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Effect of Carbide Distribution on Rolling-Element Fatigue Life of AMS 5749

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Summary

Endurance tests were run with 46-millimeter bore, split-inner-ring ball bearings made of VIM–VAR AMS 5749. Ten of these bearings were run at a 4890-N (1100-lb) thrust load and a shaft speed of 42 000 rpm. The bearings were jet lubricated with MIL–L–23699 at an oil-in temperature of 366 K (200° F). To supplement the bearing tests and aid in clarifying the results, RC rig tests were run on three lots of VIM–VAR AMS 5749 test bars with varying carbide size and distribution. The RC rig tests were run at a maximum Hertz stress of 4.83 GPa (700 000 psi) at both 12 500 and 50 000 rpm.

Spalling fatigue lives of the AMS 5749 bearings were much lower than predicted based on previously obtained data. In the RC rig tests, large, banded carbides reduced rolling-element fatigue life by a factor of approximately 4. Early spalling failures on the bearing inner raceways were attributed to the large carbide size and banded carbide distribution. The detrimental effects of large, banded carbides were observed only in the 50 000-rpm RC rig tests and not in the 12 500-rpm tests.

Introduction

Rolling-element bearings for aircraft turbine engine mainshaft applications are generally specified to be made of AISI M–50 steel. Currently the premium quality material used is double vacuum melted (VIM–VAR, for vacuum induction melt, vacuum arc remelt). This very clean, high quality material gives greatly improved rolling-element fatigue life over previously used materials.

Fatigue life is extremely important in design and specification of rolling-element bearings, but fatigue is not a common failure mode in actual aircraft bearing experience. A summary of causes for bearing rejection at a U.S. Navy facility (ref. 1) shows that corrosion accounts for nearly one third of the bearing rejections from their aircraft systems, including drivelines, wheels, and accessories. Air Force experience (ref. 2) confirms that corrosion is a major cause of rejection at overhaul of aircraft turbine engine bearings. Bearing corrosion is more severe in systems with long periods of nonuse.

A material, AMS 5749 steel, has been developed which combines the tempering, hot hardness, and hardness retention characteristics of AISI M–50 steel, with the corrosion and oxidation resistance of AISI 440C stainless steel (refs. 3 and 4). The typical chemical compositions of these materials are shown in table I. AMS 5749 contains higher percentages of carbon and chromium than AISI M–50 for improved corrosion and wear resistance. The hot hardness and hardness retention of AMS 5749 is better than AISI 440C and similar to AISI M–50 (ref. 4). Additional hot hardness data for AMS 5749 is shown in reference 5 where the material is identified as "a modified AISI 440C."

Materials such as AISI 440C and AMS 5749 are called corrosion-resistant or stainless steels; but under some severe conditions in aircraft bearings, they will corrode. They are, however, more corrosion resistant than the common aircraft bearing materials such as AISI M–50, AISI 52100 and the commonly used case-carburized materials.

AMS 5749, processed by double vacuum melting or VIM–VAR, has shown excellent rolling-element fatigue life. In five-ball fatigue tests reported in reference 6, rolling-element fatigue life of VIM–VAR AMS 5749 was significantly better than that of VIM–VAR AISI M–50. Similar fatigue tests in the rolling-contact (RC) fatigue tester showed that AMS 5749 was at least equivalent to AISI M–50.

With these encouraging results in accelerated rolling-element fatigue tests, full-scale bearing fatigue tests were planned to substantiate the promising rolling-element fatigue properties of AMS 5749. The objective of the research reported herein was to (1) determine the rolling-element fatigue life of full scale bearings made of AMS 5749 compared to that of the bearings of AISI M–50 and (2) determine the effect of carbide distribution on rolling-element fatigue life of AMS 5749.

Apparatus and Procedure

Test Bearings

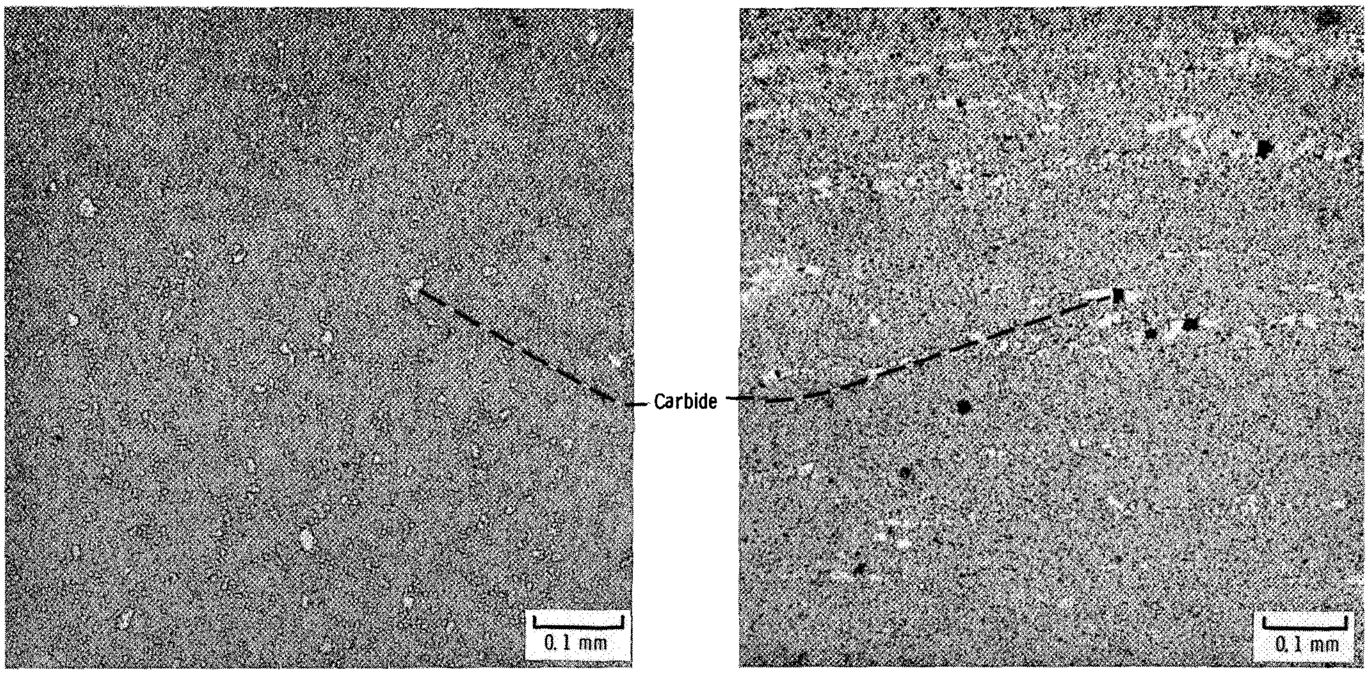
The bearing design selected for these tests is based on the thrust ball bearing from the high pressure turbine of a turboshaft engine. It is a split-inner-ring design with a bore diameter of approximately 46 millimeters. More details of the design are given in table II. The cage was a one-piece, machined, outer land riding design made of AMS 6414 (AISI 4340) and silver-plated according to AMS 2412.

