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COATINGS FOR HIGH TEMPERATURE FOIL BEARINGS

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ABSTRACT

High operating speeds and temperatures required for advanced turbomachinery necessitate the development of bearings capable of continuous operation between 3 to 4 million DN at temperatures up to 820°C. Non-contact oil-free bearings such as compliant foil bearings, active magnetic bearings and hybrid foil and magnetic bearings are alternate solutions to the current liquid-lubricated hydrodynamic and rolling element bearings, which have limited life under these extreme conditions. A critical component in these oil-free bearings is the tribological coating system that must be used on the journal and the foil pads to ensure reliable operation during transient periods and start-stop cycles. The purpose of the present investigation was to assess the reliability of tribological coatings being implemented for a large (150 mm diameter) hybrid foil/magnetic bearing. In order to be suitable for use in large turbine engine type applications, the journal coating must accommodate the thermal and centrifugal growth experienced as well as providing the wear life and friction coefficient. Based upon the limitations identified in PS304, this coating is not yet suitable for demanding high temperature and high-speed applications. On the other hand an alternative nickel-chrome based coating applied to the foils versus a shaft with thin dense chrome or a nickel-chrome based coating a has shown excellent characteristics under conditions up to 820°C.

INTRODUCTION

Current state-of-the-art, liquid-lubricated hydrodynamic and rolling element bearings suffer from temperature and speed limitations experienced by advanced turbomachinery. Non-contact bearing systems such as oil-free, high-load compliant foil bearings (CFB), active magnetic bearings (AMB) and hybrid foil and magnetic bearings (HFMB) are alternate solutions for extreme conditions required for the advanced turbomachinery. AMBs with their ability to have high static stiffness provide excellent performance at low speeds where CFB has limited load capacity. Correspondingly, CFBs provide excellent performance at high speed and under transient conditions where AMBs have transient shock and failure mode limitations. The HFMB combines those two advantages and compensates for each bearing's limitations, therefore, providing a high load capacity at all speeds [1-3].

Recent developments in advanced CFBs have begun to address the major limiting factors hindering the use of AMBs and CFBs in the larger regional gas turbine engines, namely the load carrying capacity, shock tolerance, high speed and high temperature operation [4-9]. The scalability of existing CFB designs from sizes ranging from 6 mm to 150 mm required for a wide array of MEMS to megawatt scale turbomachines has more recently begun to be addressed [10]. Beyond scale is the need to address high temperature applications such as gas turbine engines, which have also recently been receiving attention [11-14].

When addressing large-scale, high temperature machinery, true widespread application of CFBs in the 150 mm diameter range, either independently or as part of an HFMB, challenges not present in smaller CFBs arise. For example rotor journal centrifugal and thermal growth can exceed 0.750 mm requiring unique bearing internal design requirements but also placing the journal surface and any applied coatings in a very severe environment. Thus, while large CFBs will require new and innovative designs and manufacturing techniques to address the thermal growth and management of the increasing internal heat generation and the structural stiffness patterns needed to maintain the desired gas film thickness, attention must also be paid to the journal because it is an integral partner in the performance of the CFB. Thus, while the earlier demonstration of the 150 mm diameter CFB represents a technological breakthrough, much needs to be done in the area of tribosystem integration and in the development of a hybrid bearing system capable of operating at temperatures above 650^{0}C and as high as 820°C. The purpose of the present investigation, which is based upon six years test experience with PS304 was to assess the reliability of the tribological coatings used on the journal or runner and the thrust or journal foil bearing.

BEARING COATING REQUIREMENTS

In order to develop effective high temperature foil bearings, new coating combinations that exhibit good high temperature tribological characteristics must be found. Despite the large volume of literature published on high temperature coatings, very little has been written about the tribological characteristics of such coatings in foil bearing application. The scope of the present investigation was to identify improved tribological materials and coatings for use up to 800°C. The main objectives were to allow the foil bearing to be functional from low temperature start-up conditions to the maximum temperatures encountered during operation. Key criteria for the journal or thrust runner coating then was that it must not only have good wear life but must promote good hydrodynamic performance through its ability to be produced with and maintain a smooth surface finish. Additionally, the coating material must be dimensionally stable and have bond strength sufficient to withstand repeated thermal and centrifugal cycling.

