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ABSTRACT

Hot-pressed silicon nitride was evaluated as a rolling-element bearing material. This material has a low specific gravity (41 percent that of bearing steel) and has a potential application as low mass balls for very high-speed ball bearings. The five-ball fatigue tester was used to test 12.7-mm- (0.500-in-) diameter silicon nitride balls at maximum Hertz stresses ranging from 4.27×10^9 N/m^2 (620,000 psi) to 6.21×10^9 N/m^2 (900,000 psi) at a race temperature of 328K (130°F). The fatigue life of NC-132 hot-pressed silicon nitride was found to be equal to typical bearing steels and much greater than other ceramic or cermet materials at the same stress levels. A digital computer program was used to predict the fatigue life of 120-mm-bore angular-contact ball bearings containing either steel or silicon nitride balls. The analysis indicates that there is no improvement in the lives of bearings of the same geometry operating at DN values from 2 to 4 million where silicon nitride balls are used in place of steel balls.

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 [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 both with and without lubrication [2,3]. 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 [4,5].

Hot-pressed silicon nitride is a ceramic material which has been proposed for rolling-element bearings as well as for journal bearings [6]. Rolling-element fatigue testing of hot-pressed silicon nitride has resulted in seemingly contradictory results. Poor results were obtained in the limited tests reported in [7,8]; whereas the results reported in [9,10] showed the fatigue life of hot-pressed silicon nitride to exceed that of a typical rolling-element bearing steel. However, it was speculated that the porosity and impurity content of the particular grade of material as well as the surface preparation techniques had significant effects on the difference in results reported in [7,8] and [9,10]. The significance of these factors, discussed in [10], were that material porosity, inclusion content and finishing procedure significantly affected the rolling-element fatigue life of hot-pressed silicon nitride.

The objectives of the research reported in this paper were (a) to compare the lives of two grades of hot-pressed silicon nitride with typical rolling-element bearing steels and (b) predict the effects of silicon nitride balls on the fatigue life of high-speed ball bearings.

In order to accomplish the above objectives, 12.7-mm- (0.500-in-) diameter hot-pressed silicon nitride balls of two different grades were 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 328K (130°F). To establish a stress-life relation for the material, tests were run at maximum Hertz stresses in the range from 4.27×10^9 N/m^2 (620,000 psi) to 6.21×10^9 N/m^2 (900,000 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 identical bearings with steel balls.

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester was used for all tests conducted. The apparatus is shown in Fig. 1 and is described in detail in [11]. 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.

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 311K (100°F). Vibration instrumentation 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 as upper test balls were fabricated from one batch of each grade 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.

Typical mechanical properties of hot-pressed silicon nitride are shown in Table 1. Two grades of hot-pressed silicon nitride were tested in this program. These were an early grade (HS-110) with a bulk density of 3.14 g/cc and a more homogeneous and more dense grade (NC-132) with a bulk density of 3.24 g/cc. Analyses of these grades are shown in Table 2.

Fatigue Testing

The silicon nitride balls were run as upper balls in the five-ball test assembly with lower balls of AISI M-50 steel. A new set of lower balls was used for each upper ball tested. From 17 to 20 five-ball tests were run with each material grade at each stress level. Each test was terminated either when an upper ball failed by spalling fatigue or when a preset cut-off time was reached. Occasionally a lower ball failed in which case the set of lower balls was replaced, and the test was continued.

The stress that was developed in the contact area between the silicon nitride upper ball and the steel lower ball was calculated by using the Hertz formulas given in [12]. The statistical methods of [13] for analysing rolling-element fatigue data were used, and the fatigue data were plotted on Weibull coordinates.

RESULTS AND DISCUSSION

Five-Ball Fatigue Results

Two grades of 12.7-mm- (0.500-in-) diameter hot-pressed silicon nitride balls (HS-110 and NC-132) were tested as upper test balls in the five ball fatigue tester at maximum Hertz stresses ranging from 4.27×10^9 N/m^2 (620,000 psi) to 6.21×10^9 N/m^2 (900,000 psi). Test conditions included a contact angle of 30° and a shaft speed of 9400 rpm. Tests were run at a race temperature of 328K (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-) diameter balls.

