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EVALUATION OF ADVANCED SOLID LUBRICANT COATINGS FOR FOIL AIR BEARINGS OPERATING AT 25 AND 500 °C

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SUMMARY

The tribological properties of one chrome oxide and one chrome carbide based solid lubricant coating were evaluated in a partial-arc foil bearing at 25 and 500 °C. Start/stop bearing operation up to 20,000 cycles were run under 10 kPa (1.5 psi) static deadweight load. Bearing friction (torque) was measured during the test. Specimen wear and SEM/EDS surface analyses were conducted after testing to understand and elucidate the tribological characteristics observed. The chrome oxide coating which contains both (Ag) and (BaF_2/CaF_2) for low and high temperature lubrication, exhibited low friction in sliding against Al_2O_3 coated foils at 25 and 500 °C. The chrome carbide coating, which lacked a low temperature lubricant but contained BaF_2/CaF_2 as a high temperature lubricant, exhibited high friction at 25 °C and low friction at 500 °C against both bare and Al_2O_3 coated superalloy foil surfaces. Post test surface analyses suggest that improved tribological performance is exhibited when a lubricant film from the coating transfers to the foil surface.

INTRODUCTION

Significant improvements in turbomachinery performance and efficiency could be realized if the speed and temperature limitations of the oil lubricated rotor support systems (bearings) could be overcome. Various approaches towards these improvements which have been attempted include magnetic bearings (1), solid lubrication (2), vapor phase lubrication (3,4), and foil air bearings (5). Each of these approaches face technological obstacles which are formidable and yet to be overcome.

Magnetic bearings suffer from a lack of high temperature coil materials, excessive system weight and backup bearing considerations (6). Solid lubrication for rolling element bearings fail to meet life and damping requirements and vapor phase lubrication schemes are vulnerable to thermal management issues. Finally, foil air bearings have limited load capacity and damping, and under high static loading exhibit limited life due to wear (7).

Recent advances in foil bearing design and performance prediction, however, have reduced or eliminated many of the obstacles which had prevented their application for oil-free turbomachinery systems. For example, load capacities and damping levels twice the level of previous bearing limits have been reported (8,9). These improvements coupled with minimal progress in alternative rotor support technologies have renewed interest in oil-free turbomachinery systems supported by foil air bearings. However, adequate life during repeated start/stop cycles especially at high temperatures remains a technical obstacle to be overcome.

Foil air bearings are hydrodynamic bearings which float on a self generated gas film during normal operation. During initial start-up and shut down periods, prior to the development of a lubricating gas film, sliding contact occurs between the shaft or journal and the top foil surface which is typically made from a nickel-base alloy, Inconel X-750. Extensive materials screening reported recently using pin-on-disk testing indicated that unlubricated metal and ceramic sliding combinations cannot provide satisfactory friction and wear performance for practical foil bearing applications (10). To reduce friction and prevent wear and surface damage some form of solid lubrication is necessary.

To address this obstacle, a research program at Lewis was initiated with the goal of evaluating several new wear resistant materials and coatings for foil air bearings. Start/stop cyclic testing was conducted to assess tribological performance and characteristics of candidate tribomaterials. In this paper, two shaft coatings, one based on chrome oxide the other based on chrome carbide, are evaluated in sliding contact against either bare superalloy or Al_2O_3 coated foil specimens.

MATERIALS (BACKGROUND)

Experience at the authors' laboratory has suggested that effective solid lubrication can be provided by applying suitable coatings to the foil surface, shaft surface, or both (11,12). Conventional technology typically relies on soft polymer foil coatings sliding against bare metal or hard coated journals (11). For temperatures above 350 °C, the subject of this research, ceramics, cermets and selected metals and solid lubricants must be considered.

In the present research, two thermal spray journal coatings, one chrome oxide, designated PS300, and one chrome carbide, designated TBGD, are tested during start/stop operation of a partial-arc foil bearing at 25 and 500 °C with either bare or sputter coated Al_2O_3 superalloy foils. TBGD is a derivative of the NASA PS200 coating and consists of approximately 80 wt% NiCr bonded chromium carbide with 20 percent BaF_2/CaF_2 eutectic (13). It is applied to the Inconel 718 test journal by High Velocity Oxygen Flame Spraying (HVOF) followed by diamond grinding and polishing to a thickness of 250 mm and a surface finish of 0.3 mm rms. PS300 is a plasma sprayed coating consisting of 80 wt% NiCr bonded chromium oxide with 10 wt% Ag and 10 wt% BaF_2/CaF_2 eutectic. PS300 is fully described in ref. 14. Both of these shaft coatings utilize the bonded ceramic for durability and wear resistance and employ the silver and fluoride eutectic as friction reducing additives. Bearing friction and wear are monitored during the test sequence and post-test surface analyses are conducted to help understand the tribological performance of the coatings.

