NASA TECHNICAL NOTE **NASA TN D-7794**

NASA TN D-7794

(NASA-TN-D-7794) ROLLING-ELEMENT FATIGUE LIFE OF SILICON NITRIDE BALLS (NASA) 19 p HC $3.00 CSCL 13I
N74-34889
Unclas
H1/15 51735

ROLLING-ELEMENT FATIGUE LIFE OF SILICON NITRIDE BALLS

by Richard J. Parker and Erwin V. Zaretsky

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1974

ROLLING-ELEMENT FATIGUE LIFE OF SILICON NITRIDE BALLS

by Richard J. Parker and Erwin V. Zaretsky

Lewis Research Center

SUMMARY

Hot-pressed silicon nitride balls were tested under rolling-contact conditions in the five-ball fatigue tester. Test conditions were maximum Hertz stresses of 4.27×10^9 and 5.52×10^9 N/m^2 (620 000 and 800 000 psi), a race temperature of 328 K (130° F), a speed of 9400 rpm, and a super-refined naphthenic mineral oil as the lubricant. Fatigue lives were compared with those for typical bearing steels AISI 52100 and AISI M-50. A digital computer program was used to predict the dynamic performance characteristics and fatigue life of high-speed ball bearings with silicon nitride balls relative to that of bearings containing steel balls.

Extrapolation of the experimental results to contact loads which result in stress levels typical of those in rolling-element bearing applications indicate that hot-pressed silicon nitride running against steel may be expected to yield fatigue lives comparable to or greater than those of bearing quality steel running against steel. The fatigue spalls on the silicon nitride balls were similar in appearance to those observed in tests with typical bearing steels. The fatigue life with the hot-pressed silicon nitride is considerably greater than that of any other ceramic or cermet tested.

A digital computer analysis indicates that there is no improvement in the lives of 120-millimeter-bore angular-contact ball bearings of the same geometry operating at DN values from 2 to 4 million where hot-pressed silicon nitride balls are used in place of steel balls. The higher modulus of elasticity of silicon nitride tends to offset the benefits of its lower density.

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. The fatigue life of very-high-speed ball bearings can be reduced as a result of excessive centrifugal force on the balls and subsequent increased stress at the outer race (ref. 1). Lower mass balls can significantly diminish this fatigue life reduction.

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 alumina, silicon carbide, and a crystallized glass ceramic have shown fatigue lives and dynamic load capacities at room temperature much lower than those of typical bearing steels (refs. 4 and 5).

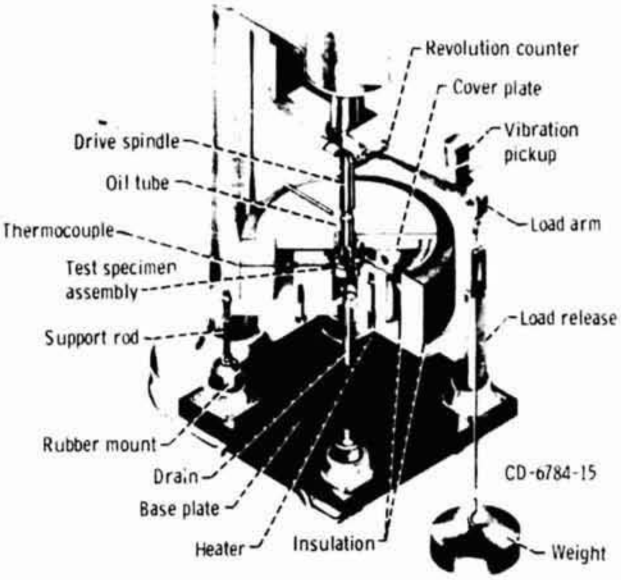
Hot-pressed silicon nitride is a ceramic material which has been proposed for rolling-element bearings as well as for journal bearings (ref. 6). It is the objective of this program to compare the rolling-element fatigue life of hot-pressed silicon nitride with typical rolling-element bearing steels and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

In order to accomplish this objective, a group of 12.7-millimeter- (0.500-in.-) diameter hot-pressed silicon nitride balls was tested in the five-ball fatigue tester. Test conditions included 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). To establish a stress-life relation for the material, tests were run at maximum Hertz stresses of 4.27×10^{9} and 5.52×10^{9} N/m^{2} (620 000 and 800 000 psi). The silicon nitride balls were used as upper balls in the five-ball test assembly with lower balls of AISI M-50 steel. A digital computer program was used to predict the dynamic performance characteristics and fatigue life of high-speed ball bearings with silicon nitride balls relative to that of bearings with steel balls.

