Valvetrain Friction Reduction through Thin Film Coatings and Polishing


Ford Motor Company, Dearborn, Michigan, 48124

Available online: 07 Nov 2011
Valvetrain Friction Reduction through Thin Film Coatings and Polishing

ARUP GANGOPADHYAY, DOUGLAS G. MCWATT, ROBERT J. ZDRODOWSKI, STEVE J. SIMKO, STEVE MATERA, KIRK SHEFFER, and ROBERT S. FURBY
Ford Motor Company, Dearborn, Michigan 48124

In a direct-acting mechanical bucket tappet-type valvetrain, the cam and tappet contact is responsible for about 85% of the total valvetrain frictional losses. Because this contact operates primarily in a mixed lubrication regime, it offers an opportunity for friction reduction through surface engineering. The friction reduction potential of thin Mn-phosphate coating, diamond-like carbon coating, and polishing on the bucket surface was explored using a motored valvetrain rig equipped with 3.5L V6 engine head. The durability of tappets and cam lobes was also evaluated using a different motored valvetrain rig consisting of a single lobe and a single tappet. The polished buckets demonstrated substantial friction benefit over current production buckets at all speeds investigated. The diamond-like carbon coated buckets did not show any additional friction reduction benefit. The wear data demonstrated much less wear with polished buckets and also for cam lobes when in contact with polished buckets compared to current production buckets and cam lobes. The composition of antiwear surface films on polished buckets was found to be similar to that on current production buckets.

KEY WORDS
Friction; Valvetrains; Wear; Polishing; DLC Coatings; surface films

INTRODUCTION
The friction between two lubricated sliding surfaces and the related wear depend primarily on the contacting materials, load, lubricant formulations, and the lubrication regimes. Under boundary and mixed lubrication conditions, where the asperities of both surfaces touch each other, friction and wear can be controlled by lubricant formulations and appropriate surface engineering. A valvetrain contributes about 6–10% of the total engine friction (Kiovsky, et al. (1)). This number, although relatively small compared to losses in other parts of an engine, can be further reduced. It is estimated that about 85% of the total friction loss in engine valvetrains comes from the cam and tappet contact (Comfort (2)). Therefore, efforts have been made to reduce friction at this contact primarily through modifying the tappet surface due to its relatively simple geometry and smaller size compared to the camshaft. In direct acting bucket tappet-type application, where the cam and tappet contact operates under boundary and mixed lubrication regimes, friction reduction has been achieved through reduced reciprocating mass, spring load, and surface finish for a given engine oil formulation. The presence of textures on contacting surfaces allows one additional degree of freedom for friction reduction. Gangopadhyay and McWatt (3) explored the friction and wear reduction potential of various surface patterns produced mechanically on tappet shims in a motored valvetrain rig. The results showed about 35% friction reduction and wear rate reduction of approximately a factor of two compared to production tappet shims. Others have shown similar friction benefits with texturing (Ryk, et al. (4); Ronen, et al. (5); Wakuda, et al. (6); Golloch, et al. (7)).

