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THE EVALUATION OF A MODIFIED CHROME OXIDE BASED HIGH TEMPERATURE SOLID LUBRICANT COATING FOR FOIL GAS BEARINGS

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ABSTRACT

This paper describes the friction and wear performance of PS304, a modified chrome oxide based coating, for foil gas bearings. PS304 contains 60 wt% NiCr binder, 20 wt% Cr_2O_3 hardener, and 10 wt% each Ag and BaF_2/CaF_2 lubricants. For evaluation, the coating is plasma spray deposited onto test journals which are slid against a superalloy partial arc foil bearing. The test load was 10 KPa (1.5 psi) and the bearings were run under start/stop cyclic conditions. The data show good wear performance of the bearing especially at temperatures above 25 °C. Bearing friction was moderate ($\mu \cong 0.4$) over the entire temperature range. Based upon the results obtained, the PS304 coating has promise for high temperature, oil-free turbomachinery applications.

Key words: Gas Bearings, Solid Lubricants, High Temperature

INTRODUCTION

Significant advances in the performance of Compliant Surface Foil Gas Bearings have renewed interest in their application in high temperature, high speed Oil-free Turbomachinery (refs. 1 and 2). These self-acting, hydrodynamic air-bearings offer much technological potential due to their low friction, and high speed, high temperature capabilities. During normal operation the bearings float on a self generating air film and experience no wear. Wear protection during start-up and shut-down, however remains a technical obstacle especially for long-life, high temperature operation (refs. 3 and 4). Recent research on PS300, a chrome oxide based solid lubricant coating, has shown promise for foil gas bearings (ref. 5).

PS300 is a plasma sprayed, NiCr bonded, chrome oxide based coating with Ag and BaF_2/CaF_2 lubricant additions. It has shown good friction and wear properties in pin-on-disk testing from 25 to 650 °C. For foil bearings PS300 is applied to the journal (shaft) by plasma spraying followed by grinding prior to testing. In a recent paper, PS300 was successful in lubricating a foil gas bearing at 500 °C for over 15,000 start-stop cycles (ref. 5). At 25 °C, however, friction and foil wear were excessive. Furthermore, repeated thermal cycling above 500 °C resulted in spalling of the coating (delamination) from the journal surface. This failure mechanism was attributed to a mismatch in thermal expansion coefficients (CTE's) between the coating and the substrate (ref. 5). Follow-on research identified a new coating composition, designated PS304, which contains the same constituents as PS304 but altered ratios of binder to chrome oxide. PS304 has nearly the same CTE as typical superalloy substrates (14×10^{-6}/C) and exhibits good friction and wear properties in pin-on-disk testing to 800 °C (ref. 6).

The present work, reported in this paper, evaluates PS304 in a partial-arc foil gas bearing from 25 to 650 °C. Results are compared to PS300 bearing tests and pin-on-disk testing for PS300 and PS304.

EXPERIMENTAL MATERIALS

Test Specimens

The PS304 coating is evaluated using a partial-arc foil bearing test rig shown in figure one and described in detail in reference 7. The specimens are a foil bearing and a coated shaft or journal. The bearing consists of a corrugated bump foil and a smooth top foil made from a precipitation hardened NiCr alloy, Inconel X-750, 0.10 mm thick. The bare foil specimens are tested against superalloy shafts coated with a 0.25 mm thick layer of PS304. Figure 2 shows, schematically, the test specimens. The PS304 coatings are applied by plasma spraying to a thickness of 0.30 mm followed by finish grinding to a diameter of 38 mm and a surface finish to 0.2 µm rms.

The PS304 coating contains 60 wt% NiCr, 20 wt% Cr_2O_3 and 10 wt% each of Ag and BaF_2/CaF_2 eutectic. The NiCr acts as a binder. The Cr_2O_3 acts as a hardening additive and as a high temperature lubricant. The silver and fluoride additions are low and high temperature lubricants respectively. Figure 3 shows a cross-section photomicrograph of a PS304 coating. The measured coefficient of thermal expansion is about 12.4×10^{-6}/C which closely matches the superalloy substrates of 14×10^{-6}/C. Reference 8 describes the coating and deposition process in more detail.