The results of the fatigue tests are shown as a Weibull plot in Fig. 2 and are summarized in Table 3. Each of the grades of silicon nitride were tested at two stress levels. In each case the life at the lower stress was greater than at the higher stress. The slopes of the Weibull lines for the HS-110 silicon nitride (Fig. 2(a)) are similar to that expected for typical bearing steels. The slope of the data for NC-132 silicon nitride (Fig. 2(b)) is slightly greater than that for the HS-110 which could be expected for the more homogeneous material. Also shown in Fig. 2 are the 90 percent confidence limits on the data as calculated by methods of [13]. 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 with the HS-110 material (Fig. 2(a)) where only six failures were recorded the confidence band is considerably wider than at the higher stress level where 19 failures occurred.

As is seen in Table 3, the more dense, more homogeneous NC-132 silicon nitride has a ten percent life more than an order of magnitude greater (13 times) than that of the HS-110 material at the common stress level of 5.52×10^9 N/m^2 (800,000 psi). The improved life is apparently related to the lower content of impurities (with the exception of tungsten) and less porosity (higher density) of the NC-132 material. The accuracy of the tungsten measurement is suspect because of difficulty in analysing for that element. If the analysis is accurate, the tungsten content is apparently not detrimental to the rolling-element fatigue properties of silicon nitride.

Fig. 3(a) shows a typical fatigue spall that developed on one of the silicon nitride balls. No differences were seen between the HS-110 and the NC-132 spalls. 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 and was unlike those on alumina and silicon carbide balls [5] which were much shallower. Typically, no wear was observed on the silicon nitride balls, except for the few cases where an overrun as a result of a malfunction of the automatic failure detection and shutdown system. In these few cases debris from the initial fatigue spall caused some wear on the running track of the silicon nitride upper ball and on the steel lower balls.

Life Comparison With Other Materials

In Fig. 4, the ten-percent life data from Fig. 2 is shown plotted as a function of 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 HS-110 and NC-132 silicon nitride. A stress-life exponent of 16 was also obtained in [9] for hot-pressed silicon nitride bars running against steel rollers in a rolling-contact (RC) fatigue tester.

For a typical bearing steel (AISI 52100) under identical conditions in the five-ball fatigue tester [14], n has been determined to be 12. These data for AISI 52100 are also shown in Fig. 4 along with further data from [15] for AISI 52100 and AISI M-50 at a maximum Hertz stress of 5.52×10^9 N/m^2 (800,000 psi).

At this maximum Hertz stress level, the NC-132 hot-pressed silicon nitride gives rolling-element fatigue life at least equal to the typical bearing steels AISI 52100 and AISI M-50. The higher-stress-life exponent for silicon nitride means that it is more sensitive to a change in stress than typical bearing steels. Thus, as stresses are reduced to the level experienced in rolling-element bearing applications, NC-132 hot-pressed silicon nitride running against steel would be expected to give fatigue lives equivalent to or greater than typical bearing steels.

In [5] the ten-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 had at that time given longer lives in similar tests than any ceramic or cermet material [4,5]. The ten-percent life of HS-110 silicon nitride against steel lower balls from Table 3 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. The difference between NC-132 silicon nitride and hot-pressed alumina would be expected to be over three orders of magnitude, illustrating the superiority of NC-132 hot-pressed silicon nitride over other ceramic materials for rolling-element bearings.

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 [16] 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-mm-bore angular-contact ball bearing. The ball diameter in both cases was 20.64 mm (0.8125 in.) The calculation of fatigue life in the analysis of [16] is based on the Lundberg-Palmgren analysis [17].

It was assumed that the theoretical distribution of failures between the rolling elements and the races as considered in [17] 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 Fig. 5(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 race will be higher than that with a steel ball on a steel race for a given contact load and geometry.) While centrifugal force is reduced by at least fifty percent, the stress at the inner race is greatly increased (Table 4(a) and (b)). 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-mm 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 force 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-mm bore bearing where chosen based on analysis for use with steel 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 [18].)

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 analysed 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 4(c) 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 N (3000 lb) case.

Fig. 5(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 N (5000 lb) thrust load and at shaft speeds greater than 2 million DN at 4450 N (1000 lb) thrust load. However, as shown in Fig. 6, 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

Two grades of hot-pressed silicon nitride balls were tested under rolling-contact conditions in the five-ball fatigue tester. Test conditions included maximum Hertz stresses ranging from 4.27×10^9 N/m^2 (620,000 psi) to 6.21×10^9 N/m^2 (900,000 psi), a race temperature of 328K (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 and other ceramic materials such as hot-pressed alumina. 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-mm 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 the silicon nitride tends to offset the benefits of its lower density.

