Effect of surface roughness on friction behavior of steel under boundary lubrication

Kazuma Yamaguchi[1], Chiaki Sasaki[1], Ryo Tsuboi[1], Mark Atherton[2], Tadeusz Stolarski[1], Shinya Sasaki[1],

[1]Department of Mechanical Engineering, Tokyo University of Science, Japan

[2]School of Engineering and Design, Brunel University, UK

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Abstract:

The friction behavior of textured steel surfaces, the roughness of which were prepared by grinding and polishing, were evaluated by using a reciprocal sliding tester under lubrication with PAO, PAO+ZnDTP and PAO+ZnDTP+MoDTC. Friction coefficients on the smooth surfaces showed higher values compared to those on the rough surfaces. For lubrication incorporating PAO and PAO+ZnDTP+MoDTC, friction coefficients on both the smoothest and the roughest surfaces decreased with sliding time. On the other hand, friction coefficients between these extremes decreased with sliding time. In this paper, the effects of surface roughness on friction behavior are discussed.

1. Introduction

It is desirable to improve the efficiency of mechanical systems, particularly regarding friction loss, which accounts for up to 48% of the developed energy consumption in a reciprocating internal combustion engine [1]. Even the powertrain friction losses of hybrid and electric vehicles cannot be ignored. Thus, it is important to know the influence of contact surface profile on lubrication conditions in order to reduce the friction loss. According to Rabinowicz [2], the relationship between friction coefficient and surface roughness is not simple linearity; hence, a smoother surface does not guarantee a lower friction coefficient. Fredrik [4] confirmed similar results. It is also important to consider the direction of grooves ('lay') on the surface, as it is known that lubricants can be trapped within the grooves, resulting in hydrodynamic effects and subsequently lower friction coefficients [5]. Moreover, they explain why, when the slider reciprocates parallel to the direction of lay on the surface, friction coefficients are higher than those in perpendicular sliding.

In the case of boundary lubrication, oil film thickness is required to protect solid contacts when the surface roughness becomes larger. Thus the friction coefficient increases as the rate of solid contacts increases due to greater surface roughness. On the other hand, wear grains trapped in the surface roughness can enhance the lubrication mechanism [6]. Furthermore, it is reported that new surfaces produced by shearing, chemically react to components of the additives in lubricants. [6]. Surface roughness is one of the important parameters that defines the tribological properties of a sliding surface and so it is important to investigate the influence of surface roughness on friction, wear, running-in behavior, and resultant surface damage **Error! Reference source not found.**. Therefore, it is expected that a suitable surface roughness is exists for a given lubricating surface. However, standard parameters of surface roughness do not describe contact surfaces sufficiently, with completely different surfaces sharing similar parameter values [7]. This study investigates the effect of surface roughness on the friction behavior of steel specimens under boundary lubricating conditions.

2. Experiments

2.1 Specimen and lubricant detail

Twelve disk-shaped test specimens made from a bearing steel (SUJ2, ANSI 52100), with a size of φ25mm and a thickness of 8mm, were given surface roughness ranging from R_a 0.05 to 0.08 μm by grinding and polishing with different grades of sand paper (#320, #500, #1200 and #2400) and diamond powders (1μm and 3μm), as shown in Table 1. The ball used to apply the friction force was 10mm diameter and had a surface roughness (Ra) of 0.017μm. Moreover, three kinds of lubricants were prepared by varying the additives ZnDTP and MoDTC within the poly-alpha-olefin (PAO) base oil. Thus, one lubricant contained PAO only; another lubricant contained PAO with ZnDTP added until there was 0.06% of Phosphorous by volume; and another lubricant contained PAO with ZnDTP added until there was 0.06% of Phosphorous by volume plus MoDTC added until there was 0.07% of Molybdenum by volume.

Table.1 Surface roughness of the disk specimens

Number	1	2	3	4	5	6	7	8	9	10	11	12
R_a[μm]	0.0055	0.0071	0.0114	0.0178	0.0185	0.0271	0.0281	0.0334	0.0355	0.0526	0.0720	0.0743

2.2 Tribological test

The sliding tests were carried out by using the reciprocating sliding tester (Optimol SRV),s illustrated in Figure 1, where the upper ball was loaded against a lower disk specimen. Before the sliding test, the specimens were cleaned with acetone and petroleum ether in an ultrasonic washer. Each of the sliding tests was conducted at a frequency of 50Hz, a stroke of 1mm, a temperature of 323K, a load of 50N and a sliding time of one hour. Friction coefficients were measured during the test. The surface roughness was measured after the sliding test. Each experiment was repeated three times under the same sliding conditions in order to verify the reproducibility of the experiments. The surface roughness was measured by confocal laser scanning microscopy (Olympus, LEXT-3500) before and after the sliding tests.

