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Tribological Performance of PM400 Bushings in Oscillatory Sliding From 25 to 927 °C

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Summary

Small-bore (6.35- and 12.7-mm) bushings, made from NASA PM400 solid-lubricant composite, were evaluated in oscillatory sliding contact against a nickel-based superalloy shaft. Tests were conducted in air from 25 to 900 °C for extended periods (1 million cycles, $\pm 15^\circ$, 1 Hz) to assess the suitability of PM400 in gas turbine and reciprocating engine exhaust gas path control valve applications. Operating torque and estimated friction were monitored throughout the test duration and wear was measured at the end of test. In general, friction, torque, and wear were low. At temperatures above 600 °C, bushing dimensional stability was achieved via short-duration pretest furnace exposure heat treatments. Preliminary test results show that bushings made from NASA PM400 are feasible for aerospace and industrial applications.

Nomenclature

EDM electrical discharge machining
EDS energy-dispersive spectroscopy
IGV inlet guide vane
PM powder metallurgy
PS plasma spray
PTFE polytetrafluoroethylene
SEM scanning electron microscope

1.0 Introduction

The effective lubrication of mechanisms and sliding contact bearings encountered in aerospace and industrial applications has been a longstanding tribology challenge (Ref. 1). At temperatures above about 250 °C, conventional lubricants like hydrocarbon-based oils and greases thermally decompose. Well-known solid lubricants like polytetrafluoroethylene (PTFE), graphite, and MoS₂ reach their limits in air at about 350 °C. Lesser known solid-lubricant materials such as CaF₂, PbO, and LiF₂ can provide low friction at higher temperatures but do not function well at low temperatures (Ref. 2). No single lubricant material has

been found to operate over the wide range of temperatures needed in an aerospace mechanism, especially those that must start cold and function up to temperatures that can exceed 600 °C (Ref. 3).

An important example of such an application is the mechanisms that change the incidence angle of inlet guide vanes (IGVs) used inside gas turbine engines (Ref. 4). These vanes (blades) rotate slightly to direct the airflow against the rotating compressor blades for maximum engine efficiency under varying operating conditions. The basic components are a shaft-mounted guide vane blade and two solid-lubricant sliding bearings, which are sometimes called bushings. The bushings allow variable oscillating (back and forth) rotation of up to $\pm 15^\circ$ while supporting the radial loads created by the momentum forces of the airstream flow impinging and then being turned by the blade surface. The loads depend upon engine operating conditions and the temperatures can vary from very low temperatures (e.g., during cold engine startup) up to 500 °C (e.g., cruise conditions).

The traditional approach to meeting this tribological need is to employ polymer-based composite bushing materials. These bushings are often complex mixtures of polyimides, graphite fibers or particles, and other additives to help them withstand the sliding environment (Ref. 5). To overcome the intrinsic temperature limitations of polymers (~ 350 °C) for long life, cooling is provided to the bushings, even though it negatively impacts the overall efficiency of the engine but is required to attain long life. As engine designs become more compact and the need for fuel efficiency grows, there are increasing engineering and economic pressures to seek and develop bushing materials able to withstand the operating temperature environment with less or even no active cooling. Therefore, the challenge is to engineer a bushing material that can reliably lubricate an IGV mechanism from cold conditions to over 500 °C with low wear and friction levels comparable to the existing composite lubricant materials.

Since no single solid-lubricant material appears to be able to lubricate over the entire operating range, a composite approach is used that somewhat mirrors the approach used in conventional polymer-based bushings. A new composite bushing material, based upon high-temperature nickel-based alloys, is considered in the present test program. Named “NASA PM400,” this composite is an evolution of earlier tribomaterials in which thermochemically stable solid lubricants and reinforcing phases are added to a wear-resistant matrix capable of sustained exposure to high temperatures (Ref. 6). By adopting a composite approach, the resulting material exhibits favorable tribological attributes, such as low wear and friction, over a wide range of temperatures.

PM400 is a composite made from a nickel-based matrix to which chrome oxide, silver, and a eutectic of barium and calcium fluorides are added. The nickel-alloy matrix provides structural integrity where chrome oxide is a hardening agent and the silver and fluorides provide low- and high-temperature lubrication, respectively. The general approach and use of these types of constituents has a long history that began in the 1970s with the plasma spray (PS) coating PS100. Invented by H.E. Sliney, PS100 combined a NiCr matrix with silicate glass, silver, and CaF_2 to achieve broad temperature spectrum performance in the form of a PS-deposited coating (Ref. 7). PS100 was superseded by PS200, which was based upon a NiCoCr matrix with chrome carbide, silver, and the eutectic (62/38 wt% ratio) $\text{BaF}_2/\text{CaF}_2$ (Ref. 8). The new coating was designed to offer higher wear resistance and comparable friction to PS100. Though it worked well, intrinsic limitations of the coating form persisted.

Coatings are optimal for large surfaces that are readily accessible to the spray process. Small parts and inaccessible locations, such as the inside diameters of bushings and pipes, are a challenge for coating deposition. To address this problem, a solid powder metallurgy (PM) version of PS200 was developed in the late 1980s (Ref. 9). It was named “PM212” and was tested successfully in several internal combustion engine applications as a seal and as an exhaust valve stem guide. As a coating, PS200 was tested in sliding against thin nickel superalloy foil bearings. In this application, friction was acceptably low but foil wear limited bearing life (Ref. 10). To address this counterface wear problem, the tribomaterials were

further reformulated, resulting in PS304, a PS coating based upon NiCr with chrome oxide, silver, and the eutectic BaF₂/CaF₂ (Ref. 11). As with the PS/PM200 family of materials, PS304 was also produced as a solid composite by PM named “PM300” (Ref. 12).

PS304 and PM300 were successfully applied to a variety of aerospace and industrial applications. PS304 coatings were tested for long-term durability as shaft coatings for foil air bearings inside small gas turbine engines. PM300 bushings were applied to conveyor wheel axles in industrial heat treatment ovens that operated continuously. In both these applications, it was observed that the PS/PM300 tribomaterials swelled (up to 7 percent) over time. An extensive investigation concluded that in the presence of fluorides, some of the metallic chromium in the matrix material reacted with oxygen in the environment to form a new chrome oxide phase (Ref. 13). This new phase directly led to the thickness increases observed in the coating as well as the bushing swell. A short-term engineering solution to this dimensional change was to implement a high-temperature heat treatment prior to use to minimize changes during operation. Such a solution is common practice but not optimal. To address this problem further, a new materials formulation was developed, PS/PM400.