TEST PROCEDURE

The specimens are tested in a high temperature foil bearing test rig under repeated start/stop cycling. Each cycle lasts 20 sec consisting of a 13 sec period in which the spindle drive motor is on, followed by a 7 sec period in which the drive motor is shut off. During the first few seconds of the on period the spindle accelerates to full speed

(13,800 rpm) and then runs at this speed for about 10 sec prior to motor shut-down. The bearing develops a hydrodynamic lubricating air film at speeds above about 4000 rpm. Following motor shut-down, the spindle coasts to a stop in about 5 sec. Sliding between the foil and the coated shaft occurs when the spindle speed drops below 4000 rpm. Bearing friction (torque) is measured continuously during the test cycle with a calibrated load cell connected to a torque arm which prevents bearing rotation. Bearing friction is then estimated by dividing the measured torque by the total bearing weight and the torque arm length. A chart recorder is used to monitor and record the torque and spindle speed data. A once-per-cycle counter keeps track of elapsed cycles. A typical friction-speed trace is shown in figure 4. The test sequence lasts for 30,000 cycles. Bearing wear was measured every 10,000 cycles by interrupting the tests and using a vernier micrometer to measure journal diameter changes (coating wear) and bearing foil thickness (foil wear). The test load was 10 kPa (1.5 psi) and is chosen to simulate a typical near term turbomachin-ery application. Test temperatures ranged from 25 to 650 °C and were achieved using quartz tube radiant heaters shown in figure 1. Reference 7 describes the test rig and procedures in more detail. Following testing, journal wear was more completely/accurately measured using stylus profilometry. Selected wear surfaces were examined with SEM/EDS to elucidate the wear process.

RESULTS AND DISCUSSION

The tribological data is comprised of foil wear, journal wear and bearing friction. Foil wear is expressed by measuring the reduction in foil thickness at the most worn area of the foil. This area is typically in the foil center since it supports the bulk of the deadweight load. The foil is considered "worn out" or no longer usable when 25 percent of the original foil thicknesses, 0.025 mm for these foils, is removed. Bearing performance can be degraded if wear beyond this point occurs in a heavily loaded application. Foil wear is measured using a micrometer with a ball tip.

Journal wear is also measured with a micrometer and checked for accuracy after testing is completed with a stylus profilometer. Journal wear is considered excessive if more than 0.025 mm is worn from the diameter. Wear beyond this point results in a significant increase in the bearing clearance and can affect bearing performance and stability especially under low loads and high speeds. Bearing friction (Torque) is presented as a friction coefficient calculated from torque measurements conducted during normal start/stop operation.

It was observed early in this test program that the bearing torque was significantly decreased by relatively small temperature increases especially at low ambient temperatures, e.g. 25 versus 200 °C. Upon closer examination of the data, it became apparent that this thermal affect was due to a reduction in preload of the foil against the journal. All foil bearings are initially sized with a small spring loading or interference with the shaft to ensure bearing stability especially under light loads. Thus the measured torque is due to both the preload or wrapping force of the foil against the journal as well as the friction contribution from the applied load (weight).

To separate the friction due to the preload from that due to the applied load, torque measurements were made under several test loads. These were then plotted against the total load and a least squares fit was applied to the data. The slope from this fit is taken as the calculated friction coefficient for the test conditions considered. Figure 5 shows this calculation graphically. By making this calculation it may be possible to compare friction from the particular bearing to results previously obtained with the pin-on-disk rig.

The tribological data is summarized in table I and shown graphically in figures 6 to 8. Data uncertainties shown represent scatter from repeated measurements made at roughly 5,000 cycle intervals and from at least 2 repeat tests of different specimens under identical test conditions. The data is characterized by a marked decrease in wear at test temperatures higher than 25 °C and uniform friction coefficients over the entire temperature range. Both foil and journal wear were 5 to 10 times higher at 25 °C than at 650 °C as shown in table I and figures 7 and 8.

At 25 °C, the foils experienced at 25 percent thickness reduction of 0.0025 cm after only 15,000 start/stops. Several tests were continued beyond this pre-established wear limit. The foil wear continued in an approximately linear fashion reaching 0.0046 cm after 30,000 cycles. The foil wear decreased drastically to about 5 percent (≈0.0005 cm) of the foil thickness after 30,000 cycles at all temperatures above 25 °C.

Journal wear mirrored the foil wear behavior. At 25 °C the diametral journal wear was 0.0025 cm reaching the established wear limit after 30,000 cycles. At elevated temperatures, the wear ranged from 0.0004 to 0.0009 cm. The reasons for the tribological behavior observed may be elucidated by examining the results of the wear surface analyses. Table II summarizes the findings of EDS X-RAY analyses conducted on foil and journal surfaces after completing 30,000 start/stop cycles.

At 25 °C the foil wear rate is high and no detectable transfer from the PS304 coating occurs. Some Fe is detected on the worn journal perhaps coming from foil wear debris. The lack of any detectable lubricant (Ag, Ca, Ba) transfer from the coating to the foil explains the high wear observed. At 204 °C, no lubricants but significant Fe and O is detected on the journal surface. Other than the appearance of an Oxygen peak, no changes to the foil surface chemistry were observed. See figure 9. Considering the dramatic reduction in foil and journal wear, compared to 25 °C, it is plausible that a lubricious iron oxide (Fe_3O_4) has formed on the journal surface. Certain oxides of iron have been shown to be good solid lubricants under certain sliding conditions (refs. 9 and 10).

