Effect of coating thickness on tribological performance of CrN in dry sliding contact

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ABSTRACT

One of the most commonly used tribological thin-film coatings is Chromium Nitride (CrN), typically deposited by PVD process. Examples of current applications of this coating include cutting and forming tools: ICE piston ring, hydrodynamic pumps, etc. In selecting coating for tribological applications, one of the critical parameter is the coating thickness. In the present work, we experimentally studied the effect of coating thickness on friction and wear performance of CrN coatings under unidirectional sliding. Test were conducted with ~ 1, 5 and 10 microns thick coatings deposited on a hardened H-13 steel substrate by plasma enhanced magnetron sputtering (PEMS) process. The friction behavior was strongly dependent on coating thickness, especially at relatively low loads. At higher load however, the thinner coating (1 μm) was quickly worn through while the thicker ones (5 and 10 μm) remained intact. Wear in both, the counterface WC material and the coating was also observed to depend on coating thickness. The observed effect on coating thickness on tribological behavior is attributed to differences in the microstructure and mechanical behaviors of coatings as function of thickness.

INTRODUCTION

Varieties of coatings are used for tribological applications, depending on the desired performance attributes. Some coatings are used for friction reduction, others for failure prevention (wear, scuffing, etc.). Effective selection of a particular coating for a particular application is a rather complex engineering problem. The same coating can be produced by different techniques, and with different properties. Some of the commercially available coatings are thick (often by plasma spray) and similar processes. Others are thin (usually by different variants of PVD or CVD). For many mechanical tribological components, thin-film coatings are usually preferred because of minimal to no post-coating processing. There are currently numerous types of thin-film coatings commercially available, TiN being the oldest or "gold-standard". Over the past decade or so, CrN is also increasingly finding more practical applications. This is in part due to its combination of desirable properties. Compared to TiN, it has slightly lower hardness, but higher fracture toughness and ductility making it more appropriate for many high stress and impact applications. Examples of applications include cutting and forming tools, dies and automotive components such as injection valves and piston rings for diesel engines [1-3]. In general, for thin-film coating, one if not the most critical, of the attributes that governs tribological performance is the coating thickness. The thickness affects the residual stress state in PVD coatings and also determines the stress field distribution under contact conditions; both of which are relevant to failure pathway and mechanisms. There is often an optimal coating thickness in terms of failure performance. If the coating is too thin it may be worn more quickly and its effect could be minimal. On the other hand if it is too thick, it exhibits high tensile residual stress state, which is detrimental to performance. If coatings could be produced with relatively high thickness, uniform microstructure and low residual stress state, their tribological performance can be enhanced. Recently, a technique to produce thick, dense and low stress coatings by PEMS was developed [4]. With this development it should be possible to evaluate the direct impact of coatings thickness on tribological performance, without the usual problems associated with thick coatings. This paper presents an experimental evaluation of the effect of coating thickness on tribological performance of CrN produced by PEMS under dry sliding contact conditions.

EXPERIMENTAL DETAILS

Friction and wear tests were conducted in unidirectional dry sliding contact using a ball-on-flat configuration. Four materials were tested: steel substrate and CrN coating with 3 different thicknesses. The 2"x1.5"x0.25" flat specimens were made of H-13 steel with hardness of (58.5 Rc). The flat

specimen surface was polished to a finish of 0.005 µm Ra. CrN coatings of three different thicknesses (1, 5 and 10 µm) were deposited on steel flat by a PEMS process. The coated flats designated CrN-1, CrN-2 and CrN-3, corresponding to 1, 5 and 10 µm thickness respectively, had corresponding surface finish of 0.011, 0.024 and 0.025 µm Ra. The hardness and Young's modulus were measured using Triboindenter TI-950, Hysitron Inc. A Berkovich diamond tip with an approximate radius of curvature of 150 nm was used as a nanoindentation tip. Table I summarizes some properties of the coatings and substrate materials.

