Wear 332-333 (2015) 1158–1163

Contents lists available at ScienceDirect

Wear

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

Effect of oil temperature on tribological behavior of a lubricated steel – steel contact

Zhen-bing Cai [a,b], Yan Zhou [b,c], Jun Qu [b,*]

[a] Tribology Research Institute, Key Laboratory of Advanced Technologies of Materials, Southwest Jiaotong University, Chengdu 610031, China
[b] Materials Science and Technology Division, Oak Ridge National Laboratory, TN 37831, USA
[c] Materials Science and Engineering, Texas A&M University, College Station, TX 77843, USA

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
21 January 2015
Accepted 27 January 2015

Keywords:
Base oil
Temperature
Moisture
Oxidation
Wear mechanism
Surface film

ABSTRACT

Tribological tests were conducted on an AISI A2 steel plate against an AISI 51200 steel ball lubricated by SAE 0W30 and PAO 4 cSt base oils containing no additive package. Friction and wear behaviors were evaluated at room temperature (RT, 23 °C) and a series of elevated temperatures (75, 100, 125 and 175 °C). The steady-state friction coefficient appeared to be proportional to the oil temperature, probably because reduced oil viscosity at a higher temperature caused more surface asperity collisions. In contrast, wear results did not follow the trend: the wear rate surprisingly decreased when the oil temperature increased from RT to 75 – 100 °C, and then turned around to increase along with the temperature at above 100 °C. Evidentially, there are other significant factors than just the oil viscosity that influence the wear process upon the temperature change. Wear scar morphology examination and surface chemical analysis revealed an oxide-containing surface film on the wear scars and higher oxide content and larger film coverage seemed to reduce the wear rate. Therefore, the wear mechanism is proposed as a combined effect of mechanical material removal and protective surface film formation: the former largely depending on oil viscosity that is inversely proportional to the temperature and the latter involving surface and wear debris oxidation that is promoted by temperature elevation as well as the water content (up to 100 °C) in the oil.

1. Introduction

The key factors affecting the tribological performance of a bearing system generally include the bearing mechanical design, material compositions, mechanical properties, lubricant rheological properties, chemistry, and operation conditions. In this study, we investigated the effects of the lubricant temperature and water content on friction and wear behavior. In boundary lubrication, a high temperature reduces the oil viscosity and the mechanical strength of the lubricant film at the interface [1–3], generally leading to increased friction and wear. In addition, high temperature promotes tribochemical reactions on contact surfaces that can either be beneficial [4] (e.g., forming a stable tribofilm) or detrimental [5] (e.g., causing corrosion) to wear behavior. A temperature increase in SAE40 oil causes increase in both adhesive and corrosive wear [6]. Temperature also affects the concentration and distribution of oil contaminants, such as air, water, and particulates, which are usually unavoidable [7–9]. Three forms of water possibly exist in oil: dissolved water, emulsion, and free water. Lubricating properties of a water–oil emulsion have been reported with poorer than those of water-free oils [10]. Particularly, emulsion or free water in oil would cause more damage than does dissolved water because of the former causes higher compressibility of the oil film at the contact area and increased risk of cavitation [11]. On the other hand, the dissolved water in the lubricant, almost inevitable in most industrial applications, is known to increase oil viscosity and metal surface oxidation [12].

Here we report interesting observations of the friction and wear behavior of a steel–steel contact lubricated by two synthetic base oils at a series of test temperatures. Wear mechanisms were discussed based on the results of surface chemical analysis.

2. Materials and methods

Two synthetic base oils, SAE 0W30 (supplied by Chevron) and polyalphaolefins (PAO) 4 cSt (supplied by Exxon Mobil), were used in this study. The 0W30 is a multiple-grade base oil blend, while the PAO is a single-viscosity base oil. Both products are neat hydrocarbons, though their exact chemical structures are not available (protected by non-analysis agreement). Neither contains

---

* Corresponding author.
E-mail address: qujn@ornl.gov (J. Qu).

http://dx.doi.org/10.1016/j.wear.2015.01.064

Table 1
Physical properties of the lubricants.

Lubricant	**Density** (g/ml, 23 °C)	**Viscosity (cP)**		
		23 °C	40 °C	100 °C
SAE 0W30 base oil	0.82	26.59	13.78	3.12
PAO 4 cSt base oil	0.80	30.45	15.38	3.27

any additive package. The oils were stored in an ambient environment for over a year, so their water contents were thought to have been at or near saturation. The measured water content in the 0W30 oil was ~2500 ppm at room temperature, as determined using Karl Fisher titration and confirmed by weight loss using a heated vacuum. It is known that synthetic oils may contain much more water than mineral oils [11]. In one set of tests, 1 wt% of distilled water was added into the 0W30 base oil and the mixture was shaken well to reach a stable emulsion. Viscosity measurements were performed with a falling ball viscometer (Petrolab Minivis II). Table 1 presents the densities and viscosities of the two lubricants at various temperatures. Five temperatures (23, 75, 100, 125, and 175 °C) were selected for 0W30 and three temperatures (23, 100, and 175 °C) for PAO in the tribological bench tests.

Tribological tests were conducted using a ball-on-flat tribometer in a reciprocating sliding configuration (PLINT TE-77) at an oscillation frequency of 10 Hz with a stroke of 10 mm. The tests were conducted under a normal load of 54 N for a sliding distance of 1000 m. A steel–steel contact was selected: (1) a grade 25 AISI 52100 bearing steel ball (Vickers hardness [HV]=976, $d=10$ mm, $R_q=0.05$ μm); (2) a hardened AISI A2 tool steel plate (HV=872, $R_q=0.18$ μm). Their roughness was measured by using a Mahr Perthometer M2 profiler. The HV was determined with a Buehler Micromet 2100 micro-indenter at a load of 100 gf. At least two repeat tests were conducted under each condition.

