**STUDIES OF DYNAMIC CONTACT OF CERAMICS AND ALLOYS
FOR ADVANCED HEAT ENGINES**

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FINAL REPORT

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STUDIES OF DYNAMIC CONTACT OF CERAMICS AND ALLOYS FOR ADVANCED HEAT ENGINES*

Abstract

Advanced materials and coatings for low heat rejection engines have been investigated for almost a decade. Much of the work has concentrated on the critical wear interface between the piston ring and cylinder liner. Simplified bench tests have identified families of coatings with high temperature wear performance that could meet or exceed that of conventional engine materials at today's operating temperatures. More recently, engine manufacturers have begun to optimize material combinations and manufacturing processes so that the materials not only have promising friction and wear performance but are practical replacements for current materials from a materials and manufacturing cost standpoint.

In this study, the advanced materials supplied by major diesel engine manufacturers were evaluated in an experimental apparatus that simulates many of the in-cylinder conditions of a low heat rejection diesel engine. Results include ring wear factors and average dynamic friction coefficients measured at intervals during the test. These results are compared with other advanced materials tested in the past as well as the baseline wear of current engines. Both fabricated specimens and sections of actual ring and cylinder liners were used in the testing. Observations and relative friction and wear performance of the individual materials are provided.

Introduction

By reducing the amount of heat rejected through an engine's cooling system, more usable heat is trapped in the exhaust. By using this excess energy that would otherwise be lost to the environment, gains in engine efficiency can be obtained. Decreasing the amount of heat lost through the cooling system can be accomplished by reducing or eliminating coolant flow, insulating the combustion chamber surfaces, or a combination of both. The extra energy contained in the hotter exhaust gases can then be used for turbocharging and turbocompounding to increase the fuel efficiency of the engines. With these engine changes, top ring

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reversal temperatures can easily exceed 300 C. These temperatures negatively affect the material properties of metallic components and quickly degrade conventional liquid lubricants.

Above their normal operating temperature, conventional fluids can provide only marginal lubrication up to about 260 C⁽¹⁾. At these temperatures, metallic piston rings and cylinder liners experience wear at least 100 times higher than the wear occurring under normal engine operating temperatures⁽²⁾. Ceramics as a class of materials offer a possible solution to the wear in this critical interface. High hardness, corrosion resistance, strength at elevated temperatures, and high elastic moduli are attractive ceramic properties not generally available in metals, which could be expected to compensate at least partially for the marginal liquid lubrication at elevated temperatures.

Monolithic ceramics and coatings have shown vastly improved wear performance over conventional piston ring and cylinder liner materials at elevated temperatures. Using a controlled laboratory apparatus which simulates the loads, speeds, and environment of advanced heat engines, the relative friction and wear performance of potential replacement materials have been evaluated. The high temperature wear of some ceramic materials is low enough that component life of ceramic piston rings and cylinder liners could equal that of current diesel engines⁽³⁾.

The study described in this paper centers on additional materials evaluations for the piston ring/cylinder liner application. Advanced materials evaluated in this current work were selected by Caterpillar, Inc. and Cummins Engine Co. not only for their low wear resistance but also from the practical production standpoints of materials and manufacturing costs. Wear specimens were either coatings applied to specially prepared substrates or they were sections cut from coated piston rings and cylinder liners. Lastly, wear tests were conducted to see if Radioactive Ion Implantation (RII), a process that shows promise in monitoring engine component wear in situ, would affect the wear performance of the implanted material.

Apparatus

The experimental apparatus used in this study was designed to reproduce most of the operating conditions of a ring/cylinder interface at temperatures to 650 C. The specimen configuration shown in Figure 1 uses the original flat "liner" specimens and straight "ring" specimens. Special fixtures that could accommodate curved ring and cylinder specimens cut from actual engine components were also used in this study. The two cylinder specimens measured 13 x 32 x 125 mm and had either a flat or concave wear surface. One liner specimen was fixed, while the other was mounted on a slideway to permit applying contact loads up to 50 N/mm and was adjustable to maintain parallelism between the liner specimens. For a comparison of ring contact loading, the peak

Figure 1. Specimen configuration.

ring loading on a typical diesel engine is approximately 35 N/mm. The straight ring specimens were 19 mm long, 19 mm wide, and 3.2 mm thick. A 32-mm-radius crown was ground on the ring specimen to provide an initial cylinder-on-flat line contact geometry. The ring specimens were allowed to pivot in their mountings to provide alignment along the length of their contact surfaces. The curved ring specimens were 19 mm sections cut from a manufactured piston ring and their holders permitted alignment with the cylinder liner as well.

