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SUMMARY

The five-ball fatigue tester was used to study the behavior of nickel-bonded titanium carbide cermet and self-bonded silicon carbide balls under repeated stresses applied in rolling contact. Test conditions were 80° and 700° F, a contact angle of 20°, and a shaft speed of 950 rpm with a mineral oil lubricant. The nickel-bonded titanium carbide - cermet balls were tested at maximum Hertz stresses from 400,000 to 550,000 psi, while the silicon carbide balls were tested at maximum Hertz stresses from 300,000 to 400,000 psi.

Failure appearance for both materials was unlike the fatigue pits found in bearing steels and a crystallized-glass ceramic. However, the pits were similar to those found in alumina balls (both hot pressed and cold pressed and sintered). A typical failure was a shallow eroded area less than 1 mil deep for the titanium carbide cermet and 3 to 5 mils for the silicon carbide. These failures evolved by progressing slowly from a very small pit to one spanning the running track width.

Tests at 80° F with mineral oil lubrication over a range of stresses show that life varies inversely with stress to a power that ranges from 9.7 to 10.5 for the titanium carbide cermet and from 6.9 to 8.6 for the silicon carbide. The load capacity of the titanium carbide and silicon carbide balls was 3 and 1 percent, respectively, that of typical bearing steel balls, and 41 and 18 percent, respectively, that of hot-pressed alumina balls.

Tests showed that both materials had shorter lives and lower load capacities at a race temperature of 700° F than they did at 80° F; these decreases were attributed to decreased lubricant viscosity with increased temperature. Failure appearance and rate of progression at 700° F were similar to those at 80° F for each of these materials.

Preliminary tests with molybdenum disulfide - argon mist lubrication at a maximum Hertz stress of 400,000 psi show that self-bonded silicon carbide will exhibit excessive plastic deformation at temperatures as low as 1600° F. Similar results were obtained with nickel-bonded titanium carbide cermet at a maximum Hertz stress of 310,000 psi at temperatures as low as 1100° F. These preliminary tests indicate that both materials are limited to less severe conditions of temperature and stress.

INTRODUCTION

Advancing technology has created a need for reliable bearings that are capable of operating at elevated temperatures for long periods of time. Since many aerospace applications today dictate operating conditions that are beyond the useful range of today's ferrous and nonferrous bearing materials, the more refractory metals and compounds must be considered (ref. 1). Among these materials are titanium-carbide cermets and silicon carbide.

The selection of the nickel-bonded titanium-carbide cermet used in this investigation was based on the relatively large amount of information available on its physical properties, which indicates that the material maintains a high modulus of elasticity and a high compressive strength at temperatures above 1000° F. Such properties indicate that the titanium-carbide cermet has promise as a high-temperature bearing material.

For many aerospace applications, it becomes necessary to use materials that retain more satisfactory strength and friction properties to higher temperatures than do cermet-type materials. Such a material is a self-bonded silicon carbide. This material also has a high hardness and a high modulus of elasticity; however, its compressive strength at 70° F is only one-third that of the titanium-carbide cermet. Typical values of the physical properties of the titanium carbide cermet and the silicon carbide are given in the section MATERIALS.

Friction and wear characteristics of these materials in both rolling and sliding contact under a variety of conditions are reported in the literature (refs. 2 to 8). The section BACKGROUND is a summary of the reported data. In view of the reported data on both the physical properties and the friction and wear properties of titanium carbide and silicon carbide, it was concluded that these materials are promising bearing materials for rolling-element bearings at temperatures to 1600° F (and possibly higher). Thus, the objective of this investigation was to examine the effects of temperature and stress on the surface failure of these materials under repeated stresses applied in rolling contact. Tests were conducted with 1/2-inch-diameter ball specimens in the five-ball fatigue tester at maximum Hertz stresses of 300,000 to 550,000 psi, a shaft speed of 950 rpm, a contact angle of 20°, and temperatures of 80° and 700° F with a highly refined naphthenic mineral oil as the lubricant.

Preliminary rolling-contact tests were also conducted on these materials in a modified five-ball tester at 450 rpm and at temperatures to 2000° F with molybdenum disulfide (MoS_2) - argon (Ar) mist lubrication. The data at 80° F obtained in this investigation are compared with data for steel ball specimens run under similar conditions. All experimental results for a given type of material were obtained with a single batch of material and lubricant.

BACKGROUND

A relatively large amount of research and development has been performed with nickel bonded titanium carbide cermets in rolling-element bearings. Considerably less data has been reported on the use of a self-bonded silicon carbide for this purpose. A large portion of the reported data on these materials is summarized in the following paragraphs.

Data reported in reference 2 indicate that 20-millimeter-bore titanium-carbide cermet ball bearings are capable of running to temperatures of 1200° F for periods of 2 to 3 hours at approximately a half million DN with a solid film lubricant. Maximum Hertz stress conditions for these tests were 320,000 psi on the outer race. The failure mechanisms for these bearings were retainer failure, wear, and surface pitting (ref. 3).

Research reported in reference 4 indicated that a titanium-carbide cermet exhibited comparable coefficients of friction to that of alumina sliding unlubricated on similar materials at temperatures up to 1650° F. Additionally, research reported in reference 5 substantiates that the titanium-carbide cermets have friction coefficients similar to the one for alumina in rolling contact and generally have over three times the impact resistance of the other refractory materials reported therein.

A titanium-carbide cermet ball bearing was run under oscillatory conditions at temperatures from 1500° to 2000° F with the major test effort at 1600° F (ref. 5). These tests indicate that titanium-carbide cermet bearings are satisfactory in air-frame-type applications for short periods of time (10 to 15 min) at 1600° F. Further, development work was reported in reference 6 using a bearing having titanium-carbide cermet races and alumina balls run at moderate loads with a molybdenum disulfide (MoS_2) lubricant carried in an inert gas. These bearings operated at temperatures to 1500° F for durations as long as 8 hours. The failure of these bearings was by pitting of the titanium-carbide cermet races.

Unlubricated rolling contact bench tests reported in reference 7 indicated that a self-bonded silicon carbide exhibited minimal wear relative to other materials (such as hot-pressed alumina, a titanium-carbide cermet, and two superalloys) at a maximum Hertz stress of 375,000 psi for over 250 million stress cycles of operation. Macroscopic examination of the wear track revealed no surface cracking or spalling. Additionally, research reported in reference 8 indicates that a titanium carbide - silicon carbide combination resulted in approximately the same sliding friction coefficients as that of a titanium carbide - alumina combination.

MATERIALS

In order to provide a background for the examination of the surface failure mechanisms of a titanium-carbide cermet and a self-bonded silicon carbide, the fabrication, constituents, structure, and physical properties of the materials were studied.

