The effect of a ZnDTP anti-wear additive on the micropitting resistance of carburised steel rollers

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1. INTRODUCTION

Micropitting is a microscopic form of rolling contact fatigue and wear, which is most often found in ground, hard steel surfaces such as those in case-hardened gears. It is normally associated with concentrated rolling-sliding contacts under conditions where the lubricant film is rather thin compared to the height of the surface roughness.

Generally, micropitting consists of numerous small, shallow pits on the surface, each pit often having the characteristic dimension of some tens of micrometers. Despite the small size of individual pit, these pits together can form a large total area of damage so that the surface has a grey, matte appearance. For this reason, micropitting is also sometimes known as grey staining and frosting in the gear industry.

Micropitting, like other wear mechanisms, has a detrimental effect on the durability of the component. It can cause a significant material loss from the damaged surface. In gears, this can result in the loss of profile of the teeth, which may then generate an increase in noise, vibration, and dynamic loads. In more severe cases, it can even cause the total fracture of the gear teeth. Furthermore, the progression of micropitting may eventually result in large scale (macro-) pitting. It may also develop into other types of surface damage, such as scuffing.

Micropitting therefore represents a potentially severe failure mode. It has caused appreciable problems in service and has received considerable attention from tribology researchers [1-4]. Recently, a number of works have investigated the effect of lubricant chemistry on micropitting [5,6]. Cardis and Webster [6] showed that a number of additives described as 'anti-wear' promoted micropitting. However, no details of the additives used were given and the mechanism by which the presence of the additives led to micropitting was not investigated.

Here, the results of a study of the effect of lubricant composition are reported. A PAO base stock was tested on its own and with a ZnDTP anti-wear additive, which is a common constituent of engine and transmission oils. The experimental results showed that the anti-wear additive has an unfavourable effect on micropitting. A possible new mechanism that might account for the results is discussed. Some preliminary results from the present study were presented in [7].

2. TEST RIG

In the present study, a three-contact disc machine has been employed for the study of the effect of lubricants on micropitting. The test roller is a cylinder, of diameter 12.0 mm which is run against three counterface rollers ('rings') which have chamfered edges forming the 3.2 mm track width. Therefore, a *line* contact is generated between a roller and rings. In addition, both specimens have a circumferential finish at their outer diameters. A dip lubrication system is employed as a mean to supply lubricant into contacts. Furthermore, a loading method is provided by the use of a motorised ball-screw, acting through a loading arm. A schematic diagram of the test rig is shown in Figure 1, more details on test rig development and its features can be found in [7].

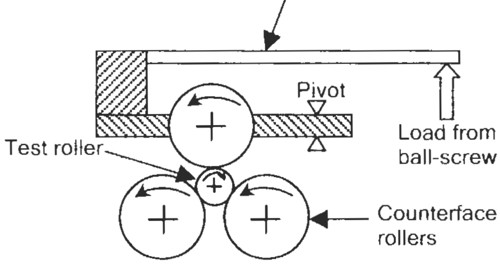


Figure 1. Schematic of test rig, showing the contact configuration and a principle of load application

3. EXPERIMENTAL METHOD

A test roller and three counterface rings are employed for each test. The general geometries of both roller and rings are shown in figure 2. Both specimens were manufactured from 16MnCr5 steel to DIN 17210, commonly used in gear industries. Both specimens were gas carburised and heat treated to the specified hardness of 660-700 HV and 730-770 HV for roller and ring respectively with minimum case depth of 0.9 mm for both specimens. The average roughness of each specimen was $R_a = 0.35$ μm and 0.5 μm for roller and rings respectively.

