Influence of Surface Texture on Micro EHL in Boundary Regime Sliding*

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INFLUENCE OF SURFACE TEXTURE ON MICRO EHL IN BOUNDARY REGIME SLIDING

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ABSTRACT

A hard steel ball was slid against textured coated and uncoated steel disks that had strongly directionally ground surfaces. The friction coefficient during ball-on-disk rotating low-speed lubricated sliding was continuously measured. The coefficient of friction rose from ≈ 0.12, which is typical for boundary lubrication regime, to as high as 0.45 whenever the ball was sliding parallel to the grinding ridges on the disc surface. The persistence of this "spike" in the friction was observed to be correlated with the hardness of the disc surface and the nature of the coating. We propose that the frictional spike is due to loss of micro-elastohydrodynamic lubrication, combined with side leakage, leading to intimate asperity-asperity contact. As a result, the coefficient of friction is close to that which is obtained there is no or minimal lubrication. This conclusion is supported by enhanced and persistent frictional spikes in tests conducted with discs coated with a very hard nitride thin film, and constant friction for a disk coated with hydrogenated amorphous carbon, which has low coefficient of friction when there is no/minimal lubrication.

INTRODUCTION

Boundary lubrication regime is often defined as the condition in which only the lubricant chemistry (boundary films) determines the friction behavior, with the fluid film having no effect [1]. Consequently, the contact of asperities in the near-surface material is expected to play a significant role in the boundary lubrication regime frictional behavior especially at very small λ. For anisotropic surface texture, such as one with a grinding lay, the interaction between asperities in lubricated contacts is expected to be non-uniform, and vary with sliding direction, and thus may produce a directional effect on the measured friction. There are numerous analytical and modeling studies focused on the effect of surface grinding lay on lubrication [e.g., 2-5]. All these studies concentrated primarily on either the hydrodynamic or the elasto-hydro-dynamic lubrication (EHD) regimes. All these analytical studies concluded that the fluid film thickness is lower when the sliding direction (or lubricant entrainment) is parallel to the grinding lay. The thicker fluid film in the perpendicular direction is attributed to a micro-EHD mechanism and partly due to lubricant side leakage in parallel direction. Some recent studies [6-8] experimentally evaluated the effect of surface texture on frictional behavior of lubricated contacts. These studies observed that the measured friction coefficient is usually higher when the sliding direction is parallel to the grinding lay.

EXPERIMENTAL DETAILS

Friction measurements were conducted using a ball-on-flat contact configuration in a commercial pin-on-disc test rig (CSEM). The disc is made of case carburized and hardened AISI 8620 steel with a surface hardness of 6.7 GPa (62 Rc). The disc surface was ground with clear directional grinding lay (Fig. 1) with 2D surface roughness Sa of 0.314 μm, kurtosis 2.5, and skewness 0.25. The ball specimen is a commercially finished bearing grade 12.7 mm (0.5 in) diameter hardened 52100 steel. The ball hardness is also about 6.7 GPa (62 Rc) with a 2-D surface finish Sa of 23 nm. Sliding friction tests were conducted with a constant deadweight load of 5 N using various types of basestock and fully formulated motor oils. Sliding rates were typically 1 cm/s or less with a lambda ratio 0.01 to 0.1.

RESULTS

The coefficient of friction and the sliding velocity as a function of time during a lubricated sliding test using a 10W30 fully formulated motor oil is shown in Figure 2. Overall, average friction coefficient was about 0.12, which is typical for boundary lubrication regime. As the disk revolves, the ball moves in a sliding direction relative to the grinding lay that is continuously changing as a function of the rotation angle.

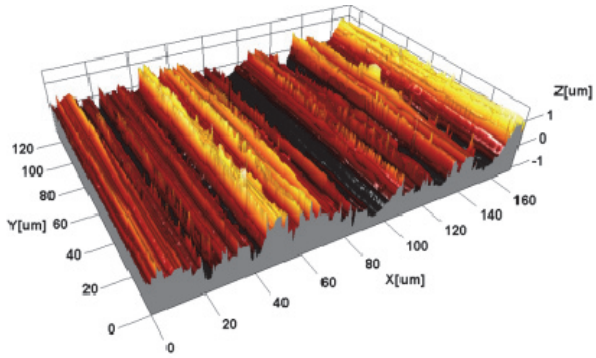

Fig. 1. Depiction of surface topography of textured disk using white-light interferometry.

When the disk was momentarily in a position that the sliding was exactly parallel to the grinding lay (designated as 0° or 180°), the friction coefficient became larger, producing an apparent "spike" in the friction coefficient.