TABLE I. - PHYSICAL PROPERTIES OF CONSTITUENTS OF SELF-BONDED SILICON CARBIDE (SELECTED DATA FROM MANY SOURCES)

Constituent	Property	Temperature, °F	Value
Silicon carbide	Lattice parameter (hexagonal phase), A	----	a = 3.073
			c = 5.026
	Lattice parameter (cubic phase), A	----	2.697
	Molecular weight	----	40.07
	Melting point, °F	----	4680 (sublimes at T > 3600° F)
	Thermal shock resistance	----	Good
	Thermal conductivity, (cal)(cm)/(cm^2)(sec)(°C)	850 to 2000	0.038
	Compressive strength, psi	70	82,000
	Tensile strength, psi	400	10,000
		1400	13,000
		1900	11,000
		2000	9,000
	Modulus of rupture, psi	70 to 2200	≅24,000
	Modulus of elasticity, psi	70	68×10^6
		2192	61.5
		2732	49.4
	Density, g/cc	70	3.217
Silicon	Lattice parameter (diamond cubic), Kx	----	5.417
	Atomic weight	----	28.09
	Melting point, °F	----	2570
	Modulus of elasticity, psi	70	16.35×10^6
	Density, g/cc	68	2.33
Disilicon carbide	Molecular weight	----	68.3
	Density, g/cc	70	2.5

Self-Bonded Silicon Carbide

The chemical composition of this material according to the manufacturers data is 96.5 percent silicon carbide, 2.5 percent silicon, 0.4 percent carbon, 0.4 percent aluminum, and 0.2 percent iron.

Although a detailed fabrication procedure for this material was not available, a general fabrication procedure is presented. Three different grain sizes of silicon carbide are mixed with graphite powder. The mixture is pressed and baked. The blanks are put into a chamber that is evacuated, and pure silicon vapors are poured in at 2150° C. The silicon combines with the graphite in the grain boundaries to form silicon carbide.

The resulting microstructure of a specimen fabricated by this technique can be seen in figure 1. The light gray matrix is silicon carbide, while the irregular white areas are unreacted silicon. The darker gray irregular areas are Si_2C, while some grain boundaries are outlined by residual unreacted dark particles of graphite.

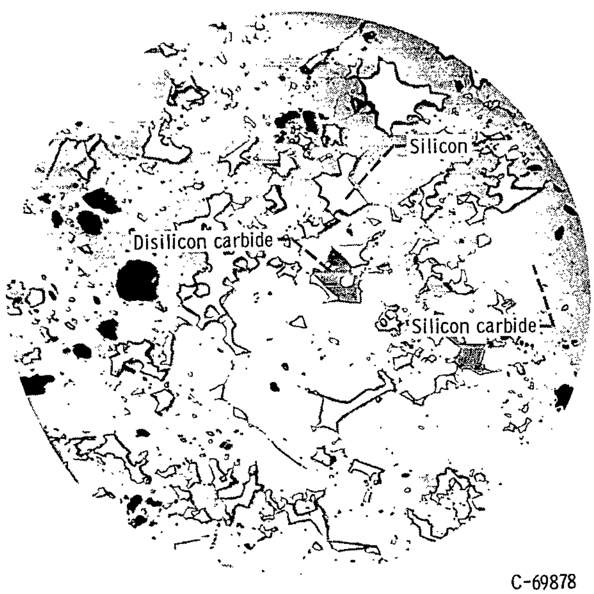


Figure 1. - Microstructure of self-bonded silicon carbide ball specimen. X140.

Some of the physical properties of each major constituent are listed in table I. These values are general literature data from a large variety of sources. For this reason they should be interpreted as average properties of the materials and are not specific values for the actual constituents of the material tested. In table II (ref. 9), the average properties of a self-bonded silicon carbide (hereinafter called silicon carbide) are presented.

From an examination of the microstructure it can be seen that the material investigated was extremely nonhomogeneous. Physical property data indicate that the primary phase of silicon carbide is hard and strong and is filled with a weak second phase of silicon. Graphite is also present at the grain boundaries.

Nickel-Bonded Titanium Carbide Cermet

The chemical analysis of this material is 70 percent titanium carbide (64 percent titanium carbide and 6 percent columbium, tantalum, titanium carbide solid solution), 25 percent nickel, and 5 percent molybdenum.

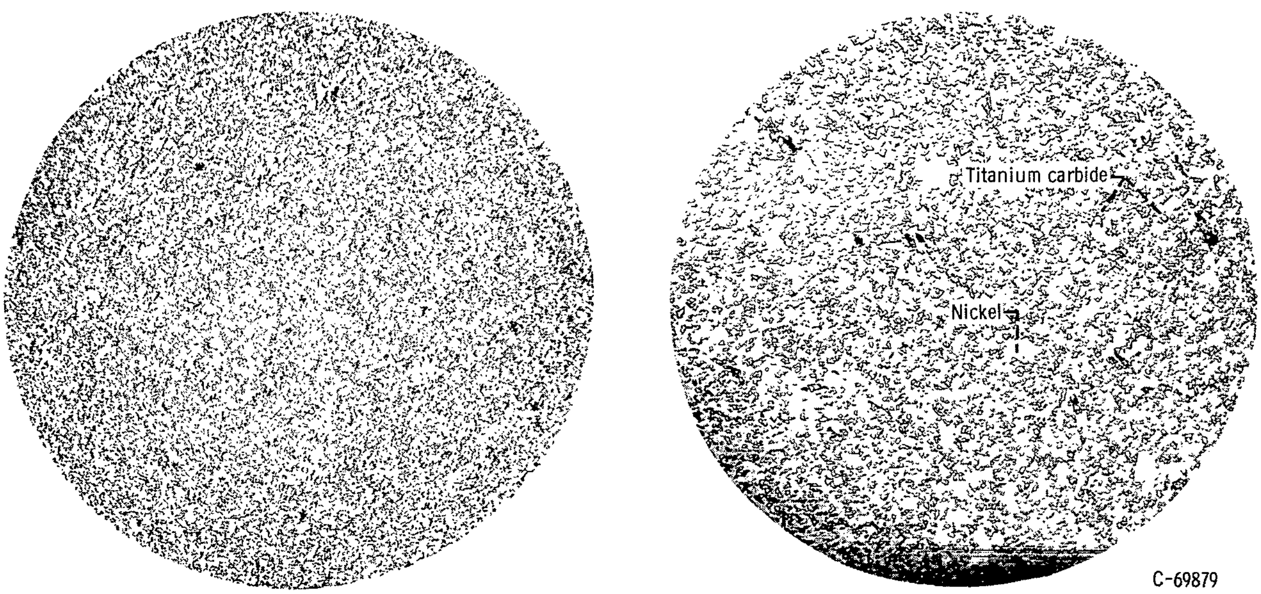
TABLE II. - PHYSICAL PROPERTIES OF SELF-BONDED SILICON CARBIDE (REF. 9)

Property	Temperature, °F	Value
Coefficient of thermal expansion, in./(in.)(°F)	70 to 2500	2.8×10^{-6}
Thermal conductivity, (Btu)(ft)/(ft^2)(hr)(°F)	1140	720
	2782	94
Knoop hardness, 100-g scale	70	2740
Compressive strength, psi	70	150,000
Modulus of elasticity, psi	70	69×10^6
	2200	49
Density, g/cc	70	3.10
Poisson's ratio	70	0.183

Cermets of this type are usually fabricated by either (1) hot pressing, (2) cold pressing and sintering, or (3) vacuum infiltration of a sintered carbide body by nickel. A typical microstructure of the actual material investigated is shown in figure 2. It can be seen that the very fine white carbide particles are dispersed in a gray nickel matrix.

The average physical properties of the constituents (see table III (ref. 10)) and the combined material system (see table IV (ref. 11)) are presented. These values are not measured properties of the actual batch of material investigated but are expected to be similar to its true properties.