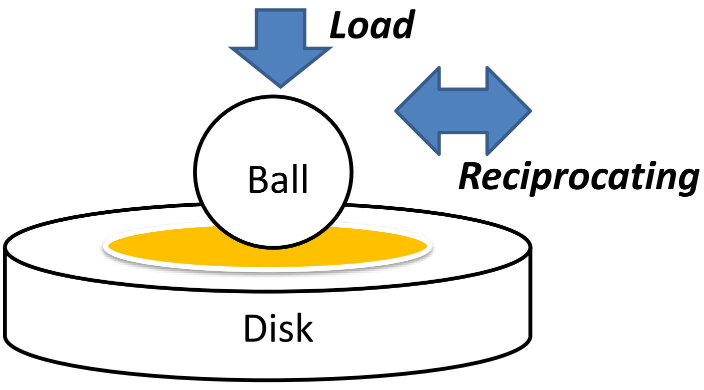
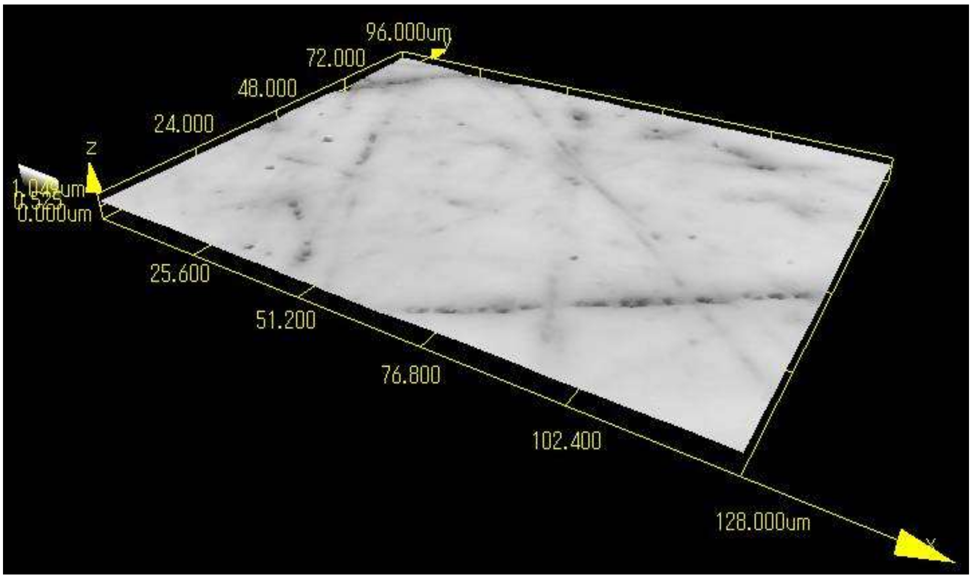


Figure 1. The test configuration under reciprocating sliding conditions using an SRV machine

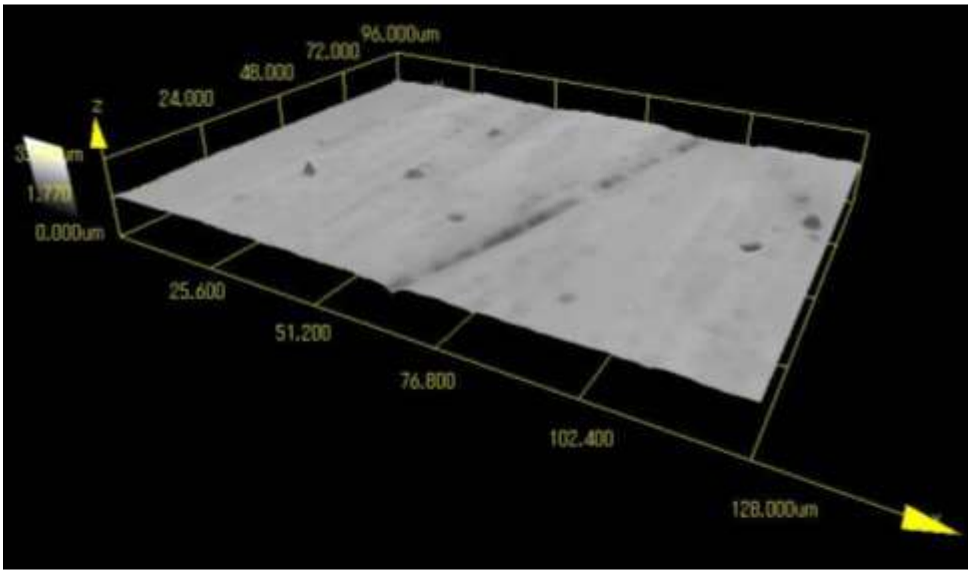
3. Results

Figure 2 shows the surface morphologies of a small area of a typical disk specimen, which was measured with

3D confocal laser microscopy before and after the sliding test. Ten measurements were taken of each surface before and after the sliding test and used to determine the surface roughness of each specimen.



