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EXPERIMENTAL INVESTIGATION OF TRANSITION IN LUBRICATION REGIME FOR THIN-FILM COATED SURFACES

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ABSTRACT

Friction and wear behavior of lubricated sliding contact is determined by the operating lubrication regime. A useful approach to determining the operating lubrication regime is the calculation of the λ ratio, which is defined as the ratio of lubricant fluid film thickness (h), and the composite surface roughness (σ) of contacting surfaces (λ=h/σ). Thin-film tribological coatings are increasingly being used for application in lubricated machine elements such as gears and bearings. It is usually assumed by design engineers that application of thin-film coatings has no effect on fluid-film lubrication. This paper presents our experimental investigation of the impact of several (5) commercially available coatings on lubrication regime during a unidirectional sliding contact. Using a ball-on-flat contact configuration and lubricated with PAO basestock oil, tests were conducted in which the λ ratio was varied as a function of time, for both uncoated and coated flat specimen. In test with uncoated flat, the various distinctive lubrication regime of hydrodynamic, mixed and boundary were observed as indicated by the measured friction coefficient (Stribeck Curve). In tests with some of the coatings, especially the carbon based DLCs, there was no obvious distinctive transition in lubrication regime. In other coatings (ex. TiCN), various lubrication regime were also observed; although the rate of transition from one regime to the other was different. The effects of coatings are attributed to their inherent mechanical and tribological properties as well as their impact on the run-in process.

INTRODUCTION

Friction and wear behavior of lubricated components are determined by the lubrication regime. Operating lubrication regime is determined by the lambda ratio (λ), which is defined as the ratio of lubricant fluid film thickness (h) and the composite surface roughness (σ) of the contacting surfaces (λ=h/σ). Under hydrodynamic regime (λ>3), and perhaps elasto-hydrodynamic (EHD) regime (1<λ<2), contacting surfaces are completely separated by the lubricant fluid film. In which case, the friction is governed primarily by shearing of the lubricant fluid film dependent on lubricant rheological properties. Some elastic deformation occurs in the EHD regime, but with minimal contribution to friction. For these full-fluid film lubrication regimes, wear is insignificant, at least in the short term. Over time, contact fatigue may occur, eventually producing material loss from the surface. Under mixed (0.5<λ<1) and boundary (λ<0.5) lubrication regimes, however, extensive interactions occur between the surface materials. Hence, friction is strongly dependent on the near-surface materials mechanical properties. Also wear and surface damage occurs which will modify the operating lubrication regime overtime, since wear changes the surface roughness with time.

Thin-film coatings with significantly different mechanical properties (elastic and plastic) are increasingly being used in tribological components that are lubricated [1]. Because these coatings inherent mechanical properties, wear rate and wear mechanism could be very different from the substrate materials; it is reasonable to expect their presence to influence transition in the operating lubrication regime. Hence, the objective of the present study is to experimentally investigate the impact of thin-film coatings on lubrication regime transitions.

EXPERIMENTAL DETAILS

Lubricated friction and wear tests were conducted with ball-on-flat contact configuration in unidirectional sliding in a commercially available tribometer (Nanovea). 12.7mm (1/2”) diameter hardened (62 Hv) 52100 steel balls with surface roughness of 60 nm Ra. were tested against carburized and hardened (64.5 Hv) 4118 steel flat specimens with a surface roughness of 13 nm Ra. Tests were conducted with uncoated and coated flat specimens. A total of (5) commercially available coatings were evaluated; DLC1, DLC2, TiN, TiCN and AlTiN. Table I shows some of the properties of the tested coatings. Note that all the coatings increased the surface roughness of the flat specimens.

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Table I: Coatings properties

Coatings	Deposition method	Thickness (µm)	Manufacture Hardness (Hv)	Nano Hardness (Gpa)	Elastic Modulus (Gpa)	Roughness (nm)
TiN	PVD	3.4	3000	30	370.5	70
TiCN	PVD	2.2	4000	40.2	345.5	41
AlTiN	PVD	2.8	3500	34.5	290	85
DLC-1	PVD	3.6	1500-3000	14.7	132.5	45
DLC-2	PACVD	1.7	1500	14.9	163.5	207

Tests were conducted with a constant normal load of 5N (0.69 GPa contact pressure) and lubricated with PAO4 (η_{40} =17 cSt) under fully flooded conditions at ambient room temperature and humidity. A discrete 24 step (2-5 minute duration) speed protocol with variation ranging from 0.04 to 26.2 cm/sec was used as means of varying the lubricant fluid film thickness and consequently the λ ratio. Tests were started at high speed, ramped down to the lowest value, and ramped back up again to the maximum value. The cycle was repeated two more times without stoppage between each cycle. This protocol will enable the assessment of run-in and its impact on friction and lubrication regime transition.

RESULTS AND DISCUSSIONS

The variation of friction coefficient at different sliding speed during the 3 cycle test duration in tests with uncoated flat is shown in Figure 1a.

