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PERFORMANCE OF HIGH-SPEED BALL BEARINGS WITH LEAD-PLATED RETAINERS IN LIQUID HYDROGEN FOR POTENTIAL USE IN A RADIATION ENVIRONMENT

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16. Abstract

Ball bearings (40-mm bore) with lead-coated, aluminum-bronze retainers were operated successfully in liquid hydrogen at 30 000 rpm under a thrust load of 1780 newtons (400 lb) for running times up to 15 hours. The lead transfer films on the bearing surfaces prevented galling of bearing components. The lead-coated retainers used in this investigation show promise for use in the high-radiation environments, where polytetrafluoroethylene (PTFE) based materials are not suitable. Failure was a result of the loss of lead lubricant on the retainer-inner-land and ball-pocket surfaces. The longest bearing life (15 hr) was achieved with a lead-coating thickness of 50 micrometers (0.002 in.) on the retainer. Other bearings had lives of 2 to 6 hours.

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SUMMARY

Lead coatings applied to aluminum-bronze alloy bearing retainers were investigated as a lubricant for 40-millimeter-bore ball bearings operating in liquid hydrogen at 30 000 rpm with a 1780-newton (400-lb) thrust load. The liquid-hydrogen flow rate through the bearing averaged 7.6×10^{-3} cubic meter per minute (2.0 gal/min). Both electroplated and ion-plated lead coatings on the retainers were investigated.

Lubrication was effected by transfer of lead by the balls from the ball pocket to the races. Profilometer tracings showed varied thicknesses of lead transfer films on the races.

Examination of the bearings indicated that there was no galling or welding of components until after bearing failure. The most common cause of failure was wear-through of lead coating in ball pockets of the retainers. A bearing using a retainer with a lead coating 50 micrometers (0.002 in.) thick achieved a useful bearing life of approximately 15 hours. Other bearings had lives of 2 to 6 hours.

Two bearings were run with 0.51-micrometer (20-μin.) thick, ion-plated lead on the races in addition to the lead coated retainers. Ion-plating of the races did not significantly improve useful bearing life.

The lead-coated retainers have capabilities for use in a high-radiation (greater than 100 joules per gram of carbon) environment, where polytetrafluoroethylene (PTFE) based retainer materials are not suitable.

INTRODUCTION

Rolling-element bearing technology for high-speed, cryogenic turbomachinery has advanced considerably during the past decade. Bearing designs have been directed mainly toward chemical-rocket-engine turbopumps that pump liquid hydrogen (refs. 1 to 3) for which bearing running times are only a few minutes. In a rocket-engine turbopump, the bearings are normally cooled by direct contact with the cryogenic hydrogen. The bearings are usually lubricated by transfer films provided by the retainer, which is fabricated from a self-lubricating material such as polytetrafluoroethylene (PTFE) (ref. 4). The PTFE material is compounded with additives such as glass fibers, bronze, or molybdenum disulfide to provide the necessary strength and wear-resistance properties (refs. 5 and 6).

The NERVA (Nuclear Engine for Rocket Vehicle Application) engine turbopump requires bearings with a radiation-resistant, nonspalling, solid lubricant having extended life capabilities. The integrated gamma radiation dose for the current NERVA engine design is estimated at 10^3 to 10^4 joules per gram of carbon in the area of the turbine bearing (ref. 7). Ball bearings with retainers made from a polymer-glass laminate material have been run in liquid hydrogen in a radiation environment (ref. 8). In two separate tests, each lasting 60 minutes, at an integrated gamma dose of 100 joules per gram of carbon, the retainer material suffered severe radiation damage. Therefore, PTFE materials seem to be unsuitable for use in a high radiation environment.

The friction and wear studies reported in reference 9 indicated that several low-shear-strength metallic coatings applied to a 440C stainless-steel substrate can provide adequate lubrication in liquid hydrogen. The best results were obtained with a lead coating. The lead coating formed a transfer film by a mechanism similar to that of PTFE materials used in cryogenic hydrogen. The results of reference 9 suggest that lead-coated retainers can be used as a means of providing lubrication for ball bearings operating at high speed in liquid hydrogen. Furthermore, lead coatings appear promising for use in bearings operating in a radiation environment.

The objectives of this investigation were (1) to evaluate the lubricating capability of lead-coated, metallic retainers in full-scale bearing tests, and (2) to determine a nominal thickness of lead that would permit a 10-hour bearing operating life.

