THE EFFECT OF ANTI-WEAR ADDITIVES AND SURFACE ROUGHNESS LAYOUT ON RUNNING-IN OF STEEL SURFACES

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ABSTRACT

The topography and structure of the surface develops during the lifetime of the component due to local plastic deformation, wear, and the formation and removal of deposited solid films. Sliding/rolling tests were carried out to investigate the influence of a ZDDP anti-wear additive on the change of surface roughness during running-in for different roughness and topography orientations. It was observed that for unidirectional finish the initial rate of formation of the tribofilm was greater, but its final thickness was lower than for isotropic finish. Surface topography measurements suggested that ZDDP postpones the running-in of rubbing rough surfaces. For longitudinal surface finish asperity smoothing was observed to be locally more prominent than for transverse finish, thus creating better surface conformity.

Keywords: running-in, anti-wear additives, ZDDP, roughness, micropitting

INTRODUCTION

Running-in is a transition from a non-equilibrium state of a rubbing system to a steady state in the initial period of the contact process [1]. It involves changes on the surfaces or just under them, which can be observed as a variation of system properties, such as wear, roughness and friction, eventually achieving and maintaining their constant levels.

Altering a single factor during running-in can have a significant impact on the long-term performance of the system. It is known that the presence of anti-wear additives such as ZDDPs can lead to a high rate of micropitting erosion, e.g. in gear teeth. Benyajati [2] suggested that ZDDPs, can prevent or postpone effective running-in of contacting surfaces, preserving the relative surface roughness and consequently maintaining the severity of stress and strain in the extreme surface, leading to micropitting damage.

The aim of the work described in this paper is to investigate the influence of ZDDP on the change of surface topography during running-in. Surfaces of different roughness and topography orientations ("layout") are considered.

EXPERIMENTAL SETUP

Tests were carried out using a Mini Traction Machine, in which a sliding/rolling contact is achieved between the test ball and the disc (Fig.1a). Spacer layer interferometry (SLIM) was used to measure sub-micron additive films on the specimens as they formed during the test. The principle is shown in Fig.1b and a more detailed description can be found in [3].

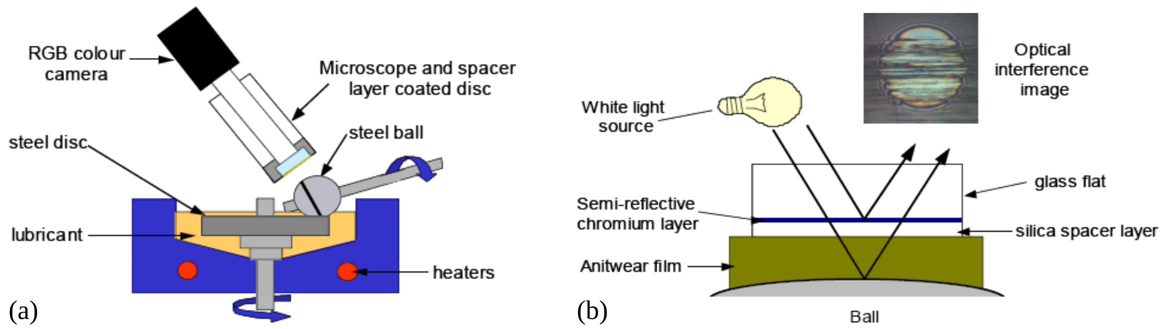

Fig. 1: (a) MTM-SLIM test setup. (b) Principle of spacer layer interferometry.