In contrast, after testing 427 °C the coatings intrinsic lubricants (Ag, Ca, Ba), not Fe oxide, appear to providing a significant lubrication role. Although detectable on the journal surface, the observed Fe peak is small compared to the Ag, Ca and Be peaks. See figure 10. The foil surface clearly shows the presence of oxygen but not transferred lubricants. In this case, the low friction and wear observed could be the result of both in-situ formed lubricious oxides and chrome oxides and lubricants found in the coating.

Bearings run at 538 °C experience detectable lubricant transfer from the journal coatings to the foil surface. See figure 11. The journal surface contains all of the coatings original constituents and exhibits an apparent rise in both Cr and Si peak heights compared to Ni. This observation may suggest the formation of a chromium silicate compound. Although not a major coating constituent, silicon is present in the coating in the form of an anticaking agent added to the NiCr binder powder by the manufacturer at concentration around 1 vol %. Independent trials at the author's lab using NiCr binder without this additive indicate that its presence has no measurable affect on the tribological properties of the coating. Nonetheless the simultaneous rise in the Si and Cr peaks in the EDS spectrum suggest an interaction. Whatever the case, tribological performance is not hindered.

After operation at 650 °C, foil surfaces show continued transfer of lubricants (Ag, Ca, Ba) from the journal as well as a clear oxygen peak. The journal surface contains all of the original constituent plus small Fe and Mo peaks (from the foil). Although the Ti peak in the spectra interferes with the Ba peak, the presence of Ca is coupled with Ba since the BaF_2/CaF_2 eutectic in the coating is prefused. Thus, if a peak is observed at the Ba/Ti location ≈4.5 KeV) without a Ca peak than the peak at ≈4.5 KeV is probably Ti. However when the Ca peak is present the peak at ≈4.5 KeV is resulting from Ba alone or Ba and titanium.

These surface analyses clearly show that there are compositional differences among the surfaces generated at varying temperatures. Despite these variations, bearings tested at elevated temperatures exhibit a common character. They all show reduced friction and wear compared to the room temperature case, which experienced high wear and no significant surface composition changes. Clearly, lubricant transfer and surface film formation has a positive effect on lowering friction and wear.

This behavior corroborates earlier work with the PS304 coating and similar coating systems (refs. 6 and 11). Pin-on-disk testing showed that good tribological properties occurred in conjunction with lubricant surface film formation and transfer to the sliding counterface. Of course, the absence of beneficial transfer at room temperature may be simply the consequence of an increased wear rate of the foil resulting in the wearing away of any transferred lubricants. The development of solid lubricants which can provide superior performance (i.e., comparable to MoS_2 or graphite) at low temperatures while being capable of surviving high temperature use remains an as yet unmet challenge (ref. 12).

Similar temperature/wear performance characteristics were observed in both partial-arc bearing and pin-on-disk (table III) tests of PS300 which differed from PS304 in its ratio of binder to Cr_2O_3. In those tests, wear was also higher at room temperature. However, the wear at 25 °C was so severe that the bearings wore through after only 3000 cycles (ref. 5). Clearly, compositional changes alone can reduce the room temperature wear but more changes need to be made to enhance performance. Fortunately, the intended applications for foil bearings (turbochargers, auxiliary power units and gas turbines) experience most of their operation at elevated temperatures. Room temperature wear, in these cases, are not an issue.

CONCLUDING REMARKS

The tribological performance of PS304 in partial-arc foil bearings was evaluated. From the friction and wear data it is observed that friction is, more or less, independent of the test temperature while wear is markedly higher at room temperature than at elevated temperatures. Post-test surface analyses suggest that reduced wear results when surface enrichment and transfer of lubricants occurs. Although the specific surface composition and apparent lubrication mechanism differs for each elevated test temperature, the wear performance is quite uniform. Based upon these results, these coatings show great promise for high temperature foil bearings in Oil-free Turbomachinery applications.

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TABLE I.—FRICTION AND WEAR SUMMARY[a]
[Test conditions: 30,000 start/stop cycles, 10.2 kPa load]

Test temperature, °C	Calculated friction coefficient[b]	Foil wear, cm	Journal coating diametral wear, cm
25	0.40±0.04	[c]0.0046±0.001	0.0025±0.0005
204	0.39±0.05	0.0005±0.0001	0.0005±0.0002
426	0.39±0.02	0.0003±0.0001	0.0004±0.0002
538	0.40±0.03	0.0004±0.0002	0.0009±0.0004
650	0.33±0.03	0.0005±0.0002	0.0005±0.0002

[a]Data uncertainies represent scatter between repeat tests. At least two repeats performed for each test temperature.

