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EVALUATION OF HIGH-TEMPERATURE BEARING CAGE MATERIALS

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SUMMARY

A cage compatibility tester was used to determine the relative wear characteristics of six cage materials with four lubricants of practical interest. Test conditions were ambient temperatures of 500° and 700° F, a shaft speed of 1200 rpm, and test durations of from 30 to 120 minutes. Measurements of the wear scar in the cage pocket were used to determine the effect of cage material, temperature, lubricant, and material hardness on cage wear.

For the temperature range of 500° to 700° F, S-Monel and M-1 materials gave the least wear. Additionally, at 500° F, 440C (modified) stainless steel and a polyimide polymer indicated low wear.

The best results in terms of low wear were obtained at 500° F with an M-1 material of Rockwell A hardness 81 run with an ester-base lubricant. At 700° F, minimum cage wear was obtained with a polyphenyl ether lubricant and S-Monel material of Rockwell A hardness 67.

For a given cage material, cage wear decreased with increased material hardness. This result suggests that cages for high-temperature application should be heat treated to their maximum practical hardness.

INTRODUCTION

In the development of accessory drives and powerplant systems for advanced aerospace applications, the need for reliable, high-speed, high-temperature bearings and lubricants has become of prime importance. The low starting torque, simplicity of design, and high reliability of rolling-element bearings make them ideally suited for turbine driven machinery (ref. 1).

At temperatures above 500° F, tests have indicated that bearing cage wear can be a limiting factor in the operation of bearings under the severe lubrication conditions encountered at these elevated temperatures. Therefore, in addition to the race and the rolling-element material, careful consideration must be given to the choice of cage (retainer) material.

In conventional rolling-element bearings, both metallic and nonmetallic cages have found widespread use. Under normal temperatures, for nonaerospace applications, practically all the roller bearings and a large percentage of the ball bearings in use have been equipped either with stamped cages of low-carbon steel or with machined cages of iron-silicon bronze or lead brass. Precision bearings, such as those used for aerospace applications, are usually equipped with cages machined from copper alloys or nonmetallic phenolic materials. In some applications, where marginal lubrication exists during operation, such as at high temperatures, silver plating on the bronze has been used. Phenolic materials are limited to temperatures of approximately 250° F, while copper-base alloys are suitable for operation to approximately 600° F. Above 600° F, some success has been obtained with low-carbon steel or cast-iron cages, but, generally, the most successful high-temperature cages have been nickel-base alloys. One of the nickel-base alloys used is S-Monel (ref. 1, pp. 328-329).

Other materials which have shown promise are high-temperature plastics which exhibit low friction and wear characteristics, high-alloy steels capable of maintaining their hot hardness at elevated temperatures, and stainless steels.

The research reported herein was undertaken to determine the capability of various cage material - lubricant combinations for operation at temperatures from 500° to 700° F. The objectives were

(1) To investigate the effect of various cage materials on bearing cage wear

(2) To determine the effect of cage material hardness and operating temperature on cage wear

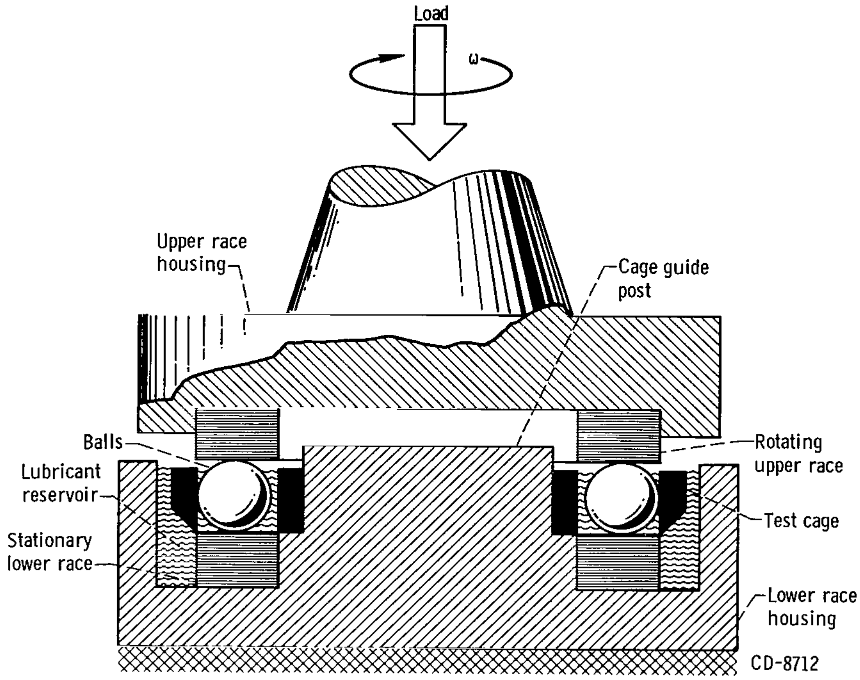
(3) To investigate the effect of lubricant type on bearing cage wear

Tests were conducted at SKF Industries, Inc., under contract to NASA (ref. 2), in a cage compatibility tester at 500° and 700° F with four lubricants and six cage materials of practical interest. These tests were run for durations from 30 to 120 minutes. At each set of conditions, the area of the wear scar produced during the test in the cage pocket was used as the measure of wear. A comparison of these data was made on the basis of material type, test temperature, material hardness, and lubricant type.

