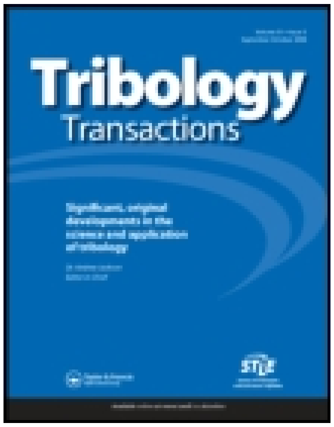


Tribology Transactions
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/utrb20

Thrust-Washer Evaluation of Self-Lubricating PS304 Composite Coatings in High Temperature Sliding Contact

Thierry A. Blanchet [a], Jong-Hwan Kim [a], Salvadore J. Calabrese [a] & Christopher Dellacorte [b]

[a] Rensselaer Polytechnic Institute, Dept. of Mechanical Engineering, Troy, New York, 12180
[b] NASA Glenn Research Center, Cleveland, Ohio, 44135
Published online: 25 Mar 2008.

Vol. 45 (2002), 4, 491-498
TRIBOLOGY TRANSACTIONS

Thrust-Washer Evaluation of Self-Lubricating PS304 Composite Coatings in High Temperature Sliding Contact©

THIERRY A. BLANCHET, JONG-HWAN KIM and SALVADORE J. CALABRESE
Rensselaer Polytechnic Institute
Dept. of Mechanical Engineering
Troy New York 12180
and
CHRISTOPHER DELLACORTE
NASA Glenn Research Center
Cleveland, Ohio 44135

*PS304 self-lubricating composite coatings were successfully deposited on steel substrates at various plasma spray facilities using mixtures blended from commercially obtained constituent particles. Coatings were evaluated in thrust-washer tests against Inconel X-750 at low contact pressures to 40kPa, sliding speed of 5.4m/s, and either ambient temperature or 500℃ chosen to simulate conditions in air foil bearings during startup and shutdown contact. Wear factors for all PS304 coatings tested, regardless of contact pressure and temperature, ranged from 1-3*10^{-4} mm^3/Nm while coefficients of friction of approximately μ=0.5 were measured in all cases. While wear and friction behavior of PS304 in air foil bearings appear to have been simulated, surface roughening was observed in these thrust-washer tests which used continuous sliding contact, as opposed to the evolution of smoother surfaces observed in high-temperature foil bearings experiencing cyclic startup/shutdown. Wear-induced surface smoothening of PS304 was additionally simulated in thrust-washer tests with sliding contact instead imposed intermittently.*

KEY WORDS

Surface Films/Coatings; Composite; Solid Lubricant Adverse Environments Tribology; High Temperature; Solid Lubricated

INTRODUCTION

PS304, a composite of silver and eutectic barium fluoride/calcium fluoride solid lubricants and a chrome oxide hardener within a nichrome matrix, evolved from NASA development of plasma-sprayed self-lubricating coatings initiated three decades ago (Sliney 1974). This 300-series replaced the harder chrome carbide of the 200-series with chrome oxide, eliminating the necessity of costly diamond grinding and providing improved resistance to oxidative changes in high-temperature air (DellaCorte and Laskowski 1997). PS304 uses chrome oxide (20% wt.) and nichrome (60% wt.) in a 3:1 ratio to cause its thermal expansion (12.4*10^{-6} /°C) to fall within a range of substrate materials such as Inconel X-750 (~14*10^{-6} /°C) and PH 13-8 steel (~12*10^{-6} /°C), for example (DellaCorte and Fellenstein, 1997). Low-temperature lubricating characteristics of silver (10% wt.) complement high-temperature characteristics of the eutectic barium fluoride/calcium fluoride (10% wt.) to provide self-lubrication from ambient to 900°C (Sliney, 1985). This is far broader than even the best oil lubricants, whose maximum service temperatures generally do not exceed 400°C (Chen, 1997).

Another approach to lubrication over a broad temperature range is through the use of gas bearings. For example, air foil bearings have been employed in air cycle machines for aircraft cabin pressurization and environmental control since the 1970s, and in the 1990s air foil bearings were laboratory-tested for cruise missile engines with bearing temperatures up to 538°C (Agrawal 1998). Air foil bearings were more recently demonstrated from ambient temperature to 650°C in a turbocharger for diesel truck engine applications, with subsequent goals for general aviation propulsion turbine engine applications involving higher temperatures (Buss, 2000).

In an air foil journal bearing, a top foil is held within the housing shell and lightly preloaded against the journal by a compliant support structure, interposed between it and the shell, such as a corrugated bump foil. Under steady operation journal rotation provides self-acting entrainment of lubricant (air), without external pressurization, while deflection of the compliant foil structure assists generation of an air film sufficiently thick to separate asperities on the foil and journal surfaces. Thus foil air bearings have a load capacity that increases with speed due to increased entrainment, in contrast to rolling element bearings where centripetal roller/outer race effects diminish load capacity.

However, intermittent foil/journal sliding contact occurs during startup and shutdown when rotational speed approaches zero.

Final manuscript approved July 30, 2002
Review led by Michael Dugger

Fig. 1—Secondary electron image of an example PS304 powder mixture (PA).