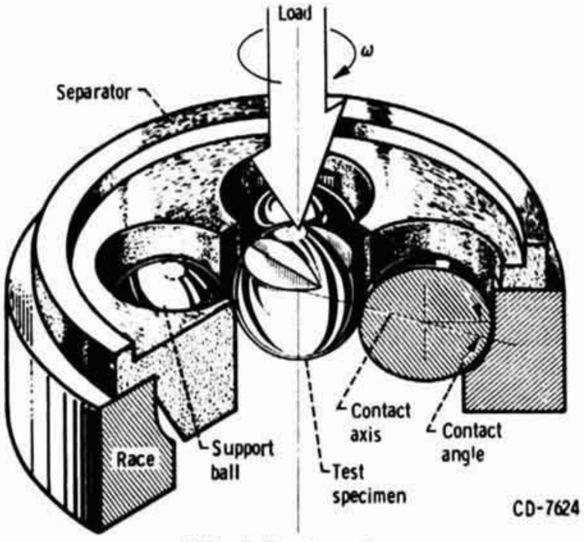
APPARATUS AND PROCEDURE

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 lower balls function in a manner similar to the cage and the balls in a bearing.



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



(b) Five-ball test assembly.

Figure 1. - Test apparatus.

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 instrumentation detects a fatigue failure on either the upper or the 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 as upper-test balls 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 2.5×10^{-6} to 5.0×10^{-6} centimeter (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 given in table I. The material tested in this program was from a billet of an early grade of hot-pressed silicon nitride (HS-110) with a bulk density of 3.14 grams per cubic centimeter and an analysis given in table II.

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 assembly was coated with lubricant to prevent wear at startup. A new set of five balls was used for each test. A new set of steel lower balls was used when a lower ball fatigue failure occurred. Each test was suspended when a fatigue failure occurred on the silicon nitride 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.

TABLE I. - TYPICAL PROPERTIES OF HOT-PRESSED SILICON NITRIDE

Chemical formula	Si_3N_4
Bulk density, g/cu cm	3.11 to 3.24
Modulus of elasticity, N/m^2 (psi)	
at 298 K (77° F)	31×10^{10} (45×10^{6})
at 1273 K (1832° F)	31×10^{10} (45×10^{6})
Thermal expansion (at 298 to 1773 K (77° to 2732° F)), K^{-1} ($^{o}F^{-1}$)	2.7×10^{-6} (1.5×10^{-6})
Flexure strength, N/m^2 (psi)	
at 298 K (77° F)	8.6×10^{8} (1.25×10^{5})
at 1273 K (1832° F)	4.8×10^{8} (0.70×10^{5})
at 1673 K (2552° F)	2.1×10^{8} (0.30×10^{5})

TABLE II. - ANALYSIS OF

HOT-PRESSED SILICON

NITRIDE (HS-110)

Element	Weight percent
Al	0.62
Fe	.50
Ca	.26
Mg	.56
Ti	.06
Mn	.07
W	1.50
Si_3N_4	Balance

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.

RESULTS AND DISCUSSION

Five-Ball Fatigue Results

Two groups of 12.7-millimeter- (0.500-in.-) diameter hot-pressed silicon nitride balls were tested as upper-test balls in the five-ball fatigue tester at two maximum Hertz stresses of 4.27×10^9 and 5.52×10^9 N/m^2 (620 000 and 800 000 psi). Test conditions included 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-millimeter- (0.500-in.-) diameter balls.

The results of the fatigue tests are shown as a Weibull plot in figure 2 and are summarized in table III. The slopes of the Weibull lines are similar to that expected for typical bearing steels. The life of the silicon nitride balls was greater at the lower stress than at the higher stress as expected. Also shown in figure 2 are the 90-percent confidence limits on the data as calculated by methods of reference 9. The interpretation of these limits is that the true life at each condition will fall between these limits 90 percent of the time. At the lower stress level where only six failures were recorded, the confidence band is considerably wider than at the higher stress level where 19 failures were obtained.

The 10- and 50-percent lives at each stress condition are plotted in figure 3 against maximum Hertz stress. Straight lines through the points indicate that for these data, life $L \propto (1/S_{max})^n$ where n equals 16 for both the 10- and 50-percent life levels. For a typical bearing steel (AISI 52100) under these identical conditions in the five-ball fatigue tester (ref. 10), n has been determined to be 12. A stress-life exponent of 16 was also obtained in reference 11 for hot-pressed silicon nitride bars running against steel rollers in a rolling-contact fatigue tester.