Experiments were conducted with 40-millimeter-bore ball bearings operating in liquid hydrogen at 30 000 rpm with a 1780-newton (400-lb) thrust load. The bearings had aluminum-bronze retainers with lead coatings, applied by either electroplating or ion-plating processes.

APPARATUS

Bearing Test Rig

The test apparatus is shown in figure 1. The test bearing was driven through a gear assembly by a variable-speed, direct-current motor. Automatic speed control (to within

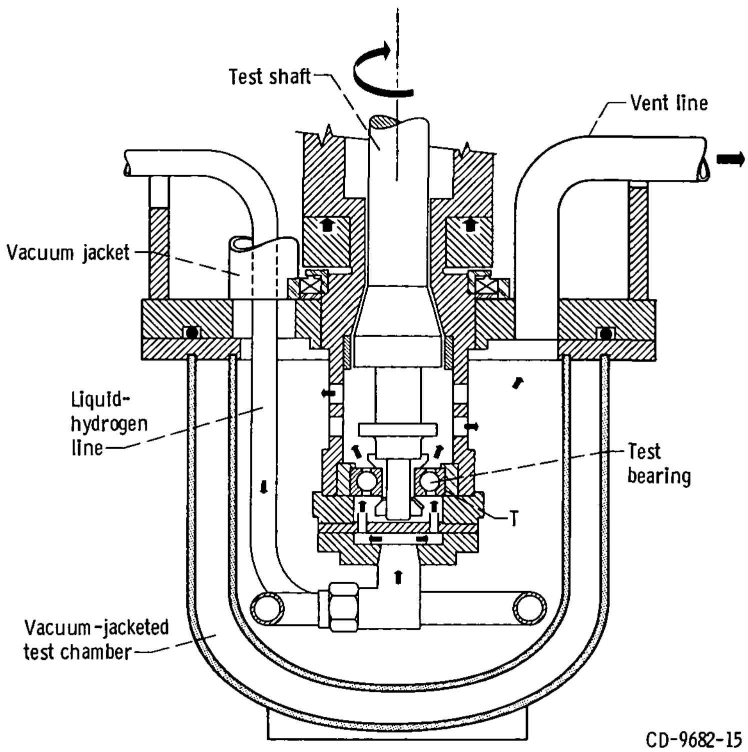

Figure 1. - Liquid-hydrogen bearing test apparatus.

±0.1 percent) was provided over a range of test-shaft speeds from 900 to 52 500 rpm. The test shaft was supported at its lower end by the test bearing and at its upper end by an oil-lubricated ball bearing. Thrust load was applied to the test-bearing housing from a deadweight load. A schematic of the test-bearing mounting and support housing is shown in figure 1. The test bearing outer-race temperature was monitored with a platinum resistance sensor (T in fig. 1).

Liquid-Hydrogen Supply and Exhaust System

The test bearing (fig. 1) was cooled by liquid hydrogen supplied from a 1.89-cubic-meter (500 gal) Dewar. The liquid-hydrogen flow rate to the test bearing was approximately 0.0076 cubic meter per minute (2 gal/min). The liquid-hydrogen flow from the Dewar was regulated by a remote-control variable-flow valve.

Test Bearings and Retainers

The bearings used in these tests were 40-millimeter-bore (108 series), deep-groove

TABLE I. - RETAINER SPECIFICATIONS AND SUMMARY OF BEARING TEST RESULTS

[Test bearings were deep-groove ball bearings, separable at outer race; bore diameter, 40 mm; race and ball material, AISI 440C stainless steel; number of balls, 10; ball diameter, 9.53 mm (0.375 in.); inner- and outer-race curvature, 0.54; radial clearance, 0.0063 cm (0.0025 in.); retainer material, aluminum-bronze alloy (85.3 percent Cu, 10.5 percent Al, 3.5 percent Fe, and 0.7 percent other substances).]