A Wyko NT9100 Optical Profiler was used for non-contact topography measurements of initial and run-in surfaces. To accurately observe differences between consecutive profiles, measurements were taken each time of the same region of the surface. This was done by marking disc surface outside the expected wear track area and choosing the starting point of a scan with respect to the mark. The preview function of the profiler allowed adjusting the position of the specimen so as to minimise rotation and shift with respect to the previous scan. Tests were run in set conditions of mean speed 2 m/s, 5 slide-roll ratio, 100°C and applied load of 50 N (maximum Hertzian contact pressure 1.12 GPa). API group I mineral oil (viscosity at 100°C = 2.72cP) with or without 1%wt secondary ZDDP was used as a lubricant. The upper specimens were 885HV AISI 52100 steel balls (R_q = 0.01 µm), lower specimens were 760HV AISI 52100 steel discs. Two types of disc surface finish were used: isotropic (R_q = 0.24±0.02 µm, Fig.2a) and unidirectional (R_q = 0.30±0.03 µm, Fig.2b,c). To examine the influence of surface roughness orientation on the running-in, two cases were considered: roughness transverse and longitudinal with relation to the rubbing direction. To examine both types of finish in a single test, discs were ground in one direction as is shown on Fig.2d.

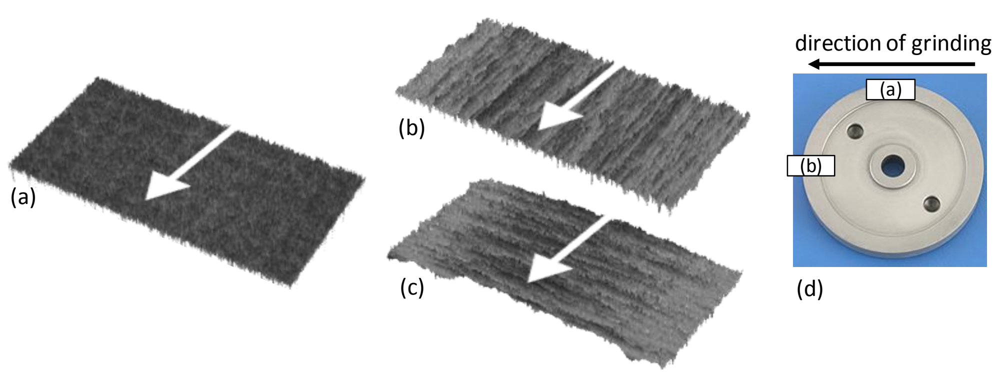

Fig. 2: Surface finish of test discs: (a) isotropic, (b) longitudinal, (c) transverse, (d) disc surface preparation. White arrows show the direction of rubbing during the tribotest.

RESULTS

For all tests conducted coefficient of friction stabilised within the first 100-120 min at the level of 0.07 for base oil tests and 0.09 for ZDDP, independently of the surface finish. Also, the fact that ZDDP presence causes an increase in friction in mixed lubrication conditions agrees with the literature [4]. However, it is known that the time to reach a steady state rate of wear is not necessarily equal to that to complete the frictional running-in period [1]. For this reason the test length was set to 240 min, to ensure the development of steady conditions.

Influence of the surface finish on tribofilm formation

Fig.3 shows the growth of average ZDDP film thickness with rubbing time (Fig.3a) calculated from optical interference images (Fig.3b). Images show that film coverage was quite uniform for unidirectional finish, whereas for isotropic finish uneven streaks of film can be observed. Measurements for film thickness calculation were taken from the central image part. It was observed that for isotropic finish the initial rate of film formation was lower, but the final, steady state film thickness was higher (110 nm) than for unidirectional finish (70 nm).