For example, in the air cycle machine of a DC-10 aircraft with a 48,000 rpm operational speed, full foil/journal separation does not occur below 2,000 rpm (Agrawal 1998). In recent foil bearing tests at NASA Glenn Research Center a rotational speed of 4,000 rpm was required for foil/journal separation, with the 35mm journal diameter corresponding to a maximum sliding speed of 7.3m/s (DellaCorte, et al. 1999). During such transients, resultant foil/journal sliding contact will occur at a modest contact pressure of only a few tenths of an atmosphere, due to the compliancy of the support structure, and alternately at ambient temperature during startup but elevated operational temperature during shutdown. Solid lubricant PS304 coatings, on the journal sleeve, are being successfully employed to address the breadth of contact temperatures to occur at this foil/journal sliding interface in proposed commercial diesel and gas turbine applications (DellaCorte, 2000, DellaCorte, et al. 1999).

Throughout its development, PS304 coating preparation has generally been performed within the NASA Glenn Research Center. In an effort to assess feasibility of broad and independent commercial preparation of PS304 coatings, this study demonstrates the ability of another party (a small group of researchers at RPI) to obtain and blend constituent particles and have PS304 coatings plasma-sprayed and finished, all by commercial means. Potential performance variability was investigated by having PS304 deposited by multiple commercial spray facilities. As several candidate PS304 powder mixtures were considered by RPI in early stages of this study, the NASA Glenn Research Center spray facility produced coatings of each under identical conditions for screening and selection of a single common powder mixture to be distributed for assessment of coating variability among commercial spray facilities. Coating assessment consisted of spectroscopic confirmation of all PS304 constituents, as well as wear and friction performance.

EXPERIMENTAL

Powder Mixture Preparation

All powders were secured from commercial sources. Chrome oxide (Cr_2O_3) hard phase was obtained in a fused grade in a 10-44 µm size range, with particles being very angular in shape. Nichrome (80% wt. nickel / 20% wt. chromium) binder was obtained in a 44-70µm size range with particles of irregular shape having nodular features. Prefused eutectic barium fluoride/calcium fluoride (62% wt. BaF_2/38% wt. CaF_2) high-temperature solid lubricant was ordered in a 44-70mm size range, with particles in this size range also being very angular in shape. However, plentiful sub-micrometer particles also existed in this fluoride powder, revealed by observation of specimens prepared by placing small quantities of powder on double-sided adhesive tape upon an SEM sample stub and blowing off the excess with an aerosol duster. Two forms of silver were obtained for consideration. An atomized form consisted of extremely spherical particles in the 44-70µm size range, while a precipitated form consisted of extremely porous particles apparently formed from neighboring particles growing into one another. A small fraction of these precipitated particles were observed to have dimensions somewhat less than 44µm, though not sub-micrometer.

Powder mixtures blended at RPI were produced by measuring out appropriate quantities of each particle type to produce 1 kg of PS304. The PS304 powder was preliminarily mixed through tumbling in a glass jar, screened through a 120mesh sieve to break up agglomerates, then finished with rotary V-blending. An example micrograph of blended PS304 powder is shown in Fig. 1. Two different PS304 powders were blended at RPI, 'PA' using atomized silver and 'PB' using precipitated silver. Two other PS304 powders were considered in this study. A NASA powder produced with atomized silver and eutectic fluoride, whose processing was revised in order to remove the sub-micrometer particles and prevent potential powder flow difficulties, was considered as a control. Additionally, a small quantity of PS304, formulated and made available commercially by the supplier of the eutectic fluoride, was obtained.

Plasma Spray Coating Deposition

Attempts were initially made to plasma-spray coatings from each candidate PS304 mixture under identical conditions at the NASA Glenn Research Center facility, with these deposition conditions noted in Table 1. From these four candidates, a single PS304 mixture was selected for plasma spraying at three different commercial spray facilities, designated 'SA', 'SB' and 'SC'. Spray conditions were not dictated to these commercial facilities, though NASA spray conditions for PS304 are published and generally available (DellaCorte and Laskowski, 1997) and were provided for reference. Facilities were permitted to arrive at spray conditions through trial-and-error, with two facilities (SA and SC) being able to also rely on past experience with previous incarnations of the material such as PS212. Final spray conditions employed by each facility are listed in Table 1.

A set of four 13-8 PH Mo steel disks, of 0.12m diameter, 12.7mm thickness and precipitation hardened to H1100 condition, were sent to each spray facility along with a set of 25mm x 25mm aluminum witness coupons. It was requested that each surface be coated with at least 0.4mm of PS304, and disk surfaces were grit-blasted prior to plasma spraying. Witness coupons were included for confirmation of all powder constituents within the resultant

Table 1—Plasma Spray Conditions for PS304 Deposition Used by NASA Glenn Research Center as well as three commercial spray facilities (SA, SB and SC)