The structure of this material is obviously different from that of the silicon carbide. Here a very large amount of a fine, uniformly dispersed hard phase of titanium carbide exists in a softer, ductile matrix of nickel. The molybdenum is in solid solution in the nickel in order to decrease the interfacial energy of the alloy and thus promote wetting of the carbide particles and subsequent bonding.



(a) X140. (b) X280.

Figure 2. - Microstructure of nickel-bonded titanium carbide cermet ball specimen.

TABLE III. - PHYSICAL PROPERTIES OF CONSTITUENTS OF NICKEL-BONDED TITANIUM CARBIDE CERMET (REF. 10)

Constituent	Property	Temperature, °F	Value
Titanium carbide	Lattice parameter (NaCl structure), A	----	4.318
	Molecular weight	----	59.91
	Melting point, °F	----	5700
	Thermal shock resistance	----	About 1/4 that of silicon carbide
	Coefficient of thermal expansion, in./(in.)(°F)	80 to 1470	4.1×10^{-6}
	Thermal conductivity, (cal)(cm)/(cm^2)(sec)(°C)	400	0.052
		490	.036
		1100	.022
		1500	.015
		1850	.011
	Hardness, DPN, kg/mm^2	70	3200
	Compressive strength, psi	70	190,000
	Density, g/cc	70	4.93
Nickel[a]	Lattice parameter (face-centered cubic structure), A	----	3.5238
	Atomic weight	----	58.7
	Melting point, °F	----	2647
	Coefficient of thermal expansion, in./(in.)(°F)	70 to 1800	7.39×10^{-6}
	Modulus of elasticity, psi	70	30×10^{6}
	Density, g/cc	70	8.9

[a]Data for pure nickel; however, the nickel-bonded titanium carbide cermet contains molybdenum in solid solution.

Both the silicon carbide and the nickel-bonded titanium carbide cermet (hereinafter called titanium carbide cermet) were fabricated into rough blanks and finished into 1/2-inch-diameter ball specimens of grade 25 specification (0.000025-in. sphericity, 0.000050-in. uniformity). Surface examination of the silicon-carbide balls indicated a much rougher "as-ground" surface (~2.0 to 6.0 μin. rms) as compared to that of the cermet balls (~0.6 to 0.8 μin. rms). The better finish on the titanium-carbide cermet balls can be traced to some smearing of the ductile nickel during grinding and to the greater homogeneity of the material.

APPARATUS

Five-Ball Fatigue Tester With Air-Bearing Support

The five-ball fatigue tester used in this investigation is described in detail in reference 12. Figure 3(a) is a section view of this tester. The test assembly (fig. 3(b)) consists of a test specimen pyramided upon four lower support balls, positioned by a separator, and free to rotate in an angular contact raceway. Specimen loading and drive are applied through a vertical spindle that is notched at its lower end to fit a tongue cut in the test specimen. Loading was accomplished by dead weights acting on the spindle through a load arm. Contact load is a function of this load and the contact angle. For every revolution of the drive shaft, the test specimen receives three stress cycles.

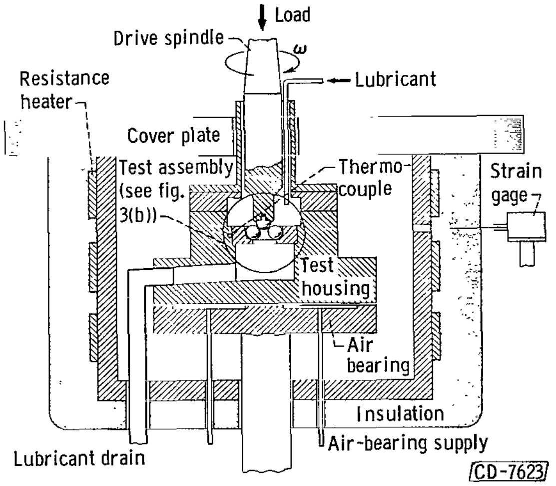
TABLE IV. - PHYSICAL PROPERTIES OF NICKEL-BONDED TITANIUM CARBIDE CERMET (REF. 11)

Property	Temperature, °F	Value
Coefficient of thermal expansion, in./(in.)(°F)	70 to 1800	5.3×10^{-6}
Thermal conductivity	----	Higher than super alloys by factor of 2 or 3
Hardness, Rockwell "A" scale	70	89
	1400	74
Compressive yield strength, psi	70	450,000
	1200	296,000
	1600	147,000
Modulus of elasticity, psi	70	57×10^{6}
	1600	48
Density, g/cc	70	6

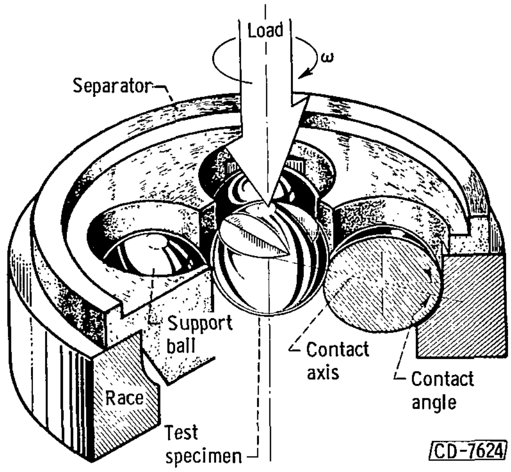
The test assembly is supported by an air bearing that permits precise horizontal alinement. The test assembly was heated by electrical resistance elements heating the ambient air. Test temperatures were measured at the outside diameter of the race. In tests at 80° and 700° F, the ball specimens were lubricated with a mist of a highly refined naphthenic mineral oil containing an oxidation inhibitor, an antiwear additive, and an antifoam additive. The lubricant mist was heated to test specimen temperature by a resistance heater wrapped around the lubricator tube. The support ball material was SAE 52100 steel for the 80° F tests and AISI M-50 steel for the 700° F tests.

High-Temperature Five-Ball Fatigue Tester

The modified five-ball tester used for the 2000° F tests is shown in figure 3(c). The nickel-base alloy housing is supported by rods held in flexible rubber mounts. Minor misalinements and vibrations are absorbed by these mounts. Operating temperatures up to 2000° F are maintained by induction heating coils wound around the test housing. Shaft speeds up to 450 rpm are con-



(a) Section view showing air-bearing support.



(b) Test assembly.

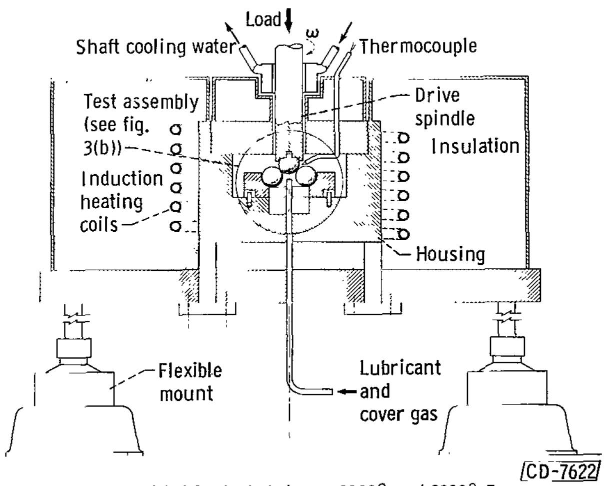
Figure 3. - Five-ball fatigue tester.

trolled by a variable-speed drive unit.

