

NASA/TM—2009-215678



# NASA PS400: A New High Temperature Solid Lubricant Coating for High Temperature Wear Applications

*C. DellaCorte and B.J. Edmonds  
Glenn Research Center, Cleveland, Ohio*

---

August 2009

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Telephone the NASA STI Help Desk at 443-757-5802
- Write to:  
NASA Center for AeroSpace Information (CAST)  
7115 Standard Drive  
Hanover, MD 21076-1320

NASA/TM—2009-215678



# NASA PS400: A New High Temperature Solid Lubricant Coating for High Temperature Wear Applications

*C. DellaCorte and B.J. Edmonds  
Glenn Research Center, Cleveland, Ohio*

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

---

August 2009

## Acknowledgments

The authors wish to acknowledge the valuable contributions made to this effort by Mr. Jeffrey Mayer (Case Western Reserve University) and Mr. Fransua Thomas (Tuskegee University) for their assistance in collecting the coating adhesion and tribological data as well as Dr. Timothy Gabb (NASA) for his helpful input on matrix alloy selection.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

*Level of Review:* This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information  
7115 Standard Drive  
Hanover, MD 21076-1320

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161

Available electronically at <http://gltrs.grc.nasa.gov>

# NASA PS400: A New High Temperature Solid Lubricant Coating for High Temperature Wear Applications

C. DellaCorte and B.J. Edmonds  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

## Abstract

A new solid lubricant coating, NASA PS400, has been developed for high temperature tribological applications. This plasma sprayed coating is a variant of the patented PS304 coating and has been formulated to provide higher density, smoother surface finish and better dimensional stability than PS304. PS400 is mainly comprised of a nickel-molybdenum binder that provides strength, creep resistance and extreme oxidative and dimensional stability. Chromium oxide, silver and barium-calcium fluoride eutectic are added to the binder to form PS400.

Tribological properties were evaluated with a pin-on-disk test rig in sliding contact to 650 °C. Coating material samples were exposed to air, argon and vacuum at 760 °C followed by cross section microscopic analysis to assess microstructure stability. Oil-Free microturbine engine hot section foil bearing tests were undertaken to assess PS400's suitability for hot foil gas bearing applications. The preliminary results indicate that PS400 exhibits tribological characteristics comparable to the PS304 coating but with enhanced creep resistance and dimensional stability suitable for demanding, dynamic applications.

## Introduction

As part of an ongoing research program in tribology, NASA has developed three distinct families of plasma sprayed, wear resistant, high-temperature solid lubricant coatings; PS100, PS200 and PS300. The PS100 family of nickel-glass-solid lubricant containing coatings resulted from a pioneering study of the concept, combining of the functions of individual constituents in a composite solid lubricant coating (Ref. 1). PS100 was followed by PS200 in which nickel-cobalt-bonded chrome carbide supplanted the nickel-glass binder used previously (Ref. 2). PS200 coatings were found to provide superior wear resistance but were also somewhat abrasive to their contacting surfaces. The PS300 coating system was developed to fit between the earlier coatings in terms of hardness and was tailored specifically to meet the needs for shaft coatings operating against high-temperature foil gas bearings (Ref. 3). PS300 contains a nickel-chrome matrix with chrome oxide hardeners combined with silver and fluoride solid lubricants. The general compositions of these three coating families are given in Table I along with their general performance characteristics.

TABLE I.—COMPARISON OF THE NASA PLASMA SPRAY (PS) COATING

Coating designation	Binder matrix	Hardener	Solid lubricants	General attributes
PS100	NiCr	Glass	Ag+fluorides	Soft-high wear
PS200	Ni-Co	Chrome carbide	Ag+fluorides	Hard-low wear, (abrasive to counter face dimensionally stable)
PS300	NiCr	Chrome oxide	Ag+fluorides	Moderate hardness, mildly abrasive to counter face, poor dimensional stability unless heat treated
PS400	NiMoAl	Chrome oxide	Ag+fluorides	TBD

While the PS300 coating has proven successful in many applications including foil bearings, opportunities for improvements continue to present themselves. For instance, early on, it was discovered that a thermal expansion mismatch between PS300 and superalloy substrates caused thermal cycle fatigue spalling in repeated use at temperatures above 500 °C (Ref. 4). The composition was tailored to modify the expansion properties without degrading the coatings tribological performance. The preferred coating for deposition on superalloys was found to be PS304. Reference 4 describes the compositional tailoring effort in detail.

After this initial challenge was overcome, several additional shortcomings of the PS304 coating were identified through Oil-Free gas turbine engine testing. These are reported in the literature and are briefly described here (Ref. 5). One problem with the PS304 coating was related to its proper deposition by plasma spray. Plasma spraying is a highly directional process in which the spray gun nozzle must be held perpendicular to the substrate. When sprayed at an oblique angle, poor density and inadequate coating cohesive strength is observed. Process improvements and the use of automated spray gun fixtures have alleviated this problem.

Coating dimensional stability was also identified as an intrinsic weakness of PS304. Early foil bearing and Oil-Free engine tests conducted at high temperature showed that the coating thickness increased significantly, as much as 7 percent, when the coating was exposed to air at temperatures over 500 °C (Ref. 6). Coating cohesive strength and hardness also increased. After extensive study, it was determined that chromium oxide phase precipitates were formed inside the matrix phase of the coating resulting in a volume increase or swelling action. This lack of dimensional stability was overcome by including a high-temperature, extended time (~150 hr) heat treatment in air prior to final grinding of the coating (Ref. 7). The resulting coating exhibited dimensional stability adequate for most applications. Unfortunately, the added heat treatment step added to the manufacturing cost and the complexity limiting applications. Further, the possibility that long-term oxidation (~10,000's of hours) might degrade the coating integrity persists as a concern.

