DOE/NASA/50306–8
NASA TM–107056

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Under Interagency Agreement DE-AI01-91CE50306

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Abstract

This paper introduces PS300, a plasma sprayed, self-lubricating composite coating for use in sliding contacts at temperatures to 800°C. PS300 is a metal bonded chrome oxide coating with silver and BaF_2/CaF_2 eutectic solid lubricant additives. PS300 is similar to PS200, a chromium carbide based coating; which is currently being investigated for a variety of tribological applications. In pin-on-disk testing up to 650 °C, PS300 exhibited comparable friction and wear properties to PS200. The PS300 matrix, which is predominantly chromium oxide rather than chromium carbide, does not require diamond grinding and polishes readily with silicon carbide abrasives greatly reducing manufacturing costs compared to PS200. It is anticipated that PS300 has potential for sliding bearing and seal applications in both aerospace and general industry.

Introduction

High temperature solid lubrication continues to be a research topic of considerable need. Demands for higher operating temperatures, lower cost, longer life and better performance drive the search for, and development of, new solid lubricant materials. (Erdemir, Fenske, et al., 1990 and Aabinski, Day, et al., 1994). One solid lubricant material system receiving attention is PS/PM200 (Sliney, 1990). This metal bonded chromium carbide based material, developed at the author's laboratory, has solved a wide range of lubrication problems in prototype hardware applications such as process control valve stems, dry running stirling engine cylinders, foil air bearings, rotating face valves and butterfly valve stems (DellaCorte, Wood, 1994).

PS/PM200 is a composite of a wear resistant nickel-cobalt bonded chrome carbide with BaF_2/CaF_2 eutectic and silver which act as high and low temperature lubricants, respectively (DellaCorte, Wood, 1994). The "PS" designates the use of the material as a plasma sprayed coating and the "PM" designates a powder metallurgy product. Further details regarding PS/PM200 have been extensively published in the literature (DellaCorte, Sliney, et al., 1992). Briefly, PS/PM200 composites function by providing a tough, wear resistant chrome carbide matrix which is self-lubricated by low shear strength solid lubricants. The silver provides low temperature lubrication and at higher temperatures, where silver is too soft to support an appreciable load, the fluoride eutectic phase softens and behaves plastically to reduce friction (Sliney, Strom, et al., 1965). Due to its composite nature, PS/PM200 can solve lubrication problems which must operate over a wide temperature range from sub-ambient to 900 °C, in air, inert or reducing environments. Because of these unique capabilities, PS/PM200 composites enable simplified designs which do not rely on extensive sealing and cooling schemes to allow the use of conventional oils, greases or other solid lubricants (e.g. graphite, MoS_2, PTFE).

A major drawback of PS/PM200, however, is cost. The matrix phase, a nickel-cobalt bonded chrome carbide, is highly processed and an expensive major constituent. The presence of chrome carbide necessitates costly diamond grinding prior to service. Furthermore, at extreme temperatures (+800 °C) in air, chrome carbide oxidizes; degrading the friction and wear properties and causing slight dimensional swelling of the PM composite form of the material (Bemis, Bogdanski, 1994).

To overcome these disadvantages, a new material system, PS300, has been developed at NASA Lewis Research Center. PS300 mirrors the composition of the PS200 series of composites except that the chrome carbide matrix has been replaced with a nickel-chromium/chromium oxide matrix. The lubricants, like PS200, are silver and the fluoride eutectic. The exact composition by weight and volume percent for both PS200 and PS300 are given in Table I.

Several manufacturing and performance advantages are realized by basing PS300 on chrome oxide. One is that chrome oxide is readily polished and ground by SiC tools, eliminating the need for diamond finishing. Another benefit is that since chrome oxide is already in an oxidized state, the PS300 coating has the potential for better tribological performance in air atmospheres at elevated temperatures. Furthermore, the nickel-chrome/chrome oxide combination is less costly than the pre-bonded chrome carbide powder used as the feedstock for PS200. Finally, at elevated temperatures, chrome oxide is itself a good solid lubricant providing the potential for improved tribological properties (Liu, Gras, et al., 1993 and Liu, Robbevalloire, et al., 1993).