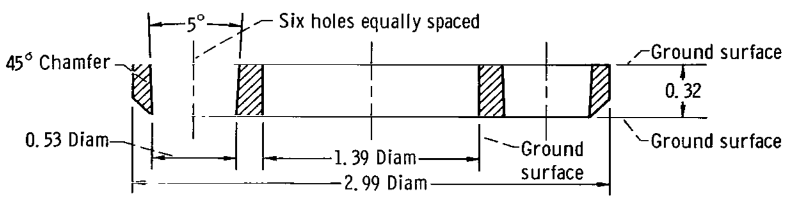
APPARATUS AND PROCEDURE

Cage Compatibility Tester

Figure 1(a) is a schematic drawing of the cage compatibility tester. Essentially this test apparatus comprises three 1/2-inch diameter balls interposed between a flat upper



(a) Schematic of cage compatibility tester.



(b) Test cage. (All dimensions in inches except where otherwise noted.)

Figure 1. - Test apparatus.

race and a lower race and positioned by a test cage. Loading and drive are supplied through a drive shaft coupled to an upper race housing. The test cage (fig. 1(b)) is supported on the stationary lower race and is centered about a cage guide post which is eccentric with respect to the axis of the rotating race. The balls are loaded against the tapered cage pocket by the variation in linear speed of the balls around the track and the tendency of the balls to creep radially outward because of centrifugal force. However, the tests are not run at a speed high enough for the centrifugal force on the balls to be an appreciable fraction of the normal ball to race load.

The races, balls, and guide post are made of M-1 bearing steel so that all wear surfaces on the cage are in contact with materials likely to be encountered by cages in high-temperature bearings. The approximate Rockwell A hardnesses of the balls, the race, and the guide post was 82 to 84. Temperatures up to 800° F measured at the outer diameter of the lower race can be maintained in the test assembly. In the event of a ball or race failure due to fatigue or other malfunction, a vibration shutoff system shuts down the rig and related instrumentation.

A nitrogen atmosphere is maintained in a lubricant supply source and around the test system. A once-through lubrication system is used with the flow rate to the test cage maintained by an oil-drip cup so that the oil level in a lubricant reservoir is kept above the lower race - ball contact.

Test Procedure

Prior to assembly in the cage compatibility tests, all mating surfaces were subjected to a surface-finish and hardness inspection. Hardnesses were measured in the Rockwell C or B scales and then converted to the Rockwell A scale for comparison purposes. All test-section components were flushed and scrubbed with ethyl alcohol and wiped dry with clean cheesecloth. The test components were then assembled. During each test, the tester was disassembled, and the major and minor axes of the wear scar on each test cage pocket were measured at half-hour intervals. The size of the elliptical wear scar area produced in the cage pocket because of contact with the ball under the action of the ball-to-cage forces was used as the criterion for evaluating the performance of cage material - lubricant combinations. A typical cage specimen wear scar is shown for the S-Monel material in figure 2. Caking of the lubricant on the cage surfaces makes weight measurements of the cage an inaccurate measure of the wear relative to the actual measuring of the wear scar.

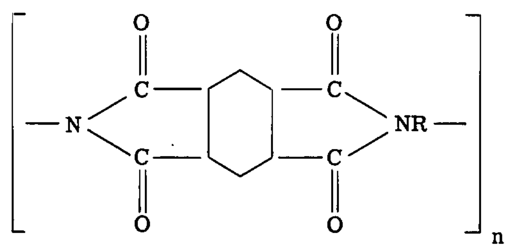
C-66-4164

Figure 2. - Typical cage specimen wear scar.