[b]Friction coefficient calculated as slope of bearing torque versus applied load plot measured at 10,000 cycle intervals from 5 to 30 kPa static loads.

[c]Testing continued beyond 0.0025 cm (25 percent foil thickness) wear limit.

TABLE II.—EDS-X-RAY ANALYSIS SUMMARY OF WORN FOIL AND JOURNAL SURFACES

Test condition/test temperature	Major elements present		Remarks
	Foil surface	Journal surface	
Pretest/unworn	Ni, Cr, Fe, Ti, Mo	Ni, Cr, O, Ag, Ba, Ca, trace Si	Constituents detected
25 °C 75 °F	Ni, Cr, Fe, Ti, Mo	Ni, Cr, O, Ag, Ca, Ba, Fe, Si	Fe transfer from foil to journal No journal coating transfer to foil
204 °C 400 °F	Ni, Cr, Fe, Ti, Mo, O	Ni, Cr, Si large Fe, O peaks	Significant Fe/O transfer to journal. No lubricants (Ag, Ca, Ba) detected on journal
427 °C 800 °F	Ni, Cr, Fe, Ti, Mo, O	Ni, Cr,O, Ag, Ca, Ba, Fe, Si, Mo	Detectable Fe/O transfer to journal. All lubricants (Ag, Ca, Ba) detected on journal
537 °C 1000 °F	Ni, Cr, Fe, Ti(Ba), Ca Ag, Mo, O	Ni, Cr, O, Ag, Ca, Ba, Si, O	Journal: increased Cr/Ni ratio, increased Si, O peak. All lubricants present. Foil surface: exhibits significant Ag, Ca possibly Ba, Si
650 °C 1200 °F	Ni, Cr, Fe, Ti(Ba), Ca Ag, Mo, O	Ni, Cr, O, Ag, Ca, Ba, Mo, Fe, Si	Journal: slight transfer of Fe, Mo (+O). All lubricants present foil surface: significant lubricant (Ag, Ca, +Ba) transfer

TABLE III.—PIN-ON-DISK DATA SUMMARY FOR IX750 VERSUS PS304 AND PS300 COATINGS
[Data from reference 6.]

Disk coating	Pin material	Temperature, °C	Friction coefficient	Kpin, mm^3/N-m	Kdisk, mm^3/N-m
PS300	INCX750	25	0.23±0.05	$3.9\pm0.5\times10^{-5}$	$6.6\pm2.5\times10^{-5}$
PS300	INCX750	500	0.29±0.04	$1.3\pm0.3\times10^{-5}$	$3.9\pm0.3\times10^{-4}$
PS300	INCX750	650	0.31±0.01	$3.1\pm0.8\times10^{-5}$	$7.1\pm1.6\times10^{-4}$
PS304	INCX750	25	0.31±0.05	$0.96\pm0.3\times10^{-5}$	$4.8\pm0.3\times10^{-4}$
PS304	INCX750	500	0.25±0.02	$0.32\pm0.5\times10^{-5}$	$2.8\pm0.3\times10^{-4}$
PS304	INCX750	650	0.23±0.02	$0.38\pm0.4\times10^{-5}$	$1.0\pm0.1\times10^{-4}$
PS304	INCX750	800	0.37±0.03	$6.9\pm2.0\times10^{-5}$	$2.6\pm0.2\times10^{-4}$

Note: Tests conducted in air, 4.9 n load, 1 m/s sliding velocity.