Lubrication is accomplished with dry powder lubricant (MoS_2) suspended in an inert gas (high purity argon) injected into the test assembly. The support balls were of 1/2-inch-diameter grade 25 hot-pressed alumina. Race and separator materials were cold-pressed alumina and Hastelloy X, respectively.

PROCEDURE

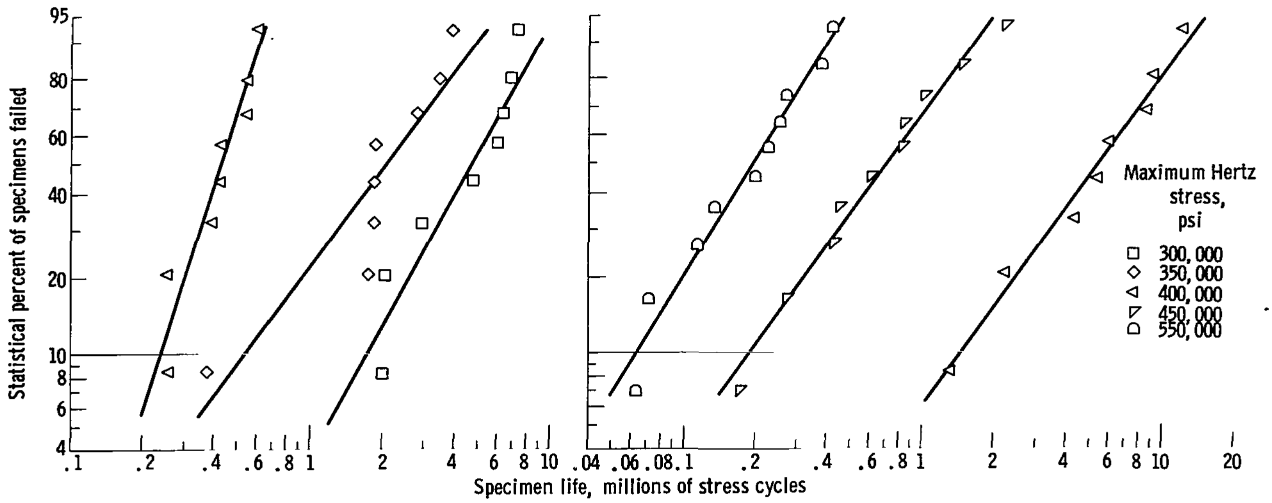
Rolling-contact life tests were conducted with titanium-carbide cermet and self-bonded silicon carbide balls in the five-ball fatigue tester described previously. Tests were performed at a shaft speed of 950 rpm, a contact angle of 20°, and race temperatures of 80° and 700° F. Step load tests at the aforementioned conditions were made with each material to determine the stresses at which the specimens could be tested to produce failure in a reasonable time. In order to determine the stress-life relation for these materials, three stresses were chosen for each material based on the step load test results. An intermediate stress was chosen for each material for tests at 700° F.



(c) Modified for tests between 1100° and 2000° F.

Figure 3. - Concluded. Five-ball fatigue tester.

Before testing, the test specimens were kept in a clean, dry atmosphere. Immediately prior to testing, the test specimens were inspected at a magnification of 15, and the size and number of initial surface pits in the running track area,



(a) Self-bonded silicon carbide.

(b) Nickel-bonded titanium carbide cermet.

Figure 4. - Rolling-contact life of 1/2-inch-diameter ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.

if any, were recorded.

At the start of a test, the test specimens and support balls were coated with lubricant and installed in the test assembly. Load was subsequently applied, and the test shaft was brought up to operating speed. In tests at 700° and above, the raceway was heated to operating temperature before the test was started. Periodic inspections of the test specimen running track were made at a magnification of 15, and observations were recorded. The time interval between inspections varied with the stress level at which the test was run and

TABLE V. - LIFE AND LOAD CAPACITY RESULTS WITH NICKEL-BONDED TITANIUM CARBIDE CERMET AND SELF-BONDED SILICON CARBIDE BALL SPECIMENS AT 80° and 700° F

Material	Maximum Hertz stress, psi	Race temperature, °F	10-Percent life, stress cycles	50-Percent life, stress cycles	Stress-life relation at 80° F	Ball normal load, lb	Load capacity, lb	Average load capacity at 80° F
Nickel-bonded titanium carbide cermet	400,000	80	1.5×10^6	5.6×10^6	9.7 to 10.5	11.7	13.1	12.6
	450,000	80	.19	.72	↓	16.8	10.4	
	550,000	80	.064	.20	↓	30.5	14.3	
	400,000	700	.39	1.65	↓	11.7	8.9	----
Self-bonded silicon carbide	300,000	80	1.75×10^6	4.7×10^6	6.9 to 8.6	4.48	5.7	5.6
	350,000	80	.54	2.1	↓	7.00	5.4	
	400,000	80	.24	.43	↓	10.6	5.7	
	350,000	700	.28	.69	↓	7.00	4.1	----

with the observed rate of growth of a failure pit. A specimen was considered failed when a pit reached the full width of the running track. The entire test assembly was cleaned and inspected between tests, and new support balls were installed before the start of another test.

RESULTS AND DISCUSSION

Rolling-Contact Life Result

The rolling-contact life data from the five-ball fatigue tester were treated statistically according to the methods of reference 13 and plotted on Weibull coordinates. A straight line was drawn through each array of points by means of the method of least squares. The results at 80° F are shown in figure 4. The 10- and 50-percent lives are tabulated in table V for both the 80° and 700° F tests. The life data show an expected decrease in life with increasing contact stress.

Figure 5 is a plot of the log of stress against the log of the 10- and 50-percent lives for both materials. Life varies inversely with stress raised to a power of 9.7 to 10.5 for the titanium-carbide cermet and 6.9 to 8.6 for the silicon carbide. (A commonly accepted range for this exponent for point contact in bearing steels is 9 to 10.) Thus, the titanium-carbide cermet shows a sensitivity to stress equal to that of bearing steels; however, the silicon carbide appears less sensitive to stress than either the cermet or bearing steels. A similar stress-life relation (6.0 to 8.1) was found to exist with cold-pressed-and-sintered alumina (ref. 14). Hot-pressed alumina exhibited a stress-life relation of 9.4 to 10.8 or about the same as that of steel and the titanium-carbide cermet. A major difference between the two types of alumina discussed in reference 14 was the original surface condition of the test specimens. The finishes on