The purpose of the research program described here is to characterize the preliminary friction and wear properties of PS300. Friction and wear tests are conducted using plasma spray coated disks sliding against superalloy, hemispherically tipped pins in a high temperature pin-on-disk tribometer. Direct comparisons will be made to PS200 tribological performance and future research and potential applications will be discussed.

Materials and Specimen Properties

The detailed compositions, by weight and volume percent, of PS300 and PS200 are given in Table I. PS300 is comprised of a wear resistant matrix of nickel-chrome bonded chromium oxide, silver, a low temperature lubricant and BaF_2/CaF_2 eutectic, a high temperature lubricant. The PS300 coating is formed by plasma spraying a simple powder blend of the constituents. Powder particle sizes range from 20-150µm and the plasma spray parameters used to apply the coating are given in Table II. The coating is characterized using cross section metallography, electron microscopy and x-ray fluorescence (for bulk composition analysis). Figure 1 shows some representative cross-section micrographs of the coating. The plasma spray process produces a fairly uniform "splat" type coating with some residual low level porosity.

To prepare a disk sample, a 0.5mm thick PS300 coating mixture is plasma sprayed onto a grit blasted disk surface which has been previously coated with a 0.1mm thick NiCr (80/20) bond coat layer. The resulting coating is then ground to a final thickness of about 0.3mm. The ground roughness is about 0.5µm rms. To achieve a smoother finish 600 grit silicon carbide abrasive paper and water is used to lightly polish the surface to a finish of 0.1-0.2 µm rms. The preparation details of PS200 can be found in DellaCorte, Sliney (1987).

The pin specimens are machined from Inconel X-750, precipitation hardened to RC 32-34. The pins are 9.5 mm in diameter, 25 mm long and are hemispherically tipped with a 4.76 mm radius of curvature. Both the pin and disk specimens are thoroughly cleaned with pure ethyl alcohol, followed by scrubbing levigated alumina and water. The cleaned specimens are then rinsed with deionized water and air dried prior to testing.

Tribological Testing:

The specimens are tested in a pin-on-disk test rig described in detail in DellaCorte, Sliney (1987). The pin wears a 51 mm diameter track into the rotating test disk which is inductively heated to the desired test temperature. The air atmosphere is controlled and maintained at 50% R.H. at 25 °C. Selected test temperatures were 25,500, and 650 °C. Test velocity was 370 rpm (1 m/s) and the load was 4.91N. These conditions were chosen to simulate the start-up/shut-down conditions for foil air bearing applications.

Friction is monitored continuously during the tests which last 30 minutes. Wear is measured using optical microscopy (for pin wear scars) and stylus surface profilometry. Three repeat tests are conducted for each test condition. Data uncertainties presented are one standard deviation.

Results and Discussion

The friction and wear results are summarized in Table III and shown graphically in Figure 2, 3, and 4. Figure 5 shows the surface morphology of a PS300 wear track and mating pin after sliding at elevated temperature.

The friction coefficients ranged from 0.23 to 0.31 for the PS300. This is about 30% lower than for PS200 except at 650 °C where both coatings exhibit the same level of friction (see figure 2).

In terms of coating wear, both the PS300 and PS200 coatings have similar wear factors which ranged from about $5x10^{-5}$ mm^3/N-m at 25 °C to about $7x10^{-4}$ mm^3/N-m at 650 °C. These wear factors are considered low to moderate (DellaCorte, Sliney, 1987).

Wear of the Inconel X-750 counterface pins shows discrimination between the two coatings. At 25°C and 650 °C, the PS300 pin wear factor is 3 to 4 times greater than PS200. At 500°C, however, the pin wear factors are about the same for both coatings (see figure 3). Clearly, from the data shown, both coatings provide similar friction and wear properties. Baseline testing of self-mated Inconel X-750 under the same test conditions resulted in high friction (≈0.6) at room temperature and severe galling at elevated temperatures.