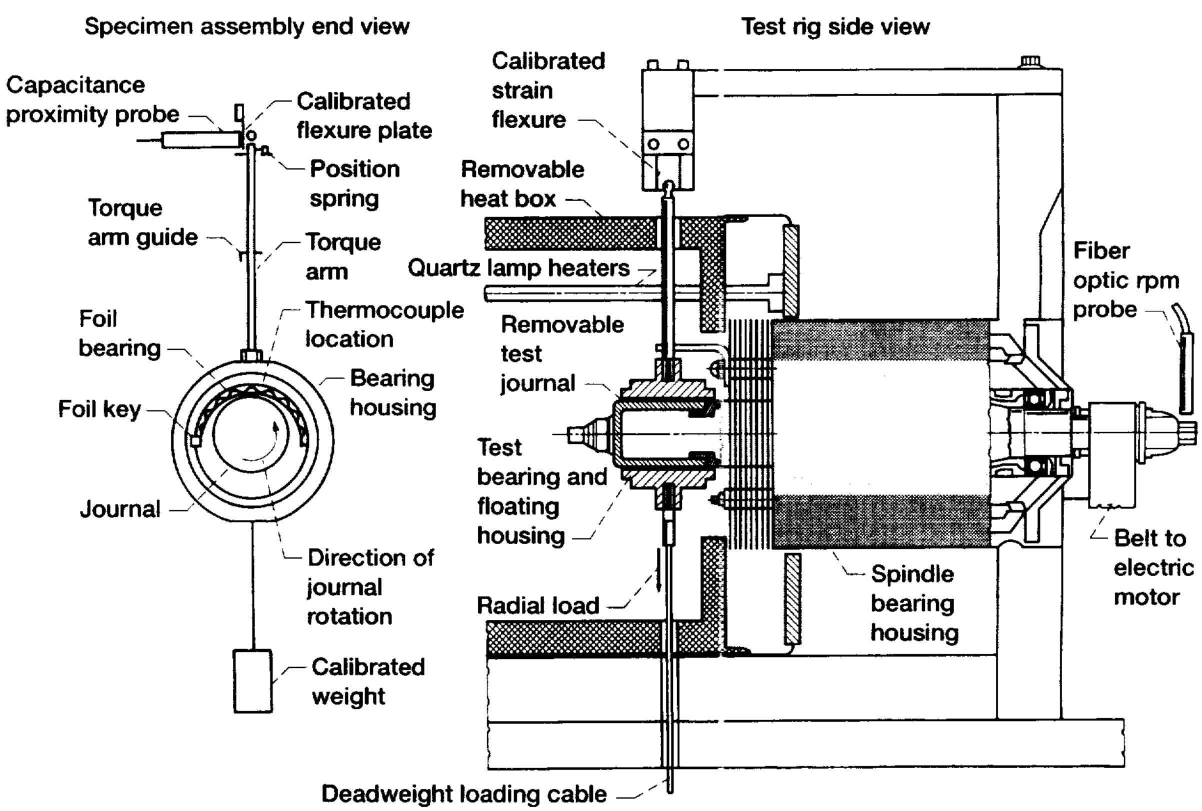

Figure 1.—Schematic view of test apparatus.

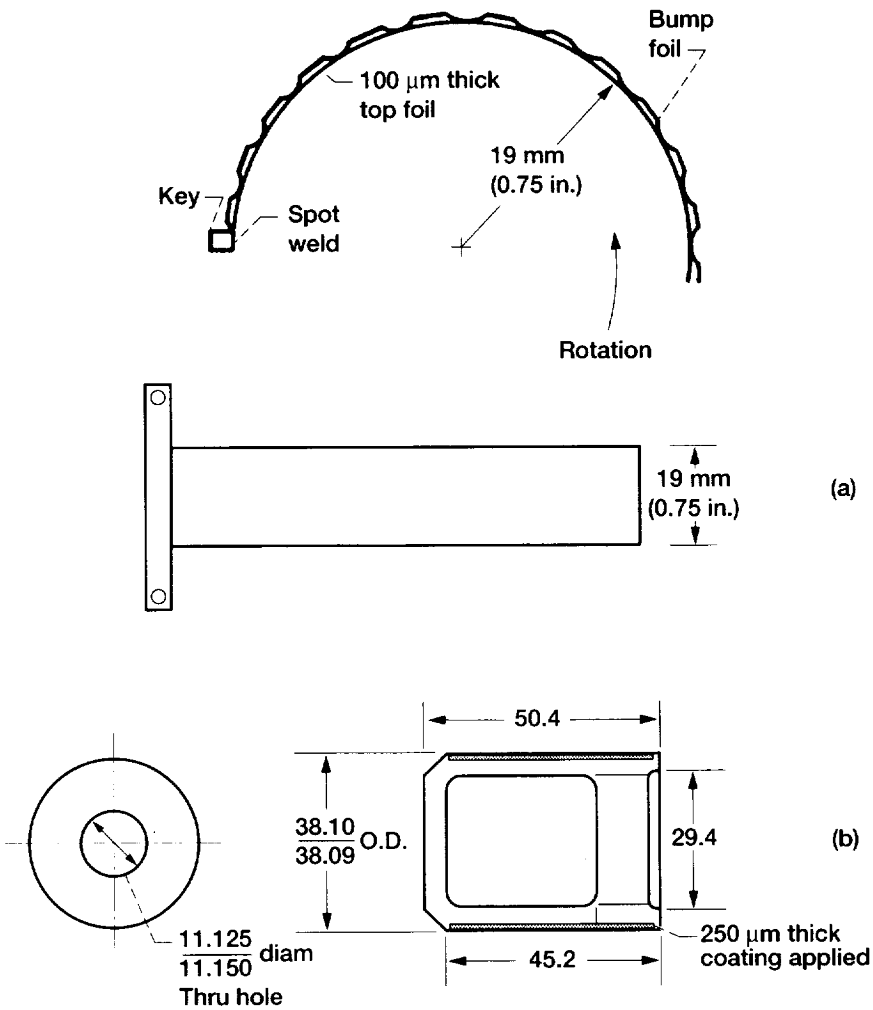

Figure 2.—Specimen geometry. (a) Foil. (b) Journal. Units in mm.

