Environmentally acceptable lubricants for marine applications

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1. Introduction

According to Vessel General Permission 2013 (VGP 2013) regulated by United States Environmental Protection Agency (US EPA), lubricants in ship equipment should be composed of no less than 90% of biodegradable materials [1]. Therefore, a shift from mineral base oils to biodegradable alternatives such as synthetic esters is needed. A change of lubricant additives may also be required where some conventional additives should be fade out due to poor biodegradability and/or the bio-accumulative tendencies. Under these circumstances, an international consortium "Arctic Thruster Eco-system" (ArTEco) was formed to investigate lubrication systems in marine thrusts [2]. As a part of the consortium, our task in this project was to evaluate environmentally acceptable lubricants (EALs) for marine applications. Different laboratory tests were conducted to survey the tribological performances of EALs in comparison with conventional mineral-based lubricants.

2. Experimental procedure

The tribological properties under boundary conditions were evaluated by reciprocating or unidirectional motion of pure sliding using a steel-ball and a steel-flat. The elasto hydrodynamic lubricating performance in rolling/sliding boundary, mixed and full film conditions were evaluated in a ball on disk test rig [3]. It has been shown earlier that ball on disk tests can be used to simulate gear contacts [4]. Commercially available EALs made of synthetic esters and mineral based lubricant as reference were employed. The lubricants have similar viscosities at 40 and 100 °C. Morphology of wear tracks were studied using an optical microscope and scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS).

3. Results and discussion

3.1. Pure sliding friction

Friction trace as a function of sliding distance in step-load tests in unidirectional and reciprocating sliding are summarized in Figures 1 and 2, respectively. Two runs of tests for each sample are shown for repeatability. All lubricants exhibited similar friction trace, although slightly higher friction for EAL2. Generally, friction increased as load increases in unidirectional, while it decreased as load increases in reciprocating.

The influence of temperature on friction was significant for EALs. Fig. 3 shows the results of temperature-programmed reciprocating tests at the load of 200 N. EALs exhibited fluctuation of friction at temperatures higher than 75 °C. It continued after cooling down to 50 °C, indicating permanent changes in lubricant properties by heating. On the other hand, mineral-based lubricant provided stable friction at higher temperatures.

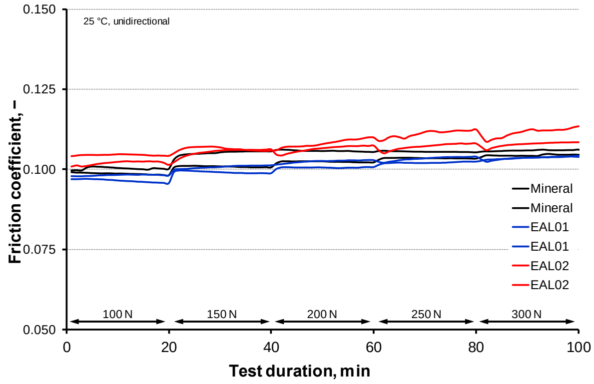

Fig. 1 Friction in unidirectional motion

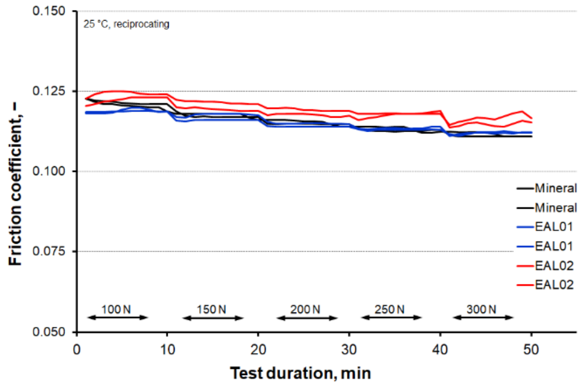

Fig. 2 Friction in reciprocating motion

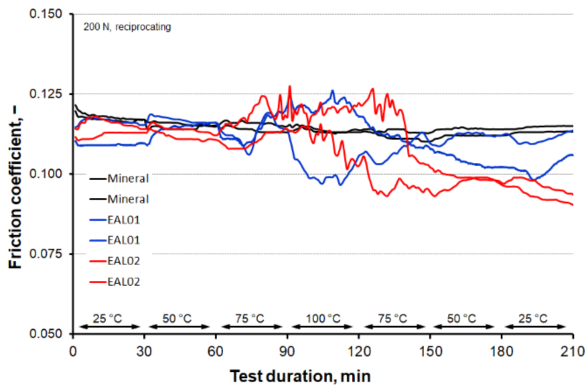

Fig. 3 Friction in temperature-programmed test

Average friction coefficient and wear volume for each lubricant are summarized in Figure 4. Both EALs gave high wear with rough surface in wear test at 75 °C, compared to those by mineral-based lubricant. Phosphorus was found by SEM-EDS on rubbed surfaces at 25 °C with both EALs. It seems the boundary film broke down at higher temperatures.