Another problem presented by using PS304 for foil bearings was that its initially high surface roughness, caused by its porosity, coarse microstructure and morphology, resulted in reduced foil gas bearing load capacity. Following finishing by grinding, PS304 exhibits a typical surface roughness of about 0.8  $\mu\text{m}$  root-mean-square (rms). This level of roughness is much higher than the industry standard shaft coatings such as thin dense chrome that typically have a smoother finish on the order of 0.2  $\mu\text{m}$  rms. This phenomenon diminishes after the bearings are "broken in" through cyclic sliding cycles at high temperatures but the reduced "as installed" load capacity can preclude the use of PS304 in certain applications (Ref. 8). To overcome this shortfall, a research effort identified that burnishing the ground, rough and porous surface with a sacrificial, temporary solid lubricant, like graphite or molybdenum disulfide, restored bearing load capacity until the breaking in process occurred (Ref. 9).

Clearly, opportunities exist to improve the PS300 series of coatings to overcome known problems and also to develop solutions that may achieve comparable performance but at lower cost and manufacturing complexity. The following research project is aimed at developing a PS300 type coating that obviates the need for a heat treatment, provides a less porous coating that may exhibit a lower achievable surface roughness while retaining good tribological performance. Towards this end, a new coating designated PS400 will be introduced and its basic tribological properties will be evaluated in a pin-on-disk tribometer. Thermal exposure to air, inert and vacuum environments followed by cross-section metallographic analyses are performed. Lastly, long-term endurance testing as a shaft coating for foil gas bearings in an Oil-Free gas turbine engine is conducted.

## **Materials**

PS400 is a plasma sprayed composite solid lubricant coating that is similar to PS304 except that a new matrix alloy has been selected to avoid oxidative effects that lead to dimensional swelling. PS400 employs a nickel-molybdenum-aluminum binder in place of the nickel-chromium binder used in PS304. This binder contains by weight, 90 percent Ni and 5 percent each of Mo and Al. Ni-Mo-Al is known to be

creep resistant and the presence of aluminum may result in an improved coating bond with the substrate (Ref. 10). Since metallic chromium was implicated in the oxidative swelling of PS304, its absence in the Ni-Mo-Al binder used in PS400 was thought to result in better dimensional stability. The new binder is available as a commercial plasma spray feedstock, is low cost and often used alone as a wear resistant, high-temperature protective coating. To strengthen the coating, chrome oxide was added. This hardening agent imparted strength and wear resistance to PS304 and was expected to behave similarly in the new coating. Finally, barium fluoride-calcium fluoride eutectic and silver were added as high and low temperature solid lubricants respectively. Table I gives the composition of PS400 along with that of PS304 for comparative purposes.

PS400 differs from PS304 in more than simply the binder alloy employed. Compared to PS304, PS400's solid lubricant content has been halved, from 10 weight percent each to 5 weight percent each. This has been done to improve the new coating's high temperature strength and possibly improve its achievable surface finish through reduced residual porosity and refined microstructure. Earlier studies of the composition of PS200 suggest that this reduced level of solid lubricant may be adequate when the coating is used in an oxidizing environment since the oxide glaze that forms on PS300 at high temperatures is expected to impart a solid lubricant effect (Refs. 2 and 11). No attempt is made in the current project to optimize the PS400 composition, though this may be undertaken in the future after a review of the performance data.

In preparing the PS400 coating, powders of the individual components, as listed in Table I, are weighed and mixed in a suitable container. By weight percent, PS400 contains 70 percent Ni-Mo-Al binder, 20 percent Cr<sub>2</sub>O<sub>3</sub>, 5 percent Ag and 5 percent fluorides. The powders in the container are first hand mixed then poured into the rotary drum of a commercial plasma spray powder feeder. In this device, the rotating motion of the drum continuously mixes the powder blend before and during the spray deposition process. To deposit a coating, the powders are injected into an argon gas carrier stream and fed into a plasma spray gun. Inside the gun, an electric field ionizes inert gas to provide the high temperatures (~10,000 K) needed to melt the particles. The molten particle-inert gas stream is projected onto the substrate where they form splats that solidify and adhere to form a coating. Many passes are made to build up a thick, dense coating approximately 300 μm thick. Table II gives the plasma spray parameters used in this process that is described in more detail in Reference 1.

TABLE II.—PLASMA SPRAY PARAMETERS USED TO DEPOSIT PS400

Parameter	Value
Current.....	600 A
Voltage .....	30 to 32 V
Standoff distance .....	8 to 10 cm
Argon arc gas flow rate.....	~35 SLPM
Powder flow rate.....	~1 kg/hr
Powder gas flow rate .....	0.4 m <sup>3</sup> /hr

The plasma spray process results in a rough surface that must be ground smooth and to the desired coating thickness and dimensions. Typical acceptable coating thicknesses range from about 200 to 400 μm. Thicker coatings can be made but often suffer from poor strength and residual stresses. Coatings thinner than 125 μm often lack adequate bond strength.

Grinding using silicon carbide or diamond abrasive wheels is usually the preferred finish process for PS400. Using standard grinding practices, surface rms finishes of about 0.25 μm are typical for PS400. A stylus surface profilometry trace of a PS400 coating is shown in Figure 1. This surface finish represents an improvement over PS304 that generally exhibit a ground surface roughness two to three times rougher

(~0.5 to 1.0  $\mu\text{m rms}$ ). The rough surface of PS304 was attributed to residual porosity and preferential removal of soft lubricant phases, namely the fluorides, present at the surface. PS324 coatings appear to have very low porosity and a finer microstructure. The reduced soft-phase content, compared to PS304, may also be contributing to the smoother final finish. In any case, the smooth finish of PS400 is an advantage for its use in gas foil bearings. Figure 2 shows typical cross section micrographs of both PS304 and PS400.