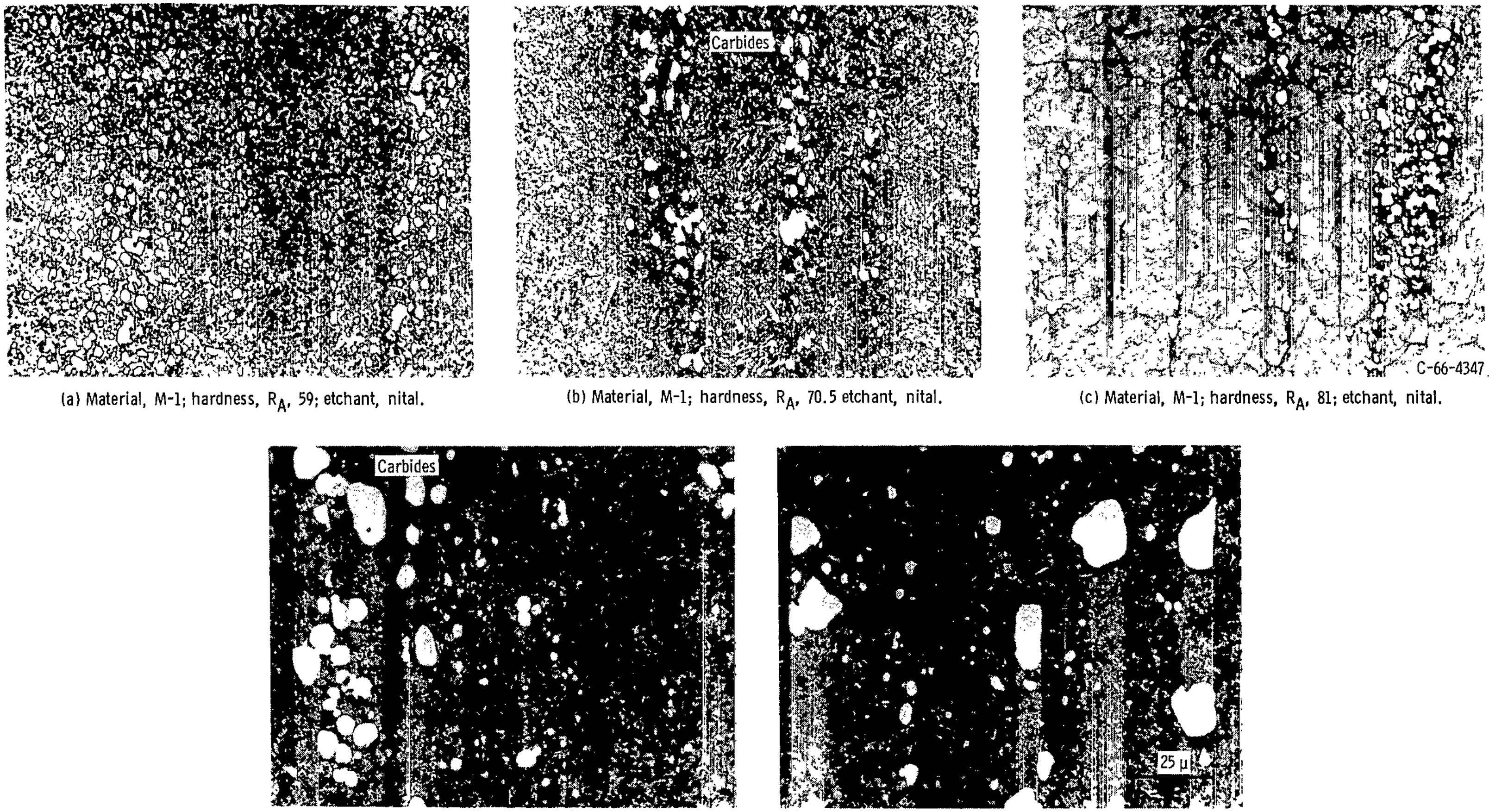
MATERIALS

Six test cage materials were investigated: S-Monel, a copper alloy, a cobalt alloy, AISI M-1 steel, polyimide polymer, and a modified 440C stainless steel. The chemical compositions of these materials are given in table I. Photomicrographs of these materials are shown in figure 3. The softer materials of the alloys tended to have larger,

TABLE I. - CAGE MATERIALS

Material	Chemical composition, percent by weight											
	Carbon	Manganese	Silicon	Nickel	Chromium	Molybdenum	Tungsten	Vanadium	Cobalt	Copper	Iron	Other
M-1	0.75 to 0.85	0.20 to 0.40	0.20 to 0.40	----	3.75 to 4.50	7.75 to 9.25	1.15 to 1.85	0.90 to 1.30	-----	---	Bal.	--
Modified 440C stainless steel	0.95 to 1.20	1.00 Max.	1.00 Max.	----	13.00 to 16.00	3.25 to 4.25	----	----	-----	---	Bal.	--
S-Monel	0.25 Max.	0.50 to 1.5	3.5 to 5.0	62 to 68	-----	----	----	----	Trace	Bal.	3.5	--
Copper alloy	----	----	0.40 to 0.80	2.0 to 3.5	-----	----	----	----	-----	Bal.	----	--
Cobalt alloy[a]	0.09	1.0 to 2.0	1.0 Max.	10	20	----	15	----	Bal.	---	3.0 Max.	1
Polyimide polymer												

[a]Includes phosphorous, 0.04; sulfur, 0.03.



(a) Material, M-1; hardness, R_A, 59; etchant, nital.

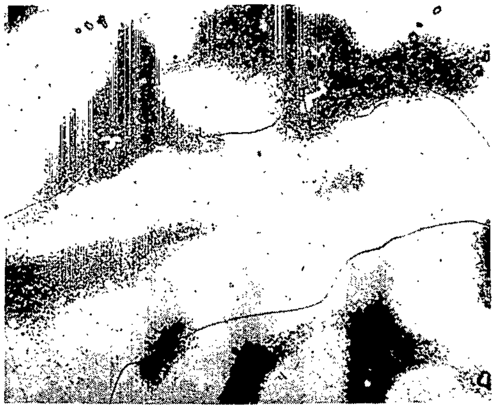
(b) Material, M-1; hardness, R_A, 70.5 etchant, nital.

(c) Material, M-1; hardness, R_A, 81; etchant, nital.

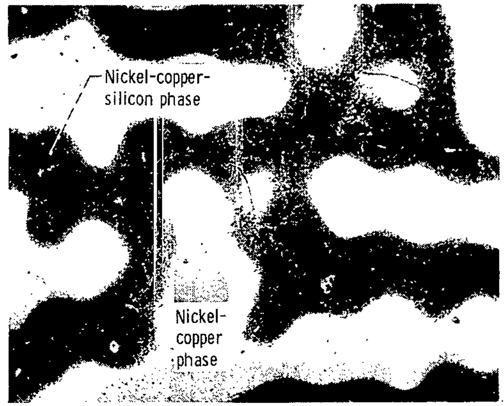
(d) Material, modified 440C stainless steel; hardness, R_A, 77; etchant, picral - hydrochloric acid.