Since foil bearings are a class of hydrodynamic bearings that operate on a thin film of air, load capacity increases with speed as self-pressurization of the air film occurs. Furthermore, since load capacity is limited by asperity-to-asperity contact through the air film, the bearing and journal must be designed to avoid asperity-to-asperity. Given that foil bearings typically operate with steady-state minimum film thickness of on the order of 0.5 micrometer, it is desired to have RMS roughness less than Rq=0.05 to 0.1 micrometer for both foil and journal surfaces. Thus to be acceptable, shaft coatings need to meet these surface finish requirements, while also meeting the high operating temperature needs of advanced turbomachinery.

SURFACE FINISH

Extensive work has been conducted on coatings for foil bearings. Bushan and Rusietto [15] evaluated a number of foil and journal coatings, which in some cases, allowed operation to 650 ºC, but the coating life was limited. Initially, DellaCorte and Sliney [16, 17] evaluated a chrome carbide journal coating in partial-arc bearing tests and found good performance. However, later difficulties were exhibited regarding coating reliability and high processing costs. Subsequently, PS304 solid lubricant coating was developed to address the limitations of chrome carbide coating. PS304 plasma-sprayed coating uses a powder mixture consisting of 10 w% silver, 10 w% BaF_2/CaF_2, 20 w% Cr_2O_3 and 60 w% NiCr as binder. Testing at NASA indicated that this coating had potential for application to compliant foil bearings due to its high temperature capabilities. Unfortunately, the porosity of PS304 coatings (as seen in Figure 1) led to a pitted surface upon finishing whose roughness was in the Rq=0.25 to 0.5 micrometer range even if polished. During run-in tests conduced over tens of thousands of high-temperature (650°C) foil bearing start/stop cycles against Inconel X750 foils it was observed that surface roughness gradually approached the target Rq=0.1 micrometer surface finish level. The irony is that this process consumed many foil bearings prior to achieving the glossy surface.

Testing by the authors confirmed the reduction in load capacity due the rough surface as noted in Figure 2. During these tests it was observed that the exact same foil thrust bearing design would produce only 10% of the load capacity when PS304 was used as compared to when thin dense chrome was used on the runner. Radil and DellaCorte [18], confirmed these results, concluding that "without the presence of polished surfaces and low friction surface films, high starting torque and reduced load capacity resulted." Similar tests with foil journal bearings have yet to be completed and may be reported in a later paper once completed.

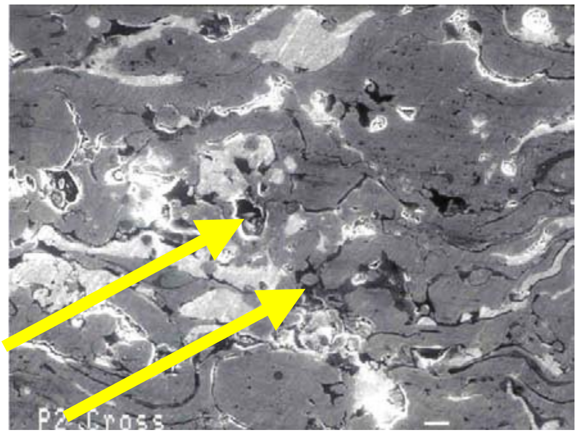

Figure 1. PS034 porosity as applied with powder particles of sizes from 10 to 72 micrometer.

