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Lubricant additives for improved pitting performance through a reduction of thin-film friction

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ABSTRACT

This paper describes an investigation into possibilities of enhancement of pitting lives of rolling components by using additive combinations with low thin-film friction. Various viscosity index improvers, anti-wear and extreme-pressure additive combinations were analysed in terms of their frictional behaviour, which in turn was compared to the oils pitting lives. For the pitting studies, a rolling four-ball test was employed. Friction was measured using a ball on disc machine as well as indirectly through "near contact" temperature measurements performed during rolling four-ball tests. The results show that additive combinations that result in low friction at the specific running condition can enhance pitting performance.

1. Introduction

Viscosity modifiers (VM), anti-wear (AW) and extreme-pressure (EP) additives are, among other additives, commonly added to base fluids in the formulation of gear oils. Their functions however vary, the requirement on VMs are mainly to provide sufficient oil film formation at operating temperatures. AW and EP additives are usually chemically active species that either adsorb onto or react with the surface and are essential in preventing scuffing, seizure and reducing wear between mating surfaces of gear teeth during highly loaded operating conditions.

Also in terms of delaying macro-scale contact fatigue (referred to as pitting [1]), their functions vary.

For VMs, mainly their ability to form sufficient oil films at the operating temperatures have been found important for pitting life [2,3]. Theoretical work has also suggested that even small variations in traction due to various VMs can have significant effects on pitting life [4], the work was however limited to full film EHL.

The effects of EP and AW on pitting is, however, not so straightforward to explain and is believed to involve both the chemical and physical characteristics of the lubricant. This aspect has been discussed at length in the literature and still a clear view of the problem seems to be missing. The issue is further complicated by the many possible chemical types that fall within a given performance functional group and it may not be prudent to arbitrarily declare a given functionality, such as AW or EP as being beneficial or detrimental. The pitting behaviour will also vary for various running conditions, material etc. This can also been seen in the incoherent results of many pitting studies presented in the literature for a range of test equipment, running conditions and additive types; a number of studies show detrimental effects on pitting life [5–7] while positive effects also have been reported [8,5,9,10,11].

The root causes as to why the additives affect the fatigue lives will likely vary from case to case and several mechanisms have been proposed, some of which are a bit speculative in nature.

Chemical reactions have been attributed to promote crack initiation by creating corrosion pits and high stress points by attacking specific points on the surfaces and promoting crack initiation [12,13]. Chemical reactivity has also been proposed to increase the propagation rate of micro-cracks [14] and evidence of lubricant additive activity inside cracks has been shown [15]. Such theories find indirect support from Wöhler fatigue tests (rotating bending in oil environment) where an AW additive caused a significant reduction of fatigue life [16]. In a similar test, the same effect was found for certain EP additives and was attributed to their chemical reactivity promoting crack initiation [17].

On the other hand, the net effect of additives in combination is rarely the sum of their individual effects and the above mentioned negatives can likely be mitigated to some extent by judicious formulation. For example, it was partly possible to counteract the negative effect of the AW in the above mentioned Wöhler test by adding detergents [16]. Similarly, a prolongation of pitting life was

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achieved by adding finely dispersed $CaCO_3$ into a sulphurized oil in a twin-disc test [11], supposedly as a result of a neutralization of sulphurous acid.

Chemical reactivity of the additives has also been found to enhance pitting life in some cases for example due to accelerated surface conditioning by EP additives which lowered bearing operating temperatures during a break-in cycle of a fatigue test [18]. A similar smoothening effect of EP additive is also considered in [19]. Additives have also been reported to inhibit crack propagation by a corrosive wear process that removes surface or near-surface cracks faster than they can propagate (pit formation occurs when a crack propagate faster than it is worn away) [5,20].

Diffusion of AW and EP additive elements into steel has been proposed as degrading its mechanical properties. The work of Evans et al. [21] however showed that such an explanation is unlikely in explaining the changes in fatigue life since their analysis showed that neither S or P diffuse into the near-surface region of steel materials.

A completely different mechanism was proposed by Meheux [22] whereby materials with surface connected cracks could find mechanical support in the thin tribofilms formed at the surface.

Something not often discussed are the direct effects of AW/EP additives on the forces acting on the contact interfaces. The work of Fowles et al. [23] touched upon the subject and showed that additives forming thick boundary films can enhance pitting life, supposedly by reducing the severity of asperity interactions which in turn reduced the rate of micro-crack initiation.

However, if one considers pitting studies regarding base oils, it can be seen that fatigue life also is very sensitive to variations in the frictional stress developed in loaded macro contacts [24–26].