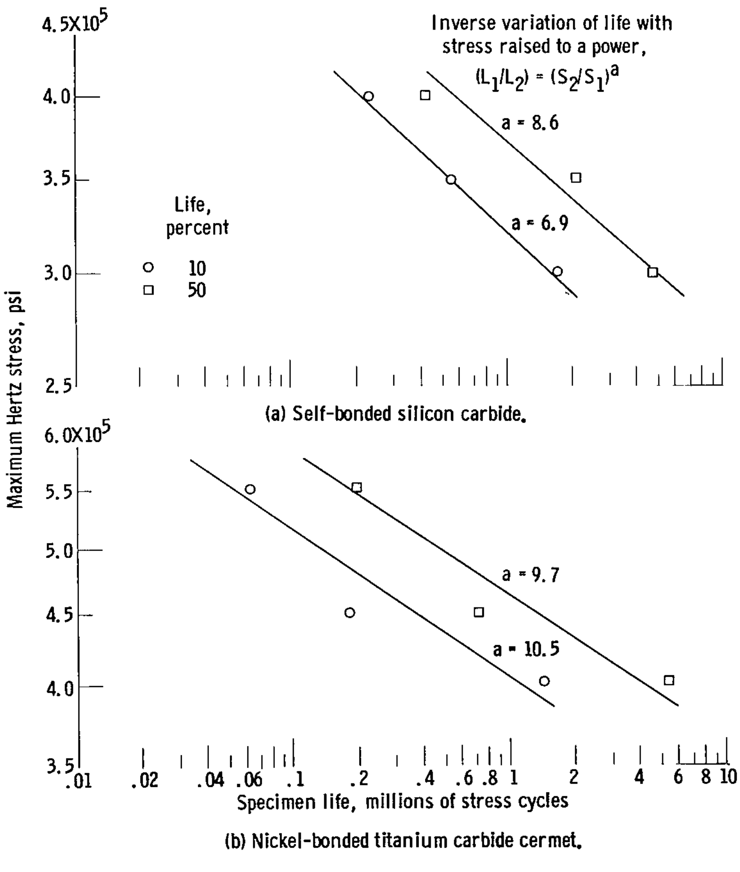
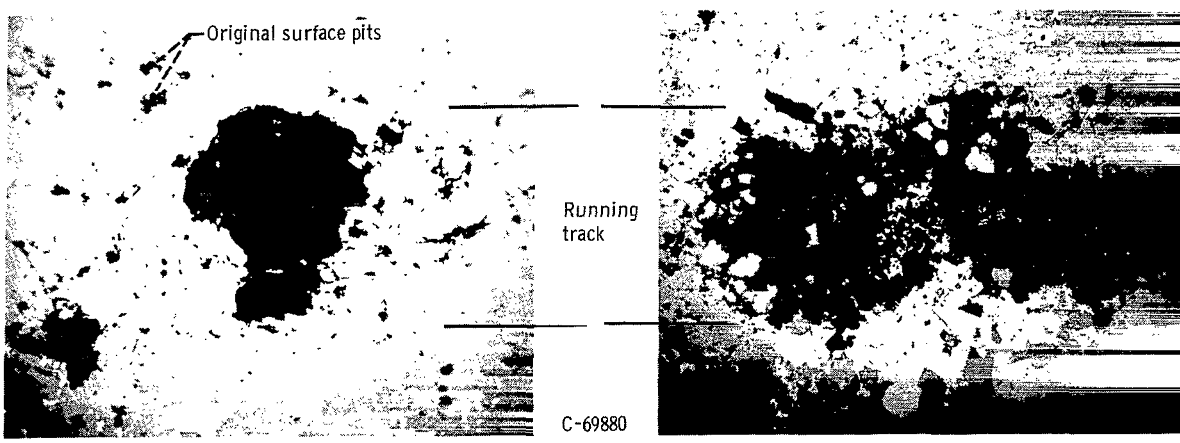


Figure 5. - Stress-life relation of 1/2-inch-diameter ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.

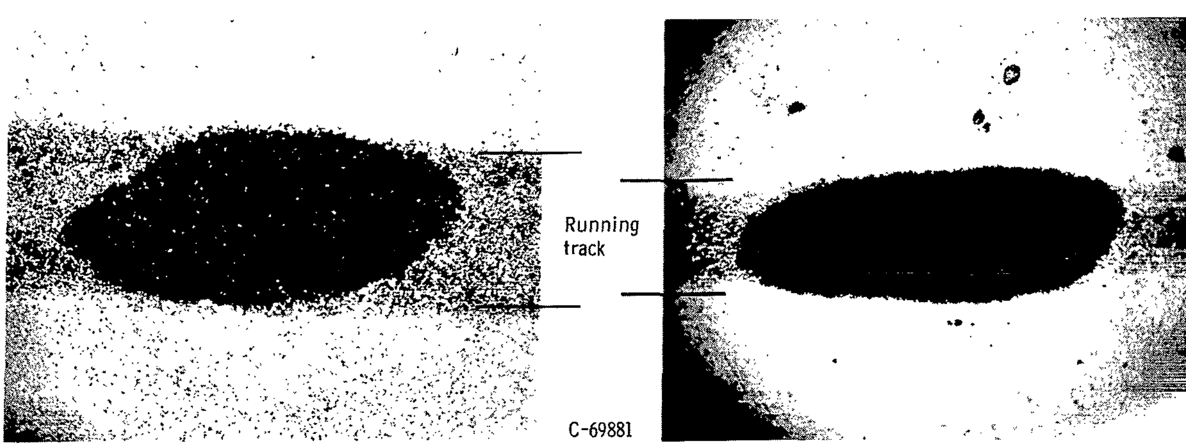
the hot- and cold-pressed specimens were 0.3 to 0.5 and 3 to 8 microinch root mean square, respectively. The silicon carbide had a surface finish similar to that for cold-pressed alumina, about 2 to 6 microinch root mean square. Thus, the lower apparent stress sensitivity of the silicon carbide and the cold-pressed alumina may be due to their poorer surface conditions. The surface pits and irregularities may cause such high stresses to exist in the zone of contact that the effect of increased stress due to a nominal increase in load (table V) is minimized; that is, the actual contact stress on these materials may not be changed to the extent that calculations show for a given change in normal load. The effect would be an apparent stress sensitivity or stress-life exponent less than that of a material with a better surface finish. This phenomenon was also observed by the authors of reference 15, where an increased surface roughness on SAE 52100 steel rollers exhibited lower load-life exponents.



(a) Race temperature, 80° F; maximum Hertz stress, 400,000 psi; specimen life, 0.39×10^6 stress cycles.

(b) Race temperature, 700° F; maximum Hertz stress, 350,000 psi; specimen life, 0.43×10^6 stress cycles.

Figure 6. - Typical failure pits on self-bonded silicon carbide ball specimens. x50.



(a) Race temperature, 80° F; maximum Hertz stress, 400,000 psi; specimen life, 9.4×10^6 stress cycles.

(b) Race temperature, 700° F; maximum Hertz stress, 400,000 psi; specimen life, 0.86×10^6 stress cycles.

Figure 7. - Typical failure pits on nickel-bonded titanium carbide cermet ball specimens. X50.

Surface Failure at 80° F

Failure appearance. - Typical failure pits in the self-bonded silicon carbide and the titanium-carbide cermet are shown in figures 6 and 7. These failures were unlike the deeper fatigue spalls observed in bearing steels (fig. 8) and a crystallized glass ceramic (ref. 12).

The surface failures in the titanium-carbide cermet were very shallow, eroded areas less than 1 mil deep and were similar to those found in hot-pressed alumina (ref. 14) and those described in titanium-carbide cermet races in references 3 and 6. The failures in the silicon-carbide were from 3 to 5 mils deep and resembled the more ragged appearance of the cold-pressed alumina failure pits described in reference 14.

