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EFFECT OF CARBON-BASED THIN-FILM COATINGS ON FRICTIONAL BEHAVIOR UNDER BOUNDARY LUBRICATION REGIME

TRACK OR CATEGORY

Surface Engineering

AUTHORS AND INSTITUTIONS

C. Lorenzo-Martin, O. O. Ajayi, R.A. Erck, G.R. Fenske
Energy Systems Division, Argonne National Laboratory; Argonne, IL 60439, USA.

INTRODUCTION

Carbon-based coatings, especially amorphous diamond-like carbon (DLC) have been developed over the past decade for a variety of tribological applications. This is because of the inherent low-friction and wear properties of this class of coatings [1, 2]. These coatings are often used in dry contact applications, e.g. mechanical face seals, forming tools, and computer hard disc. Consequently, most of the early studies on the tribological performance of DLC were conducted under dry sliding contacts. Friction coefficient as low as 0.05 (or maybe even lower) have been observed with DLC coatings when sliding in dry contact [3-5]. Similarly, low wear has been reported for DLC coatings involved in dry sliding. However, the majority of tribological components and machine elements are usually lubricated. As a result, studies on the performance of DLC coatings in lubricated sliding contact are increasingly being conducted in recent years [6-8]. Nevertheless, there is still inadequate understanding of the impact of oil lubricant on tribological performance of DLC coatings. Such knowledge is required in order to effectively integrate lubricant technologies with DLC coatings for optimal tribological performance. In this paper studies of the friction and wear performance of three different DLC coatings lubricated with four different oils are presented and their performance is compared to the performance of the uncoated steel.

EXPERIMENTAL DETAILS

Friction and wear tests were conducted with a roller-on-flat in reciprocating sliding line contact configuration, as illustrated in Figure1. The 6.3 mm diameter and 10.3 mm long uncoated steel roller was made of hardened 4140 steel (56 Rc) and has a surface roughness of 0.2 µm Ra. The 2”x1.5”x0.25” flat specimens were made of 4148 case carburized steel with hardness of (64.5 Rc). The flat specimen surface was polished to a finish of 0.019 µm Ra. Three different DLC coatings were deposited on the flat surface by a PACVD process. Some relevant properties of the coatings are summarized on table I. Lubricated tests were conducted using normal load of 150N (0.33 GPa. Average Hertzian pressure), stroke length of 10 mm, frequency of 0.5 Hz, producing a linear velocity of 10mm/s, and temperature 100 ºC for a duration of 3 hrs. Tests were conducted with four different lubricants as shown in table II. Lubricant A and B are commercially fully formulated for ferrous materials; A is optimized for friction reduction, while lubricant B is optimized for wear protection. Calculated □ ratios under the test conditions used in present study for all the lubricants at the start and finish of tests were in the range of 0.03-0.40; all of which are in boundary lubrication regime.

Table I: Properties of the coatings

Coatings	Deposition method	Type	Chemistry	Thickness (µm)	Hardness (Hv)	Roughness (nm)
DLC-1	PVD	multilayer	Me-C-H	1.9	1200-1500	172
DLC-2	PVD	multilayer	WC-C	2.6	1000-1500	133
DLC-3	PVD	multilayer	WC-C	3.5	1500-3000	56
4118	none	No layer	steel	0	850	19

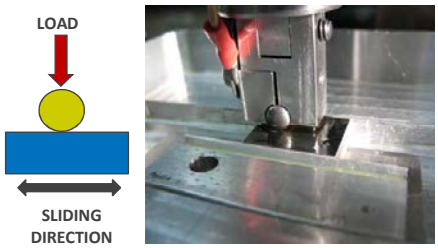

Figure 1: Test rig configuration

Table II: Properties of the lubricant

LUBRICANT	PAO-10	PAO-4+ Additives	Synthetic A	Synthetic B
Viscosity 40°C (cSt)	71.1	15-20	233.5	132
Viscosity 100°C (cSt)	10.70	4.20	18.7	17.5
Viscosity Index	-	-	92	146
Flash point (°C)	272	204	235	221
Pour point (°C)	-51	-57	-15, 5	-45
Density (kg/m³) at 15.6C	837	819	905	860