(e) Material, modified 440C stainless steel; hardness, R_A, 79.5; etchant, picral - hydrochloric acid.

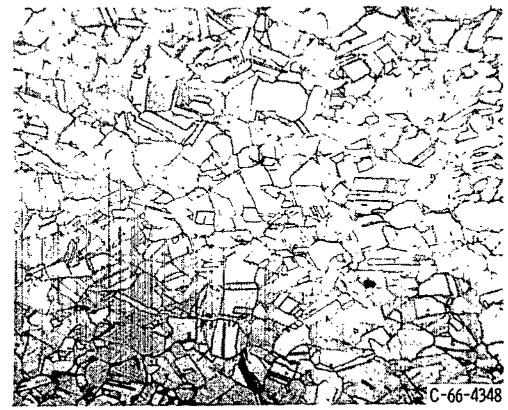
Figure 3. - Micrographs of cage materials.



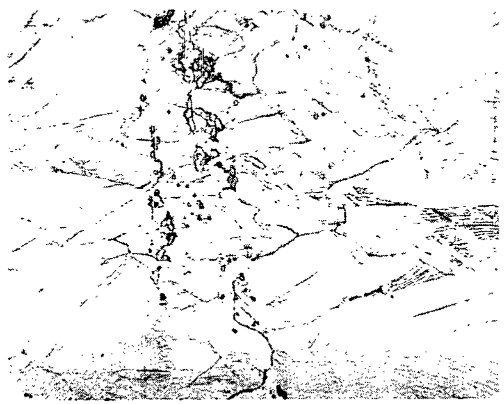
(f) Material, S-Monel; hardness, R_A, 52.5; etchant, Carapella.



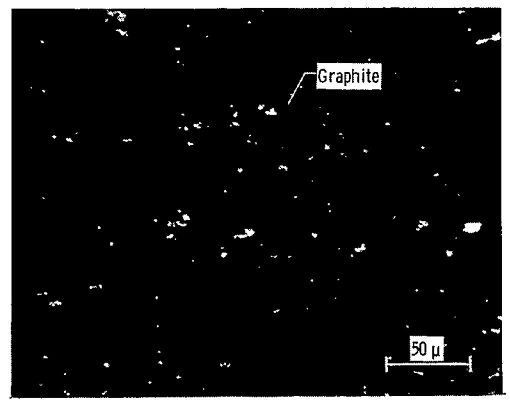
(g) Material, S-Monel; hardness, R_A, 67.0; etchant, Carapella.



(h) Material, copper alloy; hardness, R_A, 49.5; etchant, picral - hydrochloric acid.



(i) Material, cobalt alloy; hardness, R_A, 76; etchant, electrolytic chromic acid.



(j) Material, polymide polymer with 15 percent by weight graphite; unetched, dark field illumination.

Figure 3. - Concluded.

more numerous precipitated carbides and greater definition of tempered martensite. These materials were selected for high-temperature evaluation because of their availability, their usage in current bearing application, and their desirable properties.

These materials were evaluated with four lubricants, a super-refined naphthenic mineral oil, a 5P4E polyphenyl ether, an ester, and a fluorocarbon. The properties of these lubricants are given in table II. These lubricants were selected for operation with the cage materials because of their practical interest as potential high-temperature lubricants.

TABLE II. - TEST LUBRICANTS

Base stock	Additive content	Viscosity, cs,			
		100° F	210° F	500° F	700° F
Super-refined naphthenic mineral oil	Oxidation inhibitor extreme pressure additive antifoam agent	79	8.4	1.1	0.60
5P4E Poly-phenyl ether	No additive	365	13.1	1.2	0.65
Fluorocarbon	No additive	335	29	2.1	1.05
Trimethylol-propane ester	Oxidation inhibitor	16	3.55	0.88	----

RESULTS AND DISCUSSION

Dynamic cage material - lubricant compatibility tests were performed in a cage compatibility tester. The tests were conducted for a duration of 30 to 120 minutes at 1200 rpm under a nitrogen environment and a system load of 1000 pounds. The variables were as follows:

(1) Composition of cage material (table I)
(2) Cage material hardness
(3) Type of lubricating fluid (table II)
(4) Temperature (500° or 700° F)

The three elliptical wear scars produced in the test cage pockets at each set of conditions were measured and averaged. The average measured wear scar for the initial 30-minute operation varied from 0.1 to 12.2 square millimeters. For any set of test conditions, the measured wear area could vary as much as ±40 percent of the average value.