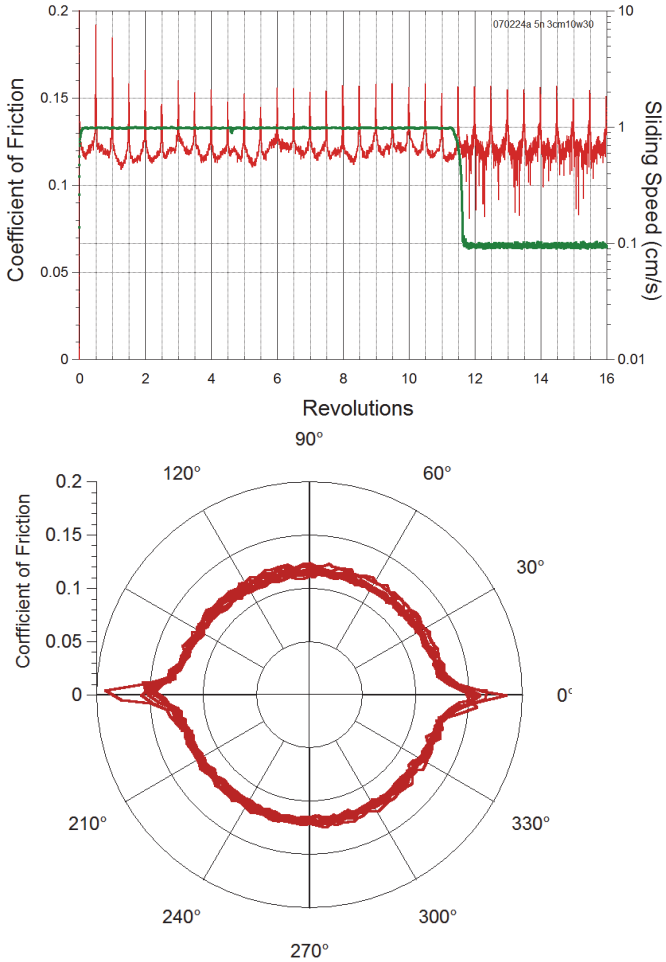

Fig. 2. Top: graph of coefficient of friction as a function of disk rotations for uncoated textured flat sliding in 10W30 oil at indicated sliding speeds. Bottom: Polar graph showing friction peaks at 0° and 180°.

When displayed as a polar plot shown in Fig. 2 bottom, the frictional spike coincides with the points when the ball specimen is sliding parallel to the grinding ridges on the disc surface. Sliding must very well aligned (within two or three degrees off parallel) with the grinding lay for the anomalously large friction coefficient to occur. Fig. 3 shows that the magnitude of the spike can become quite large for a slow sliding speed (0.05 cm/s) and a light load (1 N) when lubricated with an unadditized polyalphaolefin basestock oil. A close examination of multiple tests of this kind shows that the spike is present in all the speed ranges tested, although are more discernible at lower speed. This may be because relatively brief time is spent during sliding parallel to the grinding lay and the tribometer is not sensitive enough to detect the spike, or it may because less side leakage can occur at the higher sliding speed and thus the friction spike is actually smaller in magnitude. The magnitude decreases with increasing number of revolutions as wear occurs, but the diminution depends on counterface material. Tests with disc materials with similar surface finish but different hardness (1080 at 40 Rc, 1018 at 26 Rc and 8620 at 62 Rc) found that the base average friction was about 0.11, but that the peak friction coefficient has a maximum value during the first revolution and decreased in subsequent ones, but much faster for the softer materials. Tests were conducted with the hardened 8620 flat coated with either a 2-µm thick diamondlike carbon (DLC) layer in which with a hard 1-µm thick metal-nitride layer, where plastic deformation during sliding tests is not expected. Result of the friction did not show any grinding lay dependence for the DLC coating, but showed a strong grinding lay dependence for the nitride coating. Examination of the surface show no evidence of plastic deformation for these hard materials.

DISCUSSION AND SUMMARY

Because the tests were conducted with lubricants which that have boundary coefficients of friction near 0.12, and sliding is in boundary regime, the friction results can be explained lubricant fluid film and near surface material (asperities).
We believe that the frictional anisotropy observed with the grinding lay results from formation or lack thereof of adequate fluid film at real areas of contact. When the ball is sliding in any direction other than parallel to the grinding lay, micro-EHD lubrication, in which each asperity acts as an individual contact is occurring even though the macro-λ ratio for the nominal contact area is very low. Adequate lubricant is entrained into each asperity contact and the coefficient of friction is that of conventional oil lubrication and thus magnitude of friction coefficient is the typical value of 0.11. However, when the ball is sliding in a direction parallel to the grinding lay, there is inadequate lubricant entrainment at the tips of the grinding ridges due to fluid side leakage. Consequently, micro-EHD lubrication cannot operate and intimate asperity contact occurs. This has two effects. First, the coefficient of friction becomes or approaches that of "dry" sliding in which no lubricant molecules are present to separate the sliding surfaces, and

second, the stresses increase on the asperities themselves promoting rapid wear or local blunting.

