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Short communication

Thrust-washer tribological evaluation of PS304 coatings against Rene 41

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Abstract

To prevent surface damage, roughening, and wear of foil bearings during startup and shutdown conditions when speeds become insufficient to provide hydrodynamic air films, plasma-sprayed solid lubricant PS304 has been used as a journal coating. With increasing demands for operational bearing temperature, Rene 41 is one candidate material that may be considered as a replacement for current Inconel X-750 foil materials. In this study, the tribological behavior of plasma-sprayed PS304 coatings, as well as potentially smoother HVOF-sprayed PS304 coatings, was characterized against Rene 41 and Inconel X-750 counterfaces in thrust-washer tests. Tribological behavior of Rene 41 against plasma- and HVOF-sprayed PS304 coatings, and uncoated 13-8 stainless steel, at 538 °C was found to be equivalent to the high-temperature behavior of Inconel X-750 against the same surfaces. Typical wear factors found for the coatings were in 1.5–3 × 10^{-4} mm^3/N m range, while the coefficients of friction were generally about 0.4.

Keywords: Self-lubricating; Composite; Coating; Plasma-sprayed; High-temperature; Air bearing

1. Introduction

A foil air bearing is a self-acting hydrodynamic bearing that uses ambient air as a lubricant without any external pressurization. Unlike bearings comprised of rigid bulk components, foil air bearings operate on a structure of thin flexible foils. The bearing consists of a stationary shell containing sheet metal foil layers that provide compliance and tolerance to misalignment, distortion, and debris. The layers trap the ambient air between the rotating shaft and innermost 'top' foil, which is supported by an underlying bump foil layer as a foundation. This flexible foundation assists the necessary elastic deflection of the bearing sleeve inner surface required to attain full surface separation by a hydrodynamic air lubricating film.

Operation of foil bearings where the journal never contacts the foils would be ideal, however this only happens when the steady state high-speed design conditions are attained. In addition to situations of bearing overload, contact and corresponding wear and higher friction occur during the startup and shutdown conditions where low speeds no longer provide a full hydrodynamic air film. During startup, where the air film is evolving and is only partial, resultant journal/foil contact will occur at modest pressures associated with the compliant behavior of the foils used. These contacts can induce wear and damage to the surfaces, requiring introduction of a solid lubricating agent to lessen these occurrences and the corresponding roughening that would render attainment of a full hydrodynamic film more difficult during subsequent use.

The development of such high temperature self-lubricating composite coatings initiated at NASA three decades ago. The current form is the plasma-sprayed 300 series, having a nichrome binder matrix, wear-resistant chrome oxide hardener, and high and low temperature solid lubricants in the form of eutectic barium fluoride/calcium fluoride and silver, respectively. PS300 developed from the 200 series by replacing the harder chrome carbide with chrome oxide, eliminating the need for expensive diamond grinding to finish coating surfaces [1]. An additional advantage of the chrome oxide is its resistance to additional oxidation at high temperatures approaching 800 °C, compared to chrome carbide that may gradually swell slightly due to oxidation

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and reduce the bearing clearance. For the PS304 coating of this series the two major constituents, binder and hardener, of the composite coating are used in a 3:1 ratio (60% nichrome and 20% chrome oxide by weight) to provide a coefficient of thermal expansion ($\sim 12 \times 10^{-6}/^{\circ}$C) similar to common substrate materials such as 13-8 stainless steel. The remaining portion is comprised of the low temperature solid lubricant silver (10% wt) and high temperature solid lubricant eutectic barium fluoride/calcium fluoride (10% wt), intended to flow and transfer over surfaces during sliding contact forming low shear strength surface films.

PS304 coatings have been used in a recent generation of foil journal bearings demonstrating high steady-state values of load bearing coefficient, D, of about 1, as defined in the 'rule of thumb' model proposed by DellaCorte and Valco [2]. Radil and DellaCorte reported lower load bearing coefficients in the initial tests of the coated surfaces, attributed to the higher values of roughness existing prior to the transfer lubrication and smoothening which takes place during run-in [3]. Depending on the surface finishing technique, the plasma-sprayed PS304 surfaces as-finished have typical rms roughness in the range of $R_q = 0.25–0.8$ μm. Desired roughness corresponding to performance at a high load bearing coefficient approaching 1 is in the range of $R_q = 0.05–0.1$ μm. Kim et al. reported roughness of high velocity oxyfuel (HVOF) sprayed PS304 coatings to be as low as $R_q = 0.05$ μm once polished, enabled by reduced coating porosity [4]. Such HVOF-deposited coating may therefore offer foil bearings high load bearing coefficient as-finished, without necessity of additional run-in.