EXPERIMENTAL APPARATUS/PROCEDURE

The test specimens consist of a test journal or shaft onto which one of the coatings is applied and an Inconel X-750 partial-arc foil bearing which is either bare or sputter coated with a 2 mm thick Al_2O_3 film. The specimens are shown in figure 1 and are fully described in reference 12. They are tested in a high temperature foil air bearing test rig driven by an electric motor in a start/stop mode. The test cycle and apparatus are also fully described in reference 12. Figure 2 shows a schematic of the test set-up.

Briefly, the foil is loaded against the test journal by dead weights under a 10 kPa (1.5 psi) load (typical for many small turbomachinery applications). During the initial motor start up, dry sliding occurs between the shaft and foil. When the shaft reaches about 5 000 rpm a hydrodynamic gas film develops which lifts the foil off of the journal surface eliminating the rubbing contact. After operating the motor for about 13 sec and reaching a shaft speed of 13 800 rpm, the motor is turned off and coasts to a stop. Again, sliding contact occurs when the shaft speed drops below about 5 000 rpm. The off portion of the cycle lasts about 7 sec. Friction or (estimated) bearing torque is measured with a load cell mounted outside a furnace enclosure which is capable of heating the specimens to over 650 °C. For the current research, test temperatures of 25 and 500 °C were selected to simulate start-up and steady-state temperature operation of an anticipated turbomachinery application. Tests were run until bearing failure or 20 000 cycles was achieved. Figure 3 shows a speed torque trace for one typical cycle.

SPECIMEN PREPARATION

Two journal coatings, designated TBGD and PS300 which are described in references 13 and 14 were applied by thermal spraying and finished by grinding to a final thickness of 0.25 mm (0.010 in.) and a surface roughness of approximately 0.3 mm rms. Some of the tests included Al_2O_3 coated foils which were prepared by sputter depositing a 2 mm thick film onto the foil surface after the surface has been sputter etch cleaned. Substrate preheating to 600 °C ensured that the deposited film will have a stable alpha crystal structure. Reference 15 gives more details of the deposition process. Repeat tests were conducted for all of the PS300 tests to assess data scatter. Sufficient journal specimens coated with the chrome carbide coatings, TBGD, were not available to allow repeat tests but it is expected that they would experience comparable reproducibility to the PS300 tests.

RESULTS

The data consists of bearing friction coefficient, change in foil thickness and change in journal diameter. As mentioned previously, bearing friction is recorded during the test. The friction coefficients presented are an average of up to 200 measurments made for each test every 100 start-stop cycles. Results from repeat tests (PS300 samples) are then averaged to assess data satter. Wear is measured with a micrometer periodically during the tests and verified (for the journal) with a stylus profilometer at the end of the test. The data are presented in table I and shown graphically in figures 4 to 6.

For proper bearing operation, foil wear must not exceed about 25 percent or 25 mm of the original 100 mm foil thickness. Journal wear is also limited to 25 mm in order to prevent excessive clearance changes which can degrade bearing performance. Based upon these considerations, it is apparent that foil wear, shown in figure 5, was excessive when sliding against PS300 at 25 °C. When coated with Al_2O_3, the foil wear rate was reduced by a factor of 25 when sliding against PS300 at 25 °C. The improvement was less dramatic, but still significant, a factor of 5, when sliding against PS300 at 500 °C. Clearly, PS300 was abrasive to the bare Inconel X-750 foils. The chrome carbide coating, TBGD, was significantly less abrasive to the bare foils than PS300. The excellent wear properties of the foils sliding against the carbide coating was further improved, by a factor of about 2 to 4, when coated with Al_2O_3. Wear of both the foils and the journals was lower at 500 °C than at 25 °C. See figure 6.

In terms of friction, plotted in figure 4, the best combination was Al_2O_3 coated foils sliding against PS300. The friction coefficients ranged from 0.31 at 25 °C to 0.27 at 500 °C. For the carbide coating, the friction at 25 °C was 0.52 to 0.56 regardless of the counterface material. At 500 °C, the friction was slightly lower against Al_2O_3 coated foils (0.32) compared to bare foils (0.42).

DISCUSSION

The rationale used to formulate the chrome oxide and chrome carbide coatings is to combine a thermochemically stable, wear resistant matrix with solid lubricant additives to help reduce friction. Generally, the fluoride additions are made to reduce friction at temperatures above 500 °C and the silver is added to PS300 to reduce friction from ambient to about 500 °C (14). From the data it appears that this rationale is effective when sliding the coated journals against the Al_2O_3 coated foils. PS300, which contains both silver and fluoride additives, exhibited low friction at both 25 and 500 °C. TBGD, which only contains a fluoride additive, exhibited high friction at 25 °C and low friction at 500 °C.