This higher stress-life exponent means that the hot-pressed silicon nitride is more sensitive to a change in stress than typical bearing steels. Thus, as stresses are re-

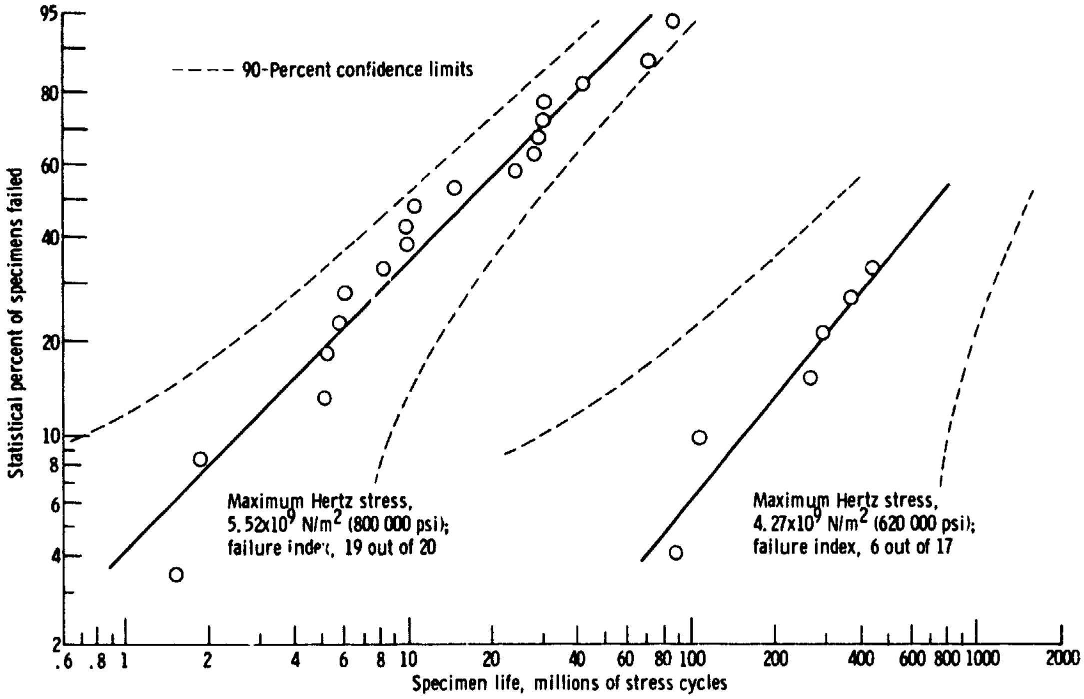


Figure 2. - Rolling-element fatigue life of 12.7-millimeter- (1/2-in. -) diameter HS-110 hot-pressed silicon nitride upper balls running against steel lower balls in five-ball fatigue tester. Shaft speed, 9400 rpm; race temperature, 328 K (130° F); contact angle, 30°; lubricant, super-refined naphthenic mineral oil.

TABLE III. - FATIGUE TEST RESULTS WITH HS-110 HOT-PRESSED SILICON NITRIDE BALLS RUNNING AGAINST AISI M-50 STEEL BALLS

[Shaft speed, 9400 rpm; race temperature, 328 K (130° F); contact angle, 30°; lubricant, super-refined naphthenic mineral oil.]

Item	Maximum Hertz stress, N/m^2 (psi)	
	4.27×10^9 (620 000)	5.52×10^9 (800 000)
Ten percent life, stress cycles	155×10^6	2.5×10^6
Fifty percent life, stress cycles	740×10^6	17×10^6
Weibull slope	1.21	0.99
Failure index[a]	6 out of 17	19 out of 20

[a] Failure index indicates number of upper balls that failed out of those tested.

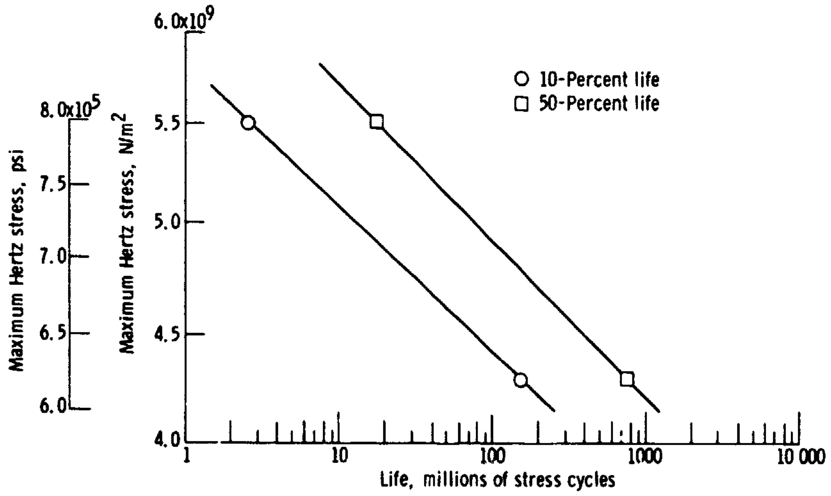


Figure 3. - Effect of maximum Hertz stress on rolling-element fatigue life of HS-110 hot-pressed silicon nitride upper balls running against steel lower balls in five-ball fatigue tester. $L \propto (1/S_{max})^{16}$.

duced to the level experienced in rolling-element bearing applications, silicon nitride running against steel would be expected to give fatigue lives equivalent to or greater than typical bearing steels.

