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Friction and wear of tribofilms formed by zinc dialkyl dithiophosphate antiwear additive in low viscosity engine oils

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Abstract

Friction and wear characteristics of low viscosity SAE 5W-20 engine oils containing different amounts of phosphorus were studied using two different test devices. One was a laboratory high frequency reciprocating rig (HFRR) testing new and used oils at low and elevated temperatures. A direct acting mechanical bucket (DAMB) sliding valvetrain bench test apparatus was used to measure the friction and wear performances of fresh engine oils containing 0, 0.05 and 0.1 wt% phosphorus for a cam lobe rubbing against a tappet insert. The tester was coupled with a radioactive tracer machine (RTM). The results show that in the region of low phosphorus concentration, friction is inversely correlated to temperature. The friction coefficient slightly drops with increasing temperature and increases with increased phosphorus concentration at elevated temperatures. Significant wear is produced at phosphorus concentrations lower than 0.02 wt% at most temperatures. Friction and wear are reduced with the addition of supplemental antiwear additives. MoDTC reduces wear more effectively than ZnDTC in the presence of ZDDP.

Keywords: Zinc dialkyldithiophosphate; Friction; Wear; Film formation; Supplemental antiwear additive

1. Introduction

The key driving forces influencing the advancement of engine oil and additive technology are enhanced fuel economy, environmental protection and longer drain intervals. Corresponding to these drivers there is an increasing desire to reduce elements, such as phosphorus, that are detrimental to emission system durability and to use low viscosity engine oils for a better fuel economy. To insure adequate wear protection, substantial understanding of the effect of reduced phosphorus concentration on friction and wear performance in the highly stressed boundary lubrication regime is needed. Reduction of phosphorus is accomplished by reducing zinc dialkyldithiophosphate (ZDDP) concentration in motor oils.

ZDDPs are synthesized by the reaction of alcohols with phosphorus pentasulphide and zinc salts. The performance of ZDDPs is strongly influenced by the type and molecular weight of alcohols used for their synthesis [1]. ZDDPs in lubricants are multifunctional acting as antioxidants, antiwear/extreme pressure additives and corrosion inhibitors [2]. Friction characteristics of ZDDPs in combination with molybdenum dialkyldithiocarbamate (MoDTC) were studied in boundary lubrication and the synergistic effects of ZDDP on MoDTC were reported [3–6]. The formation of friction reducing molybdenum disulfide (MoS_2) was enhanced by the presence of ZDDP. The wear performance of various ZDDPs species was studied by Yamaguchi [7] and Unnikrishnan et al. [8]. Meanwhile, the composition and characterization of antiwear films formed by ZDDPs were investigated and metal polyphosphates and sulphides were found to form on the rubbing surfaces [9,10]. In addition, the friction and wear behavior of fully formulated lubricants containing ZDDP were studied using an electrical contact resistance (ECR) technique [11,12]. The film development was investigated with rubbing time or distance and a direct correlation was observed between friction and film as measured by the ECR. This technique provided useful information on film formation of additives. However, the effects of phosphorus concentration on friction and wear were not reported in the previous studies.

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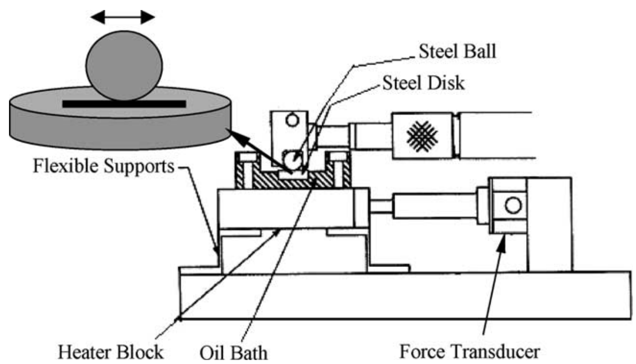

Fig. 1. Schematic diagram of high frequency reciprocating rig.

