NASA TECHNICAL MEMORANDUM

NASA TM X-68174

NASA TM X-68174

ROLLING-ELEMENT FATIGUE LIFE OF SILICON NITRIDE BALLS - PRELIMINARY TEST RESULTS

by Richard J. Parker and Erwin V. Zaretsky
Lewis Research Center
Cleveland, Ohio

November 1972

This information is being published in preliminary form in order to expedite its early release.

ABSTRACT

Hot-pressed silicon nitride was evaluated as a rolling-element bearing material. The five-ball fatigue tester was used to test 12.7 mm (0.500 in.) diameter balls at a maximum Hertz stress of 5.52×10^{9} N/m^2 (800,000 psi) at a race temperature of 328 K (130° F). The fatigue spalls in the silicon nitride resembled those in typical bearing steels. The ten-percent fatigue life of the silicon-nitride balls was approximately one-eighth to one-fifth that of typical bearing steels (52100 and M-50). The load capacity of the silicon nitride was approximately one-third that of typical bearing steels. The load capacity of the silicon nitride was significantly higher than previously tested ceramic materials for rolling-element bearings.

ROLLING-ELEMENT FATIGUE LIFE OF SILICON NITRIDE BALLS - PRELIMINARY TEST RESULTS

by Richard J. Parker and Erwin V. Zaretsky

Lewis Research Center

E-7219

INTRODUCTION

Ceramic materials offer some potential advantages for rolling-element bearing components because of their capability of operating over a wide temperature range and their low density relative to rolling-element bearing steels. The low density of ceramics make them attractive as ball materials for very high speed bearings. Lower mass balls can diminish the reduction in fatigue life of high-speed ball bearings that results from excessive centrifugal force on the balls and subsequent increased stress at the outer race (ref. 1).

Ceramic materials generally maintain their strength and corrosion resistance over a range of temperatures much greater than typical rolling-element bearing steels. As a result they have been proposed for very high temperature rolling-element bearing applications (refs. 2 and 3) both with and without lubrication. Life tests with ceramic materials such as aluminum oxide, silicon carbide, and a crystallized glass ceramic have shown fatigue lives and load capacities much lower than those of typical bearing steels at room temperature (refs. 4 and 5).

Hot-pressed silicon nitride is a ceramic material which has been proposed for rolling-element bearings as well as for journal bearings (ref. 6). It is the objective of this program to compare the rolling-element fatigue life of hot-pressed silicon nitride with typical rolling-element bearing steels.

In order to accomplish the above objective, a group of 12.7 mm (0.500-in.) diameter hot-pressed silicon nitride balls was tested in the five-ball fatigue tester. Test conditions included a maximum Hertz stress of 5.52×10^{9} N/m^{2} (800,000 psi), a contact angle of 30°, a shaft speed of 9400 rpm, a super-refined naphthenic mineral oil lubricant, and a race temperature of 328 K (130° F). The silicon nitride balls were used as upper balls in the five-ball test assembly with lower balls of AISI M-50 steel.

APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester was used for all tests conducted. The apparatus is shown in figure 1 and is described in detail in reference 7. This fatigue tester consists essentially of an upper test ball pyramided upon four lower balls that are positioned by a separator and are free to rotate in an angular-contact raceway. System loading and drive are supplied through a vertical drive shaft, which grips the upper test ball. For every revolution of the drive shaft, the upper test ball received three stress cycles from the lower balls. The upper test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and the lower balls function in a manner similar to the cage and the balls in a bearing.

Lubrication is provided by a once-through, mist lubrication system. The lubricant was a super-refined naphthenic mineral oil with a viscosity of 79 centistokes (79×10^{-6} m^2/sec) at 311 K (100° F). Vibration instrumentatio detects a fatigue failure on either the upper or a lower ball and automatically shuts down the tester. This provision allows unmonitored operation and a consistent criterion for failure.

Silicon Nitride Balls

The hot-pressed silicon nitride balls used in these tests were fabricated from one batch of material. The balls were made from cubes cut from silicon nitride plate material and were finished to a AFBMA grade 10 specification. Surface finish of the balls was 2.5 to 5.0×10^{-6} cm (1 to 2 μin.) rms. The silicon nitride balls were notched to form a tongue (shown in fig. 1(b)) to facilitate location and rotation by the drive shaft.