The data against bare foils is not quite as clear since both journal coatings exhibit high friction at 25 °C. For TBGD this is probably due to the lack of a low temperature lubricant additive. For PS300 the high friction may be due to the excessive foil wear rate which precludes the formation of a silver rich transfer film forming on the foil surface which can reduce friction. The reasonably low foil wear rate for the TBGD at 25 °C can be attributed to its optimized fine grain structure which limits its abrasiveness even to bare foils (13).

To better understand the tribological mechanisms for the sliding couples tested the specimens were analyzed using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrocopy (EDS). These analyses help to confirm the initial data assessment and give guidance for materials improvements. Bare foil surfaces slid against either of the shaft coatings at 25 °C do not show any detectable lubricant transfer. A lack of lubricant transfer, especially Ag from the PS300, helps to explain the high friction observed at 25 °C.

In contrast, at 500 °C the EDS spectrum for the bare foil slid against the PS300 journal exhibited silver transfer as shown in figure 7. Analysis of the corresponding journal surface (fig. 8) shows the presence of all of the lubricant and matrix phases of PS300. The transfer of lubricants (Ba/Ca peaks) was detected for the bare foil slid against TBGD at 500 °C as well. This helps to explain the good performance (reduced friction) of TBGD at 500 °C. When the foil surfaces were coated with Al_2O_3, lubricant transfer and reduced friction and wear were observed for PS300 at 500 and 25 °C but only at 500 °C for TBGD. Corresponding micrographs also shown in figures 7 and 8 show the smooth wear surfaces generated by the PS300/bare foil sliding couple. Smooth surfaces are critical to acceptable foil bearing performance.

These surface analyses, in certain respects, contrast pin-on-disk testing for these materials reported in the literature (16,17). In that work, Al_2O_3 and superalloy pins were slid against PS300 coated disks. Under the contact conditions tested, friction and wear were high for Al_2O_3/PS300 sliding couples at 25 °C and low for superalloy/PS300 couples at 25 °C. At 500 °C, both combinations performed reasonably well. For this pin-on-disk research, it was concluded that where transfer of lubricants from the coating to the counterface occur, friction and wear are reduced.

When comparing these pin-on-disk results to the present foil bearing tests, the conclusions are corroborated. Low friction and wear for the foil bearings generally occurs when lubricants are present on the couterface (foil) surface. However, the pin-on-disk results do not help explain why the silver in PS300 does not form a transfer film on the bare foil thereby reducing friction and wear at room temperature. It appears that under the foil bearing test conditions, characterized by a low pressure contact, transfer is prevented or is insufficient.

Clearly, if the reduction in friction results from the development of a low shear strength transfer film on the counterface, as has been reported (12), to obtain good tribological properties a coating must contain lubricant additives capable of forming a lubricous transfer film. Furthermore, the wear rate of the film and the counterface must not exceed the film formation rate.

Considering only the wear rate, TBGD, the carbide coating, sliding against bare or Al_2O_3 coated foils produce acceptable results. To achieve low friction and wear the coating with both high and low temperature lubricants (PS300) coupled with an Al_2O_3 coated foil must be used. The performance of the carbide coating against a bare foil at 25 °C suggests that given the proper surface finish and coating structure, foil wear can be controlled even when sliding against bare foils. Thus, through appropriate coating refinement, reducing the abrasivity of the PS300 to the bare foil may be possible. This would allow the successful operation of the bearing at room temperature without the need to coat the foils with Al_2O_3.

CONCLUSIONS

1. The wear characteristics of the foils are greatly improved by either applying a protective Al_2O_3 coating or providing a smooth shaft coating, such as TBGD, as a counterface.
2. To achieve an effective friction reduction, a transfer of lubricants from the journal to the foil surface must occur.
3. Under the test conditions described, a useful life in excess of 20 000 start/stop cycles can be expected with low friction at 25 and 500 °C when a coating containing both high and low temperature lubricants (BaF_2/CaF_2 and Ag respectively) is coupled with a wear resistant foil coating like Al_2O_3.
4. If low friction is not a primary consideration, the TBGD carbide coating provides low wear performance at both low and high temperatures.

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TABLE I.—FRICTION AND WEAR DATA SUMMARY

Foil surface	Journal coating	Temperature	Friction coefficient, µ	Test duration cycles	Foil wear,[a] Δ thickness	Projected life	Diametral journal wear[b]	Projected life
Bare	PS300	25 °C	0.52±0.04	2,000	25 µm	2,000	2.5 µm	20,000
		500 °C	0.27±0.05	20,000	50 µm	10,000	5 µm	100,000
Bare	TBGD	25 °C	0.55±0.03	20,000	25 µm	20,000	20 µm	25,000
		500 °C	0.42±0.02	20,000	20 µm	25,000	5 µm	100,000
Al_2O_3	PS300	25 °C	0.31±0.03	20,000	10 µm	50,000	2.5 µm	200,000
		500 °C	0.27±0.04	20,000	10 µm	50,000	2.5 µm	200,000
Al_2O_3	TBGD	25 °C	0.56±0.05	20,000	18 µm	30,000	12.5 µm	40,000
		500 °C	0.32±0.03	20,000	5 µm	100,000	2.5 µm	200,000

[a] Projected life based upon 25 µm maximum permitted foil thickness reduction (wear).

