Tribology International 81 (2015) 199–208

Contents lists available at ScienceDirect

Tribology International

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

Tribological behaviors and wear mechanisms of ultrafine magnesium aluminum silicate powders as lubricant additive

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ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form
26 August 2014
Accepted 4 September 2014
Available online 16 September 2014

Keywords:
Attapulgite
Ultrafine
Lubricant additive
Tribological properties

ABSTRACT

The ultrafine attapulgite powders (UAP) were prepared using natural attapulgite powders (NAP) by the ball-milling dispersion method. The tribological behaviors of surface-modified NAP and UAP dispersed into mineral base oil were investigated. SEM, EDS, XPS and a microhardness tester were utilized to analyze the tribofilm formed on the worn surfaces. It is found that both the additives can improve the friction-reduction and anti-wear properties of the base oil. A tribofilm mainly composed of FeO, Fe_2O_3, FeOOH and SiO formed on the worn surface lubricated with oil containing NAP and UAP. And the content of iron oxides and SiO formed on the worn surface lubricated with oil containing UAP is much higher, which is responsible for the better friction-reduction and anti-wear properties of UAP.

1. Introduction

Owing to their outstanding physio-chemical properties [1], nanomaterials have attracted great attention in many fields, such as tribology. Plentiful reports have indicated that adding nanoparticles into lubricants is effective in improving their lubricity [2–18]. However, for the micro-materials, due to their poor dispersibility and stability in liquid lubricants, they are seldom used as lubricant additive [19].

In recent years, some reports have shown that micro-scale serpentine mineral powders can be utilized as additives to improve the lubricity of lubricants [20–22]. Yu et al. [20] investigated the tribological properties of serpentine powders as lubricant additives by an MM-10W sliding friction tribotester. Results demonstrated that a tribofilm with excellent mechanical properties formed on the worn surface. Zhang et al. [21] studied the tribological behaviors of serpentine powders suspended in diesel engine oil using an Optimal SRV friction and wear tester. It is found that a tribofilm is mainly composed of iron oxides, silicon oxides, graphite and organic compounds formed on the worn surface. Jin et al. [22] researched the self-reconditioning effect of serpentine powders in railway field trials. Outcomes indicated that a protective layer about 10 μm in thickness was generated on the cast iron cylinder liner.

Attapulgite is another type of magnesium aluminum silicate mineral powder.The component and crystal structure of attapulgite are remarkably similar to that of serpentine. However, the cost of attapulgite is much lower. Nan et al. [23] investigated the tribological properties of natural attapulgite powders in mineral lubricating oil for a steel–steel friction pair by using an Optimal SRV friction and wear tester. The results presented that the natural attapulgite powders can remarkably improve the friction-reduction and anti-wear ability of the base oil. The 0.5 wt% content of natural attapulgite powders displays the best tribological properties. A complex smooth tribofilm mainly composed of iron oxides and silicon oxides formed on the worn surface, which was responsible for the excellent tribological properties of attapulgite. However, the length of the attapulgite particles is larger than 0.5 μm, which does not meet the size standard regarding solid additives in lubricating oil.

In this work, the ultrafine attapulgite powders were prepared. The tribological behaviors of the modified NAP and UAP as lubricant additives were also investigated. The tribofilms formed on the worn surfaces were analyzed with SEM, EDS and XPS to disclose the wear mechanism of the additives.

2. Experimental details

2.1. Materials

The natural attapulgite powders were purchased from JIUCHUAN scientific and technical corporation (Jiangsu Province, China). The UAPs were prepared by milling the NAPs in the ball mill at room temperature for 8 h. The milling jar was made of agate. The grinding balls that were of 0.4 mm diameter were made of ZrO_2. The rotating

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http://dx.doi.org/10.1016/j.triboint.2014.09.006

speed is 250 r/min, and the ball to powder ratio is 40:1. The X-ray patterns of NAP and UAP shown in Fig. 1 demonstrate that their compositions are basically uniform. The shape change process of the attapulgite powders is shown in Fig. 2. It can be observed that the natural attapulgite particles are fibrous and the particles agglomerate together to form large particles. Many fibrous particles changed into big irregular spherical particles after milling for 2 h. After milling for 4 h, all particles changed into spherical shape. Moreover, the particles possessed more regular shape and smaller size. With the extension of milling time, the particles subsequently became smaller and smaller. In addition, the shape of the particles became more and more regular.

The mineral lubricating oil (150SN) with typical physicochemical properties shown in Table 1 was used as the base lubricant. In order to obtain good dispersing stability in the oil, the powders were modified with oleic acid. The FTIR spectra of NAP, UAP and modified UAP are presented in Fig. 3. The spectrum of NAP presents the typical bands of this silicate material. The band at 3560 cm^{-1} is assigned to (Fe, Mg)–OH. The band at 3423 cm^{-1} is attributed to zeolitic water. The band at 1644 cm^{-1} matches with the OH bending vibration band of coordinated and adsorbed water. The bands at 1195 and 1030 cm^{-1} are assigned to the Si–O stretching vibration and the band at 466 cm^{-1} belongs to the Si–O–Si in-plane bending vibration [24,25]. Whereas for UAP, the intensities of bending bands at 3560, 3423 and 1195 cm^{-1} are much lower than that of the corresponding bands of NAP. This outcome can be attributed to the breakage of the crystal structure of attapulgite. And for the UAP after modification, the bands at 2930 and 2857 cm^{-1} show that CH_3 and CH_2 exist in the crystal structure of modified powders. The band at 1455 cm^{-1} indicates that the C=O is present [26,27]. From the FTIR analysis result, it can be concluded that an organic modified layer formed on the surface of UAP. Fig. 4 shows the particle size histogram of the UAP and modified UAP. The average particle size of UAP and modified UAP is about 1300 and 330 nm respectively, which indicated that the UAP possesses much better dispersing stability in an organic solvent after modification.