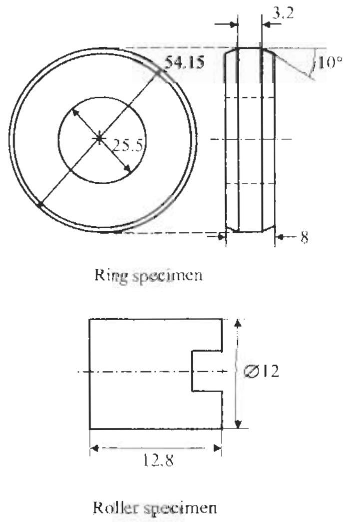


Figure 2. General geometries of ring and roller specimen (dimension in mm, not to scale)

A poly-alpha-olefin (PAO) base stock was employed in this work. The viscosity of the lubricant was 13.7 cP at 40 °C and was 2.9 cP at 100 °C. The base stock was tested on its own and also with anti-wear additive present. The additive use in this paper was a secondary C_6 zinc dialkyl-dithio-phosphate (ZnDTP) dissolved in a high-viscosity base. The treat rate was 1.3% to give 0.1% Phosphorus by mass.

For all tests, the roller, the rings, and assembly components including the damper rings were ultrasonically cleaned in solvent before mounted on the shafts. After assembly, the test started by heating up the test oil to the specified temperature. Next, the load was gradually applied at a uniform rate over 5 minutes. When the load reached the required value, the electric motors applied the required rolling and sliding speeds to roller and rings. The rig would then run for a pre-determined period. Except where stated, all the tests in this paper were carried out under the same operating condition, which was 70 °C bulk oil temperature, under a Hertz pressure of 1.7 GPa, and a slide-roll ratio ($\Delta v / \bar{v}$) of 5.2 % (roller surface slower) with $\bar{v}$ = 3.15 m/s. (Here, Δv is the difference in speed and $\bar{v}$ is the mean speed of the surface with respect to the contact). Under these operating conditions, using a simple thermal model [8], the surface temperature at the inlet of contact was predicted to be 76.2 °C. At this temperature, the corresponding viscosity and pressure viscosity coefficient of the base stock was 4.77 cP and 11.2 GPa^{-1} respectively. The corresponding smooth-body minimum film thickness was predicted to be 61 nm.

The tests were stopped at pre-determined intervals for specimen inspection. The inspection process involved measuring the surface profile across the wear track and taking images of the surface using a Form Talysurf Series 2 stylus profiler with 0.8 mm cut-off length and a digital microscope respectively. For the surface profile measurement, four measurements were made in axial direction of the roller across the wear track.

An example of a worn surface profile is shown in figure 3. It can be seen that the wear is greater near the edges of the track. This may be due to the edge-pressure from the chamfer corners of the rings. Only the central part of the running track was used for the wear determination.

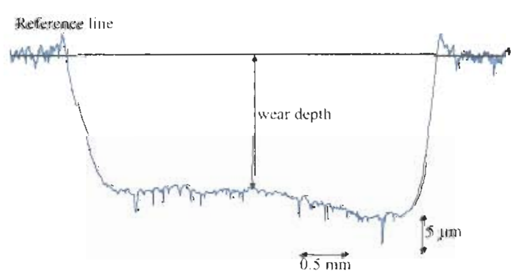


Figure 3. An example of worn surface profile, showing determination of effective wear depth

The loss in diameter of the roller against test time was employed as the means to evaluate micropitting wear. From the profile in figure 3, the wear depth was estimated by fitting a reference mean line through the unworn surface profile. The distance between this reference line and the central part of wear track was taken as the wear depth.

4. RESULTS

4.1 Tests with PAO base stock

Resulting wear curves from the tests with PAO on its own are shown with a dashed line in figure 4. There are two plots corresponding to each of two tests under the same conditions. The appearance of the wear track at the end of the test (4.4 million contact cycles) is shown in figure 5(a) and 5(b).

For the tests with PAO only, it was found that micropitting wear did not occur on the roller specimen but there were a few surface cracks. However, despite the absent of micropitting, a little initial wear was presented. It can be seen from the wear curve that the roller was already worn at an early stage of the test but the progression of wear soon stopped so that there was no further loss in diameter through out the rest of the test.

Upon closer inspection with the microscope, it was found that the surface generally had become fairly smooth with a few pits on it. There was also a newly formed layer, which appeared to be dark purplish and bluish in colour, on the surface of the worn roller.