This effect is illustrated in figure 4 where contact load in the five-ball fatigue tests is plotted against fatigue life and extrapolated to lower loads or stress levels experienced in rolling-element bearing applications. The reader must be cautious in extracting life data from this extrapolation, since little is known about the behavior of hot-pressed silicon nitride at those low stresses.

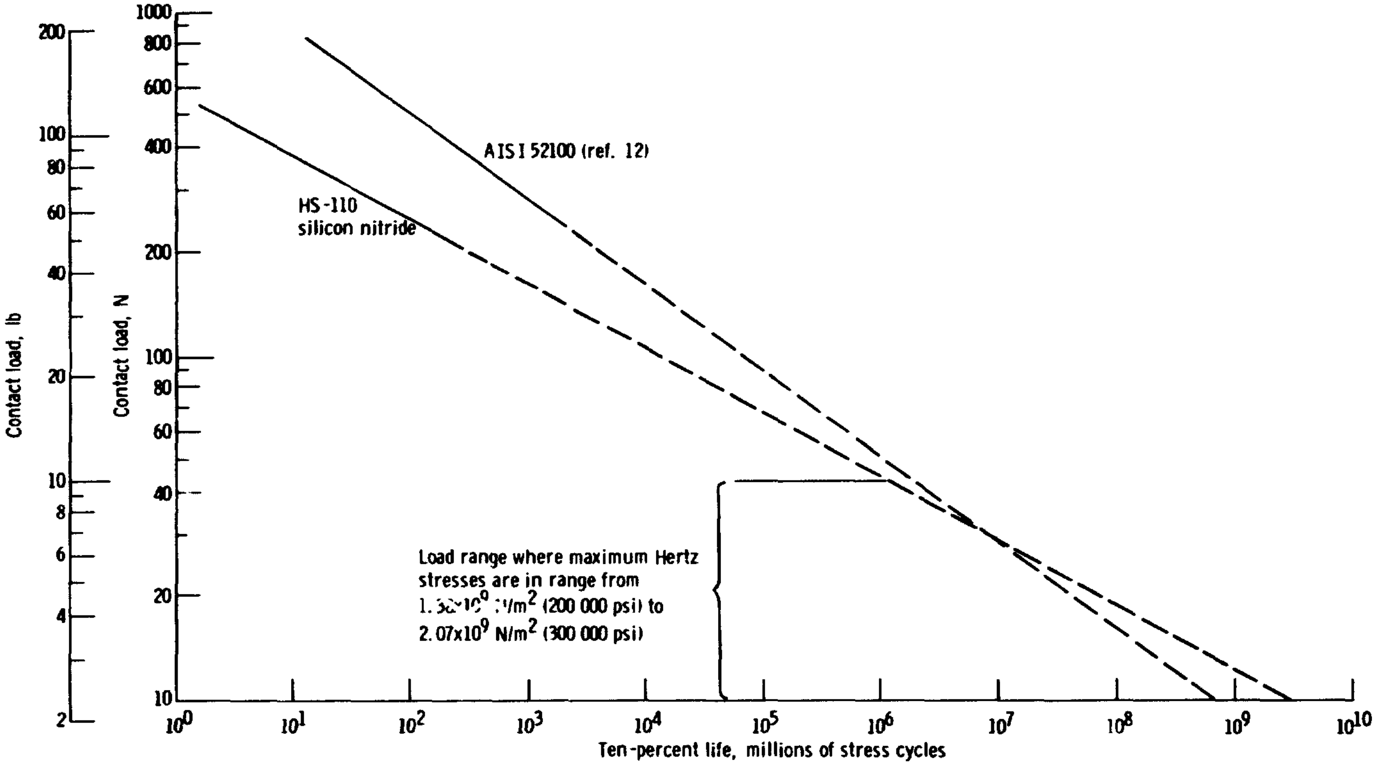


Figure 4. - Extrapolation of life data from five-ball fatigue tester to loads which yield maximum Hertz stresses in range experienced in rolling-element bearing applications.