Bearing	Type of plating on retainer	Lead-coating thickness on retainer		Retainer clearance after plating				Hours run at 30 000 rpm	Mode of failure	Weight change, percent			
		μm	in.	Inner race		Ball pocket				Inner race	Outer race	Ball set	Retainer
				mm	in.	mm	in.						
1	Electroplating	[a]50	0.002	0.81	0.032	0.31	0.012	5.8	Coating worn through	Not measured	Not measured	Not measured	Not measured
3	Electroplating	50	0.002	0.81	0.032	0.33	0.013	14.9	Excessive power-input	-1.56	+0.11	-1.07	-2.33
9	Electroplating	50	0.002	0.76	0.030	0.33	0.013	5.4	Coating worn through	+0.08	Negligible	-0.02	-1.51
4	Electroplating	50	0.002	1.42	0.056	0.33	0.013	3.3	Coating worn through	-0.02	+0.01	Negligible	-0.60
2	Ion plating	[a]0.51	0.00002	0.81	0.032	0.43	0.017	2.5	Coating worn through	-0.02	-0.07	+0.02	-2.98
5	Ion plating	[b]0.51	0.00002	0.97	0.038	0.43	0.017	3.8	Excessive power-input	+0.01	Negligible	+0.02	-0.21
6	Ion plating	10	0.0004	1.40	0.055	0.76	0.030	1.8	Coating worn through	+0.03	Negligible	+0.05	-0.87
7	Ion plating	10	0.0004	0.97	0.038	0.64	0.025	1.9	Coating worn through	Negligible	Negligible	+0.01	-0.25
8	Ion plating	10	0.0004	1.55	0.061	0.61	0.024	2.0	Coating worn through	-0.05	Negligible	+0.03	-2.39

[a]With a 0.51-μm- (0.00002-in.-) thick, ion-plated lead coating on the races.
[b]With a 50-μm- (0.002-in.-) thick, electroplated lead coating on the inner diameter of the retainer.

ball bearings manufactured to ABEC-5 tolerances. One shoulder on the outer race was relieved to make the bearings separable. The inner- and outer-race curvatures were both 0.54. The average internal radial clearance was 0.0063 centimeter (0.0025 in.). The ball and race material was AISI 440C stainless steel.

The retainers were inner-race located and of one-piece construction machined from a cast aluminum-bronze alloy. The alloy composition was 85.3 percent copper, 10.5 percent aluminum, 3.5 percent iron, and 0.7 percent other constituents. The diametral clearance between the retainer and the inner race shoulder (i.e., the land clearance) ranged from 0.076 to 0.155 centimeter (0.030 to 0.061 in.), and the ball-pocket clearance ranged from 0.031 to 0.076 centimeter (0.012 to 0.030 in.), as indicated in table I.

The retainers were plated with thin lead coatings applied either by electroplating or by ion-plating techniques. Two sets of bearing races were also ion plated with lead. The ion-plating process is described in detail in reference 10. Coating thickness and the type of coating for each bearing retainer is given in table I.

PROCEDURE

Pre-Test Procedure

In preparation for testing, the bearings first were degreased with three solvents (trichloroethylene, acetone, and alcohol). Next, they were inspected and measured for clearances. Finally, individual components of the bearings were weighed.

Test Procedure

After the test bearing was installed, the test chamber, and all hydrogen lines were purged for 15 minutes with helium gas. After the purge operation, liquid hydrogen was force-fed to the bearing and test chamber. The test shaft was rotated at 900 rpm during the 10-minute cool-down period. The thrust load was applied after the start of rotation at the beginning of the cool-down period. When the system reached liquid-hydrogen temperature (22 K), the shaft speed was increased to 30 000 rpm (normally in 5000-rpm increments every 5 min).

The 1.89-cubic-meter (500-gal) supply of liquid hydrogen normally provided enough fluid for a bearing test run of about 4 hours. The test speed was 30 000 rpm, and the thrust load was 1780 newtons (400 lb). The liquid-hydrogen flow rate to the test bearing at these test conditions was approximately 7.6×10^{-3} cubic meter per minute (2.0 gal/

min) over a range of supply pressures from 127.5×10^3 to 189.5×10^3 newtons per square meter absolute (18.5 to 27.5 psia).

The operating life of a test bearing in liquid hydrogen was established as the total running time that the bearing could endure at the test conditions specified previously, before the lead coating on the retainer had worn through to the substrate material. A bearing test was suspended prematurely if (1) the bearing seized abruptly, or (2) the power input to the drive system exceeded 10 kilowatts (see table I).

Post-Test Inspection of Bearings

After each run, the test bearing was inspected for wear. The retainer ball pockets and inner diameter were inspected for insufficient lead-coating thickness and for excessive wear of the aluminum-bronze substrate. The bearing was also washed with three solvents (trichloroethylene, acetone, and alcohol) and weighed, to determine the weight change of each component. The balls, races, and retainer were examined visually and by optical microscopy (at magnifications from 7 to 25) to determine the extent of surface damage. Photographs of the retainers were made to illustrate the wear patterns that occurred during the test period. For several bearings, at the end of a run series, profile traces of the inner-race grooves were made to determine the thickness of the lead film transferred during bearing operation.