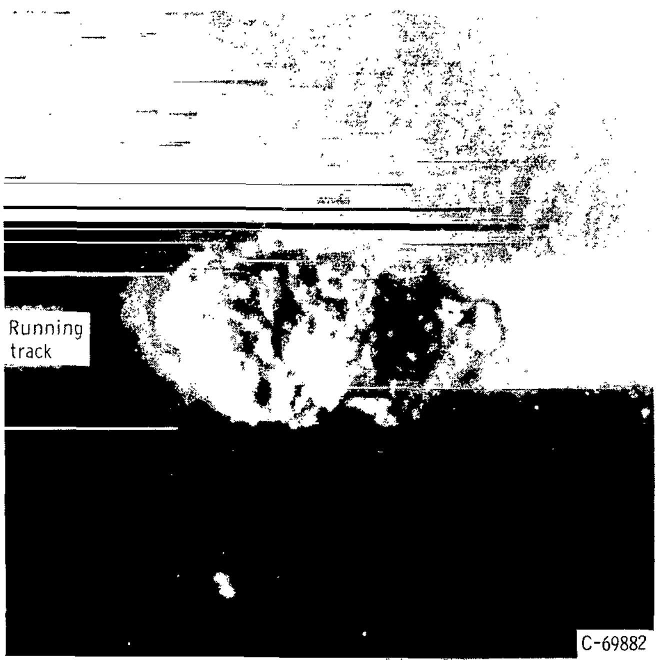
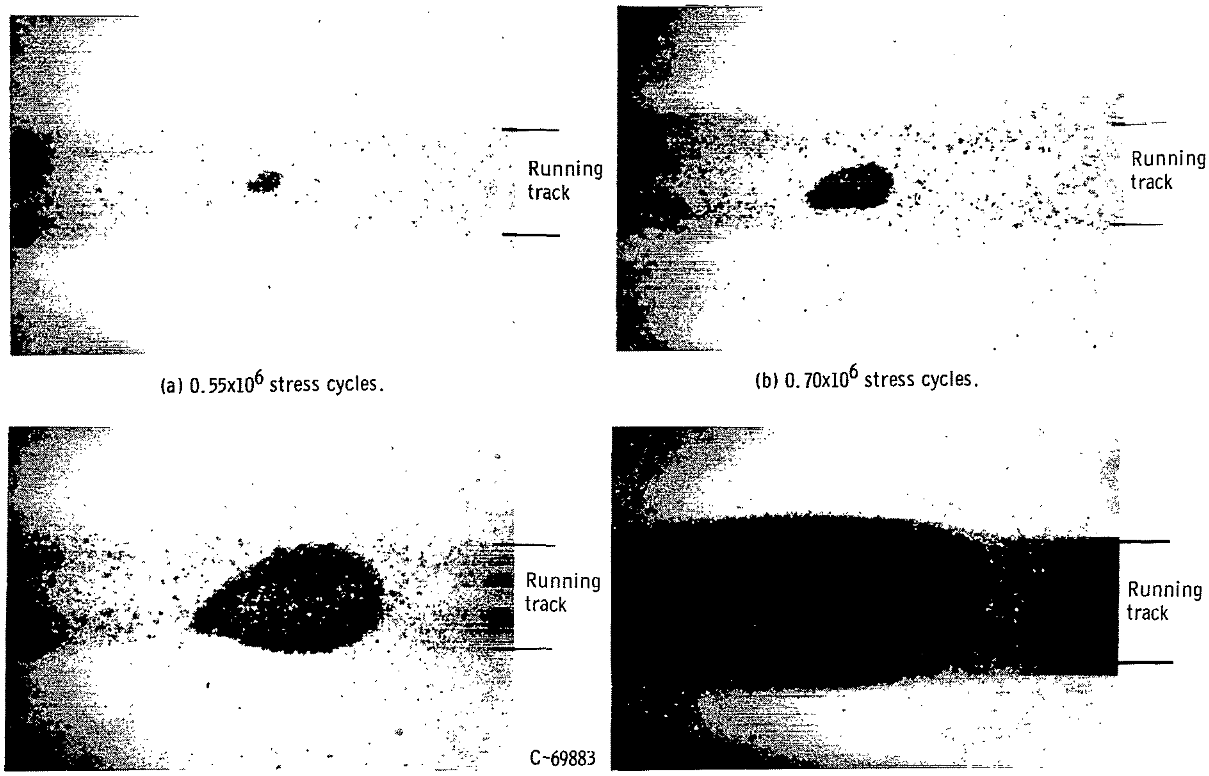


Figure 8. - Failure pit in steel (ref. 12).

In all tests with the silicon carbide and several of the tests with the titanium carbide cermet, the failure started at a small pit in the original ball surface and progressed in size to the full track width. These original surface pits in the silicon carbide can be seen in figure 6 in the areas outside the running track. No pits other than the failure can be seen in the titanium-carbide cermet in figure 7; however, a few pits did exist on the as-received surface.

Since the test specimens were inspected periodically during a test, it was possible to observe the progression of the failure pit to full track width. When the failure pit width was equal to the width of the running track, the test specimen was considered failed and the test was terminated.

The progression of the pores or pits to full-track-width pits was a slow, erosive process frequently consuming one-half the total running time of the specimen. In all tests with the silicon-carbide, several smaller failure pits on the running track were at various stages of progression when the largest pit reached the width of the running track. Only a few of the tested titanium-carbide cermet balls exhibited pits on the running track other than the pit that produced failure. Figure 9 shows a sequence of photographs of a preliminary test with titanium-carbide cermet taken from the time a failure pit was first observed (fig. 9(a)) to the time when the pit was about full track width (fig. 9(c)). Figure 9(d) is an intentional overrun.



(a) 0.55x10^6 stress cycles.

(b) 0.70x10^6 stress cycles.

(c) 0.78x10^6 stress cycles.

(d) Overrun. 0.86x10^6 stress cycles.

Figure 9. - Sequence of failure pit growth in nickel-bonded titanium carbide cermet. Shaft speed, 2600 rpm; contact angle, 20°; race temperature, 80° F; maximum Hertz stress, 535,000 psi.

Failure mechanism. - There are a number of factors that affect the mechanical properties of a two-phase composite material. These have been enumerated in a report on dispersion strengthened alloys (ref. 16) and those pertinent to this investigation are as follows:

(1) Particle size, interparticle spacing, and volume fraction of the dispersed phase

(2) Particle morphology

(3) Hardness or strength of the dispersed phase

(4) Characteristics of fracture

The two materials systems examined in this investigation are markedly different. The self-bonded silicon carbide involves a brittle primary phase containing approximately 12 V/O of silicon, which is soft and has a low modulus of elasticity. The silicon particles are large irregularly shaped areas concentrated at the grain boundaries and corners of the silicon-carbide matrix. On the other hand, the nickel-bonded titanium-carbide cermet involves a ductile matrix that is loaded with fine, evenly dispersed, hard, brittle particles. In this system there is about 29 V/O of the softer, more ductile nickel matrix.

This matrix exists as a thin film completely surrounding each particle. (Average property values are shown in table IV, p. 8.)

Since cermets, in general, are extremely structure dependent, it can be seen that the well-dispersed, small titanium-carbide particles in nickel produce a stronger material than that which arises when large irregular silicon particles are present in the silicon-carbide matrix.