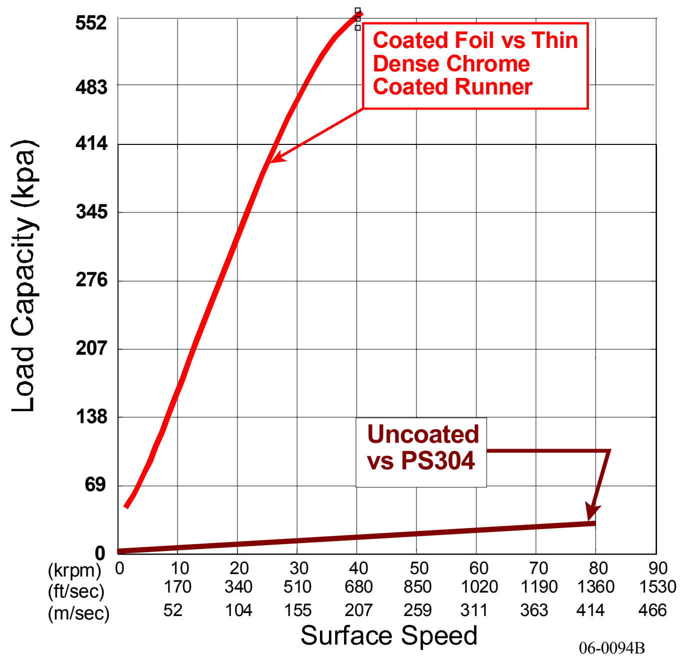

Figure 2. Comparison of thrust foil bearing load capacity for runners coated with thin dense chrome or PS304 vs polyimide coated or uncoated foils

Given this shortcoming, effort was expended to improve the surface finish of PS304 through reduction in particle size and changes to the application process including using the High Velocity Oxy Fuel (HVOF) process. The HVOF deposition of PS304 was attempted under the hypothesis that this higher velocity would lead to augmented compaction and coating density. In an initial attempt using a conventional propylene HVOF fuel, however, sufficient melt of the particles of chrome oxide hardener and nichrome binder was not achieved and these particles simply rebounded from the target substrate leaving a coating of inadequate thickness (only ~10 micrometer) that was primarily composed of the easily-melted silver solid lubricant which exists in the feed powder at only a 10% concentration. To address this shortcoming, a higher HVOF temperature was attempted using hydrogen fuel. Despite the use of H2 fuel, the conventional larger chrome oxide and nichrome particles still didn't melt sufficiently, and the coating remained inadequate to even attempt any form of polishing or finishing. Even though smaller particles were used in earlier plasma-spray depositions, a porous and rough coating characteristic of plasma-spray with conventionally sized PS304 constituent particles resulted (Table 1). As such, the combination of high Temperature HVOF and a reduction in size of chrome oxide (decreased from 10-44 to 5-30 micrometer) and nichrome (decreased from 44-72 to 10-30 micrometer) particles was attempted to hasten particle melting. The combination of small particle and HVOF deposition resulted in a dense thick PS304 coating.

Table 1 RMS surface roughness of PS304 deposited by Plasma Spray or H2-fueled HVOF

Spray	NiCr and Cr_2O_3 particle size	Finishing Method	Measured R_q (μm)		Mean R_q (μm)
Plasma	large	Al_2O_3	0.25	0.38	0.32
		1500 SiC paper	0.26	0.23	0.25
Plasma	small	Al_2O_3	0.43	0.47	0.45
		1500 SiC paper	0.28	0.42	0.35
HVOF	small	Al_2O_3	0.065	0.059	0.062
		1500 SiC paper	0.052	0.046	0.049

For the H2-fueled HVOF deposition using smaller chrome oxide and nichrome particles, the target Rq< 0.1 micrometer was attained by either polishing with 0.3mm alumina particles or 1500 grit SiC abrasive paper, which each provided RMS roughness in the Rq=0.05-0.06 micrometer range. Using 9mm and 15mm diamond polishing compounds, RMS roughness of Rq=0.055 and 0.081 micrometer were attained respectively.

Thus it appears that Rq<0.1 mm PS304 coatings can be prepared, with perhaps higher values of bearing load coefficient being available immediately without depending on run-in. However, Blanchet [19] observed during preliminary intermittent-contact thrust testing of a conventional plasma-sprayed PS304 coating, that roughness would first increase from the as-polished value before run-in would begin to decrease it towards the target value. He concluded that if this initial roughening behavior also occurs for PS304 that has been successfully finished to the Rq<0.1 mm level, there is little benefit provided by the additional efforts put forth using, for example, H2-fueled HVOF deposition with smaller chrome oxide and nichrome particles.