[b] Projected life based upon 25 µm maximum permitted diametral coating wear.

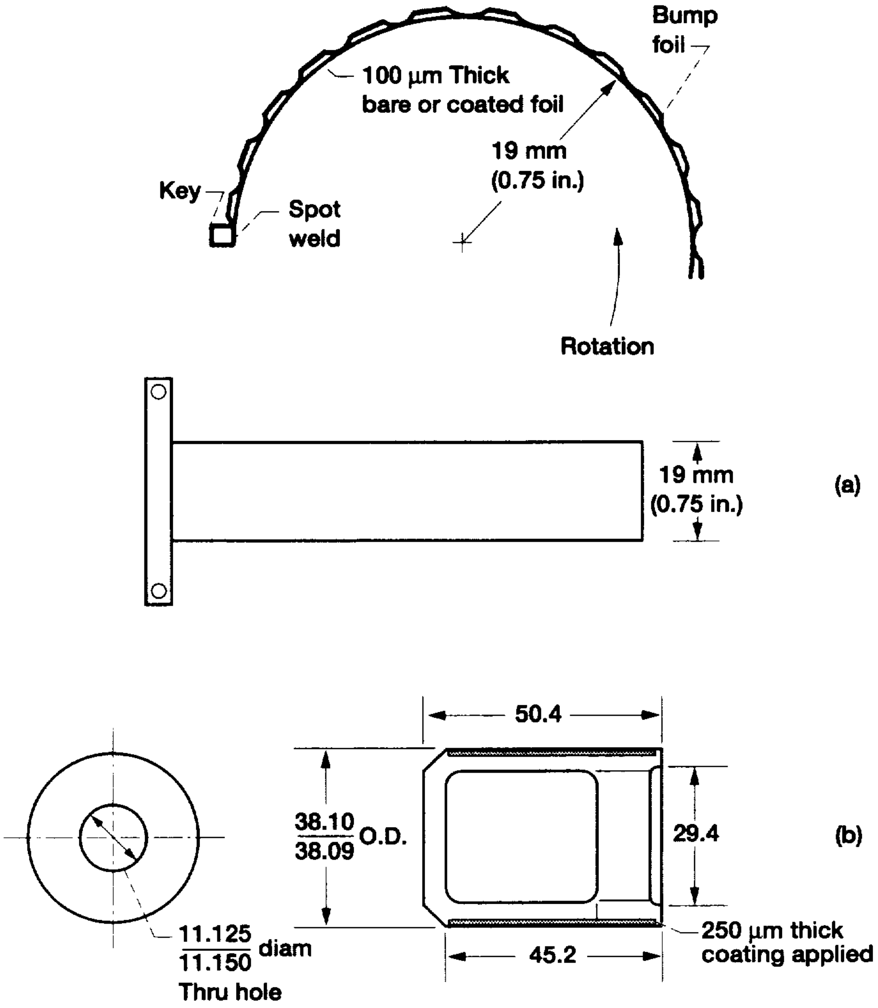

Figure 1.—Specimen geometry. (a) Foil. (b) Journal. Units in mm.