Spray Facility	NASA	SA	SB	SC
Spray System	BSA	9MB	7MC	9MC
Current (A)	650	460	460	500
Voltage (V)	32	32	32	70
Standoff (in)	3.5 - 4	5 - 6	6	3 - 5
Primary Gas Type	Ar	Ar	Ar	Ar
Primary Gas Flow Rate (scfh)	75	100	100	100
Secondary Gas Type	He	H2	H2	H2
Secondary Gas Flow Rate (scfh)	20	25	25	20
Powder Feed	Internal	External	External	External
Feed Rate (lbs/hr))	2.2	2.5	3	4

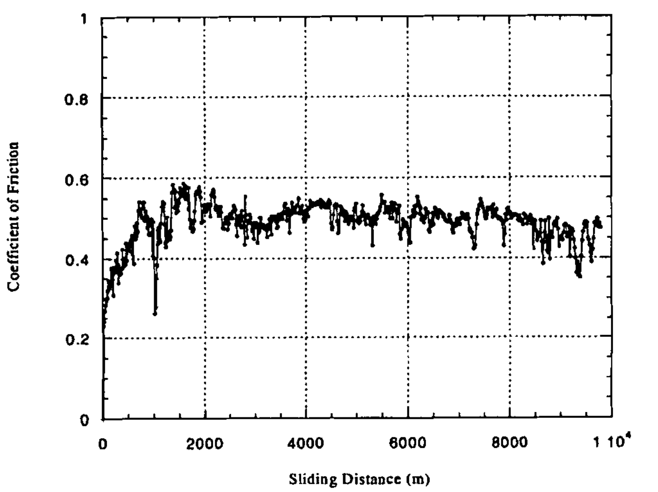


Fig. 2—Example friction coefficient record from a thrust-washer sliding test.

coating by X-Ray Fluorescence spectroscopy at NASA and for observation of coating cross-sections.

Wear and Friction Analysis

PS304-coated steel disks were evaluated at RPI in thrust-washer sliding tests against rings of Inconel X-750, a common foil material. PS304-coated disks were roughed flat on a reciprocating grinder using a SiC wheel, and subsequently finished with wet 600 SiC paper to typical initial RMS roughness (R_q) of 1μm. Inconel X-750 rings were age-hardened (20 hours in argon at 700°C) and their flat 'washer' surfaces (10.2cm outer diameter and 7.1cm inner diameter) lapped with 0.3μm alumina particles in diesel fuel to typical roughness R_q =0.05μm.

Sliding contact was produced by clamping the Inconel X-750 ring within a spindle collet, rotating it while pneumatically loading the stationary PS304-coated disk against its washer surface. Normal loads of 84 and 168N were used to produce modest contact pressures of 20 and 40kPa at the conformal coating/washer interface, typical of those found in foil journal bearings. The disk was mounted atop a mantle containing three cartridge heaters so that tests could be performed at either ambient temperature or 500°C, representing startup and shutdown conditions, respectively. A spindle speed of 1,200rpm was employed to produce an average sliding speed of 5.4m/s, also typical of sliding contact of foil journal bearings during startup/shutdown. Prior to testing, the disk was momentarily loaded against the ring and turned by hand through a few rotations, then separated and inspected for continuous traces of wear tracks on both the surfaces, confirming parallelism. Each coating was then tested for 30 minutes of continuous contact, a total sliding distance of nearly 10km. At the conclusion of the test, the disk was separated from the ring before halting spindle rotation.

The base of the disk assembly and the pneumatic piston that loads it against the ring were separated by a hydrostatic air bearing, with radial arms from the disk baseplate contacting two inertial cantilevers and resisting disk rotation. Strain gauges attached to these cantilevers allowed friction to be continuously recorded on a computer data acquisition system, with an example friction record shown in Fig. 2. Average steady-state friction coefficients and standard deviations were determined over the last half of the test. Sliding wears a circular track, of inner and outer diameter corresponding to that of the ring's washer surface, into the coating. An example of a ring and corresponding disk with coating wear track is shown in Fig. 3. Upon test completion wear track cross-sectional area was determined through radial stylus profiles, using unworn regions on either side as a baseline (Fig. 4). Two such profiles were taken at 180° separation about the wear track, with cross-sectional areas averaged to account for any slight deviations from disk/ring parallelism. From track cross-sectional area multiplication by mean track circumference approximates total coating wear volume. Division by the product of normal load and total sliding distance provides an estimate of wear factor (mm^3/Nm), presuming steady wear through the test.

RESULTS

Various Candidate PS304 Powder Mixtures Deposited at NASA

Of the four candidate PS304 mixtures whose plasma spray deposition was attempted at NASA Glenn Research Center, only the NASA (control) and RPI (PB) powders were deposited without difficulty. PA experienced flow difficulties, and its deposition was discontinued after only a single disk. The commercially available formulated PS304 powder presented flow difficulties immediately, and no disks could be coated. Microscopic inspection of this formulated PS304 revealed that it also contained both spherical atomized silver particles and sub-micrometer eutectic

TABLE 2—X-RAY FLUORESCENCE DETERMINATION OF COMPOSITIONS OF PS304 COATINGS DEPOSITED AT VARIOUS SPRAY FACILITIES (NASA OR THREE COMMERCIAL FACILITIES SA, SB, OR SC) USING VARIOUS POWDER MIXTURES (MASA-PREPARED OR TWO RPI-PREPARED POWDERS PA AND PB), AS COMPARED TO STANDARD COMPOSITION