Three types of coating specimens are fabricated for use in the present investigation. All are made from a precipitation-hardened nickel-based superalloy, Inconel X-750. For measuring coating strength and making metallographic cross section samples, cylindrical coupons that are 25 mm in diameter and 6 mm thick are coated on one face with PS400. For evaluating the basic friction and wear properties, disk specimens, 63 mm in diameter and 12.5 mm thick are coated on one face with PS400 which is then ground to a smooth surface and a final coating thickness of about 250  $\mu\text{m}$ . Finally, Oil-Free turbine engine shafts are fabricated and coated on the hot journal bearing location with PS400. Like the disk specimens, the engine shaft coatings are ground to a smooth finish and a final thickness of 250  $\mu\text{m}$ . Figure 3 shows a turbine engine shaft coated with PS400.

Two counter-face specimen geometries are used in sliding contact operating against the PS400 coatings; pins and foil bearings. For the pin-on-disk testing, hemispherical tipped pins are made from the common nickel base superalloy Inconel X-750. For the foil bearing evaluations, Inconel X-750 foil sheet is formed into a curved shape that is wrapped around the PS400 coated engine shaft. Details about the foil bearing geometry and fabrication can be found in the literature (Refs. 5 and 12).

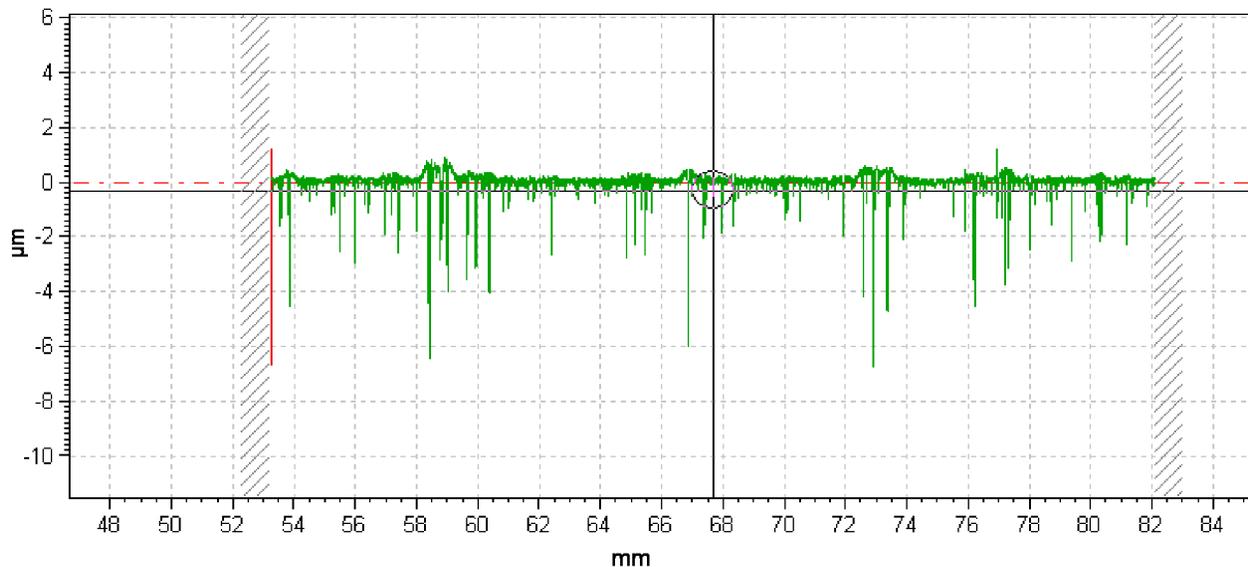


Figure 1.—Surface roughness profile for ground PS400 showing a smooth finish of ~0.2  $\mu\text{m rms}$ .