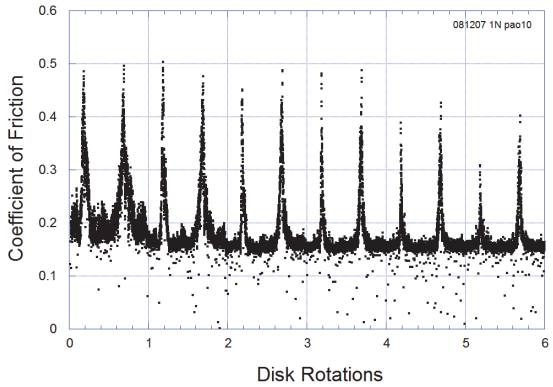

Fig. 3. Graph of coefficient of friction as a function of disk rotations for uncoated flat sliding in a PAO basestock oil at 0.05 cm/s at 1 N load in which the friction variation is large.

If this interpretation is valid then larger friction spikes should occur for sliding couples which have high dry sliding friction coefficients, and small friction spikes should occur for couples which have low dry sliding friction coefficients. Fig. 4 shows a strong effect of sliding direction on friction with oil-lubricated hard nitride and hard steel surface, but no effect with DLC in either air or oil.

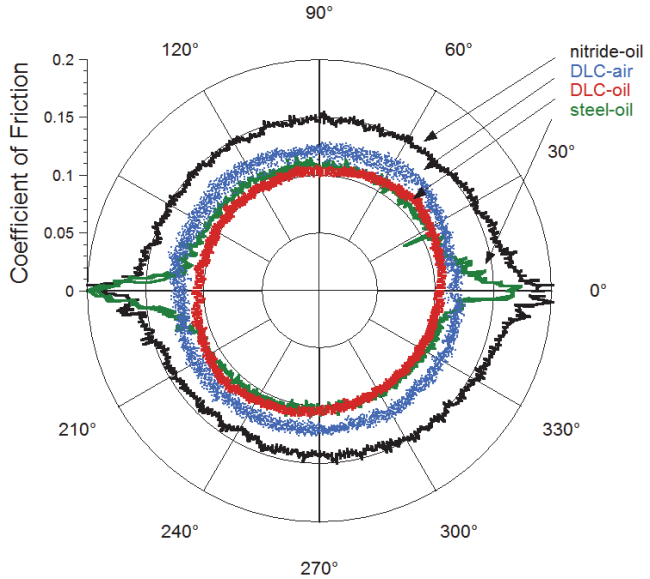

Fig. 4. Polar graph of representative sliding materials showing strong effect of sliding direction on friction with oil-lubricated hard nitride and hard steel surface, but no effect with DLC in either air or oil.

Elimination of blunting (by whatever means) should preserve the friction anisotropy. For the hard nitride coating, extended sliding was possible (>2000 revolutions) with little diminution in spike effect. The use of a fully formulated oil lubricant containing an antiwar additive tended to preserve the friction spikes vs. use of an unadditzed basestock of the same viscosity.

Profilometric comparison of worn and unworn areas showed no obvious differences, but the numerical kurtosis of the surface decreased, indicating asperity blunting. There are two instances in every revolution where sliding is parallel to the grinding lay, 0° or 180°, and in general the spikes are different from each other, due to difference in grinding. If sliding is reciprocated back and forth over a parallel area, small asymmetrical frictional details are reproducible for each direction of sliding, but the spike is not mirror imaged when sliding is reversed.
In summary, when the ball was sliding parallel to (or within a degree or two of) the grinding ridges, a substantial increase in friction coefficient (as high as 2x) was measured compared to the values for sliding in other directions. This observation is attributed to loss of micro-EHD lubrication on the grinding ridges. The magnitude of the resulting friction spike is dependent on the intrinsic coefficient of friction between the sliding surfaces with no/minimal lubrication. No spike occurred for diamondlike carbon, for which the coefficient of friction is insensitive to the presence or absence of an oil film. The persistence of the friction spike is dependent on the ability of the ridges to resist blunting.

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