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Evaluation of DLC coatings for spark-ignited, direct-injected fuel systems

J. Hershberger*, O. Öztürk[1], O.O. Ajayi, J.B. Woodford, A. Erdemir, R.A. Erck, G.R. Fenske

Energy Technology Division, Argonne National Laboratory, Bldg. 212, Rm. D204, 9700 S Cass Ave., Argonne, IL 60439, USA

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Abstract

The suitability of diamond-like carbon (DLC) coatings for reduction of friction and wear in spark-ignited, direct-injected fuel systems has been investigated. Three commercially available DLC coatings have been compared to near-frictionless carbon (NFC) coatings and to uncoated metal in standardized lubricity tests and custom wear tests intended to simulate the fuel system environment. The coatings were applied to both laboratory balls and flats and to production fuel injector tips. These coatings provided improvements in friction and wear over uncoated surfaces, with the greatest improvements found in parts coated with NFC.

Keywords: Amorphous; Profilometry; Plasma-assisted chemical vapor deposition (PACVD); Carbon

1. Introduction

The results presented in this paper were produced as part of a US Department of Energy (DOE) program called Partnership for a New Generation of Vehicles (PNGV). The PNGV goals included helping automakers to bring to market a passenger car possessing the functional specifications of a 1994 family sedan but achieving 80 mpg fuel economy and drastically reduced emissions of unburned hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter.

Spark-ignited, direct-injected (or SIDI) engine technology is under development for delivering fuel to the combustion chambers of an engine without mixing it with air beforehand. This technology has the potential to help meet the fuel efficiency and emission reduction goals of the PNGV effort. The DOE research programs in SIDI were focused on three barriers to its commercialization in the United States. First, the proposed Tier 2 emissions standards of the Environmental Protection Agency, intended to come into effect in 2004, included limits on emission of HC, NO_x and particulate matter. Current SIDI designs meet limits on particulate emission but require further work to meet HC and NO_x limits. Strategies being pursued to meet SIDI emission limits have included more advanced combustion control and exhaust aftertreatment technologies.

The second barrier to US adoption of SIDI is the high cost of the fuel system hardware required. Direct injection requires a high-pressure fuel pump to achieve the desired spray characteristics when gasoline is injected into the cylinder and mixes with the air. In addition, the fuel injectors themselves must meet more stringent design criteria due to their operation at higher pressures and in the more aggressive environment of the combustion chamber. The work reported here seeks to improve the reliability and lifetime of injectors and pump hardware experiencing wear in gasoline engines.

Third, the fuel efficiency of SIDI systems is an improvement over that of port fuel-injected gasoline engines but does not yet meet goals. One impediment to SIDI efficiency is frictional losses in the high-pressure fuel pump. These losses can offset half of the fuel savings gained by the direct injection (DI) technology. Reduction of friction between key parts in fuel pumps would provide fuel economy benefits for the vehicle as a whole. This friction reduction provided an additional motivation for the present work.

Near-frictionless carbon (NFC) coatings are a surface treatment designed to reduce friction, wear and catastrophic failure of contacting surfaces in relative motion.

*Corresponding author. Tel.: +1-630-252-7361; fax: +1-630-252-4798.
E-mail address: jhersh@anl.gov (J. Hershberger).
[1] Currently at: Izmir Institute of Technology, Department of Physics, Gulbahce-URLA, IZMIR, 35437, Turkey.

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The NFC series of coatings was invented at Argonne National Laboratory (ANL) and belongs to a class of coatings known as amorphous diamond-like carbon (DLC), which are under development primarily but not exclusively for their mechanical properties. The NFC coatings are named for their behavior in wear tests in the presence of inert gases, where they display friction coefficients as low as 0.001, among the lowest recorded for solid–solid contact [1]. NFCs also show greatly reduced rates of material removal in wear tests when compared to uncoated materials.

The process by which NFC coatings are deposited is vacuum-based. As a result, the substrates to be coated cannot be volatile. No heating is involved, so temperature-sensitive substrates are not damaged by the process and the coatings are sufficiently thin that mechanical tolerances of coated parts are not affected. NFC coatings, like other DLCs, are temperature sensitive and lose their superior tribological properties above approximately 250 °C. For applications where these restrictions are not critical, NFCs are an attractive candidate for solution of tribological problems in the mass market.