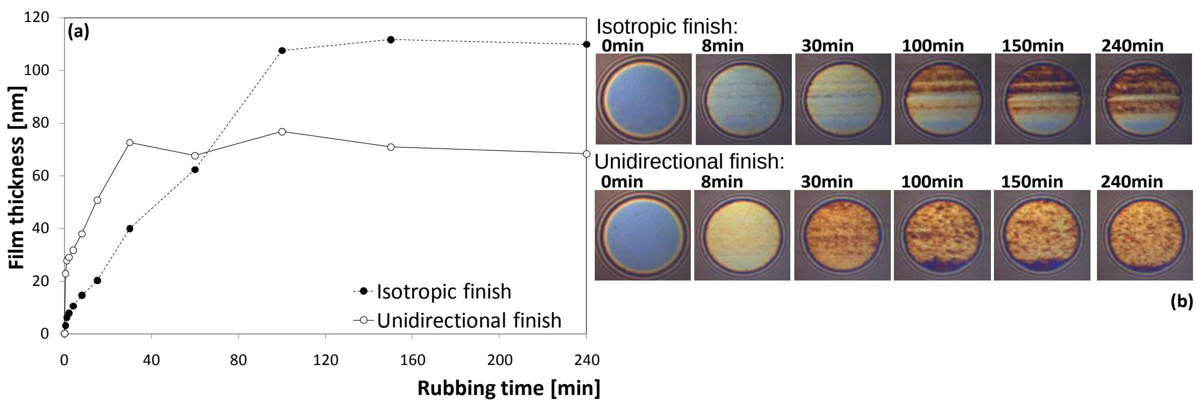

Fig. 3: ZDDP film growth: (a) as a function of rubbing time (b) interference images.

Reliability of optical topography measurement

It was initially observed that surface scans taken after tests with 1% ZDDP unexpectedly showed a higher level of wear and more roughness reduction. This can be best seen on the disc surface of isotropic finish (Fig.4a). However, Benedet et al. [5] performed topography measurements of a surface with a ZDDP tribofilm with an AFM and an optical profiler. The profiles obtained were substantially different, with the latter showing much more wear. It is well known that on rubbing steel surfaces ZDDP forms a solid-like film, which consists primarily of glassy phosphate, therefore its optical properties might influence the measurement. No further insight into this problem has been reported yet.

To establish the extent of this error, tribofilm was removed from the surface using a solution of EDTA, as described in [6], and a surface profile taken again of the same area. It can be seen (Fig.4b) that after ZDDP film removal the worn surface profile shows much less wear and roughness change.

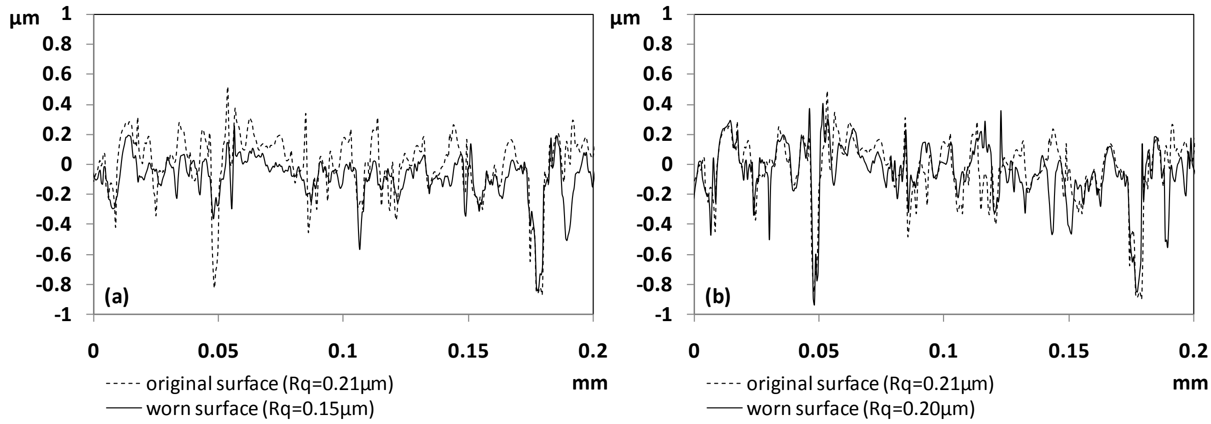

Fig. 4: Comparison of initial and final line profiles taken along the wear track on disc surfaces of isotropic finish: (a) with ZDDP film present on the surface, (b) after film removal. R_q- root mean square roughness.

To evaluate this difference quantitatively, wear volume observed in both cases (with and without the tribofilm on the surface) was calculated. As the initial surfaces were rough and wear was mostly only on the asperity level, a novel method of wear calculation had to be used basing on the comparison of the 3D surface scans of initial and worn surfaces.

