



Article

The Influence of Material Roughness, Hardness and Lubricant Additives on Micropitting Behaviour in Rolling-Sliding Contacts

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Manuscript received 11 November 2019; accepted 25 January 2020; published 30 April 2020

Presented at the International Tribology Conference Sendai 2019, 17-21 September, 2019

Abstract

Regarding micropitting, which is one of the fatigue damages that occur under conditions where the oil film thickness is smaller than the surface roughness, the effects of hardness and roughness of the test piece and differences in lubricants were confirmed. Endurance tests and friction tests were conducted using two-disc test rig. On the condition with harder and rougher surface of test pieces, deeper micropits were produced. The phosphorus additive blended oil led to a shallower pit depth than the sulfur additive blended oil. It was further suggested that the friction coefficient had little effect on micropit progress, and the influence of the lambda ratio (ratio of the oil film thickness to the root mean square roughness) after initial running-in was large. In a surface of high hardness and high roughness, micropitting tend to progress more easily. However, it was found out that the progress can be suppressed by suitable lubricants additives.

Keywords

tribology, micropitting, roughness, hardness, lubricant, additive, oil film thickness, lambda ratio

1 Introduction

Currently, there are demands for higher efficiency of various devices against the background of environmental problems, and many efforts have been made to reduce the size and weight to increase the efficiency of transmissions. Conventionally, a high-viscosity gear oil has been selected to secure a sufficient oil film thickness from the viewpoint of preventing damage. However, low-viscosity gear oil are required to improve efficiency by reducing stirring resistance. As a result, lubricants are required to suppress various types of damage for a long time under harsh condition if the roughness between two contacting surfaces is greater than the oil film thickness. Under such lubrication conditions, micropitting has become a problem. Micropitting, which is one form of fatigue damage, can lead to serious breakage if it progresses. Many considerations have been given to the mechanism of micropitting and it has been suggested that the roughness and hardness of the surface influence the progress of micropitting [1, 2]. Most of them used a single lubrication condition or a single type of lubricant. However, it is necessary to consider the influence of the lubricant on micropitting. For example,

the effectiveness of extreme pressure additives depends on the changes of the contact surface conditions. In this study, discs with different surface roughness and hardness were prepared, and experimented to use two types of lubricants with different additives. Furthermore, the amounts of fatigue wear and friction coefficient under different conditions were investigated.

Nomenclature

h_0	: Oil film thickness with assumption that the contact surface is smooth
R_q	: Root mean square roughness of contacting surface
R_y	: Equivalent radius of curvature in the direction of rolling
R_x	: Equivalent radius of curvature perpendicular to the direction of rolling
A	: Pressure-Viscosity coefficient
E	: Young's modulus
ν	: Poisson's ratio
η_0	: Lubricant viscosity at atmospheric condition
U	: Average rolling speed
W	: Load

Subscripts

- 1 : Corresponding to the test shaft
 2 : Corresponding to the counter shaft
 x : the rolling direction
 y : perpendicular to the rolling direction

2 Test method

2.1 Twin disc roller endurance test

The tests were carried out on two-disc test rig (Fig. 1) [3]. The tests were performed using the conditions shown in Table 1. The test conditions were based on the FVA-FZG-micropitting test [4] which is widely used as a micropitting test for lubricating oil. In FVA-FZG-micropitting test, it is known that micropitting tends