Table I: Coatings properties

Coatings	Deposition method	Thickness (µm)	Elastic Modulus (GPa)	Hardness (GPa)	Roughness (nm)
CrN-1	PEMS	1	220	18	11
CrN-2	PEMS	5	180	12	25
CrN-3	PEMS	10	220	16.5	24
H-13	none	0	212	8.4	5

Dry unidirectional sliding tests were conducted using a ball-on-flat configuration (Figure 1) with 1/2" diameter WC ball, polished to 0.038 µm Ra. sliding against uncoated and coated specimens. Normal loads of 5, 10 and 20 N (1.07, 1.15 and 144 GPa. average Hertzian pressure) were used for testing. Tests were run for 60 minutes with a linear speed of 1cm/s. Friction coefficient was continuously measured during the testing. Wear on flats and counterface ball materials were evaluated at conclusion of the test. Worn surfaces were characterized by optical and scanning electron microscopy equipped with EDAX analysis.

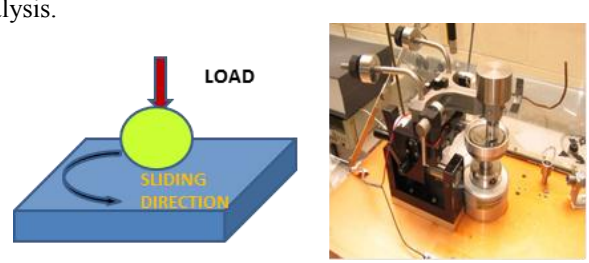

Figure 1: Ball-on-flat test rig for unidirectional sliding testing.

RESULTS AND DISCUSSION

Figure 2 summarizes the friction behavior of the three CrN coatings and steel substrate tested under unidirectional dry sliding with WC ball. For the uncoated steel flat, the friction behavior at 5 and 10 N loads are nearly identical. In both cases, the friction coefficient increased rapidly at the start of the test to a maximum value of about 0.6. This is followed by a gradual decrease to a minimum value of about 0.4, after which a continually gradual increase occurred to the end of test. At the higher load of 20N, somewhat a different friction behavior was observed (figure 2C). Similar trend of rapid increase, followed by both gradual sequential increase and decrease, was observed for the first 1200 sec. of sliding. This was then followed by a sudden rapid decrease to a near constant value of 0.35 for the remaining duration of test. This frictional behavior is attributed to the extensive formation of transfer film on the uncoated steel flat as shown in Figure 3.

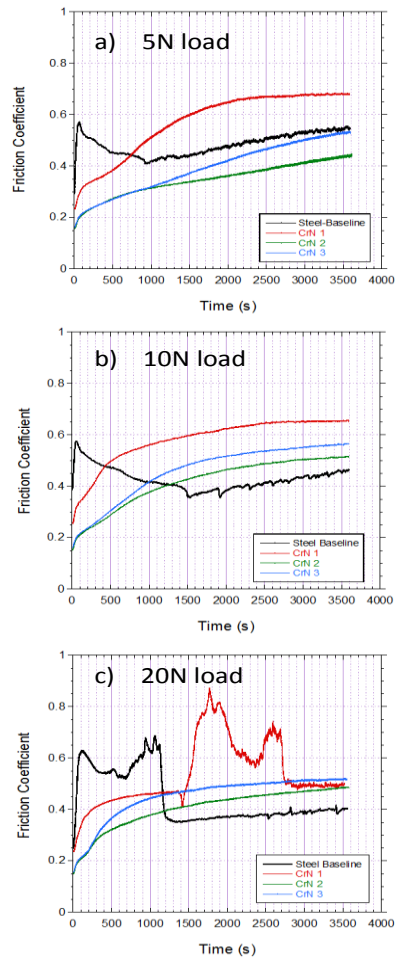

Figure 2: Friction evolution with time for unidirectional dry sliding

It was observed that higher loads produced more transfer film. In the 20N load test, the rapid decrease in friction is attributed to large coverage of contact area by WC transfer film, such that in the later stage of test, the contact interface consist of sliding of WC transfer film on WC; which is known to have friction of about 0.35 [5].