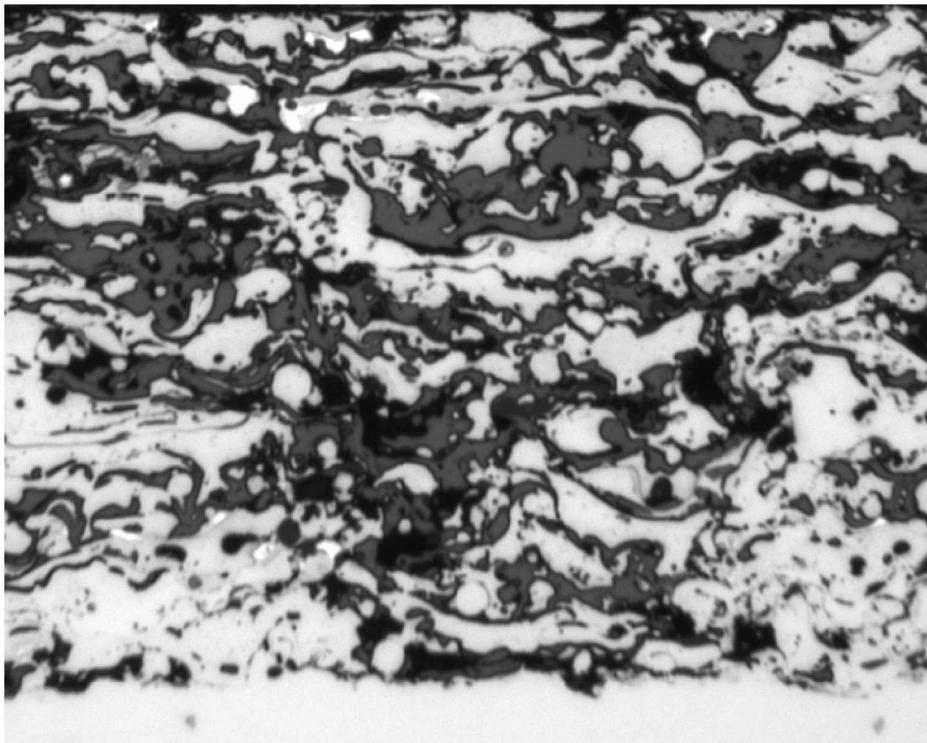
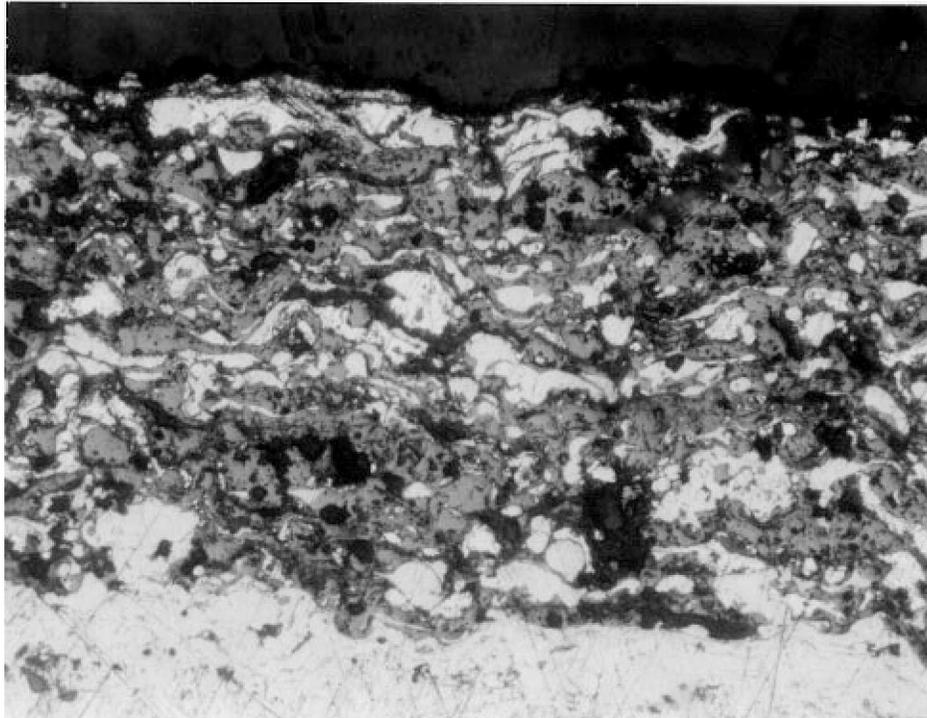


Figure 2.—Comparative cross section micrographs of PS304 (upper) and PS400 (lower) coatings showing a similar splat layered morphology typical for thermal spray coatings.



Figure 3.—Turbine engine shaft coated with PS400 after grinding.

### Test Apparatus and Procedure

The PS400 coating was evaluated using the tests: (1) coupon level coatings which were heat treated and tested for adhesion and then cross sectioned for coating microstructure analyses; (2) bench type friction evaluations using a standard pin-on-coated disk tests; and (3) foil bearing evaluation in a hot bearing location within a microturbine engine.

The coating strength and adhesion tests are carried out using a commercially available adhesion tester (Ref. 7). In this device, an aluminum stud is glued to the coating surface with a catalyzed epoxy adhesive. The stud is then pulled from the coating using an instrumented pneumatic cylinder that records the pull off pressure from which the force is calculated. If the coating separates from the substrate, the pull-off force reflects the adhesion strength. For plasma sprayed coatings, the substrate-coating bond often exceeds the cohesive strength of the coating itself or the bond between the epoxy and the coating. In these cases, the strength results thus reflect the coating strength under tensile loads or the glue bond strength, respectively.

In the study reported here, coated coupons were heat treated in air and vacuum at 760 °C for 15 hr then evaluated via pull-testing to see the effects, if any, thermal exposure may have on coating strength. In previous studies with PS304, thermal exposure to air for varying times and temperature resulted in a significant increase in coating strength. For evaluating possible effects of thermal exposure on the microstructure of PS400, coated coupons were exposed to air, argon or vacuum at 760 °C for 24 hr, and then cross sectioned and polished using conventional metallographic techniques. These cross sections were examined using optical microscopy.

A pin-on-disk rig was used to slide coated disks against the superalloy pins in room air at 25, 500 and 650 °C. The load was 0.5 kG (4.9 N) and the sliding speed was 3 m/s with a wear track diameter of 50 mm. The tests were generally run for 90 min at each temperature in three equal 30-min segments beginning with the highest test temperature with subsequent tests working down to room temperature. Three repeat sequences were run using a new pin and disk specimen set to assess data scatter. Selected

experiments were run longer to evaluate test duration effect on steady-state friction. Friction was measured continuously using a chart recorder. Wear was measured after each 30 min test using optical microscopy measurements of the pin wear scar diameter and stylus surface profilometry of the disk wear track. Wear factors (incremental wear volume normalized by the load and incremental sliding distance) were calculated for each segment and averaged to obtain the reported values. The friction and wear data was compared to PS304 to examine the effects of the compositional change on tribological performance.

Evaluation of the coating in a hot foil bearing was conducted using a Capstone 30 kW, Oil-Free Microturbine engine. In this engine test the cyclic and long-term durability of the coating is characterized by running one engine cycle at full power for 12 hr once per day. This subjects the coating to brief sliding during a cold start and a hot shut down with nearly 12 hr of operation under high centrifugal stresses due to the high shaft speed (96,000 rpm) and high temperature (~500 °C). This test is detailed in reference 5 and provides coating exposure in a representative engine environment in a convenient, cost effective manner. For characterization, engine start torque is monitored and on occasion the engine is disassembled and the coating is inspected.