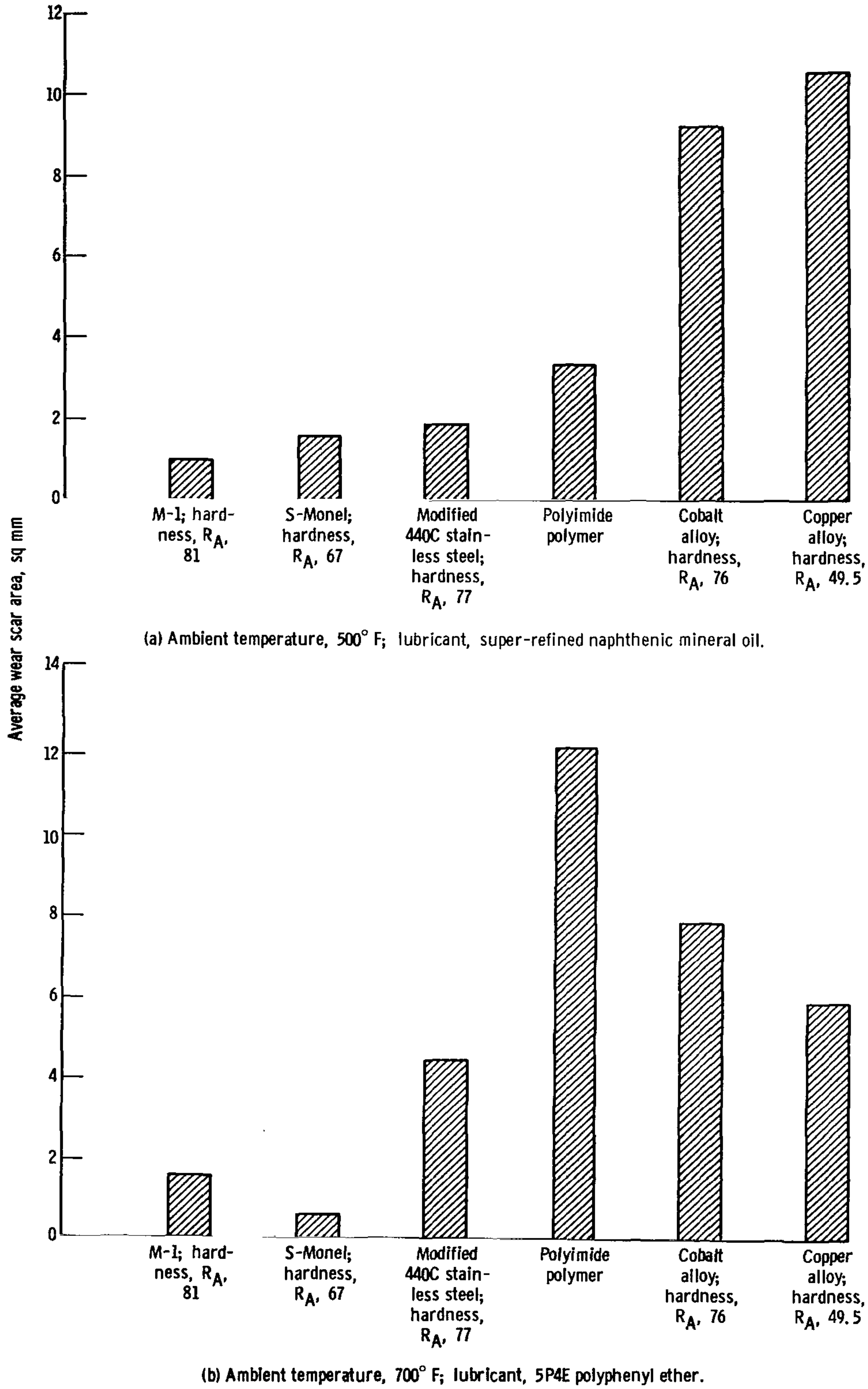


Figure 4. - Wear of various materials in inert environment. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes; room temperature hardness given.