The reciprocating motion of 108 mm stroke was provided by attaching the ring specimen holder to one piston of a motored four cylinder engine. The top of the engine also provided the solid base for supporting the specimen holders and loading mechanism, Figure 2. A 5.2 kW electric motor with an eddy-current clutch to provide a continuously variable speed was used to drive the engine. While the engine was capable of operation to 2200 rpm, balancing problems limited the upper speed to 1500 rpm. The specimen holder connecting rod was instrumented to measure dynamic loads to enable measuring the friction forces at the ring/cylinder interface. The electric current needed to actuate the eddy current clutch was found to correlate linearly with the dynamic force measurements, which provided a simple and reliable means for monitoring the dynamic frictional forces.

Temperature and atmospheric control was provided by an insulated stainless steel chamber around the specimens and heaters within the enclosure. The specimen chamber was designed for operation to 650 C. A 4.5 kW single cylinder diesel engine was used to provide exhaust gases to the enclosure to reproduce the actual diesel cylinder environment. The exhaust gas stream was passed through a heating chamber before introduction to the test chamber to heat it to the test temperature. While the capabilities of the apparatus are described above, the standard test conditions used in this study are given in Table 1.

Experimental procedures

Material Selection

Table 2 summarizes the materials used in the most recent phase of this study. Most of the materials evaluated were selected by Caterpillar, Inc. and Cummins Engine Co. Candidate materials were first screened by these companies on bench wear testers (such as pin-on-disk, Hohman A-6, and Cameron Plint TE77). Those that produced encouraging wear results were evaluated further in this study. For the radioactive ion implantation, Si_3N_4 was chosen as the material to be implanted because of its wear resistance and its popularity as a direct ceramic replacement for many metallic engine components.

Figure 2. Photograph of wear apparatus.

Table 1. Summary of Testing Conditions.

Sliding Contact:	Initial "line" contact becoming flat-on-flat
"Cylinder" Specimens	13 x 32 x 127 mm
"Ring" Specimens	3.2 x 19 x 19 mm or 19-mm section of piston ring
"Ring" Crown Radius	32 mm or as supplied
Motion	Reciprocating, 108-mm stroke
Reciprocating Sped	500 rpm
Average Specimen Speed	1.8 m/s
Ring Loading	10.6 N/mm for coatings 2.3 N/mm for monolithic ceramics
Temperature	R.T. or 260 C
Atmosphere	Diesel exhaust
Measurements	Ring Wear (after test) and dynamic friction

Table 2. Materials used in this study.

Material	Specimen	Supplier
High Carbon Iron Molybdenum	liner	Caterpillar
Chromia-Silica	ring	Caterpillar
Molybdenum-Chrome Carbide	ring	Caterpillar
Chrome Oxide (SCA)	liner	Kaman Science/Caterpillar
Aluminum Titanate	ring	Caterpillar
HVOF Chrome Carbide-Nickel Chrome	ring	Turbine metal Technology
HVOF Tungsten Carbide-Cobalt	ring	Turbine metal Technology
APS Chrome Oxide	ring	B.I.R.L.
H13 Tool Steel	liner	Cummins

Modifications for Testing Curved Specimens

Some of the materials provided by Caterpillar were supplied in the form of piston rings and cylinder liners. While the experimental rig could not be easily modified to run complete rings and liners, testing curved sections cut from them was possible. Evaluating actual piston rings and cylinder liners when possible was preferred over specially prepared "flat" rings and liners because of manufacturing variability. By using sections of rings and liners, one is assured that the coating or material composition, coating process, substrate material, surface finish and all of the other manufacturing variables of the wear specimens is identical to those of the manufactured components.