The inner and outer races were machined from bars approximately 64 millimeters (2.5 in.) in length and 102 millimeters (4 in.) in diameter, respectively. No forging processes were used. The balls were made from 12.7-millimeter (0.5-in.) diameter ball wire and upset into rough spherical blanks. All races and balls were from a single heat of VIM-VAR AMS 5749 material. The heat treatment for the balls and races are given in table III. Resulting hardnesses and retained austenite are given in table IV.

The microstructures of the ball and race materials are shown in figure 1. Due to the additional rolling and forging received by the ball material, a more uniform distribution of smaller carbides was accomplished. The race material contains banded carbides, some much larger than those in the ball material.

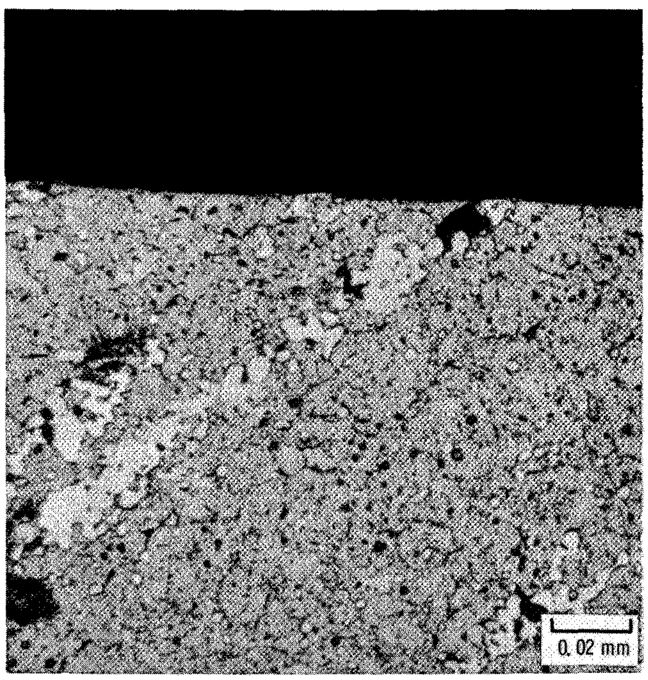
Bearing Testing

The bearings were tested using three identical fatigue test rigs, one of which is shown in figure 2. In these rigs, two test bearings were fixed through the inner ring to a single shaft. The outer ring of each bearing was fixed to a cantilevered, radially flexible sleeve. Each flexible sleeve was fixed at one end in the bore of each bearing housing. The bearing housings were slightly loose in the bore of the test rig housing. An axial load was applied equally to the test bearings by applying a load with a calibrated spring through a load plunger, load sensor, and load



(a) Carbide structure of ball.

(b) Carbide structure of race.



(c) Carbides at inner raceway surface.

Figure 1. - Typical microstructure of AMS 5749 ball bearing material.