(a)Before the test (R_a: 0.005μm)



(b)After the test (R_a: 0.036μm)

Figure 2: Surface morphologies of the specimens measured with a laser microscope

The relations between friction coefficients and surface roughness are shown in Figure 3, where the friction coefficients are an average taken over one-minute duration after five minutes into the test. For the rough surfaces having a value of R_a over 0.030μm, the friction coefficients with the PAO+ZnDTP lubricant were higher than those with the PAO lubricant. However, the friction coefficient for the PAO lubricant increases with decreasing surface roughness, indeed at low surface roughness the friction coefficient becomes higher than that for the PAO+ZnDTP lubricant. The friction coefficient for the PAO+ZnDTP lubricant remains almost constant regardless of the value of surface roughness. The friction coefficient for the PAO+ZnDTP+MoDTC lubricant remains much lower than those for the other lubricants, increasing with surface roughness to a maximum of 0.082 at R_a = 0.010

μm, and then decreasing slightly thereafter.

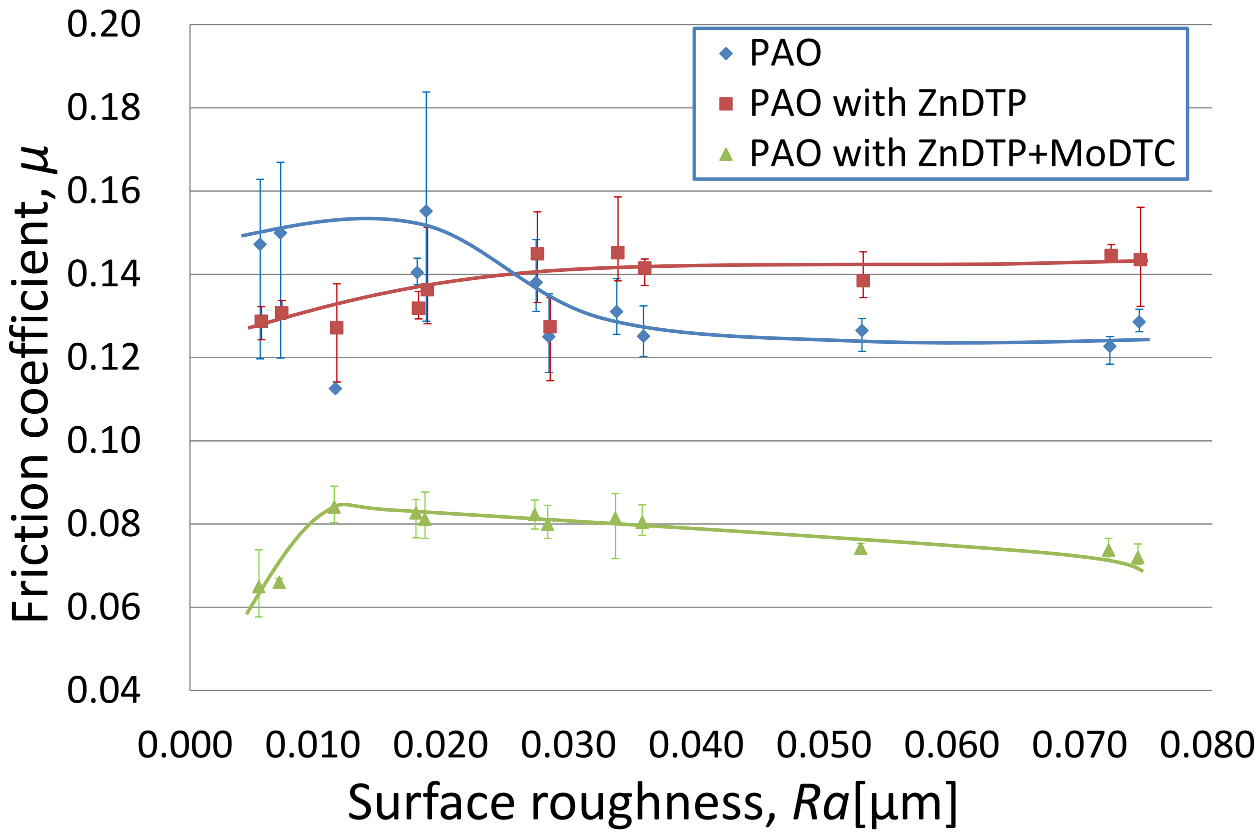


Figure 3: Effects of surface roughness on friction coefficients for three different lubrication conditions

The changes of friction coefficient over time for the PAO lubricant with different surface roughness regimes are shown in Figure 4. For the roughest surface (R_a = 0.0720 μm), the friction coefficient is larger at the beginning of the sliding test and then decreases with the progress of time. For the smoother surface (R_a = 0.0185 μm), the friction coefficient progressively increases. For the smoothest surface (R_a = 0.0178 μm), the friction coefficient slowly increases and remains similar to the roughest surface. These results are in contrast with general results, in which the rate of surface contact is high on the rough surface and so the friction coefficient is a high value; and the rate of surface contacts is low on the smooth surface and so the friction coefficient is a low value.