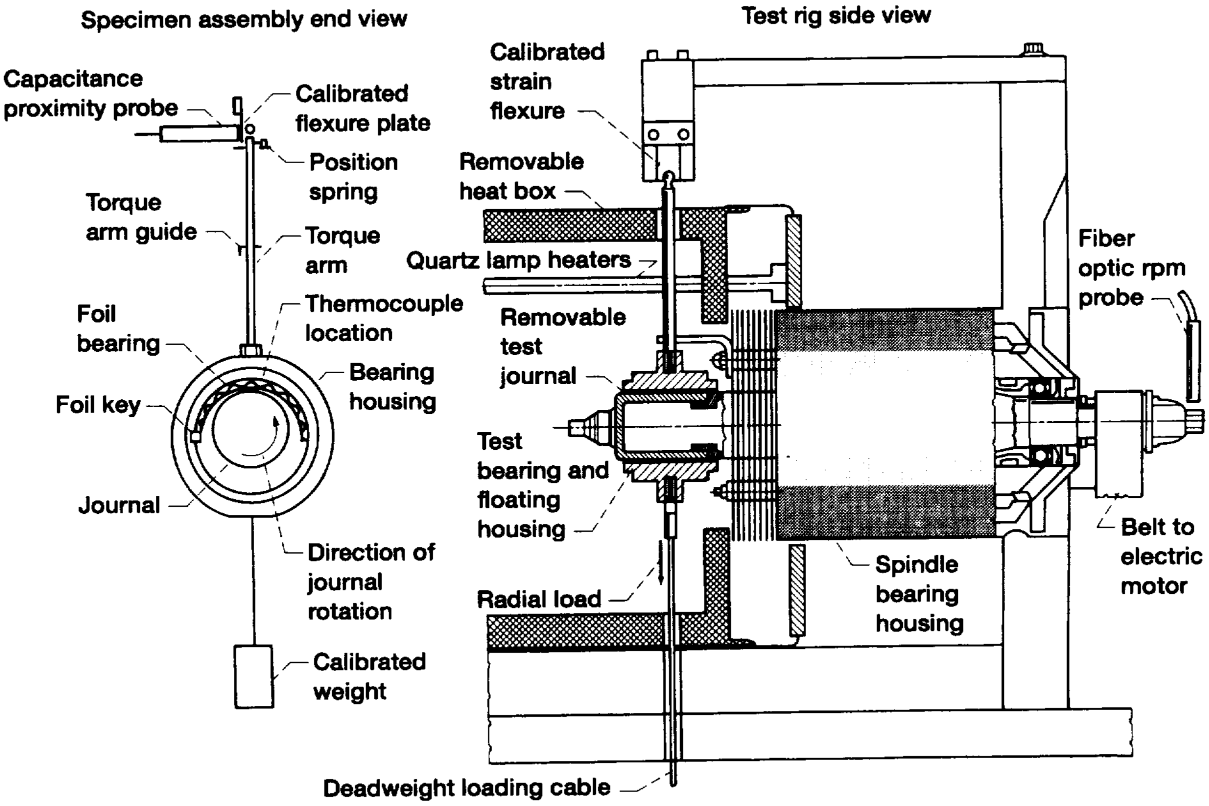

Figure 2.—Schematic view of test apparatus.

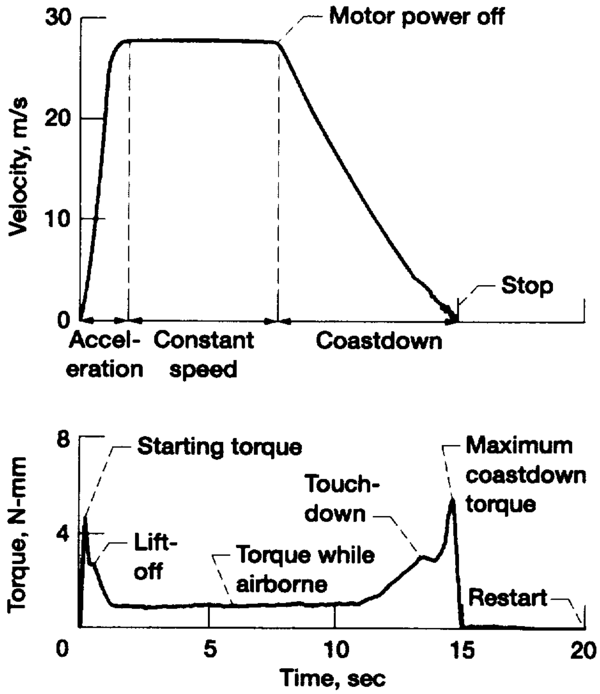

Figure 3.—Typical test cycle speed/torque trace.