1.1. Application of coatings to engine parts

A study by Gorel et al. reported an engine test of a thermal barrier coating applied to surfaces inside the combustion chamber, including the piston crowns [2]. The coatings were intended to reduce particulate emissions, although no fuel economy improvements could be associated with coatings applied in the cylinder. Thermal barrier coatings were also attempted for control of unburned hydrocarbon emissions from a homogeneous charge-compression ignition engine, as reported in a paper by Hultqvist et al. [3]. However, the emissions actually increased due to flame quenching; catalytic action of the coatings may have contributed to this problem. On the subject of wear-resistant coatings, Gahlin et al. give an overview of one manufacturer's DLC coatings for automotive applications [4]. They noted that the roughness and hardness of the substrate are important parameters in tailoring a coating-substrate system for performance. A paper by Erdemir et al. described the wear resistance of Argonne's DLC coating in diesel fuels with a variety of sulfur levels, including the low-lubricity, low-sulfur fuels, which are desired for environmental protection [5]. It was found that NFC coatings consistently reduced wear, particularly in the fuels with the lowest sulfur levels.

1.2. NFC research

In 1994 Erdemir et al. experimented with ion-beam-deposited DLCs and concluded that their friction coefficient of 0.05–0.07 in laboratory air was due to the formation of a carbon-rich transfer film [6]. Meletis et al. deposited those films on nitrided steels and found that the reduced substrate deformation improved the lifetime of the film [7]. Later, Liu et al. investigated the load and speed dependencies of the graphitization-transfer process [8]. They noted hydrogen depletion of the sp3 atomic structure of the DLC and described the transformation kinetics analytically.

In 1997 Erdemir et al. took a crucial step by forming DLC films from source gases, including methane, acetylene and combinations of hydrogen and methane [9]. Friction coefficients as low as 0.01 were measured in dry nitrogen environments. Further studies explored the effect of source gases on tribological properties [1,10,11].

Raman spectroscopy and electron microscopy were used by Erdemir et al. to study the transfer films formed by ion-beam-deposited DLCs [12]. Later studies included transmission electron microscopy and infrared spectroscopy and concluded that some graphite was being formed during wear of those DLCs [13,14]. The effect of applying the ion-beam DLCs to hard zirconia substrates was also investigated by Erdemir et al. [15]. The influences of humidity and temperature were reported later by Liu et al. [16].

More recent NFC films, made from hydrogen-enriched plasmas, were investigated by Erdemir et al., who found friction coefficients as low as 0.003 [17]. Heimberg et al. reported on the time and speed effects involved in this superlow friction coefficient [18]. They found that friction changes in NFCs could be explained by gas adsorption kinetics. Raman spectroscopy, transmission electron microscopy and other techniques were used to describe the structure of the coatings, transfer films and wear debris of the NFCs [10,11,16]. Erdemir and Fenske studied the high-temperature performance of both diamond and DLC films [19]. The diesel-lubricated scuffing performance of NFC coatings was investigated by Ajayi et al. who found that coated surfaces would scuff only at contact stresses high enough to deform the substrate and delaminate the film or after the NFC was removed by wear [20]. The scuffing performance of NFC in dry sliding conditions was then tested by Alzoubi et al. [21]. Again, NFC was found to improve scuffing resistance by two orders of magnitude.

Based on the tribological performance of NFC coatings in various environments, they are good candidates for reducing the friction in delivery of fuel to SIDI engines. The present paper evaluates the friction and wear performance of two variations of NFC and other commercially available DLC coatings under SIDI fuel system conditions.

2. Experimental procedures

2.1. Coating deposition

Deposition of NFC coatings was performed with a Perkin–Elmer 2400 sputtering system using plasma-assisted chemical vapor deposition (PACVD). The system's radio-frequency etching mode was used to deliver RF power to a water-cooled substrate table, creating the plasma. This arrangement delivered ion current to the surfaces of the samples across a DC voltage drop between the plasma (the source of the ions) and the sample surface. The RF power supply can be as high as 2000 W for the table and all substrates and was manipulated to provide the bias needed between the plasma and samples.

Before deposition, the substrates were ultrasonically degreased and solvent cleaned. Once substrates were arranged in the chamber, the system was sealed and pumped down to a base pressure of 10^{-6} Torr (1.3×10^{-4} Pa) using a turbopump. Argon gas was introduced into the chamber to achieve a pressure of 10 mTorr (1.3 Pa) and the RF power to the substrates was increased to provide the DC bias for a period of 30 min to sputter clean the sample surfaces. The argon flow and RF power were then stopped and silane (SiH_4) was introduced into the chamber to achieve a pressure of 3 mTorr (0.4 Pa). The RF power was increased to provide the DC bias for a period of 5 min. This procedure creates a silicon–hydrogen plasma and coats the substrates with a layer of amorphous hydrogenated silicon approximately 100 to 200-nm thick, which improves adhesion between the substrate and the NFC coating. The silane flow and RF power were then stopped and methane and hydrogen gas were introduced into the chamber to provide a pressure of 15 mTorr (2 Pa). The ratio of methane flow to hydrogen flow depended on the type of film being deposited; it was 50% H_2 for NFC2 and 75% H_2 for NFC6. The RF power was then increased to provide the DC bias for a period of 200–300 min, depending on the coating being deposited. The samples were allowed to cool before venting the chamber and removing them. The resulting coatings were $\approx$2-μm thick.