2.2. Experimental design

To investigate the friction-reduction and anti-wear properties, the Optimal SRV-IV oscillating friction and wear tester was utilized to carry out the tribology test. The upper specimen was an AISI 52100 steel ball of 10 mm in diameter. The lower specimen was an AISI

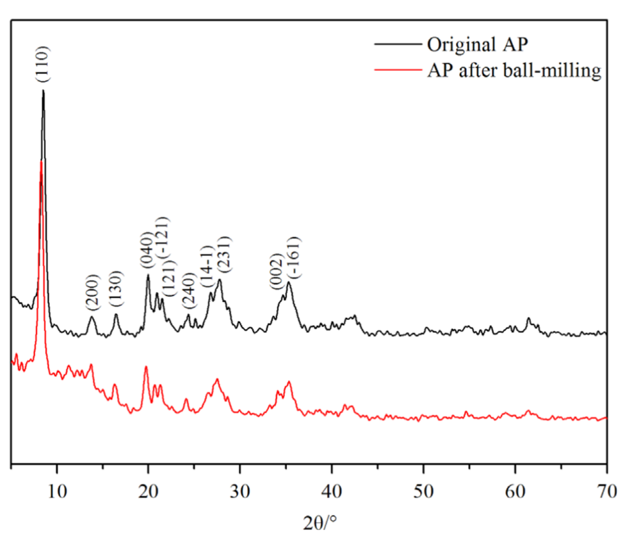

Fig. 1. XRD patterns of the NAP and UAP.

1045 steel disc (⌀24 mm × 8 mm). In all the tests, the ball slided reciprocally on the stationary disc at an amplitude of 1 mm for 30 min. The testing temperature was kept at 50 °C. The effect of AP concentration, applied load and sliding frequency on the tribological properties of the lubricants was investigated. The tribology test conditions are presented in Table 2. Each tribology test was repeated three times. The friction coefficient was recorded by a computer connected to the test rig. The volume loss of the disks was measured with a MicroXAM three-dimensional non-contact surface mapping profilometer. The wear volume of each worn scar was measured thrice and the mean value was calculated.

2.3. Worn surface analysis

The morphologies and chemical constituents of the worn surfaces on the disks were characterized by SEM, EDS and XPS. The microhardness of the tribofilm formed on the worn surfaces was measured by a microhardness tester.

3. Results

3.1. Tribological behaviors

The effect of additives concentration on the friction coefficient and wear volume is displayed in Figs. 5 and 6. The friction-reduction and anti-wear properties of the base oil could be remarkably improved after adding NAP and UAP into it. The most appropriate additive amount of the NAP and UAP is 0.5 wt%.

The effect of applied load on the friction coefficient and wear volume of base oil (SR0), the oil containing 0.5 wt% NAP (SR1) and the oil containing UAP (SR2) is presented in Figs. 7 and 8. Under the lubrication of base oil (SR0), the friction coefficient displays high value and acute fluctuation at high loads. Whereas with the addition of NAP and UAP, the friction coefficient decreases slightly and presents little fluctuation. Moreover, the friction coefficient of oil containing UAP is a little smaller than that of oil containing NAP. The corresponding wear volume related to different loads demonstrates that lower wear volumes were observed with the lubrication of the oil containing NAP and UAP, especially at 50 N and 100 N. In addition, the UAP possesses better anti-wear property than NAP.

The effect of sliding frequency on the friction coefficient and wear volume of SR0, SR1 and SR2 is shown in Figs. 9 and 10. When the base oil was used as lubricant, the friction coefficients show high value at all frequencies. Under the lubrication of SR1 and SR2, the friction coefficients present different values at the early stage of the tests. However, as the experimentprogresses, the friction coefficients gradually decrease to nearly the same value.

It is found from the friction and wear test results that both the NAP and UAP can improve the tribological properties of the base oil. And the UAP has better friction-reduction and anti-wear properties than the NAP. This may be interpreted as follows: during the lubrication of oil containing NAP and UAP, a tribofilm with excellent self-lubricating and anti-wear properties formed on the worn surfaces. Furthermore, compared with SR1, the tribofilm formed on the worn surface under the lubrication of SR2 possesses better self-lubricating and wear-resistant properties.

3.2. Worn surface analysis

3.2.1. Morphology and elementary analysis of the worn surface

The morphologies of the worn surfaces lubricated with SR0, SR1 and SR2 at 100 N are shown in Fig. 11. There are many deep pits and large-area exfoliation on the worn surface lubricated with SR0, indicating that severe adhesive wear has happened. However, the worn surfaces lubricated with SR1 and SR2 are more smooth