Tribological Behavior of Boundary Lubricated Sliding Surfaces Using Three Different Spacing of Surface Profiles

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The ball-on-disk type sliding tests with boundary lubricated steels were carried out to verify the effect of initial spacing in surface profiles on wear and scuffing. Three kinds of surface spacing, which are closely related with initial surface micro-cracks on sliding surfaces, were produced on AISI 1045 steel surfaces using different grinding and polishing processes. Frictional forces and time to scuffing were measured, and the shape and amount of wear particles were analyzed to compare the with original surface profiles. From the tests, it was confirmed that the size of wear particles are related closely to the original spacing of the surface profile. The time to failure and amount of wear were sensitive to the surface spacing. The wider surface spacing shows much longer sliding life and smaller amount of wear than the others. Time to scuffing was increased with increasing surface profile spacing. The size of wear particles increased while the wear and wear rate K were decreased with an increase in surface spacing. After the sliding tests, surface cracks of inner parts of the wear track formed due to scuffing were observed and compared among the specimens having the different surface spacing.

Key Words : Friction, Wear, Scuffing, Surface Profile Spacing, Wear Particle, Surface Crack

1. Introduction

Most mechanical components that experience sliding motion operate under the boundary lubricating condition and the surfaces of such mechanical components are subjected to damage by wear and scuffing. Thus, the surface failure which is very difficult to predict will occur. Scuffing is a catastrophic failure of sliding surface, which is generally accompanied by sudden increase in friction force and roughening of surface (Kim and Ludema, 1995 ; Lee and Ludema, 1990).

There have been many research works done to identify the causes of such surface failure (Lee and Cheng, 1991 ; Lee and Cheng, 1991). The causes are believed to be the changes in material surface and protective layer (Lee and Ludema, 1991 ; Park and Ludema, 1994). Recent researches suggest that the surface failure is related to the changes in subsurface since surface interaction effects the subsurface under sliding without any lubricants (Sheiretov et al., 1998). One of the proposed mechanism in scuffing is the low cycle fatigue (Lee and Kim, 1999 ; Kim and Lee, 2002), in which the time to failure is closely related with the increment of strain on the sliding surfaces. Mechanical components, which are subjected to scuffing operate in repeated-pass sliding. Due to the repeated-pass sliding the surfaces experience fatigue characteristics. Before scuffing based on adhesive wear occurs, cracks will be generated on the surface (Fan et al., 1993).

The objective of this paper is to demonstrate the effect of initial surface cracks on the wear amount and time to scuffing. The scuffing and the wear characteristics are studied by conducting

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sliding tests. When two surfaces are in sliding motion, high contact pressure is generated on the contacting surfaces causing surface crack propagation. As the result of continuous sliding motion, wear occurs on the surface due to crack propagation. Once the surface is damaged by wear the performance of the machine component degrades significantly. The surface crack and the wear particles generated on the wear track due to the scuffing will be examined as well.

2. Experiment

Three types of disk specimens with different surface profile spacing were prepared using AISI 1045 steel with 60 mm in diameter and 10 mm in thickness, and AISI 52100 steel balls with 1/4 inch in diameter were used as the counter part. The disk specimens were heat-treated in a furnace at 870 ℃ for 1 hour and tempered to obtain a hardness of 590HB. In the case of the soft material, the main mechanism of wear would be plastic flow of material. To verify the effect of initial crack it is useful to do tests with hard materials. To differentiate the surface condition for the three types of disk specimens, the surface was ground with a different grade grindstone for each type of specimen but was polished with the same grade emery paper. Table 1 shows the surface parameters of the three types of specimens. S_m is the mean wavelength of surface profile, which is the mean lateral distance between the peak and the valley, and R_q is the root mean square value of asperity heights. The sliding tests were carried out using a ball-on-disk type tribometer, as shown in Fig. 1, for repeated pass sliding. The apparatus is capable of measuring the frictional force as well as the normal force. To maintain a stable rotational motion a servomotor was used to rotate the disk. A cylinder was located in a holder that was clamped to a fixed arm with a transducer for friction force measurement. The lower flat disk was mounted on a rotating shaft in an oil bath. Mineral oil was used as the lubricant and the normal load and the friction force were measured by the load cells. The friction force and the coefficient of friction were measured by a data

Table 1 Surface parameters of three specimens

Parameters		Type 1	Type 2	Type 3
S_m	[mm]	0.0385	0.0617	0.1049
R_q	[μm]	0.2571	0.7441	1.1503