RESULTS AND DISCUSSION

Evidence of Lead Transfer Film

Visual examination revealed that the lead coating on the retainers was effectively transferred by the balls to the race grooves. Figure 2 is a profile trace across the inner-race groove, normal to the ball-rolling direction, of bearing 4. The maximum transfer-film thickness measured was 6.1 micrometers (240 μin.). These lead films are considerably thicker than the films obtained from PTFE composition retainers (ref. 4). The lead transfer films were normally deposited uniformly around the circumference of the race groove. Examination of the inner race of bearing 6 at a low magnification also revealed a transfer film with a blistered appearance (fig. 3). Blisters were also observed on the ball set of bearing 9. These blisters may have resulted from fatigue of the transfer film or may indicate that the lead transfer film was excessively thick and poorly adherent to the race groove.

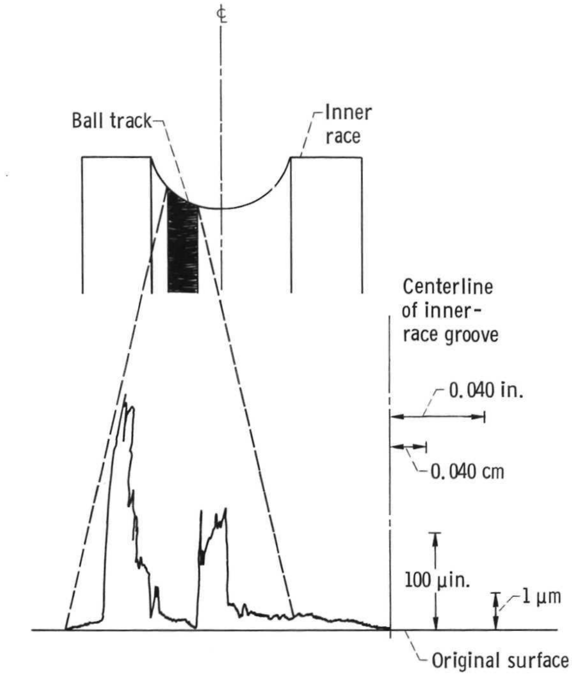

Figure 2. - Profile traces of inner-race ball track (normal to ball rolling direction) of bearing 4. Running time, 3.3 hours.

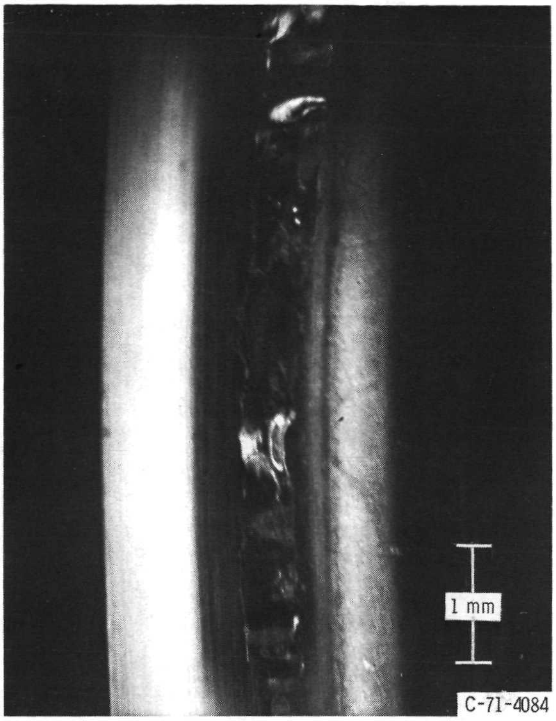

Figure 3. - Blistered lead transfer film on inner race of bearing 6.

Effect of Retainer Coating Thickness

The maximum operating life of the bearings tested was 14.9 hours, obtained with bearing 3 (fig. 4). The bearing was inspected after 11.3 hours of running, and the lead coating had not worn through. Bearing 3 was the only bearing to surpass the objective life of 10 hours. In the following run, power input to the bearing exceeded 10 kilowatts and therefore required a shutdown. Total bearing operating time at this point was 14.9 hours. Examination of the retainer showed that the lead coating had worn through in the ball pockets and at the inner locating diameter. After the lead coating had worn away, the retainer substrate material wore rapidly and increased the retainer-land and the ball-pocket clearances. The rate of wear is intrinsic to the substrate material used.