Deposition of thin low-friction coatings has also been evaluated for valvetrain friction reduction. Recent advances in deposition of diamond-like carbon (DLC) films in large volumes while maintaining quality have prompted several investigations. The friction reduction potential of DLC films in the absence of lubricants has been studied in great detail. Recent studies have focused on the interaction of DLC films with lubricant additives, in particular antiwear additives and friction modifiers. The use of DLC films on various engine parts has been limited mostly to racing applications, although applications in mass volume production vehicles are emerging. Recently, Nissan introduced hydrogen-free DLC-coated tappets in their commercially available VQ engines (Okuda, et al. (8)). In laboratory evaluations of friction in the boundary lubrication regime, DLC-coated parts showed significant friction reduction compared to uncoated steel. Broda and Bethke (9) evaluated the friction coefficient of three different DLC films in the presence of three different oils with varying amounts of Mo-based organic friction modifier. DLC films showed a 40% lower friction coefficient compared to uncoated steel parts in the presence of a low to medium level of Mo-based friction modifier in the oil without any additives. In the high Mo-containing oil, the friction coefficient of uncoated steel was low and the difference between uncoated and DLC-coated parts was small. Okuda, et al. (8) showed similar results with high Mo-containing oils and developed an alternative ashless friction modifier for friction reduction with hydrogen-free DLC films.
Kano, et al. (10) demonstrated a friction coefficient as low as 0.006 in the presence of polyalphaolefin-based oil containing glycerol monooleate (GMO) friction-reducing additive. Shinoyoshi, et al. (11) reported that the wear of DLC films increased in the presence of molybdenum dithiocarbamate (MoDTC) in the oil. The decomposition of MoDTC produced MoO3, which interacted with DLC film, resulting in increased wear. Haque, et al. (12) observed that the low friction of hydrogenated DLC films was due to the transfer of a carbon layer from the DLC-coated part to the counterbody. However, they did not find any zinc dialkylthiodiophosphate (ZDDP)-derived antitrust film on the DLC film and the Mo-dimer and Mo-trimer friction modifier interacted with the DLC coating to form MoS2 and MoO3 compounds. They observed that a higher ratio of MoS2/MoO3 reduced the friction coefficients. Deposition of coatings other than DLC has also been attempted. Gangopadhyay, et al. (13) reported the formation of a Ca-phosphate film on the DLC surface. Masuda, et al. (14) showed that deposition of a hard and thin TiN coating on a mirror-polished (Ra = 0.02 µm) steel reduced cam lobe surface roughness to Ra = 0.02 µm in a short running time. The low surface roughness of both of the contacting surfaces achieved a 40% reduction in friction torque compared to a conventionally finished insert.

Valvetrain friction reduction through improved surface finishing has also demonstrated encouraging results. The friction reduction is achieved by pushing the lubrication regime to more mixed lubrication. Katoh and Yasuda (15) showed that a significant reduction in valvetrain friction torque can be obtained if the surface roughness of both the camshaft and inserts is reduced. It has been reported that silicon nitride inserts with mirror-polished surfaces (Ra = 0.02 µm) reduced valvetrain friction by about 20–25% in a motored test. The polishing method was also found to be important for friction reduction (Gangopadhyay, et al. (16)). Shimada, et al. (17) achieved 10–40% friction reduction in Nissan HR and MR engines by reducing the composite surface roughness of both the camshaft and inserts by 50%.

The objective of the article is to evaluate the friction reduction potential of thin-film coatings and improved surface roughness of bucket tappets from a 3.5L V6 engine. It is possible that a particular surface treatment may be very effective in friction reduction but may not provide the desired durability of contacting components. Therefore, the second objective of this work is to assess the durability of both camshaft lobes and tappets.

**EXPERIMENTAL DETAILS**

**Materials**

Two thin-film coatings and a mirror-polished surface were evaluated for friction reduction and the results were compared to the steel production bucket tappets. The thin-film coatings were Mn-phosphate, between 4 and 6 µm thick, and DLC, between 1 and 2 µm. The Mn-phosphate coating was deposited directly on the production bucket tappet; the DLC was also deposited on the production bucket but after polishing. The DLC coating was deposited using the physical vapor deposition technique and contained tungsten and silicon. The initial centerline average surface roughness of production, Mn-phosphated, DLC-coated, and polished buckets was 0.10, 1.7, 0.04, and 0.04 µm, respectively. Figure 1 shows scanning electron micrographs of the surfaces prior to friction evaluation. The production bucket surface contained abrasion marks left behind by the last processing step. The Mn-phosphate-coated surface shows a crystalline structure with a large variation in crystal sizes. The DLC-coated surface shows a highly polished surface, though at a higher magnification it had a granular structure. The polished surface shows very fine abrasion marks. The camshafts were made out of either chilled cast iron or steel and the tappet was made out of through-hardened 16CrMn5 steel with a hardness of 62 RC. The friction reduction potential of different surface modifications was evaluated using a motored valvetrain rig as shown in Fig. 2. A right-hand cylinder head from a 3.5L V6 engine was used for the test. The cylinder head was mounted at a 60° angle on an aluminum support to represent the actual position in this engine. This engine had four camshafts, two in the left-hand cylinder heads and two in the right-hand cylinder heads. Only one camshaft was used for this investigation and it was driven by an electric motor connected to a flywheel and a set of couplings. An in-line torque meter measured the average torque. Each camshaft contained six cam lobes rotating against six tappets. SAE 5W-20 GF-4 engine oil was used at various temperatures. The engine oil was heated externally in a sump and pumped into the engine inlet; from there it flowed through the original channels to lubricate the cam and tappet contact interface. The lubricant pressure was maintained at 40 psi. The coolant was also heated in an external sump and pumped into the engine inlet and then flowed through the original channels. The circulation of hot coolant helped to bring the cylinder head to the required temperature quickly.