Table 2 Surface parameters of the peaks for three specimens Parameters

Parameters		Type 1	Type 2	Type 3
S_m	[mm]	0.0393	0.0417	0.0422
R_q	[μm]	0.2123	0.2303	0.2192

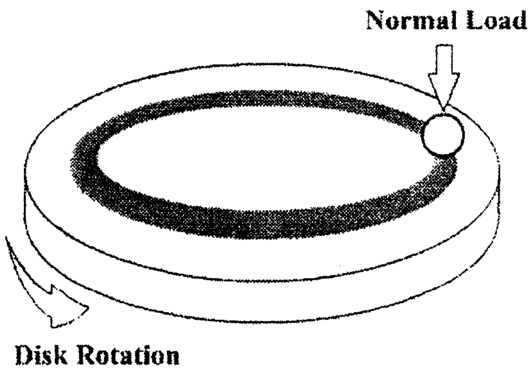


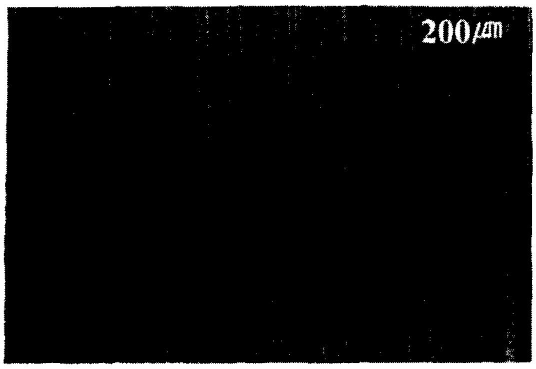
Fig. 1 Ball-on-disk type sliding test

acquisition system connected to the tester. Contact was achieved by pressing the ball against the flat surface under a normal load applied by a spring force, which reduced the variation of normal force during sliding.

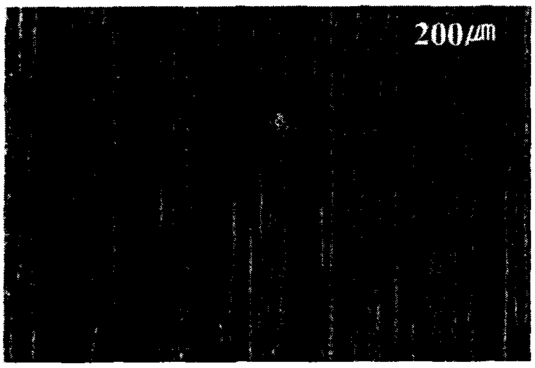
Tests were conducted at room temperature. The friction force and the coefficient of friction were measured by connecting the data acquisition system to the tester. The initial normal load was 20 kgf and the load was increased by 20 kgf at every 1000 cycles until scuffing occurred at which point the test was stopped.

By polishing the surface, the same contact condition was maintained while S_m was different for the three types of disks. Table 2 shows the similarity in surface roughness at the peaks, the so called plateau parts, among the disk types.

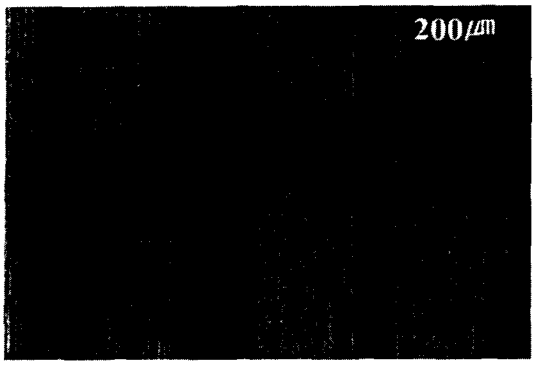
Figure 2 shows the surfaces of specimens as polished. As shown in the figure, the S_m of type 1 is much shorter than that of type 3. The bright portions are the flattened peaks of surface asperities due to polishing. In Fig. 3, the surface



(a) Type 1



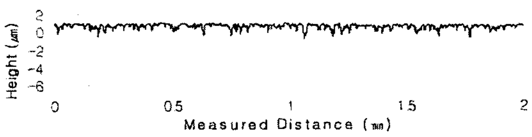
(b) Type 2



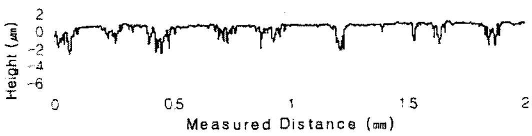
(c) Type 3

Fig. 2 Surface of three different specimens

profile of each specimen type is shown. By comparing the surface profiles, it can be verified that the peaks were polished to make the plateau. Also, different values of S_m according to the specimen types could be obtained. After the sliding tests, the sizes of wear particles on the wear tracks were measured using an optical microscope and analyzed based on the S_m value. The wear particles were obtained by collecting them four times from each section very carefully



(a) Type 1



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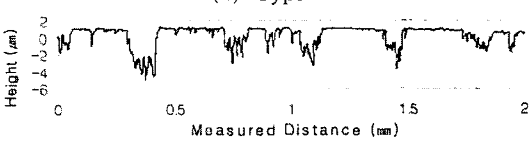


(c) Type 3

Fig. 3 Surface profile of three different specimens

after dividing the wear track into four sections.