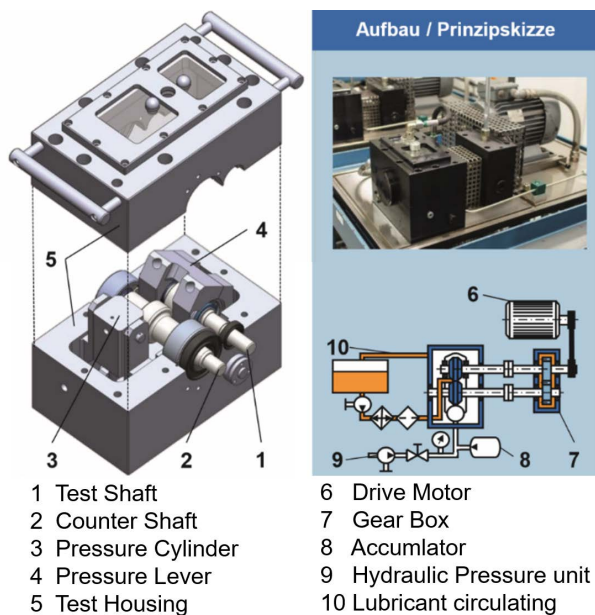


Fig. 1 WZL two-disc rolling contact fatigue test rig

Table 1 Endurance test conditions

Oil temp	90°C
Rotational speed	3,000 rpm
Slip ratio	-62.5%
Contact Pressure	1.6 GPa
Running-in	0.8 GPa , 1h
Test period	139h (25 million cycles)
Number of repetitions	3

to occur on the tooth root side of the pinion gear. As a result of calculating the conditions at the lowest point of single tooth contact on the pinion gear loaded by the 10th load stage, which is the maximum load in the test method, the maximum contact pressure is 1.6 GPa, the slip ratio is -60%. The test conditions were set close to that for reproducing the micropitting observed in FVA-FZG-micropitting test. Average wear depth and maximum depth were calculated from the surface shape of test pieces before and after the test measured using a roughness measuring instrument. The measurement conditions shown in Table 2. Figure 2 shows the measurement method of average wear depth and maximum depth. About average wear depth, taking the average of the measured roughness every 200 μm for

Table 2 Measurement conditions

	Wear and Pit depth	Roughness
Machine name	Hommel-Etamic nanoscan 855	
Sampling length	16 mm	4.8 mm
Cutoff value	-	0.8 mm
Measurement interval	0.5 μm	
Tip radius of stylus	2 μm	2 μm
Taper angle of stylus	60°	60°

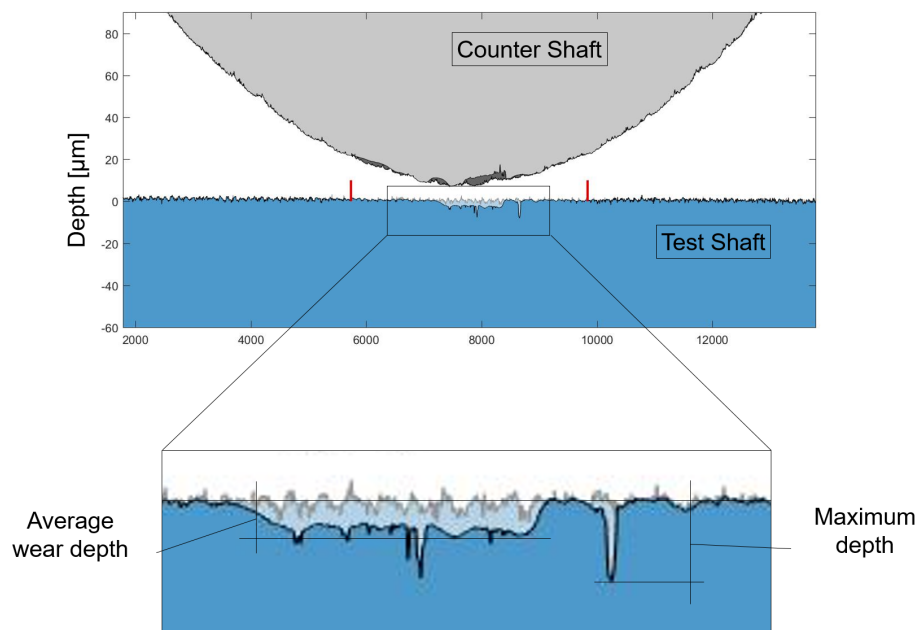


Fig. 2 Measurement method of average wear depth and maximum depth

eliminating the influence of the peak, and the maximum value of the differences between before and after the test was taken as average wear depth. About maximum depth, taking the minimum value of the roughness chart in the contact area was taken as maximum depth. Measurements were taken at three locations per test piece, and the average value was calculated. Results that showed significantly different damage compared to others, such as in case of significant wear due to quenching errors, were excluded.