2.2. Wear tests

A Falex ball-on-three-disc (BOTD) tester was used to evaluate the lubricity of the fuels studied (regular gasoline, E85 and M85). The test conditions were as follows: load, 24.5 N (10 N between the ball and each flat due to geometry); speed, 60 rev./min; temperature, 25–30 °C; duration, 45 min; air atmosphere. The three discs were composed of AISI 52100 (UNS# G52986) steel with a ground finish (surface roughness R_a=0.1–0.2 μm) hardened to 57–63 Rockwell C (R_c). The ball was Al_2O_3 with a diameter of 0.5 in. (1.3 cm) and a surface roughness R_a of 0.008–0.01 μm. Discs to be coated were first polished with alumina slurry with a grit size of 1 μm. Separate tests verified that polishing did not significantly affect the wear scar diameters of uncoated discs. Before testing, the ball, discs and the parts of the tester, which contact the gasoline were ultrasonically degreased and solvent rinsed. After testing, the discs were inspected in an optical microscope and the diameter of the wear scar was recorded for all three discs from each test.

Bench tests to measure reciprocating wear were performed with a customized wear tester called the Fretting Tester. It was designed for sealed operation with wear track lengths from 0.5 inches (1.3 cm) down to as little as a few micrometers. Having an enclosed volume of approximately 0.5 foot^3 (0.01 m^3), it is ideal for use with volatile liquids such as gasoline. This tester allows addition of liquid to the sample cup without opening it to the environment and can be filled and vented with specific flow rates of any desired gas. In this study, the samples were ultrasonically degreased and solvent rinsed, dried and placed in the chamber and then the chamber was sealed. The air in the chamber was exchanged with dry nitrogen for 30 min at a flow rate of 10 standard liters per minute. At that point the flow rate was reduced to under 2 standard liters per minute, gasoline was added to the sample cup and the test was started.

Reciprocating motion was applied to the counterface (ball or fuel injector), which was mounted on a horizontal slider and connected to bellows on the sides of the chamber. The slider was driven through the bellows by an electromagnetic shaker similar to a loudspeaker voice coil. The shaker was driven by a high-current amplifier, which took its drive signal from a frequency generator outputting a sine waveform. Inside the chamber, the sample resided in a cup for liquids, which was mounted on a lateral load-sensing assembly. The lateral load due to friction was sensed by a piezoelectric load cell whose sensitivity was approximately 0.001 lb (0.45 g). The cup and load sensor were mounted on a pair of vertical sliders to allow sample exchange. A linear variable differential transformer (LVDT) was used to measure the relative displacement of the sample and counterface; the body of the LVDT was mounted to the sample cup, while its core was attached to the slider and, therefore, oscillated with the counterface. The normal load was sensed by a load cell on the mechanism used to raise the cup to the counterface. For each test, the load required to raise the cup was zeroed out, the sample and counterface were brought into contact and the normal load between them was measured. The signals from the LVDT and friction force sensor were displayed on an oscilloscope, which was connected to a computer running a program written in National Instruments' LabVIEW environment. The computer calculated the test duration based on the operator's input and after the test started, the computer collected 200 digitized dual traces from the oscilloscope throughout the test.

After the test, both the flat and counterface were inspected in a MicroXAM three-dimensional optical

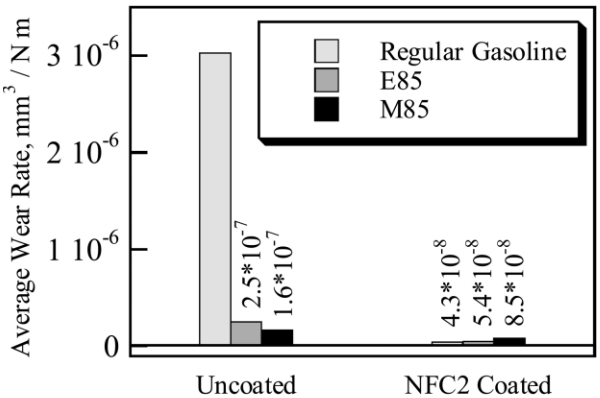

Fig. 1. Average wear rates for coated and uncoated discs in BOTD tests run in three fuels.