Based upon these preliminary friction and wear results, it appears that PS300 is a viable substitute for PS200 coatings in applications where PS200 has been successful. Such applications include back-up journal lubrication for foil bearings, rotary face seals, valve stems for poppet and butterfly valves and dry running limited life piston ring/cylinder wall contacts (Sliney, 1990; DellaCorte, Wood, 1994; and Sliney, 1988).

There are, however, additional benefits in using the PS300 coating. One is processability. In the author's plasma spray facility, PS300 was found to be easier to spray than PS200, having less of a tendency to clog the spray gun ports. Composition and general coating quality (density, uniformity, etc.) were less sensitive to plasma spray process variations than with PS200. The specific reasons for this improvement are unclear and are under investigation.

Another significant benefit of the PS300 is in the finishing process. PS300 was readily ground using SiC grinding tools. Final polishing was accomplished by hand using conventional sandpaper (SiC-grit 600) and water yielding smooth bearing surfaces. This "polishability" advantage over the previous coating is due to the nature of the Cr_2O_3 matrix which is softer than the Cr_3C_2 matrix used in PS200 which requires diamond finishing. Yet, despite being softer, PS300 displays coating wear comparable to PS200. This is probably due to the lubricating effects of the Ag and BaF_2/CaF_2 additives (Sliney, Storm, 1965 and DellaCorte, Sliney, 1987). Whatever the reasons, ease of finishing is a highly desirable coating quality.

Concluding Remarks

This paper presents preliminary tribological data on PS300, a new plasma sprayed composite self lubricating coating. PS300 exhibits tribological properties similar PS200 which has experienced successful application in a wide variety of prototype applications. PS300 provides advantages over PS200; most notably, added ease of plasma spraying and finishing using conventional SiC grinding. These attributes may lead to significantly lower costs and more widespread use than the PS200 coating has achieved. Future efforts will be aimed at determining the effects of composition variations on coating performance and establishing limits (temperature, load, speed, etc.) under which the coating can provide tribological benefit.

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TABLE I.—COMPOSITION BY WEIGHT AND VOLUME PERCENT OF PS300 AND PS200

Coating	Density	Constituent, wt% (vol%)			
Designation	P, g/cm^3	*NiCr-Cr_2O_3	+Ni-Co-Cr_3C_2	Ag	BaF_2/CaF_2
PS300	5.81	80 (80.3)	-------------	10 (5.5)	10 (14.2)
PS200	6.75	----------	80 (77.1)	10 (6.4)	10 (16.5)

*By wt% contains 80 Cr_2O_3, 16Ni, 4Cr.

+By wt% contains 54 Cr_3Cr_2, 28Ni, 12Co, 2Mo, 2Al, 1B, 1 Si.

TABLE II.—PLASMA SPRAY PARAMETERS
[Used to apply PS300 coatings]

Parameter	Value
Current	600 amps
Voltage	30–32 volts
Standoff distance	8–10 cm
Argon Arc gas flow rate	35 sl/min
Powder flow rate	≈1 kg/hr
Powder gas flow rate	0.4 m^3/hr

TABLE III.—FRICTION AND WEAR SUMMARY
[1m/s sliding velocity, 4.9N load, 30 min test, air atmosphere at 50% R.H. at 25 °C]