PS/PM400 adopts a matrix based on Ni with Mo and Al additions in place of the NiCr matrix used in the predecessor PS/PM300 series. By supplanting the metallic chromium in the matrix, the potential formation of new chrome oxide precipitates (linked to the dimensional swell in PS/PM300 materials) is eliminated. The incorporation of alloying elements, such as Mo and Al, serves to strengthen the Ni matrix material and enhance its creep resistance (Ref. 6). Similar to the other NASA tribomaterials, chrome oxide particles serve as a wear-resistant phase while silver and the BaF₂/CaF₂ eutectic act as low- and high-temperature lubricants, respectively. Table I reviews the NASA tribomaterials, their constituents, and functionalities.

Dimensional stability when exposed to air at high temperatures was among the earliest characterizations of the PS400 coating. In a series of experiments, 1-in.-diameter nickel-based alloy disks coated with PS400 were cut into two semicircular pieces. One piece was exposed to air, argon, or a vacuum at 760 °C for 15 h. The exposed and unexposed pieces were then sandwiched (coating surfaces face to face), encapsulated in epoxy, and then the exposed cross sections were metallographically polished. This arrangement allows direct comparison of nearly identical regions of the coating before and after exposure. Unlike PS304, no microstructural or dimensional changes were observed (Refs. 6 and 14).

The tribological properties of PS400 were then evaluated using a pin-on-disk tribometer. PS400-coated superalloy disks were slid against a superalloy pin in air from 25 to 800 °C. The results were compared to those for PS304 under identical test conditions and reported in the literature. In general, PS400 was found to exhibit friction and wear properties comparable to PS304 (Ref. 6). It appeared that the friction and wear behavior of both coatings was largely influenced by the silver and fluoride solid lubricants and not the chemistry of the matrix material.

TABLE I.—COMPARISON OF THE NASA SOLID LUBRICANTS

Series designation	Binder	Hardener	Solid lubricants	General attributes
PS100	NiCr	Glass	Ag + fluorides	Soft-high wear
PS/PM200	Ni-Co	Chrome carbide	Ag + fluorides	Hard-low wear (abrasive to counterface)
PS/PM300	NiCr	Chrome oxide	Ag + fluorides	Moderate hardness, mildly abrasive to counterface, and poor dimensional stability
PS/PM400	Ni (Mo, Al)	Chrome oxide	Ag + fluorides	Moderate hardness and good dimensional stability

Based upon this preliminary data, which indicated good tribological behavior and dimensional stability, PS400 was evaluated as a shaft coating in sliding against small bore cobalt alloy bushings in a nonconformal line contact (flat cobalt alloy vs. PS400-coated-diameter shaft) configuration (Ref. 15). This configuration allowed for very high contact stress expected in the target application under consideration at that time. Oscillating sliding tests were conducted from 260 to 927 °C under loads typical for the target application. Observed friction ranged from 0.84 to 0.43 and generally decreased with temperature. Wear factors for both the coating and the counterface surfaces were in the 10^{-5} to 10^{-6} mm³/Nm range. Extensive analyses were conducted on the worn surfaces by using scanning electron microscope (SEM) and energy-dispersive spectroscopy (EDS) x-ray methods and it was observed that at differing test temperatures, different surface films containing oxides and solid lubricants were present. These findings were comparable to analyses done previously on PS200 and PS304 coatings (Refs. 10 and 16).

The friction levels observed for PS400 in the line contact tests were higher than desired but could have arisen from the high contact stress, which could have led to rupture of the lubricating surface films. The counterface surfaces were also tested in an “as cut” by wire electrical discharge machining (EDM) state, which is rougher than the present tests and this could have caused higher friction. In addition, it was observed that at the highest test temperature, 927 °C, the thickness of the PS400 coating increased several percent. Based upon these results, the use of PS400 coatings above 760 °C under high stress (~20 MPa) was discouraged. In order to evaluate the tribomaterial in a more conformal contact, the test program was extended beyond coatings by using the PM400 bushing.

2.0 Materials

To make PM400, a powder blend of constituents (Table I) is mixed and fed into a tool steel die. A punch is then inserted into the die and the powder is cold pressed into a solid bushing with sufficient strength to allow for handling and transport. These green state PM400 bushings are sintered in a hydrogen atmosphere above 1,080 °C to ensure that the silver and fluorides are in a liquid state, thus enhancing particle bonding and densification. Once the sintering process is completed, the PM400 bushings are allowed to cool before being exposed to air. Figure 1 shows a typical metallurgical cross-section image taken with an SEM in backscattered mode, where the pores are black and the heaviest elements (silver) appear as bright white.

Based on these images, the PM400 bushings are estimated to be approximately 95 percent dense with the residual porosity evenly distributed. This microstructure is typical for the cold-press and sinter process used to make the bushing. At higher magnification, individual phases can be more easily seen and identified as shown in Figure 2.

The as-sintered microstructure of PM400 is typical of PM composites. The different particle constituents can be readily identified as separate phases. Those that are melted or nearly melted at the sintering temperatures; namely, silver, fluorides, and the nickel alloy, have rounded phase shapes. The ceramic constituent, chrome oxide, has a much higher melting point and retains its original angular shape. During sliding, wear of the phases promotes the development of a thin surface layer comprising oxides, fluorides, and metals in the form of a glaze that helps reduce friction and wear. In effect, the bushing below the sliding surface is a reservoir for lubricants that are exposed by the wear process.

For applications where precision fits and tight clearances exist, any significant dimensional changes during use can be problematic. For instance, in the targeted turbine engine guide vane application, the running clearance between the PM400 bushing inside diameter is small (~0.03 mm) and must be maintained for long periods at high temperatures (~600 °C). Since dimensional growth (swelling) for the PS400 coating

was observed in prior testing (Ref. 15), the dimensional stability of PM400 at the target temperature was evaluated. Figure 3 shows how the diameter of a PM400 bushing changes over a long exposure period. For comparison, the swelling of a similarly sized PM300 bushing is also presented (Ref. 13).