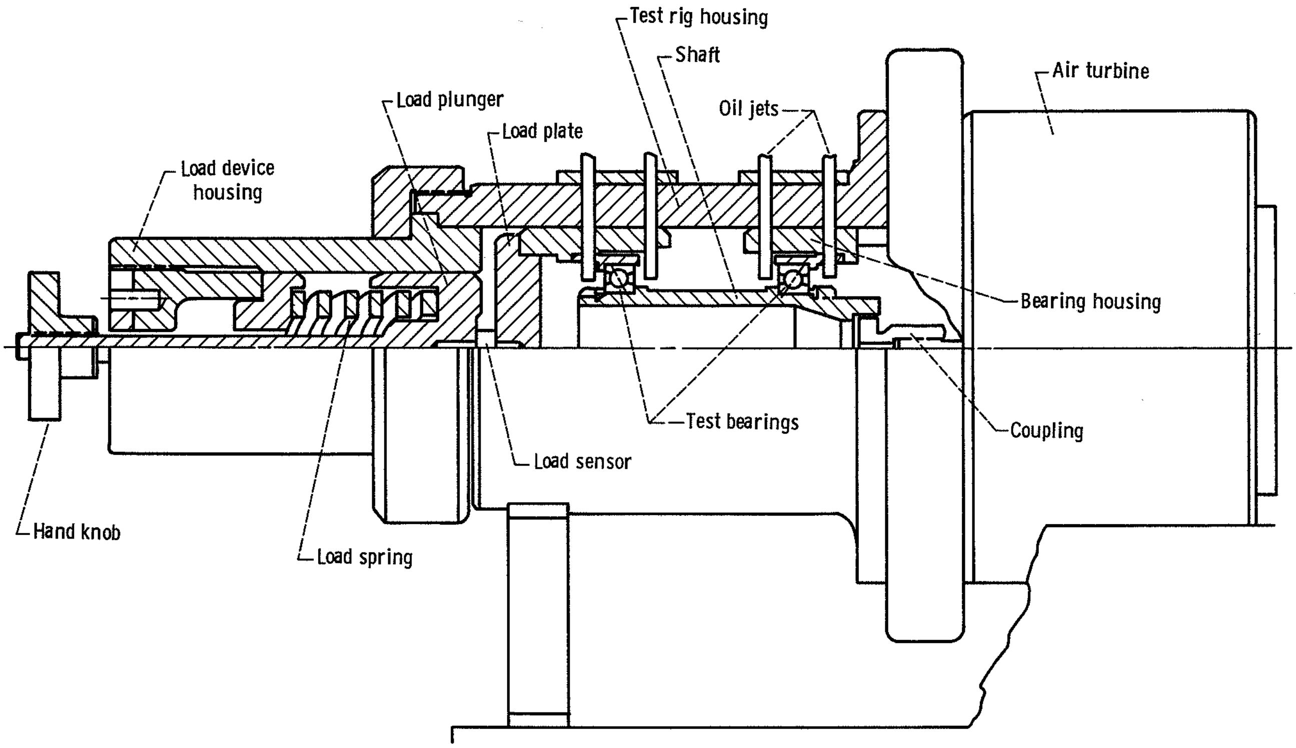


Figure 2. - Bearing fatigue test rig.

plate to the front bearing housing. Spring load adjustment was made by turning the load nut in the load device housing. The adjustment was held fixed by a ring locknut. The hand knob was used only to hold the load device together during disassembly. The test rig shaft was driven by a governed air turbine through a drive coupling. Each bearing was lubricated by two jets, one forward and one aft of each bearing. The oil-in temperature was maintained at the desired level with steam and water heat exchangers in the oil system.

For these tests, the axial load was 4890 N (1100 lb) and the shaft speed was 42 000 rpm. The bearings were lubricated with MIL-L-23699 at an oil-in temperature of 366 K (200° F). Test rig vibration and test bearing temperature were monitored, and the lubrication system contained magnetic chip detectors to sense bearing failures.

Test Bars

The RC test bars were 76.2 millimeters (3.00 in.) long and 9.52 millimeters (0.375 in.) in diameter with a surface finish of 0.1 to 0.2 μm (4 to 8 μin.) CLA. All bars were from a single heat of VIM-VAR AMS 5749 material. Three groups of bars were prepared. Lot A bars were prepared from material which had been rolled to 12.7-millimeter (0.5-in.) diameter bar stock. Lots B and C were prepared from material which had been rolled to round-cornered square bar stock of approximately 140 millimeters (5.5 in.) on a side.

Lot B bars were made from blanks which were oriented along the axis of the bar stock. The blanks for lot B bars were cut midway from the centerline of the bar to the outside of the bar. Lot C bar blanks were oriented transverse to the bar stock axis and were cut from the center of the bar. These orientations are shown in figure 3. Bars from both lots B and C were cut into 15-millimeter (0.6-in.) square blanks, heat treated according to the procedures given in table III, and then ground to test bar specifications. Hardnesses and retained austenite of the three lots of bars are shown in table IV.

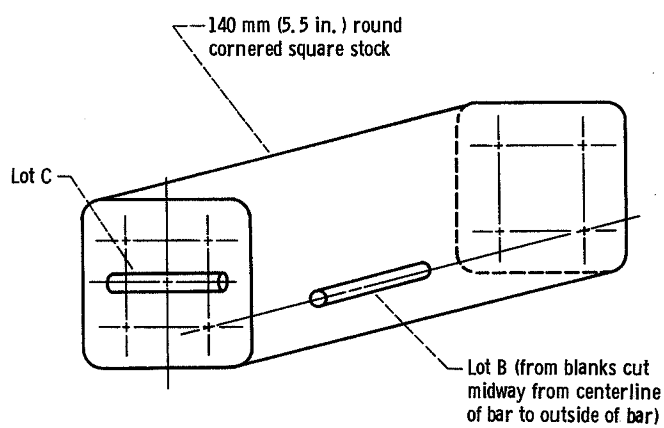
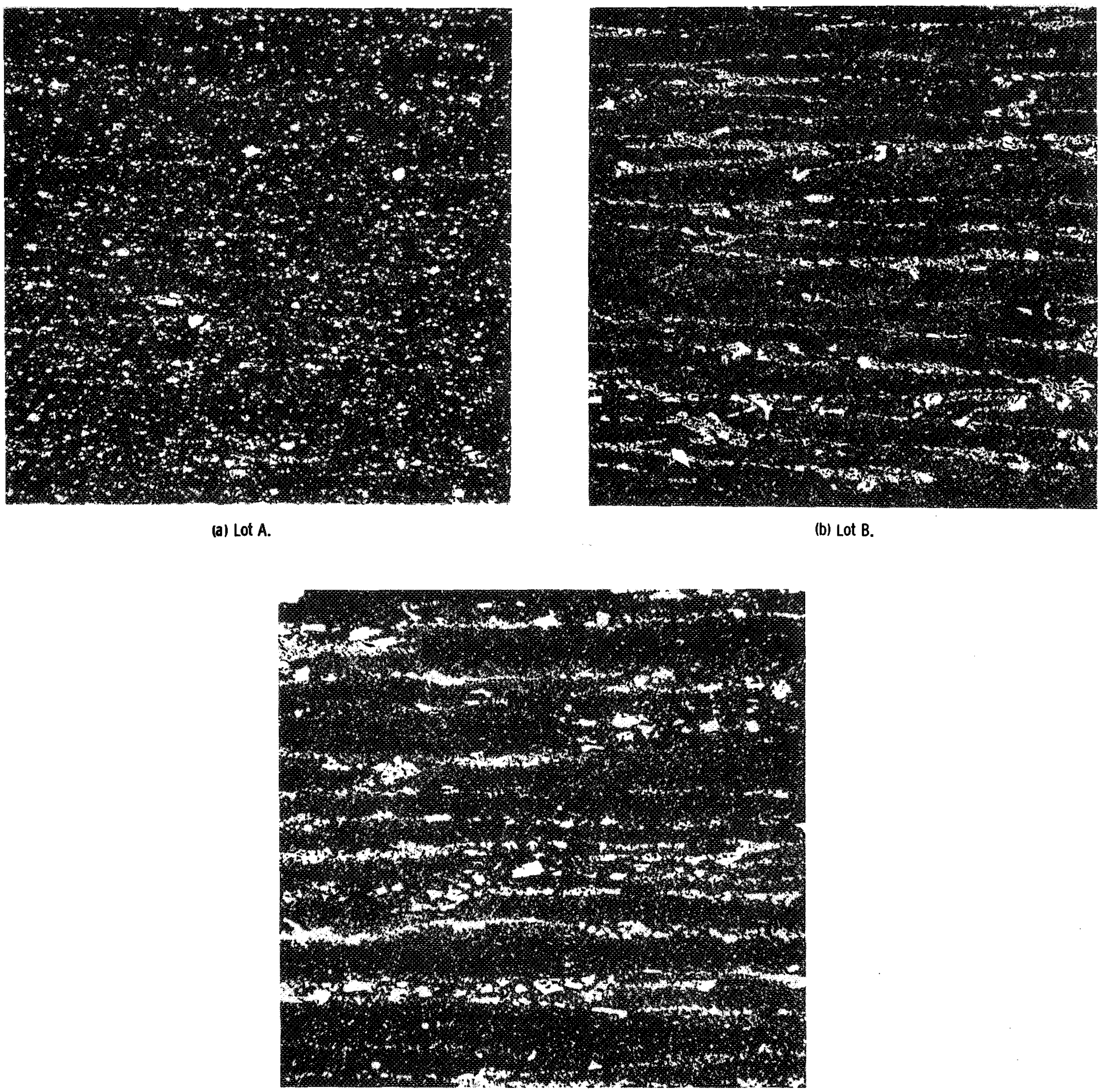


