Effect of Contact Configuration on the Tribological Performance of Micro-Textured AISI 1045 Steel under Oscillating Conditions

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The tribological performance of micro-textured AISI 1045 steel was investigated by an oscillating test. This study compared two contact schemes: (1) ball-on-disk and (2) line contact configuration. Texturing fractions of 5, 10, 15, and 20% were used. Results of the ball-on-disk oscillating test revealed that this contact scheme is not appropriate for an ordinary mechanical element in relative contact motion because very high concentrated contact stress is generated. In the case of the line contact test, a load dependency was observed for the coefficient of friction in spite of the lowered contact stress. The coefficient of friction for a load of 50N was higher than that of the bare specimen over the entire texturing range. However, for a load of 20N, a reduced coefficient of friction was observed in all cases. [doi:10.2320/matertrans.M2013214]

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1. Introduction

Surface texturing has been widely used to enhance the frictional performance of tribological components during sliding. Surface texturing captures worn debris during sliding and stores a lubricant that can be supplied when necessary. The former function mainly reduces third-body abrasions, and the latter lowers the coefficient of friction. Furthermore, it has been reported\(^1\) that textured pores can act as microbearings. All of the above benefits are based on the fact that micro-dimples or micro-pores do not deform or disappear during contact. Otherwise the micro-pores can no longer store the lubricant or capture worn fragments. Even worse, wear fragments formed during the failure of microstructures will cause a significant tribological problem.

To some extent, the loss of the micro-structured shape seems dependent on the contact configuration. That is, a point contact that causes a high concentrated stress is a harsh contact condition when compared to a planar contact. Many works have dealt with either the planar-to-planar\(^2,3\) or ball-on-flat\(^4,5\) contact scheme. Most tribocomponents are designed to function under an area contact or a line contact rather than a point contact in order to avoid severe stress concentration. Nevertheless, the ball-on-disk sliding configuration has been widely used because it is adequate for evaluating the performance of various surface coatings, including textured surfaces. For example, Anderson et al.\(^6\) reported that the friction and wear of M2 high-speed steel against an AISI 316 stainless steel ball were significantly reduced by introducing micro-texturing in the oscillating ball-on-disk contact. They also found that a low texturing density, the use of high viscosity oil, and relatively deep micro-cavities enhance tribological performance. Vilhena et al.\(^7\) showed that an Nd:YAG laser can be used to micro-texture 100Cr6 steel. Their point contact tests yielded no beneficial results of friction and wear. In flat contact, friction was slightly reduced but was dependent on the sliding speed. It appears from their work that the size of textured micro-pores and the sliding conditions are closely related in the enhancement of tribological performance. Voevodin et al.\(^8\) used a solid lubricant such as molybdenum disulfide (MoS\(_2\)) powder to fill the micro-textured holes through a burnishing process. However, MoS\(_2\) is ineffective in humid conditions because of its weakness and high moisture susceptibility. In other words, the solid lubricant should be kept underneath or mixed with another protective layer. When a burnished MoS\(_2\)/graphite/\(\mathrm{Sb}_2\mathrm{O}_3\) layer was used, the lubrication was smooth in both dry and humid environments because MoS\(_2\) works well in dry conditions, and graphite acts as an effective lubricant in humid air. Li et al.\(^9\) also reported that the coefficient of friction of a Ni-based composite decreased by introducing micro-texturing filled with the solid lubricant MoS\(_2\). The results showed that abrasive wear occurred and consequently led to a change in the dimensions of the dimples. The depth and diameter of dimples along the wear track appeared to change considerably.

The micro-dimples inevitably wear out after prolonged sliding contact, and the degree of wear of micro-pores depends on the contact configuration, such as ball-on-disk, line, or planar. Therefore, preserving the shapes of micro-pores becomes critical to maintain their original function as a lubricant supplier and as micro-bearing. This study first considered the fabrication of micro-pores in order to obtain highly reliable specimens and then varied the contact scheme to investigate the wear and applicability of each contact method under various sliding conditions by using reciprocating tests.

2. Experimental Details

2.1 Materials

Plain carbon steel (AISI 1045 with no additional heat treatments) was used for micro-texturing. Its yield strength and hardness (HV) are about 500 MPa and 170, respectively. The diameter and height of the steel disk were 24 and 7.9 mm, respectively. Each sample surface was first abraded to remove the deep machining scratches resulting from the turning process. In order to remove turning scratches, the sample surface was lapped using emery paper in a grit number order of 400–800–1000–2000. Finally, the samples

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were polished to smooth and mirror-like surfaces. Fine polishing eliminates the effect of surface roughness and lays produced by abrasion. The polished samples were used for texturing. First, after laser texturing, the same steps were repeated to eliminate burrs formed around the micro-pores, except for polishing with emery papers with low grit numbers of 400 and 800. Ultrasonication was used to remove fine steel particles from the micro-pores generated during the deburring process. All samples were then cleaned by a stream of fresh water, dried, and stored in a hot chamber. Before storage, all samples were cleaned with methanol to remove oily residue on the sample surfaces.