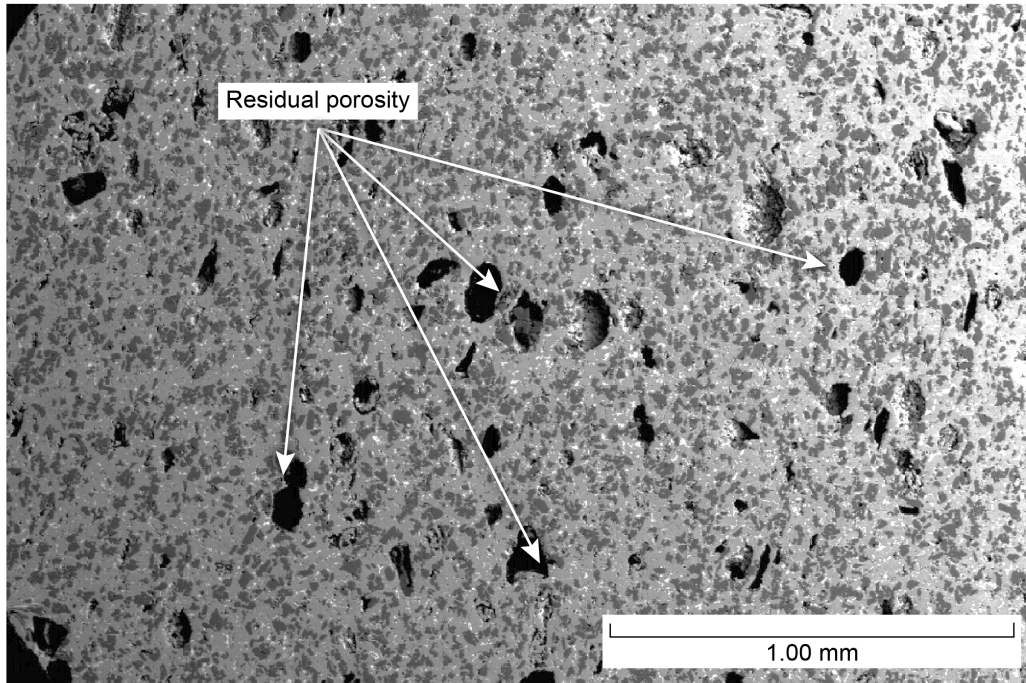


Figure 1.—PM400 using scanning electron microscopy in backscattered mode cross-section image.

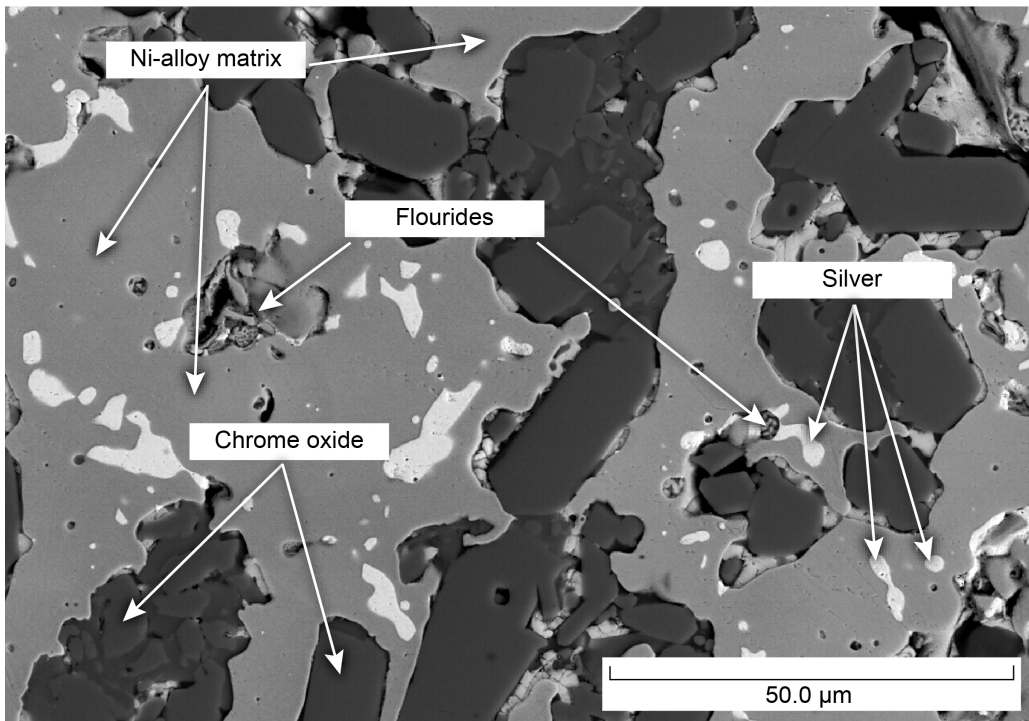


Figure 2.—High-magnification ($\times 1000$) backscattered scanning electron microscopy image of PM400 illustrating different phases present in composite.

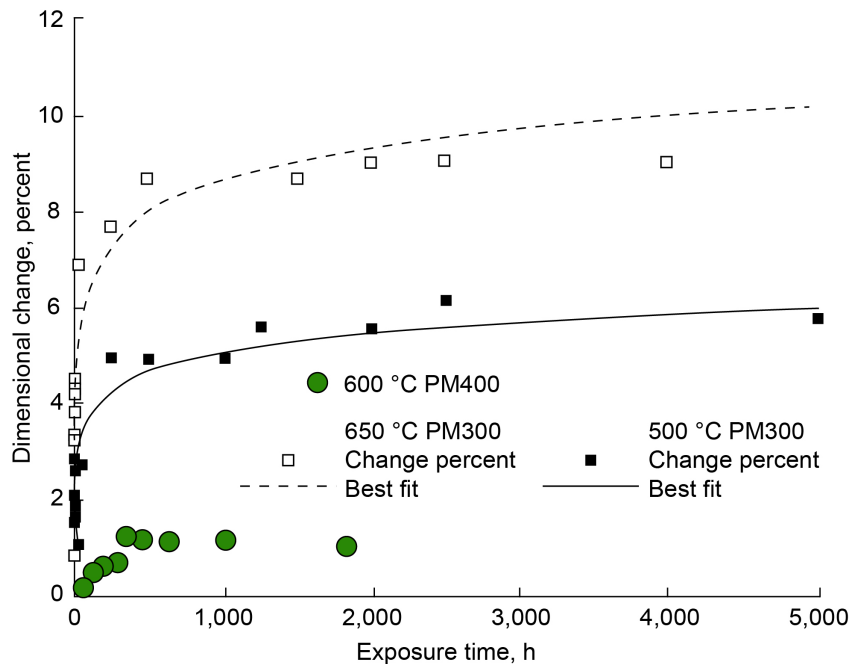


Figure 3.—Dimensional (diameter) change of PM400 during long-term exposure to air at 600 °C. For comparison, published data for PM300 tested at 500 and 650 °C is provided (Ref. 13).

As shown in the figure, soaking the bushing at 600 °C causes it to swell by about 0.8 percent. To simplify production, it is often recommended practice to preswell parts prior to installation. This is typically done in an accelerated manner by exposing the parts to a higher temperature for a short period until growth has reached stability for the target temperature.