3. The ten-percent fatigue life of hot-pressed silicon nitride is at least two to three orders of magnitude greater than any other ceramic or cermet materials tested at approximately the same stress level.

4. The ten-percent fatigue life of the more homogeneous, more dense NC-132 hot-pressed silicon nitride is at least an order of magnitude greater than that of the HS-110 hot-pressed silicon nitride at a maximum Hertz stress of 5.52×10^9 N/m^2 (800,000 psi).

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

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TABLE I - TYPICAL PROPERTIES OF HOT-PRESSED SILICON NITRIDE

Chemical Formula	Si_3N_4
Bulk density, g/cc	3.11 to 3.24
Modulus of elasticity, N/m^2 (psi)	
at 298K (77°F)	$31x10^{10}$ ($45x10^6$)
at 1273K (1832°F)	$31x10^{10}$ ($45x10^6$)
Thermal expansion, K^{-1} ($°F^{-1}$)	
298 to 1773K (77 to 2732°F)	$2.7x10^{-6}$ ($1.5x10^{-6}$)
Flexure strength, N/m^2 (psi)	
at 298K (77°F)	$8.6x10^8$ ($1.25x10^5$)
at 1273K (1832°F)	$4.8x10^8$ ($0.70x10^5$)
at 1673K (2552°F)	$2.1x10^8$ ($0.30x10^5$)

TABLE 2 - ANALYSIS OF HOT-PRESSED SILICON NITRIDE

	Weight Percent	
Element	HS-110	NC-132
Al	0.62	0.23
Fe	0.50	0.32
Ca	0.26	0.05
Mg	0.56	0.70
Ti	0.06	~0
Mn	0.07	~0
W	1.50	2.80
Si_3N_4	balance	balance

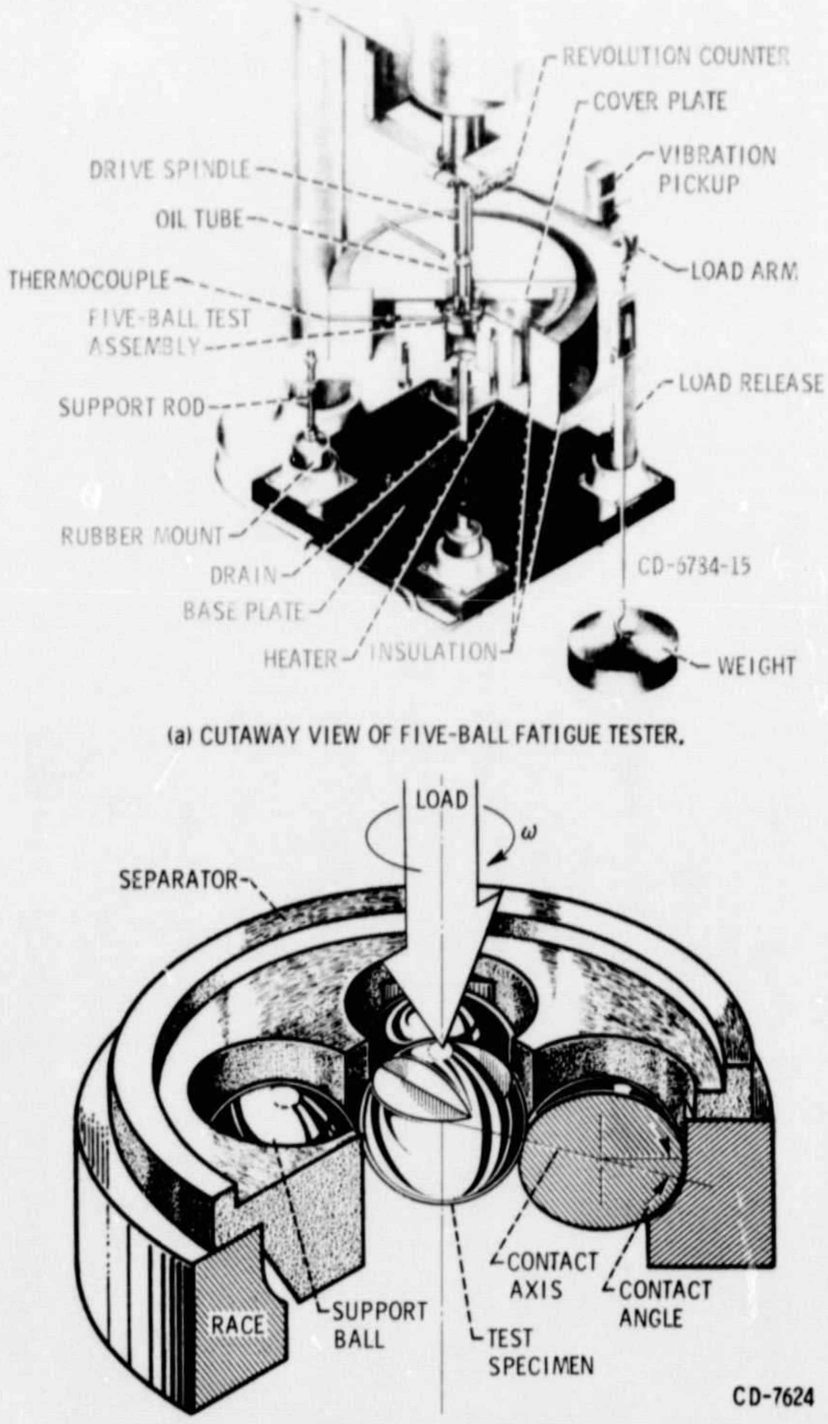
Table 3 - Fatigue test results with hot-pressed silicon nitride balls. Shaft speed, 9400 rpm; contact angle, 30°; race temperature, 328K (130°F); lubricant, super-refined naphthenic mineral oil.