2.2 Laser texturing

Micro-pores were fabricated using the INYA 20 laser system (IN Laser System, Korea), which is a ytterbium-pulsed fiber laser operating at a wavelength of 1064 nm, with a 20 KHz repetition rate and 20 W nominal average output power. The laser system used in this study has been widely used as a marking laser. To create micro-dimples, two different processing control methods were initially studied in order to obtain better pore shape. The first method is to use a line to construct a circle that eventually becomes a pore. The size of the pore can be controlled by the speed of the laser scanner. However, this method does not create a clear-cut micro-pore. Therefore, the point generation method was next employed. In this method, the duration and the number of shots could be easily controlled, and the shape of each pore was further enhanced. Burrs around the micro-dimples were created as a result of laser irradiation regardless of the processing method. The energy fluency of the laser used in this study was not significantly high, and as a result, ablation was not a dominant effect. Instead, melting behavior was always observed to some extent. The burrs were always completely removed by light lapping and polishing. The fraction of texturing was calculated using the center-to-center distance between two adjacent pores after the deburring process.

2.3 Oscillating tests

Friction and wear of the textured samples were investigated using the Optimol SRV® tribometer under a ball-on-disk and line contact reciprocating configurations. The ball-on-disk oscillating configuration was used first and is shown in Fig. 1(a). The steel ball is 100Cr6 with a diameter of 10 mm. Secondly, for the line contact, a short-round bar, which is a roller pin used in the roller bearing, was inserted into a specially designed holder, as shown in Fig. 1(b). The diameter and length of the bar were 5 and 8 mm, respectively.

The bar was also made of 100Cr6. The lubricant was the common automotive engine oil SAE 5W-30, and a few drops of the lubricant (~0.5 cc) were applied to the sample surface before installation of the steel disk. The oscillating tests were carried out using an oscillating frequency of 20 Hz and a travel distance of 1.5 mm. The loads used were 20, 50, and 100 N, and the Hertzian contact pressures for the ball-on-disk were 1260, 1710, and 2155 MPa, respectively. Each test was performed for 20 min regardless of the contact scheme. The test temperature was 80°C in order to maintain a low viscosity of the lubricant.

3. Results and Discussion

3.1 Laser texturing

As stated, the pores developed by the line method were poor in shape and quality regardless of the scanner speed, as shown in Fig. 2. The pore quality worsened as the texturing fraction increased. One of the biggest drawbacks was the formation of very fine burr fragments after deburring. These fragments were locked in the pores as seen in Fig. 2(a) and were not easily removed. The fragments caused third-body abrasion during oscillations, leading to high wear. When the micro-pores were shallowly processed, their size and shape were irregular, as shown in Fig. 2(b). Therefore, this study did not consider the above method for preparation of micro-pores. Instead, the point or dot method was used to create the micro-pores.

Figure 3 shows typical micro-pores produced by different durations of laser irradiation under the same laser specifications. The figure clearly shows that the depth increases with irradiation duration. One very distinct feature is the formation of a large solid burr, as indicated in Figs. 3(c) and 3(d). Such a large burr can be easily removed by a fine lapping process without clogging the pore. The pore wall appears smooth and homogeneous. Depth control can be used to study the effect of pore depth on friction and wear of a specimen. However, this study uses a single depth value. In-depth experimental works are now in progress in a separate study.

The depths of the micropores shown in Fig. 3 after a deburring process were estimated to be approximately 5, 35, 80, and 120 µm, respectively. Among these, the parameters in Fig. 3(b) were chosen to produce micro-pores hereafter in this study. The resulting surface after a deburring process is shown in Fig. 4 using three-dimensional topography. The measured depth was about 30–35 µm, and the diameter of the pore was about 75 µm. Burrs are completely removed,
and the micro-pores are regularly arrayed. The floors of the pores are flat and smooth.