To characterize the long-term, steady-state swell effect, a series of tests were conducted in which PM400 bushings were exposed to air at differing temperatures for up to several thousand hours. The results are shown in tabular form in Table II. At 600 °C, the swelling is essentially complete in about 250 h. At 800 and 927 °C, the dimensional growth is complete in less than 24 h.

For the present test program, which is intended to provide data for the turbine guide vane application, the following preswell heat treatment was undertaken. Prior to sliding tests, the as-sintered PM400 bushings are exposed to air at 800 °C for 48 h to ensure dimensional stability when in use at 600 °C. When these bushings are tested above 800 °C, it is expected that they will eventually swell up to the levels commensurate with the exposure temperature shown in Table II. Figure 4 shows an SEM backscattered cross-section image of a PM400 bushing prior to and following the heat treatment.

Though an approximate 1 percent swelling of the bushings was noted, cross-sectional imaging alongside EDS x-ray examinations have not yet revealed any changes that elucidate the dimensional growth mechanism. This topic is under further study.

To ascertain the tribological response of PM400, heat-treated bushings were tested in oscillatory sliding against a precipitation-hardened nickel-based superalloy (Inconel® 718, Special Metals Corporation) shaft. The test procedure and protocols are described in the following section.

TABLE II.—BUSHING DIMENSIONAL SWELL PERCENT INCREASE

Material	500 °C	600 °C	650 °C	800 °C	927 °C
PM300	6 percent	-----	9 percent	-----	-----
PM400	0 percent	0.8 percent	-----	1.0 percent	2.3 percent

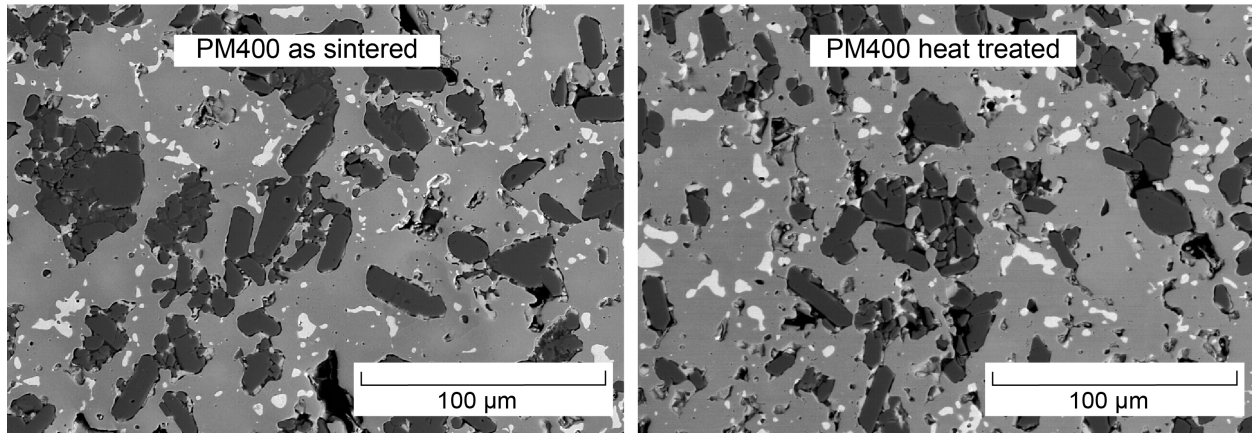


Figure 4.—PM400 cross-sectional images. (a) As sintered (before heat treatment). (b) After heat treatment. Exposure to air at 800 °C for 48 h. No obvious microstructural changes observed.

3.0 Tribological Test Method and Procedures

A conformal contact bushing test rig was used to evaluate the tribological properties of PM400 (Ref. 12). PM400 bushings with inside diameters of 6.35 or 12.7 mm were slid against similarly sized metal shafts in oscillatory motion. Figure 5 shows a photograph of the test rig with a closeup view of the sliding specimen configuration.

Recent improvements to the test rig include the addition of a swinging torque tube into which the bushing is positioned. Figure 6 shows an end view closeup of the torque tube. The torque tube is free to move vertically, allowing a radial load to be placed on the bushing-shaft contact while preventing other bushing motions, such as rotation and pivot action, that might lead to edge loading, which could corrupt the friction and wear measurements.

To conduct a test, a heat-treated PM400 bushing is placed into the bushing holder. The holder is placed into the torque tube and secured with small Allen screws. The test shaft is placed inside the bushing and affixed to the test rig drive shaft using set screws. The furnace is closed over the specimens and energized so as to heat the specimens to the desired test temperature. Once the setpoint is reached, the specimens are allowed to soak for 30 min to allow the specimen temperature to equilibrate. Then the drive motor is started and the test is begun.

Friction torque is measured by an inline torque meter located between two test rig shaft support bearings. This configuration ensures that the torque meter experiences pure torque and no wide loads. A consequence of this arrangement is that the torque measured by the meter includes the drag torque from two of the grease-lubricated pillow block bearings. These ball bearings have low and relatively constant friction, but in this case, their contribution to the measured torque is not negligible. To account for the support bearing drag, a calibration correction is made by using the technique described in detail in Reference 13 and briefly reviewed in this section.