Life Comparison with Other Materials

Figure 5 shows a comparison of life data for hot-pressed silicon nitride and for typical bearing steels, AISI 52100 and AISI M-50, (ref. 12) at a maximum Hertz stress of 5.52×10^9 N/m^2 (800 000 psi). The 10-percent fatigue life of the silicon nitride balls was approximately one-eighth that of the AISI 52100 balls and approximately one-fifth that of the AISI M-50 balls.

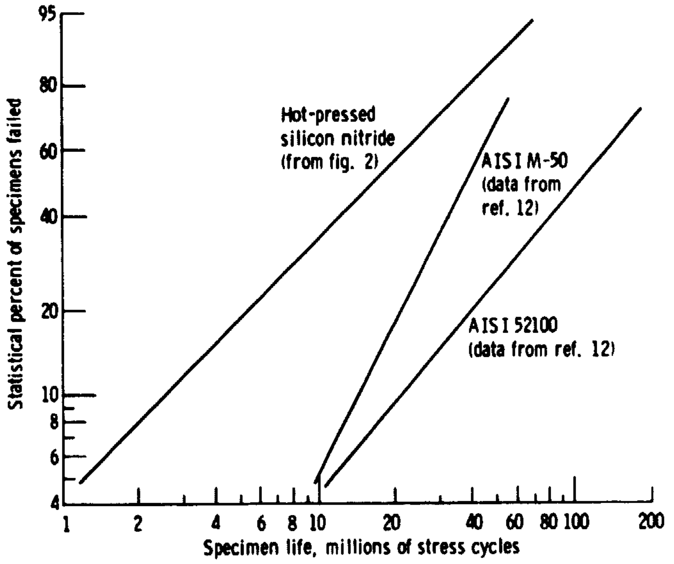


Figure 5. - Rolling-element fatigue life of hot-pressed silicon nitride balls and steel balls in five-ball fatigue tester. Maximum Hertz stress, 5.52×10^9 N/m^2 (800 000 psi); shaft speed, 9400 rpm; race temperature, 328 K (130° F); contact angle, 30°; lubricant, super-refined naphthenic mineral oil.

Figure 6(a) shows a typical fatigue spall that developed on one of the silicon nitride balls. The spalls are similar in appearance to those on bearing steels (fig. 6(b)) except that those on the silicon nitride balls were slightly smaller. The spall depth was similar to those on steel balls and was unlike those on alumina and silicon carbide balls (ref. 5) which were much shallower. No wear was observed on any of the silicon nitride test balls.

The silicon nitride balls that were tested were from a billet of an early grade of hot-pressed silicon nitride material (HS-110). A more recently available grade of hot-pressed silicon nitride (NC-132) (refs. 11, 13, and 14) is more dense, and more homogeneous and has a higher flexural strength than the early material. It would be expected that balls made from the newer material would have an improved fatigue life and dynamic capacity than the early material. This effect was realized in the tests of reference 11 where the life of the NC-132 silicon nitride exceeded that of AISI M-50 steel. The tests of reference 11 were also in the maximum Hertz stress range from 4.14×10^9 to 5.52×10^9 N/m^2 (600 000 to 800 000 psi) and were performed on a commonly used rolling-contact fatigue test machine utilizing a 0.952-centimeter- (0.375-in.-) diameter test ball.

Preliminary tests in the five-ball fatigue tester with NC-132 silicon nitride indicate an improvement in fatigue life over the HS-110 material. At a maximum Hertz stress of 5.52×10^9 N/m^2 (800 000 psi), the 10-percent life of NC-132 in these preliminary tests is about equal to AISI 52100 at the same conditions. In reference 5 the 10-percent life of hot-pressed alumina balls running lubricated against steel lower balls in a five-ball fatigue tester was 0.5×10^6 stress cycles at 4.14×10^9 N/m^2 (600 000 psi). Hot-pressed alumina gave the longest lives in similar tests of any ceramic or cermet material (refs. 4 and 5). The 10-percent life of the silicon nitride-steel combination from table III is 155×10^6 stress cycles at 4.27×10^9 N/m^2 (620 000 psi) or over two orders of magnitude greater than the hot-pressed alumina at a similar maximum Hertz stress.

(a) Hot-pressed silicon nitride.

(b) AISI M-50.

Figure 6. - Typical rolling-element fatigue spalls on upper test balls in five-ball fatigue tester.