The present work reported the friction and wear performances of tribofilms formed by ZDDP in low viscosity SAE 5W-20 engine oils that contain varying amounts of phosphorus using a high frequency reciprocating rig (HFRR) and a valvetrain bench test apparatus coupled with a radionuclide technique. The effectiveness of supplemental antiwear additives in association with reduced amounts of ZDDP was evaluated using a DAMB type of valvetrain bench test equipment.

2. Experimental

2.1. Friction and wear tests

The friction and wear performances of oils containing different levels of phosphorus were evaluated using the HFRR as shown in Fig. 1. The HFRR measures the friction and wear under boundary lubrication conditions using a highly stressed ball-on-disk contact. A 6.0 mm diameter harder steel ball (650–670 Hv) reciprocates on a softer steel disk (190–210 Hv) under the fully submerged oil condition at a normal load of 9.8 N and a maximum sliding velocity of 40 mm/s for a test length of 1 h. Both ball and disk were made of AISI 52100 steel. The oil temperature was controlled by a heater block underneath the oil bath. Each oil was tested at a temperature range of 40–135 °C to cover most of the operating temperatures in a vehicle. The friction force was measured by a piezoelectric force transducer that was attached to the heater block. The formation of electrically insulating films at the sliding contact was measured by the ECR technique. Each oil was run for at least twice and the mean values were reported to represent the friction coefficient and film formation in this study.

A wear track was produced on the steel disk surface after each test as seen in Fig. 2. Wear was evaluated by using the cross-section area of wear scars assuming the cross-section area is uniform along the entire reciprocating stroke. The worn disk was cleaned with hexane before the wear profile was taken using a stylus surface tracer along the transverse direction of the wear scar. The cross-section area of the wear scar was calculated by integrating the wear depth along the scar width.

2.2. Valvetrain friction and wear tests

The valvetrain wear was measured using a laboratory valvetrain bench apparatus coupled with a radioactive tracer machine (RTM). The radioactive wear debris was generated by the sliding contact between a cam lobe and a tappet insert. The radioactive debris carried in the lubricant was circulated through a radioactive tracer system as shown in Fig. 3. A gear pump sucked lubricant from the oil sump where the debris was collected into a concentration-measuring device (CMD). The intensity or counting rate of γ-ray from wear debris was measured by a NaI crystal detector inside the CMD and then converted into mass loss using the calibrated specific activity of isotope ^{56}Co. At the same time, the radioactivity decays with time. Therefore, the half-life of the radioisotope was checked on-line by another similar detector in a reference-measuring device (RMD). The decay-corrected count rate in each spectrum was used to calculate the mass loss accurately. Scherge et al. [13] introduced the wear measurement mechanism using the radionuclide technique in more detail. After the lubricant flows out of the radioactivity measuring chamber, the lubricant was pumped back into the oil sump through

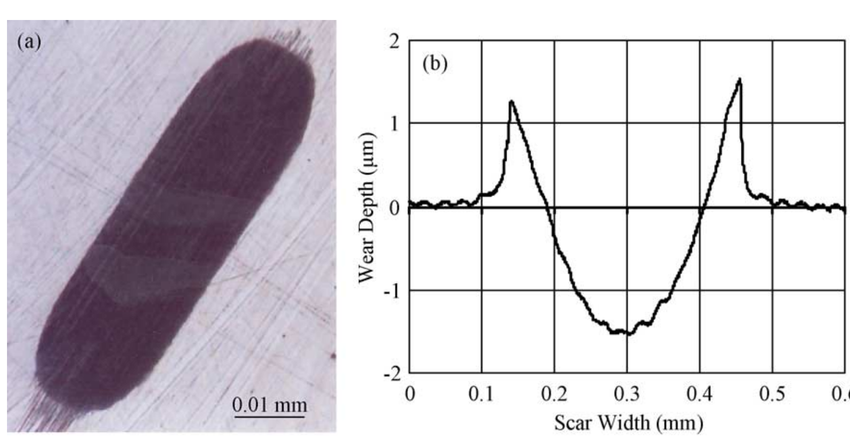

Fig. 2. Optical micrograph of wear scar and wear depth as measured by surface tracer: (a) optical graph; (b) surface profile.