2.2 Twin disc roller friction test

The tests were carried out on a friction force tribometer (Fig. 3) [3]. The tests were performed using the conditions shown in Table 3. The friction coefficients were calculated from the ratio between the friction force and the vertical load. As with the endurance fatigue test, at the lowest point of single tooth contact on the pinion gear of FVA-FZG-micropitting test was used as a reference, however, the maximum speed in this test rig was lower than that of the endurance test rig. In order to make the amount of heat generated at the contact area close to the endurance test, the pressure was set to 1.9 GPa which is higher than the endurance test.

2.3 Test pieces

The properties of the parts used in the test are shown in Fig. 4 and Table 4. Hardening was performed after rough machining, and finally the target roughness is adjusted by grinding.

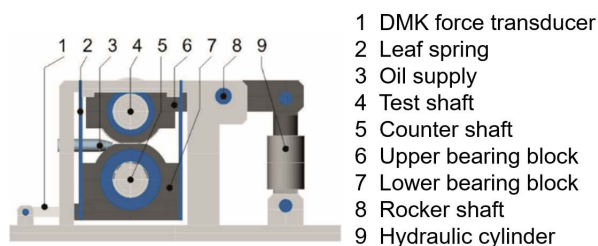
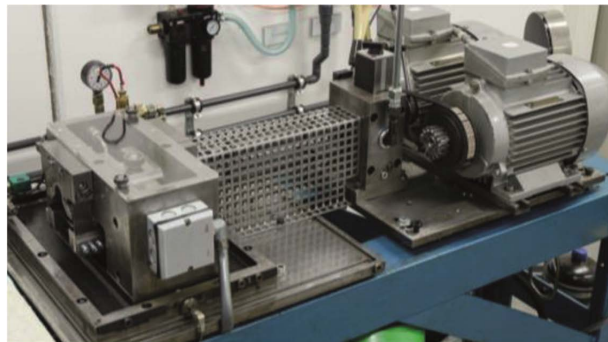


Fig. 3 WZL friction force tribometer

Table 3 Friction test conditions

Oil temp	90°C
Rolling speed	Average 5.25 m/s
Slip ratio	-62.5%
Contact Pressure	1.9 GPa
Running-in	1h (-10%) + 1h (-30%)
Test period	4 h
Evaluation	Average μ of last 1min

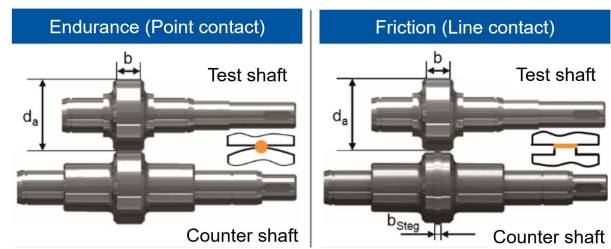


Fig. 4 Test pieces

Table 4 Test pieces

Test method	Endurance	Friction
Material	20MnCr5 (SCr420)	
Diameter (d_a)	42.05 mm	
Width(b) -Test shaft	16 mm	16 mm
-Counter shaft	16 mm	3.8 mm
Crowning-Test shaft	None	None
-Counter shaft	R166 mm	None
Target Roughness	Ra = 0.5 μm or 0.3 μm	
Target Hardness	750 Hv or 670 Hv	

2.4 Test lubricants

The properties of the lubricants used in the test are shown in Table 5. All lubricants use mineral oil as the base oil. Each lubricant contains an acid phosphate or sulfurized oil. Both lubricants contain anti-oxidant additives to suppress degradation during the test.

3 Test result

3.1 Twin disc endurance test

Figure 5 shows the average wear depth after the test. In a condition of initial Ra = 0.5 μm , larger wear depths showed on 750 Hv discs than 670 Hv discs. In a condition of initial Ra = 0.3 μm , the influence of the difference hardness was slight. In any conditions, the influence of additives on the wear depth was not significantly observed.

Figure 6 shows the maximum depth before and after the test. In conditions of initial Ra = 0.5 μm and 750 Hv, the maximum depth increased after test compared to before test. The result of Lubricant B was deeper than Lubricant A. In other conditions, there was no significant difference, and the maximum depth before and after the test was almost the same.