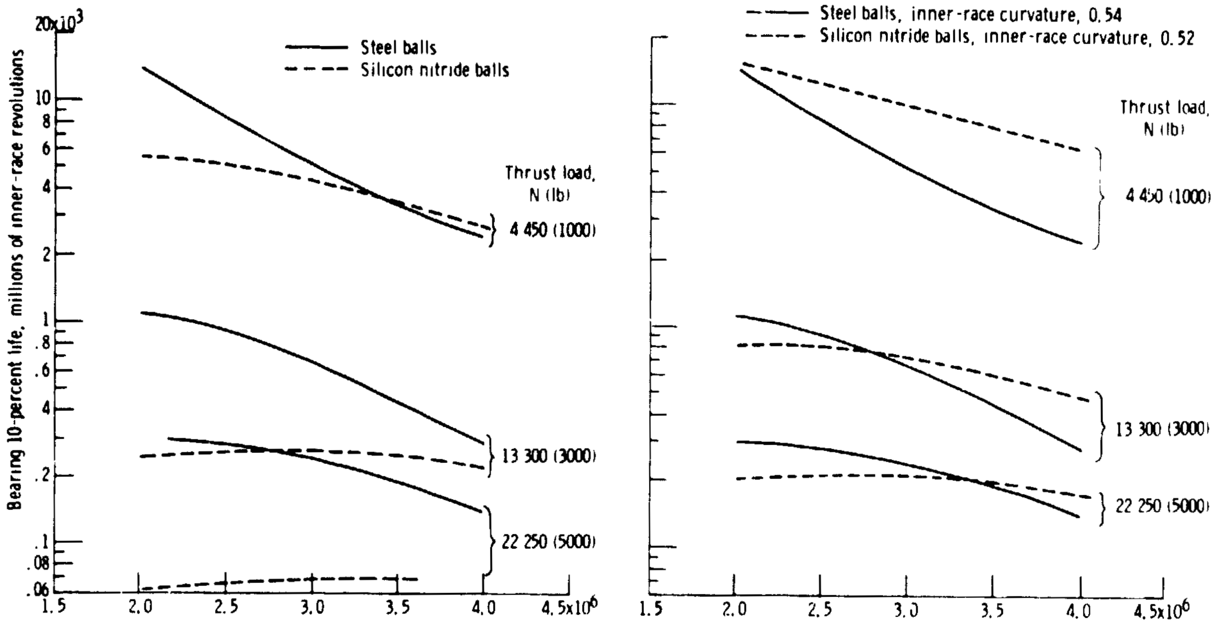
Predicted Bearing Life with Silicon Nitride Balls

It was speculated that the use of silicon nitride balls in very high-speed ball bearings can reduce the centrifugal load of the balls on the outer race from that experienced with steel balls. A digital computer program for the analysis of dynamic performance characteristics of ball bearings (ref. 15) was used to evaluate the effect of the low mass silicon nitride balls on ball bearing fatigue life. The analysis was performed with both steel and silicon nitride balls with steel inner and outer races of a 120-millimeter-bore angular-contact ball bearing. The ball diameter in both cases was 20.64 millimeters (0.8125 in.). The calculation of fatigue life in the analysis of reference 15 is based on the Lundberg-Palmgren analysis (ref. 16).

It was assumed that the theoretical distribution of failures between the rolling elements and the races as considered in reference 16 is not altered by the substitution of silicon nitride balls for steel balls. That is, it was assumed that the silicon nitride balls will have lives equal to or exceeding those of the steel balls.

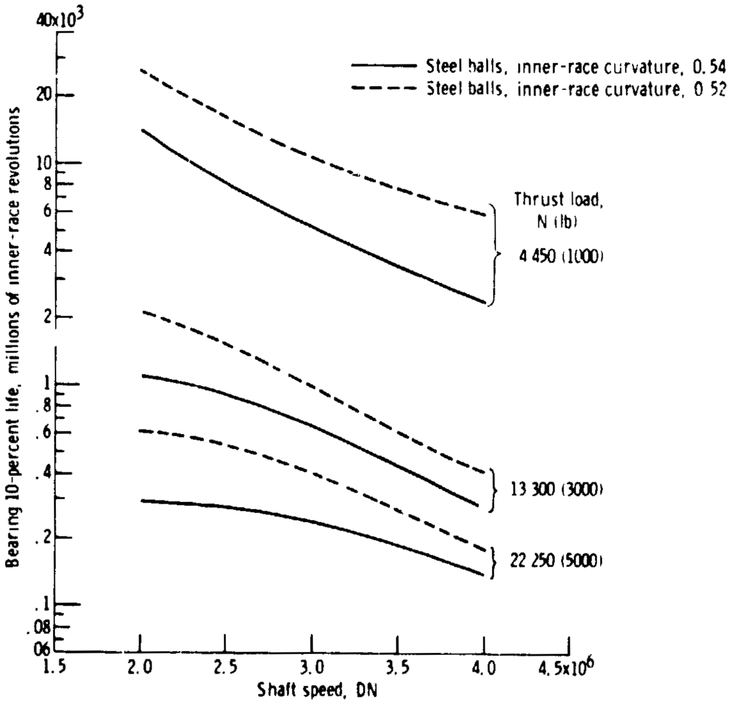
The analytical bearing life results for three thrust loads are seen in figure 7(a). For a bearing containing silicon nitride balls with internal geometry identical to that with the bearing containing steel balls, bearing life is not improved at speeds to at least 3.5 million DN. This lack of life improvement is due to the very high modulus of elasticity of silicon nitride and the resulting increase in Hertz stress for a given contact load. (The modulus of elasticity of silicon nitride is approximately 1.5 times that of steel. Because of this difference, the Hertz stress in the contact of a silicon nitride ball on a steel will be higher than that with a steel race for a given contact load and geometry.) While centrifugal force is reduced by at least 50 percent, the stress at the inner race is greatly increased (table IV). The stress at the outer race is nearly unchanged. As a result, bearing life is decreased. From this analysis, it may be concluded that the life of 120-millimeter-bore ball bearings of the same geometry operating at DN values from 2 to 4 million are not improved by substituting silicon nitride balls in place of steel balls.