Figure 3. - Orientation of lots B and C bars in AMS 5749 round cornered square stock.

As a result of rolling the stock for the lot A bars to the smaller 12.7 millimeter (0.5 in.) diameter, the size and distribution of carbides is significantly different from that of lots B and C bars. This difference is readily apparent in the photomicrographs in figure 4. The carbides in the lot A bars are smaller and more uniformly dispersed than the banded distribution of larger carbides in lots B and C. The bars cut transversly from the larger stock (lot C) had slightly more banding and larger carbides than the longitudinally cut bars (lot B).

Additionally, the grain flow, or orientation of the carbide bands, is parallel to the axis of the lot B bars. It is also parallel to the rolling contact surface. In the lot C bars, the grain flow is transverse to the bar axis and varies around the bar circumference from perpendicular to parallel to the rolling contact surface.

The lot C bar carbide banding and orientation most closely resembles that of the bearing races. The bearing races were machined without forging such that the raceway grooves contained grain flow which was not



(a) Lot A.

(b) Lot B.

(c) Lot C.

Figure 4. - Typical microstructures of AMS 5749 RC rig test bars.

parallel to the rolling contact surfaces. (This will be discussed further in a later section.) The carbide size and distribution of lot A bars more closely resembles that of the bearing balls. The similarities of the carbide distributions can be seen by comparing figures 1 and 4.

Rolling Contact Fatigue Testing

The test bars were run in either the standard or the high speed rolling-contact fatigue testers (RC rigs). The high speed RC rig is shown in figure 5. This rig was first described in reference 7 and is the same in principal as the standard RC rig. The high speed RC rig uses an electric motor to drive an air bearing spindle that supports the test bar in a precision chuck to speeds up to 50 000 rpm. In both rigs, the load is applied by closing two idler rollers against the test bar using a micrometer threaded turnbuckle and a calibrated load cell. Lubrication is supplied by a drip feed system using a needle valve to control flow rate. Several tests can be made on one test bar by indexing the bar in the axial direction relative to the idler rollers. Vibration instrumentation detects a fatigue failure and terminates a test.

All tests were performed with a lubricant bulk temperature of 297 ±3 K (75 ±5° F) at a maximum Hertz stress of 4.83 GPa (700 000 psi). Tests were run at 12 500 rpm in standard RC rigs with a MIL–L–7808 lubricant. In the high speed rigs, tests were run at 50 000 rpm with a MIL–L–23699 lubricant. Twenty tests were run with each lot of test bars at a given speed. Each test was run to fatigue failure or to a preset cutoff time.

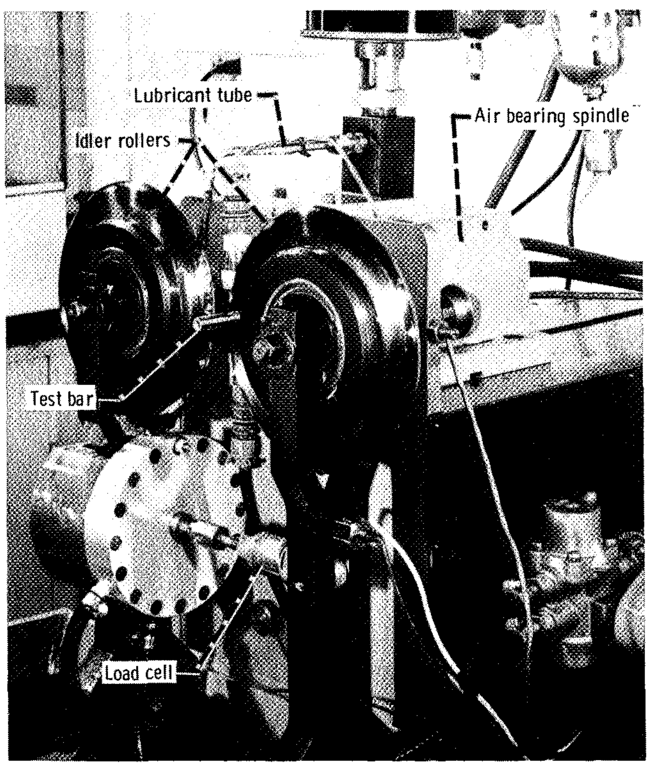


Figure 5. - High-speed rolling-contact fatigue tester (RC rig).