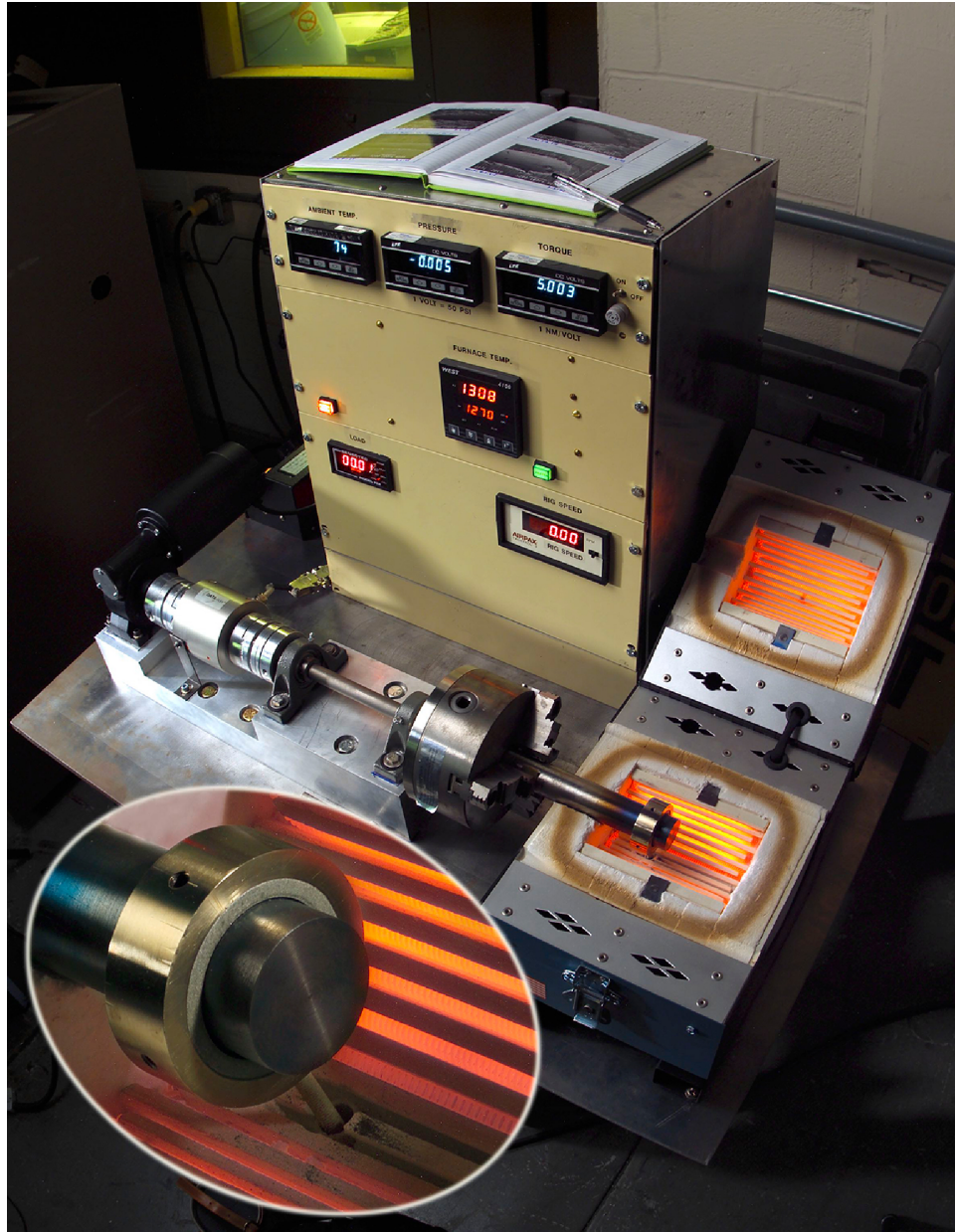


Figure 5.—High-temperature bushing test rig. Inset shows PM400 nickel-based superalloy general shaft specimen configuration.

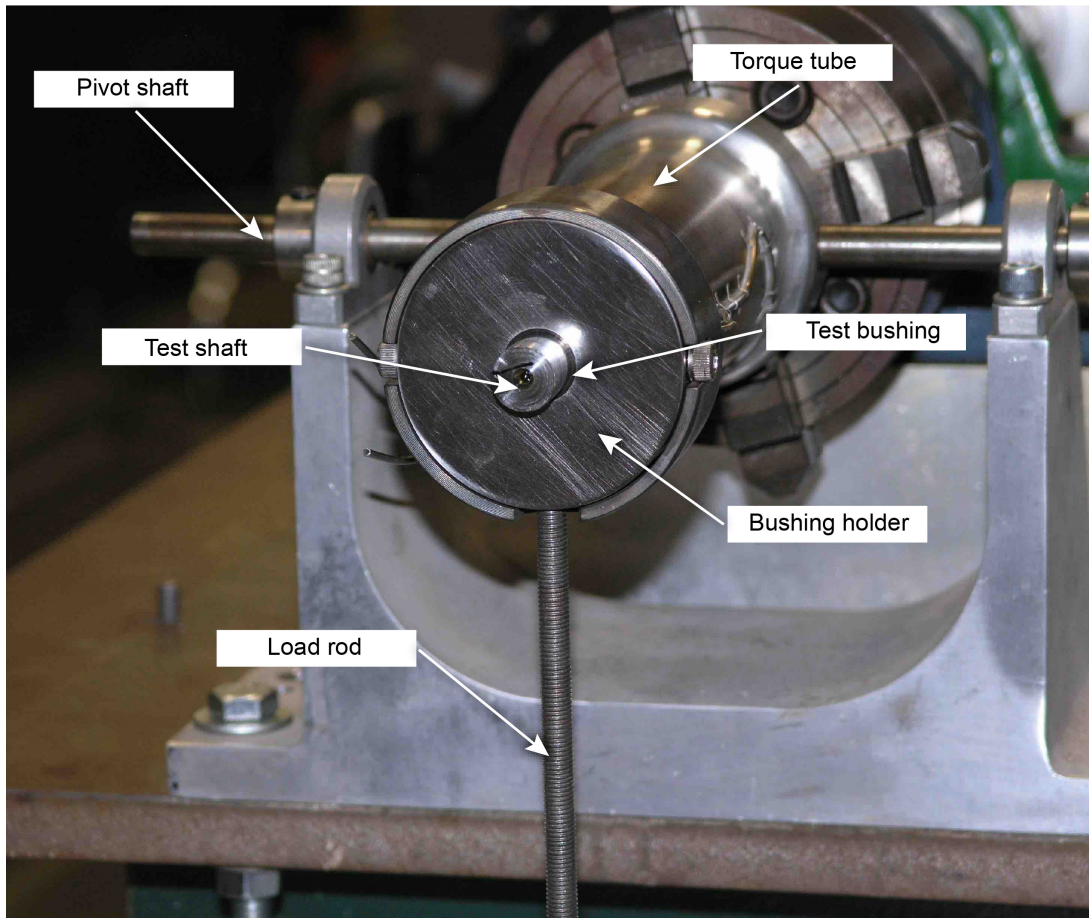


Figure 6.—Torque tube specimen holder configuration. Torque tube pivots (up and down) to allow loading of test shaft-bushing contact while preventing unwanted bushing rotation and misalignment (twist).

To characterize the rig support bearing drag torque, the drive motor is run with no test specimen in place. The torque measured by the torque meter represents the drag of the two support bearings with no test load. Then a small diameter ball bearing (with low friction) is mounted in the test bushing location and loaded at loads up to the level expected for the bushing test. The drive motor is run and the torque measured by the torque meter is recorded. This torque includes the support bearings and the contribution from the replacement ball bearing used to apply the calibration load. By neglecting this small drag torque contribution calibrator load bearing, the drag of the support bearings under anticipated test loads can be estimated. For the three radial load test conditions considered in the present paper (89, 196, and 445 N) the support bearing drag varied less than 10 percent (0.38, 0.38 and 0.40 N•m). The test bushing drag torque values reported in Table III have calculated accounting for the corresponding residual support bearing drag torque at the tested load.