Disk coating	Pin material	Temperature, °C	Friction coefficient	Kpi, mm^3/N-m	Kdisk, mm^3/N-m
PS300	INCX750	25°C	0.23±0.05	$3.9\pm0.5\times10^{-5}$	$6.6\pm2.5\times10^{-5}$
PS300	INCX750	500°C	0.29±0.04	$1.3\pm0.3\times10^{-5}$	$3.9\pm0.3\times10^{-4}$
PS300	INCX750	650°C	0.31±0.01	$3.1\pm0.8\times10^{-5}$	$7.1\pm1.6\times10^{-4}$
PS200	INCX750	25°C	0.37±0.04	$1.0\pm0.2\times10^{-5}$	$5.0\pm0.8\times10^{-5}$
PS200	INCX750	500°C	0.40±0.05	$1.2\pm0.4\times10^{-5}$	$4.1\pm1.5\times10^{-4}$
PS200	INCX750	650°C	0.30±0.04	$1.4\pm0.5\times10^{-5}$	$6.5\pm2.1\times10^{-4}$

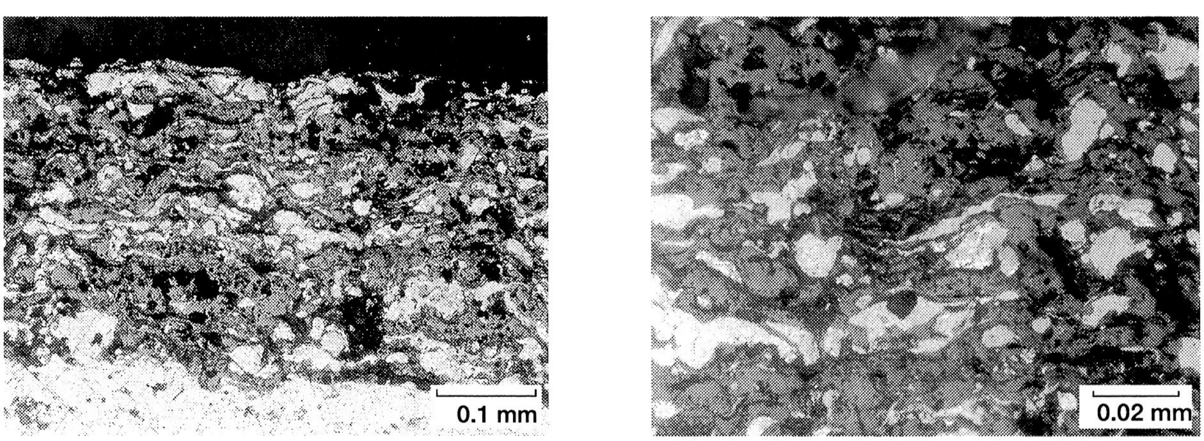

Figure 1.—Cross-sectional optical micrographs of PS300 showing plasma sprayed composite coating structure.

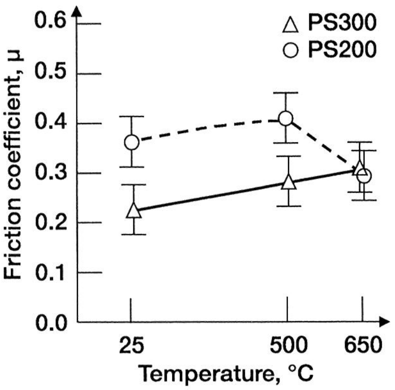

Figure 2.—Friction coefficient vs. temperature for PS300 coatings sliding against Inconel X-750 pins. 4.9 N load, 1 m/s sliding velocity, air atmosphere.

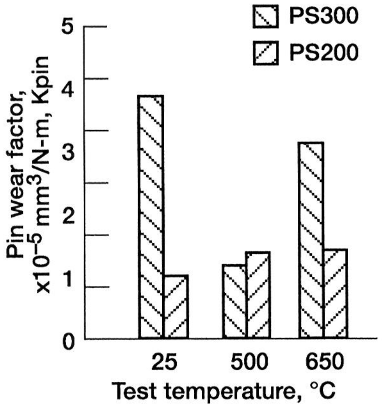

Figure 3.—Wear factor for Inconel X-750 pins sliding against PS300 and PS200 coatings.