surface profiler from ADE Phase Shift. This system reconstructed a three-dimensional topographic map of the sample surface, with magnifications and lateral resolutions similar to those of an optical microscope. The system calculated the volume of the areas of the topographical map, which lay below the plane of the sample surface and a numerical wear volume in cubic micrometers. In the case of injectors and balls, whose unworn surfaces are spherical, the system mathematically subtracted the curvature of the sphere from the data set of three-dimensional heights. The volume removed from the sphere was then calculated in cubic micrometers.

The flats of AISI 440C (UNS# S44004) steel with hardness 60 R_c were polished to $R_a = 0.010–0.015$ μm. The ball counterfaces were also AISI 440C steel, 3/8 in. (0.9 cm) in diameter, while the production fuel injectors had a spherical steel tip of diameter 2.85 mm. In reciprocating ball-on-flat tests, the coating was applied to the flat, whereas in reciprocating injector-on-flat tests, the injector tips were coated.

3. Results

3.1. BOTD tests

A limited set of BOTD tests was performed to determine what benefits, if any, might be expected from use of NFC coatings. Regular gasoline was used in the tests, as well as E85 and M85 alternative fuels. The results are shown in Fig. 1, giving wear rates for uncoated discs and discs coated with NFC2. Wear rates are determined from the volume removed per unit load and sliding distance. The formula for volume as a function of wear scar diameter is

$$V = \frac{\pi h}{6}(3r^2 + h^2). \quad (1)$$

In this equation,

$$h = R - \sqrt{R^2 - r^2}, \quad (2)$$

where R is the radius of the sphere and r is the radius of the wear scar.

Significant wear-rate improvements from the NFC2 coating are evident in Fig. 1. The largest wear rate observed for any fuel on a coated sample was lower than the smallest wear rate observed on an uncoated sample. For regular gasoline, application of a coating to the discs reduced the wear rate by approximately a factor of 70 under these test conditions.

Optical micrographs were used to determine the wear scar diameters. Fig. 2 illustrates the wear modes under the test conditions. The uncoated steel disc worn in regular gasoline (Fig. 2a) shows signs of abrasive wear from debris. In contrast, the NFC2-coated disc worn in the same fuel (Fig. 2b) has a small wear-scar diameter and less abrasion. Fig. 2b also shows some evidence of delamination of the NFC, where it was thinned by wear

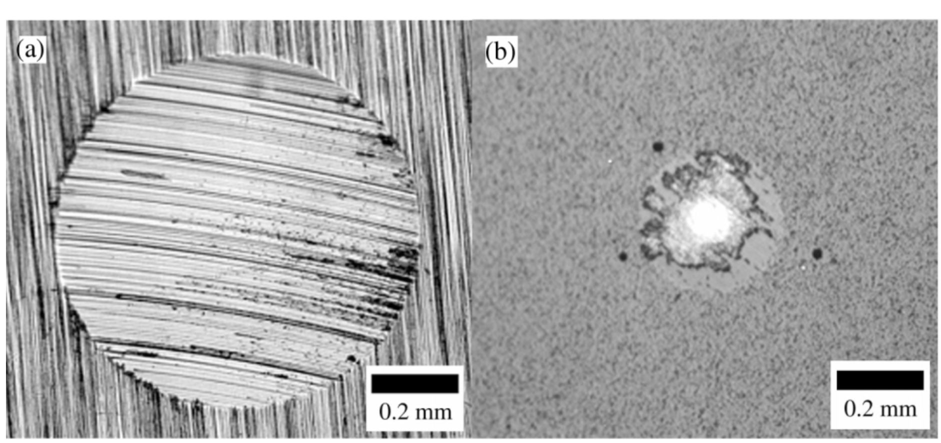

Fig. 2. Optical micrographs of (a) uncoated and (b) NFC2-coated discs from BOTD tests conducted in regular gasoline.