3.2 The ball-on-disk oscillating tests

The ball-on-disk oscillating tests were performed using various conditions of texturing fraction, load, speed, etc. The effect of load was first examined using some samples, including the non-textured sample. The loads used were 20, 50, and 100 N, and the corresponding Hertzian contact stresses for the ball-on-disk were calculated and compared. As a result, the smallest load of 20 N produced 1260 MPa of the Hertzian contact stress, which is significantly greater than the yield strength of the specimen. Therefore, severe wear during oscillation was expected, and the results for the wear surface are described next. Figure 5 shows worn surfaces for the bare sample after oscillation. The initial finishing scratch marks were completely removed after oscillation regardless of the applied load due to high concentrated stress from the ball contact. The width of the contact area continued to increase with the load, whereas the travel distance remained constant. This indicates that the number of micro-pores in contact with the steel ball differs according to the texturing fraction and applied load. If a light load and low texturing fraction are used together, no pores would exist in the contact zone because of a small contact area. This implies that an optimum texturing density can be achieved by considering the applied load. High wear led to the formation of stepped edges, as indicated in the boxed region of Fig. 5(b). This is because of the flow of material, which is caused by the very high contact stresses in the ball-on-disk contact.

The effect of load on the micro-pores in contact with the steel ball was also examined. Figure 6 shows deformed micro-pores after the oscillating test. The pore was already deformed with the 20 N load, as shown in Figs. 6(a) and 6(c), and attrition of the pore for a 50 N load appears significant.
Failure of the micro-pores was extensive, and pores were filled with worn fragments. Wear of the steel surface was significant, as shown in Fig. 6(d). The wear depth was about 15 µm and increased toward the contact center. As explained, very high contact stresses caused the gross wear of the specimens. We concluded that even a small load cannot practically be used in the ball-on-disk contact configuration due to severe failure followed by wear of the micro-pores. Also, the results imply that the ball should be large enough to reduce the contact stress, or the applied load must be small. A simple calculation shows that the ball used in this study should be at least 50 mm in diameter in order for the stress to be lower than the yield strength of the specimen. In conclusion, because of significant wear, the coefficient of friction is no longer meaningful and is therefore not discussed in this study.

3.3 The line contact oscillating tests

Before the official tests, a number of oscillating tests were performed to determine the Striebeck curve of the material, as shown in Fig. 7. The objective was to see how the coefficient of friction from the line contact is influenced by load and speed. The load range, stroke range, and frequency range used in this study to obtain the Striebeck curve were 20–80 N, 0.2–
2.0 mm, and 20–60 Hz, respectively. As shown in Fig. 7, the coefficient of friction was high at high loads and low sliding speeds, as expected. With decreased loads and increased sliding speeds, however, the coefficient of friction started to decrease, indicating the change in lubrication regime from boundary to mixed lubrication. The test conditions used in this paper correspond to the mixed lubrication regime, where partial metal-to-metal contact occurs.

The texturing fractions used for the line contact oscillating tests were 5, 10, 15, and 20%. A texturing fraction greater than 20% was not considered because of the reduced load-supporting capability and the formation of very fine failure particles around the micro-pores. The oscillating tests were carried out for 20 min using a frequency of 20 Hz and a travel distance of 1.5 mm. To investigate the effect of load on the wear and friction, three loads of 20, 50, and 100 N were initially selected with a corresponding Hertzian contact stress\(^9\) of about 190, 300, and 425 MPa, respectively. The stress values are still lower than the yield strength of 500 MPa. However, the load of 100 N could cause a relatively severe deformation of the micro-pores regardless of the texturing fraction. Therefore, 100 N was discarded in this study.

Figure 8 shows the coefficients of friction as a function of the texturing fraction under loads of 20 and 50 N. Regardless of the texturing fraction, the 50 N load showed higher friction values than the non-textured specimen for all texturing fractions. In general, the friction of the 50 N load was relatively unstable during the tests, indicating a stronger interaction at the contact interface. As a result, the lubrication regime was pushed to the boundary regime with micro-texturing, where the metal-to-metal contact would be prevalent, and lead to an increase in the coefficient of friction. Therefore, we concluded that a relatively high contact load can be detrimental even in a line contact.

On the other hand, the friction of the 20 N load was lower than that of the pristine specimen. The coefficient of friction decreased continuously with texturing up to 15% and became constant at 20%. In addition, the friction became stable as oscillations continued. With the addition of micro-texturing in the case of 20 N load, the lubrication regime seemed to change to the mixed lubrication regime, as shown in Fig. 7. This implies that surface texturing can reduce the coefficient of friction when the applied load is significantly lower than the yield strength of a material, where the formation of a thin
and uniform lubricating film would be responsible for low friction.