Typical mechanical properties, as furnished by the manufacturer, of the hot-pressed silicon nitride are shown in table I.

Fatigue Testing

Before they were assembled in the five-ball fatigue tester, all test-section components were flushed and scrubbed with ethyl alcohol and wiped dry with clean cheesecloth. The test balls were examined for imperfections at a magnification of 15 diameters. After examination, all test balls were coated with test lubricant to prevent corrosion and wear at startup. A new set of five balls was used for each test. Each test was suspended when a fatigue failure occurred on an upper test ball or when a preset cutoff time was reached. The speed, outer-race temperature, and oil flow were monitored and recorded at regular intervals. After each test, the outer race of the five-ball system was examined visually for damage. If any damage was discovered, the race would be replaced before further testing. The stress that was developed in the contact area was calculated by using the Hertz formulas given in reference 8.

Method of Presenting Fatigue Results

The statistical methods of reference 9 for analyzing rolling-element fatigue data were used to obtain a plot of the log-log of the reciprocal of the probability of survival as a function of the log of upper-ball stress cycles to failure (Weibull coordinates). For convenience, the ordinate is graduated in statistical percent of specimens failed. From a plot such as this, the number of upper-ball stress cycles necessary to fail any given portion of the specimen group may be determined.

For purposes of comparison, the 10-percent life on the Weibull plot was used. The 10-percent life is the number of upper-ball stress cycles within which 10 percent of the specimens can be expected to fail; this 10-percent life is equivalent to a 90-percent probability of survival. The failure index indicates the number of specimens that failed out of those tested.

RESULTS AND DISCUSSION

Five-Ball Fatigue Results

Twenty 12.7-mm (0.500-in.) diameter hot-pressed silicon nitride balls were tested as upper test balls in the five-ball fatigue tester. Test conditions included a maximum Hertz stress of 5.52×10^9 N/m^2 (800,000 psi), a contact angle of 30°, and a shaft speed of 9400 rpm. Tests were run at a race temperature of 328 K (130° F) with a super-refined naphthenic mineral oil as the lubricant. Lower balls in the five-ball assembly were AISI M-50 12.7-mm (0.500-in.) balls.

The results of the fatigue tests are shown as a Weibull plot in figure 2 and are summarized in table II. The scatter in the fatigue life data, as indicated by the slope of the Weibull line, is similar to that expected for typical bearing steels. Also shown on figure 2 for comparison purposes are data from reference 10 for AISI 52100 and AISI M-50 steel balls tested under identical conditions. The ten-percent fatigue life of the silicon nitride balls was approximately one-eighth of that of the AISI 52100 balls and approximately one-fifth that of the AISI M-50 balls.

Figure 3(a) shows a typical fatigue spall that developed on one of the silicon nitride balls. The spalls are similar in appearance to those in bearing steels (fig. 3(b)) except that those on the silicon-nitride balls were slightly smaller. The spall depth was similar to those on steel balls, unlike those on aluminum oxide and silicon carbide balls (ref. 5) which were much shallower. No measurable wear was detected on any of the silicon nitride test balls.

Load Capacity Comparison

On the basis of load capacity (the contact load in pounds that will produce failure of ten-percent of a group of test balls in one million stress cycles), the silicon nitride balls were compared with the AISI 52100 and AISI M-50 data from reference 10. In the present tests, it should be recalled, the silicon nitride balls were tested in contact with AISI M-50 steel lower balls. For a maximum Hertz stress of 5.52×10^9 N/m^2 (800,000 psi) the contact (normal) load, P_o, between the silicon nitride upper ball and a steel lower ball was 512 N (115 lb).

Assuming that the accepted load-life relation for steel is applicable to silicon nitride (which is necessary until further data are available), the capacity, C, of the silicon nitride-steel combination is

$$C = P_o \sqrt[3]{B_{10} \times 10^{-6}}$$

$$= 670 \text{ N } (150 \text{ lb})$$

where B_{10} is 2.5 million revolutions from figure 2.