Firstly, the profiles were tilted into a horizontal position using a least square plane fitting in the selected areas outside the wear zone. Then the best overlapping position of the initial and worn surfaces was found by a cross correlation function. The position of the best fit of both surfaces corresponds with the maximal correlation coefficient. Finally, the wear volume was calculated as the difference between the initial and worn surface.

The calculated wear volume was found to be 5.66×10^4 $\mu m^3/mm^2$ for a measurement taken with ZDDP film present on the surface and 3.15×10^4 $\mu m^3/mm^2$ after film removal. It is clear that only profiles obtained after film removal can be accepted as correct.

Influence of surface roughness orientation on the running-in

It was observed that for base oil tests wear of the specimens of unidirectional finish was noticeably higher than when the additive was present (Fig.5). By comparison of profiles obtained before and after the test it is possible to observe smoothing of asperities as a result of running-in. All profiles shown were taken along the wear track. ZDDP tribofilm was removed with EDTA solution before the measurements.

Table 1 shows that as a result of running-in surface roughness in the wear track area became lower. Observed roughness reduction was lower when ZDDP additive was present in the oil. No clear influence of the initial of the surface topography on the change of R_q value was observed. All measurements shown in Table 1 were taken in the direction perpendicular to the grinding direction, so along the wear track for transverse and across for longitudinal finish. This was because R_q values vary a lot if measured along the grinding direction, making any reliable quantitative comparisons impossible.

The nature of unidirectional finish, i.e. linear rather than point features, makes it more difficult to relocate the surface examined with respect to the previously taken scan due to its sensitivity to angular errors. Therefore it was not possible to use an aforementioned wear calculation method in this case, as it needs the rotation errors to be very small.