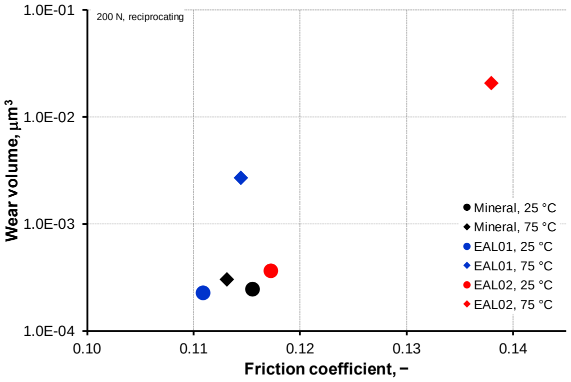

Fig. 4 Average Friction and wear for each oil

3.2. Rolling/sliding friction

Figure 5 shows the result from friction tests performed in a ball on disk test rig at 80 °C with a load of 600 N corresponding to a maximum nominal contact pressure of 2.4 GPa. A constant slide-to-roll ratio (SRR) of 50 % was used while the entrainment speed was varied between 7.2 and 0.007 m/s. In this case, the slide-to-roll ratio is defined in such a way that the disks surface speed was higher than the balls. Here, the EALs provides a lower coefficient of friction in both boundary, mixed and full film lubrication.

In Fig. 6 the results from “mu-slip” tests are shown. Here, the SRR was varied from 2 to 115 % with a constant entrainment speed of 3 m/s at 80 °C at a pressure of 2.4 GPa. Even here, the EALs are providing a lower coefficient of friction compared to the mineral oil. The same trend is also seen in tests performed at a lower pressure of 1.35 GPa (100 N).

Figure 7 shows the result from 2-hour wear tests conducted at 80 °C, 2.4 GPa of pressure and with an entrainment speed of 0.5 m/s and a SRR of 150 %. Aside from providing significantly lower friction coefficients, the EALs quickly reaches a steady-state friction level whereas the mineral oil has a continuous decrease throughput the 2-hour test duration. Optical interferometry studies show deeper wear scars on the disk for the mineral oil compared to the EALs. SEM-EDS analysis show the presence of phosphorous on the disk surface with all lubricants, indicating the formation of protective boundary films.

4. Conclusions

Under pure sliding boundary conditions, EALs exhibited similar tribological properties to mineral-based lubricants at temperature below 50 °C, while they did not at higher temperatures. Under sliding-rolling conditions, EALs provided better tribological performances in terms of friction and wear. These results clearly show the benefit of EALs under mixed lubrication and EHL conditions. However, it still needs improvements for harsh boundary conditions. Boundary film composed of phosphorus was found for all lubricants evaluated here.

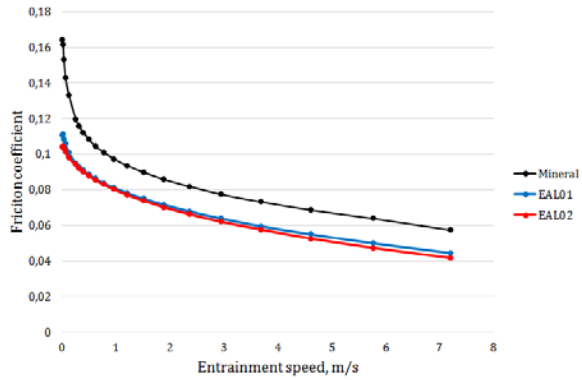

Fig. 5 Rolling/sliding friction vs entrainment speed

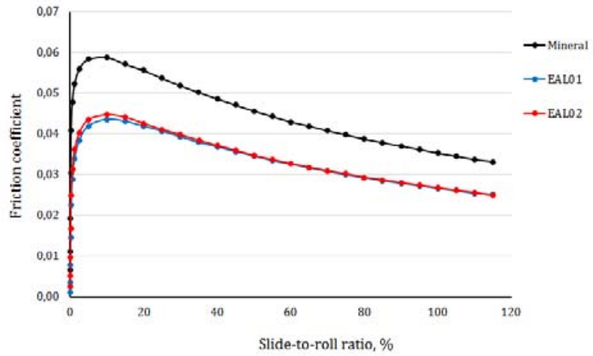

Fig. 6 Rolling/sliding friction vs slide-to-roll ratio

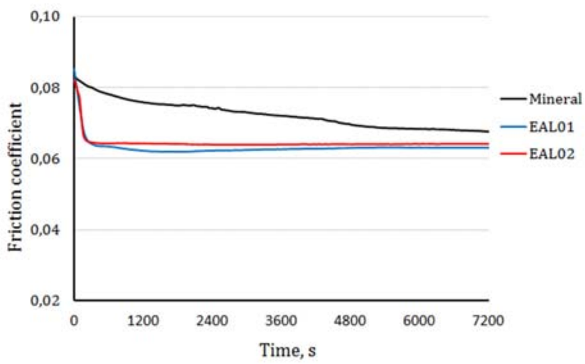

Fig.7 Friction vs time in rolling/sliding wear test

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