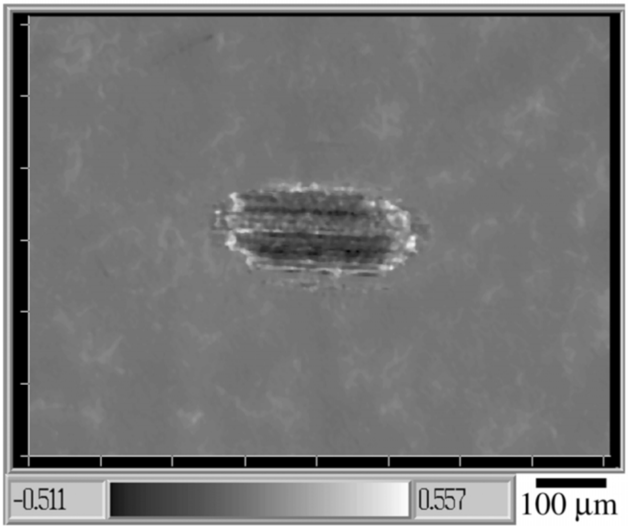

Fig. 3. Plan view of three-dimensional optical surface profile. The sample is from a ball-on-flat reciprocating test with track length 200 μm. The horizontal scale marker is at lower right, while the vertical (out-of-page) grayscale is given at the lower left (see text).

close to the circle of exposed metal in the center. This effect may be due to the fact that the coating is significantly harder than the steel. In any case, although the coating reduced the wear rate of the disc, these tests showed that adhesion of the coating to the AISI 52100 steel BOTD discs needed improvement.

3.2. Reciprocating ball-on-flat tests

Reciprocating tests were performed to obtain a more accurate simulation than BOTD for engine parts such as fuel injectors. Fuel injectors experience reciprocating, not unidirectional, sliding and the oxygen-poor combustion chamber is better simulated by a dry nitrogen environment than laboratory air. In this exploratory study, regular gasoline was the fuel used, with ethanol included in the tests as a control. The wear behavior of the surfaces in an unlubricated condition, with laboratory air, was also tested as a worst-case scenario. This gauged the effectiveness of the coatings in protecting against failure in unlubricated engine operation.

The testing was performed with a stroke length of 200 μm and a duration of 100 000 cycles, giving a total sliding distance of 40 m. Tests in ethanol or gasoline were performed with the chamber sealed and filled with dry N_2, while unlubricated tests were performed in laboratory air. The drive frequencies were 50 and 100 Hz, giving average speeds of 0.02–0.04 m/s. Loads of 2 N and 5 N were applied, giving average Hertzian contact pressures of 0.86 and 1.17 GPa and peak Hertzian contact pressures of 1.29 GPa and 1.75 GPa, respectively. Typical conditions were 50 Hz and 2 N.

The wear volumes were measured from three-dimensional optical surface profiles, such as the one shown in Fig. 3. The image consists of a top-down view of an uncoated steel flat worn against steel in ethanol, with the horizontal scale marker given at the lower right. At the lower left is a gray scale from dark to light, corresponding to heights in the image; also given is a range (in μm) for the heights of the deepest and highest points in the data set. A height value of 0 μm corresponds to the plane of the image. The wear scar was approximately 100 μm wide and showed signs of material pushout, debris re-adhesion or some other form of buildup around the edge.

To illustrate the performance of the Fretting Tester's data-collection capabilities, Fig. 4 shows plots of friction from a typical reciprocating test. In this test an NFC2-coated flat was worn against a steel ball in ethanol at 50 Hz and 5 N load. Fig. 4a shows average friction as a function of cycle number throughout the test. The average friction numbers reported in the rest of this paper are obtained from plots like Fig. 4a. In this case, the friction was stable at 0.10, a value typical of the boundary lubrication regime. The average friction for a

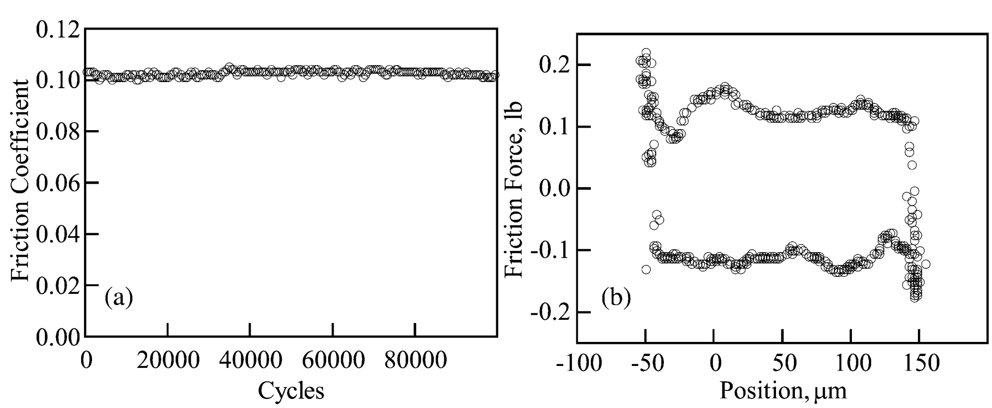

Fig. 4. Plots of (a) friction vs. cycle and (b) frictional force vs. position for typical cycles in a ball-on-flat reciprocating test ofAISI 440C steel against NFC2-coated AISI 440C steel in ethanol.