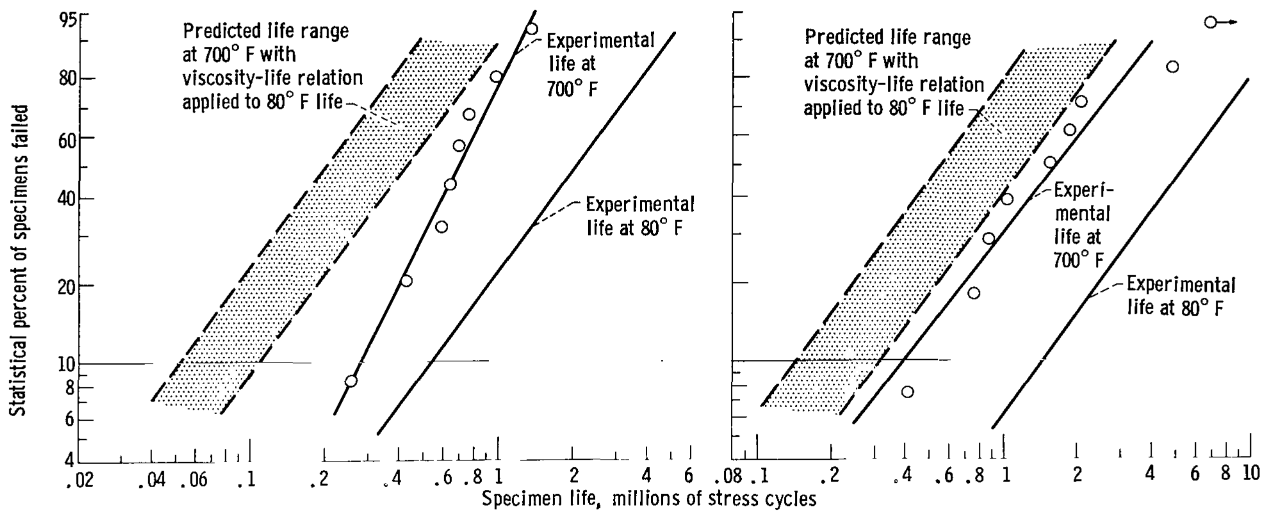
Since the possibility of crystallographic coherency is negligible, interfacial energy considerations become important. The molybdenum addition to the nickel matrix in the cermet promotes complete wetting of the carbide by the matrix. This factor enhances bonding between these two materials and promotes uniform dispersion of the carbide particles. Both better bonding and uniform dispersion contribute to improved physical properties and to resistance to failure under repeated stresses. In the case of the titanium-carbide - nickel cermet, the exact mode of surface failure is difficult to specify. It is generally accepted, however, that when a moving dislocation passes between obstacles such as the dispersed carbide particles, a dislocation loop is left behind encircling the obstacle. Subsequent dislocations passing by the obstacles encounter ever increasing resistance (i.e., back stress) until a point is reached where the required shear stress for deformation exceeds the shear stress of the particle or of the matrix. The cermet investigated contained such a high volume of carbide particles that it is believed that local failure occurred in the carbide obstacles as well as in the matrix. The determination of the exact mode of failure under the conditions of cyclic stress present in rolling contact would require a detailed electron-microscopy analysis, which is beyond the scope of this report.

In the case of the silicon carbide and its undesirable excess of silicon, however, little quantative information is available on the interfacial energy. Figure 1 (p. 5) qualitatively indicates complete filling of the vacant spaces in the silicon carbide matrix by the silicon poured over it (i.e., low interfacial energy between the two materials). This condition would indicate good bonding. During testing, however, large pieces of the soft, weak silicon came out of the running track. The preceding information indicates that, although the bonding of the silicon to the matrix was adequate, the inherent weakness of this second phase was responsible for its removal. Where silicon was removed, cracks were initiated in the matrix at the points of sharp irregularity vacated by the silicon. Fractures appeared to occur by a brittle fracture mechanism, and at the time the failure criteria were met, these pits were from 0.003 to 0.005 inch deep.

Effect of Temperature

One group of specimens of each material was run to failure at a race temperature of 700° F to determine the effect of a higher temperature on their life and surface failure characteristics. This temperature was chosen because it is the highest temperature at which adequate lubrication could be provided by the mineral oil lubricant. These tests were run at maximum Hertz stresses of 400,000 and 350,000 psi for the titanium-carbide cermet and the silicon carbide, respectively. The results of these tests are plotted on Weibull coordinates in figure 10.

In addition to the experimental life at 700° F, figure 10 shows the experimental life at 80° F (at the same stress) and the predicted life at 700° F. The accepted relation between life L and lubricant viscosity μ is $L = K\mu^n$, where K is a constant and n = 0.2 to 0.3 (refs. 17 and 18). If the 80° F



(a) Self-bonded silicon carbide. Maximum Hertz stress, 350,000 psi.

(b) Nickel-bonded titanium carbide cermet. Maximum Hertz stress, 400,000 psi.

Figure 10. - Effect of 700° F race temperature on life of 1/2-inch-diameter ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; lubricant, highly refined naphthenic mineral oil; viscosity at 80° F, 150 centistokes; viscosity at 700° F, 0.6 centistoke.

life were adjusted to 700° F by means of the relation

$$\frac{L_{80}}{L_{700}} = \left(\frac{\mu_{80}}{\mu_{700}}\right)^n$$

a life within the range indicated in figure 10 would be expected. Although the viscosity-life relation was obtained in fatigue tests with steels where the failures were largely subsurface in origin, the relation appears to apply to surface-failure life, such as that of alumina (ref. 14).

The experimental lives of both the titanium-carbide cermet and the silicon carbide at 700° F approached the predicted life range. Thus, the decrease in life at 700° F for the titanium-carbide cermet may be accounted for by changes in the viscosity of the lubricant. These results could be expected since the physical properties of these materials do not change appreciably in this temperature range. Silicon carbide, however, exhibited a life at 700° F considerably higher than the predicted range (fig. 10(a)). Here, as with the stress-life relation, the effect of surface pits and irregularities on these specimens may minimize the effect of lubricant viscosity change due to the increase in

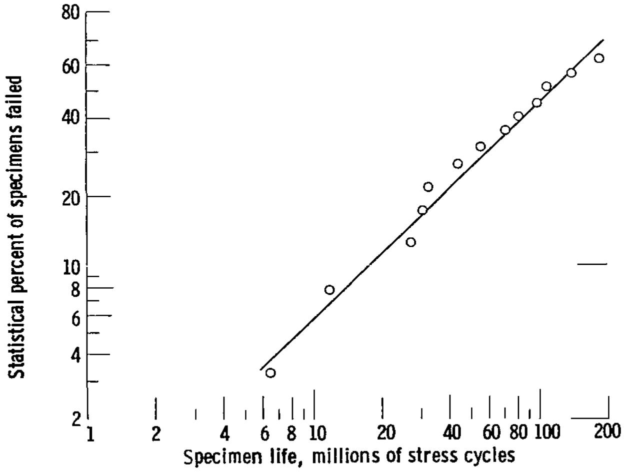


Figure 11. - Rolling-contact fatigue life of AISI M-1 steel ball specimens in five-ball fatigue tester. Shaft speed, 10,000 rpm; contact angle, 20°; race temperature, 145° F; lubricant, synthetic diester; maximum Hertz stress, 800,000 psi; failure index, 13 out of 21 (data from ref. 19).

temperature. In general, for both materials, the appearance of the failure pits in the 700° F tests (fig. 6(b) and 7(b), p. 12) was similar to that at 80° F.

Load Capacity

The lives of materials tested in a bench-type tester such as the NASA five-ball fatigue tester are frequently compared on the basis of load capacity. Load capacity is the contact load in pounds that will produce failure of 10 percent of a group of test specimens in 1 million stress cycles. This basis of comparison is most useful when a number of materials have been tested at different stress levels.