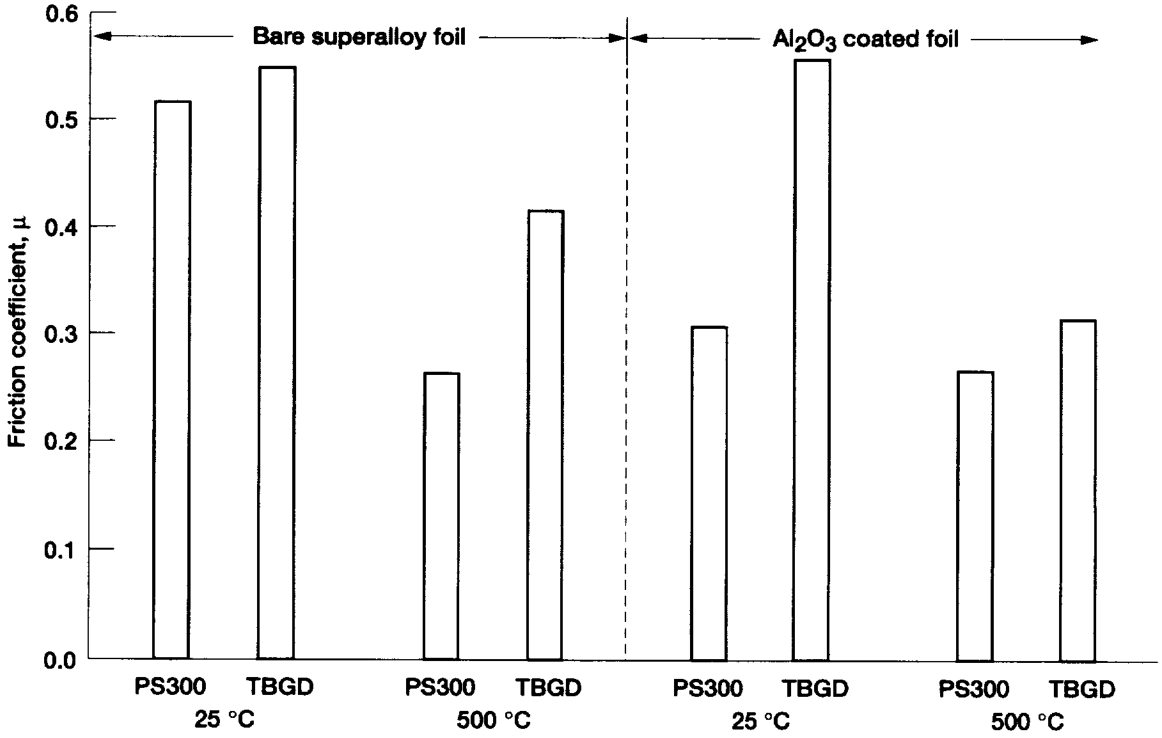

Figure 4.—Friction coefficient data.

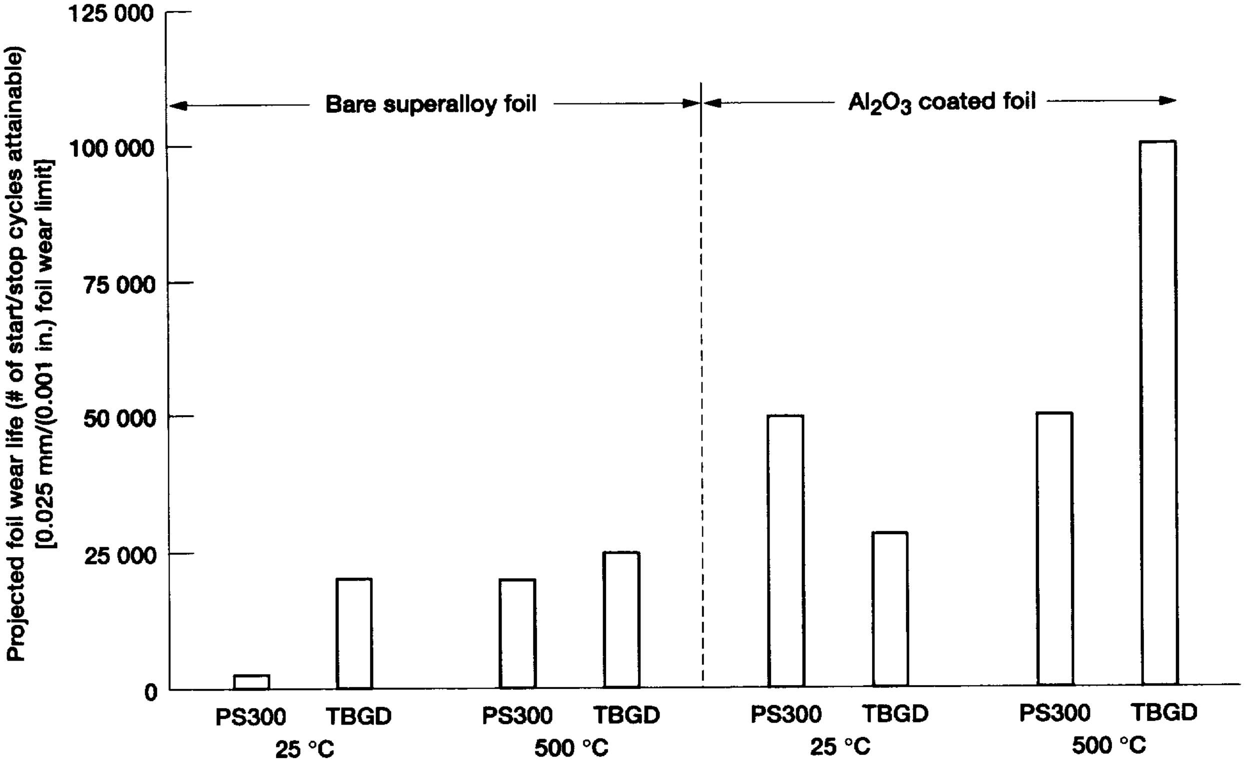

Figure 5.—Foil wear data.