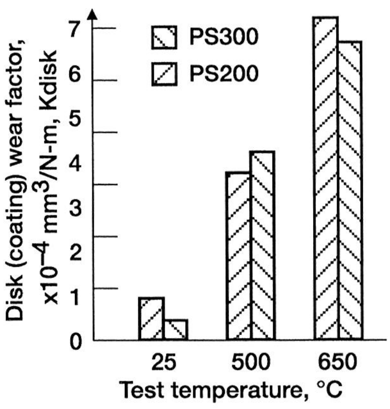

Figure 4.—Wear factor for PS300 and PS200 coatings sliding against Inconel X-750 pins.

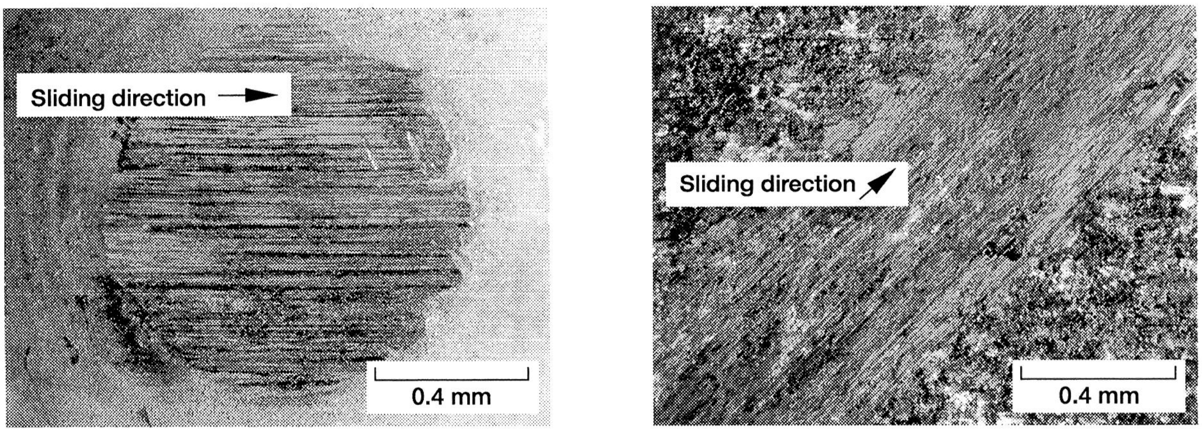

Figure 5.—Photomicrographs of PS300 vs. Inconel X-750 specimens after testing at 500 °C. (a) Pin wear scar. (b) Disk wear track.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 1995

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Preliminary Evaluation of PS300: A New Self-Lubricating High Temperature Composite Coating for Use to 800°C.

5. FUNDING NUMBERS
WU–505–63–5A

6. AUTHOR(S)
C. DellaCorte and B.J. Edmonds

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–9907

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107056
DOE/NASA/50306–8

11. SUPPLEMENTARY NOTES
Prepared for the Energy Week Conference and Exhibit cosponsored by API and ASME, Houston Texas, January 29–February 2, 1996 under interagency Agreement DE–AI01–91CE50306. Responsible person, C. DellaCorte, organization code 5140, (216) 433–6056.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 23

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE
DOE Category UC–23

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

This paper introduces PS300, a plasma sprayed, self-lubricating composite coating for use in sliding contacts at temperatures to 800°C. PS300 is a metal bonded chrome oxide coating with silver and BaF_2/CaF_2 eutectic solid lubricant additives. PS300 is similar to PS200, a chromium carbide based coating, which is currently being investigated for a variety of tribological applications. In pin-on-disk testing up to 650°C, PS300 exhibited comparable friction and wear properties to PS200. The PS300 matrix, which is predominantly chromium oxide rather than chromium carbide, does not require diamond grinding and polishes readily with silicon carbide abrasives greatly reducing manufacturing costs compared to PS200. It is anticipated that PS300 has potential for sliding bearing and seal applications in both aerospace and general industry.

14. SUBJECT TERMS
Tribology; Lubrication; Coating; High temperatures

15. NUMBER OF PAGES
09

16. PRICE CODE
A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	