## Results and Discussion

Table III shows the coating adhesion results. For comparative purposes, the results for PS304, reported previously are listed. The coating pull-off adhesion test results indicate that, for both the PS304 and PS400 coatings, the failure location is within the body of the coating itself, not at the glue-coating or coating-substrate interface. Thus the pull-off strength is a semi-quantitative measure of the coating strength in tension. For PS304, the strength as deposited is about 20 MPa. After a heat treatment in air, this value nearly doubles to 34 MPa due to the growth of a second phase oxide precipitate. This hardening effect is accompanied by a volume expansion (thickness increase) of approximately 7 percent and is well documented in the literature (Ref. 6).

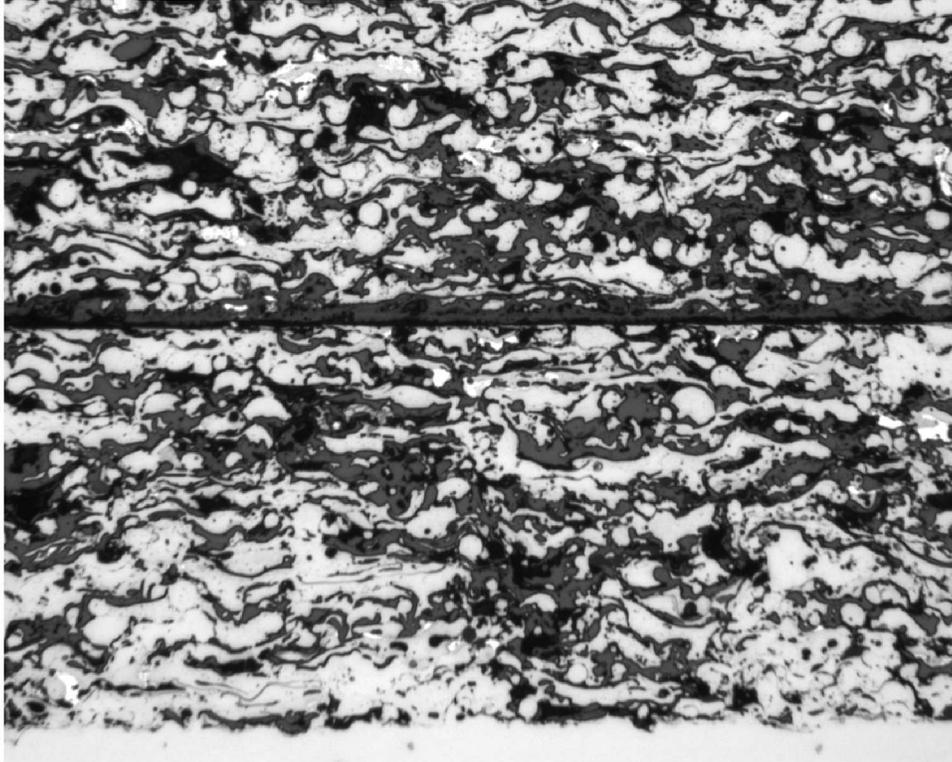
TABLE III.—PULL-OFF STRENGTH/ADHESION DATA SUMMARY FOR PS400 AND PS304 COATINGS

Coating Designation	Heat treatment			<sup>a</sup> Pull-off strength		Failure location
	Temperature, °C	Atmosphere	Duration, hr	ksi	MPa	
PS304	None	N/A	N/A	2.9	20	Within coating
PS304	650 °C	Air	24	4.9	33	Within coating
PS400	None	N/A	N/A	2.9	20	Within coating
PS400	760 °C	Air	15	3.3	23	Within coating
PS400	760 °C	Vacuum	15	3.4	24	Within coating

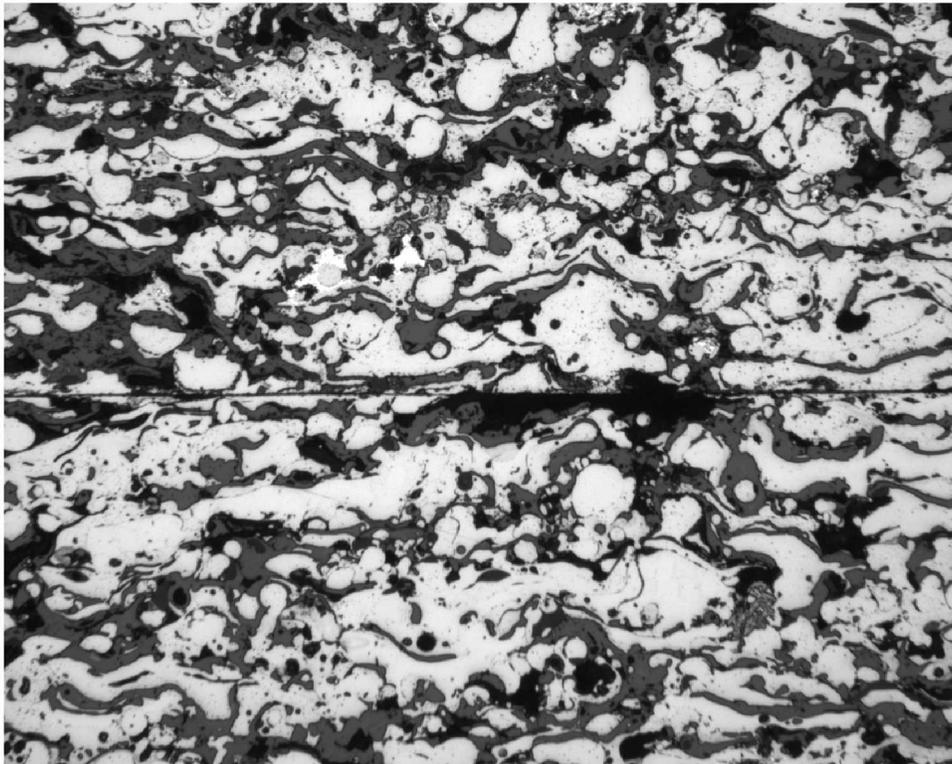
<sup>a</sup>Data scatter for pull-off strength typically  $\pm$  5 percent of reported value.