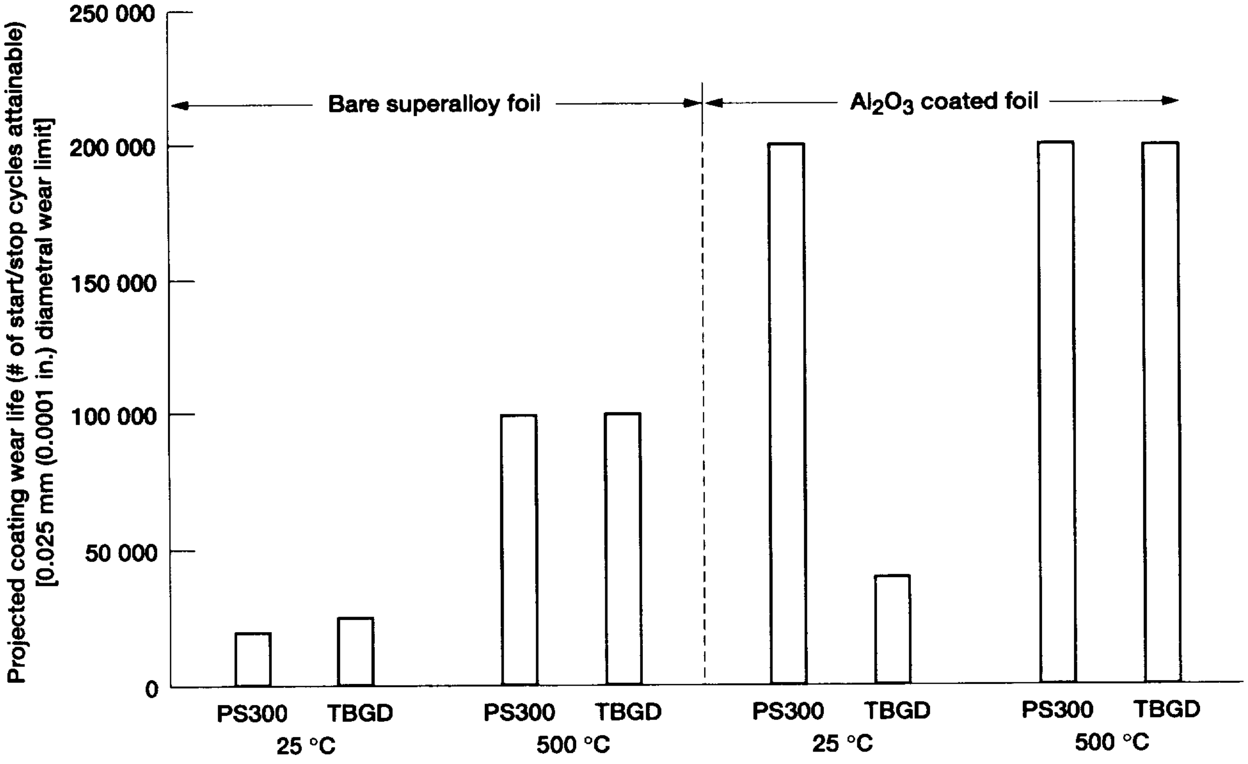

Figure 6.—Journal coating wear data.