Where silicon nitride balls are used, refinements in bearing internal geometry may be needed to account for the effects of initial radial clearance, thermal expansion and centrifugal forces on operating clearance, contact angle, and heat generation. As a result, the optimum internal geometry of a bearing containing silicon nitride balls may be different from that of a bearing containing steel balls because of the differing thermal expansion coefficients and densities of the two materials. Based on the preceding assumption, it is probable that there may be an optimized bearing geometry and operating condition wherein it would be advantageous to use silicon nitride balls in place of steel balls. As an example, the inner- and outer-race curvatures of 54 and 52 percent, respectively, for the 120-millimeter-bore bearing were chosen based on analysis for use with steel



(a) Steel balls and silicon nitride balls with inner-race curvature of 0.54.

(b) Steel balls and silicon nitride balls with inner-race curvatures of 0.54 and 0.52, respectively.



(c) Steel balls with inner-race curvatures of 0.54 and 0.52.

Figure 7. - Predicted life of 120-millimeter-bore angular-contact ball bearing. Ball diameter, 20.64 millimeters (0.8125 in.).

TABLE IV. - PREDICTED LIFE OF 120-MILLIMETER-BORE HIGH-SPEED ANGULAR-CONTACT BALL BEARING WITH EITHER STEEL OR SILICON NITRIDE BALLS

[Thrust load, 13 300 N (3000 lb); ball diameter, 20.64 mm (0.8125 in.).]

Shaft speed		Centrifugal force, N(lb)	Maximum Hertz stress, MN/m^2 (ksi)		Bearing fatigue life, revs (hr)
DN	rpm		Inner	Outer	
		Steel balls; inner race curvature, 0.54			
2.0×10^6	16 700	1690(379)	1800(258)	1680(244)	1090×10^6(1090)
2.5	20 850	2630(591)	1750(254)	1810(263)	900(720)
3.0	25 000	3750(842)	1740(252)	1940(282)	650(433)
3.5	29 150	5000(1124)	1720(250)	2080(301)	432(247)
4.0	33 300	6360(1429)	1710(248)	2210(320)	282(141)
Silicon nitride balls; inner race curvature, 0.54					
2.0×10^6	16 700	667(150)	2110(306)	1780(259)	248×10^6(248)
2.5	20 850	1040(235)	2090(303)	1850(268)	260(208)
3.0	25 000	1510(339)	2080(301)	1920(279)	262(175)
3.5	29 150	2060(462)	2050(298)	2010(292)	251(144)
4.0	33 300	2670(600)	2040(296)	2100(305)	225(112)
Silicon nitride balls; inner race curvature, 0.52					
2.0×10^6	16 700	667(150)	1780(259)	1750(254)	820×10^6(820)
2.5	20 850	1040(234)	1750(254)	1810(262)	812(650)
3.0	25 000	1490(336)	1720(250)	1880(272)	739(492)
3.5	29 150	2010(452)	1700(247)	1960(284)	617(352)
4.0	33 300	2570(578)	1680(244)	2040(296)	481(240)

balls considering minimal heat generation and maximum fatigue life. Bearings of this design with steel balls have been fabricated and tested at speeds to 3 million DN (ref. 17).

For purposes of discussion, it will be assumed that the inner-race curvature is reduced from 54 to 52 percent for the bearing to be analyzed with silicon nitride balls. This modification is made to reduce the stress at the inner-race ball contact to approximately the level calculated for the referenced steel-ball bearing. Table IV shows the resulting stress reduction calculated for this modified geometry and a modest fatigue life improvement predicted for shaft speeds greater than 3 million DN for the 13 300-newton (3000-lb) case.