3. Results and Discussion

3.1 Sliding test results

Table 3 shows the sliding test results of the three types of disks. The coefficient of friction before scuffing, during which the friction force increased rapidly, was very close to each other ranging from 0.114 to 0.117. However, the number of cycles to scuffing for the type 1 was shorter than that of the type 3. The wear amount for the type 3 was smaller than that of the type 1. It is believed that in case of wider spacing the initial cracks are difficult to propagate. Therefore, wear resistance and scuffing life increase with increasing S_m.

3.2 Scuffing and wear characteristics based on S_m

From the sliding test results, it was clear that the scuffing characteristics was related to S_m. Figure 4 shows the relationship between the number of cycles to scuffing and S_m. The number of cycles to scuffing increased as S_m increased. Figure 5 shows the variation of wear amount as a function of S_m. It was evident that the wear amount decreased as S_m increased. The effect of S_m on the wear rate is shown in Fig. 6. The wear rate decreased as S_m increased due to the

Table 3 Results of sliding test

	Type 1	Type 2	Type 3
Coefficient of friction	0.115	0.114	0.117
Scuffing life [cycles]	2383	4062	4621
Wear volume [mm^3]	0.1818	0.1485	0.0835
Wear rate [$\times 10^{-6} mm^3/N\cdot m$]	2.491	0.802	0.236

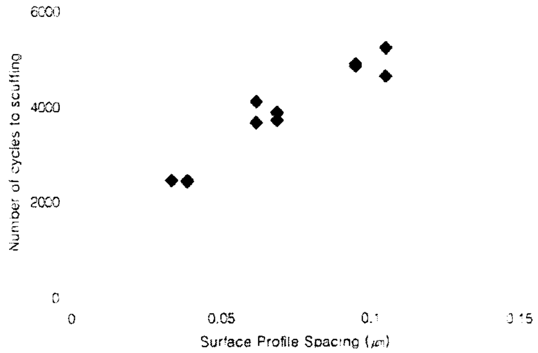


Fig. 4 Effect of surface profile spacing on the number of cycles to scuffing

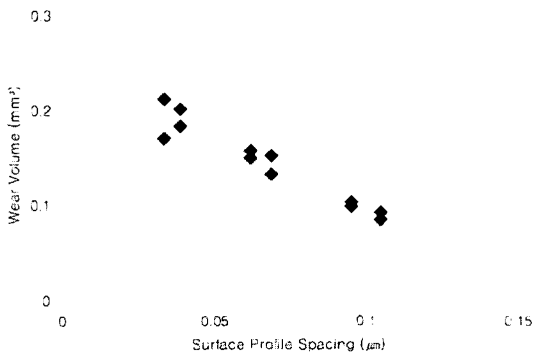


Fig. 5 Effect of surface profile spacing on the wear volume

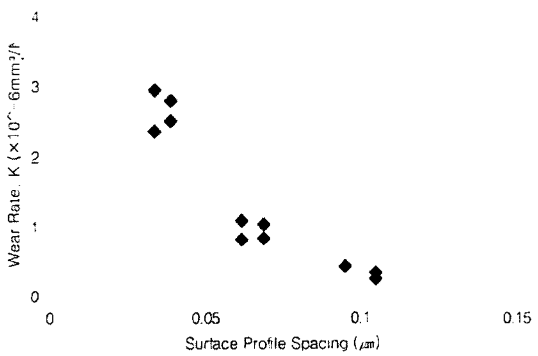


Fig. 6 Effect of surface profile spacing on the wear rate

decrease in wear amount. Thus, the wear resistance increases as S_m increases based on the above results.

In the experiments, S_m was the only variable which led to significant difference in the scuffing and wear characteristics. Therefore, it can be assumed that it is due to the difference in initial crack length which depends on surface spacing.

3.3 Effect of S_m on the size of wear particle

The wear particles on the wear tracks of the three types of disks were obtained. Their sizes were measured and their mean values for each type are listed in Table 4. The mean size of wear particles for the type 1 is much smaller than that of the type 3. Therefore, the mean size of wear particles increases as S_m increases.