Figure 3.—Cross section SEM photomicrograph (backscattered) of PS 304.

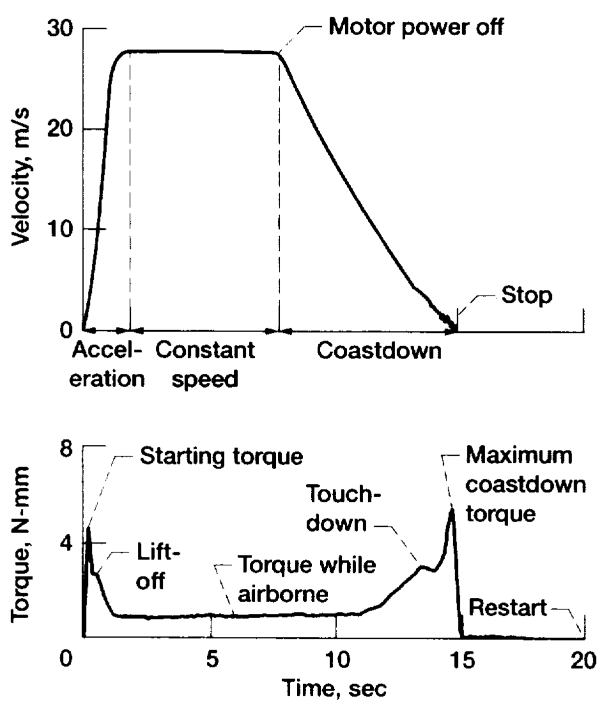

Figure 4.—Typical test cycle speed/torque trace.

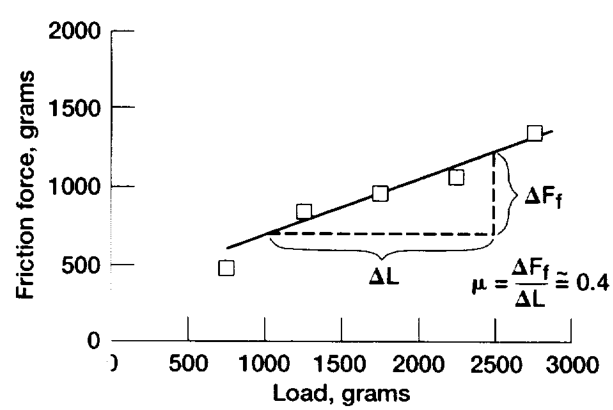

Figure 5.—Example of friction force (bearing torque) versus load at 25 °C (78 °F) showing calculation of friction coefficient.

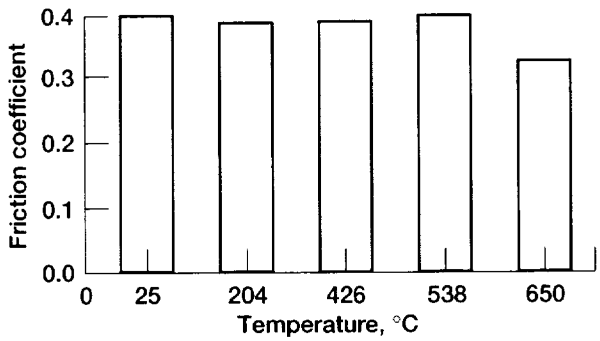

Figure 6.—Friction coefficient (calculated from apparent bearing torque) for PS 304 coated journals sliding against IX750 foil bearings.

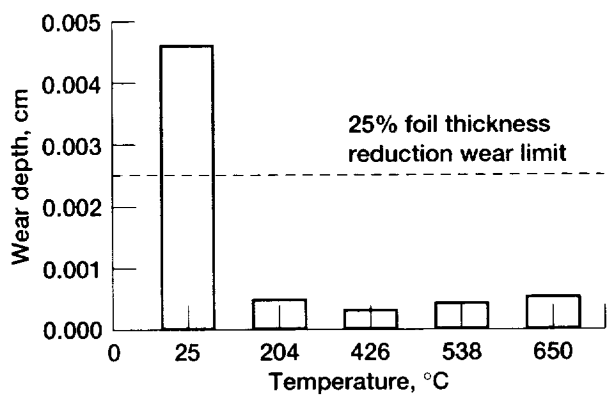

Figure 7.—Foil wear for IX750 foils slid against PS 304 coated journals under 10.4 kPa load, 30,000 start/stop cycles.