Grade of Hot-Pressed Silicon Nitride	Maximum Hertz Stress, N/m^2 (psi)	Life, millions of Stress Cycles		Weibull Slope	Failure index[a]
		B_{10}	B_{50}		
HS-110	4.27×10^9 (620,000)	155	740	1.21	6 out of 17
	5.52×10^9 (800,000)	2.5	17	0.99	19 out of 20
NC-132	5.52×10^9 (800,000)	30.5	77	2.05	15 out of 17
	6.21×10^9 (900,000)	4.5	21	1.24	16 out of 17

[a]Failure index denotes number of failed silicon nitride test balls out of those tested.

TABLE 4 - Predicted life of 120-mm bore high-speed, angular-contact ball bearing with either steel or silicon nitride balls. Thrust load, 13,300 N (3000 lbs); ball diameter, 20.64 mm (0.8125 in.)

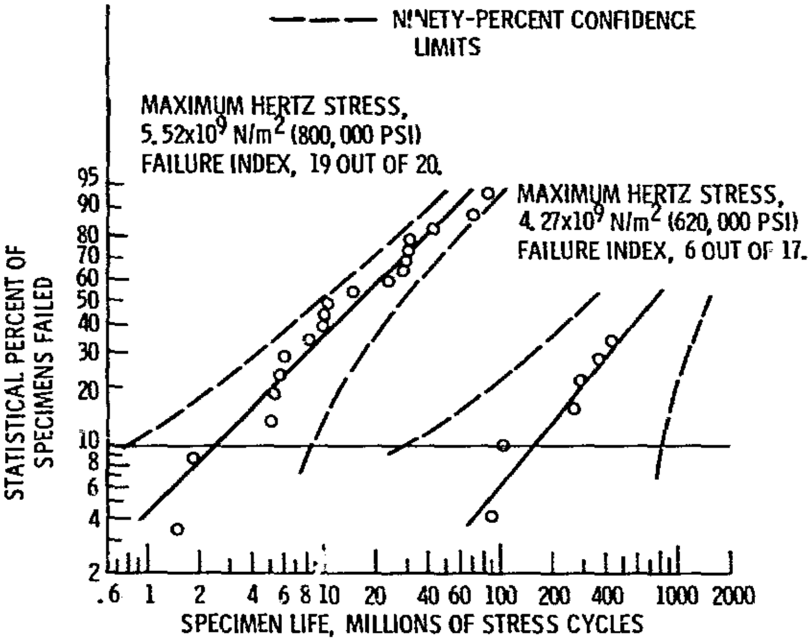
Shaft Speed		Centrifugal Force, N(lbs)	Maximum Hertz Stress, MN/m^2 (ksi)		Bearing Fatigue Life, 10^6 revs(hrs)
10^6DN	RPM		Inner	Outer	
A. Steel balls; inner race curvature, 0.54					
2.0	16700	1690(379)	1800(261)	1680(244)	1090(1090)
2.5	20850	2630(591)	1750(254)	1810(262)	900(720)
3.0	25000	3750(842)	1740(252)	1940(282)	650(433)
3.5	29150	5000(1124)	1720(250)	2080(301)	432(247)
4.0	33300	6360(1429)	1710(248)	2210(320)	282(141)
B. Silicon nitride balls; inner race curvature, 0.54					
2.0	16700	667(150)	2110(306)	1780(259)	248(248)
2.5	20850	1040(235)	2090(303)	1850(268)	260(208)
3.0	25000	1510(339)	2080(301)	1920(279)	262(175)
3.5	29150	2060(462)	2050(298)	2010(292)	251(144)
4.0	33300	2670(600)	2040(296)	2100(305)	225(112)
C. Silicon nitride balls; inner race curvature, 0.52					
2.0	16700	667(150)	1780(259)	1750(254)	820(820)
2.5	20850	1040(234)	1750(254)	1810(262)	812(650)
3.0	25000	1490(336)	1720(250)	1880(272)	739(492)
3.5	29150	2010(452)	1700(247)	1960(284)	617(352)
4.0	33300	2570(578)	1680(244)	2040(296)	481(240)