To run curved wear specimens some minor modifications to the wear test rig were needed. Spacers were placed behind the thinner curved liner specimens so that the clamping mechanism did not have to be changed, and special ring specimen holders were fabricated from a piston as shown in Figure 3. The top compression rings supplied for testing had a "keystone" cross section. This shape allowed the ring section to fit snugly in the groove of the piston section without any additional clamping measures. The outer radius of the piston section, however, was ground back so the crown of the piston ring extended past it when it was fully seated in the ring groove.

The only problem encountered when setting up to run curved specimens was that the curvature of the ring and cylinder segments did not match. Unconstrained by a circular cylinder liner, the ring segments assumed the larger curvature of a ring in its relaxed state. Even sections cut from near the ring gap did not exactly match the liner curvature indicating that perhaps the cylinder liner had relaxed somewhat itself when cut into sections. In an attempt to bend the ring segments to the proper curvature, radial relief cuts were made in the back of them to minimize the tensile stress produced during bending. When the cuts had been made, the curvature matched up very well without having to try to bend (and probably break) the rings. Apparently the internal stresses were such that the ring took on a smaller radius of curvature when the relief slots were cut.

Material Evaluation

The standard operating conditions for this study were presented in Table 1. The test sequence started with a 1 hour run at room temperature for an initial break-in period. Ring profile wear measurements were made using a Talysurf 6 surface profilometer before and after the break-in test to see how wide the worn "flat" was across the crowned face of the ring specimens. The specimens were then reassembled and run for at least one 4-hour period at 260 C. Specimens showing particularly low wear after the second profile measurement were run for one or more additional 4-hour periods to establish the long-term wear rates, with the wear measurement repeated between each of the subsequent test intervals. In most cases the wear rates after the second 4-hour period were not significantly

Figure 3. Curved ring specimen holder.

different from those of the first 4-hour interval, which indicated that break-in had occurred and the contacts had reached an equilibrium wear condition.

Results and Discussion

Ring specimen wear is presented in terms of a wear factor to permit a direct comparison for the various material combinations obtained at different load and speed combinations. The wear of the ring specimens alone was used as the measure of relative performance since the majority of the wear occurred on the ring specimens. It was also difficult to get accurate liner wear measurements after only a few hours of running. The average ring wear factor given in the results is the average of all of the tests portions conducted with each material combination. When multiple 4-hour runs were conducted, wear factors from all test portions were included in the average. The wear factors were calculated as follows:

$$k = \frac{V}{Lx} \text{ mm}^3/\text{Nm} ,$$

where:

k = wear factor

V = wear volume, mm^3

L = applied load, N

x = sliding distance, m

Values of the wear factor can range from 10^{-3} for severe unlubricated wear to 10^{-9} or lower for the extremely low wear rates experienced under conditions of full hydrodynamic lubrication.

Baseline Wear Goal

The first bar in Figure 4 represents the calculated wear factor of a conventional electroplated chrome piston ring running against a cast iron liner in an over-the-road diesel truck engine. A wear factor of $3 \times 10^{-10} \text{ N/mm}^3$ was calculated assuming an average engine speed of 2000 revolutions per minute, 483,000 km between overhaul, an average unit ring loading of 17.5 N/mm, and 0.25 mm depth of chrome worn from the ring.

When the same materials were tested in the experimental apparatus, an average wear factor of $3 \times 10^{-9} \text{ N/mm}^3$ was measured as represented by the second bar in Figure 4. While this experimental wear factor is an order of magnitude higher than the predicted factor based on field experience with the

Figure 4. Baseline wear results.

same materials, slightly different test conditions and relatively high experimental error with these kinds of wear tests help explain the difference. The reason lower levels of ring loading were used in the experimental testing than in the prediction model was because the rig was run at a lower reciprocating speed to minimize vibration. The lower reciprocating speed made it difficult to produce elasto-hydrodynamic lubrication under equivalent loads, so the ring load was reduced to compensate. Because all of the subsequent tests were to be tested under the same experimental conditions, the experimental wear factor of $3 \times 10^{-9} \text{ mm}^3/\text{N-m}$ was chosen for the baseline goal. If a wear factor of $3 \times 10^{-9} \text{ mm}^3/\text{N-m}$ can be obtained with advanced materials at higher temperatures, the wear life of current production engines and low-heat-rejection engines should be similar.