Worn surfaces were examined after oscillating tests to study the relationships between friction and wear of the micro-textured specimens. First of all, there was no direct contact or wear around the micro-pores, as shown in Figs. 9(a) and 9(b). To investigate the cause, three-dimensional surface analysis was carried out (Fig. 9(c)), and the result showed a slightly curved feature toward a hole center, as shown in Fig. 9(d). As a result, the diameter of the hole remained approximately the same even after the oscillating tests. In addition, the area of the non-contact portion around the pores decreased with load. In other words, the nominal contact area was greater for a load of 50 N compared to a load of 20 N. The worn surface in the 50 N load case was much smoother than that in the 20 N load case, as shown in Figs. 9(a) and 9(b). These findings support the possibility of increased real area of contact in the 50 N load case, which accordingly provides a greater contact interaction between the two mating surfaces, leading to a higher coefficient of friction for 50 N cases regardless of the texturing fraction. The presence of low shear strength lubricant reduces the adhesion effect; however, plowing action caused by high contact stress is instead a dominant factor of the coefficient of friction. As explained above, a higher fluidic disturbance due to the micro-textured surface morphology and the change in surface roughness will cause the formation of a uniform and thin lubricating film.

Worn surfaces for all micro-textured samples were examined using a scanning electron microscope (SEM), and most of the textured holes showed very similar features, as explained above. Therefore, a few typical cases were selected and used to discuss the wear characteristics of micro-textured specimens in this study. Figure 10(a) shows the pristine pore shape. A small amount of very fine debris from the previous lapping process was present in the pore. The debris appeared different from fragments formed by the wear process, as shown in Figs. 9(a), 9(b), and 10(b). Wear fragments examined after oscillating tests were mostly thin, flat, and relatively large. The formation of such flake-like fragments can be explained using Figs. 10(b) and 10(c). Figure 10(c) shows that the sheared layer with surface scratches seems to cover a very smooth surface near the hole. Thus, continuous shearing action may lead to the generation of dangling fragments around and toward the pores, which are finally separated and locked within the holes. This finding can explain one of the roles of texturing as a pocket for trapping worn particles. Texturing can also contribute to decreased third-body abrasion action. Figure 10(d) shows an oscillating edge, where the worn surface is well described against the highly smooth surface.

Finally, the wear rate was calculated and compared among the different surfaces. To accomplish this, a surface profilometer was used, and a typical surface roughness profile was acquired as shown in Fig. 11. The sample used in the figure was the non-textured specimen tested under a load of 50 N. Also, a three-dimensional light interferometer was used to examine the worn profile, and the result is shown in Fig. 12. Both provided very similar profile shapes, which were used together to calculate volume. As a result, the wear rate of the non-textured specimen was $8.89 \times 10^{-7} \text{mm}^3/\text{N}\cdot\text{m}$. The wear rate for the 5% texturing fraction and 50 N load, which lead to the highest coefficient of friction, was also calculated. The worn surface was accordingly examined and is shown in Fig. 13, where the increase in wear depth from 0.8 to 1.5 µm is apparent. The wear rate
was about $2 \times 10^{-5} \text{mm}^3/\text{N·m}$, which is significantly higher than the previous rate. The high coefficient of friction contributed to this high wear rate. Lastly, we observed that wear rates in the 20 N load case were considerably lower than those in the 50 N load case regardless of texturing density. Although wear scratches were visible, their depths were insignificant, leading to a low wear rate.

4. Conclusions

This study examined friction and wear of micro-textured AISI 1045 steel, and the conclusions are summarized as follows.

(1) The ball-on-disk contact configuration causes a very high concentrated stress, as expected. The load of 20 N caused very high concentrated stress, which exceeds the yield strength of the specimen, due to the small ball size. Although the coefficient of friction can be reduced by sacrifice of the weak and soft superficial layer, such a reduction does not imply a useful contact element due to significant wear.

(2) The line contact produces less contact pressure than the ball contact. Nonetheless, a load of 50 N causes a higher coefficient of friction than the non-textured specimen. This indicates that the load and surface interactions at the oscillating interface are critical factors, especially when a large number of micro-pores are introduced. Also, like ball contact, a hard coating should be applied to prevent wear regardless of surface texturing.

(3) The role and effect of surface texturing were not observed when 50 N was used with the line contact scheme. Meanwhile, a decrease in friction was observed for the 20 N case. This result indicates that the role of surface texturing can be masked regardless of texturing density, especially when the contact pressure is relatively high.

(4) Shearing of the superficial surface due to oscillatory motion can generate a stepped surface morphology, and plate-like wear fragments form from continuous shearing action, especially around micro-pores. Micrographs clearly showed that worn fragments were captured in the micro-pores, leading to decrease in third-body abrasion action.

(5) The highest wear rate in this study was obtained from the 5% texturing fraction and 50 N load case. This result indicates that a high coefficient of friction is responsible for a high wear rate. On the other hand, wear rates in the 20 N load cases were lower than those in the 50 N cases regardless of texturing fraction, indicating that a greater load is highly detrimental to the anti-wear characteristic.
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REFERENCES