SPRAY FACILITY	POWDER	COMPOSITION (wt.%)				
		Ni	Cr	Ag	Ca	Ba
Standard	Standard	51.7	14.1	8.2	1.4	0.9
NASA	NASA	46.0	11.2	11.4	1.9	2.0
NASA	PA	58.4	13.1	12.5	1.5	0.7
NASA	PB	50.2	19.4	9.1	1.1	0.7
SA	PB	53.7	12.7	9.7	1.3	1.1
SB	PB	51.7	14.5	14.5	1.5	2.2
SC	PB	51.7	13.8	8.2	1.6	1.2

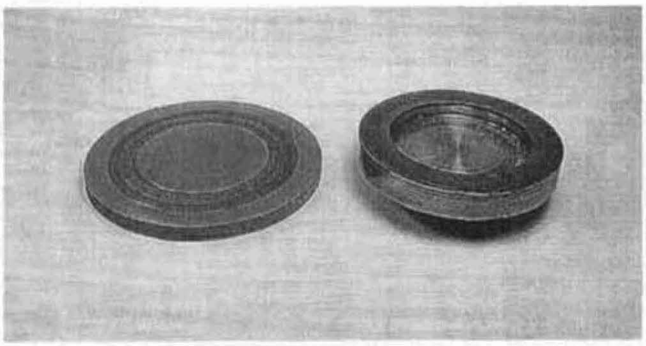


Fig. 3—Example PS304-coated steel disk (left) and washer surface of Inconel X-750 ring following thrust-washer testing, with circular track worn into PS304 coating.

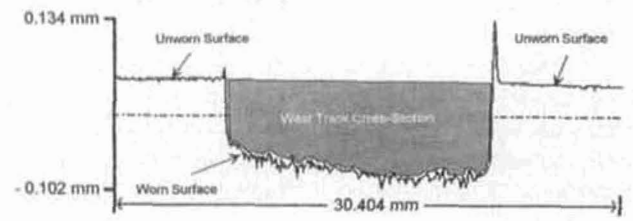


Fig. 4—Example stylus profile taken across PS304 wear track, illustrating wear track cross-sectional area.

fluoride fines, as found in PA also experiencing flow difficulties, a combination that may apparently lead to a 'jamming' of the mixture.

X-Ray Fluorescence characterization of PS304 coatings sprayed from three of the candidate powders is shown in Table 2. These characterizations are not exact quantitative compositions, but are instead intended for qualitative comparison against a NASA control 'standard'. This standard is a reference that would be expected if all constituents were deposited in proportion to their presence in the initial powder, thus rough comparison will indicate whether any constituents are deficient or overly abundant in sprayed coatings. Note even in the standard that compositions

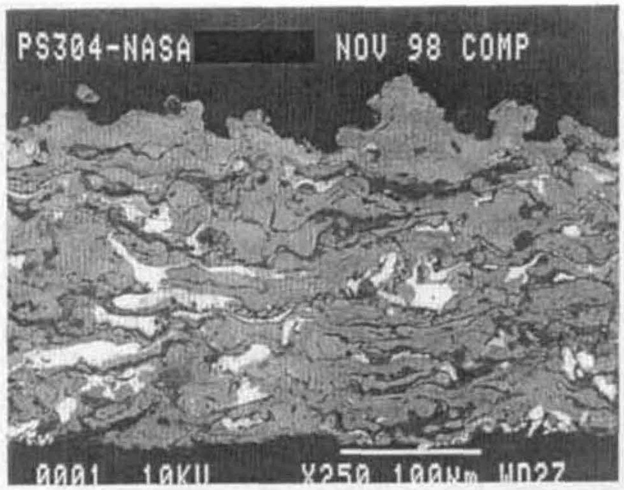


Fig. 5—Backscattered electron image of an example PS304 coating atop substrate at bottom, and unground surface at top.

do not sum to 100%, as attempts are made to account for factors such as the insensitivity of the technique to low atomic number elements such as fluorine and oxygen. Despite reports of potential loss of barium fluoride and calcium fluoride solid lubricants during plasma spraying, for example (Liu, et al. 1993), these results suggest the high-temperature solid lubricant remains intact within the coating. Figure 5 shows a backscattered electron image of an example PS304 coating section, with particle 'splats' generally parallel to the substrate surface. Compositional contrast causes silver (highest atomic number constituent) to be bright while chrome oxide (lowest average atomic number constituent) appears dark gray. The plentiful nichrome binder is medium gray, as is the eutectic fluoride of similar average atomic number. Plasma-sprayed coatings typically have porosity in the 5-20% range (Tucker, 1990), and during the preparation of coating cross-sections for microscopic inspection such pores are filled with epoxy, whose very low average atomic number causes these pores to appear black.

Volumes worn from coatings sprayed using the three PS304 powders at NASA Glenn Research Center during 30 minute sliding tests are represented in a bar graph, Fig. 6. Generally disks were coated in sets of four, with one being used for each combination of contact pressure (20 or 40kPa) and temperature (ambient or 500°C). In cases where sufficient coating remained after a test, the coating was ground back and refinished for a repeat test under the same conditions. In such cases bar height represents the average wear volume, with wear volumes from each of the two repeat tests indicated by the top and bottom of an error bar placed about the average bar height. In the case of powder PA, where flow difficulties only allowed one disk to be coated, all tests were run on that single disk. Following the first three tests, the coating remaining was insufficient to regrind and conduct the remaining 40kPa/ambient temperature test.