Figure 7 shows Ra before and after the test. After the test, Ra decreased compared to before test in all conditions. In initial Ra = 0.3 μm disc condition, the influence of hardness and lubricant on Ra were not significantly observed. Only in initial Ra = 0.5 μm and 750 Hv condition, lubricant A led to a lower Ra than Lubricant B.

Table 5 Lubricants

Name	Lubricant A	Lubricant B
Viscosity Grade	100	
Base Oil	Mineral Oil	
Anti-oxidant additive	Included	
EP Additive (element in oil)	Acid phosphate (P = 200 ppm)	Sulfurized oil (S = 0.4 mass%)

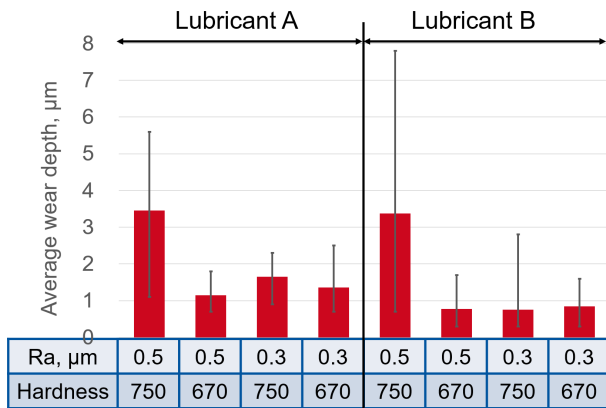


Fig. 5 Average wear depth

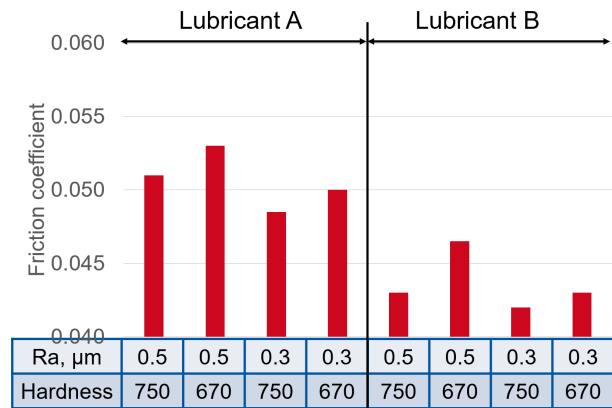


Fig. 8 Friction coefficient

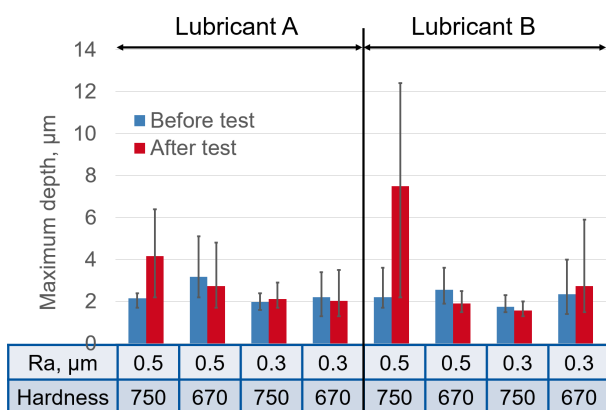


Fig. 6 Maximum depth

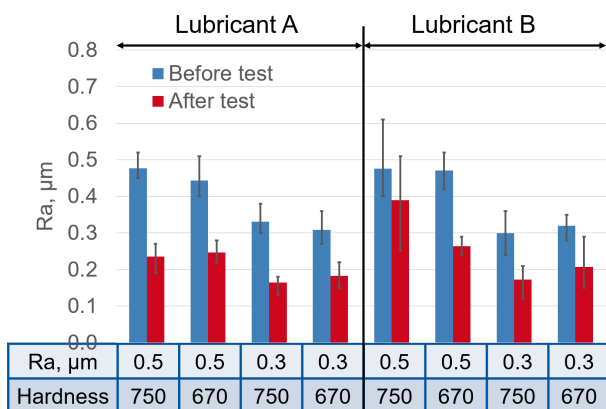


Fig. 7 Roughness (Ra)

3.2 Twin disc friction test

Figure 8 shows the result of the friction coefficient measurements. The initial $Ra = 0.5 \mu\text{m}$ discs had a higher friction coefficient than the initial $Ra = 0.3 \mu\text{m}$ discs. Furthermore, 750 Hv discs showed a lower coefficient of friction than 670 Hv discs. Lubricant B led to a lower coefficient of friction than Lubricant A. Although there are reports that the friction coefficient of the contact part affects the occurrence of micropitting [5, 6], there was not particular correlation in this study.

