EVALUATION OF NEAR FRICTIONLESS CARBON COATINGS USING FOUR-BALL WEAR TESTER

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ABSTRACT
Near frictionless carbon (NFC) coatings were deposited in a large-area filtered cathodic arc system by plasma-enhanced chemical vapor deposition. An NFC coating with carbon-enriched TiC bond layers was deposited on half inch diameter steel (M50) balls. The four-ball wear test was used to evaluate the performance of the NFC coating. The endurance limit of the NFC coating was determined by starting the wear test at a relatively low load and increasing the load by a fixed amount after a given time interval to a final load at which the friction force reached a certain level. The four-ball wear test was conducted in fully flooded, starved, and dry lubrication conditions. MIL-PRF-23699 oil was the lubricant. Test results indicated a much higher endurance limit for the NFC-coated balls compared to that of uncoated balls.

Key words: Carbon Coating, NFC, Filtered Arc, Four-Ball Wear Test, Endurance.

1.0 INTRODUCTION
The unique properties of diamond-like carbon (DLC) films make them suitable for a variety of applications that require high wear resistance, low friction coefficients, and chemical inertness. The tribological properties of the DLC films depend upon the method of preparation and the test environment (humidity level). In the recent past, a form of DLC film known as near frictionless carbon (NFC) was developed [1]. This material provides a friction coefficient of 0.001–0.0003 and wear rates of $10^{-9}$ to $10^{-10}$ mm$^3$/Nm in inert gas environments (negligible humidity). Even in a laboratory environment (humidity ~40–50%), the NFC film provides relatively low friction and wear. The NFC films are originally produced by plasma enhanced chemical vapor deposition (PECVD) using a mixed gas of CH$_4$ and H$_2$. In this process a thin layer of Si (50-70 nm) was deposited as bond layer.

Recently, we developed NFC films in a large-area filtered arc deposition system using plasma-enhanced chemical vapor deposition (PECVD). A NFC film with carbon-enriched TiC as a bond layer was deposited on steel substrates. The friction and wear characteristics of the NFC films were characterized in dry (N$_2$), humid (laboratory atmosphere), and salt spray atmosphere utilizing the pin-on-disc technique. The details of the deposition and characterization the NFC films are described in an earlier paper [2]. In this paper, we report the friction and wear characteristics of NFC films determined by the four-ball wear test.

2.0 EXPERIMENTAL
Conventionally, four-ball wear tests are used to determine the wear preventive and extreme pressure characteristics of greases and lubricating oils in the sliding steel-on-steel configuration. The point-contact interface is obtained by rotating a 0.5-inch-diameter steel ball (drive ball) under load against three stationary steel balls (test balls) immersed in the lubricant. A damped pneumatic cylinder achieves loading. The cup holding the test balls floats on a frictionless air bearing, resulting in a fairly accurate measure of friction force. The rotating speed, normal load, temperature, and run time can be varied.

A number of 0.5-inch-diameter M50 steel balls were coated with NFC films having carbon-enriched TiC as a bond layer. MIL-PRF- 23699 was used as lubricant. Tests were conducted in fully flooded, starved, and dry conditions. In the fully flooded condition, sufficient lubricant was placed in the housing to keep the test balls immersed (ASTM D4172). The starved condition was obtained by dipping the drive ball in the lubricant, taking it out, and inserting it into the chuck. No lubricant was used in dry test conditions. Fully flooded (F) and starved (S) tests were conducted at a load of 20 kg (initial Hertzian stress, 3.31 GPa). Both F and S tests were done at room temperature (RT) and 200°C. Dry tests were done at a load of 5 kg (initial Hertzian stress, 2.14 GPa) and at RT. Variable load tests were done at RT. All the four-ball wear tests were done at a speed of 1200 RPM and in the laboratory atmosphere. Two tribocontact configurations were used. In one configuration, the drive ball and the test balls were uncoated (M50/M50), and in the second configuration, the drive ball was uncoated whereas the test balls were coated with NFC (M50/NFC). After each test the balls were cleaned in hexane, acetone, and isopropanol. The wear scar diameter on each of the test balls was measured, and the average was taken. Friction force was continuously monitored during the test.
3.0 RESULTS

Table 1 depicts the average wear scar diameters of the test balls in fully flooded and starved conditions. The wear in M50/M50 and M50/NFC under F, RT tests was found to be about the same. This observation indicates that the given test conditions are not adequate to provide the differentiation in wear between M50/M50 and M50/NFC configurations. Perhaps under such wear test conditions the lubricant effect is dominant over surface chemistry. In F, 200°C tests, some difference in the wear was observed with M50/NFC showing lower wear. However, in S (RT and 200°C) tests, there is a significant difference between the two configurations, with M50/NFC exhibiting much lower wear.

Table 1. Relative Wear

<table>
<thead>
<tr>
<th>Test (Drive Ball/Test Balls, Fluid Level, Temperature)</th>
<th>Average Test Ball Wear Scar Diameter (mm)</th>
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</thead>
<tbody>
<tr>
<td>M50/M50,F,RT</td>
<td>0.29</td>
</tr>
<tr>
<td>M50/NFC,F,RT</td>
<td>0.28</td>
</tr>
<tr>
<td>M50/M50,F,200°C</td>
<td>0.54</td>
</tr>
<tr>
<td>M50/NFC,F,200°C</td>
<td>0.43</td>
</tr>
<tr>
<td>M50/M50,S,RT</td>
<td>1.65</td>
</tr>
<tr>
<td>M50/NFC,S,RT</td>
<td>0.91</td>
</tr>
<tr>
<td>M50/M50,S,200°C</td>
<td>0.80</td>
</tr>
<tr>
<td>M50/NFC,S,200°C</td>
<td>0.28</td>
</tr>
</tbody>
</table>

For the endurance (scuffing) limit, four-ball wear tests were performed by increasing the load by a fixed amount after a fixed time interval until the friction force reached a certain level. To accomplish, the wear test was started at a load of 20 kg and after every five minutes the load was gently increased by 10 kg. A time interval of 5 minutes roughly corresponds to 6000 cycles. The load increase was done manually and was completed within 30 seconds. Such tests were performed in both F and S conditions. The friction force profile was continuously monitored during the entire test. Figure 1 is friction force vs. number of cycles plots for M50/M50 and M50/NFC under F condition. For both configurations, friction increases with increasing load. In M50/M50, friction spikes initially at each load increase and then settled down to a steady state regime. At 80 kg load the friction force spiked to over 1600 g when the wear test was terminated. In the case of the M50/NFC configuration, the friction spikes were absent up to a level of 130 kg (maximum initial Hertzian stress ~6 GPa). At 130 kg load, the friction force spiked over 2000 g when the test was terminated. In conclusion, the data clearly indicate better tribological performance of NFC coated balls under fully flooded, starved, and dry wear conditions compared to that of the uncoated balls. This work also demonstrates the potential of the four-ball wear test in evaluating the performance of tribological coatings.

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