Comparison of Cage Materials

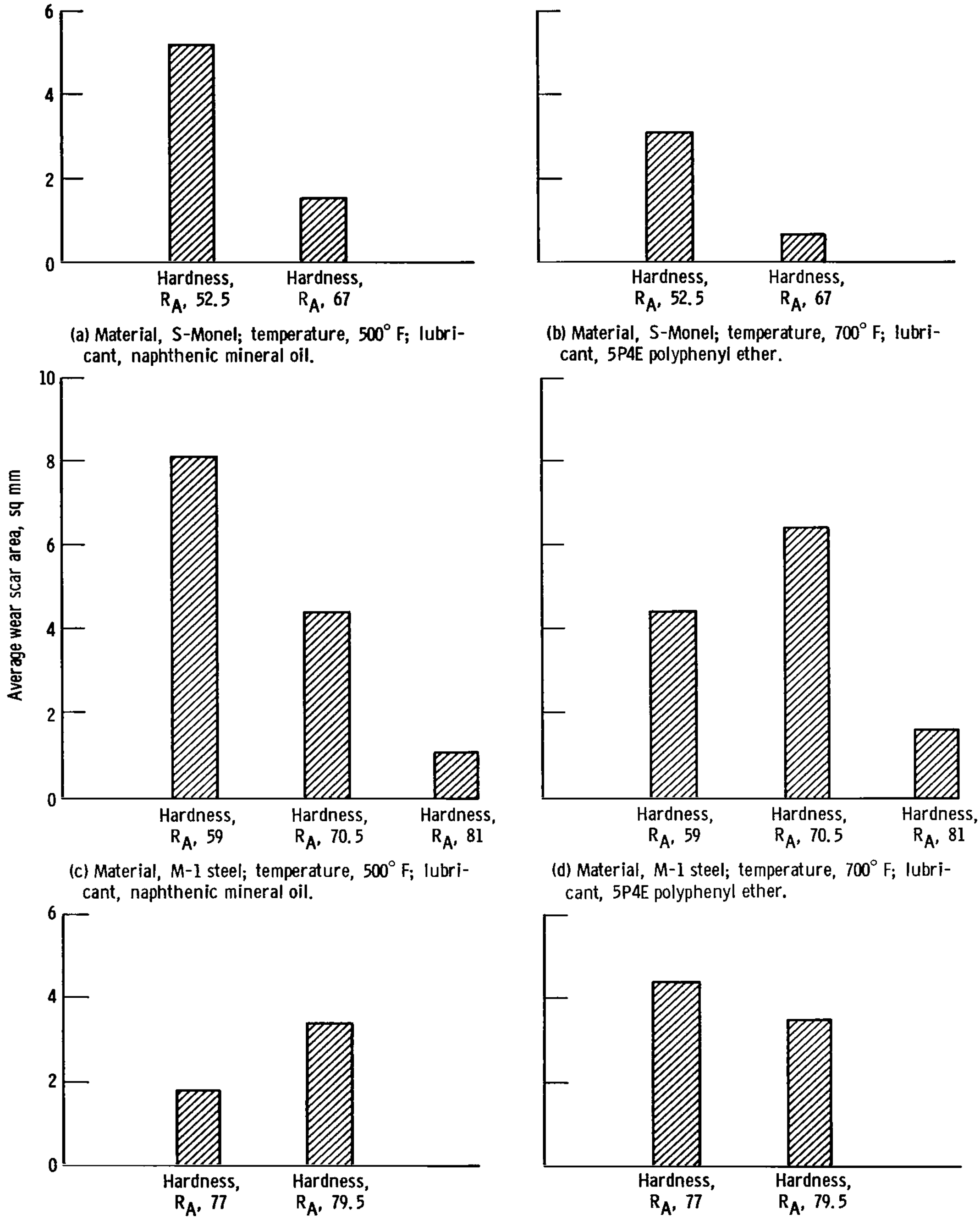
Results of 30-minute tests at a test temperature of 500° F with a naphthenic mineral oil as the lubricant for six materials are shown in figure 4(a). At this set of conditions, four materials show promise of operating for extended periods of time: M-1, S-Monel, modified 440C stainless steel, and a basic polyimide polymer. Tests were also conducted at 700° F with the same materials but with the 5P4E polyphenyl ether as the lubricant. The results of these tests are shown in figure 4(b). At this condition, the M-1, S-Monel, and 440C stainless-steel materials show the greatest promise. The high wear with the polyimide is not totally unexpected inasmuch as thermal degradation of this polymer begins at 700° F (ref. 3). The addition of 15 percent by weight graphite to the basic polyimide polymer (fig. 3(j)) had no effect on the wear results at 500° F.

In both the 500° and the 700° F tests, the M-1 and S-Monel materials exhibited the least amount of wear relative to the other materials. It, thus, can be concluded that for elevated-temperature bearing applications M-1 and S-Monel of Rockwell A hardnesses 81 and 67, respectively, have potential bearing cage application.

Effect of Hardness on Cage Wear

The bar graphs in figure 5 show the results of increased hardness on cage wear for three materials, S-Monel, M-1, and 440C stainless steel, with the naphthenic mineral oil and the 5P4E polyphenyl ether as lubricants at 500° and 700° F, respectively. As would be expected, wear decreased with increasing hardness for the S-Monel and M-1 materials. However, for the small difference in hardness of the modified 440C stainless-steel materials, there was apparently no significant difference in wear. These data indicate that, for the M-1 and S-Monel materials, cage wear decreases with increasing hardness.

In addition to heat-treatment effects on material hardness, operating temperature also affects hardness. Increasing the operating temperature will, of course, decrease material hot hardness. The effect of increasing temperature from 500° to 700° F with M-1 and S-Monel cage materials run with the naphthenic mineral oil as the lubricant is shown in figure 6. These results show that wear will increase two to five times, depending on the material and its heat treatment. However, examination of the curves in figure 7 shows that the Rockwell A hardness for M-1 and S-Monel decreases approximately 1 and 0.5 point, respectively, because of the increase in temperature from 500° to 700° F. These differences in hardness are not sufficient to account for the marked increases in wear indicated by the data presented in figure 5. It can therefore be concluded that, with these materials, temperature affects the amount of wear through its effect on the lubrication process.



(a) Material, S-Monel; temperature, 500° F; lubricant, naphthenic mineral oil.

(b) Material, S-Monel; temperature, 700° F; lubricant, 5P4E polyphenyl ether.

(c) Material, M-1 steel; temperature, 500° F; lubricant, naphthenic mineral oil.

(d) Material, M-1 steel; temperature, 700° F; lubricant, 5P4E polyphenyl ether.

(e) Material, modified 440C stainless steel; temperature, 500° F; lubricant, naphthenic mineral oil.

(f) Material, modified 440C stainless steel, temperature, 700° F; lubricant, 5P4E polyphenyl ether.

Figure 5. - Effect of hardness on cage wear. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes.