Wear of the three PS304 mixtures sprayed at NASA did not appear to change substantially with temperature between ambient and 500°C. As expected, however, greater contact pressures

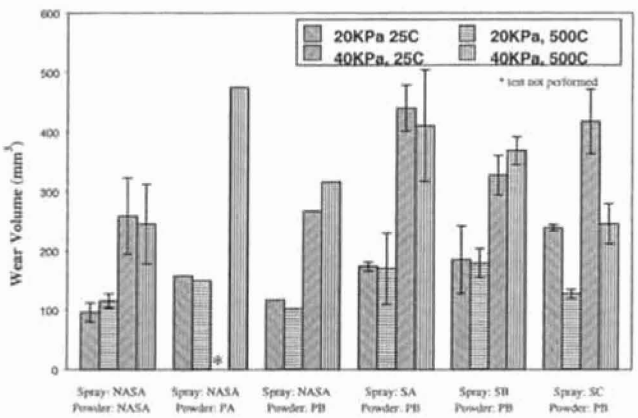


Fig. 6—Wear volumes from PS304 coatings deposited at various spray facilities (NASA, SA, SB and SC) using various powder mixtures (NASA-prepared and RPI-prepared PA or PB) sliding against Inconel X-750 during thrust-washer tests at various combinations of contact pressure (20 or 40kPa) and temperature (ambient or 500°C).

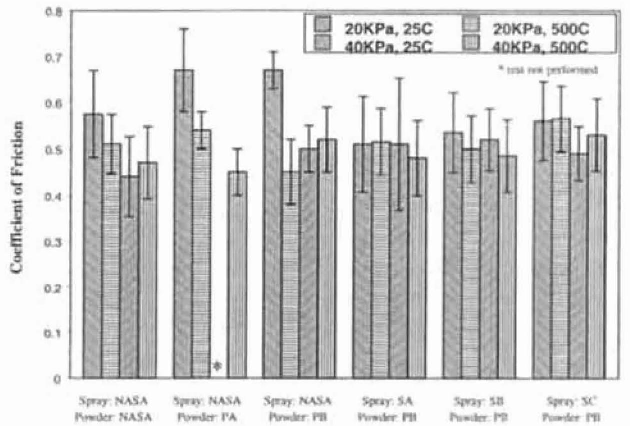


Fig. 8—Friction coefficients of PS304 coatings deposited at various spray facilities (NASA, SA, SB and SC) using various powder mixtures (NASA-prepared and RPI-prepared PA or PB) sliding against Inconel X-750 during thrust-washer tests at various combinations of contact pressure (20 or 40kPa) and temperature (ambient or 500°C).

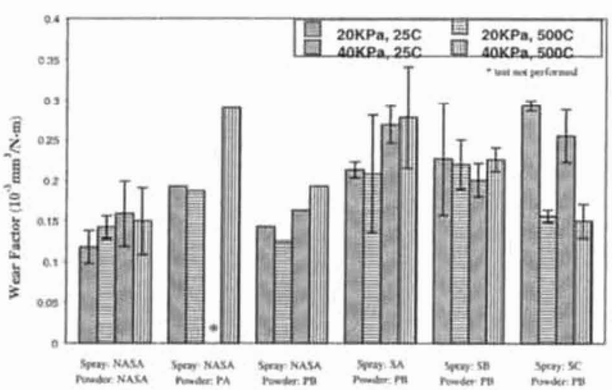


Fig. 7—Wear factors (mm^3/Nm) of PS304 coatings deposited at various spray facilities (NASA, SA, SB and SC) using various powder mixtures (NASA-prepared and RPI-prepared PA or PB) sliding against Inconel X-750 during thrust-washer tests at various combinations of contact pressure (20 or 40kPa) and temperature (ambient or 500°C).

resulted in greater wear. Wear volume was roughly in proportion to contact pressure, causing wear factors (mm^3/Nm) for any single PS304 powder sprayed at NASA to not experience large changes with contact pressure or temperature over the values investigated. As shown in Fig. 7, the NASA control and the RPI-prepared PB powders sprayed by NASA each resulted in coating wear factors of roughly $1.5*10^{-4}$ mm^3/Nm, while coatings produced with powder PA generally experienced slightly higher wear rates. The steady-state friction behavior of these NASA-sprayed coatings, shown in Fig. 8, have coefficients that are generally in μ=0.5 range, and perhaps suggest a friction coefficient which may increase slightly with decreasing contact pressure, especially if at lower temperature.