For the AISI 52100 and AISI M-50 data of reference 10, the capacities of these steels are 2110 N (475 lb) and 1860 N (418 lb), respectively. Thus, the capacity of the silicon nitride-steel combination is only about one-third of that of two typical high quality bearing steels. In comparing these results with those obtained with other ceramic materials (refs. 4 and 5), the silicon nitride appears to be superior to materials such as aluminum oxide, silicon carbide, and crystallized-glass ceramic for rolling-element bearing applications. These materials have shown capacities from one to seven percent that of bearing steels. These comparisons neglect the small differences in stressed volume of the various materials due to differences in elastic modulus of the various materials.

SUMMARY OF RESULTS

Silicon nitride balls were tested under rolling-contact conditions in the five-ball fatigue tester at 5.52×10^9 N/m^2 (800,000 psi), at a race temperature of 328 K (130° F), and a speed of 9400 rpm with a super-refined naphthenic mineral oil as the lubricant. Fatigue lives were compared with those for typical bearing steels, 52100 and M-50. The following results were obtained.

1. The ten-percent fatigue life of the silicon nitride was approximately one-eighth to one-fifth that of typical bearing steels (52100 and M-50) under the same test conditions.

2. The load capacity of the silicon nitride balls is about one-third that of typical bearing steels under the same test conditions.

3. The fatigue spalls on the silicon nitride balls were similar in appearance to those obtained with typical bearing steels.

REFERENCES

1. Harris, T. A.: On the Effectiveness of Hollow Balls in High-Speed Thrust Bearings. ASLE Trans., vol. 11, no. 4, Oct. 1968, pp. 290-294.

2. Taylor, K. M.; Sibley, L. B.; and Lawrence, J. C.: Development of a Ceramic Rolling Contact Bearing for High Temperature Use. Paper 61-LUB-12, ASME, Oct. 1961.

3. O'Rourke, W. F.: Research on Developing Design Criteria for Anti-Friction Airframe Bearings for High Temperature Use. General Motors Corp. (WADD-TR-60-46), Oct. 1960.

4. Zaretsky, Erwin V.; and Anderson, William J.: Rolling-Control Fatigue Studies with Four Tool Steels and a Crystallized Glass Ceramic. J. Basic Eng., vol. 83, no. 4, Dec. 1961, pp. 603-612.

5. Parker, Richard J.; Grisaffe, Salvatore J.; and Zaretsky, Erwin V.: Rolling-Contact Studies with Four Refractory Materials to 2000 F. ASLE trans., vol. 8, no. 3, July 1965, pp. 208-216.

6. Dee, C. W.: Silicon Nitride: Tribological Applications of a Ceramic Material. Tribiology, vol. 3, no. 2, May 1970, pp. 89-92.

7. Carter, Thomas L.; Zaretsky, Erwin V.; and Anderson, William J.: Effect of Hardness and other Mechanical Properties on Rolling-Contact Fatigue Life of Four High-Temperature Bearing Steels. NASA TN D-270, 1960.

8. Jones, A. B.: New Departure - Analysis of Stresses and Deflections. Vols. 1 and 2. New Departure Div., General Motors Corp., 1946.

9. Johnson, L. G.: The Statistical Treatment of Fatigue Experiments. Rep. GMR-202, General Motors Corp., Apr. 1959.

10. Parker, R. J.; and Zaretsky, E. V.: Rolling-Element Fatigue Lives of Through-Hardened Bearing Materials. J. Lub. Tech., vol. 94, no. 2, Apr. 1972, pp. 165-173.