The retainer of bearing 3 was electroplated with a lead coating 50 micrometers (0.002 in.) thick. This coating thickness was based on friction and wear experiments of lead coatings in liquid hydrogen (ref. 9). The retainers of bearings 1, 4, and 9 were also electroplated with a lead coating 50 micrometers (0.002 in.) thick. All of these bearings, however, wore through the coating in less than six hours of running time (table I).

Five of the retainers were ion plated with lead. Reference 9 indicates that ion-plated lead adheres more tenaciously to the substrate than does electroplated lead. However,

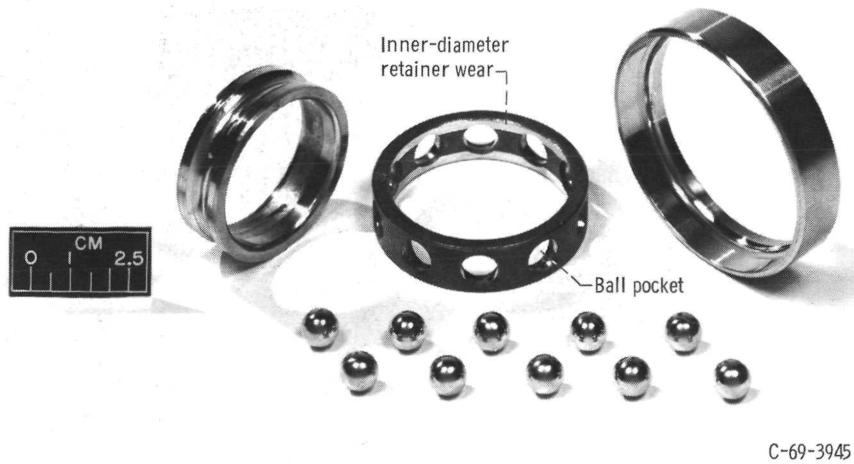

Figure 4. - Bearing 3 with lead-coated inner-race-riding retainer. Running time, 14.9 hours.

the ion-plating apparatus used for this investigation was limited to providing maximum film thicknesses of 10 micrometers (0.0004 in.). The lives of the bearings using the retainers with the thinner, ion-plated lead were generally lower than for those bearings using electroplated lead. This indicates that the lead-coating thickness is an important consideration in the design of this type of bearing for longer life.

Although thicker lead coatings appear to result in longer bearing life, there is evidence showing that excessive lead accumulation in a bearing is detrimental. Figure 5 shows excessive lead accumulation adjacent to the rubbing area of the ball pocket of bearing 5. Figure 6 shows an excess of lead debris transferred to a ball surface of bearing 8. This type of accumulation of lead has the potential of jamming the bearing at high speeds and causing a catastrophic failure of the bearing.

Effect of Retainer Clearances

Wear occurred in a 360° arc of the retainer ball pockets, which indicated insufficient ball-pocket clearance. It was believed that increasing the retainer ball-pocket and retainer inner-land clearances would alleviate this.

Subsequent running of bearings 4, 6, 7, and 8 revealed that the possible benefits of increasing the inner-land and/or ball-pocket clearances were negated by other problems. For instance, the larger clearances increased the probability of retainer unbalance and led to uneven and heavy wear at the contacting surfaces. Inner-race-riding retainers are not self-balancing as wear progresses; therefore, any unbalance is compounded by un-

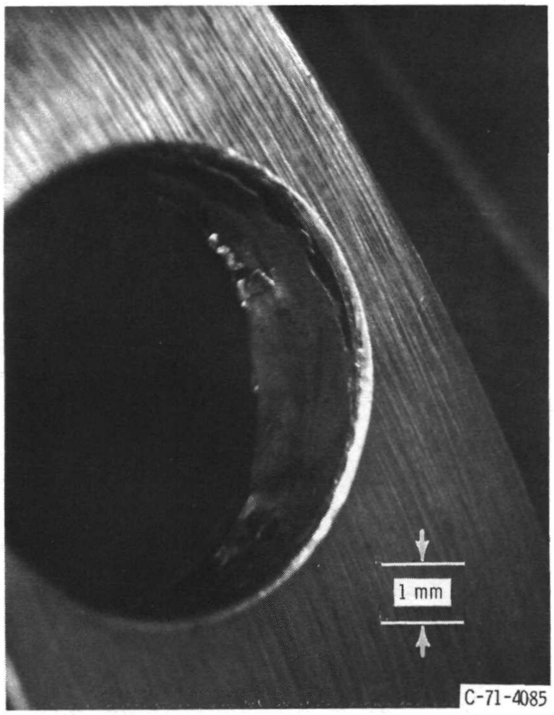

Figure 5. - Lead accumulation in retainer ball pocket of bearing 5.