The worn surfaces of both plates and balls were cleaned using isopropanol before imaging. The wear volume and scar depth and width were quantified using a Wyko NT9100 optical profiler. Wear scar morphology was inspected using an optical microscope (OM, Nikon Labophot-2) and a field-emission scanning electron microscope (SEM) (Hitachi S-4800) equipped with energy dispersive spectroscopy (EDS). Further surface chemical analysis was conducted on a Thermo Scientific K-Alpha x-ray photoelectron spectroscopy (XPS) instrument. The x-rays used were monochromatic Al-kα photons; photo-emitted electrons were analyzed with a hemispherical energy analyzer. Wide survey scans were collected from 0 to 1350 eV at a pass energy of 200 eV to determine overall elemental composition. Core level spectra were collected using a pass energy of 50 eV.

3. Results

Fig. 1 shows the friction coefficient (COF) in the two oils at various temperatures. For both oils, increased testing temperature resulted in higher COF, probably due to the decrease in oil viscosity leading to more frequent and more severe surface asperity contacts. The COFs at 175 °C were the highest in each group. The addition of water resulted in a slight increase in COF (Fig. 1a). Each test showed a slow decrease in COF after running-in, which may have been due to the change in contact condition from point contact to more or less conformal contact during the wear process.

The wear on the plates was too low to quantify. The wear rates of the balls are compared in Fig. 2; selected cross-sectional wear scar profiles (after subtracting the original ball curvature) are also shown in Fig. 2. For the tests in both oils, the wear rate had the lowest value at around 75–100 °C and was higher at room temperature (RT, 23 °C) or above 100 °C. The wear increase along with the temperature increase from 100 to 175 °C was expected, considering the oil viscosity drop. However, the wear rate at 100 °C was notably lower than that at RT, which is unexpected, even though the oil viscosity was one order of magnitude lower

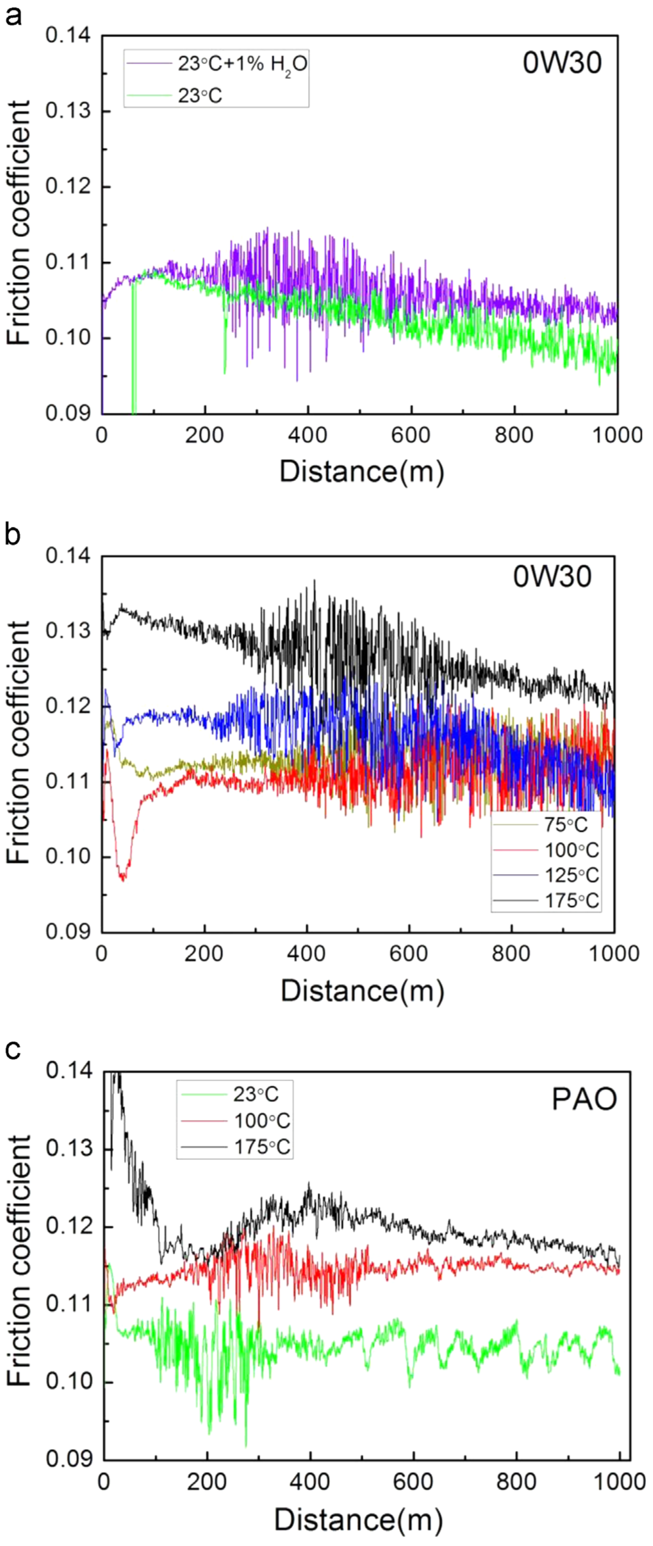

Fig. 1. Friction traces of tests in (a) 0W30 at RT with and without addition of water, (b) 0W30 at various temperatures from 75 to 175 °C, and (c) PAO at temperatures of 23, 100, and 175 °C.