Method of Presenting Fatigue Results

The statistical methods of reference 8 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 stress cycles to failure (Weibull coordinates). For convenience, the ordinate is graduated in statistical percent of specimens failed. A straight line, determined by the method of least squares, is fitted to the experimental data points. From a plot such as this the number of stress cycles necessary to fail any given portion of the specimen group may be determined.

For purposes of comparison the 10- or 50-percent lives on the Weibull plot were used. The 10-percent life is the number of 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.

Confidence numbers, which indicate the statistical significance of the fatigue life results, were calculated by the method given in reference 8. A confidence number is the probability, expressed as a percentage, that lot B, which is used as a baseline, actually has a fatigue life greater than that of the particular lot being considered. A confidence number of 95 percent or greater, which is a 2σ confidence level (twice the standard deviation), indicates a high degree of certainty.

Results and Discussion

Bearing Test Results

Ten bearings were tested in pairs under a thrust load of 4890 N (1100 lb) at 42 000 rpm with an oil-in temperature of 366 K (200° F). At these conditions, the calculated bearing 10-percent life is 47 hours as determined by the computer analysis SHABERTH described in reference 9. This life analysis accounted for centrifugal effects on load and contact angle variation within the bearing as well as elastohydrodynamic (EHD) lubrication effects. Bearing temperatures of 422 K (300° F) were assumed which were the average inner and outer ring temperatures measured during the testing.

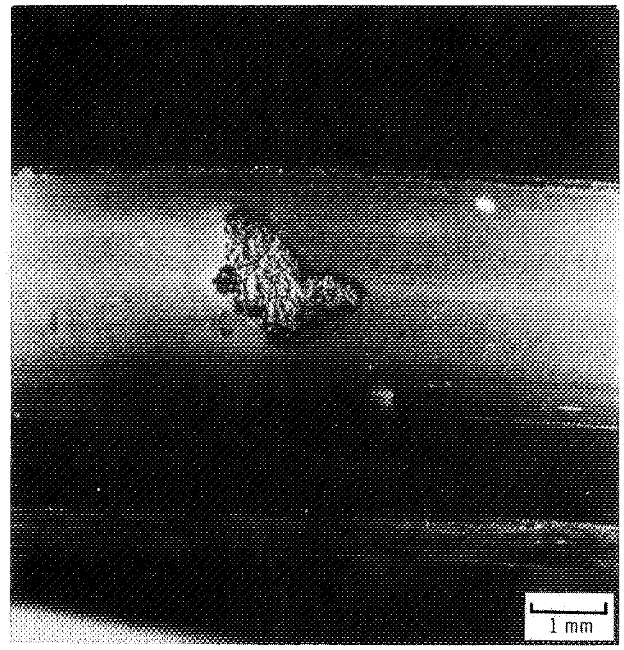
A material factor of one was assumed in the life calculation. The material factor in the SHABERTH analysis is intended to include both bearing material and processing life modifying effects as described in the ASME Design Guide (ref. 10). Such factors have not been determined for AMS 5749, but results of accelerated rolling-element fatigue tests with VIM-VAR AMS 5749 (refs. 6 and 11) have shown lives at least equivalent to VIM-VAR AISI M-50. Bearings made of VIM-VAR AISI M-50 have shown lives more than 40 times the calculated life which includes centrifugal and EHD effects (ref. 12). It was expected that the VIM-VAR AMS 5749 bearings would have a 10-percent life of 1900 hours based on this previous work.

Eight of the ten VIM-VAR AMS 5749 bearings developed spalls on their inner raceways after times ranging from 46 hours to 1012 hours. The times to spalling failure are shown in table V. These lives are much shorter than those expected for bearings made of this material. A Weibull analysis (ref. 8) of the experimental bearing lives yields a 10-percent life of 32 hours which is over an order of magnitude less than expected.

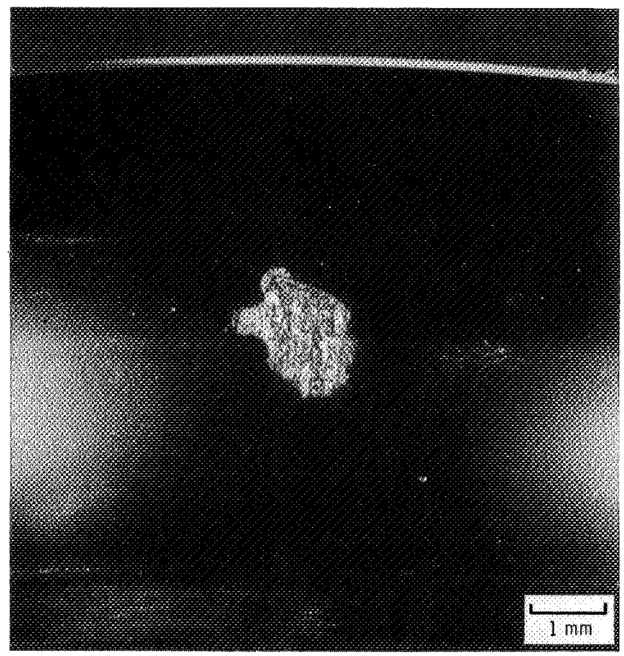
Observations of the failed bearings after the first four bearing pairs were tested revealed that the inner raceway grooves have the appearance of significant metal-to-metal contact and obliteration of the original grinding marks. Typical spalls on inner raceways are shown in figure 6. The spalls appeared to be surface originated. Condition of the outer raceway surface was much better. The condition of the inner raceway surfaces was believed to be due to a marginal elastohydrodynamic (EHD) film thickness, allowing significant surface contact in the ball-raceway conjunction.