In addition to the test bushing friction measurements, after each test period the specimens are removed from the rig to assess wear. Under some conditions of high wear (high load and low temperature), shaft wear is measured by using a stylus surface profilometer. At high temperatures, the test durations were not generally long enough to produce measurable wear, and for this reason, the data presented typically are focused on friction coefficient and rotational drag torque.

4.0 Results and Discussion

Table III summarizes the friction coefficient and drag-torque behavior of PM400 at varying bushing size (6.35- and 12.7-mm bore), varying loads (89, 196 and 445 N), and test temperatures that ranged from 25 to 927 °C. To assess data scatter and repeatability, duplicate tests with new specimens were run for the 180-N load case over all the test temperatures. Friction levels varied by no more than 20 percent from the average values reported in Table IV. Further, a statistically significant number of repeat tests were run at 600 °C and 84 N for the 6.35-mm-sized bushing that represents the most likely operating condition of a near-term application of interest. In this case, all the calculated friction coefficients were within the range bounded by the average $(0.20) \pm 0.03$ or about ± 15 percent.

In order to make an engineering comparison to conventional bushing materials, a commercial polyimide was tested up to its temperature limit of 400 °C. The data are summarized in Table IV. Like the PM400 data, only friction is presented since no measurable wear resulted from the limited test duration. As before, friction data scatter was observed from repeat tests and found to typically be ± 10 percent or ± 0.02 . In one similarity to PM400, the SP-21 polymer's friction decreased when temperature increased from 25 to 400 °C.

Figure 7 shows a bar graph of the friction for both PM400 and SP-21.

TABLE III.—FRICTION SUMMARY FOR PM400 BUSHING-
INCONEL® SHAFT, $\pm 15^\circ$ OSCILLATORY AT 1 Hz

Nominal shaft diameter, mm	Test load, N	Test temperature, °C	No. of test cycles	Torque, N•m	Calculated friction coefficient
6.35	89	25	1,000,000	-----	-----
6.35	89	200	1,000,000	0.28	0.25
6.35	89	400	1,000,000	0.38	0.34
6.35	89	600	1,000,000	0.22	0.20
6.35	89	800	1,000,000	0.28	0.24
6.35	89	927	1,000,000	0.19	0.19
12.7	196	25	1,000,000	1.7	0.41
12.7	196	200	1,000,000	1.8	0.44
12.7	196	400	1,000,000	0.88	0.20
12.7	196	600	1,000,000	0.58	0.15
12.7	196	800	1,000,000	0.57	0.14
12.7	196	927	1,000,000	1.1	0.26
12.7	445	25	1,000,000	3.4	0.36
12.7	445	200	1,000,000	-----	-----
12.7	445	400	1,000,000	-----	-----
12.7	445	600	1,000,000	1.89	0.20
12.7	445	800	1,000,000	-----	-----
12.7	445	927	1,000,000	-----	-----

TABLE IV.—FRICTION SUMMARY FOR SP-21 POLYMER
BUSHING-INCONEL® SHAFT, ±15° OSCILLATORY AT 1 Hz

Nominal shaft diameter, mm	Test load, N	Test temperature, °C	No. of test cycles	Torque, N•m	Calculated friction coefficient
6.35	196	25	172,800	1.1	0.27
6.35	196	200	172,800	0.70	0.17
6.35	196	315	172,800	0.70	0.17
6.35	196	400	172,800	0.42	0.10
12.7	196	25	172,800	1.0	0.25
12.7	196	200	172,800	0.71	0.17
12.7	196	315	172,800	0.75	0.18
12.7	196	400	172,800	0.47	0.11

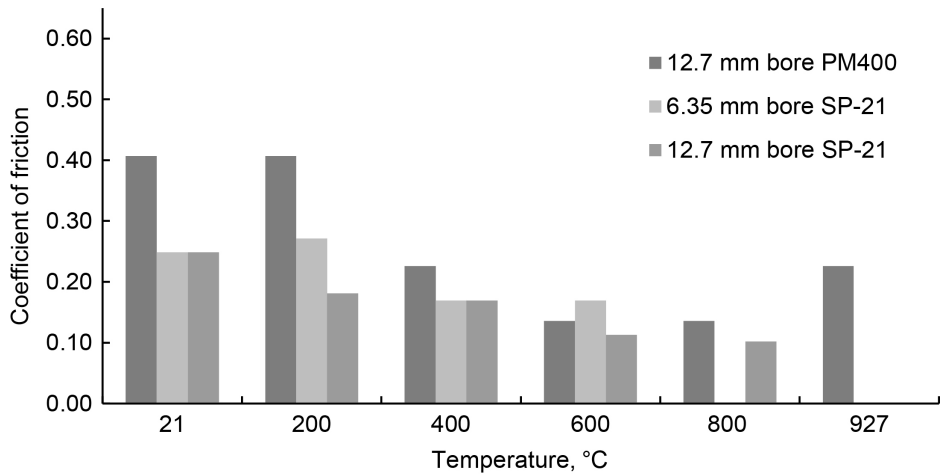


Figure 7.—Coefficient of friction versus temperature data graph for polyimide SP-21 (blue bars) compared to PM400 (green bars). PM400 exhibits higher friction at lower temperatures but comparable friction at high temperatures beyond long-term operating limits (~315 °C) of polyimide.

Select test specimens were evaluated after testing to assess wear. Photographs were taken of the bushing contact surfaces and wear profiles were made from the corresponding shaft surfaces. In general, PM400 bushing wear was too small to measure in these limited duration tests. At room temperature and 200 °C, there was obvious shaft wear to depths of about 50 and 10 µm, respectively. Above 200 °C, shaft wear ceased. In fact, above 200 °C, a thin surface glaze, typically 5 to 10 µm thick, typically forms on the surface. In a sense, the shaft wear is negative. Similar to PM400, the wear of the polyimide bushings was too low under these tests to quantify.

Figure 8 to Figure 11 show representative low- and high-temperature shaft wear profiles and wear surface images from tests at 25 and 600 °C.

Figure 9 shows closeup photographs of the specimens corresponding to the wear profile in Figure 8.