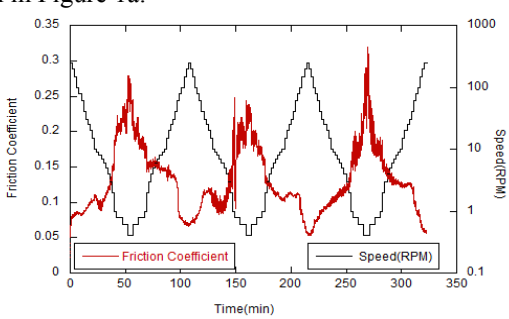

Figure1a: Friction coeffcient at different speeds for uncoated surface.

In order to effectively identify the operating lubrication regime, the variation of friction coefficient with λ ratio during each of the speed ramps is shown in Figure 1b. In the figure, distinctive lubrication operating regimes can be easily discernible. For the full-fluid film regime (λ>2), the friction coefficient was lowest and nearly constant. Furthermore, the friction coefficient is independent of the number of speed ramp cycle. In the EHD, mixed and mild boundary lubrication regime (0.2<λ<2), there was a gradual increase in friction coefficient with decreasing λ ratio. This is attributed to more contribution from the near-surface material to interfacial friction. As the contact transition to severe boundary regime, (λ<0.2), rapid and significant increase in friction was observed as the λ ratio decreases. In this regime, the shearing of near-surface materials dominates the friction behavior, consequently the friction was observed to be independent of the number of speed ramp cycles.

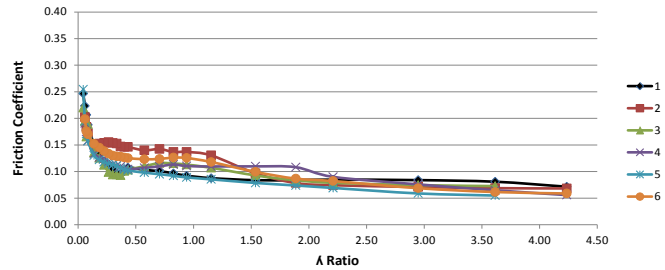

Figure 1b: Friction coefficient versus λ ratio for uncoated surface.

The presence of DLC coatings on the flat specimen produced a substantial change to the friction behavior as shown in figure 2. In general, for the two DLC coatings tested, there was no clear transition in friction behavior as the λ ratio varies. Rather, there was a gradual (almost linear) increase in friction coefficient as the λ ratio decreases. In the severe boundary regime (λ<0.2), the friction coefficient in tests with both DLCs was very low compared to uncoated surface under the same test conditions. This is attributed to the general low friction characteristic of DLC coatings. This class of coating often exhibit friction coefficient in the range of 0.1 and 0.2 under dry sliding contact condition [2-3]. The only subtle difference observed in the friction behavior of the two DLC coatings is the effect of the number of speed ramps. For DLC1, the friction under severe boundary lubrication regime is the same for all ramps, but here was a slight decrease in friction under fluid film lubrication for subsequent speed ramps (Fig 2a). On the other hand, friction was unchanged for all speed ramps under fluid film lubrication for DLC2, but increased slightly in subsequent cycles under severe boundary condition (Fig 2b.).

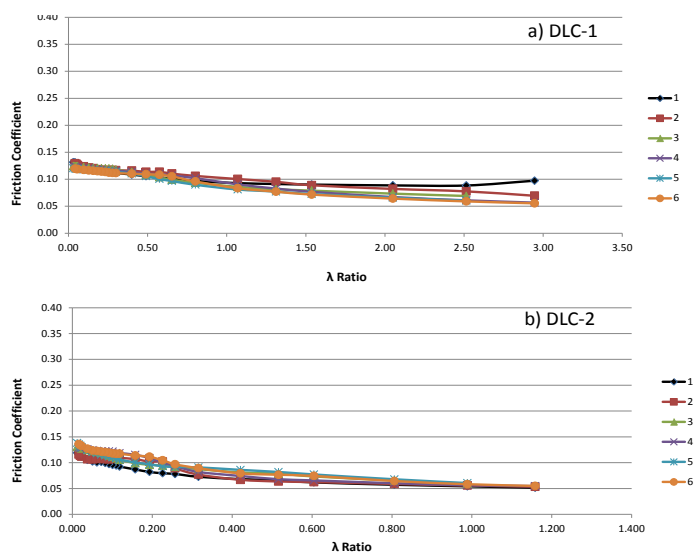

Figure 2: Friction versus λ ratio for: a) DLC-1 and b) DLC-2

The variations of friction with λ ratio for the Ti-based coatings (TiN, TiCN and AlTiN) are shown in Figure 3. For TiN (Figure 3a) the fluid film regime was operating to λ ratio as