The marginal EHD film condition apparently was due to lubricant starvation at the inner-raceway-ball contact. Increasing lubricant jet velocity and adjusting the jet direction for the next pair of bearings tested effectively eliminated the marginal film condition. In this test, the grinding marks were visible on both raceways of both bearings after 106 hours. However, one of the bearings in this test also had a spall on the inner raceway. Thus, it is apparent that the marginal film condition was not the sole cause of the early failures.

Testing was suspended at this time, and several bearings were sectioned for metallurgical examination. Typical microstructures of the bearing races are shown in figures 1(a) and (c). The large size of the carbides and the severe banding of the carbide stringers is apparent. Where these large carbides intersect the raceway surface (shown in fig. 1(c)) the structure is likely to be very weak in rolling-element fatigue. Also, the carbide stringers or grain flow lines were oriented at an angle to the contact surfaces, since these bearings were run with a thrust load and the balls run at an angle from the groove bottom as shown in figure 7. This so-called end-grain effect has been found to be very weak in rolling-element fatigue (refs. 13 to 17). It is believed that the early failures were primarily due to the undesirable carbide structure, in particular, the large carbide stringers that were at or very near the rolling surface. Further, it has been shown (ref. 18) that large carbides are generally detrimental to rolling-element fatigue life.



(a) Bearing serial number R5; test time, 1012 hours.



(b) Bearing serial number R10; test time, 106 hours.

Figure 6. - Typical fatigue spalls on inner raceways of AMS 5749 ball bearings.

RC Rig Test Results

In order to further study the effect of an undesirable carbide distribution on rolling-element fatigue and substantiate that the early bearing fatigue failures were carbide related, a series of RC rig tests were performed. The RC test bars made by the processes described earlier with variations in carbide size and distribution were subjected to rolling-element fatigue tests.

Initial tests were run at 12 500 rpm in standard RC rigs at 4.83 GPa (700 000 psi) with MIL-L-7808 as the lubricant. Lots A and B bars were tested. The results are shown in the Weibull plots in figure 8 and are summarized in table VI. No significant difference in fatigue life was seen between the Lot A bars with the small evenly distributed carbides and Lot B bars with the larger banded carbides. This result was not expected.

Subsequent tests were run at 50 000 rpm in high-speed RC rigs with MIL-L-23699 as the lubricant at otherwise identical conditions. At the higher speed and with the more viscous MIL-L-23699 lubricant, the EHD film thickness in the contact is expected to be greater. Under this thicker film condition, the amount of surface-to-surface contact is expected to be less. It is expected that, at the lower speed and lower lubricant viscosity condition (12 000 rpm with MIL-L-7808), the EHD film was thin enough that significant surface-to-surface contact existed to mask the effects of carbide distribution. It has been shown that tests at higher speeds in the RC rigs have significantly longer lives that are attributed to decreased surface contact (refs. 7 and 19).

At 50 000 rpm with the MIL-L-23699 lubricant, tests were run with lots A, B, and C bars. The results of these tests are shown in figure 9 and are summarized in table VI. A typical fatigue spall is shown in figure 10. At the higher speed, expected differences in rolling-element fatigue life were observed. Lot A bars had significantly greater lives than lot B or C bars (approximately five and three times, respectively). The detrimental effects of the poor carbide distribution and large carbide size (fig. 4) of lots B and C are clearly seen. The orientation of the carbide bands (transverse or axial grain flow) between

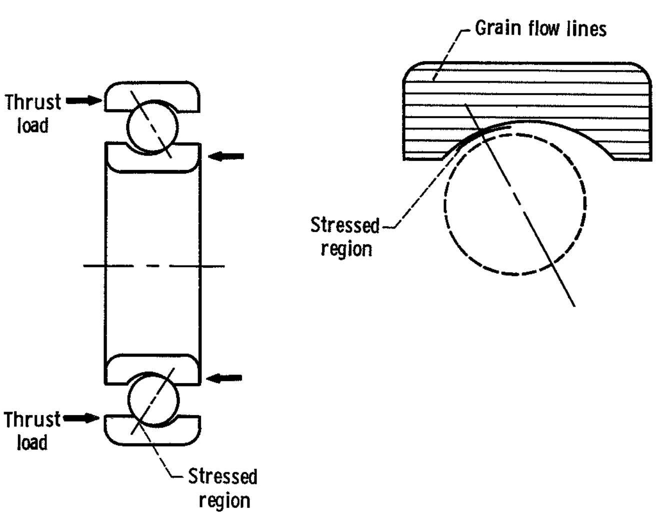


Figure 7. - End grain in stressed region of thrust loaded ball bearing.