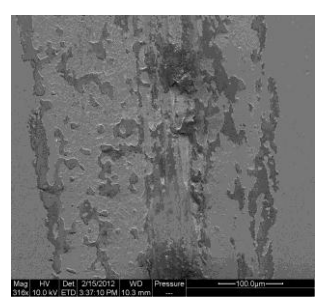

Figure 3: steel flat tested against WC ball in dry unidirectional sliding

The friction in test with CrN coated flats was almost identical at 5 and 10 N loads, too. For the three coatings, friction coefficient showed a general gradual increase. For both loads, the friction coefficient in CrN-1 (1 µm thickness) was consistently higher for the entire test duration. CrN-2 and crN-3 coatings showed identical friction coefficient for the first few 100 sec of testing, but by the end test, friction with CrN-2 was lower. At high load of 20N, the friction behavior in test with CrN-2 and CrN-3 remained unchanged, but a sudden rapid increase in noise behavior was observed in test with coating CrN-1 after 1500 sec. This transition in CrN-1 coincided with the coating being worn through as shown in figure 4.

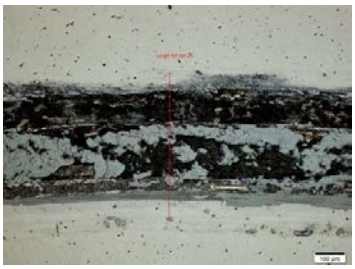

Figure 4: CrN-1 coating tested against WC ball in unidirectional sliding

Wear in both the ball and the flat specimens were measured at the conclusion of each test with optical profilometry. Figure 5 shows the wear results in the ball and flat specimens. Except for test with CrN-1 at 20N, the wear in WC balls appears to increase nearly linearly with load. Abrasive wear is the predominant material removal mechanism in the WC ball. The much higher wear in CrN-1 test at 20N is the result of the coating wearing through thereby producing more damaging hard coating abrasives.

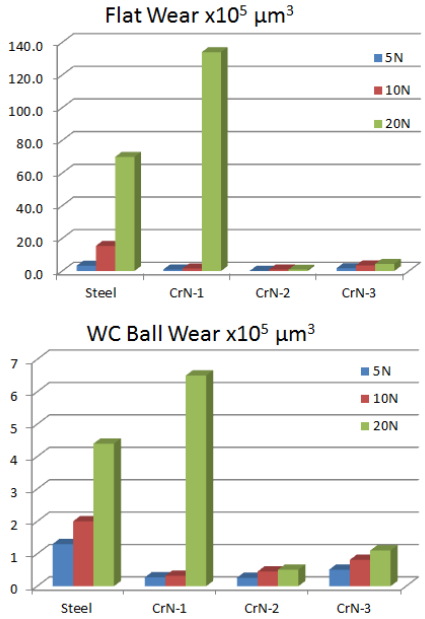

Figure 5: flats and WC ball wear after unidirectional dry sliding tests.

It is also observed that the uncoated H-13 steel flat produced more wear on the WC balls than the harder CrN coating. This is attributed to the presence of relatively hard carbide particles, notably VC, MoC and CrC on the steel sample microstructure and surface. In the flat specimen, minimal wear was observed on the CrN coating, except again for the CrN-1at 20N. In the steel flat, wear increased with load. The only observed wear mechanism in the CrN coatings is polishing wear and some localized damage as, shown in Figure 6.

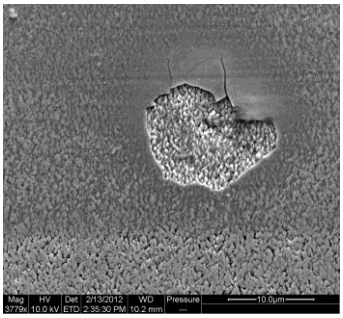

Figure 6: localized damage in CrN coating after dry sliding test.

Overall, results of the present study clearly showed that thin-film coating thickness could have a significant impact on their tribological behavior. In the present study, CrN with thickness of 5 µm showed optimal performance in terms of friction and wear. It showed the lowest friction and the least wear. CrN-3 (10 µm thickness) also showed superior tribological properties compared to the 1 µm coating. Under high contact pressure (20N load), the thinner coating was quickly worn through while the thicker ones showed minimal damage. Undoubtedly, there will be optimal coating thickness for different contact configuration and tribological applications.

ACKNOWLEDGMENTS

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