4 Discussion

In initial $Ra = 0.5 \mu\text{m}$ and 750 Hv conditions, the average wear depth, maximum depth and Ra after testing were larger than in other conditions. The differences due to lubricants were manifested in the maximum depth and Ra in the above conditions, and the maximum depth was particularly close to doubled due to the choice of lubricant. While discussing these causes, the effects of roughness, hardness, and lubricants on micropitting conditions were considered.

Figure 9 shows observation results of the disc surface after test with a laser microscope. Compared with those before test, fine metalworking marks disappeared and the overall surface became smooth. In addition, there were several pits approximately 10 to 60 μm wide near the top of roughness ridge. The number of pits was higher in initial $Ra = 0.5 \mu\text{m}$ conditions than in $Ra = 0.3 \mu\text{m}$. Furthermore, in 750 Hv conditions, the metalworking marks were almost disappeared and lots of pits were seen throughout. It is estimated that smoothing by removing fine protrusions and roughening by micropitting occurred simultaneously on the surface of the disc.

In order to confirm when the roughness change occurred, the change over time of Ra (Fig. 10) and the maximum wear depth (Fig. 11) are graphed. The measurements were performed after 1, 3, 6, 10, 15 and 25 million cycles. In all conditions, significant decreases of Ra were shown at first 1 million cycles and in most conditions there was little change in roughness thereafter. Therefore, it is assumed that smoothing is almost completed at 1 million cycles. Only in the condition of Lubricant B, $Ra = 0.5 \mu\text{m}$ and 750 Hv, Ra increased after 3 million cycles and then kept constant values. Regarding to the maximum depth in initial $Ra = 0.3 \mu\text{m}$ or 670 Hv conditions, the values before test (approximately 2 μm) were maintained until the end of the test. Considering the observation result with a laser microscope, it is inferred that the deep grooves formed at metalworking remained after the test and the groove depth was measured as the maximum depth. In initial $Ra = 0.5 \mu\text{m}$ and 750 Hv conditions, the maximum depth increased with time, therefore it is suggested that micropitting expanded with time.

According to the change over time of Ra and maximum depth, it was suggested that initial conformability was completed in 1 million cycles, and then micropitting expanded in some conditions. Therefore, it was confirmed how roughness after conformability was related to the final maximum depth in this test. Figure 12 shows the relation between Ra after 1 million cycles and maximum depth after 25 million cycles. These plots