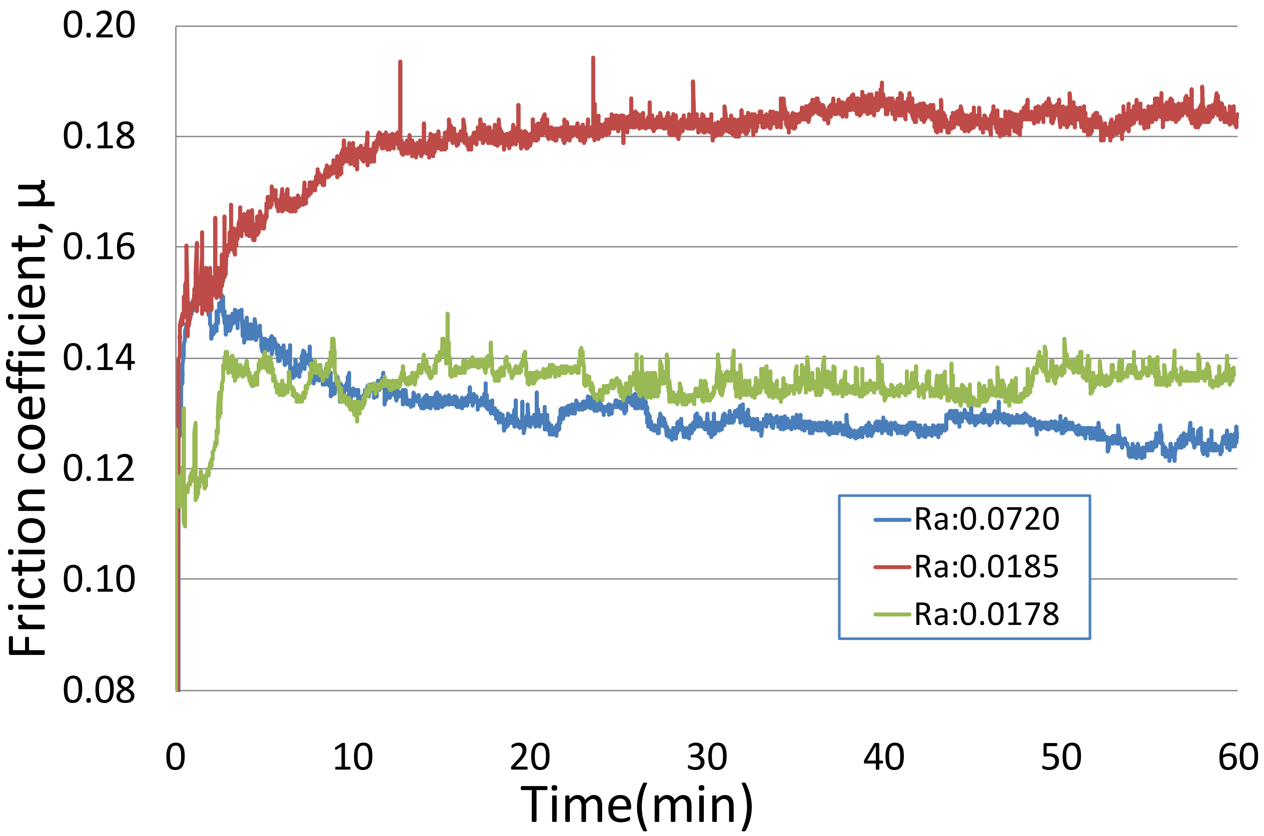


Figure 4: Changes of the friction coefficient for the PAO lubricant with progress of time, for three different initial surface roughness values (R_a)

Figure 5aFigure 5a shows changes of the friction coefficients for the PAO lubrication for each disk specimen at the start and at the end of the sliding test. Whereas at the start of the test these friction coefficient values were an average taken over one minute duration five minutes into the test; the end of the test values were determined as an average taken over one minute after fifty five into the test. For the smooth surfaces with an R_a value under 0.034 µm, most friction coefficients have lower values at the start of the test, except the friction coefficient for the R_a value of 0.0114µm. Meanwhile, for the rough surfaces with an R_a value over 0.034 µm, most friction coefficients decreases with the progress of the sliding time, except the friction coefficient for the R_a value of 0.0526 µm.

Figure 5aFigure 5b illustrates changes in the friction coefficient with the PAO+ZnDTP lubricant for each disk specimen at the start and at the end of the sliding test. For the rough surfaces with an R_a value over 0.017 µm, most friction coefficients showed lower values at the end of the test, except the friction coefficient for the R_a value of 0.0271 µm.

Figure 5c shows changes in the friction coefficient with the PAO+ZnDTP+MoDTC lubricant for each disk specimen at the start and at the end of the sliding test. For the smooth surfaces with an R_a value under 0.0071 µm and for the rough surfaces with an R_a value over 0.0526 µm, most friction coefficients showed higher values at the start of the test.