(a) CUTAWAY VIEW OF FIVE-BALL FATIGUE TESTER.

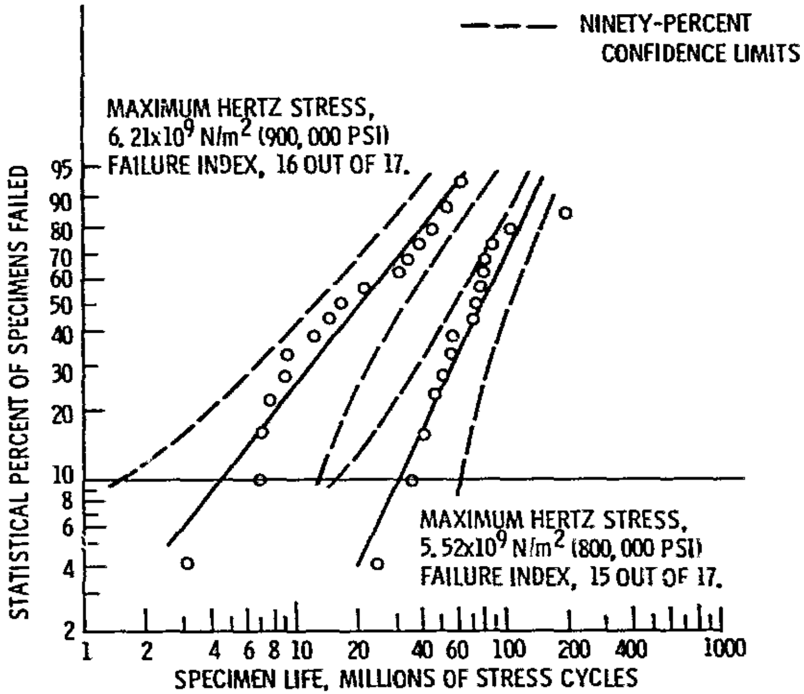
(b) FIVE-BALL TEST ASSEMBLY.

Figure 1. - Test apparatus.



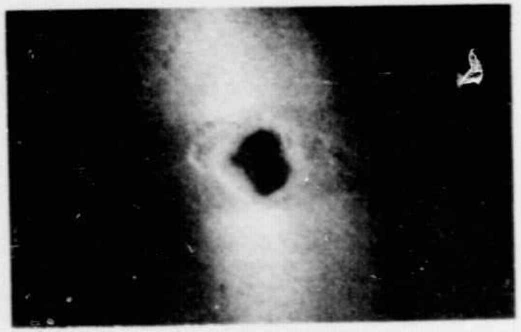
(a) HS-110 HOT-PRESSED SILICON NITRIDE.

Figure 2. - Rolling-element fatigue life of 12.7-mm-(0.500-in.-) diameter hot-pressed silicon nitride upper balls running against steel lower balls in the five-ball fatigue tester. Shaft speed, 9400 rpm; race temperature 328 K (130° F); contact angle, 30°.



(b) NC-132 HOT-PRESSED SILICON NITRIDE.

Figure 2. - Concluded.