The experimental capacity of 1/2-inch-daimeter balls at 80° F (table V, p. 10) averaged 12.6 pounds for the titanium carbide cermet and 5.6 pounds for the silicon carbide. The rolling-contact fatigue life of a typical vacuum melt M-1 bearing steel tested under similar conditions is shown in figure 11 (ref. 19). This series of steel balls exhibited a load capacity of about 450 pounds. Thus, at 80° F the load capacities of the titanium carbide cermet and silicon carbide balls are about 3 and 1 percent, respectively, that of M-1 bearing steel and 41 and 18 percent, respectively, that of the hot-pressed alumina used in reference 14. Table VI shows relative load capacities at 80° F of several materials that have been tested under similar conditions in the five-ball fatigue tester.

TABLE VI. - LOAD CAPACITY OF SEVERAL MATERIALS TESTED UNDER SIMILAR CONDITIONS IN FIVE-BALL FATIGUE TESTER

[Race temperature, 80° F; contact angle, 20°; specimen, 1/2-in.-diam. balls.]

Material	Load capacity as percent of load capacity of AISI M-1 steel	Reference
AISI M-1[a]	100	19
Hot-pressed alumina	7	14
Crystallized glass ceramic	6	12
Nickel-bonded titanium carbide cermet	3	--
Self-bonded silicon carbide	1	--
Cold-pressed-and-sintered alumina	1	14

[a]Race temperature, 140° F.

Increasing the race temperature from 80° to 700° F in the five-ball fatigue tester resulted in a reduction in load capacity of 29 and 27 percent for the titanium carbide cermet and the silicon carbide, respectively. This reduction results from the effect of the change in viscosity of the lubricant with temperature on life, as discussed previously.

Rolling-Contact Tests From 1100° to 2000° F

Several ball specimens of each material were run in a modified five-ball fatigue tester with MoS_2-argon mist lubrication. Tests were performed at a shaft speed of 450 rpm, a contact angle of 20°, maximum Hertz stresses of 310,000 and 400,000 psi, and temperatures from 1100° to 2000° F. The results of these tests are shown in table VII.

TABLE VII. - RESULTS OF TESTS IN MODIFIED FIVE-BALL TESTER AT TEMPERATURES UP TO 2000° F

[Shaft speed, 450 rpm; contact angle, 20°; lubrication, molybdenum disulfide - argon mist; support balls, hot-pressed alumina, race material, cold-pressed-and-sintered alumina.]

Test ball material	Test ball	Temperature, °F	Maximum Hertz stress, psi	Test time, min	Change in surface condition of track	Track width, in. (a)	Track depth, μin. (a)	Total stress cycles at end of test
Self-bonded silicon carbide	1	2000	400,000	5	Some plastic deformation; one area of greater plastic flow	0.011	70	6700
	2	2000	400,000	5	Some plastic deformation	0.012	95	
				15	Excessive plastic deformation and wear; considerable surface pitting	.015	200	20,200
	3	1600	400,000	10	Some plastic deformation	-----	---	
				25	Increased plastic deformation	0.012	70	33,800
Nickel-bonded titanium carbide cermet	1	1600	310,000	19	Considerable plastic deformation and some wear	-----	---	25,600
	2	1350	310,000	15	Gross pitting or welding and wear around entire length of track[b]	-----	---	20,200
	3	1100	310,000	10	Same as test ball 2[c]	-----	---	13,500
	4	1100	310,000	10	Slight plastic deformation; no wear	0.008	40	
				25	Increased plastic deformation	.010	70	
				50	Increased plastic deformation	.010	90	
				75	Increased plastic deformation	.010	100	101,000

[a]Measured from profile trace.

[b]Nickel-bonded titanium carbide cermet support balls and race.

[c]Nickel-bonded titanium carbide cermet support balls.

Failure of silicon carbide ball specimens at a 400,000-psi maximum Hertz stress was by excessive plastic deformation at both 1600° and 2000° F. Some random surface pitting was observed accompanying the plastic deformation in specimens run at 2000° F. Tests with titanium carbide cermet at 310,000-psi maximum Hertz stress and hot-pressed alumina support balls resulted in excessive plastic deformation at temperatures as low as 1100° F. Tests with support balls of titanium-carbide cermet at 1350° and 1100° F exhibited gross pitting or welding and wear of the titanium-carbide cermet test balls and support balls.

These tests show that excessive plastic deformation will limit the use of self-bonded silicon carbide to temperatures less than 1600° F at a stress of 400,000 psi and nickel-bonded titanium carbide cermet to temperatures less than 1100° F at a stress of 310,000 psi. The importance of using dissimilar materials for bearing components in contact under these conditions is also shown.

SUMMARY OF RESULTS

Surface failure tests in rolling contact were conducted with groups of nickel-bonded titanium-carbide cermet and self-bonded silicon-carbide ball specimens in the five-ball fatigue tester. These tests were performed at a contact angle of 20°, a shaft speed of 950 rpm, race temperatures of 80° and 700° F, and maximum Hertz stresses of 300,000 to 550,000 psi with a mineral oil lubricant. Support balls were SAE 52100 and AISI M-50 steel in the 80° and 700° F tests, respectively. Preliminary tests were conducted at temperatures to 2000° F in the modified five-ball fatigue tester using hot-pressed alumina support balls and molybdenum disulfide lubrication. The following results were obtained:

1. The load-carrying capacity at 80° F of the titanium-carbide cermet was more than twice that of the silicon carbide; however, the capacity of the titanium-carbide cermet was only ~3 percent that of M-1 bearing steel tested under similar conditions.

2. The life of the titanium-carbide cermet at 80° F varied inversely with stress to a power that ranges from 9.7 to 10.5, and thus exhibited about the same stress-life sensitivity as that for bearing steels. In contrast, the life of the silicon carbide was found to vary inversely with stress raised to a power that ranges from 6.9 to 8.6.

3. Increasing the race temperature from 80° to 700° F resulted in a reduction in load capacity for the titanium-carbide cermet and silicon carbide of approximately 27 and 29 percent, respectively. The reduction was attributed to the decrease in viscosity of the lubricating fluid at the elevated temperature. Failure appearance at 700° F was similar to that at room temperature for both materials.

4. The surface failures in the titanium-carbide cermet were very shallow, eroded areas less than 1 mil deep and were similar to failures found in alumina but unlike fatigue pits found in bearing steels.

5. The failures in the silicon carbide were from 3 to 5 mils deep and were unlike those failures found in either the titanium-carbide cermet or bearing steels.

6. Progression of an incipient failure to a full size failure for both the titanium-carbide cermet and the silicon carbide was a slow process that frequently consumed one-half of the total running time of the specimen.

7. Failure of self-bonded silicon carbide ball specimens in preliminary tests run at 400,000-psi maximum Hertz stress with molybdenum disulfide - argon mist lubrication was by excessive plastic deformation at temperatures above 1600° F.

8. Preliminary tests to temperatures of 1600° F and a maximum Hertz stress to 310,000 psi with molybdenum disulfide - argon mist lubrication indicate that the titanium-carbide cermet is limited to temperatures below 1100° F and stresses less than 300,000 psi for reliable operation. Failure in the titanium-carbide cermet was due to excessive cumulative plastic deformation.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 15, 1964

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