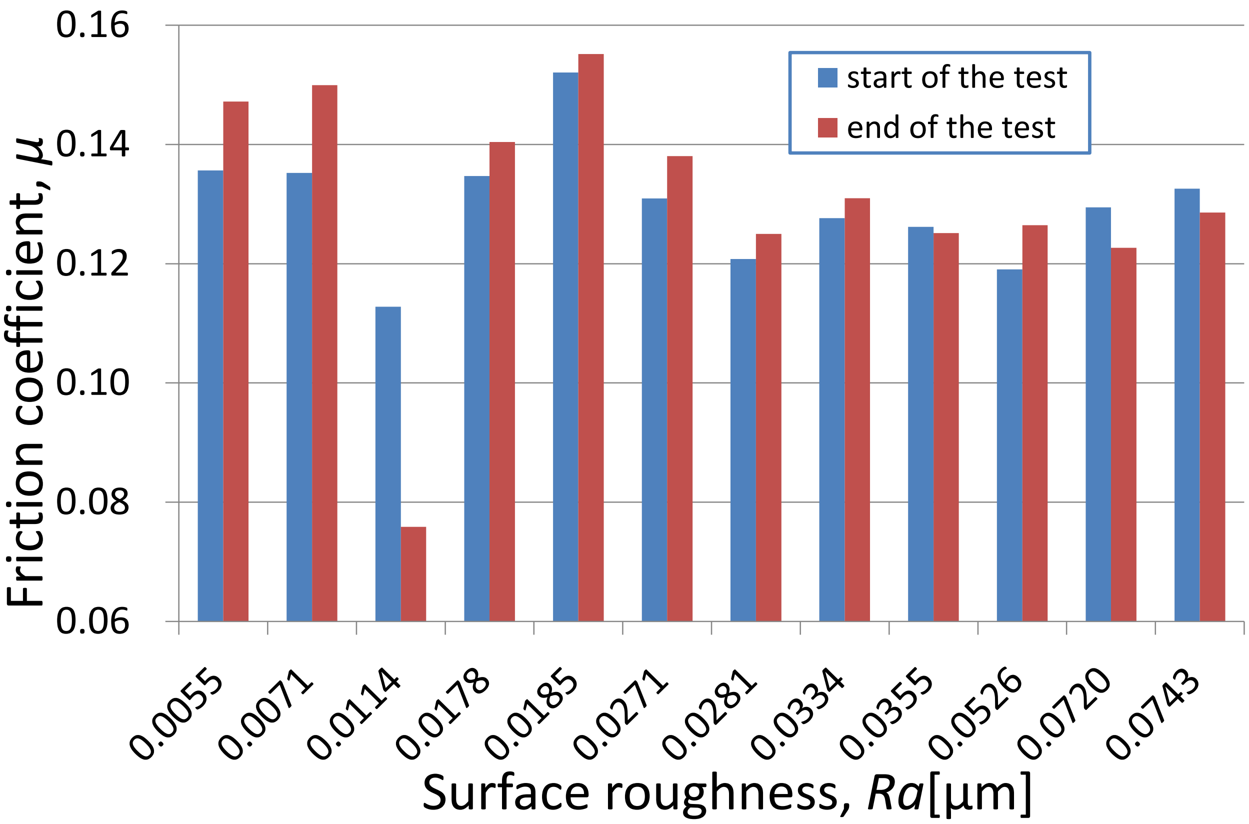


Figure 5a: Friction coefficients for the PAO lubricant at the start and the end of the sliding test