RESULTS AND DISCUSSION

Figure 2 summarizes the friction behavior of three DLC coatings tested with four different lubricants in comparison to the baseline uncoated steel. In the absence of additives (basestock PAO10) friction coefficient for all DLC coatings is practically constant for the duration of the test with a value of almost 0.1. For uncoated steel flat, friction coefficient was also nearly constant, but noticeably higher (0.15) for the same lubricant (Fig. 2A). In tests with formulated lubricants, a variety of frictional responses are observed. By adding ZDDP and MoDTC additives to PAO, friction for the steel flat was rapidly reduced to a steady value of (0.04) as the additives in the lubricant reacted with the surface materials to form tribochemical films. The same additives were also effective in reducing friction when tested in the hydrogenated carbon coating (DLC-1) to a value 0.05, although at a lower rate compared to uncoated surface. DLC-2 and DLC-3 tested with the same lubricant showed a rapid decreased in friction during the run in period (first few minutes) but afterward friction coefficient showed a gradual increase with time to a final value of 0.09 at the conclusion of the test, and no steady value was reached (Fig. 2B). For both of the fully formulated lubricants (A and B) coatings and uncoated steel substrate exhibited the same frictional behavior (Fig. 2C and 2D). Lubricant A was very efficient in reducing friction in a short period of time to a steady value around 0.04 for the uncoated steel substrate, and (0.045-0.05) for the different carbon coatings. Fully formulated lubricant B had minimal effect on frictional response of the different materials. Friction coefficient remained nearly constant with time for the uncoated steel substrate (0.09) and the three DLC coating (0.09-0.1).

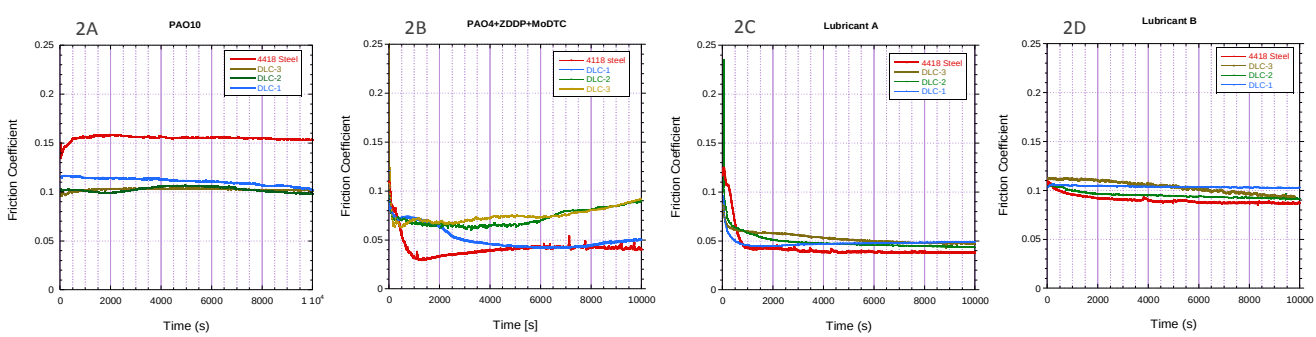

Figure 2: Friction coefficient variation with time for different DLC coatings and uncoated steel substrate lubricated with: (a) basestock PAO, (b) PAO with ZDDP and Mo-DTC additives, (c) lubricant A, (d) lubricant B.