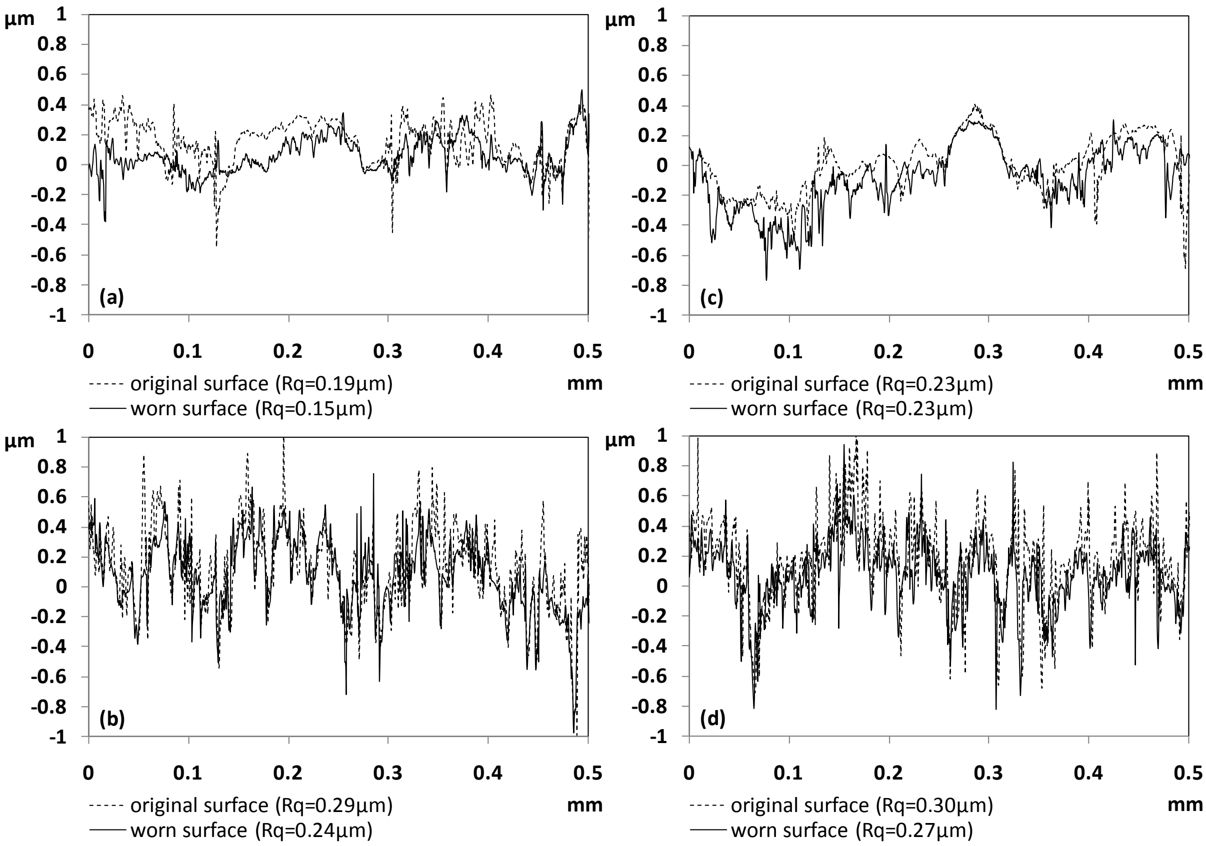

Fig. 5: Comparison of initial and final line profiles taken along the wear track on disc surfaces of isotropic finish: (a) base oil, longitudinal finish; (b) base oil, transverse finish; (c) 1% ZDDP, longitudinal finish; (d) 1% ZDDP, transverse finish.

Surface	**Initial** R_q [µm]	**Final** R_q [µm]	R_q **after film removal with EDTA** [µm]
longitudinal finish, base oil	0.30 ± 0.03	0.27 ± 0.03	-
transverse finish, base oil		0.26 ± 0.02	-
longitudinal finish, 1% ZDDP		0.25 ± 0.01	0.28 ± 0.01
transverse finish, 1% ZDDP		0.26 ± 0.01	0.28 ± 0.01

Table 1: Roughness changes observed for specimens of unidirectional finish.

DISCUSSION AND ANALYSIS

ZDDP film formation is dependent on the extent of direct solid solid contact during rubbing. Fujita et al. [7] observed that the lower the lambda ratio (λ, ratio of fluid film thickness to composite roughness R_q), the faster tribofilm growth and higher its final thickness. In their work, however, the fluid film thickness was varied while initial roughness was the same.

For tests described here, the smooth-body minimum fluid film thickness is predicted to be 28 nm. Composite initial R_q was 0.24 µm for isotropic, 0.30 µm for unidirectional finish (ball roughness was assumed to be negligible), which gives λ of 0.12 and 0.09, respectively. Therefore, for higher λ the initial rate of tribofilm formation was lower, which agrees with [7]. However, the final steady state tribofilm thickness was higher for higher (110 nm) rather than lower λ (70 nm). This shows that while the rate of film formation can be related to the value of λ, other factors contribute to the rate of its removal, such as surface roughness orientation. The faster tribofilm removal for unidirectional finish might be attributed to the presence of sharper transverse ridges, which did not wear-in as much as those of longitudinal finish, and can be a cause of more severe conditions favouring tribofilm removal.

R_q values shown in Table 1 indicate that the roughness decreased more for tests performed with base oil than when ZDDP was present and R_q did not differ substantially for different roughness orientations. However, when comparing profiles along the wear track, (Fig.5), it seems apparent that for longitudinal finish asperity smoothing is locally more prominent than for transverse finish, thus creating better surface conformity.

CONCLUSIONS

A study of the effect of a secondary ZDDP additive on the evolution of roughness during rolling-sliding contact has been carried out. This involved measurements of roughness and wear volume and of the thickness and growth rate of the ZDDP tribofilm. In order to accurately assess the wear volume, the tribofilm was chemically removed from the surface.

Results showed that the additive slowed the progressive smoothing of the rough surface that occurs during initial running. The growth rate and final thickness of the tribofilm was also influenced by the character of the pre-existing roughness.

The findings support the idea that anti-wear additives can inhibit running-in and postpone the development of steady conditions. This is consistent with earlier observations of the higher level of damage observed in micropitting experiments [2, 8] for ZDDP-containing lubricants

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