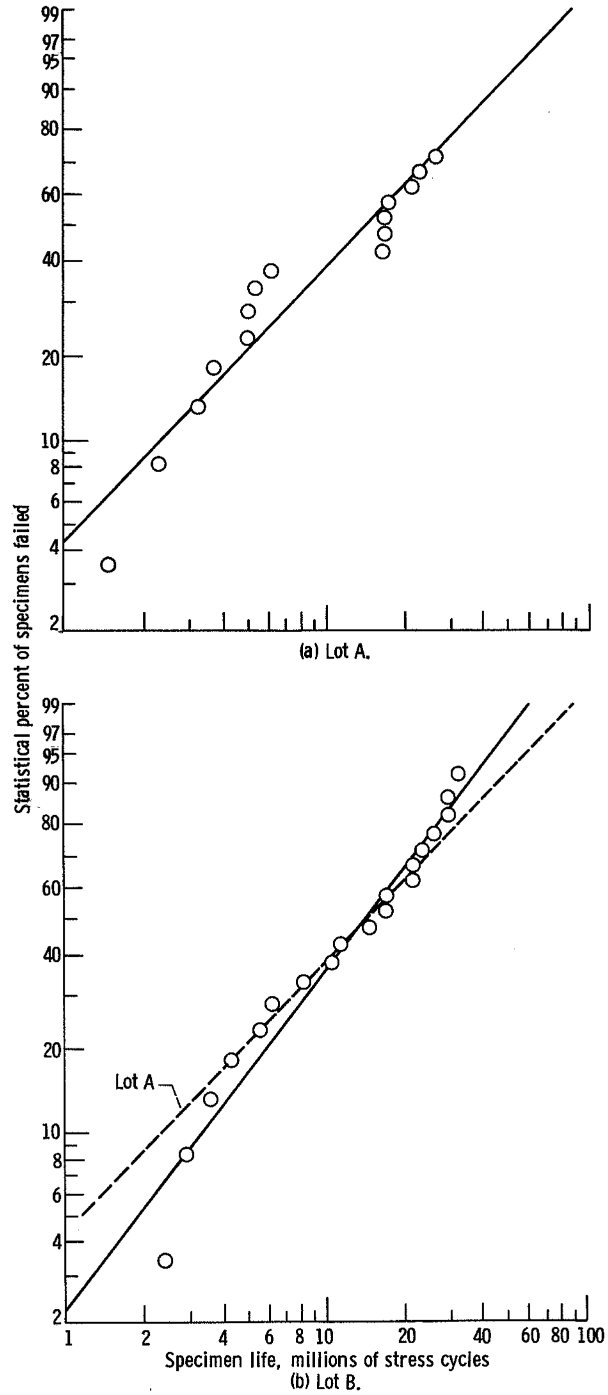


Figure 8. - Rolling element fatigue life of AMS 5749 test bars in the rolling-contact fatigue tester (RC rig) at 12 500 rpm. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75° F).

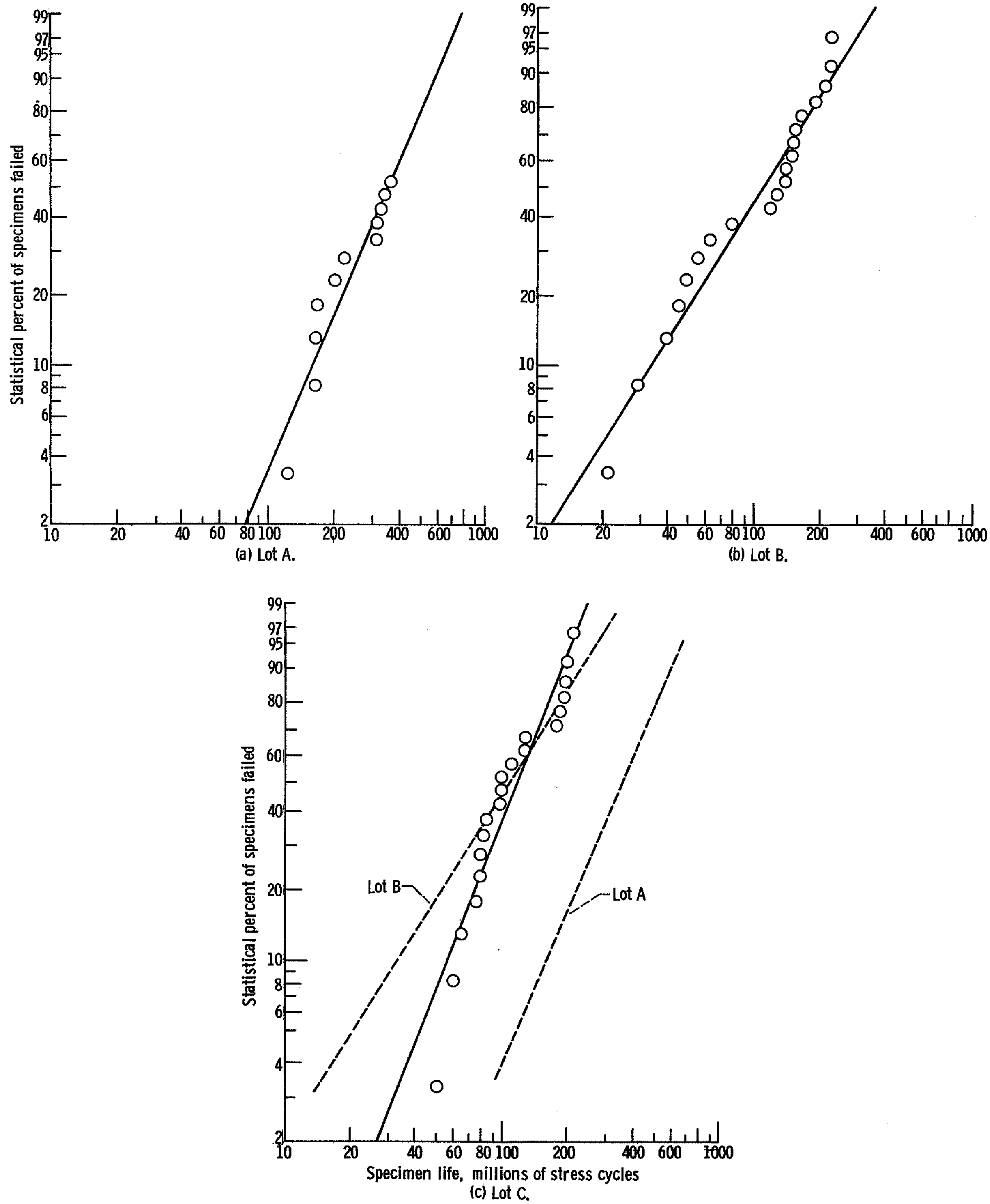


Figure 9. - Rolling-element fatigue life of AMS 5749 test bars in the rolling-contact fatigue tester (RC rig) at 50 000 rpm. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75° F).

lots B and C had an insignificant effect on rolling element fatigue life. In both cases (lots B and C) it was apparent that the large carbides were at or near the surface and contributed to earlier fatigue spalling.