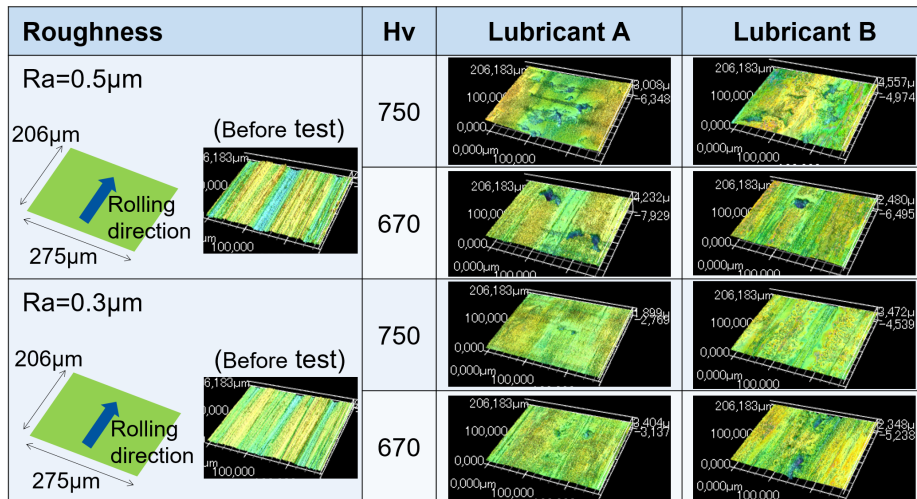


Fig. 9 Laser microscope picture

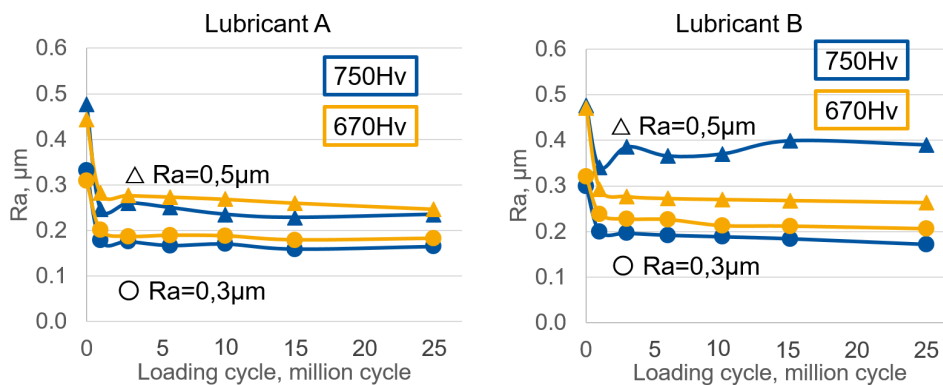


Fig. 10 Roughness change over time

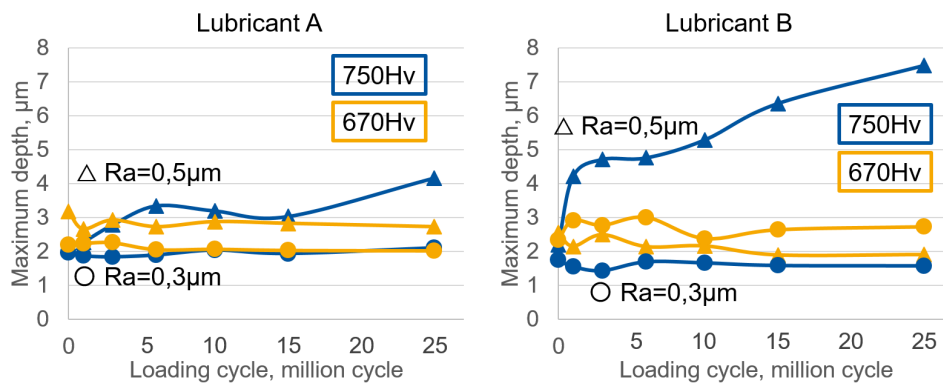


Fig. 11 Maximum depth change over time

are shown as individual data, not average values. The larger the Ra after initial conformability, the greater the final maximum depth. There is a high correlation between them.

It has been confirmed that micropitting damage is greatly affected by lambda ratio (λ , ratio of the oil film thickness to the root mean square roughness) [7]. Equations (1)-(8) shows a formula for calculating λ . The values of parameter are shown in Table 6.

λ is calculated from the formula of Tallian [8]

$$\lambda = \frac{h_0}{\sqrt{Rq_1^2 + Rq_2^2}} \quad (1)$$

The oil film thickness is calculated from the formula of Archard-Cowking [9]

$$H = 2.04 \mathcal{O}^{0.74} \frac{(G \cdot \bar{U})^{0.74}}{\bar{W}^{0.074}} \quad (2)$$

(A) Dimensionless film parameter:

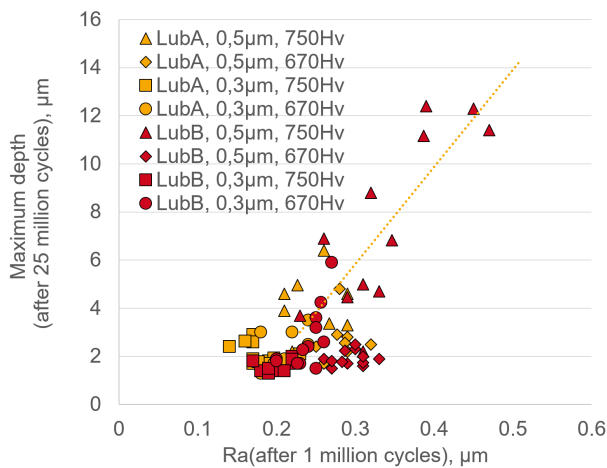


Fig. 12 Relation between Ra (1M) and maximum depth (25M)