Inconel X-750 has generally been used as the foil material in bearings where it is mated against PS304 journal coatings, and such foil bearings have been successfully demonstrated to 650 °C. Above this temperature the mechanical properties of Inconel X-750 begin to diminish more sharply. However even at 815 °C Rene 41 maintains values of elastic modulus, yield strength and ultimate strength exceeding those of Inconel X-750 at its 650 °C demonstration temperature. Thus, with prospects for eventual higher temperature application, in this study Rene 41 was investigated as a candidate foil material against plasma- and HVOF-sprayed PS304 coatings in preliminary thrust-washer sliding tests whose conformal geometry enables modest contact pressures such as those found in foil bearings.

2. Experimental procedure

PS304 feed powder constituents were obtained as particles from commercial suppliers, with particle sizes as described in Kim et al. [4]. In the case of HVOF, which was observed to be less effective than plasma spray in its heating of feed powder, maximum particle size was reduced from 70 to 30 μm for the nichrome and 44 to 30 μm for the chrome oxide in order to attain melting and successful coating deposition. The powder mixture was prepared in 2.3 kg batches, with nichrome (60%), chrome oxide (20%), Ag (10%), and eutectic BaF_2/CaF_2 (10%), by weight. Upon weight measurements of each group of particles to be added to the batch, sieving was performed to eliminate the very small fraction of oversized particles or agglomerates that may potentially pose powder feed or particle melt difficulties during spraying. Following sieving, particles were mixed preliminarily in a plastic bag, then electric V-blender, and finally tumbled in a glass jar. Throughout this process the powder may pick up humidity in air, which can cause agglomeration and flow problems, thus the powder is subsequently placed in a heated oven to drive off such adsorbed water before spraying.

The PS304 powders were deposited as coatings at a commercial spray facility. Two different methods of deposition, plasma spray and HVOF, were utilized at the same facility, with the flame of this HVOF system being hydrogen-fueled. Resulting coatings as-finished have comparatively lower roughness for the HVOF deposition process due to higher density with reduced porosity that is provided by a higher particle velocity [4]. The coatings were deposited onto 13-8 PH Mo stainless steel disks having a diameter of 0.12 m and thickness of 8 mm. Typical as-deposited coating thickness was about 0.4 mm.

PS304 coatings were evaluated in thrust washer tests against Rene 41 machined having a flat washer contact surface with an outside diameter of 96.1 mm and inside diameter of 63.2 mm, and compared to such tests performed previously against Inconel X-750 [4,5]. These nickel-based high-temperature alloys were both obtained from commercial sources, with approximate compositions of primary constituents stated, by weight: Rene 41 (Cr 18–20%, Co 10–12%, Mo 9–10.5%, Ti 3–3.3%, Al 1.4–1.6%, Fe 0–5%, Ni balance); Inconel X-750 (Cr 14–17%, Fe 5–9%, Ti 2.25–2.7%, Al 0.4–1%, Co 0–1%, Ni balance).

Sliding contact was produced by securing a ring within a spindle collet that was rotated at 1200 rpm providing a 5 m/s average ring velocity, for a total test sliding distance of 10 km. Pneumatically loaded PS304 coated disks were brought into continuous contact with the rotating ring at constantly applied normal loads of 84 and 168 N, creating pressures of 20 and 40 kPa distributed over the washer surfaces typical of those found in foil journal bearings. To model high-temperature operation of foil air bearings, three 500 W cartridge heaters are placed beneath the disk assembly to produce bulk disk temperatures of $T = 538$ °C. Between tests Rene 41 counterfaces were lapped with 0.3 μm alumina particles dispersed in diesel oil, and then finished in water by 600 grit abrasive SiC paper. Coated disks were also prepared by wet abrasive paper, in order of 120, 400, and then 600 grit SiC paper. Both Rene 41 and coated surfaces were ultrasonically bathed in methanol prior to testing.

The disk assembly is supported upon the underlying pneumatic load piston by an air bearing. Two radial arms extend from the disk assembly and come in contact with vertical posts that restrict the rotational motion of the disk assembly that would otherwise occur due to the frictional forces