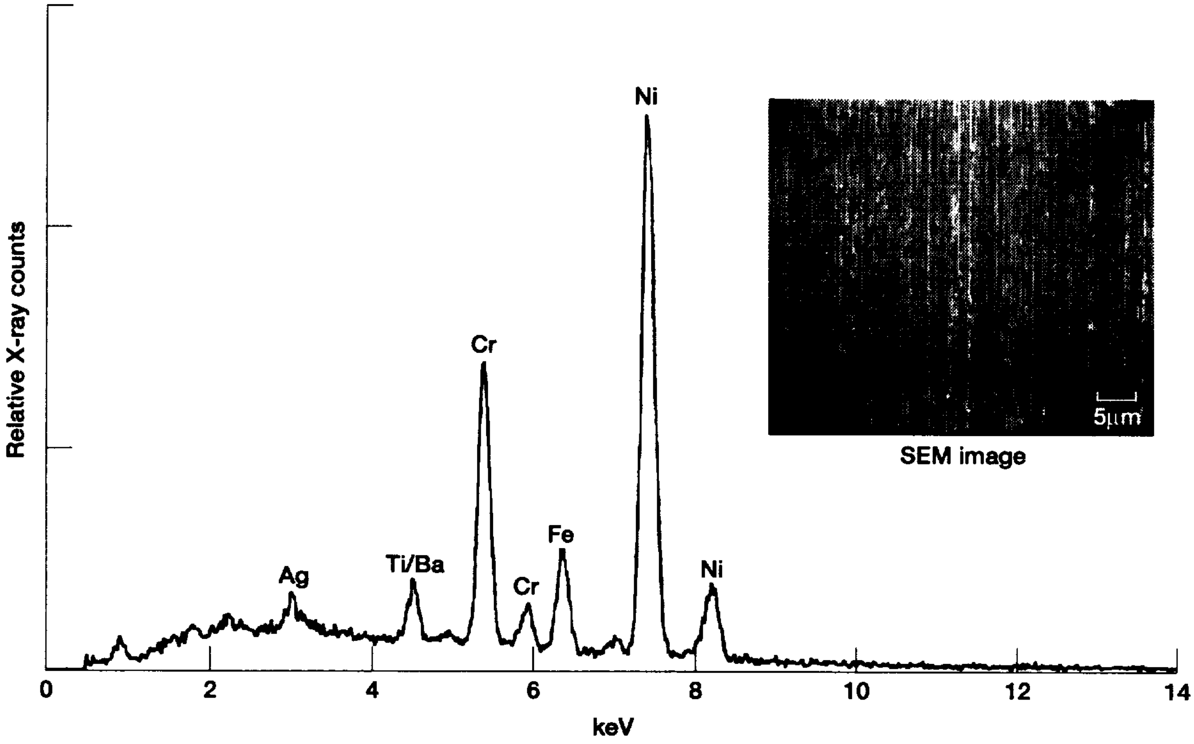

Figure 7.—SEM image and corresponding EDS X-ray spectrum of bare foil surface after sliding against chrome oxide (PS300) shaft coating at 500 °C.

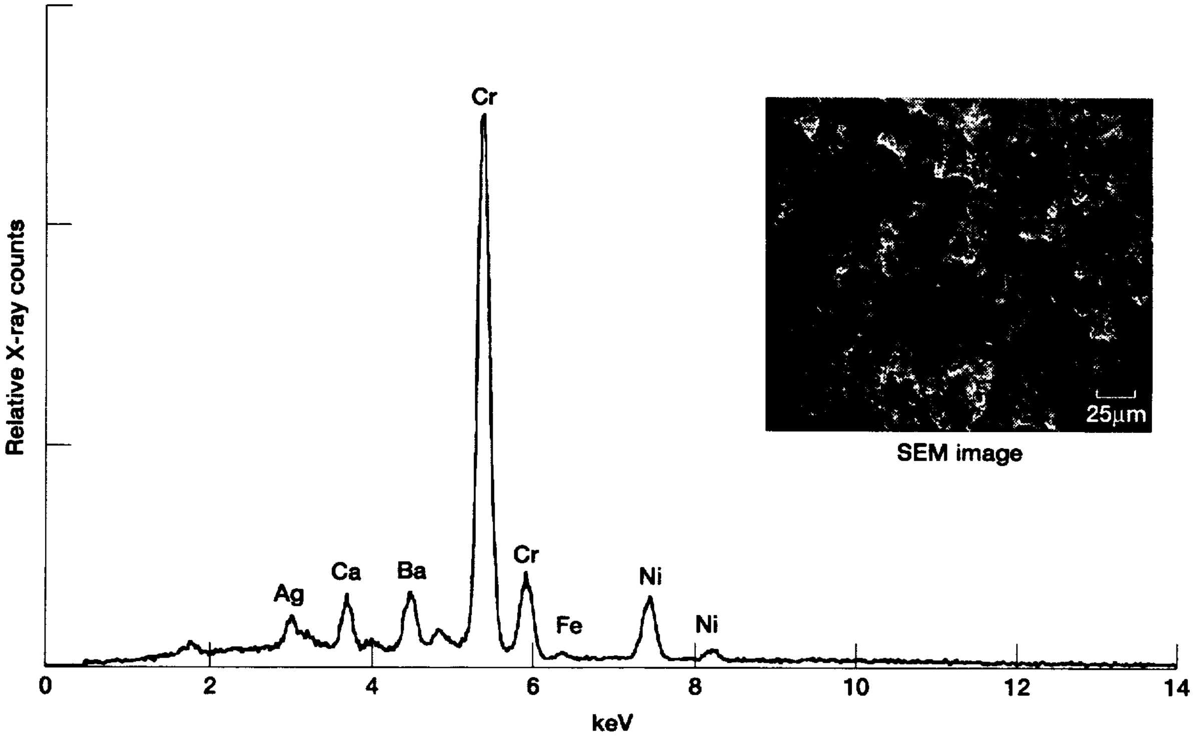

Figure 8.—SEM image and corresponding EDS X-ray spectrum of chrome oxide (PS300) coated journal after sliding against bare foil at 500 °C.

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13. ABSTRACT ***(Maximum 200 words)***

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