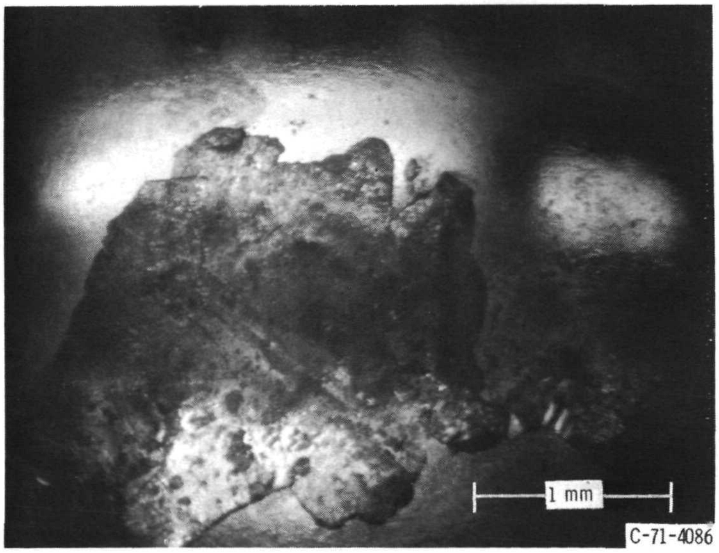

Figure 6. - Lead debris transferred to ball surface from retainer of bearing 8.

even wear. Bearings 7 and 8 were both run with retainers that were ion plated with equal thicknesses of lead (10 μm) and balanced dynamically before running. They both survived only 2 hours of running. However, bearing 8 had 10 times more retainer wear (weight loss) than did bearing 7 (table I). The inner-land clearance of bearing 8 was 60 percent greater than that of bearing 7. It is believed that the excessive inner-land clearance in bearing 8 was conducive to uneven wear and, therefore, to increasing dynamic unbalance.

Effect of Ion Plating of Bearing Races

In addition to coating the retainers, the races of bearings 1 and 2 were ion plated with lead. The coating thickness was 0.51 micrometers (20 μin.). These bearings with lead coatings on the races and on the retainers showed no noticeable improvement in bearing life or performance over bearings with lead coatings on only the retainers (see table I). For example, bearings 1, 3, and 9 had retainers with 50-micrometer (0.002-in.-) thick, electroplated lead coatings on the retainers, with the same clearances. The life of bearing 1 (5.8 hr) was equivalent to that of bearing 9 (5.4 hr). However, these lives were less than the life of bearing 3 (14.9 hr).

CONCLUDING REMARKS

Reproducibility of results with similar bearings was not established. For example, bearing 9 was similar to bearing 3 in design, lead-coating thickness, and clearance; however, the useful life of bearing 9 was only 5.4 hours, whereas that of bearing 3 was 14.9 hours. Bearing 1 was also similar to bearing 3, but, in addition, the races of this bearing had ion-plated, 0.51-micron (20-μin.-) thick lead coatings. This bearing achieved a useful life of 5.8 hours. Greater reproducibility of longer bearing life might be achieved by incorporating some of the following ideas: (1) alloying the lead coating to obtain a more wear-resistant coating; (2) using a more wear-resistant retainer substrate material; and (3) using outer-race-riding retainers, which tend to be self-balancing as they wear.

SUMMARY OF RESULTS

Lead coatings applied to aluminum-bronze alloy bearing retainers were investigated as a lubricant for 40-millimeter-bore ball bearings operating in liquid hydrogen at 30 000 rpm with a 1780-newton (400-lb) thrust load. The liquid-hydrogen flow rate through the bearing averaged 7.6×10^{-3} cubic meter per minute (2.0 gal/min). Both electroplated and ion-plated lead coatings on the retainers were investigated. This investigation produced the following results:

1. Lead formed an effective lubricant transfer film on the balls and in the race grooves.

2. A bearing life of approximately 15 hours was achieved with a lead-coating thickness of 50 micrometers (0.002 in.). Other bearings had lives of 2 to 6 hours.

3. Two bearings were run with 0.51-micrometer- (20-μin.-) thick, ion-plated lead coatings on the races in addition to the lead coatings of the retainers. This ion-plating of the races produced no significant improvement in bearing performance or life.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 22, 1971,
132-15.

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