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Influence of PMA on the anti-scuffing properties of AW/EP additives

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1. Introduction

Scuffing is becoming a common failure mode in gears and bearings. It has been shown that AW/EP additives are effective in preventing scuffing, but only if they are able to form a thick tribofilm before encountering severe scuffing-type conditions. This study has employed a contra-rotating, step-sliding speed scuffing test to explore the impact of PMAs on the ability of ZDDP to prevent scuffing when subjected to immediately severe conditions. It is found that some PMAs can greatly enhance the anti-scuffing performance of ZDDP. They do this by forming thick, adsorbed boundary films that can withstand high speed sliding conditions and protect the rubbing surfaces long enough for latter to generate tribofilms [1].

2. Test methods

A step-sliding speed scuffing test based on contra-rotation using MTM-SLIM has been employed to observe concurrently tribofilm thickness and the onset of scuffing [2,3]. As shown in Table 1, after the running-in stage, the main step-speed sequence was carried out. Each sliding speed stage lasted 30 s during which the entrainment speed was held constant at 0.2 m/s. In most tests, this sequence started from an initial sliding speed of 0.1 m/s or 2.0 m/s, and this was increased in increments of 0.1 m/s until scuffing occurred or the maximum possible sliding speed value of 5.0 m/s was reached by increasing slide-roll-ratio (SRR). The effect of various PMAs in a GTL base oil and GTL+ ZDDP solutions was studied. All blends were formulated to have a KV of 4.1 mm2/s at the test temperature of 100 ºC by controlling the GTL type and the dosage of the polymers. The corresponding dynamic viscosity at the test temperature of 100 ºC was 3.2 cP. At the entrainment speed of 0.2 m/s used in the main test sequence, the calculated theoretical lambda ratio (ratio of EHD film thickness to composite surface roughness) is ca. 0.5, and thus to mixed lubrication conditions.

Table 1 Scuffing test conditions using MTM

	Running-in stage	Test stage	Rest stage
Test load (N) (Max. Hertzian Pressure (GPa))	20 (0.80)	45 (1.05)	Unload the ball from the disc and load it against a glass flat under stationary contact to capture a SLIM image
Entrainment speed (m/s)	0.003	0.2	
Sliding speed (m/s)	0.01	Test type1: 0.1, 0.2, 0.3… 5.0 Test type2: 2.0, 2.1, 2.2… 5.0 Test stopped when scuffing occurs	
Duration (s)	600	30	30
Test temperature (ºC)	100		

3. Results

3.1 Effect of PMA on Scuffing

The scuffing performance of ZDDP-free PMA solutions was studied for tests starting at 2.0 m/s sliding speed. Fig. 1 shows the variation of friction during the main step-speed sequence after running-in. PMA2, D-PMA3, D-PMA5 film-PMA8, OCP and GMO solutions gave scuffing immediately after the tests started. By contrast, PMA1, D-PMA4, comb-PMA6 and D-comb-PMA7 slightly delayed scuffing onset above 2.0 m/s. Note that since ZDDP was not present to form a solid-like tribofilm, observable tribofilms from these four oils were not seen in SLIM images.

Fig. 2 shows how friction coefficient varied in the test sequences for twelve ZDDP-containing lubricants. GTL4+ZDDP and GTL3+ZDDP with PMA2, D-PMA3, D-PMA5, film-PMA8, OCP and GMO all gave scuffing immediately after the tests started at 2.0 m/s sliding speed. By contrast, addition of PMA1, D-PMA4, comb-PMA6 and D-comb-PMA7 to GTL3+ZDDP prevented scuffing up to the maximum sliding speed tested of 5.0 m/s. |It is noteworthy that these four PMAs are the ones that enabled ZDDP to form a tribofilm and prevent scuffing up to 5.0 m/s sliding speed. These PMAs appear to form adsorbed films that

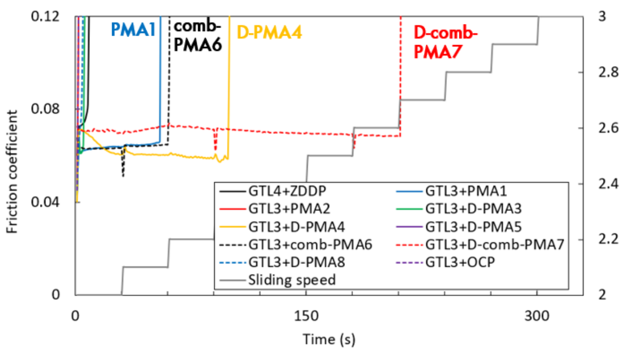

Fig. 1 The effect of PMAs on friction coefficient in GTL3. The initial sliding speed was 2.0 m/s.

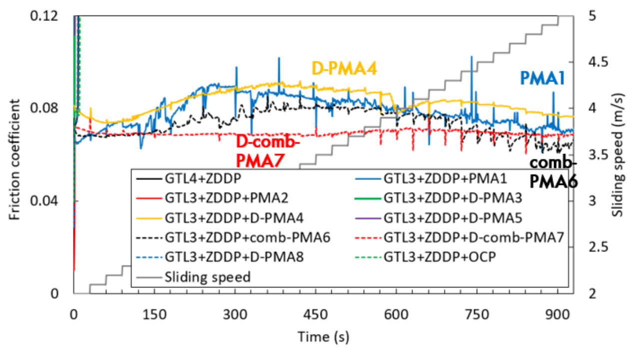

Fig. 2 The effect of PMAs, OCP and GMO on friction in ZDDP solutions. The initial sliding speed was 2.0 m/s.

provide enough protection to enable ZDDP to form a tribofilm at high sliding speeds.