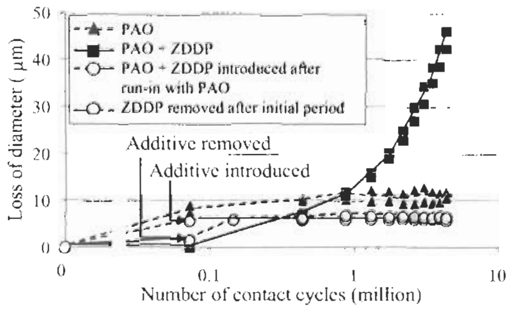
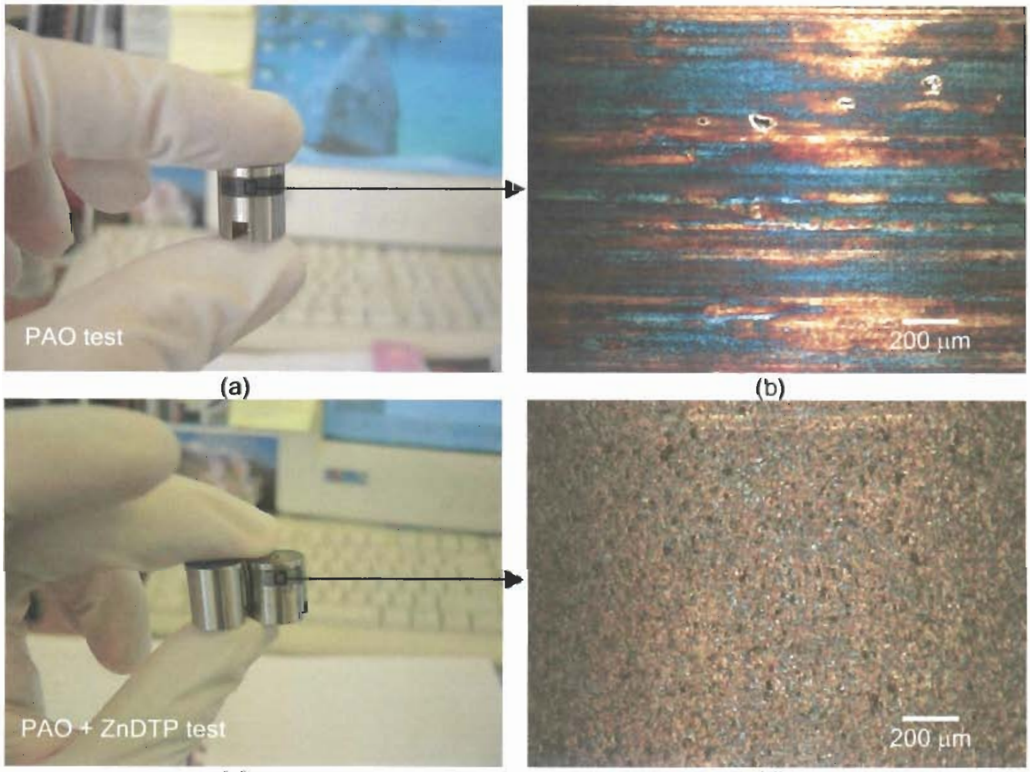


Figure 4. Evolution of wear as a function of contact cycles during the tests



(a) (b) (c) (d)

Figure 5. Images of the tested roller after 4.4 millions contact cycles (5 hours), (a) general appearance from PAO test, (b) microscopic image shows no micropitting, (c) general appearance from PAO + ZnDTP test compared with untested roller, (d) microscopic image shows micropitting covers the entire running track

4.2 Test with PAO + ZnDTP

For the test when 1.3% ZnDTP were added into the PAO, extensive micropitting occurred on the roller specimen. The resulting wear curves are shown in figure 4 with a solid line. They show a fairly steady wear rate. The general appearance of the micropitted roller is shown in figure 5(c) along with a normal roller for comparison. It can be seen that the micropitted specimen has a grey and matte appearance on the wear track compared to a normal surface. A microscopic image of the micropitted surface is shown in figure 5(d); numerous micropits on the surface can be seen clearly from the image

The transverse roughness of three counterface rings was measured using a stylus instrument. The roughness of the counterface was found to decline gradually during the test. This is shown graphically in figure 6 where each point represents the averaged value of R_a roughness over three rings. The plots show a similar trend between two sets of tests such that there was a significant drop in the roughness value at an early stage followed by a very slow decline for the rest of the test. However, the main difference between the results is that when ZnDTP was present, the roughness declined more slowly as can be seen from the plot.