The third bar in Figure 4 demonstrates the reason for conducting this work; at the higher temperatures expected of future low-heat-rejection engines, wear of conventional ring materials increased by more than two orders of magnitude (to $4 \times 10^{-7} \text{ mm}^3/\text{N-m}$) over the same materials running at conventional temperatures. Finding advanced replacement materials for metallic engine components may be one way to obtain the low wear rates of today's engines at tomorrow's operating temperatures.

The average dynamic friction coefficient results are also presented in Figure 4. No attempt is made to identify a baseline friction coefficient goal because the fluctuation in the friction measurements typically vary as much as plus-or-minus 40 percent of the average throughout the test. Work at Cummins has identified a target friction coefficient goal of 0.1 or less for lubricated systems⁽⁴⁾. All of the tests reported in this paper meet or exceed this friction requirement. What appears to be a correlation between the average friction coefficient and the log of the wear factor in Figure 3 is probably coincidental as this behavior is not seen in all of the tests.

Summary of Previous Studies

To gain an understanding of how attainable this wear performance goal is, some highlights of earlier phases of work are presented here. Figure 5 shows the wear results of the five best material combinations obtained during the first two phases of work. The specific materials and suppliers can be found in earlier publications⁽⁵⁾. One of these material combinations exceeds the baseline goal and the other four are within an order of magnitude of it. Again, average dynamic friction coefficients are presented to show the variability of that measurement and are not used to correlate wear performance.

Materials from Diesel Engine Manufacturers

While the materials tested in earlier phases of the study had excellent friction and wear behavior under high temperature conditions, they may or may not be practical from a materials cost and/or manufacturing standpoint. The purpose of

Figure 5. The best material combinations from earlier test phases.

this phase of the work was to test materials that a) diesel engine companies had at least some manufacturing experience with and b) had performed well in the bench tests they conducted. Figure 6 shows the wear and friction results of the materials supplied by Caterpillar for additional testing in the engine simulation rig. Again the baseline wear goal is provided for comparison.

The chromia-silica sliding against high-carbon iron-molybdenum had the lowest wear of the ring coatings supplied by Caterpillar ($9 \times 10^{-9} \text{ mm}^3/\text{N-m}$) and was within an order of magnitude of the baseline goal. For such low wear, this coating also had an unusually high average dynamic coefficient of friction throughout the test. The reason for this is not presently known. The molybdenum-chrome carbide and aluminum titanate coated ring specimens were cut from piston rings from an engine with an approximate bore of 125 mm. These coatings showed good, but less encouraging, wear results with average wear factors close to $1 \times 10^{-7} \text{ mm}^3/\text{N-m}$ when tested against chrome oxide (SCA) coatings. Apparently, these coatings were baseline materials in their own right and were intended to be compared with additional materials with enhanced wear performance. The additional materials (in the form of piston rings with a different geometry) were unable to be tested because suitable specimen holders could not be made within the scope of the study. While the curvature of the specimens alone should not affect the wear results significantly, perhaps additional baseline tests should be conducted using specimens cut from chrome plated piston rings and cast iron liners of similar curvature for comparison. These data agree with what Caterpillar achieved in their bench and fired engine tests⁽⁶⁾.

The coatings that Cummins Engine Co. found to have promising wear performance in their bench tests were also evaluated. In this series of tests the uncoated cylinder liner specimens were made from hardened H13 tool steel. Similarly, the substrates for the ring coatings were also hardened H13 tool steel. The ring coatings were high-velocity oxy-fuel (HVOF) coatings of chrome carbide-nickel-chrome, HVOF tungsten carbide-cobalt, and plasma sprayed chrome oxide. Figure 7 shows the friction and wear results of these materials compared with the baseline goal. The most similar bench test data from Cummins is also shown for comparison⁽⁷⁾. Average wear factors were similar for all three materials and ranged from $6 \times 10^{-8} \text{ mm}^3/\text{N-m}$ to $2 \times 10^{-7} \text{ mm}^3/\text{N-m}$ in the tests conducted in this study. The relative wear factors of the three materials correspond to the results obtained in bench tests at Cummins, however, the absolute wear factors are about an order of magnitude higher. Different ring specimen substrates and cylinder liner materials used during testing may be one reason for the differences. In the Cummins testing, Type 422 stainless steel ring substrates were used as well as pearlitic grey iron liners. As mentioned earlier, this study used H13 tool steel for both the ring substrates and liners. Similar cobalt-bonded tungsten carbide and the chrome oxide coatings were tested in the earlier test phases (Figure 4) and produced wear results which agree more closely with the Cummins data.