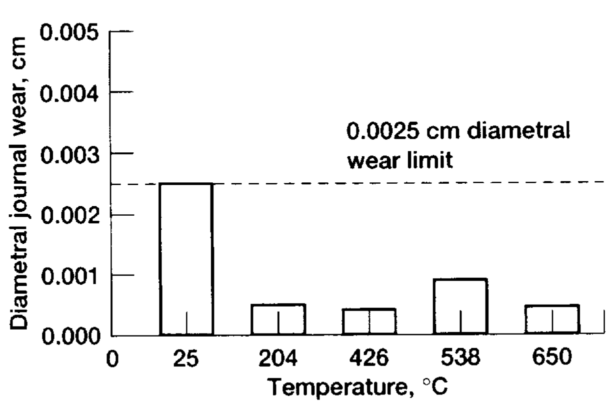

Figure 8.—Diametral journal wear of the PS 304 coating after sliding against IX750 foils under a 10.4 kPa load, 30,000 start/stop cycles.

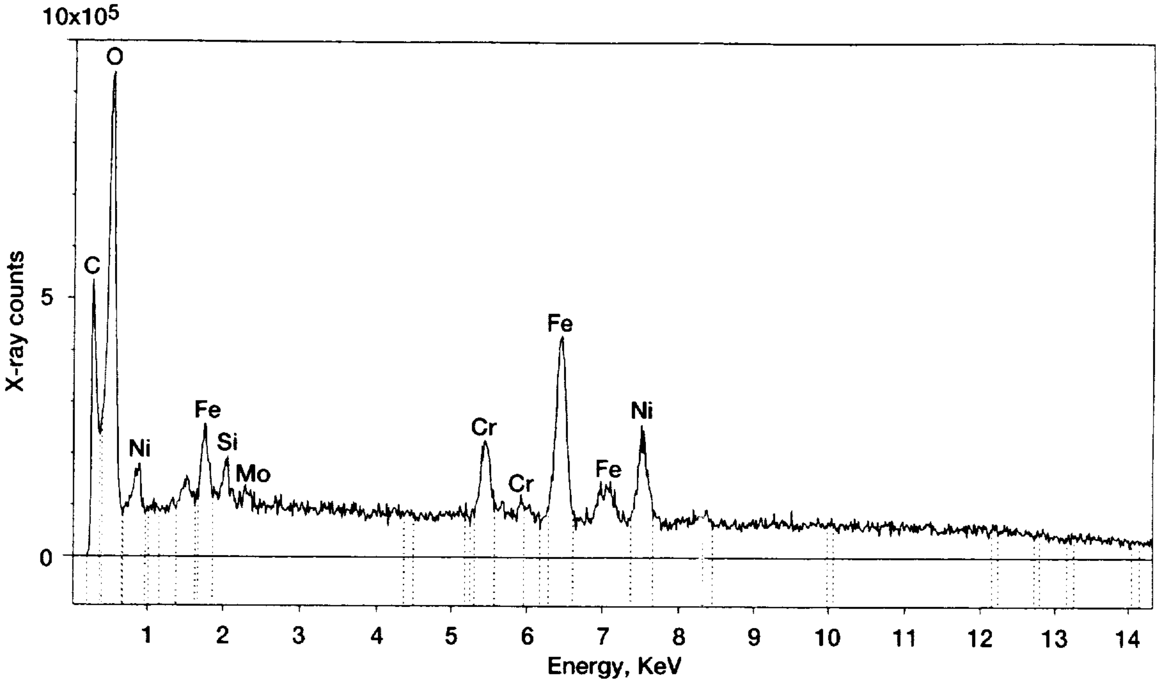

Figure 9.—EDS x-ray spectrum of PS 304 coated journal after sliding against foil at 204 °C (400 °F) for 30,000 start/stop cycles.