Apart from carrying out the tests with ZnDTP under those operating conditions explained in section 3, an additional test was carried out with the same additive in order to examine the effect of slide-roll ratio on micropitting. In this test, $\Delta v / \bar{v}$ was increased to 15% and the bulk oil temperature was reduced to 55 °C while the other parameters were kept the same as the previous tests. Under these operating conditions, the thermal model [6] predicted a surface temperature at the inlet of contact to be approximately the same as the previous tests and hence a similar smooth-body minimum film thickness.

By increasing $\Delta v / \bar{v}$, it was found that extensive micropitting also occurred on the roller specimen. The resulting wear curve is shown in figure 7(a) together with those from lower $\Delta v / \bar{v}$ tests. The curve shows a higher wear rate compared to the lower $\Delta v / \bar{v}$ tests. Furthermore, the general appearance and microscopic image are similar to those shown in 5(c) and 5(d) respectively. For the transverse counterface roughness, the measured values are shown in figure 7(b). The plot also shows a similar trend to those of lower $\Delta v / \bar{v}$ tests.

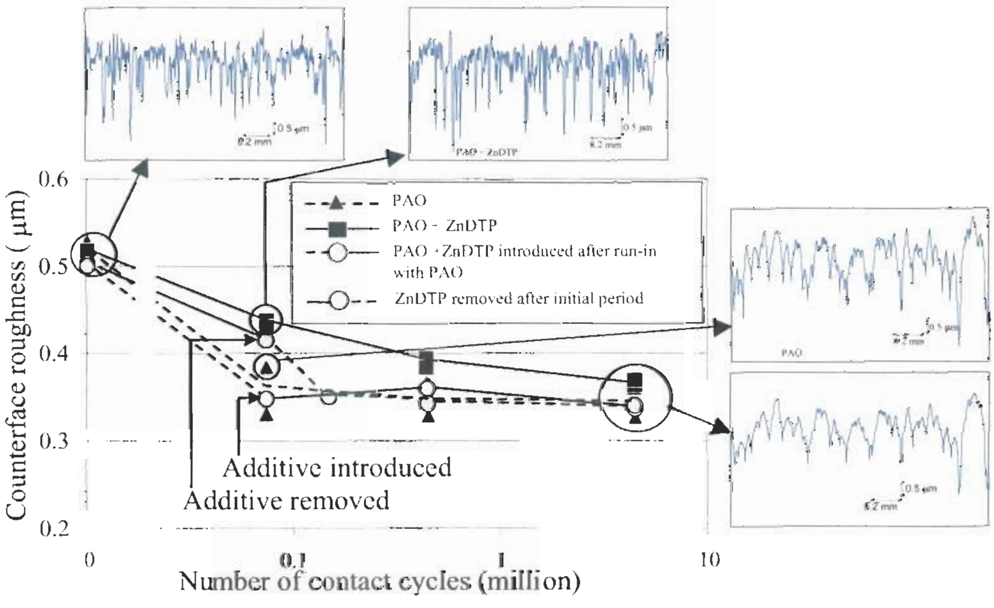
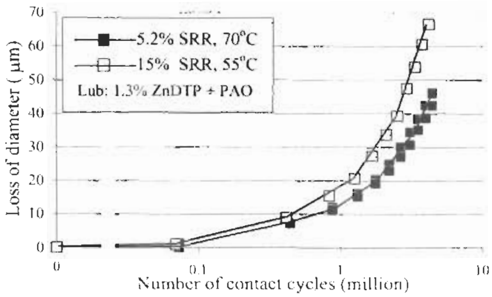


Figure 6. Variation of counterface transverse roughness (R_a) during the test for PAO only and with ZnDTP tests. In general, the roughness of the counterface decline gradually during the test. Typical surface profiles before, during, and after the test are shown on the top and on the right hand side of the plot respectively.