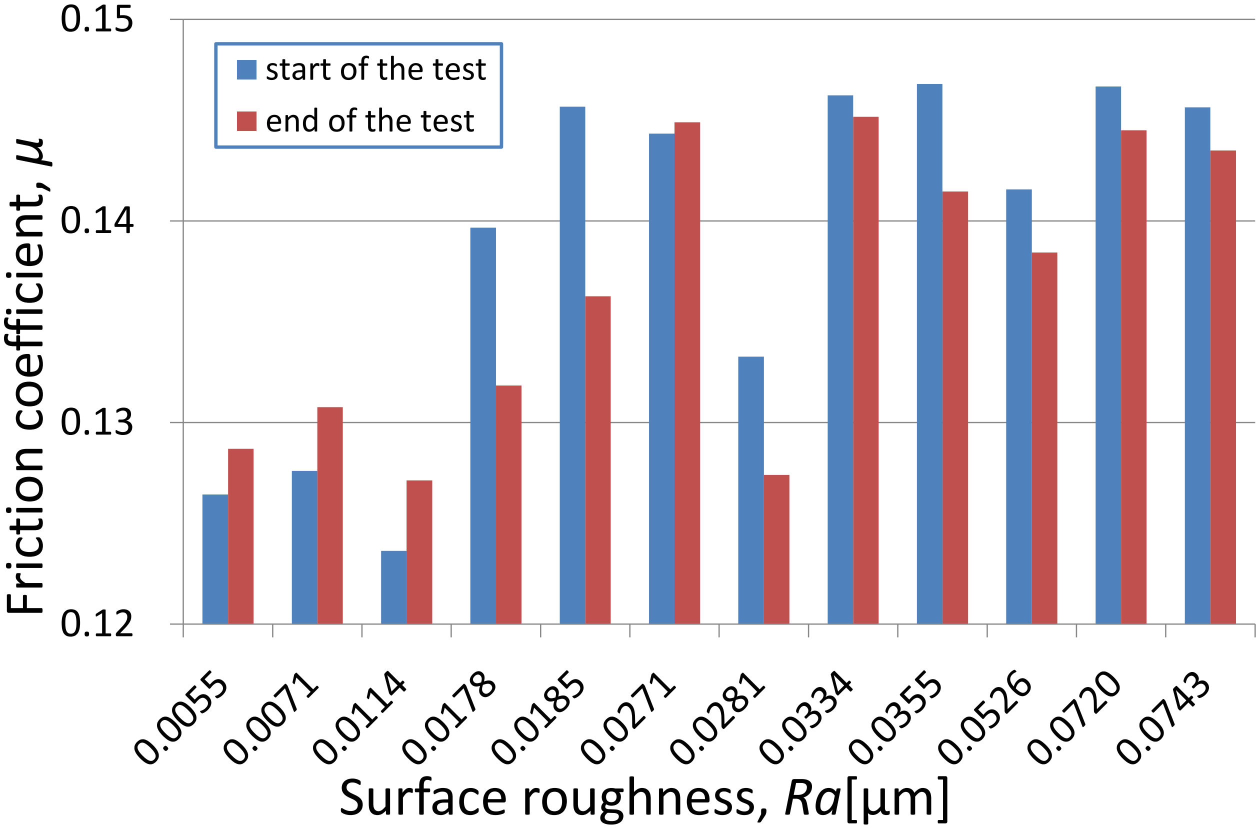


Figure 5b: Friction coefficients for the PAO+ZnDTP lubricant at the start and the end of the sliding test