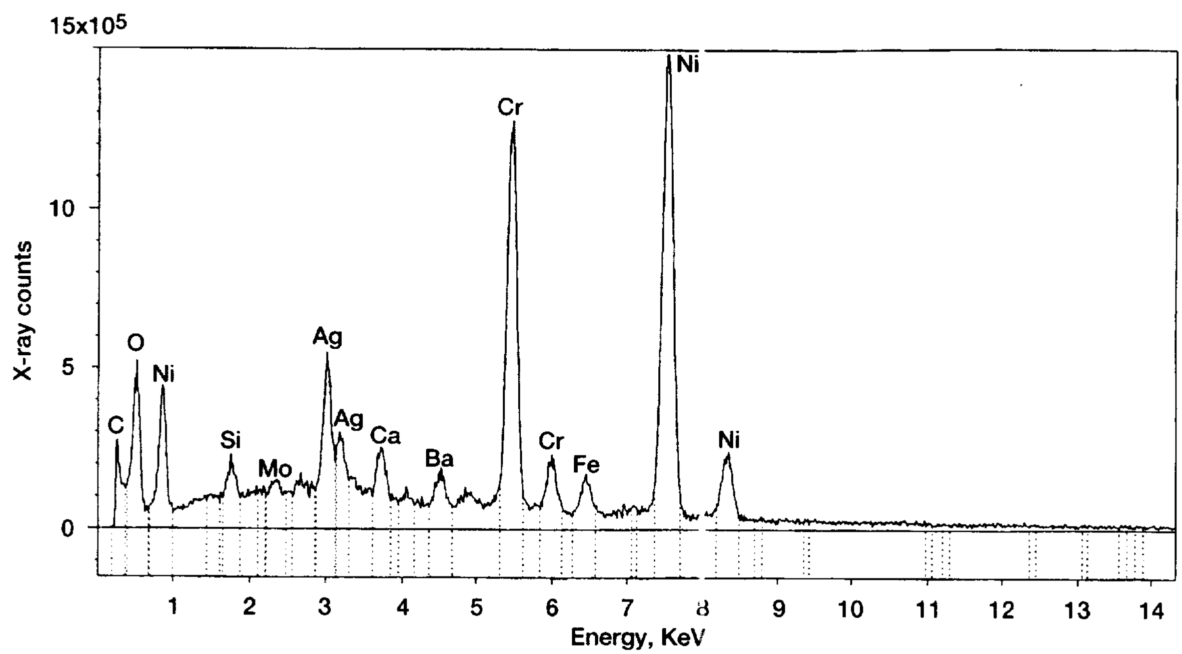

Figure 10.—EDS x-ray spectrum of PS 304 coated journal after sliding against foil at 427 °C (800 °F) for 30,000 start/stop cycles.

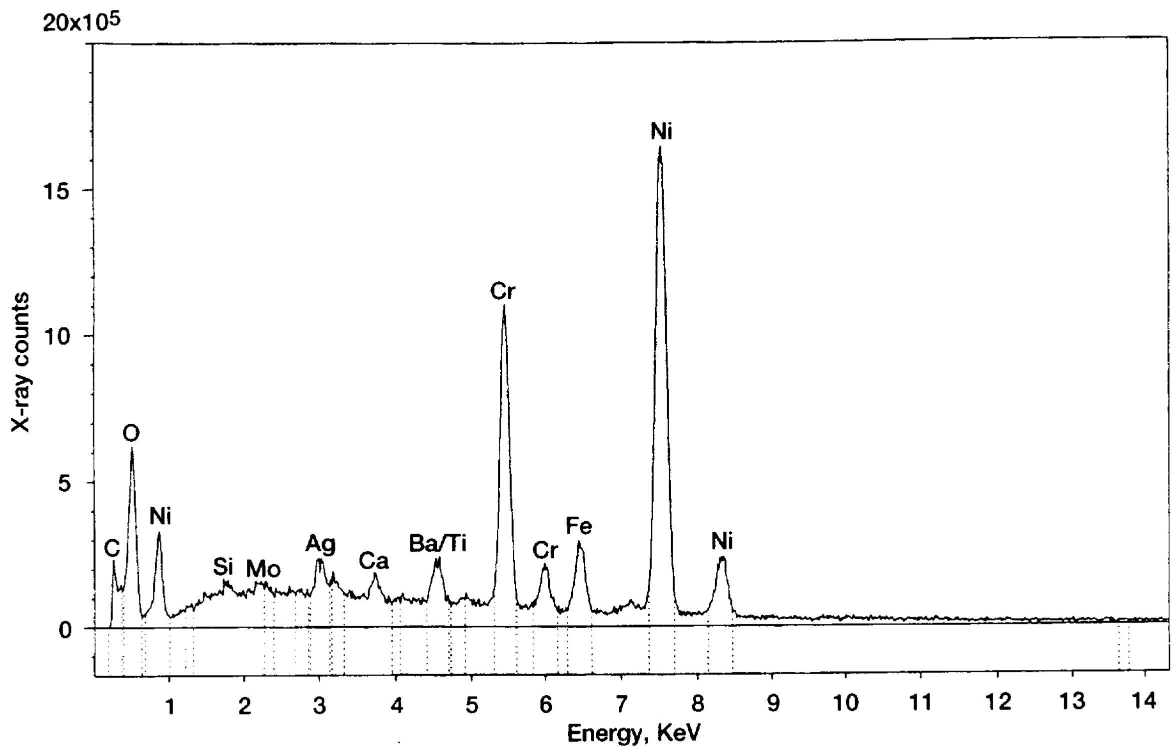

Figure 11.—EDS x-ray spectrum of foil surface after sliding against PS 304 coated journal at 538 °C (1000 °F) for 30,000 start/stop cycles.

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13. ABSTRACT *(Maximum 200 words)*

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