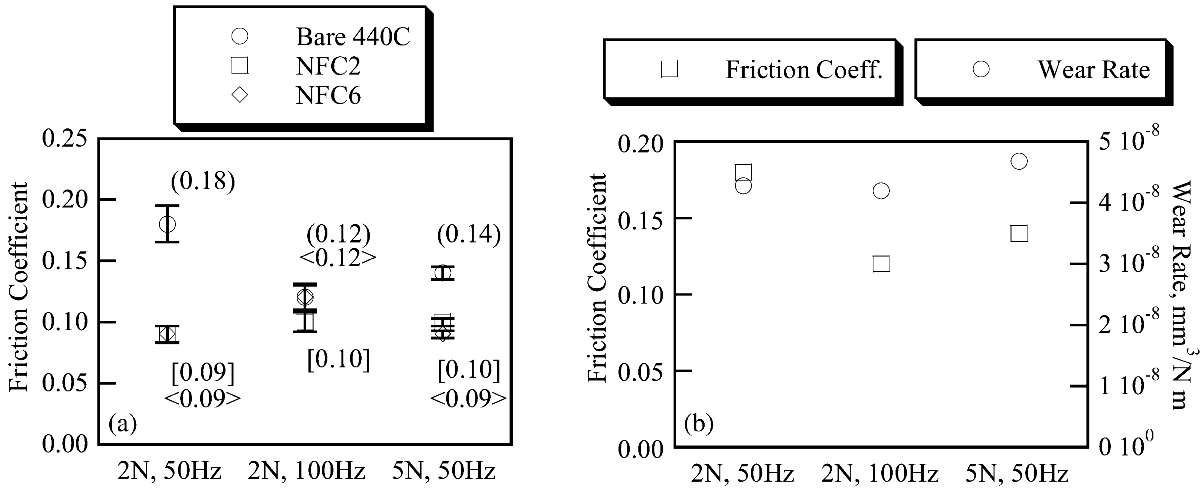

Fig. 5. Friction and wear results from ball-on-flat reciprocating wear tests lubricated by ethanol at several load and speed conditions. (a) Friction coefficients for uncoated AISI 440C steel worn against coated and uncoated AISI 440C steel. Numerical values in parentheses or brackets (see text). (b) Friction coefficients and wear rates for the uncoated against uncoated steel pair.

given cycle was calculated by averaging the absolute value of frictional force during the cycle. Fig. 4b shows frictional force as a function of the relative position of the counterface and the flat. Three cycles from approximately cycle 50 000 are shown and the time in the force-vs.-position loop is in a clockwise direction. A 200-μm track length was observable as the range of values on the position axis. The force loop showed a nearly square-wave force response, with some ringing overlaid as motion in each direction. This ringing was a common observation and was probably caused by the resonant frequency of either the counterface mount or the sample cup mount.

Experiments were performed in ethanol to determine the speed and load sensitivity of the coating wear. Fig. 5a plots friction vs. severity for bare AISI 440C steel, NFC2 and NFC6 flats worn against steel in ethanol under dry nitrogen. Since some data points overlapped, the numerical values were provided on the plot. Values in parentheses are for bare steel, those in square brackets are for NFC2 and those in angle brackets are for NFC6. Bare steel gave the highest friction at the low frequency of 50 Hz, especially at the low load of 2 N. At high frequency and low load, all three materials displayed the same friction within the experimental error. The friction values from NFC2 and NFC6 were the same and did not depend significantly on load or speed. Fig. 5b gives both wear rate and friction vs. severity for the case of uncoated steel against steel in ethanol (the friction data are reproduced from Fig. 5a). The wear rate is somewhat, but not strongly, correlated to the friction and is only a weak function of severity for these ethanol-lubricated tests.

