fortifying anti-wear and friction-reducing abilities of rapeseed oil in the lubrication of magnesium alloy against steel could be mainly ascribed on one hand to the strong adsorption of the SRO molecules onto the friction surfaces, and on the other hand to the tribochemical reactions of SRO with magnesium alloy. As a consequence, a composite boundary lubrication film was formed on the lubricated surfaces and the friction and wear performances of magnesium alloy−steel tribopairs were improved.

4 Conclusions

1) SRO, a S-containing additive derived from rapeseed oil by chemical modification, provides good anti-wear and friction-reducing abilities in rapeseed oil in the lubrication of AZ91D magnesium alloy against GCr15 bearing steel. The friction coefficients and the wear volume loss of magnesium alloy decrease with increasing contents of SRO in rapeseed oil in a certain extent.

2) The surface lubricated with SRO-doped rapeseed oil exhibits mild wear as compared with that lubricated with net rapeseed oil, and was characterized by the formation of a composite boundary lubrication film mainly composed of adsorbates of SRO and rapeseed oil and tribochemical resultants such as MgS.

3) The formation of the composite lubrication film might be the attribute for SRO to improve the friction and wear performances of magnesium alloy against steel under the lubrication of rapeseed oil.

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硫化菜籽油润滑添加剂对钢−镁摩擦副摩擦学性能的影响

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摘 要：在菜籽油(RO)分子中引入硫，合成一种改性菜籽油润滑添加剂(SRO)。结果表明：以菜籽油为基础油的硫化菜籽油润滑添加剂对钢−镁摩擦副具有优良的抗磨减摩性能；镁合金的摩擦因数和磨损体积随着 SRO 添加量的增加而减小；与菜籽油润滑的镁块表面相比，用含 SRO 菜籽油润滑的镁块表面摩擦划痕较轻微。SRO 对钢−镁摩擦副具有优良抗磨减摩作用的机理是由于添加剂和菜籽油分子在摩擦表面吸附并与镁合金发生了摩擦化学反应而生成了一层复杂的边界润滑膜。

关键词：抗磨；减摩；钢−镁摩擦副；硫化改性菜籽油

(Edited by LI Xiang-qun)