**Break-In**

Prior to evaluation of each surface modification, it was important to ensure that the surfaces of the cam lobes and bucket tappets were adequately broken in. The break-in of a new camshaft and new tappets was conducted to ensure stable friction by monitoring the friction torque as a function of time. The break-in procedure consisted of running the system at 300, 500, 700, 800, 900, 1,100, 1,300, 1,500, 2,000, and 2,500 rpm, with more time spent at lower speeds. The oil temperature was maintained at 100°C.

The system was considered broken in when a stable friction was reached at each speed of revolution, which generally took about 150–200 h. The break-in characteristics were similar for each tappet surface modification.

A new camshaft and a set of six tappets were used for each type of surface modification investigated and the lash between the cam lobes and the tappets was maintained within the specified limit, 0.15–0.25 mm. The surface roughness of the cam lobes and tappets was also measured using a stylus profilometer before and after the tests.

**Wear Evaluations**

The wear of tappets and cam lobes was measured using a radionuclide technique in which the entire top surface of a tappet and the entire width of the cam nose and 5 mm on either side of the nose were activated to Co60 by bombarding the surface with a proton beam. The initial radioactivity was 17–22 MBq/mg.
The depth of the activated surface was about 30 µm, which was much smaller than the wear depth experienced from tests in the past (Gao, et al. (18); Gagopadhyay, et al. (19)). Wear evaluations were conducted on a motored valvetrain rig in which a single cam lobe rotated against a single tappet. One cam lobe was cut from a production 3.5L V6 engine intake camshaft, bored, and press-fitted onto a shaft, which was driven by a 2-HP motor. A production tappet was mounted on a production spring in the same manner as in an engine. The tappet reciprocated inside an aluminum sleeve made of the engine material and the same clearance between the tappet and the sleeve as in the engine was maintained. The tappet was in contact with a steel valve that had
a mass equivalent to the mass of an intake valve. In an engine the center line of the tappet is at 1 mm offset from the cam lobe centerline. Experiments were conducted at two offset values of 1 and 7 mm to understand its effect on wear. The contact area of the tappet and the cam lobe was lubricated by a jet of GF-4 SAE 5W-20 engine oil at 85 psi, which is higher than in the engine, the reason for which is explained later.

The principle behind the wear measurement is as follows. When an unactivated cam lobe rotates against an activated tappet, radioactive wear debris is generated and is mixed in the oil. An external pump draws the oil out of the rig, and then the oil passes through a radiation detector, which measures the radioactivity of the oil and converts it into wear mass using an appropriate computer program; then the oil is pumped back into the rig. As the test continued, more wear debris was generated and the radioactivity in the oil increased, which enabled continuous monitoring of wear. A high oil pressure was needed to ensure that all wear debris was flushed out of the test chamber and accounted for by the radiation detector. The oil was heated through an external in-line heater and the oil temperature is maintained at 90°C. The wear measurement was conducted with one radioactivated component at a time, and the other component was nonactivated. The test was run for 100 h.

RESULTS AND DISCUSSION

Friction Evaluation

Figure 3 shows the repeatability of friction torque measurements for the production camshaft and production bucket system at 100°C oil temperature. The friction torque decreased with increasing speed due to increased oil entrainment, which changed the lubrication regime from a boundary condition at lower speeds to a hydrodynamic condition at higher speeds. The data showed excellent repeatability and the variation observed was a small fraction of the variation observed from one tappet surface modification to the other. Similar repeatability was observed at other temperatures and surface modifications. Figure 4 shows the effect of temperature on friction torque as a function of camshaft speed. The data clearly demonstrate that the camlobe–tappet shim contact operated primarily in the mixed lubrication regime. The friction torque decreased as the oil temperature decreased. This was due to increased oil viscosity resulting in higher oil film thickness and thereby reducing the severity of asperity interactions. In addition, with decreased temperature the friction torque curve became flatter compared to that at higher temperatures. The higher the temperature, the greater the change in friction torque with speed.