Figure 6. Ring wear factors of specimens provided by Caterpillar.

Figure 7. Ring wear factors of material combinations recommended by Cummins.

A summary of all of the different wear test results discussed thus far is shown in Figure 8. The material combinations tested during this phase were selected because of their potential for production as much as for wear resistance. For this reason, wear rate may be compromised somewhat for the sake of manufacturing considerations.

Wear of Ion-Implanted Silicon Nitride

The feasibility of implanting ^7Be and ^{22}Na ions in ceramic materials for the purpose of wear studies has been demonstrated by researchers at Michigan State University (M.S.U.)^(8,9). The intensity of low-level γ radiation emitted from the wear surface of the radioactive-ion-implanted (RII) material can be correlated to the depth of wear. This method is said to be capable of resolving wear as low as 50 nm.

Wear tests were conducted to determine if the implantation itself would influence the wear rate of the material. M.S.U. supplied a number of control silicon nitride ring specimens, as well as some that were implanted with six doses of 10^{12} particles of ^{20}Ne . This non-radioactive ion is similar in size to ^{22}Na and should produce similar implantation damage. The dosage was 2 to 3 orders of magnitude higher than required for using ion-implantation as a wear diagnostic tool so that any damage would be intensified. Each of the six doses was implanted to different depths, which ranged from less than 5 μm to about 10 μm . Any damage, characterized by an increase in wear rate, would be located in the region between these depths.

Tests were run with ten mating pairs of silicon nitride rings and chrome oxide-coated cylinder liners. Five of the silicon nitride rings were control specimens and five were implanted with ^{20}Ne . Each test consisted of three portions, a one-hour break-in followed by two two-hour runs. Ring wear measurements were taken before and after each of the two-hour test portions to obtain an average wear factor for each test portion specimen and to ensure that the wear was confined to the first 10 μm . The two wear factors for each ring specimen were then averaged to get a single wear factor for each ring specimen.

The results are presented in Figure 9. All ten of the average wear factors measured are within an order of magnitude of each other (between 8×10^{-9} and $4 \times 10^{-8} \text{ mm}^3/\text{N-m}$), which is typical for these wear tests. The average wear factor for all of the control specimens compared with all of the implanted specimens also indicates that there is no significant difference in the wear rate performance of the control and implanted specimens. Since these ions are similar in size to ^{22}Na ions, it is expected that the effect of implanting silicon nitride with ^{22}Na would also be negligible.

Figure 8. Summary of test results.

Ion Implantation Specimens Silicon Nitride vs Chromia

Figure 9. Ring wear factors of silicon nitride with and without ion-implantation .

Conclusions

Diesel engine manufacturers supplied or recommended material combinations for this study based primarily on the wear performance achieved during screening tests. Selection criteria for the materials, however, also included practicality issues related to manufacturing. Additional testing of these material combinations was performed in this study on an experimental wear apparatus that simulates the piston ring/cylinder liner interface. The results showed that the wear performance of these materials was generally lower than both the baseline wear goal as well as some of the material combinations tested in previous phases of this program. Perhaps there currently is a compromise between ultimate wear performance and manufacturability. Continued testing of manufactured engine components as opposed to specially prepared specimens should help reduce or eliminate this compromise. Finally, Radioactive Ion Implantation was not shown to affect the wear performance of monolithic silicon nitride adversely. The in situ monitoring of engine wear using this safe and extremely accurate method could also increase the practicality of fired engine tests since the engine would not have to be periodically disassembled to measure wear.

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