PS400 exhibits a pull-off strength comparable to PS304 in the as-deposited state, about 20 MPa. This value represents the cohesive strength in tension of the PS400 coating and is fully adequate for the intended coating applications. Following a heat treatment in air, or vacuum, at 760 °C for 15 hr the strength rose moderately to 23 MPa. Testing is underway to examine the effects of heat treatment temperature and duration to identify any thresholds for microstructural or chemical change. Early indications are that PS400 is physically very stable. Close examination of the coating cross sections before and after heat treatment indicates no obvious microstructural or other physical changes to the coating.

Figure 4 (a), (b), and (c) shows photomicrographs of PS400 coating cross-sections with and without heat treatments in air, inert gas and vacuum. No microstructural or thickness changes are observed. The modest increase in strength may be related to enhanced bonding between coating phases or possibly the formation of intermetallic phases within the Ni-Mo-Al binder phase. The literature suggests that nickel-aluminide may form during the heat treatment, enhancing the strength of the coating's binder phase but this has not been confirmed (Ref. 10). Based upon these coupon level tests, it is clear that the PS400 coating has achieved one important goal, to improve dimensional stability and to obviate the need for post deposition heat treatment

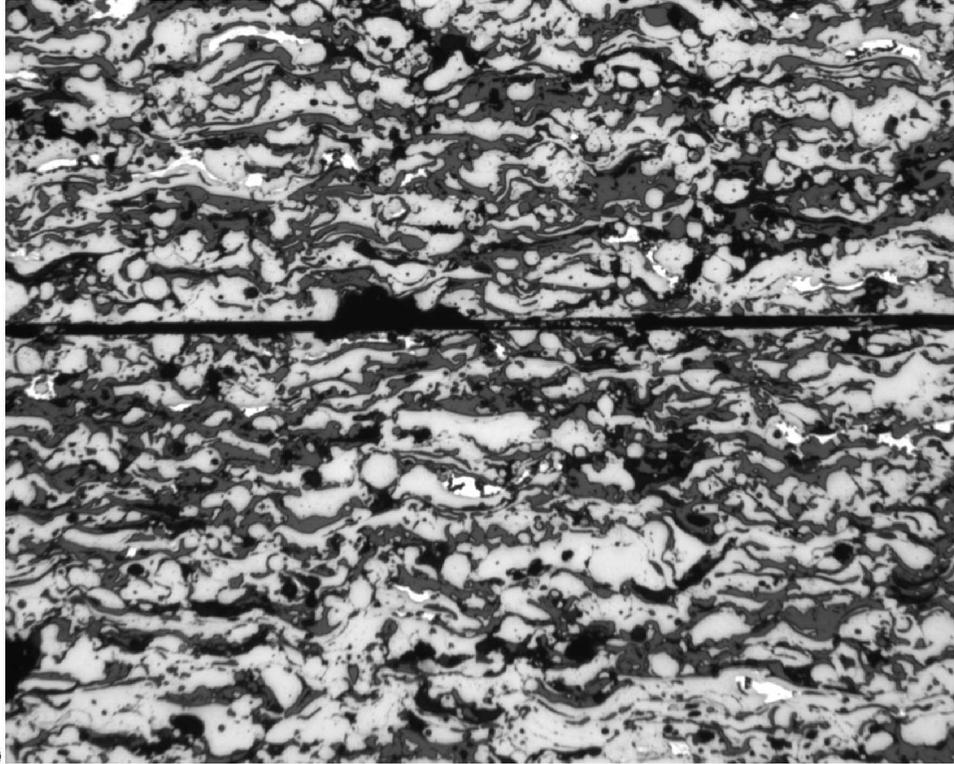


(a)



(b)

Figure 4.—(a) PS400 cross section sandwich sample. Top layer exposed to air at 760 °C, 15 hr. Lower layer as-deposited control coating. Slight oxide layer observed after exposure but no microstructural changes noted following exposure. (b) PS400 cross section sandwich sample. Top layer exposed to argon at 760 °C, 15 hr. Lower layer as-deposited control coating. No microstructural changes noted following exposure.



(c)

Figure 4.—Concluded. (c) PS400 cross section sandwich sample. Top layer exposed to vacuum at 760 °C, 15 hr. Lower layer as-deposited control coating. No microstructural changes noted following exposure.

The pin-on-disk friction and wear data is summarized in Table IV. For comparison purposes, the tribological behavior for the original PS304 coating is shown alongside the data for the newly formulated PS400. The data trends show that both PS304 and PS400 behave in a similar manner. They exhibit markedly lower wear and somewhat lower friction at high temperatures as compared to room temperature measurements. For both coatings, friction is essentially identical at 25 and 650 °C but the PS400 exhibits far lower friction at 500 °C, 0.16 compared to 0.23 for PS304. In terms of wear, the picture is less clear-cut. At high temperatures, PS400 offers over an order-of-magnitude reduction in coating wear and roughly an order of magnitude reduction in counter-face pin wear factor. This is a major improvement in performance. However, the wear factors for both the PS400 coating and the mating pin at room temperature is two to three times higher than PS304. Clearly, the reduction in solid lubricant content, most likely the silver, from the 10 to 5 weight percent, leads to higher room temperature wear for PS400.