Wear tracks on the flats as well as in the steel rollers counterface were characterized at the conclusion of the tests. Because the wear on the flats was minimal (not measurable), an assessment of effect of coatings on wear was conducted by measuring only the wear on the rollers counterface. Figure 3 shows a comparison of wear in rollers rubbed against different flat materials in different lubricants used in this study. Formulated lubricants were highly beneficial in reducing roller wear when slid against the uncoated steel substrate. Compared to unformulated lubricant (PAO10), wear was reduced by 25 times when additives in the formulated lubricants were able to react with steel rollers to produce tribochemical films. Substantial reduction in roller wear was observed when sliding against any of the DLC coatings compared to the uncoated steel in the unformulated lubricant PAO10. In tests with formulated lubricants, more wear was observed in the rollers rubbed against DLC compared to unformulated oil. This low wear in PAO 10 may be attributed to a possible transfer of surface

carbon film into the roller. DLC coatings are known to protect the counterface surfaces under dry condition by transfer of an amorphous carbon film from the coating to the counterface [9]. Although the current study is lubricated, DLC effectively reduced wear in the counterface especially in the absence of additives, as indicated in Figure 3. The increased wear in roller sliding against DLC in formulated lubricant could be as a result of interference of the oil additives with carbon transfer process.

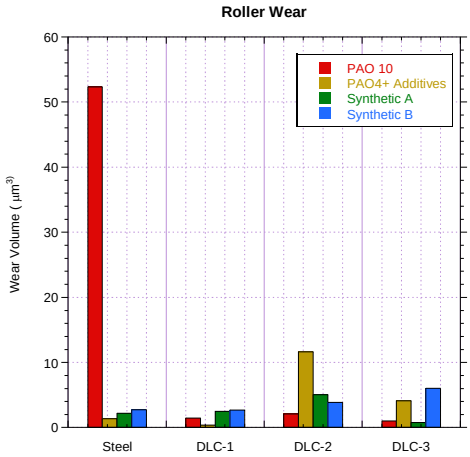

Figure 3: Roller wear volume after sliding against DLC coatings and uncoated steel substrate.

Optical microscopy and SEM characterization of the flat surfaces showed minimal damage in all DLC coatings for the four lubricants evaluated. In the uncoated steel substrate, minimal damage was observed only when additives in the lubricant were able to form tribochemical films on the surfaces in contact. Rollers tested with formulated lubricants, all exhibited some mild polishing due to run-in process and it is accompanied by tribochemical film formation in areas of higher contact stress. In the absence of lubricant additives (basestock PAO), roller damage was very different when tested against the uncoated steel substrate and DLC coatings. Abrasive wear and oxide formation were dominant when sliding against the uncoated steel substrate, while some transfer films with almost no wear were observed when sliding against DLC coatings. The lack of wear might suggest that these films were probably transferred at the very beginning of the test, hence protecting the surface against wear damage. More work is needed to understand the origin and nature of this transfer film.

CONCLUSIONS

Based on experimental results from the present study DLC coatings have beneficial effects on tribological performance by reducing both friction and wear in contacts lubricated with unformulated basestock oils compared to uncoated steel substrate. In fully formulated lubricants, DLC coatings were not as effective as the uncoated steel substrate, although still beneficial.

REFERENCES

[1] A. Grill, Surf. Coat. Technol. 9495 (1997) 507.
[2] K. Holmberg, A. Matthews, Coating tribology-properties, techniques and applications in surface engineering, Tribology Series 28, Elsevier, Amsterdam (1994), p.442.
[3] A. Erdemir, C. Bindal, G.R. Fenske, C. Zuiker, P. Wilbur, Surf. Coatings Technol. 86-87 (1996) 692-697.
[4] D.S. Kim, T.E. Fisher, B. Gallois, Surf. Coatings Technol. 49(1991) 537.
[5] B. Marchon, M.R. Khan, N. Heiman, P. Pereira, A. Lautie, IEEE Trans. Magnet. 26 (5) (1990) 2670.
[6] T. Haque, A. Morina, A. Neville, R. Kapadia, S. Arrowsmith, Wear 266 (2009) 147-157
[7] M. Kalin, E. Roman, L. Ozbolt, J. Vizintin, Thin Solid Films 518 (210) 4336-4344
[8] K. Topolovec- Miklozic, F. Lockwood, H. Spikes, Wear 265 (2008) 1893-1901
[9] Alfred Grill, “Diamond-like carbon: state of the art”. Diamond and Related Materials 8 (1999) 428-434.

KEYWORDS

Coatings, boundary lubrication, additive-deposited film.