3.2 Oil film thickness of PMAs

The EHD film-forming properties of the test oils were measured at 100 ◦C using optical interferometry (EHD2, PCS Instruments). Oil film thickness was measured using a steel ball/glass disc tribopair. Fig. 3 shows measured oil film thicknesses at 0 % SRR and 150 % SRR. At pure rolling condition, aside from GTL+ZDDP and GTL+ZDDDP+OCP, all oils form boundary film at very low speed to have over 10 nm oil film thickness at 10 mm/s. At 150 % SRR, GMO, PMA2 and PMA8 no longer formed a thick boundary film and behaved very similarly to GTL4, while at 450 % SRR PMA3 was no longer able to form a boundary film. The figure of test result at 450 % SRR is not shown here, but the remaining PMAs, D-comb PMA-7, D-PMA5, comb-PMA6, PMA1 and D-PMA4 all continued to form a boundary film of between 10 and 15 nm thickness. It is noteworthy that four of these PMAs (all except D-PMA5) were the ones able to extend the scuffing performance of ZDDP. Test at 250 % and 350 % SRR gave similar response to that at 150 % SRR, while it was not possible to test at 550 % SRR without damaging the glass disc coatings. The results show that the boundary film forming properties of PMAs are influenced by the degree of sliding, and thus the shear stress experienced by the film in the contact.

3.3 Mechanism

Based on the results in this study, the relevant mechanism by which scuffing is prevented in PMA blends is suggested. At the start of test at 2 m/s, PMAs whose boundary films are able to survive this high sliding speed, i.e. PMA1, D-PMA4, comb-PMA6 and D-comb-PMA7, provide a thick boundary film at the initial phase of test where otherwise a protective tribofilm is absent since a certain rubbing time is required to form the latter. This alleviates the asperity contacts, reducing temperature at surfaces and results in prevention of scuffing. Based on scuffing results of PMA solutions without ZDDP boundary film, adsorbed PMA boundary film partially or fully collapsed at sliding speeds slightly above 2 m/s, but when ZDDP was present this had already formed 5-10 nm of tribofilm and this gave enough surface protection to prevent scuffing. The role of PMA at higher sliding speed is unclear, but some adsorbed PMA is still likely to be present on the tribofilm even up to the highest sliding speed. Regardless of such PMA adsorption, as sliding distance increases, ZDDP tribofilm becomes thick enough to protect the sliding surfaces until the end of the tests.

4. Conclusions

The impact of PMAs in a ZDDP solution on scuffing has been studied using a test method based on contra-rotation and a step-sliding speed sequence. The results show that some PMAs markedly improve the anti-scuffing performance of ZDDP. They do this by adsorbing on steel and tribofilm surfaces to form thick boundary lubricating films. These are then able to protect the surfaces long enough for ZDDP to react with the rubbing surfaces to form protective tribofilms. It is found that all the PMAs tested are able to adsorb to form thick boundary films on surfaces but only some of these are able to survive high speed sliding conditions; these latter PMAs are the ones that can augment the anti-scuffing properties of ZDDP. The insights presented here should help with the design of low viscosity lubricants that are effective in controlling scuffing by optimizing both the boundary oil film and the tribofilm.

5. Reference

[1] M. Ueda, A. Kadiric, H. Spikes, Influence of PMA on the anti-scuffing properties of AW/EP additives, Tribol. Int. 174 (2022) 107756.

[2] B. Peng, H. Spikes, A. Kadiric, The Development and Application of a Scuffing Test Based on Contra-rotation, Tribol. Lett. 67 (2019) 1–25.

[3] M. Ingram, C. Hamer, H. Spikes, A new scuffing test using contra-rotation, Wear. 328–329 (2015) 229–240.

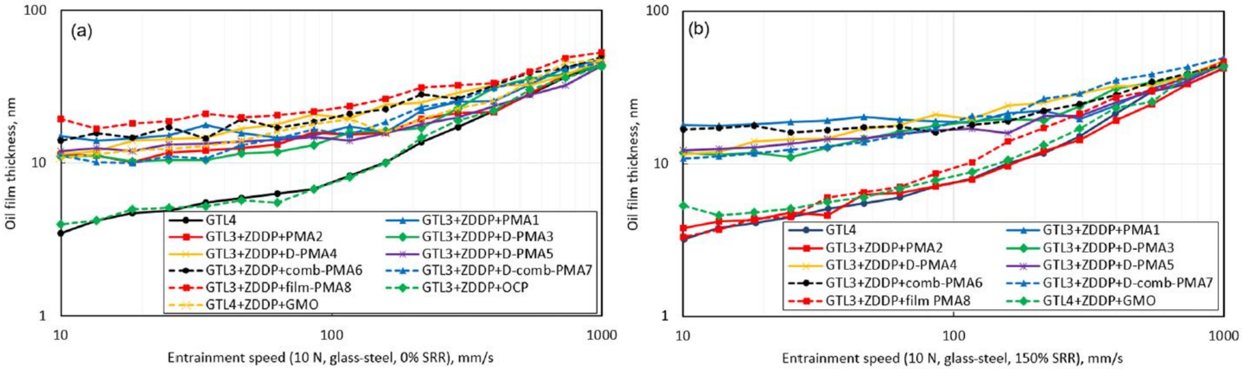

Fig. 3 EHD oil film thickness of PMAs, OCP and GMO in ZDDP solutions using glass disc-steel ball at 10 N with (a) 0 % SRR and (b) 150 % SRR