TABLE I. - PROPERTIES OF HOT-PRESSED SILICON NITRIDE

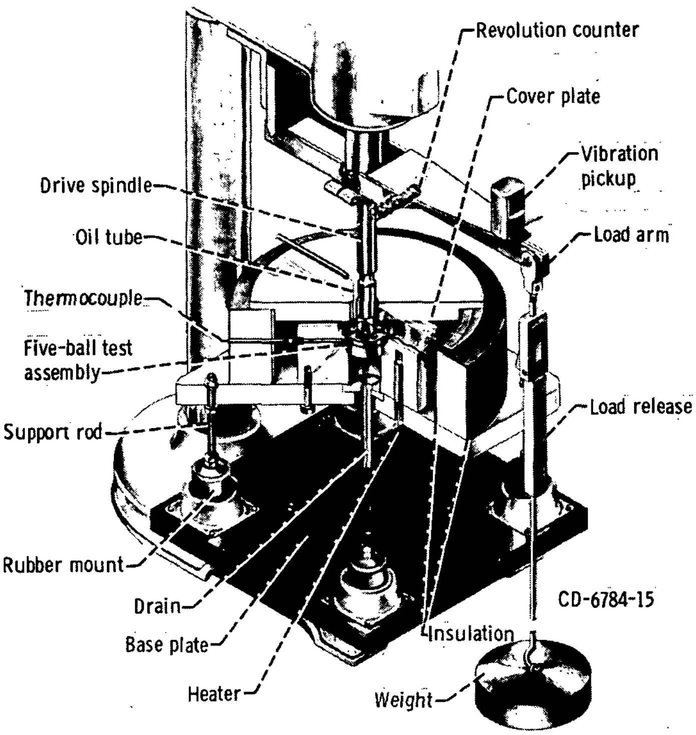
Chemical formula	Si_3N_4
Bulk density, g/cc	3.11 to 3.2
Modulus of elasticity, N/m^2 (psi)	
at 289 K (77° F)	31×10^{10} (45×10^{6})
at 1273 K (1832° F)	31×10^{10} (45×10^{6})
Modulus of rupture, N/m^2 (psi)	
at 289 K (77° F)	8.3×10^{8} (1.2×10^{5})
at 1173 K (1652° F)	7.6×10^{8} (1.1×10^{5})
at 1673 K (2552° F)	0.34×10^{8} (0.5×10^{5})
Thermal expansion, K^{-1} ($^\circ F^{-1}$)	
289 to 1773 K (77 to 2732° F)	2.75×10^{6} (1.5×10^{6})

TABLE II. - FATIGUE TEST RESULTS WITH SILICON NITRIDE BALLS

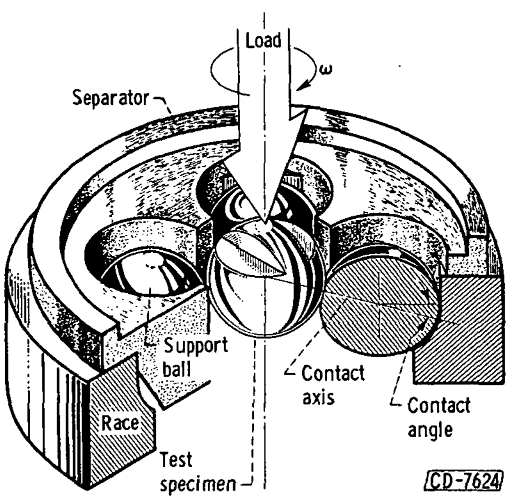
[Maximum Hertz stress, 5.52×10^{9} N/m^2 (800,000 psi); race temperature, 328 K (130° F); contact angle, 30°; shaft speed, 9400 rpm.]

Ten percent life, stress cycles	2.5×10^{6}
Fifty percent life, stress cycles	17×10^{6}
Weibull slope	0.99
Failure index	19 out of 20

E-7219



(a) Cutaway view of five-ball fatigue tester.



(b) Five-ball test assembly.

Figure 1.- Test apparatus.