At the same time, numerous studies have shown that both AW/EP [27] as well as VM additives [28] can have large effects on load dependent frictional forces, especially for contact operating in the mixed lubrication regime. This possible correlation, that the effects of AW/EP and VMs on pitting, under certain conditions can be due to their influence on mixed friction seems to have been overlooked.

In the present study, this correlation has been investigated. A total of 18 oils are included; 16 of which are blended so that AW/EP and VMs additives control friction. The remaining two oils contain a commercial API GL5 additive package and are included as references.

To reduce the number of oils for the pitting studies, the frictional behaviour of the 16 experimental oils were measured using a ball on disc machine. The running conditions were set to span from the border of boundary/mixed lubrication up to very thin EHL oil films (this region is here summarised as the “thin-film” region). From these studies, two oils with interesting thin-film frictional behaviour were chosen for further studies together with the two GL5 oils. Their pitting performance was evaluated using a rolling four-ball setup. The results were compared to “near contact” temperatures, also measured in the rolling four-ball test to verify that their pitting performance correlate to their friction levels. To rule out the influence of other oil properties on pitting, the four oils were also carefully characterized in terms of various other physical properties that may affect pitting lives. A number of ball samples were also analysed using SEM to rule out influence of other factors.

This initial study serves to analyse a new mechanism by which additive chemistry can influence pitting. However, the exact mechanism that governs the measured friction is only briefly discussed; a more detailed analysis is left for later studies.

2. Material and methods

2.1. Test oils

A total of 18 oils were included in this study. 16 experimental oils (MO-B 1–16) were based on a Group III mineral base oil and the thin-film friction was varied by addition of additives. The blend matrix consisted of four different thio-phosphate based AW additives, four different sulphur based EP additives and two different types of viscosity modifiers (VM). These were added to the base oil in either a low or high concentration or not at all.

The first reference oil was based on the same Group III mineral base oil but contained a commercial API GL-5 additive package. The second reference used the same API GL-5 additive package but was based on a poly-alpha-olefin (PAO) base oil.

The GL-5 package included AW, EP and VMs of different types than in the 16 experimental oils. The GL-5 package also contained friction modifiers.

Since the polar AW and EP additives interact at the metal surfaces, the tribofilms formed will be governed by both [29]. None of the three types of VMs used contain functionalized groups and should have limited interaction with the steel surfaces. All AW and EP additives are metal free or “ashless”.

2.2. Thin-film friction characteristics

The frictional properties of all the 18 oils were characterised using a PCS ball on disc mini traction machine (MTM). It employs a highly polished steel disk (AISI 52100) in contact with a 19.05 mm diameter bearing steel ball (AISI 52100). Both the disc and the ball have a mirror finish with $R_a < 0.01$ μm. The steel disc is immersed in oil which is pulled into the contact during the test. Bulk oil temperature was maintained at 125 °C. The tests were run under a range of conditions, from boundary lubrication up to full-film EHL to investigate how the relative ranking of the oils varied. Mean entrainment speeds between 20 and 2000 mm/s and loads of 20, 35 and 50 N were used. Slide-to-roll ratio (SRR), defined as

$$\mathrm{SRR} = \frac{\text{sliding speed}}{\text{mean rolling speed}} = \frac{|U_1 - U_2|}{(U_1 + U_2)/2} \times 100\% \qquad [1]$$

(where U_1 and U_2 are the surface entrainment speeds) were varied from 2 to 70%. The SRR of the rolling four-ball test can be calculated to 0% in the region of the contact centre and $\pm \sim 10\%$ at the contact edges by using the equations developed by Krüger and Bartz [30]. Such a motion is not possible to replicate exactly but was approximated with fixed SRRs. The high contact pressure used in the rolling four-ball test is also not possible to replicate in the MTM.

2.3. Rolling four-ball tests

The rolling four-ball (RFB) test was originally designed to test the pitting life of oils and materials by simulating the combination of rolling and sliding experienced in angular-contact ball bearings [31]. The loads typically used in the test are substantially higher than those found in practice. Despite this, test results have been found to be reasonably reproducible and have in many instances been found to correlate well with full-scale test results and service experience for gears [30,32]. Similar experience has also been reported for rolling element bearings [31]. Experimental work has also shown that AW and EP additives form tribofilms on the contacting surfaces of the test specimens [25,33]. It is therefore reasonable to assume that conclusions drawn using the RFB test regarding effects of additives also have relevance and are meaningful for practical applications.

The tests were performed using a computer controlled Phoenix TE 92 HS four-ball test machine configured for rolling tests, as shown in Fig. 1. Three of the four balls are placed in a raceway in which they are free to roll (planet balls). During testing, these are pressed against and driven by the fourth ball (driving ball) which is fitted in a collet and mounted on to the drive spindle. With this setup, the lower balls run along a single track on the driving ball