(a) HOT-PRESSED SILICON NITRIDE.

(b) AISI M-50.

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

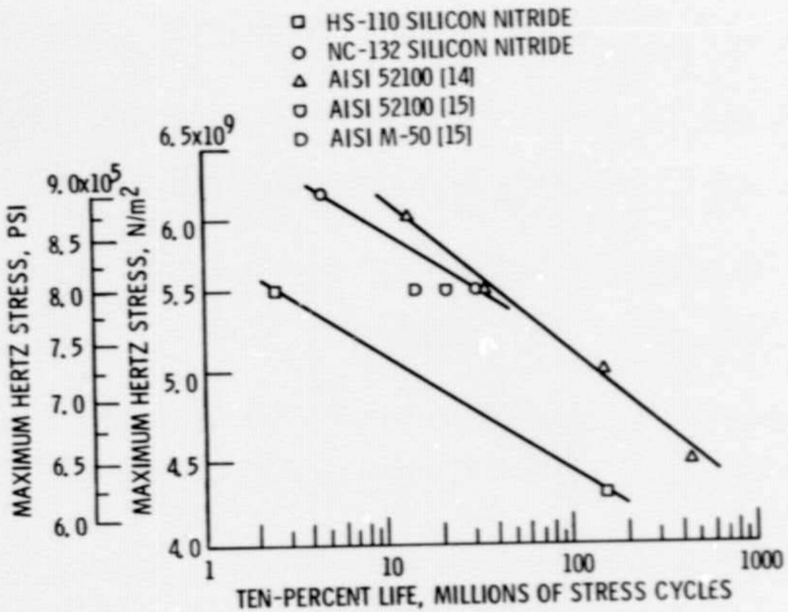
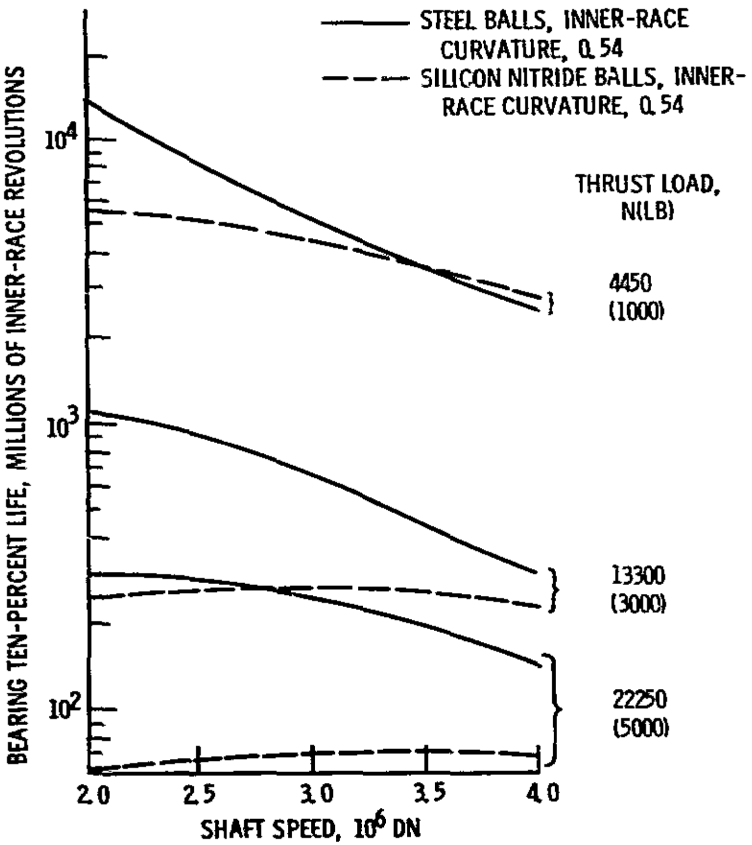
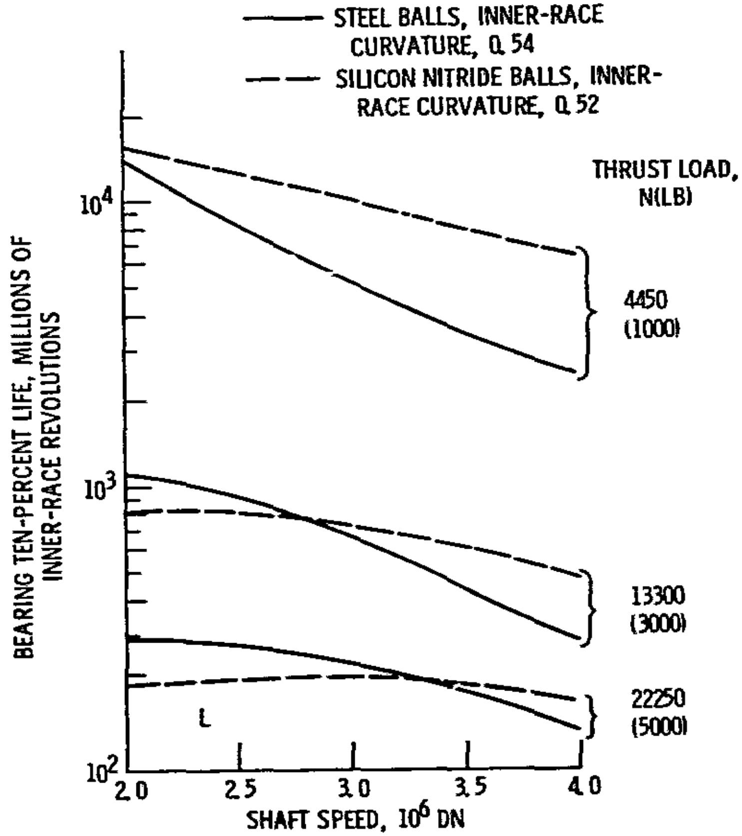