BOND STRENGTH

In order to obtain a good bond between the substrate metal and the plasma sprayed coating, the metal surface must be well cleaned beforehand. Typical methods include sand blasting with fine abrasives or chemical cleaning in alkali using ultrasonic excitation. During the course of our experience with PS304, instances of coating delamination on some of our 35 mm diameter journals and 90 mm diameter thrust runners has been experienced. Initial reaction was that the coating delamination was due to improper coating application process, improper specimen preparation, or inadequate post application heat treatment. Subsequent experience however, revealed that the inherent material bond strength combined with cracking through the thickness induced by shaft centrifugal stresses might be another possible cause for delamination. As seen in Figure 3 through Figure 5 both delamination and considerable distress were observed in the PS304 coating after a single test. The journal and 150 mm foil journal bearing was designed for testing to speeds in excess of 20,000 rpm and temperatures to 820°C. However, the failure occurred after only 10 minutes run time at 650°C and 9500 rpm, followed by a low temperature test to 15,000 rpm when the coating delaminated.

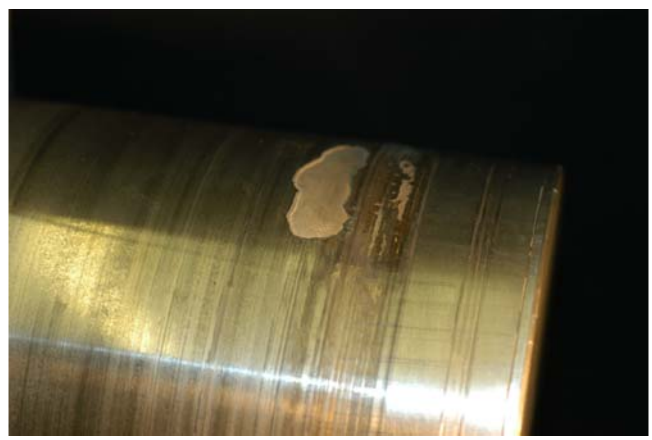

Figure 3. Delaminated section of PS304 from 150 mm journal after high temperature test

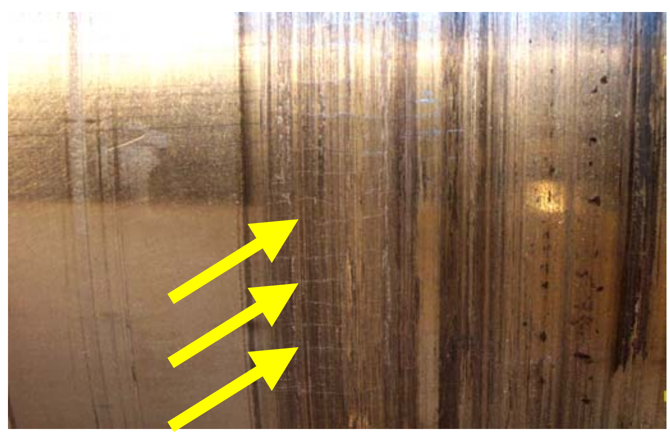

Figure 4. Close of view of additional shaft regions after delamination event showing cracking in PS304 coating.

An alternative to PS304 as a tribological shaft coating in foil bearing applications is thin dense chrome (TDC). TDC may be applied directly to the base metal in most cases and does not require an intermediate layer. The coating thickness can range from 1 to 15 µm with an excellent adhesion to the substrate demonstrated by bend tests. The hardness of the TDC is approximately 72 RC (over 100 Vickers). The safe operating temperature range for this coating is reported by manufacturers to be 710 °C, since the coating can undergo oxidation and diffusion at temperatures above this value. While thermal degradation of TDC may occur at temperatures as low as 550-600°C, uncoated shaft materials including ceramics are being examined to increase operating ranges to above 750°C.