3.3. Reciprocating injector-on-flat tests

Having established that the NFC coatings were effective at reducing wear when lubricated by fuels under conditions simulating the operating parameters of a fuel injector, we initiated a comprehensive study to compare the fuel-lubricated wear behavior of NFCs with that of three commercial DLC coatings. For these tests, the stroke length was increased from 200 μm to 1 mm. The five plots in Fig. 6a–e show the friction and wear results for dry (unlubricated) tests and tests with ethanol, E85, M85 and gasoline in the sample cup, respectively. In each of these plots, the friction is given as a solid bar with error and is read on the left *Y*-axis; the wear rates are read off the right *Y*-axis. The wear rates are presented as a bar of two shades of gray with a total height corresponding to the total wear rate. The light gray part of the bar gives the wear rate of the flat, while the dark gray part of the bar gives the wear rate of the coated injector. The *X*-axis specifies the coatings applied to the injector tip (the flats were uncoated). The abbreviation ‘C.DLC’ refers to commercial diamond-like carbon. All coatings were applied to the same type of parts.

For the unlubricated contacts (Fig. 6a), the uncoated case forced the wear rate axis to a scale two orders of magnitude larger than in Fig. 6b–e. No coating achieved low friction in lab air without lubricant. Note that the total wear rate of C. DLC 2 was over half that of uncoated steel, indicating that this coating would be a poor choice for applications where it might be run dry. Even C. DLC 3 showed a wear rate several times that of the worst lubricated wear, which was for uncoated parts lubricated by M85 fuel. By comparison, wear rates for NFC2, NFC6 and C. DLC 1 were several orders of

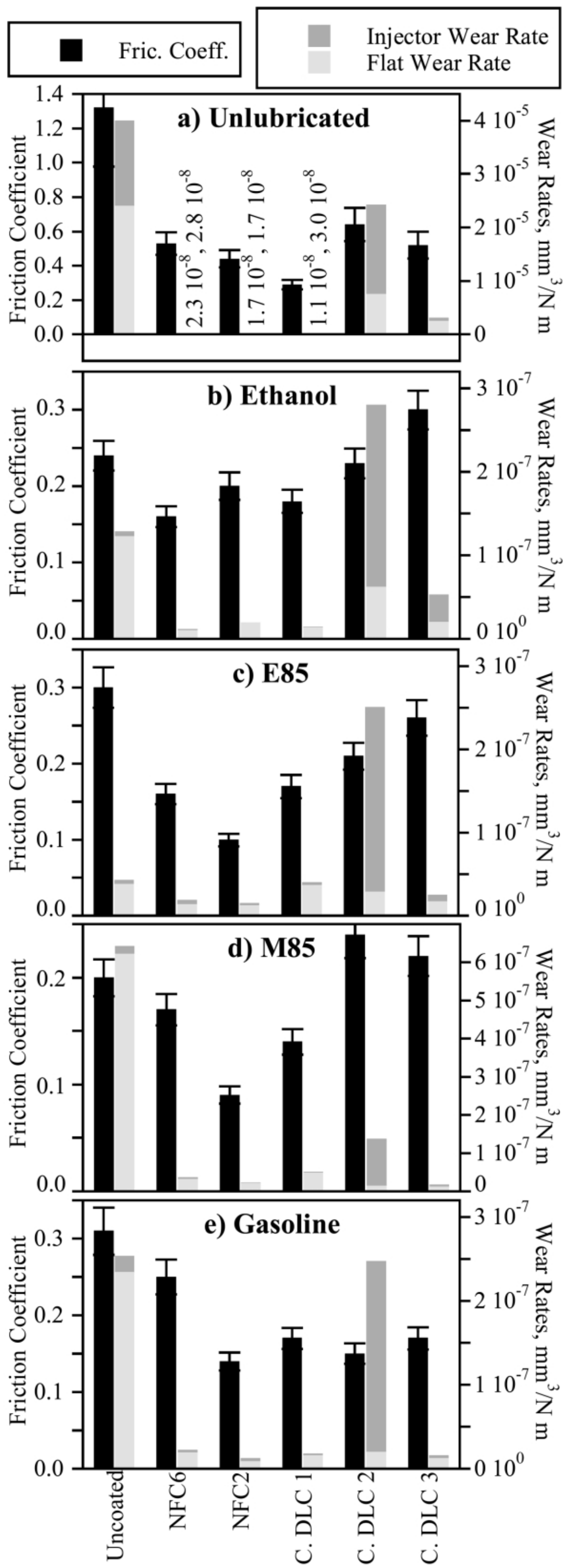

Fig. 6. Friction coefficients and wear rates from reciprocating tests of uncoated and coated fuel injector tips worn against uncoated AISI 440C steel flats in various fuels. Results are given from (a) the unlubricated case and tests performed with samples submerged in (b) ethanol, (c) E85 fuel, (d) M85 fuel and (e) regular gasoline.

magnitude lower than the other surface treatments. NFC6 outperformed C. DLC 1 by 15%.