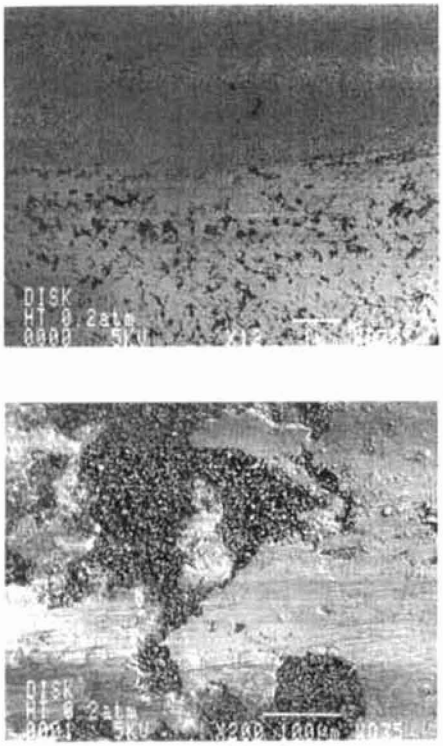
Single PS304 Powder Mixture Deposited at Various Commercial Spray Facilities

In selecting a single powder to evaluate coating variability as a function of commercial spray facility, powder PA (as well as the commercially available formulated PS304 mixture) was ruled out due to potential powder flow difficulties. Of the remaining powders, RPI-prepared PB was selected to emphasize complete independent preparation of resultant coatings by commercially available means. As shown in Table 2, all constituents of powder PB were observed in resultant coatings deposited by each commercial spray facilities SA, SB, and SC.

Wear volumes of coatings deposited by the commercial spray facilities (Fig. 6) in general appear to be greater than those deposited by NASA Glenn Research Center, though only slightly. Again, higher contact pressures lead to greater wear volumes. When expressed in units (mm^3/Nm), coatings sprayed by SA suggest a wear factor that may increase with contact pressure while those sprayed by SC suggest a wear factor that may decrease with temperature increase to 500°C (Fig. 7). These changes, however, are not drastic but two-fold at most. Indeed, PS304 coatings sprayed by SB display independence of wear factor from both contact pressure and temperature over the range investigated. Furthermore, all wear factors of coatings sprayed by the three commercial facilities and tested at the four different combinations of contact conditions are contained within the reasonably narrow range $1.5\text{-}3*10^{-4}$ mm^3/Nm, and PS304 coating wear performance did not vary greatly among the commercial facilities selected. Regarding friction performance (Fig. 8), average coefficients for PS304 coatings deposited by SA, SB and SC all were very nearly μ=0.5 and did not vary systematically with contact pressure or temperature over the range investigated, nor with commercial spray facility.

DISCUSSION

This study has demonstrated the ability of a non-NASA party to formulate PS304 mixtures and have their coatings successfully sprayed and finished, all by commercially available means. Tribological performance of such coatings was similar to those produced at NASA Glenn Research Center using either the same powder or a NASA-prepared powder, with the exception of wear



(a)

(b)

Fig. 9—Secondary electron images of an example wear track worn into PS304 coating during continuous contact thrust-washer test at 500°C and 20kPa contact pressure.
(a) Low-magnification image at edge of wear track (bottom) and unworn PS304 (top).
(b) Higher-magnification image of large recesses in worn PS304, containing fine debris.

factor of NASA-sprayed coatings possibly being slightly lower. Performance of coatings produced completely by commercially available means did not vary greatly between three commercial facilities selected for plasma spraying.

Wear factors of all PS304 coatings deposited by commercial spray facilities using RPI-prepared powder PB remained in the range $1.5\text{-}3*10^{-4}$ mm^3/Nm, whether tested at ambient temperature or 500°C. These wear factors are all within the $1\text{-}4.8*10^{-4}$ mm^3/Nm range of values previously reported by DellaCorte and Fellenstein (1997), sliding PS304-coated disks against Inconel X-750 at temperatures ranging from ambient to 800°C. In those tests, though, friction coefficient only ranged from μ=0.23 to 0.37, considerably less than the typical μ=0.5 values reported here. However, that previous study (DellaCorte and Fellenstein, 1997) utilized hemispherically-tipped Inconel X-750 pins creating concentrated contacts with pressures orders-of-magnitude greater than those existing in the conformal sliding contacts of foil bearings or the thrust-washer geometry used here. Indeed, in more conformal partial arc foil bearing tests (DellaCorte, 2000) nearly constant friction coefficients of approximately μ=0.4 were reported over the entire range of temperatures from ambient to 538°C, more similar to those reported from these thrust-washer tests. Thus it may be argued that PS304 coating wear and friction behavior in foil bearings may be approximated by conformal thrust-washer sliding tests, if conditions are selected to match contact pressure in addition to sliding speed.

However, the thrust-washer tests reported in this study did not sufficiently simulate the surface topography evolution of PS304 coatings that has been observed in air foil bearings. To achieve target load capacity in air foil bearings, it is desired that journal and foil surfaces be smooth (R_q=0.1μm or less) to prevent asperity contact through the air film. Though finish grinding of PS304-coated journals with a 500-grit wheel only provides an average surface roughness of 0.8μm typically, repeated high-temperature start-stop cycling as occurs during endurance testing of a foil bearing produces a run-in surface with a polished glossy dark gray appearance with average roughness reduced to the 0.05 to 0.1μm range (Radil and DellaCorte, 2002). Upon completion of thrust-washer tests reported in this study, increased roughness of typically R_q>2μm were instead measured on worn PS304. Figure 9(a) is a low-magnification image of the inside edge of a wear track worn into a PS304 coating during thrust-washer testing, neighboring the inner unworn region. In that unworn region, fine surface pits from coating porosity and possibly eutectic fluoride pullout during finishing are observed. However, within the wear track, large recesses with dimensions across of 100μm or more have been formed. Upon closer inspection (Fig. 9(b)) these are seen filled with fine debris worn from neighboring flat contact regions.