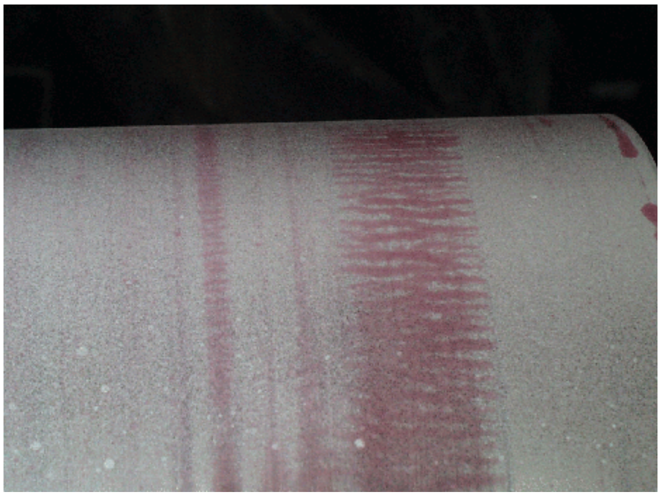

Figure 5. Results of Magnaflux inspection of PS304 coated 150 mm journal

In a parallel test using a thin dense chrome coated shaft and the foil coated with a multi-layered, high-temperature composite coating, the same test rig was operated without incident (see Figs. 6 and 7). For this test temperatures were measured by using K-type thermal couples. One thermocouple was mounted to the bearing static structure and one thermocouple was welded to the backside of the bearing foil in the high load region. Posttest examination of the journal revealed no surface distress and a slight film transfer from the tungsten disulfide based foil coating to the shaft. This film transfer likely occurred during startup when there is contact between the foil and journal surfaces. This transfer film served to enhance start/stop characteristics on subsequent test runs. The burnishing marks highlighted in Fig. 7 are light film transfer only and did not alter the surface finish of the shaft.

In another series of tests with a small turbojet gas turbine engine employing a foil bearing directly behind the turbine, a multi-layered, high-temperature composite coating was applied to the foil-bearing surface and corresponding 850°C tribological coating was applied to the journal. Testing to 120,000 rpm and 850°C was successfully completed, including numerous start stop cycles and a transient compressor ingestion event. As seen in Figure 8 and Figure 9 the posttest photos show the journal and the foil bearing to be in excellent condition.

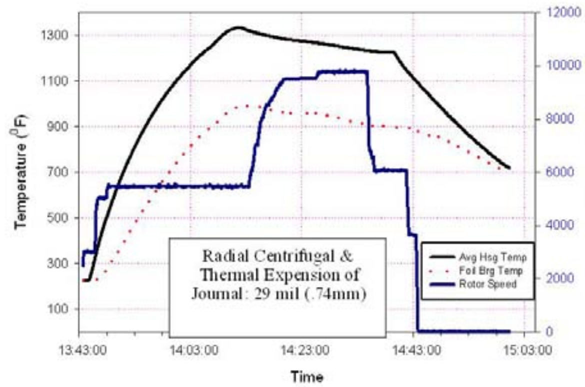

Figure 6. Test with thin dense chrome coated journal versus tungsten disulfide/nickel-chrome based foil coating.

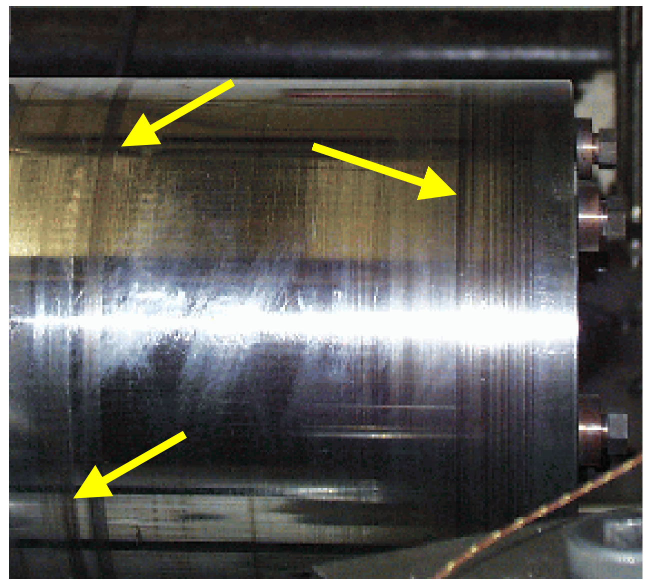

Figure 7. Thin dense chrome coated journal showing evidence of tungsten disulfide foil coating film transfer.