The effect of various tappet surface modifications on friction torque is shown in Fig. 5 as a function of camshaft speed at different oil temperatures. Each data point is the average of three tests. The Mn-phosphate coating showed up to 18% improvement in friction torque compared to the production tappets depending on the oil temperature and the camshaft speed. The polished bucket tappets showed up to 26% improvement, and the DLC coating showed similar performance (up to 32%). It is interesting to note that the polished tappets and DLC-coated tappets had similar initial centerline average roughness ($R_a$) and both showed similar friction reductions, suggesting that friction is controlled by the initial surface roughness and the DLC coating itself did not offer any additional benefit. The friction reduction was greater in the lower speed range than in the higher speed range because more asperity–asperity interactions occurred in lower speed range due to lower oil film thickness.

Friction evaluations were conducted in the order of production tappets, followed by Mn-phosphated, polished, and DLC-coated. The data in Fig. 5 show that with each successive test, the friction was reduced. In order to ensure that progressive friction reduction is not due to any uncontrolled noise factors, a test was repeated with the production tappets tested earlier at the end of the program and compared to results obtained before. Figure 6 shows that friction torques with production buckets were very close to previous data at 100°C oil temperature. This suggests no change or shift in the torque measurement system providing confidence that observed differences between various surface modifications are significant.

At the end of tests the surface roughness was measured using a stylus profilometer and compared to the pretest values. In addition, profilometer traces were compared before and after the tests to ensure that there were no undesirable changes in the profiles.
The profilometer traces before and after tests were not obtained in exactly the same locations but they were very close. The cam lobe surface roughness was measured at the nose area and data are the average of two measurements. Similarly, two traces were taken on each tappet and two tappets were measured. Therefore, the values represent an average of four measurements and each measurement was very close to the others. In general, the profile appeared smoother after the test, as expected. Table 1 shows the centerline average surface roughness (Ra) of the cast iron cam lobes and tappets before and after the tests. The cam nose was highly polished at the end of tests and the production tappet was polished to some extent. The surface roughness of the Mn-phosphate-coated bucket was high before the tests due to the presence of crystals on the surface; after the tests the surface roughness was reduced due to breakage of crystals and polishing of the edges, as evidenced from scanning electron micrographs (not shown). The surface roughness of the polished and

<table>
<thead>
<tr>
<th>Process</th>
<th>Camlobes</th>
<th>Tappets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Before</td>
<td>0.09–0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Production After</td>
<td>0.03–0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Phoshpated Before</td>
<td>0.09–0.12</td>
<td>0.17</td>
</tr>
<tr>
<td>Phoshpated After</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>DLC        Before</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>DLC        After</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Polished   Before</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Polished   After</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>
DLC-coated tappets was low before the tests and remained the same after tests. It is important to notice that the surface roughness did not increase with continued testing. It was estimated that the total test time on each cam and bucket system was about 300 h including break-in time. This provides confidence that the friction benefit of polished surfaces would be retained.

The optical micrographs shown in Fig. 7 compare the condition of various tappets and the corresponding cam lobes after the tests. The production tappets showed circular wear marks, which are typical, whereas the nose of the cam lobes appeared quite polished, although a few light contact marks could be observed. The phosphated tappets still contained the phosphate coating.
Examination of the tappets at higher magnification using a scanning electron microscope showed that the tips of the asperities were worn away, leaving patchy areas, which were in contact with the cam lobes. In addition, circular wear marks were visible but fainter than those on the production tappets. The nose of the cam lobes contained pits, unlike the production cam lobes, but otherwise the cam nose appeared polished. The polished tappets remained polished after the test, although a few very faint circular wear marks could be observed. The cam lobes appeared polished but did not contain any wear marks or pits. The DLC-coated tappets looked similar to the polished tappets; they remained polished with a few very light circular lines. The coating remained intact with no apparent damage. The cam lobes appeared polished and contained a few light wear marks similar to those observed on the buckets tested against the production camshaft.

Wear Results

Figure 8 shows typical tappet wear progression as a function of time for a tappet with a 7-mm offset. It is interesting to note that even after 100 h the total tappet wear was less than 0.5 mg, which probably could only be measured using this technique. It is important to realize that wear progressed fairly linearly following a rapid initial increase in some cases. The important thing to look into is the wear rate and not the absolute wear number at the end of the test. The data showed repeatability of wear measurements. The wear rates for the two tests with production tappets and cast iron cam lobes were 0.004 and 0.003 mg/h, respectively, for the last 50 h of the test, when the wear progressed quite linearly. The polished tappets showed significantly lower wear rate. The 3.5L V6 engine has all cast iron camshafts for the port fuel-injection engine, whereas the turbo direct-injection version uses three cast iron camshafts and one steel camshaft in the intake position. The durability of polished buckets was evaluated against each type of cam lobe. The polished tappet wear rate was higher (0.0009 mg/h) against steel lobes compared to that against cast iron lobe (0.0001 mg/h), but both wear rates were lower than the current production cam lobe and tappet combination.