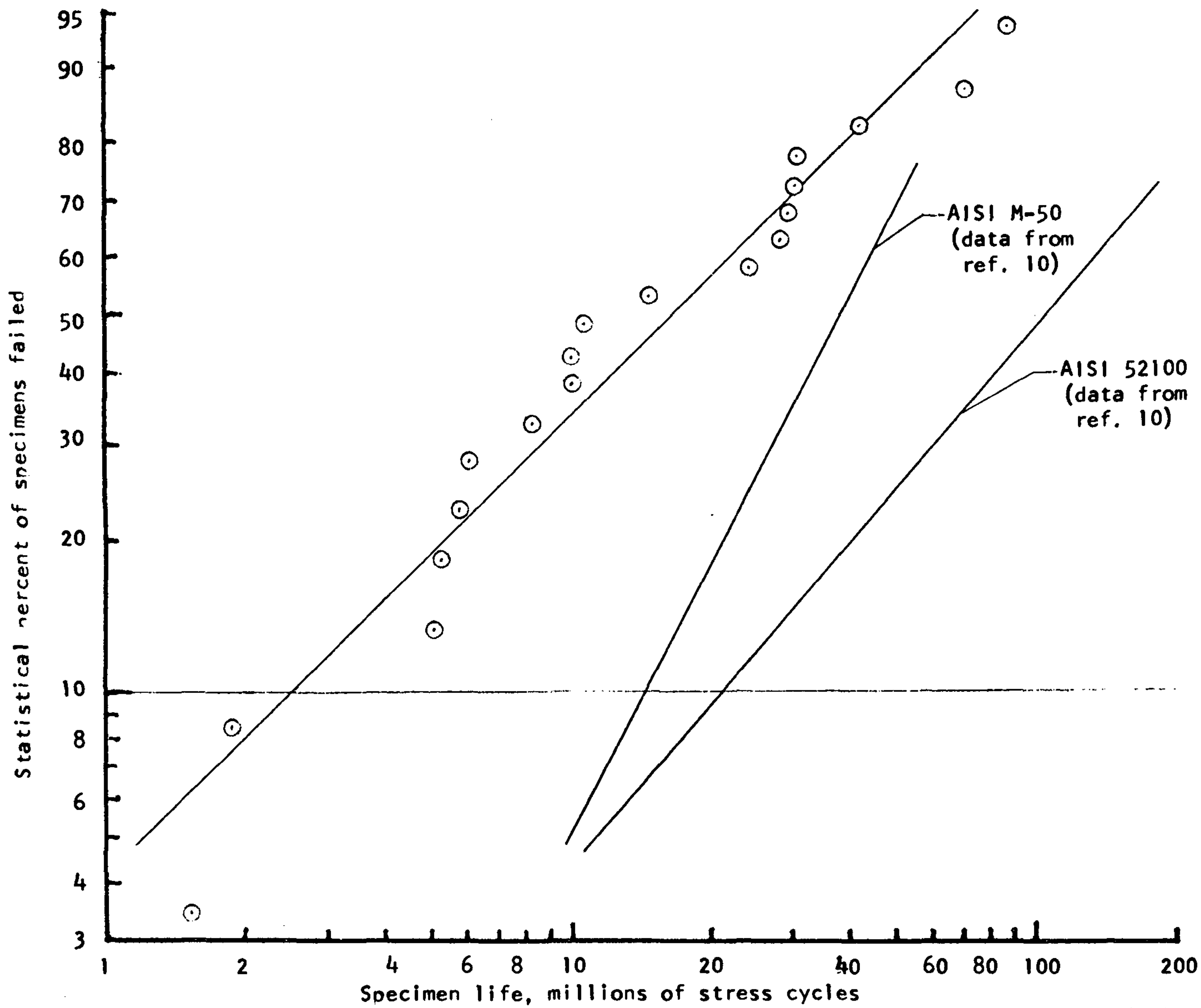
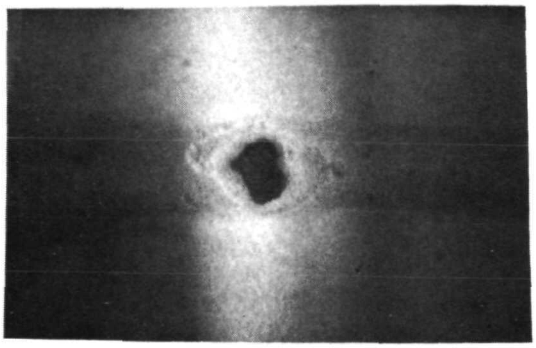


Figure 2.- Rolling-element fatigue life of hot-pressed silicon nitride balls in the five-ball fatigue tester. Maximum Hertz stress, 5.52×10^9 N/m^2 (800,000 psi); shaft speed, 9400 rpm; race temperature, 328K (130°F); contact angle, 30°; lubricant, super-refined naphthenic mineral oil.



(a) Hot-pressed silicon nitride.

E-7219

(b) AISI M-50.

Figure 3.- Typical rolling-element fatigue spalls on upper test balls in five-ball fatigue tester.