The wear particle size is plotted as a function of the normal distribution in Fig. 7. From the figure, it can be said that the sizes of wear particles follow the normal distribution since the normal distribution curves for the wear particle size are bell-shaped. The mean size of wear particles for type 1 is smaller than that of type 3 and most of the sizes of wear particles for type 1 are very close to their mean value, which is unlike the type 3's.

Table 4 The size of wear particle after sliding test

	Type 1	Type 2	Type 3
Average particle size [μm]	15.60	20.63	26.65
Variation [μm]	70.16	131.68	406.96
Maximum particle size [μm]	55	100	180

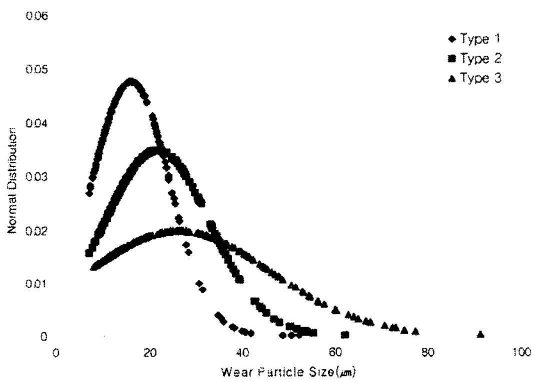
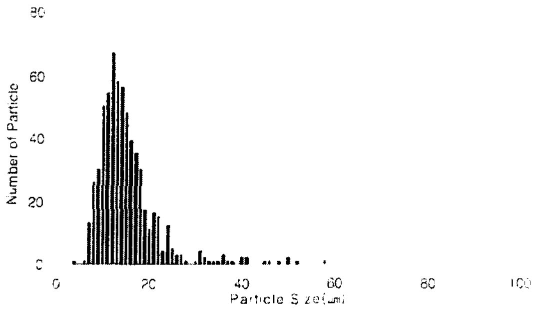
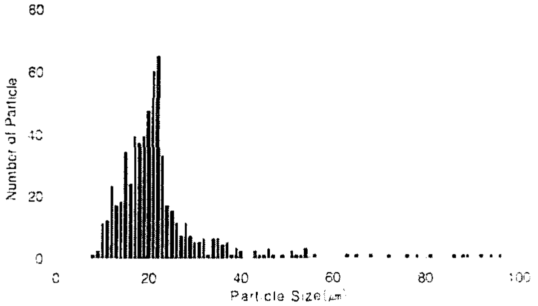


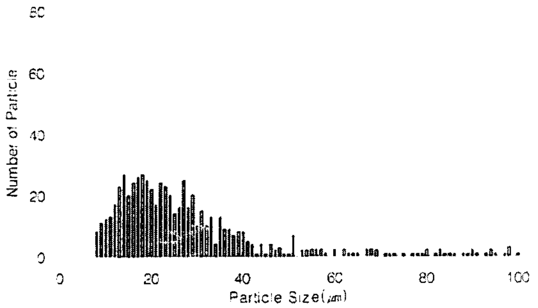
Fig. 7 Normal Distribution of wear particles



(a) Type 1

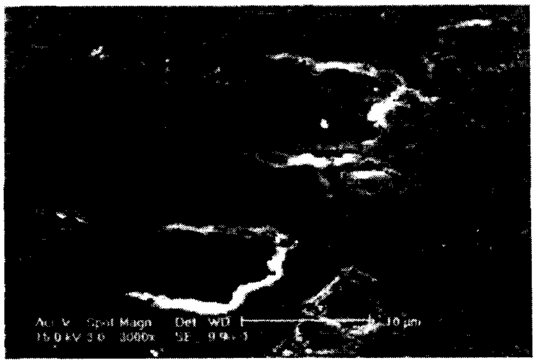


(b) Type 2

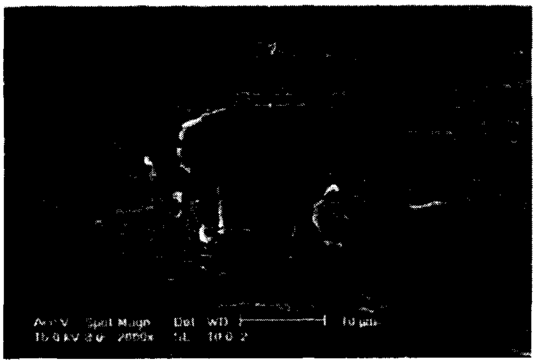


(c) Type 3

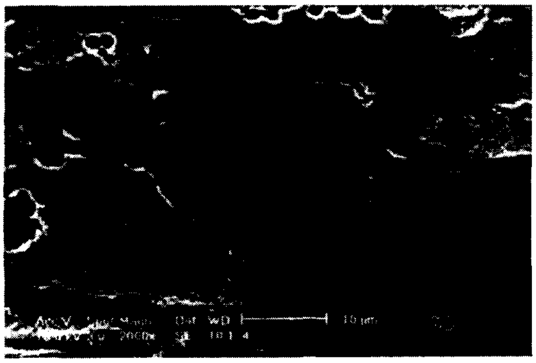
Fig. 8 The number of wear particle for each specimen