Figure 9 shows cam lobe wear against the production and polished buckets at a 7-mm offset. The wear of the cast iron cam lobe was initially high for the first few hours, following which the wear increased almost linearly up to about 70 h, after which the wear progressed at a higher rate. After about 70 h, the test was stopped due to an oil heater malfunction. The test was resumed after the repair and wear progressed at a faster rate, the reason for which is not understood. The wear of the cast iron cam lobe against the polished bucket increased for the first 25 h, after which it reached a plateau, whereas the wear of the steel cam lobe continued to increase steadily for the duration of the test. The wear rate of the cast iron cam lobe against the production bucket between 25 and 70 h, during which the wear progressed almost linearly, was 0.0010 mg/h, which is comparable to the wear rate of the steel cam lobe for the last 50 h (0.0013 mg/h). But when the polished bucket was used, the wear rate of the cast iron cam lobe dropped significantly to almost 0 mg/h.

Figure 10 shows steel cam lobe wear as a function of test duration in contact with production and polished buckets at a 1-mm offset. The wear of the steel cam increased rapidly initially and then increased nearly linearly after about 50 h. The wear of the cam lobe was higher in contact with the production tappet than with the polished bucket. The wear rate for the last 50 h was 0.0087 mg/h in contact with the production bucket compared to 0.0044 mg/h for the polished bucket, a reduction of a factor of 2.

The combustion in direct-injection engines produced soot and also resulted in fuel dilution, which reduced engine oil viscosity and hence the potential for wear due to reduced oil film thickness at critical contacts, including the cam and tappet. Soot is also generally known to cause wear. To explore this effect, wear measurements were performed on a steel cam lobe in contact with a polished bucket using fresh oil. The oil was drained at the end of test and then replenished with oil drained from a 350 h fired engine test. The oil contained about 1% soot as measured by thermogravimetric analysis and 4.6% fuel as measured using a Fourier transform infrared technique. The additive package in this oil was 10% less than that of the GF-4 formulation to increase the severity. The same cam lobe and tappet were used
with no flushing between oil changes. At the conclusion of this test, aged oil was drained and replenished with fresh oil with no flushing in between to simulate an oil change event. The results in Fig. 11 show that the wear of the cam lobe slowed after an initial high wear rate (judged by the slope of the curve). There were a few spikes in the wear graph, the reasons for which are not well understood. The wear rate of the cam lobes for the last 50 h of the test was 0.0044 mg/h. When the fresh oil was replaced with aged oil, the wear of the cam lobes progressed slowly, although an initial high wear was observed. The wear rate for the last 50 h of the test was only 0.0008 mg/h. A reduction in wear with aged oil was also observed previously (Gangopadhyay, et al. (19), (20)) and it was determined through surface analysis that the composition of the surface film was quite different, probably making it more wear resistant. When the aged oil was replaced with fresh oil again, the wear rate increased slightly to 0.0012 mg/h but remained much lower than that observed initially with the fresh oil and a new cam and tappet.

The wear results demonstrated that the wear of polished bucket tappets decreased substantially in comparison to the current production tappet in contact with a cast iron camshaft. In contact with a steel camshaft, the wear of the polished tappets increased slightly but remained lower than the current production tappet. The wear of both cast iron and steel camshafts in contact with polished tappets was no worse than the current production tappet. In the presence of aged oil containing soot and fuel the wear of the steel camshaft in contact with the polished tappet did not increase. These results demonstrate the robustness of the polished tappets.