For wear in ethanol (Fig. 6b), included in this study as a control, the friction and wear data did not vary among coatings as much as in the unlubricated case. The lowest friction values were achieved by NFC2, NFC6 and C. DLC 1, while C. DLC 2 and C. DLC 3 gave friction equal to or greater than that of uncoated steel. The wear rate for C. DLC 2 was the highest, exceeding even uncoated steel. The lowest wear rates were again achieved by NFC2, NFC6 and C. DLC 1, with NFC6 outperforming C. DLC 1 by 24%. These rates represent an improvement of approximately a factor of 10 compared to uncoated surfaces.

Friction and wear rates in E85 fuel (Fig. 6c) showed NFC2, NFC6 and C. DLC 1 with typically low friction values, but C. DLC 1 suffered a wear rate more than double that of the NFCs. Commercial DLC 2 showed an anomalously high wear rate, far exceeding that of the uncoated surface; it would be a poor choice for alternative fuel applications. The results for M85 fuel (Fig. 6d) were similar. NFC2, NFC6 and C. DLC 1 had the lowest friction and C. DLC 3 showed a surprisingly low wear rate (25% better than that of NFC2 in this fuel) considering its high friction.

The results for wear in regular gasoline are given in Fig. 6e. NFC2 provided the best friction, with the three commercial DLCs giving values almost as low. The lowest friction of the commercial DLCs was number 2, which unfortunately again produced an anomalously high wear rate. The lowest wear rate of the group was achieved by NFC2, followed by C. DLC 3; wear rates in gasoline were generally proportional to friction, with the exception of the uncoated case and C. DLC 2.

4. Discussion

One of the objectives of this study was the deposition of NFC coatings on production fuel injectors and the optimization of these coatings. NFC was successfully deposited on the samples for this study and deposition conditions were found which produced an appropriate film thickness. The optical microscopy analysis of the samples in the BOTD wear tests determined that the adhesion of the NFC coating was failing after the NFC had worn very thin. Steps were taken to modify the deposition technique for coating NFC on the other steel flats and injectors in this study and the problem did not recur. Friction and wear rate were reduced sufficiently for NFC-coated materials in the preliminary BOTD and reciprocating ball-on-flat tests to provide a firm basis for the more detailed comparisons made in the reciprocating injector-on-flat tests. Friction and wear rate were not strongly sensitive to load and contact velocity within the ranges studied.

The comparison between NFC coatings and three commercial DLCs showed that the former were generally the best choice for reducing friction and wear, although C. DLC 1 rivaled the NFC performances in several tests. The differences were statistically significant, i.e. larger than the experimental error. Commercial DLCs 2 and 3 displayed poor performance under certain conditions, such as unlubricated or ethanol-lubricated wear. The coatings NFC2, NFC6 and C. DLC 1 achieved the lowest wear rates in different test conditions. NFC6 performed the best in dry or ethanol-lubricated wear, C. DLC 1 performed the best when lubricated by E85 or M85 fuel and NFC2 had the best performance in regular gasoline. Arguably, these differences could allow the coatings to be tailored for use in different environments. However, the most relevant condition for fuel injector applications was obviously the tests in regular gasoline, for which NFC2 provided both the best friction and the lowest wear rate.

The coating NFC2 reduced friction in all liquid lubricants compared to uncoated materials in the same fluids; NFC6 did also, but not to as great an extent. The wear rates for tests where a liquid lubricant was present were improved by a factor of three to four when NFC2 coatings were applied compared to uncoated surfaces. M85 fuel was the most aggressive in terms of causing wear, perhaps because of the large amount of oxygen present in the methanol. The decrease of friction for coated surfaces compared to uncoated surfaces indicated that solid–solid contact was indeed taking place; in other words, the contact severity was in the boundary lubrication regime, rather than in the elastohydrodynamic regime where the load is entirely supported by the fluid.

5. Conclusions

NFC coatings were successfully deposited on gasoline fuel injectors, and their properties were optimized for this application. Customized wear tests were performed to simulate the operating environment of fuel injectors. Compared to three commercial DLC coatings in those wear tests, the NFC2 coating provided the best friction reduction and protection from wear in regular gasoline. Two of the commercial DLCs displayed excessive wear and/or friction when run dry or when lubricated by ethanol. The other commercial coating displayed the best performance of any coating when lubricated by E85 or M85 fuel. The best performance in dry conditions and under ethanol lubrication was provided by the NFC6 coating. The application of coatings generally, but not always, reduced friction relative to the uncoated state; the NFC2 coating always reduced friction and provided the lowest friction of any coating for tests lubricated by E85, M85 and regular gasoline.

Acknowledgments

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