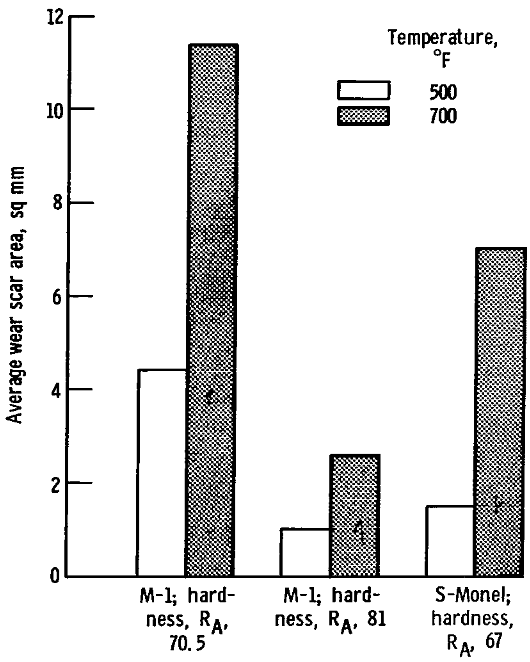


Figure 6. - Effect of temperature on cage wear for M-1 and S-Monel with naphthenic mineral oil. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes.

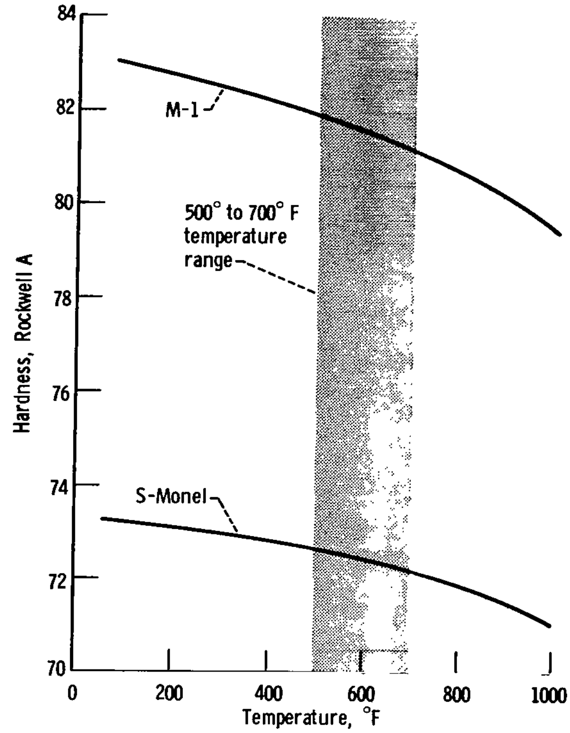


Figure 7. - Effect of temperature on hot hardness of M-1 steel and S-Monel.

From these results it can also be concluded that, in general, potential high-temperature cage materials of the types reported herein should be heat-treated to their maximum room-temperature hardness, while sufficient ductility to prevent cracking is maintained. In application, however, the rolling-element material should be somewhat harder than the cage material to prevent damage to the rolling elements. Wear resistant platings or coatings may also be used to reduce cage wear.

Effect of Lubricant on Cage Wear

Four lubricants of practical high-temperature interest were selected for evaluation with the cage materials previously discussed. Figures 8(a) and (b) show the effects at 500° F of two lubricants, the naphthenic mineral oil and the ester, on cage wear for M-1 and S-Monel of Rockwell A hardnesses 81 and 67, respectively. The wear of the M-1 material with the ester-base lubricant was significantly less than the wear obtained with the naphthenic mineral oil (fig. 8(a)). However, the wear of the S-Monel (fig. 8(b)) with the ester-base lubricant was greater than that obtained with the mineral oil.

Tests were conducted at 700° F with the M-1 and S-Monel materials and two additional fluids beside the mineral oil and the ester. The additional lubricants were the polyphenyl ether and a fluorocarbon-base fluid. The results of these tests are shown in

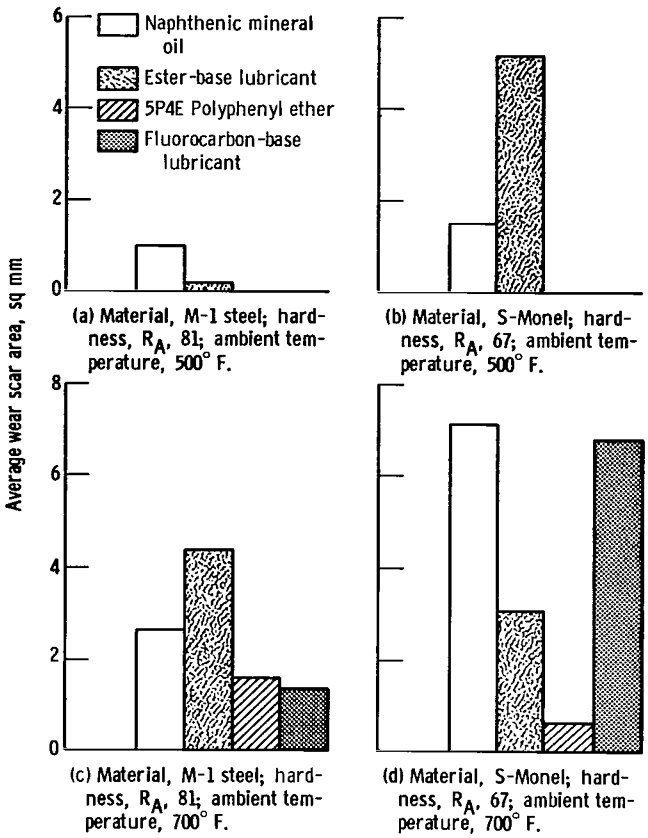


Figure 8. - Effect of various lubricants on cage wear. Shaft speed, 1200 rpm; system load, 1000 pounds; duration, 30 minutes.