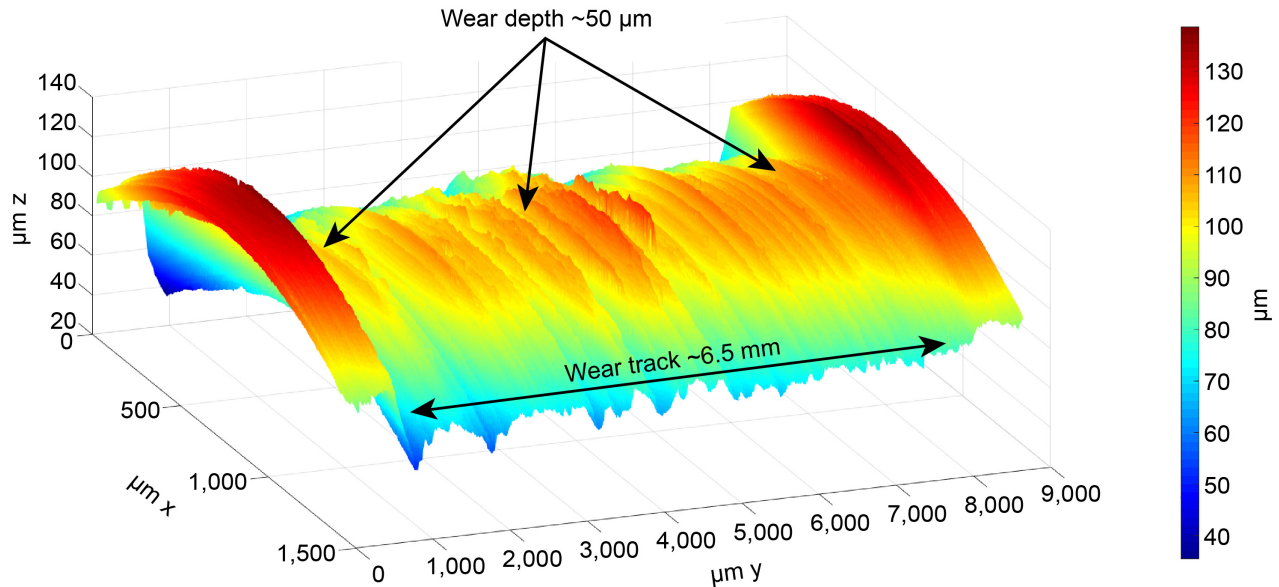


Figure 8.—Wear of nickel-alloy shaft after sliding against PM400 bushing for 1 million cycles at 196-N load at 25 °C.

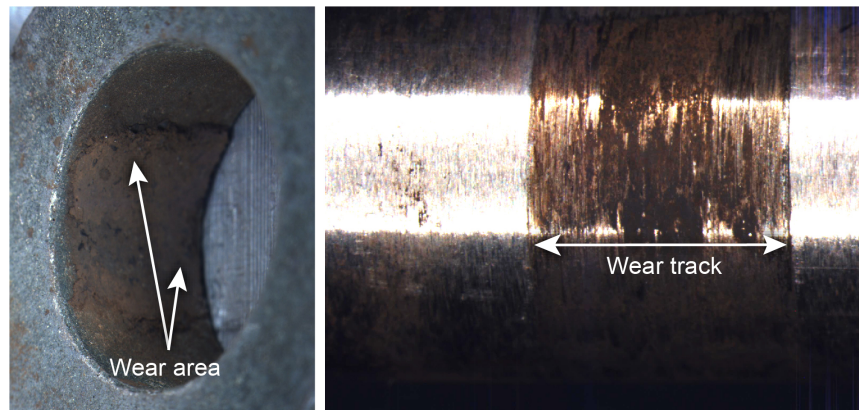


Figure 9.—Specimens tested at 25 °C depicted by the wear profile shown in Figure 8. (a) Specimen wear area. (b) Specimen wear track.

At temperatures above 200 °C, friction and wear decrease significantly. This improvement in performance has been repeatedly observed with the solid lubricants used in PM400. Foil bearings lubricated with PS200 and PS304 exhibited similar drops in start torque and foil wear above 204 °C (Ref. 16). PS400-coated shafts sliding in line contact against a cobalt alloy in a previous test program also showed friction and wear drops above 200 °C (Ref. 15). In Figure 10, a surface topography map is shown for a shaft run against PM400 at 600 °C for a million cycles under a 180-N load. Though the wear area is apparent, no shaft material loss is observed. In fact, a slight buildup of glaze is present and is about 10 μm thick.

Commensurate with the reduction in friction, the corresponding wear surface photos for the surface profile shown in Figure 10 appear in Figure 11.

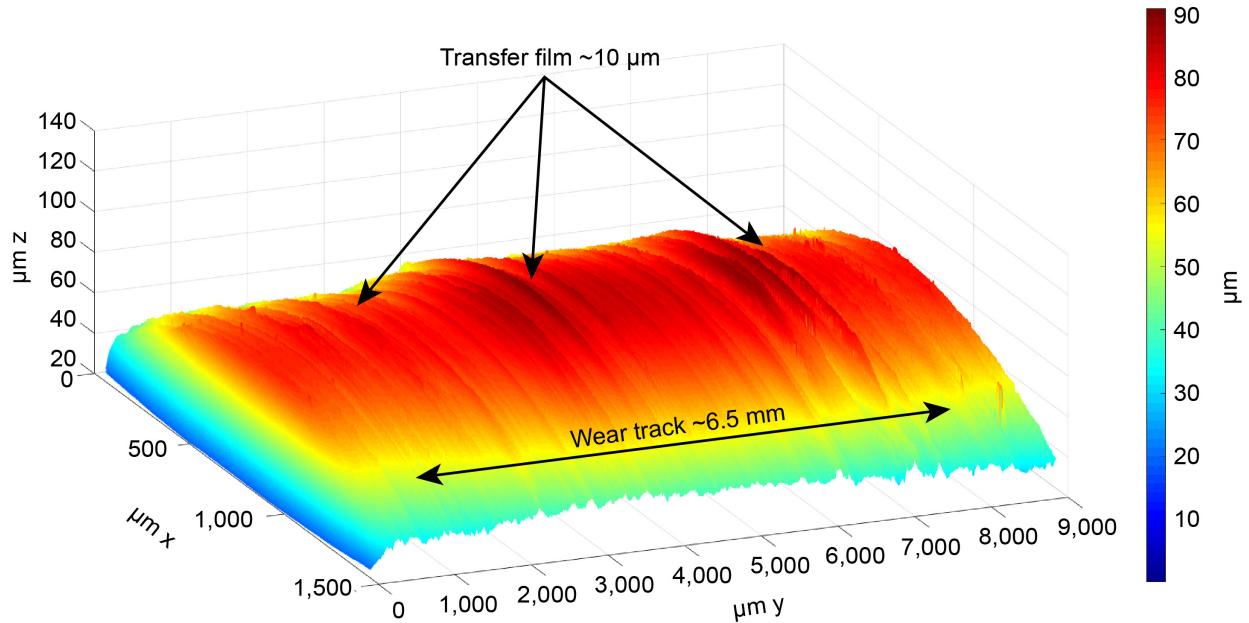


Figure 10.—Surface topography map of nickel-alloy shaft after sliding against PM400 bushing for 1 million cycles at 196-N load at 600 °C, showing slight (~10 µm) buildup of surface glaze.