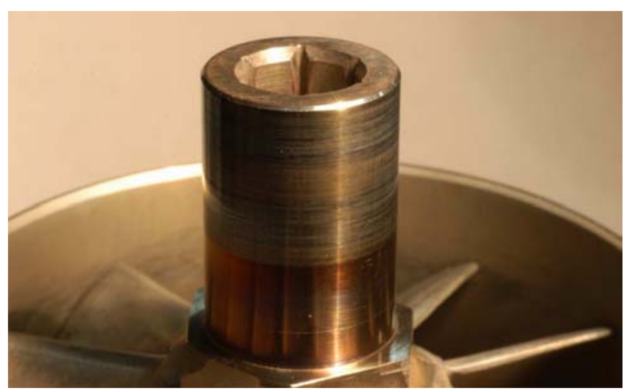

Figure 8. Oil-free turbojet aft foil bearing with high temperature coated journal after 850°C test

Figure 9. Nickel-chrome based coated foil bearing after 850°C test in oil-free turbojet engine.

In comparing the success achieved with shaft coatings such as TDC and an alternate high temperature coating it should be noted that the delamination and centrifugal stress cracking and delamination were avoided due to two primary differences with PS304. First the alternate coatings are very thin being on the order of 5E-6 m compared to up to 250E-6 m. Secondly, the alternate coatings both form a chemical bond with the substrate as opposed to relying solely on a mechanical bond as PS304 does. Given these two differences, the ability of the thin coatings to accommodate the shaft growth is expected. Correspondingly, the increased mass and thickness of the PS304 placed it under a higher stress state. It was for these reasons that efforts were attempted to enhance the bond strength of the coating via HVOF application methods and smaller constituent particle sizes.

DIMENSIONAL STABILITY

Finally it is important that the foil bearing and journal coating have dimensional stability. As reported by Lubell and DellaCorte [8], numerous efforts at thermally stabilizing PS304 have been undertaken to stabilize and enhance bond strength of the coating, including heat treatment cycles greater than 500 hours at 650°C. The need for additional efforts was experienced with several different test articles fabricated for test. In the first case a PS304 runner was coated with PS304 and underwent a 100-hour heat treatment. After six months storage at room temperature, the part was being prepared for installation in a test rig when an anomaly was noted. There appeared to be a bubble/raised section within the PS304 coating. Based upon inspection, the surface imperfection was found to be approximately 200 micrometer high and 10 mm in diameter (see Fig. 10). In discussions with the coating applicator, it was hypothesized that an oxide layer may have formed between the PS304 and the substrate due to improper cleaning or surface preparation resulting in eventual delamination of the coating. Since the part was not useable for the desired testing, it was modified for future use.

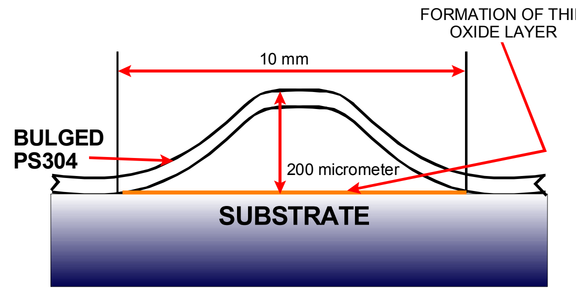

Figure 10. Schematic of hypothesized delaminated PS304 coating as result of 6-month open shelf storage.

In another case, a 229 mm diameter thrust disc was prepared and coated with PS304. After application and heat treatment of the PS304, it was observed that the PS304 had shrunk leaving a large gap between the PS304 and the machined in disc containment lip (see Fig. 11). This shrinkage and resulting gap made the disc unusable. At this point in the evaluation of the coating it was difficult to determine if the observed gap was due to coating shrinkage during heat treatment or if it was due to incorrect application. However, having worked closely with the applicator over many years to resolve application issues, the latest specifications for disc preparation, the best practices identified at the time of coating application were followed.

Figure 11. Coating instability showing shrinkage at the rim.

SUMMARY AND CONCLUSIONS

In summary, developing a foil bearing system capable of operating at high speed and temperature requires attention to the complete tribological system. The bearing and shaft coatings must have the desired surface finish, dimensional stability, and integrity and bond strength. In order to be suitable for use in large turbine engine type applications, the journal coating must accommodate the thermal and centrifugal growth experienced as well as have a long wear life and low friction coefficient. Based upon the limitations identified in PS304, it would appear that this coating is not yet suitable for demanding high temperature and high-speed applications. On the other hand other coatings applied directly to the foil and both thin dense chrome and alternate high temperature shaft coatings have shown excellent behavior and life under test conditions up to 820°C.