**Surface Analysis**

**Infrared Reflectance–Absorbance Spectroscopy**

The surfaces of the polished tappets tested in contact with a cast iron camshaft and a steel camshaft were examined to understand the chemical composition of the surface films formed. The infrared reflection–absorbance spectra represent the composition of the film deposited in a 2-mm-diameter circle on the tappet. Because the deposited material was not a continuous film, the spectra obtained were averages over the spot examined and over the entire thickness of the films. The green, red, and blue colors represent spectra taken from the center, middle, and edge of a tappet, respectively, as shown in Fig. 12. The peak intensities varied depending on the locations the spectra were obtained from, but the composition remained the same. The strong peak around 1,300 cm$^{-1}$ was associated with phosphate-type inorganic compounds and the other peak around 1,450 cm$^{-1}$ was associated with carbonate material deposited due to interactions of detergents with the surface. The broad band around 3,400 cm$^{-1}$ was...
indicative of –OH groups and involved in hydrogen bond–type interactions. The data suggest that the composition of the surface films did not change with the type of camshaft material.

Auger Electron Spectroscopy

The elemental compositions of the thin films that formed during the wear tests were measured by Auger electron spectroscopy (AES) using a PHI model 680 scanning Auger spectrometer (Chanhassen, MN, USA). Data were collected using a 10-kV, 10-nA electron beam. Areas of interest on the heterogeneous samples were selected by first collecting a secondary electron (SE) image of the wear scar. Selected area analyses were then performed on regions that showed contrast differences in the SE images. Sputter depth profiling with a 2-kV argon ion sputter gun was employed to characterize thin films and to examine the subsurface regions. Using a standard protocol for the sputtering experiments, the sputter rate was measured as 7.5 nm/min with a standard thickness SiO₂ film. Though the antiwear films generated in these wear tests probably sputter at different rates than SiO₂, the use of this sputter rate provides a first approximation of the depth examined in the depth profile experiments.

Representative secondary electron images from both the production bucket and the polished bucket are shown in Fig. 13. The surfaces of both buckets were covered with a mottled light–dark tribofilm. This layer was uniformly distributed on the polished bucket but showed some heterogeneity on the production bucket. There were regions on the production bucket that looked like long, narrow score marks and/or valleys that do not appear to be covered with a tribofilm because they have a uniformly light grey appearance. The elemental compositions of the tribofilms

![Fig. 13—Secondary electron images of the tribofilms that formed on the (a) production tappet and (b) polished tappet against a cast iron camshaft. (color figure available online.)](image1)

![Fig. 14—Sputter depth profiles of the tribofilms that formed on the (a) production bucket and (b) polished bucket against a cast iron camshaft. Both profiles were obtained from a general area on the bucket. (color figure available online.)](image2)
were determined using AES and sputter depth profiling. A general region was examined on the polished tappet. Two regions were examined on the production tappet. These are delineated by the (blue) boxes in Fig. 13 and they represent the elemental composition on the general surface and in the valleys. Results for the general areas of both tappets are shown in Fig. 14. The elemental composition of the tribofilms in both regions is virtually identical. The films were dominated by calcium and oxygen with trace amounts of sulfur. Trace amounts of phosphorus were also present on the production tappet. These are typical elemental compositions of tribofilms that form on metal parts operated in fully formulated engine oils. Calcium and oxygen were likely deposited from the overbased detergent package in the oil. Sulfur and phosphorus were likely deposited from the antiwear additive. The scored/valley regions on the production tappet were covered with tribofilms of the same elemental composition. The films found in these regions were approximately a quarter of the thickness of the films found in the general areas. This difference in thickness was likely the cause of the variations in appearance in these regions in the SEM image.

CONCLUSIONS

Tappets with Mn-phosphate and DLC coatings as well as polished tappets showed reduced friction compared to the current production tappets at all engine oil temperatures investigated. The DLC-coated tappets showed similar friction reduction to that of the polished tappets, suggesting that improved friction is more due to improved surface finish and not the coating itself.

The wear rate of polished tappets in contact with a cast iron cam lobe was significantly lower than that of the current production tappets.

The wear of the cast iron cam lobe in contact with a polished tappet was lower than that of the production tappet. The wear of steel cam lobes was also lower in contact with polished tappet than that of the production tappet. The wear of the steel cam lobe was similar to the cast iron cam lobe in contact with the current production tappet.

The wear characteristics of the steel cam lobe in the presence of engine oil containing soot and fuel from dyno tests was no worse than that of fresh oil.

The composition of the tribofilms that formed on contacting components did not change significantly with variations in cam lobe material or tappet surface finish.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of Nick Wade and Greg Ciavattone in the maintenance of the rig and data acquisition system.

REFERENCES