(a) Type 1 [3000×]



(b) Type 2 [2000×]



(c) Type 3 [2000×]

Fig. 9 Surface crack for three specimens

Figure 8 shows the wear particles as a function of their sizes. The number of wear particles was the highest at the mean particle size and as the size either grows or reduces from the mean, the number decreased. In addition, if Figs. 7 and 8 are laid on top of each other, very similar trend can be observed. The largest wear particle size was about 55μm, 100μm and 180μm for the type 1, 2 and 3, respectively. The common characteristic among the three sizes is that they were very close to their respective surface asperity size. In general, the scuffing occurs due to the high adhesion force between two materials in sliding motion. However, the wear particles cannot come off from the material only due to the adhesion force since the contact diameter of the three type of surfaces was around 100μm. Thus, it can be assumed that such large wear particles come off due to the generation and propagation of surface crack by the applied load in the direction of sliding and the adhesion force. Based on the above discussion, it can be seen that the scuffing behavior differs by the surface condition when wear occurs due to scuffing. In other words, as

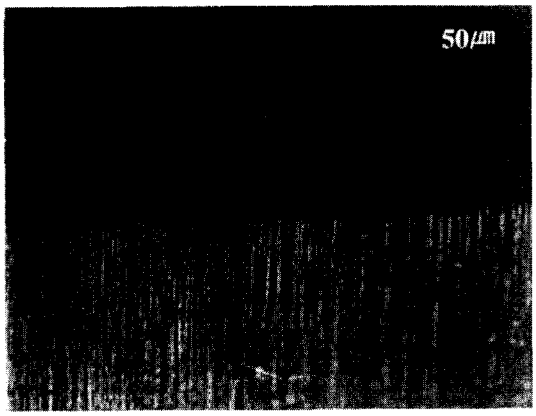


Fig. 10 The propagation of surface crack

S_m increases, the size of wear particles increases, the wear rate decreases and the wear resistance increases. This is because when S_m is small, the number of surface cracks increases and longer cracks that will have an effect on the wear of surface are generated. Thus, it can be assumed that the surface wear caused by scuffing occurs on the surface in the presence of many cracks.

3.4 Surface crack based on S_m

Figure 9 shows the SEM (Scanning Electronic Microscope) photographs of the surfaces for the three types of disks. The surface cracks generated by the sliding test can be observed for each type. As seen in Fig. 9, the surface cracks propagated in different directions but at the end they joined with each other to cause wear particle generation. The wear scar sizes for the type 1 were smaller than that of type 3. This is due to the proportionality of the size of wear scar to the size of wear particles. The propagation mechanism of surface cracks was sliding motion and high contact pressure built up from the motion. Figure 10 shows the photograph of the side view of the surface crack at the contact part. If the sliding test continued, the crack would propagate in the direction marked on the figure and cause the wear particle to come off.

4. Conclusions

The effects of S_m on the number of cycles to scuffing and the wear characteristics were investigated by the ball-on-disk type sliding test. Three types of disk specimens were prepared using AISI 1045 steel and the wear particles. The surface cracks were examined and the following conclusions were obtained fram the experinents ;

(1) As S_m increases, the number of cycles to scuffing increases. This is believed to be due to the difference in the contact area of the two surfaces when sliding. The number of cycles to scuffing increases since as S_m increases the contact area also increases causing the contact pressure to drop even under same load. Also, the wear amount reduces up to the occurrence of scuffing and therefore, the wear rate becomes low. This is because the wear resistance increases as S_m increases under the same test condition.

(2) The size of wear particles can be plotted as a function of normal distribution. From the plot, it can be verified that the size forms a normal distribution and the mean size and the size variance increases as S_m increases. In other words, it can be verified that the size wear particles becomes close to the mean size as S_m decreases.

(3) As S_m increases, the size of wear particles increases. Size of the large wear particles is very close to the value of S_m. Therefore, when two materials are under contact sliding condition, the surface crack is generated and the wear particles come off causing scuffing to occur.

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