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REFERENCES

[1] Heshmat, H., Chen, H.M., and Walton, J.F., 2000, "On the Performance of Hybrid Foil-Magnetic Bearings ", J. of Engr for Gas Turbines & Power, 122, pp73-81.

[2] Swanson, E. E, Heshmat, H., and Walton, J.F., 2000a, "Performance of a Foil-Magnetic Hybrid Bearing," ASME Paper 2000-GT-0411.

[3] Swanson, E.E, Walton, J.F., and Heshmat, H. 2000b, "A Gas Turbine Engine Backup Bearing Operating Beyond 2.5 Million DN," ASME Paper 2000-GT-0622.

[4] Heshmat, H. and Hermel, P., 1992, "Compliant Foil Bearing Technology and their Application to High-speed Turbomachinery." *19th Leeds-Lyon Symposium on Thin Film in Tribology - From Micro Meters to Nano Meters*, D. Dowsen, et. al., eds., Elsiver, Leeds, UK, pp. 559-575.

[5] Heshmat, H., 1994, "Advancement in the Performance of Aerodynamic Foil Journal Bearings- High Speed and Load Capacity", ASME J. Tribol., 116, pp 287-95.

[6] Heshmat, H., 2000, "Operation of Foil Bearings Beyond the Bending Critical Mode." ASME J. Tribol., 122(2), pp. 192-198.

[7] Salehi, M., Heshmat, H. and Walton, J.F., 2003, "On the Frictional Damping Characterization of Compliant Bump Foils." ASME J. Tribol., 125(4), pp. 804-813.

[8] Salehi, M., Heshmat, H., Walton J. F., 2004, "Advancements In The Structural Stiffness and Damping Of A Large Compliant Foil Journal Bearing: An Experimental Study," ASME Paper No. GT2004-53860.

[9] Heshmat, H., 2005, "Major Breakthrough in Load Capacity, Speed and Operating Temperature of Foil Thrust Bearings." ASME Paper No. WTC2005-63712.

[10] Salehi, M., Heshmat, H., Walton J. F., "Operation of a Mesoscopic Gas Turbine Simulator at Speeds in Excess of 700,000 rpm on Foil Bearings," ASME Paper GT2004-53870.

[11] Walton J. F., Heshmat, H., and Tomaszewski, M., 2004, "Testing of a Small Turbocharger/Turbojet Sized Simulator Rotor Supported on Foil Bearings'" ASME Paper GT2004-53647.

[12] Heshmat, H., Walton J. F. and Tomaszewski, M., 2005, "Demonstration of a Turbojet Engine Using an Air Foil Bearing,"Paper ASME Paper GT2005-68404.

[13] Heshmat, H., Tomaszewski, M., and Walton J. F.,2006 "Small Gas Turbine Engine Operating With High-Temperature Foil Bearings," ASME Paper GT2006-90791.

[14] Lubell, D, DellaCorte, C, and Stanford, M, 2006, "Test Evolution and Oil-Free Engine Experience of a High Temperature Foil Air Bearing Coating," ASME Paper No. GT2006-90572.

[15] Bushan, B., and Rusietto, D., and Gray, S., 1978, "Hydrodynamic Air Lubricated Compliant Surface Bearing for an Automotive Gas Turbine Engine II – Materials and Coatings," report NASA CR-135402.

[16] DellaCorte, C. and Sliney, H. E., 1987 "Composition Optimization of Chromium Carbide Based Solid lubricant Coatings for Foil Gas Bearings at Temperatures to 650°C," NASA CR-179649.

[17] DellaCorte, C. and Sliney, H. E., "Composition Optimization of Self-Lubricating Chromium Carbide Based Comparative Coatings for Use to 760°C," Trans. ASLE, 30(1), pp. 77-83 (1987).

[18] Radil, K., and DellaCorte, C.D., 2000 "The Effect of Journal Roughness and Foil Coatings on the Performance of Heavily Loaded Foil Air Bearings," NASA TM2000-210941.

[19] Blanchet, T.A., 2002 "Coating for Foil Seals/Foil Bearings for Gas Turbine Engines", Report to Mohawk Innovative Technology, Inc.