In foil bearing application PS304 contact is intermittent. For example, in proposed general aviation propulsion turbine engine applications, the PS304 will be separated from the foil by a high-temperature air film for periods on the order of an hour between sliding contacts at startup and shutdown. This intermittent nature of contact has also been approximated in foil bearing tests at NASA Glenn Research Center (DellaCorte, et al. 1999, DellaCorte, 2000), where for each cycle, the short durations (~1s) of sliding contact at startup and shutdown are separated by a ~12s period of the PS304-coated journal riding on an air film from liftoff to touchdown. It is hypothesized that this intermittent nature of sliding contact is critical to the evolution of smooth PS304 that is observed in foil bearings. The noted color change, to dark gray, is indicative of surface chemical interaction likely occurring between the PS304 and air lubricating film, while subsequent foil sliding contact provides a mechanical polishing action.

The continuous nature of contact during thrust-washer tests reported here would not provide periods for formation of surface reaction films in the absence of competitive removal due to sliding wear. In an attempt to replicate PS304 surface evolution observed in foil bearings, a thrust-washer test with 4s of loaded (20kPa) sliding contact alternating with 56s of coating/washer separation in 500°C air was performed with RPI-prepared PS304 powder (PB) sprayed at NASA. The test was conducted for 450 loading/unloading cycles to achieve the same sliding distance as in previous 30-minute tests of continuous contact, with the test periodically halted to characterize surface roughness along the sliding direction. The PS304 surface, which was finished with 600 SiC paper to approximately R_q=1μm, roughened over the first 3km of sliding to R_q>2μm but then gradually smoothed with increasing cycles of intermittent sliding contact. The generation of smoothened PS304 regions under intermittent contact can clearly

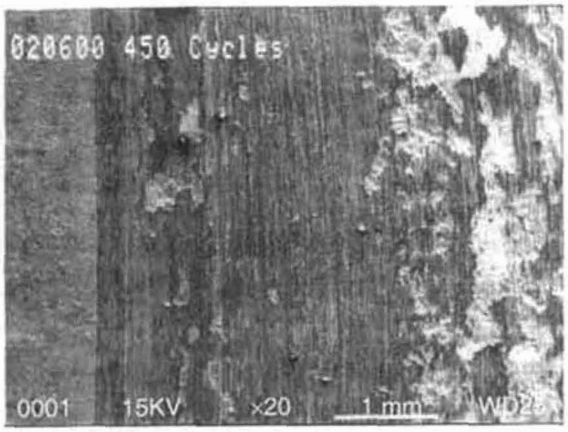


Fig. 10—Secondary electron images of wear track worn into PS304 coating during intermittent contact thrust-washer test at 500°C and 20kPa contact pressure. Low-magnification image at edge of wear track (right) and unworn PS304 (left).

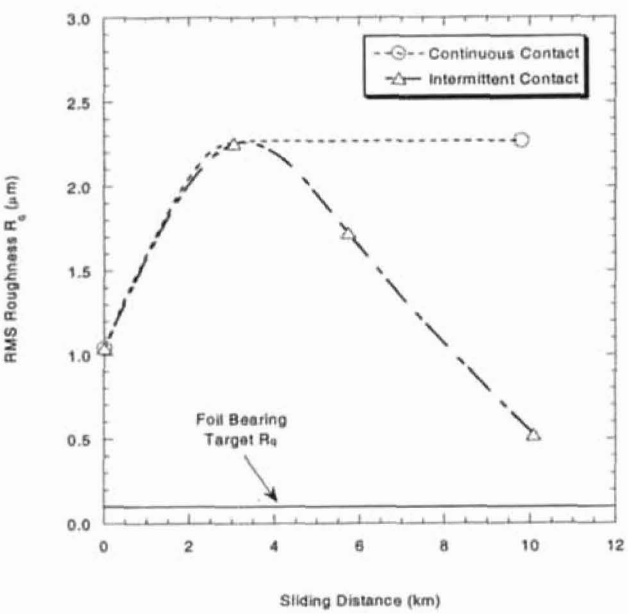


Fig. 11—Roughness of PS304 coating as a function of sliding distance during intermittent contact thrust-washer test at 500°C and 20kPa contact pressure. Also noted are roughness produced during typical continuous contact thrust-washer test at same temperature and pressure, as well as R_q=0.1μm target roughness of PS304 coatings for foil bearing applications, which is achieved during run-in under cyclic start/stop high-temperature operation.