Figure 7(b) indicates that the beneficial effect of the reduced mass of silicon nitride balls can be realized at shaft speeds greater than 3.5 million DN at 22 250-newton

(5000-lb) thrust load and at shaft speeds greater than 2 million DN at 4450-newton (1000-lb) thrust load. However, as shown in figure 7(c), the use of an inner-race curvature of 0.52 for the steel-ball bearing also would have a life improvement over the steel-ball bearing with an inner-race curvature of 0.54. The heat generation in the inner-race steel-ball contact will be higher with the 0.52 curvature because of the larger contact area associated with smaller curvatures. It should be recalled that the inner-race curvature of 0.54 for the steel-ball bearing was an optimized design based in part on minimized heat generation.

In general, this analysis indicates that the use of silicon nitride balls to replace steel balls in high-speed bearings will not yield an improvement in fatigue life over the speed range of anticipated advanced airbreathing engine mainshaft ball bearings or up to 3 million DN. However, at some conditions of very high speeds and light loads, modest life improvements are indicated, but only if modifications are made in bearing internal geometry (inner-race curvature, for example).

SUMMARY OF RESULTS

Hot-pressed silicon nitride balls were tested under rolling-contact conditions in the five-ball fatigue tester. Test conditions were maximum Hertz stresses of 4.27×10^9 and 5.52×10^9 N/m^2 (620 000 and 800 000 psi), a race temperature of 328 K (130° F), a speed of 9400 rpm, and a super-refined naphthenic mineral oil as the lubricant. Fatigue lives were compared with those for typical bearing steels, AISI 52100 and AISI M-50. A digital computer program was used to predict the dynamic performance characteristics and fatigue life of high-speed ball bearings with silicon nitride balls relative to that with bearings containing steel balls. The following results were obtained:

1. Extrapolation of the experimental results to contact loads which result in stress levels typical of those in rolling-element bearing applications indicate that hot-pressed silicon nitride running against steel may be expected to yield fatigue lives comparable to or greater than those of bearing quality steel running against steel.

2. A digital computer analysis indicates that there is no improvement in the lives of 120-millimeter-bore ball bearings of the same geometry operating at DN values from 2 to 4 million where hot-pressed silicon nitride balls are used in place of steel balls. The higher modulus of elasticity of silicon nitride tends to offset the benefits of its lower density.

3. The fatigue life of hot-pressed silicon nitride, is considerably greater than that of any other ceramic or cermet tested.

4. The fatigue spalls on the silicon nitride balls were similar in appearance to those observed in tests with typical bearing steels.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 30, 1974,
501-24.

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. WADD-TR-60-46, Wright Air Development Div., Wright-Patterson Air Force Base, 1960.

4. Zaretsky, Erwin V.; and Anderson, William J.: Rolling-Contact 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 Engineering Data; Analysis of Stresses and Deflections. Vols. 1 and 2. General Motors Corp., 1946.

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

10. Parker, Richard J.; and Zaretsky, Erwin V.: Reevaluation of the Stress-Life Relation in Rolling-Element Bearings. NASA TN D-6745, 1972.

11. Baumgartner, H. R.: Evaluation of Roller Bearings Containing Hot Pressed Silicon Nitride Rolling Elements. Paper presented at "Second Army Technology Conference, Ceramics for High Performance Applications," Hyannis, Mass., Nov. 13-16, 1973.

12. 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.

13. Baumgartner, H. R.; Sundberg, D. V.; and Whieldon, W. M.: Silicon Nitride in Rolling Contact Bearings. Norton Co. (AD-771393), 1973.

14. Alliegro, R. A.; Richerson, D. W.; Torti, M. L.; Washburn, M. E.; and Weaver, G. Q.: Silicon Nitride and Silicon Carbide for High Temperature Engineering Applications. Paper presented at British Ceramic Society Convention 1972, Basic Science Section, Trinity College, Cambridge, U. K., July 4-6, 1972.

15. Crecelius, W. J.; Harris, T. A.; and Mindel, M. H.: Dynamic Analysis of High Speed Ball Bearings Under Combined Loading. Rept. AE72A004, SKF Industries, Inc., 1972.

16. Lundberg, G.; and Palmgren, A.: Dynamic Capacity of Rolling Bearings. ACTA Polytechinca, Mechanical Engineering Series, Proceedings of Royal Swedish Academy of Engineering, vol. 7, no. 3, 1947.

17. Signer, H.; Bamberger, E. N.; and Zaretsky, E. V.: Parametric Study of the Lubrication of Thrust Loaded 120-mm Bore Ball Bearings to 3 Million Dn. Paper 73-LUB-24, ASME, Oct. 1973.

NASA-Langley, 1974