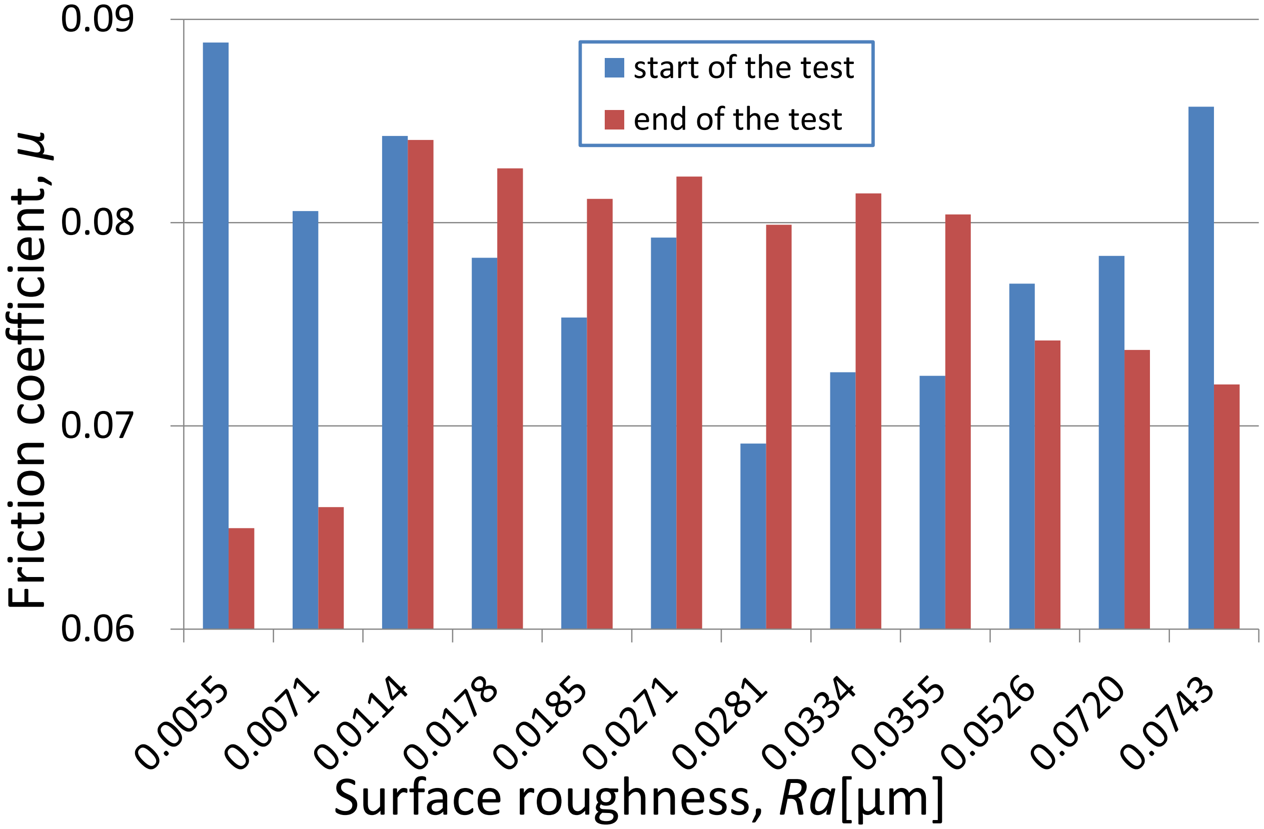


Figure 5c: Friction coefficients for the PAO+ZnDTP+MoDTC lubricant at the start and the end of the sliding test

Figure 6 shows the relationship between surface roughness before and after the sliding test for each lubricant. The vertical axis shows the surface roughness of wear tracks after the sliding tests, and the horizontal axis shows initial surface roughness of the disk specimens before the sliding tests. The dotted line represents initial surface roughness, as a cross plot of the horizontal axis and the vertical axis. For the smoother surfaces, the final surface roughness with the PAO and the PAO+ZnDTP+MoDTC lubricants is close to the initial surface roughness, whereas for the rougher surfaces the changes of surface roughness are larger. In the case of lubrication with PAO+ZnDTP, the surface roughness after the sliding test reaches a fairly constant value.