be seen through comparison of the wear track in Fig. 10 to that previously shown from continuous contact in Fig. 9(a). By 450 loading/unloading cycles (10km of sliding) roughness had attained R_q=0.5μm, as shown in Fig. 11, and was still diminishing as rough recessed regions formed during the initial 3km of sliding cycles continue to be replaced by smoothed PS304 surface. The PS304 wear factor during this intermittent contact test, $1.8*10^{-4}$ mm^3/Nm, remained similar to those observed in continuous contact tests. Though the chemistry of PS304 surface smoothening during high-temperature intermittent sliding contact is not fully understood at this time, it has been noted by Energy-Dispersive X-ray Spectroscopy that chromium/nickel ratio is higher in these surfaces when compared to that observed from unworn or continuously worn surfaces. DellaCorte (2000) has reported similar enhancement of chromium in PS304 surfaces exposed to cyclic start/stop contact of partial-arc foil bearings at 538°C. While such sliding-induced polishing during intermittent contact is important to current understanding of foil bearing operation, the development of coating deposition and finishing processes that do not induce porosity or grain pullout remains an important challenge, so that PS304 roughness of R_q<0.1μm and full load capacity may be realized immediately from the onset of foil bearing operation.

CONCLUSIONS

1. Independent production of self-lubricating PS304 coatings, including powder mixture preparation, plasma spray deposition, and surface finishing, completely by commercially-available means has been successfully demonstrated.
2. Friction and wear performance of PS304 coatings originating from a single powder mixture, as measured in thrust-washer sliding tests, did not vary greatly among three different commercial plasma spray facilities selected for deposition.
3. Friction and wear performance of PS304 coatings evaluated in thrust-washer tests may be representative of that expected in foil bearings, provided test contact pressure is simulative of application.
4. To achieve the PS304 surface smoothening effect that is noted in high-temperature air foil bearings subject to cyclic start/stop operation, thrust-washer tests must be conducted with intermittent, as opposed to continuous, sliding contact.

ACKNOWLEDGMENTS

This project was supported under a NASA STTR Phase II award NAS3-97206 to Mohawk Innovative Technology Inc., with RPI serving as subcontractor to MiTi. The authors wish to particularly acknowledge the guidance and support of Hooshang Heshmat and Mohsen Salehi of Mohawk Innovative Technology Inc. during the course of this project, as well as Pat Benoy of St. Louis University who performed the preliminary Phase I portion of this project. The assistance of Brian Edmonds and Victor Lukaszewicz of NASA Glenn Research Center in the preliminary plasma spraying of disks and X-Ray Fluorescence spectroscopy, respectively, is also greatly appreciated. Finally, the authors also wish to thank Andy Korenyi-Both of Hohman Plating & Manufacturing, Klaus Dobler of St. Louis Metallizing, and Bob Johnson of General Electric Energy Services for their cooperation in commercial plasma spraying of PS304.

REFERENCES

(1) Agrawal, G. L. (1998), "Foil Air Bearings Cleared to Land," *Mech. Eng.*, **120**, pp 78-80.
(2) Buss, W. (2000), "Running on Air…Bearings," *Lubr. Eng.*, **56**, pp 15-19.
(3) Chen, C. -I. (1997), "Typical Lubricating Oil Properties," *Trib. Data Handbook*, CRC Press, New York, Booser, E. R., ed., pp 3-33.
(4) DellaCorte, C. and Fellenstein, J. A. (1997), "The Effect of Compositional Tailoring on the Thermal Expansion and Tribological Properties of PS300: A Solid Lubricant Composite Coating," *Trib. Trans.*, **40**, pp 639-642.

(5) DellaCorte, C. and Laskowski, J. A. (1997), "Tribological Evaluation of PS300: A New Chrome Oxide-Based Solid Lubricant Coating Sliding against Al_2O_3 from 25°C to 650°C," *Trib. Trans.*, **40**, pp 163-167.

(6) DellaCorte, D., Valco, M. J., Radil, K. C. and Heshmat, H. (1999), "Performance and Durability of High Temperature Foil Air Bearings for Oil-Free Turbomachinery," *NASA Technical Memorandum*, **TM-1999-209187**.

(7) DellaCorte, C. (2000), "The Evaluation of a Modified Chrome Oxide Based High Temperature Solid Lubricant Coating for Foil Gas Bearings," *Trib. Trans.*, **43**, pp 257-262.

(8) Liu, G. H., Robbevalloire, F., Gras, R. and Blouet, J. (1993), "Improvement in Tribological Properties of Chromium Oxide Coating at High Temperature by Solid Lubricants," *Wear*, **160**, pp 181-189.

(9) Radil, K. C. and DellaCorte, C. (2002), "The Effect of Journal Roughness and Foil Coatings on the Performance of Heavily Loaded Foil Air Bearings," *Trib. Trans.*, **45**, pp 199-204.

(10) Sliney, H. E. (1974), "Plasma-Sprayed Metal-Glass and Metal-Glass-Fluoride Coatings for Lubrication to 900°C," *ASLE Trans.*, **17**, pp 182-189.

(11) Sliney, H. E. (1986), "The Use of Silver in Self-Lubricating Coatings for Extreme Temperatures," *ASLE Trans.*, **29**, pp 370-376.

(12) Tucker, R. C. (1990), "Thermal Spray Coatings," *ASM Handbook Volume 5: Surface Engineering*, ASM International, Metals Park, pp 497-509.