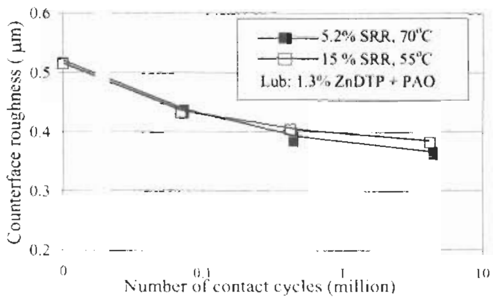


Figure 7. Effect of slide-roll ratio ($\Delta v / \bar{v}$) on micropitting, (a) resulting wear curve, (b) variation of counterface transverse roughness (R_a)

4.3 Effect of running-in with base stock

Another test was carried out in order to determine the cause of the difference between the results of base stock only and with ZnDTP. In this test, the specimen roller and counterface rings were run with PAO only, for 5 minutes (73,000 contact cycles). After the routine inspection on the specimens, ZnDTP additive was introduced into PAO and the test was then carried on in the same manner as the previous ones.

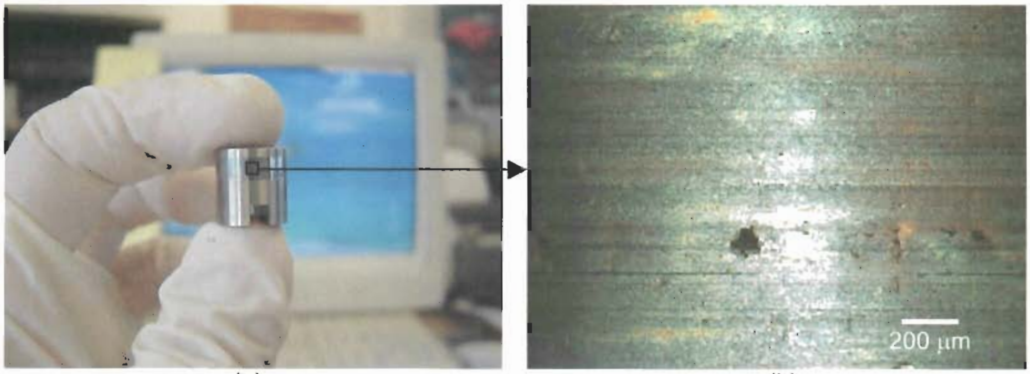
The wear curve obtained from this 'additive introduced' test is shown in figure 4. On the graph, the dashed line represents the period when only PAO was present whereas the solid line indicates the period when ZnDTP had been introduced into the PAO. The curve shows that a little wear occurred at an early stage, and then stopped. In figure 8, the microscopic image of the wear track shows a generally smooth surface with *no micropitting*. A light bluish layer can also be seen on the surface. Furthermore, the transverse roughness of the counterface was measured in the same fashion as the previous tests. The measured surface roughness is shown in figure 6. The plot shows a similar trend to the results from section 4.1.

4.4 Effect of removing ZnDTP

A further test was carried out in a reverse fashion. This test started by running the specimen roller and counterface rings with PAO containing ZnDTP for 5 minutes (73,000 contact cycles). After that the test lubricant was changed to PAO only, for the rest of the test.