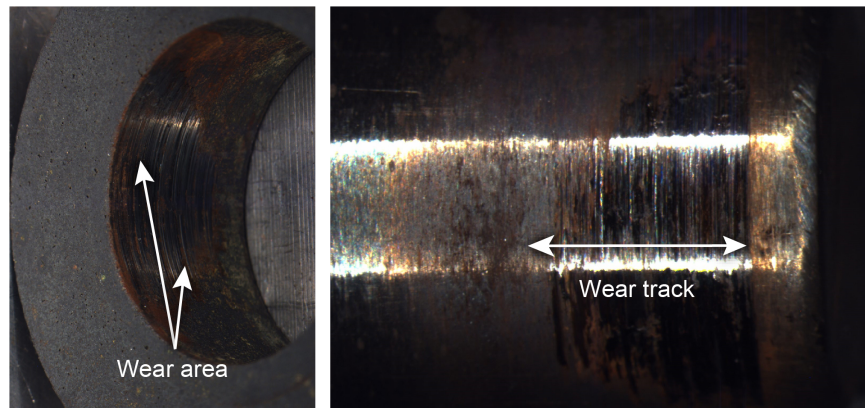


Figure 11.—Specimens tested at 600 °C depicted by the surface topography map shown in Figure 10. (a) Specimen wear area. (b) Specimen wear track.

Based upon the tribological response of PM400 to the tested sliding conditions, it appears that PM400 can be a viable substitute for bushing applications currently served by polyimide bushings. The one exception may be those applications in which the higher observed friction of PM400 at lower temperatures is not acceptable. By 400 °C and above, PM400's friction (and drag torque) is about the same, within data scatter, as the polyimide. Below 400 °C, PM400's friction is higher by a factor near two (0.4 vs. 0.2). The reason or reasons for the higher friction at lower temperature are not completely known nor confirmed at this early stage of research, but a reasonable explanation can be derived from existing understanding of the nature of the solid lubricants in PM400.

In a previous program, the sliding behavior of PS400 coatings was evaluated in less conformal but otherwise similar contact conditions (Ref. 15). There too, friction levels were higher than those observed for the polyimide. Following testing, SEM and EDS x-ray surface analyses were conducted that showed

that the sliding surfaces were covered with a glaze layer comprising metal oxides and the solid lubricants used in PS/PM400 (namely the fluorides and silver). The chemistry of the glaze was dependent upon the sliding temperature.

Though surface analyses of the specimens in the current work has not been undertaken, the wear surfaces (shaft and PM400 bushing) appear similar to those from the PS400 tests (Ref. 13). In addition, early work with similar tribomaterials; namely, NASA PS200 and PS300 coatings, responded to high-temperature sliding in similar fashion (Refs. 16 and 17). After high-temperature sliding, the contact surfaces developed a polished glaze that reduced friction and wear. In all cases, the observed friction below 400 °C was typically above 0.20 and often near 0.4. It appears that the shear strength of this self-generated surface glaze is higher than those that form when sliding traditional solid lubricants, like the polyimides, at low temperatures.

The friction behavior observed in these tests can be combined with previous experience with the PS400 coating and predecessor materials (PS200 and PS300) to draw some general conclusions. Though PM400 can withstand much higher temperatures than conventional solid lubricants, this benefit must be countered by the reality of higher sliding friction and counterface wear at temperatures below 400 °C.

The low-temperature lubricant phase in PM400 is silver. Below 400 °C, the shear strength of silver is higher than traditional solid lubricants like graphite, PTFE, and polyimide. Thus, it is not surprising that friction is higher. At intermediate temperatures (400 to 800 °C), the shear strength of the surface glaze appears, based upon friction comparable to the SP-21 polyimide at 400 °C, to be reduced. Interestingly, at the highest test temperature, 927 °C, friction again increases. This signifies that the properties of the glaze formed at such a high temperature differ, and this results in increased but still modest friction levels.

Despite the slight increase in friction at 927 °C, wear of both the PM400 bushing and the nickel-base alloy shaft are low and comparable to the polyimide, except at 25 and 200 °C. This indicates that as long as higher levels of low-temperature friction can be tolerated, PM400 is a viable engineering approach for long-lived mechanisms operating at temperatures well beyond the capabilities of conventional lubricant materials.

5.0 Concluding Remarks

Conventional self-lubricating composite materials, such as oil-filled bronze, glass fiber composites filled with PTFE, and graphite-filled polymers, offer many operational benefits to machinery and mechanisms. They are low cost, simple to engineer, and require no maintenance. However, all of these traditional solid-lubricant materials are limited to temperatures below ~400 °C due to thermal and environmental degradation. Materials capable of higher temperature lubrication often cannot endure the wide range of temperatures encountered in many machine applications. Good examples are heat engines, which must be able to startup cold and then reliably operate as they warm to their steady-state temperatures, which can exceed 800 °C.

PM400 was engineered for such wide-temperature range applications. It contains thermochemically stable solid lubricants and structural constituents that can reduce friction and wear at low temperatures and withstand long-term use at temperatures up to and including 927 °C. One drawback is that friction levels at low temperature can be higher than conventional solid lubricants.

In our studies, friction for PM400 up to 400 °C is measurably higher than conventional composites such as graphite-filled polyimide. Thus, should PM400 be engineered into an existing application currently served by a conventional solid lubricant, accommodations must be made for higher drag torque. The potential benefit of using PM400 is the much higher temperature capability (927 vs. ~400 °C). This benefit could enable a reduction or elimination of bushing cooling provisions, thereby opening the

possibility of placing sliding mechanisms more deeply inside hot zones in machinery, which could lead to other design advantages.

It is unlikely that tribologists will find a means to reduce friction levels for PM400 or similar materials to those routinely exhibited by traditional solid lubricants. However, for many current and future applications, the high-temperature capabilities of PM400 may well enable breakthroughs in design and performance of a wide range of engineered mechanisms and machinery currently limited by conventional lubricants.

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