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low as 0.6, compared to 2.0 for the uncoated surface. Except for the first speed ramp cycle, the friction was observed to be independent of number of cycles in this lubrication regime. Below λ of 0.5, transition in friction behavior somewhat similar to uncoated surface was observed (compare Figure 3a and 1b). However, under severe boundary regime, the friction coefficient decreased in subsequent speed ramps. Transitions were also observed in friction for tests conducted with TiCN coatings (Figure 3b). It should be noted that this coating showed the highest friction, especially in the mixed and boundary regime, of all the materials evaluated. In spite of clear transition in friction as the lubrication changes, the friction coefficient shows a tendency to increase with decreasing λ ratio in all the regimes. In addition, the first speed cycle clearly showed a much higher friction than subsequent ramps. Figure 3c shows the frictional behavior for tests with AlTiN coatings. For this coating no obvious frictional transition was observed until extremely low λ (<0.1). The friction coefficient increased in a near linear manner with decreasing λ ratio. It was also observed that the friction coefficient decreased significantly each subsequent speed cycle in all the lubrication regimes. The first cycle showed much higher friction that subsequent ones.

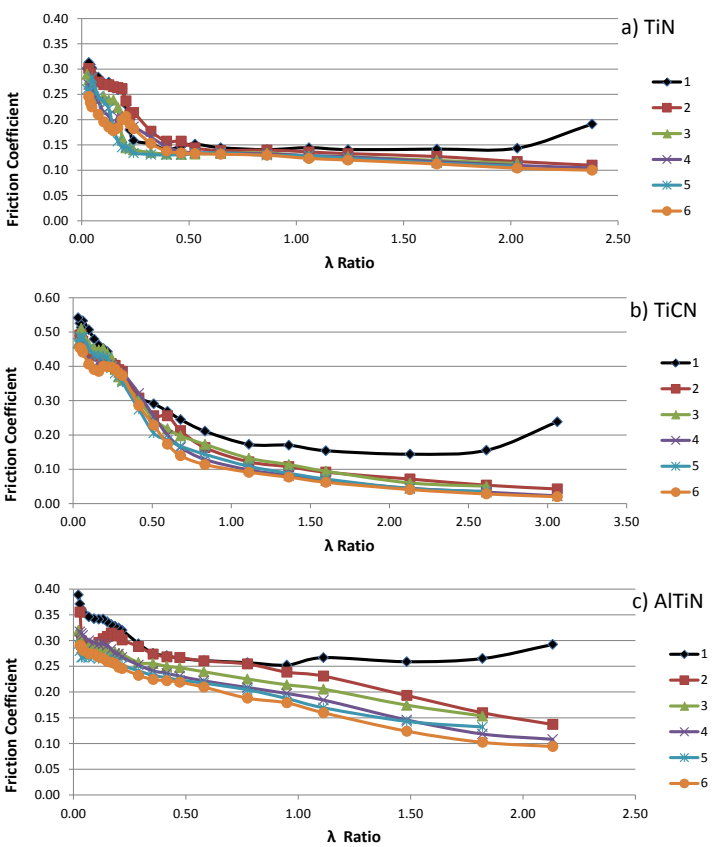

Figure 3: Friction coefficient versus λ ratio for Ti-based coatings: a) TiN, b) TiCN and c) AlTiN

In general, for the 3 Ti-based coatings evaluated, the magnitude of friction coefficient in the severe boundary regime (λ<0.2) appears to be dependent on the coating hardness. TiCN has the highest hardness (Table I) and the highest severe boundary friction, followed by AlTiN and finally TiN; commensurate with their respective hardnesses. This is the consequence of the near surface materials contribution to friction under extreme boundary lubrication. It was also observed that for these three coatings the first speed cycle test usually starts with relatively higher friction, and the first speed ramp exhibits higher friction than the subsequent ones. This may be result of the presence of macro-particles in these coatings. If removed by a wear process during the early stages of testing, macro-particles may have minimal effect as the test progresses. On the other hand, macro particle could serve as initiation sites for metal transfer from the steel ball counterface. Transfer of metal unto ceramic surface in metal/ceramic contact pairs has been observed in previous studies [4]. The Ti-based coatings are ceramics, and hence there is the possibility of metal transfer unto the coating surface. Such transfer is expected to affect the frictional behavior during subsequent cycles. Indeed examination of the wear track on the Ti-based based coatings showed the presence of metal transfer around macro-particles as illustrated in Figure 4. Nevertheless, further work will be conducted to further elucidate this observation.

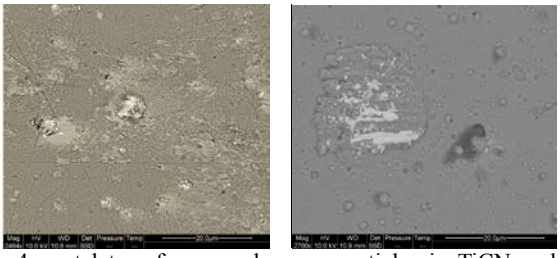

Figure 4: metal transfer around macro-particles in TiCN and AlTiN coatings.

ACKNOWLEDGMENTS

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