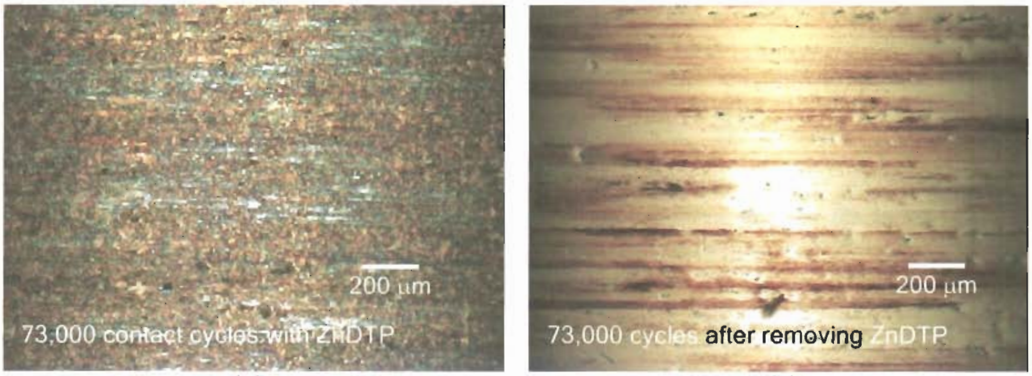
The wear curve obtained from this 'additive removed' test is shown in figure 4. As in the previous sections, the solid line represents the period when ZnDTP was present whereas the dashed line shows the period when the test lubricant was PAO only. The curve shows a very little wear, less than that in 'additive introduced' test, at an early stage of the test when ZnDTP was present. Then, immediately after removing the additive, there was further small amount of wear before its progression stopped. Figure 9(a) and (b) show microscopic images of the wear track before and shortly after removing ZnDTP respectively. It can be seen that figure 9(a) indicates an onset of micropitting on the surface of a roller after 73,000 contact cycles when ZnDTP was present. After removing ZnDTP and further 73,000 contact cycles, the microscopic image shows a generally smooth surface with only a few micropits as shown in figure 9(b).

Moreover, the general and microscopic appearances of the roller at the end of the test show *no micropitting* and are comparable to those shown in figure 8(a), (b) for 'additive introduced' test. The transverse surface roughness of the counterface was measured in the same way as the other tests. The plot is shown in figure 6. It can be seen from this plot that the surface roughness declined in the same fashion to those in section 4.2 when ZnDTP was present. However, there was a significant drop in a surface roughness after the additive was removed from the test and the trend then resembled those from section 4.1. The significance of the results of the 'additive introduced' and 'additive removed' test will be discussed later in section 5.



(a) (b)

Figure 8. Images of tested roller after the test (4.4 millions contact cycles or 5 hours), in which ZnDTP was added after short test period with PAO only, (a) general appearance shows shiny, bluish surface of wear track, (b) microscopic image shows no micropitting with smooth surface.



(a) (b)

Figure 9. Microscopic images of tested roller from the test, in which ZnDTP was removed after short test period, (a) roller surface after short period test with ZnDTP illustrated an onset of micropitting, (b) roller surface after the same short period test following a removal of ZnDTP showed no micropitting with smooth surface.

4.5 Test with formulated oils

In this section we present results from the tests on two commercial formulated oils that contain anti-wear additives. The two oils were an ester-based aviation turbine lubricant, which is also used in some high-speed gearing applications and a mineral-based gear oil.

The tests were carried out under conditions such that the predicted EHL (smooth body) film thicknesses were similar to those in the other tests reported here. Since the oils had different viscosities, this was achieved by modification of the bulk temperature and the entrainment speed. The results are shown in Figure 10 in which the viscosities are reported at the predicted inlet temperature.

Both oils showed results similar to the tests reported here for the PAO + ZnDTP lubricant, although the turbine oil gave the greater wear.

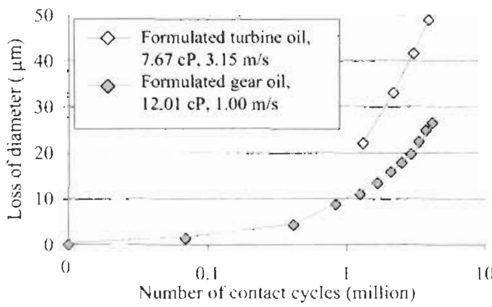


Figure 10. Wear curve from tests with two different formulated oils containing anti-wear additive. The viscosity given is corresponding to the inlet temperature for each test. The speed shown is the entrainment speed. Slide roll ratio was 5.2% in both cases.