figures 8(c) and (d). The M-1 material exhibited the highest amount of wear in the mineral oil and the ester. However, less wear was obtained with the polyphenyl ether and the fluorocarbon than was obtained with the previous two fluids. The S-Monel material (fig. 8(d)), run with the mineral oil and the fluorocarbon, resulted in the highest amount of wear.

These results indicate that, since boundary lubrication predominates in the cage pocket surface, chemical effects are of prime importance. No generalization of these data is possible. However, it can be concluded that at 500° F low wear can be achieved with the ester lubricant and the M-1 material; at 700° F, low wear is obtained with S-Monel run with the polyphenyl ether as the lubricant.

Wear Rate

Since, under marginal lubricating conditions, cage wear can be a limiting factor in bearing operation, material wear rate becomes important. The effect of running time on

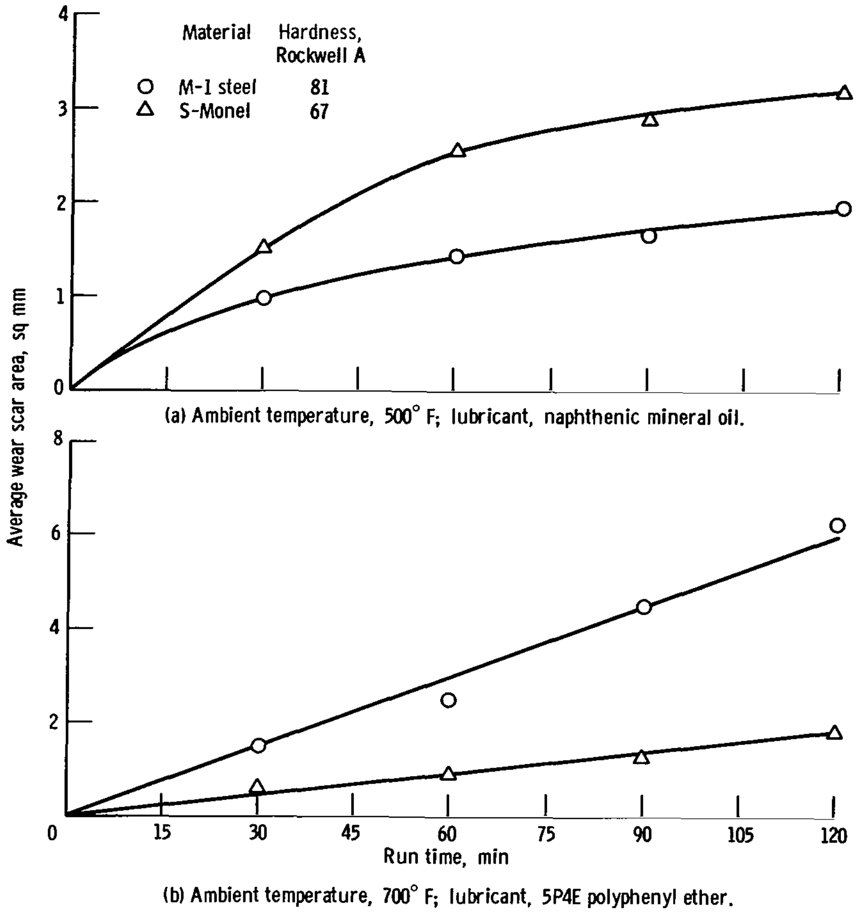


Figure 9. - Effect of running time on cage wear. Shaft speed, 1200 rpm; system load, 1000 pounds.

wear of the S-Monel and the M-1 materials at 500° F run with the mineral oil as the lubricant is shown in figure 9(a). For both materials, wear rate decreases with running time. It is speculated that eventually the wear rate would level off at a low level and remain constant. These data are consistent with sliding wear data, which show a decrease in the wear rate with time (ref. 1, p. 49).

The results at 700° F with the polyphenyl ether with the same two cage materials are shown in figure 9(b). For the S-Monel and the M-1 materials, the wear rate is apparently constant.

SUMMARY OF RESULTS

A cage compatibility tester was used to determine the capabilities of six bearing-cage materials to operate in the temperature range from 500° to 700° F. The effect of material hardness, lubricating fluid, and temperature was investigated. The following results were obtained:

1. At temperatures of 500° and 700° F, S-Monel and M-1 materials gave least wear relative to the other cage materials studied.

2. For S-Monel and M-1, wear decreased with increasing material hardness.

3. At 500° F, minimum cage wear was obtained with the M-1 material of Rockwell A hardness 81 run with an ester-base lubricant.

4. At 700° F, minimum cage wear was obtained with the S-Monel material of Rockwell A hardness 67 run with a polyphenyl ether lubricant.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 19, 1966,
720-03-01-01-22.

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