TABLE IV.—FRICTION AND WEAR DATA SUMMARY<sup>a</sup>

Coating designation	Test temperature, °C	Friction coefficient	Pin wear, K <sub>pin</sub> mm <sup>3</sup> /N-m	Coating wear, K <sub>disk</sub> mm <sup>3</sup> /N-m
PS304	25	0.31 ± 0.05	96 ± 30×10 <sup>-7</sup>	480 ± 30×10 <sup>-6</sup>
PS304	500	0.25 ± 0.02	32 ± 5×10 <sup>-7</sup>	280 ± 30×10 <sup>-6</sup>
PS304	650	0.23 ± 0.02	38 ± 4×10 <sup>-7</sup>	100 ± 10×10 <sup>-6</sup>
PS400 <sup>b</sup>	25	0.31 ± 0.04	141 ± 28×10 <sup>-7</sup>	1180 ± 380×10 <sup>-6</sup>
PS400	500	0.16 ± 0.02	2.1 ± .3×10 <sup>-7</sup>	6.3 ± 1.0×10 <sup>-6</sup>
PS400	650	0.21 ± 0.03	8.9 ± 2×10 <sup>-7</sup>	7.6 ± 1.2×10 <sup>-6</sup>

<sup>a</sup>Test load 5 N, 3 m/s sliding velocity, air atmosphere 50 percent relative humidity, Inconel X-750 pins.

<sup>b</sup>Test data at 25 °C collected after previous sliding occurred at 650 and 500 °C.

The results presented here do not fully reveal the tribological behavior of PS400. During the course of this investigation, an additional pin-on-disk specimen set was run in a reversed temperature sequence; first at 25 then at 500 and lastly at 650 °C. The wear data for this test mimicked that shown in Table IV but the friction behavior varied significantly. Friction at room temperature increased nearly 40 percent with an observed coefficient of  $0.49 \pm 0.01$ . A second room temperature test of this same specimen set after sliding tests at 500 and 650°C were completed showed that low friction ( $\sim 0.30$ ) returned. Thus to achieve low friction with PS400, a sliding break-in period at elevated temperature is required. This result mirrors the authors' experience with PS304 when used in foil gas bearings (Refs. 8 and 9) and is most likely due to need to form a lubricious surface glaze in order to achieve a significant friction reduction.

Previous research with PS304, which is tribo-chemically similar to PS400, has revealed that different surface layers form on the coating and its mating surface is dependent on the test temperature (Ref. 11). These films exhibit unique tribological properties and are generally more capable at mitigating friction and wear than the intrinsic solid lubricants present in the coatings (i.e., silver and fluorides). The surface films, or glazes, form most readily at high temperatures in the presence of sliding contact, and function as effective solid lubricants even when the test temperature is returned to 25 °C. Exposing the PS400 coating to high temperature air is insufficient to develop the lubricious surface glaze; sliding contact is also required. Thus it is not surprising to see moderately high friction and for the new PS400 coating at low temperature until after it has been slid at elevated temperature. Further research will be required to identify methods to create the lubricious glazes prior to using this coating or to allow for a benign break-in process before optimal solid lubrication can be achieved. For foil gas bearings employing PS304 coatings, sacrificial overlay coatings of graphite were found to be effective. It is expected that this line of research will continue. In any event, low friction and wear at elevated temperatures makes PS400 a good candidate for applications that require improved tribological performance as compared with PS304.

Lastly, the PS400 coating was extensively tested as a shaft coating operating against a hot section foil bearing in a Capstone Oil-Free 30 kW microturbine engine. After 2200 start-up and shut down cycles conducted over 8000 hr of operation at 96,000 rpm and approximately 540 °C, the engine was disassembled and the shaft was inspected. Figure 3 shows the shaft before testing and Figure 5 shows the same shaft as it appeared at engine teardown inspection. The PS400 shaft coating has visually changed



Figure 5.—Capstone turbine engine shaft coated with PS400 after undergoing 2200 start-stop cycles and 8000 hr of high speed and high temperature operation. Dark shiny appearance is typical for the coating following a break-in period.

from a metallic silver color to a dark grey with surface that is polished smooth. This surface is ideal for foil bearings and displays the development of the lubricious surface glazes conducive to good tribological performance. Shaft diameter measurements show no wear on the shaft. This is not surprising. Extensive high-temperature foil bearing test experience for PS304 coatings routinely demonstrated over 100,000 start stop rub cycles before measurable wear was observed. Since PS400 appears to exhibit lower wear during high temperature sliding, like that encountered in these engine bearing tests, wear after only 8000 cycles was not anticipated. Following an inspection, the PS400 shaft was returned to the engine and continues to accumulate operating hours. At the time of this writing (spring 2009) over 3000 cycles and 10,000 hr have been successfully logged.

## Summary Remarks

The development of PS400 was undertaken to tailor the coating composition to overcome difficulties in deploying PS304 in high temperature sliding applications. Specifically, an attempt has been made to improve selected coating characteristics such as surface finish, dimensional stability and processing costs while retaining positive performance attributes of PS304 such as low friction and wear. The primary differences between PS304 and the new coating, designated PS400 is a change in binder or matrix material from NiCr to Ni-Mo-Al and a reduction in solid lubricant concentration from 20 to 10 total weight percent.

The results of this research project convincingly show that the goals have been met. The new coating is dimensionally stable regardless of high temperature exposure to air, inert gas or vacuum. The friction and wear properties are comparable to PS304 at room temperature and significantly improved, especially with respect to wear, at elevated temperatures. The achievable surface finish is smoother for PS400 by a factor of three or four and finally, the PS400 requires no post deposition heat treatment to achieve high strength or dimensional stability, thus reducing processing costs. The only characteristics that may need further investigation and development is in the initial tribological performance at room temperature, prior to coating use at high temperature. This has been attributed to the absence of a lubricious glaze on the rubbing surfaces that only seems to form during sliding at high temperatures. PS304 has shown the same need for a high temperature break-in period or the use of sacrificial solid lubricant overlay coatings. Further work to overcome this need is warranted.