Figure 4. - Effect of maximum Hertz stress on fatigue life of 12.7-mm-(0.500-in.-) diameter balls tested in the five-ball fatigue tester.



(a) STEEL BALLS AND SILICON NITRIDE BALLS WITH INNER-RACE CURVATURE OF 0.54.

Figure 5. - Predicted life of 120-mm bore angular contact ball bearing with silicon nitride balls. [Ball diameter, 20.64 mm (0.8125 in.)]



(b) STEEL BALLS AND SILICON NITRIDE BALLS WITH INNER-RACE CURVATURES OF 0.54 AND 0.52, RESPECTIVELY.

Figure 5. - Concluded.

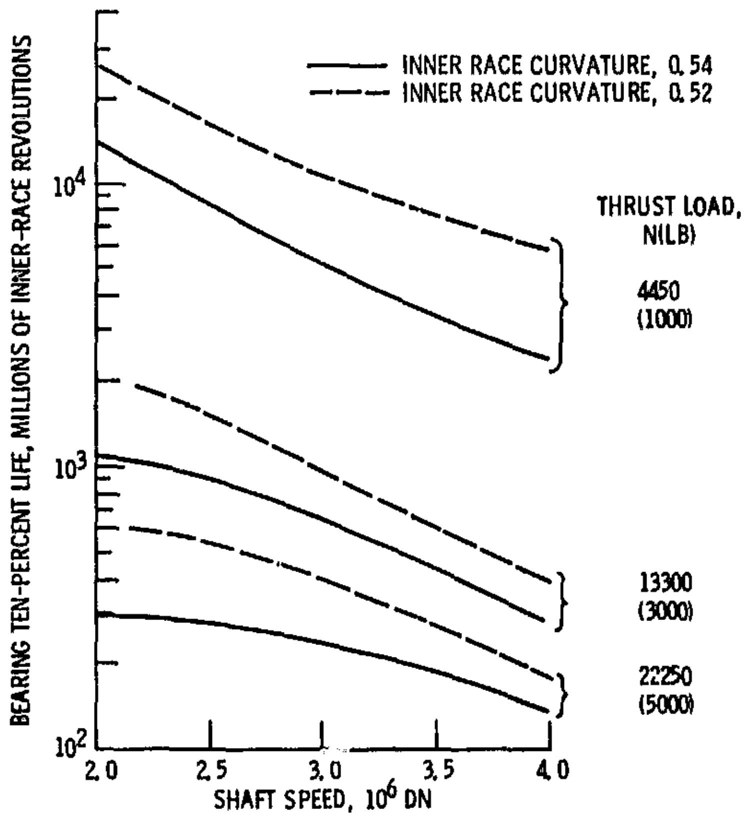


Figure 6. - Predicted life of 120-mm bore angular contact ball bearings with steel balls. [Ball diameter, 20.64 mm (0.8125 in.)]