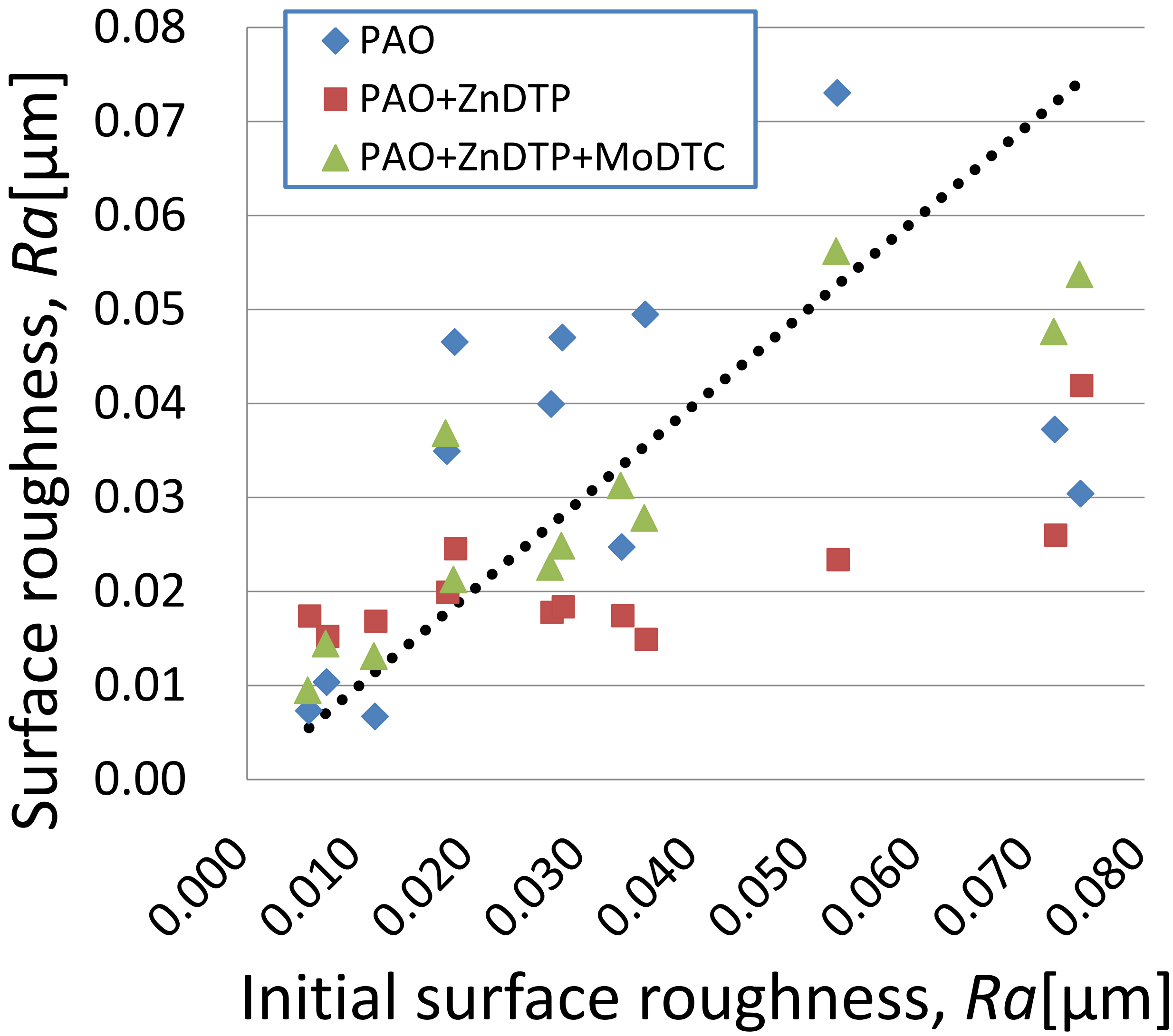


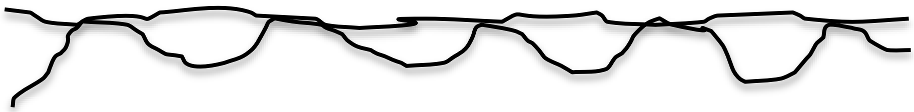
Figure 6: Changes of surface roughness before and after the sliding test for the PAO, PAO+ZnDTP and PAO+ZnDTP+MoDTC lubricants

4. Discussion

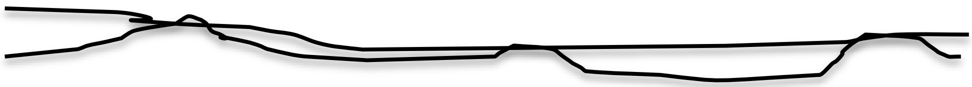
For rough surfaces, the friction coefficient with the PAO+ZnDTP lubricant is higher than that with the PAO lubricant whereas the friction coefficient with the PAO+ZnDTP+MoDTC lubricant is much lower than that with the PAO lubricant. These results indicate that friction properties strongly depend on the lubricating effect of each additive, ZnDTP and MoDTC. ZnDTP has the effect of protecting against wear and seizure of a sliding surface. Moreover, for ZnDTP it is known that a chemical reaction film is produced by the reciprocating action, which tends to increase the friction coefficient [REF]. In contrast, it is considered that friction coefficient with the MoDTC lubricant decreases due to the formation of MoS_2, which is a solid lubricant of iron phosphate that is made through reciprocating action in any lubricant with ZnDTP.

As regards to surface roughness, friction coefficient with the PAO lubricant exhibits maximum values on the smoother surface at a surface roughness R_a value around 0.015μm. A similar tendency is observed with the PAO+ZnDTP+MoDTC lubricant. In the case of the smoothest surface at a surface roughness R_a value under 0.01 μm, friction coefficient has low values

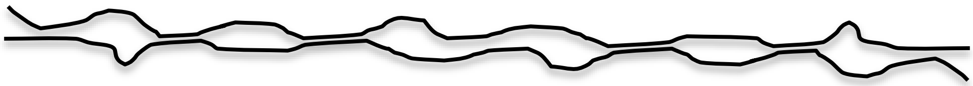
It is generally understood that there are adhesions between local contacts over the range of surface roughness values tested (see Figure 7a, 7b), thereby the friction coefficient increases with pressure increase. However, for the smoothest surface, adhesion does not tend to take place as the many small contact points disperse the pressure (see Figure 7c) and therefore the friction coefficient is lower.



(a)For the rough surface (Ra: over 0.01); the rate of surface contacts is high



(b)For the smooth surface (Ra: around 0.01); adhesion at local contacts



(c)For the smoothest surface (Ra: under 0.01); many contact points

Figure 7: Portrayals of the sliding surfaces for different roughness values

Based on the result shown in Figure 5, it is considered that running-in process made the friction coefficient lower at the end of the sliding tests for the rough surface. On the other hand, the friction coefficients for the smooth surface increased because of insufficient lubricant supply to the friction surfaces, which prevented the running in process and damaged the friction surfaces.

For the results shown in Figure 6, it can be concluded that the roughness of the ball influenced the roughness of the disk specimens with the PAO and the PAO+ZnDTP+MoDTC lubricants. The surface roughness increases over the duraction oif the test, with a commensurate increase in friction coefficient. In addition, the surface roughness with PAO+ZnDTP lubricant showed a fairly constant value over the sliding tests due to the thick film that was produced by the sliding process. In this case, the thick film reduces the relation of friction coefficient on initial surface roughness.

5. Conclusions

The following conclusions are drawn:

1. The friction coefficient of reciprocating sliding steel with PAO and PAO+ZnDTP+MoDTC lubricants has its maximum value on smooth surfaces with a surface roughness value of R_a = 0.01 μm.
2. The friction coefficient for the smooth surfaces increases in proportion to sliding distance with PAO and

PAO+ZnDTP lubricants. On the other hand, the friction coefficient decreases when using PAO+ZnDTP+MoDTC lubricant.

3. The surface roughness at the end of the sliding test with PAO+ZnDTP lubricant has a constant value regardless of any initial surface roughness.
4. The influence of surface roughness on friction behavior changes during the running-in process.

5. References

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