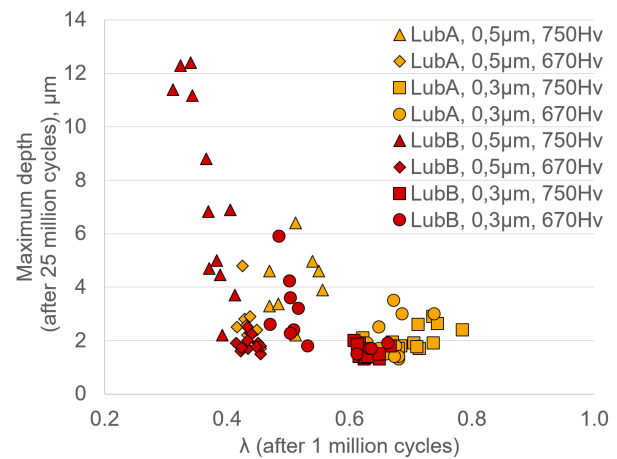


Fig. 13 Relation between λ (1M) and maximum depth (25M)

Table 6 Parameters used in oil film thickness calculation

Parameter	Symbol	Value
Equivalent radius of curvature in the direction of rolling	Ry	10.51 mm
Equivalent radius of curvature perpendicular to the direction of rolling	Rx	166 mm
Pressure-Viscosity coefficient	α	18.4 GPa ⁻¹
Young's modulus	E ₁ , E ₂	210 GPa
Poisson's ratio	ν_1 , ν_2	0.3
Lubricant viscosity at atomospheric condition	η_0	0.0125 Pa·s
U:Average rolling speed	U	8.67 m/s
Load	W	1730 N

$$H = \frac{h_0}{R_y} \quad (3)$$

(B) Side leakage parameter:

$$\phi = \left(1 + \frac{2R_y}{3R_x}\right)^{-1} \quad (4)$$

(C) Dimensionless material parameter:

$$G = \alpha E' \quad (5)$$

where

$$E' = \left\{ \frac{1}{2} \left[\left(\frac{1-\nu_1^2}{E_1} \right) + \left(\frac{1-\nu_2^2}{E_2} \right) \right] \right\}^{-1} \quad (6)$$

(D) Dimensionless speed parameter:

$$\bar{U} = \frac{\eta_0 U}{2E'R_y} \quad (7)$$

(E) Dimensionless load parameter:

$$\bar{W} = \frac{W}{E'R_y^2} \quad (8)$$

Figure 13 shows the relation with λ value after 1 million cycles and the final maximum depth. In case of λ is less than 0.6, the maximum depth begins to increase. In particular, λ is less than 0.4, the maximum depth increases rapidly. Lubricant A has larger λ than lubricant B, therefore the contact surface is protected by the oil film easily and it is considered that the progress of micropitting can be prevented.

On the other hand, in 670 Hv conditions, the maximum

depths were low although the λ were approximately 0.4. Other roughness parameters (R_z , R_{Sm} , R_{Sk} , R_{ku} , R_{pk} , R_{vk}) were confirmed, however, no significant difference was found between 750 Hv and 670 Hv. In addition to the roughness, it is suggested that residual stress affects the progress of micropitting [10], so it is necessary to consider not only the surface condition but also internal changes such as internal stress and chemical composition due to additives.

5 Conclusion

The following results were obtained showing the influence of hardness, roughness and lubricant on the micropitting condition.

- 1) The harder test pieces tend to have larger wear depths, however, the differences are minor when the roughness is smooth.
- 2) Lubricants containing the phosphorus additive show less change in maximum depth due to changes in hardness and roughness than sulfur additive.
- 3) The friction coefficients are not necessarily low at conditions where wear was small.

In a surface of high hardness and high roughness, pits tend to progress more easily. However, it was found out that the pit growth can be suppressed by suitable lubricants and additives.

Acknowledge

The author would like to thank people who have greatly supported this study in the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University.

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