Overall, based upon the coupon level tests, pin-on-disk bench tests and full foil bearing engine tests, it is clear that PS400 represents a marked improvement over PS304 and may open new applications in high temperature tribology.

## References

1. Sliney, H.E.: "Wide Temperature Spectrum Self-Lubricating Coatings Prepared by Plasma Spraying," *Thin Solid Films*, Vol. 64, 1979, pp. 211–217.
2. DellaCorte, Christopher and Sliney, H. E.: "Composition Optimization of Self-Lubricating Chromium-Carbide-Based Composite Coatings for Use to 760 °C," *ASLE Trans.*, Vol. 30, No. 1, Jan. 1987, pp. 77–83.
3. DellaCorte, Christopher and Edmonds, B.J.: "Preliminary Evaluation of PS300: A New Self-Lubricating High Temperature Composite Coating for Use to 800 °C," NASA TM 107056, Prepared for Energy Week Conference and Exhibition cosponsored by API and ASME Houston, TX, Jan. 29–Feb. 2, 1996.
4. DellaCorte, Christopher: "The Effect of Compositional Tailoring on the Thermal Expansion and Tribological Expansion and Tribological Properties of PS300: A Solid Lubricant Composite Coating," NASA TM–107332, Prepared for the 1997 STLE Annual Meeting. *Tribology Transactions*, Vol. 40, pp. 639–642, Oct.1997.
5. Lubell, D., DellaCorte, C., and Stanford, M.K. "Test Evolution and Oil-Free Engine Experience of a High Temperature Foil Air Bearing Coating," *Proceedings of GT2006:ASME Turbo Expo 2006*, May 8–11, 2006, Barcelona, Spain, paper number GT2006–90572.

6. DellaCorte, Christopher; Edmonds, Brian J.; and Benoy, Patricia A.: "Thermal Processing Effects on the Adhesive Strength of PS 304 High Temperature Solid Lubricant Coatings," NASA/TM—2001-210944, May 2001.
7. DellaCorte, Christopher: "The Effects of Substrate Material and Thermal Processing Atmosphere on the Strength of PS304: A High Temperature Solid Lubricant Coating," Tribology Transactions, Vol. 46, No. 3, pp. 361–368, 2003. Also NASA/TM—2002-211483, Sep. 2002.
8. Radil, Kevin C.; DellaCorte, Christopher: "The Effect of Journal Roughness and Foil Coatings on the Performance of Heavily Loaded Foil Air Bearings," Tribology Transactions, Vol. 45, No. 2, Apr. 2002, pp. 199–204. Also NASA/TM—2001-210941, Jun. 2001.
9. DellaCorte, Christopher; Zaldana, Antonio; Radil, Kevin: "A Systems Approach to the Solid Lubrication of Foil Air Bearings for Oil-Free Turbomachinery," ASME Journal of Tribology, Vol. 126, pp. 200–207, Jan. 2004. Also NASA/TM—2002-211482, ARL-TR-2867, Oct. 2002.
10. Metco Technical Bulletin 10-133; "Metco 447 and Metco 447NS Self-Bonding Molybdenum-Nickel-Aluminum Composite powder," Metco, Inc., Westbury, NY, Mar. 1982.
11. DellaCorte, Christopher: "The Evaluation of a Modified Chrome Oxide Based High Temperature Solid Lubricant Coating for Foil Gas Bearings. NASA/TM—1998-208660, Oct. 1998. Tribology Transactions, Vol. 43, No. 2, pp. 257–262, Apr. 2000.
12. Bosely, R.W.: "Compliant Foil Hydrodynamic Fluid Film Radial Bearing," U.S. Patent No. 5,427,455, Jun. 1995.

**REPORT DOCUMENTATION PAGE**

*Form Approved*  
**OMB No. 0704-0188**

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

<b>1. REPORT DATE (DD-MM-YYYY)</b> 01-08-2009		<b>2. REPORT TYPE</b> Technical Memorandum		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> NASA PS400: A New High Temperature Solid Lubricant Coating for High Temperature Wear Applications				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> DellaCorte, C.; Edmonds, B., J.				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b> WBS 877868.02.07.03.01.01.14	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> E-17044	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration Washington, DC 20546-0001				<b>10. SPONSORING/MONITOR'S ACRONYM(S)</b> NASA	
				<b>11. SPONSORING/MONITORING REPORT NUMBER</b> NASA/TM-2009-215678	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Unclassified-Unlimited Subject Categories: 27, 23 and 07 Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> A new solid lubricant coating, NASA PS400, has been developed for high temperature tribological applications. This plasma sprayed coating is a variant of the patented PS304 coating and has been formulated to provide higher density, smoother surface finish and better dimensional stability than PS304. PS400 is comprised of a nickel-molybdenum binder that provides strength, creep resistance and extreme oxidative and dimensional stability. Chromium oxide, silver and barium-calcium fluoride eutectic are added to the binder to form PS400. Tribological properties were evaluated with a pin-on-disk test rig in sliding contact to 650 °C. Coating material samples were exposed to air, argon and vacuum at 760 °C followed by cross section microscopic analysis to assess microstructure stability. Oil-Free microturbine engine hot section foil bearing tests were undertaken to assess PS400's suitability for hot foil gas bearing applications. The preliminary results indicate that PS400 exhibits tribological characteristics comparable to the PS304 coating but with enhanced creep resistance and dimensional stability suitable for demanding, dynamic applications.					
<b>15. SUBJECT TERMS</b> Solid lubricants; Friction; Wear; High temperature; Turbines; Bearings					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
				18	<b>19b. TELEPHONE NUMBER (include area code)</b> 443-757-5802