General Comments

Tests with the high speed RC rig successfully showed the expected difference in rolling-element fatigue life

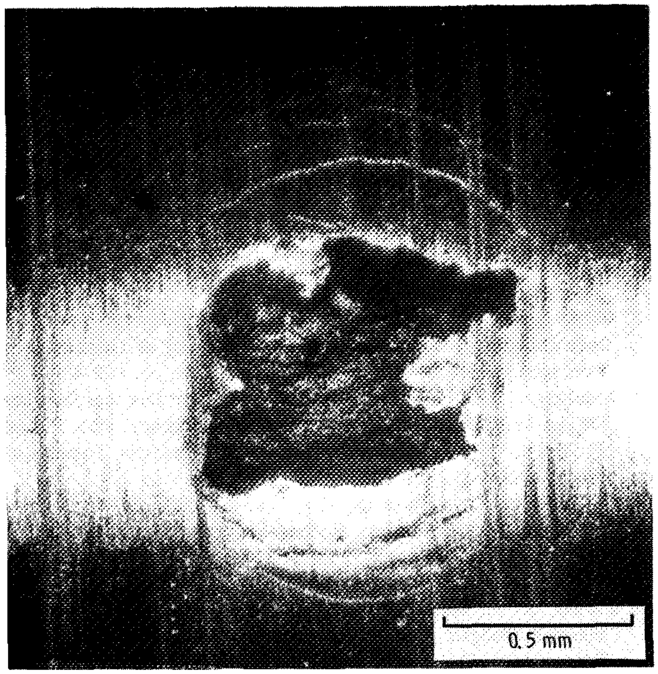


Figure 10. - Typical spall on AMS 5749 RC rig test bar. (Lot A; 50 000-rpm bar speed; life, 372.8 million stress cycles.)

between the poor and the more desirable carbide distributions. Such differences were not seen in tests at 12 500 rpm in the standard RC rig. It is believed that the effects on fatigue life of surface-to-surface contact at the lower speed masked the effects of the carbide distribution variations.

Previous accelerated rolling-element fatigue tests (refs. 6 and 11) have shown the VIM-VAR AMS 5749 has a fatigue life at least as good as VIM-VAR AISI M-50. Reference 7 contains results of high-speed RC rig tests with VIM-VAR AISI M-50 at 50 000 rpm with MIL-L-23699 lubricant and at conditions identical to those in the present tests. The 10- and 50-percent lives of VIM-VAR AISI M-50 were 48 and 584 million stress cycles, respectively. These lives are in the same range as those with the three lots of VIM-VAR AMS 5749 at 50 000 rpm (see table VI). This comparison agrees with the results of references 6 and 11, that is, confirming that the fatigue life of AMS-5749 is at least as good as that of AISI M-50. The 10-percent life of the lot A bars (160 million stress cyles) is more than three times that of AISI M-50 tests of reference 7. These comparative results tend to agree best with those of reference 6, which show the life of AMS 5749 to be significantly greater than that of AISI M-50.

The results of these tests with various carbide distributions tend to confirm that the low life problem with the AMS 5749 bearings is related to a poor carbide distribution in the races. Several means of solving this problem with bearing races may be considered. Adequate working or forging of the material would tend to break up the larger carbides and more evenly distribute them (as was done with the bar stock for the lot A bars.) Hot isostatic pressed (HIP) powder processing techniques may result in better carbide distribution with AMS 5749 as it has with AMS 5900 (ref. 20). Modifications in the chemistry of AMS 5749 to allow case carburizing of the material (lower carbon levels) may result in a more uniform distribution of smaller carbides. Any of these potential solutions would require significant research and development to prove their usefulness. The improved corrosion resistance with AMS 5749 should be of sufficient value to pursue a means to solve the observed carbide distribution problem with AMS 5749 races.

Summary of Results

Endurance tests were run with 46-millimeter bore, split-inner-ring ball bearings made of VIM-VAR AMS 5749. Ten of these bearings were run at 4890 N (1100 lb) thrust load at a shaft speed of 42 000 rpm. The bearings were jet lubricated with MIL-L-23699 at an oil-in temperature of 366 K (200° F). To supplement the bearing tests and aid in clarifying the results, RC rig tests were run on three lots of VIM-VAR AMS 5749 test bars with varying carbide size and distribution. RC rig tests were run at a maximum Hertz stress of 4.83 GPa (700 000 psi) at both 12 500 and 50 000 rpm. The following results were obtained.

1. Spalling fatigue lives of the AMS 5749 bearings were much lower than were predicted based on previously obtained data.
2. In the RC rig tests, the large, banded carbides reduced rolling-element fatigue life by a factor of approximately 4.
3. Early spalling failures on the bearing inner raceways were attributed to the large carbides and banded carbide distribution.
4. The detrimental effects of large carbide size and banded carbide distribution were not observed in the 12 500 rpm low speed RC rig tests.
5. The 10-percent rolling-element fatigue life of VIM-VAR AMS 5749 RC test bars was more than three times greater than that of VIM-VAR AISI M-50 bars at 50 000 rpm.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 22, 1983

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TABLE I. - TYPICAL CHEMICAL COMPOSITIONS OF BEARING MATERIALS

Material	Chemical composition, weight percent (a)					
	C	Si	Mn	Cr	Mo	V
AMS 5749	1.15	0.30	0.50	14.5	4.0	1.2
AISI M-50	.85	.25	.35	4.0	4.25	1.0
AISI 440C	1.00	.50	.50	17.5	.5	---

[a]Balance iron.

TABLE II. - TEST BEARING SPECIFICATIONS

Pitch diameter, mm (in.)	59.792 (2.3540)
Bore diameter, mm (in.)	45.923 (1.8080)
Outside diameter, mm (in.)	73.665 (2.9002)
Width (outer), mm (in.)	16.129 (0.635)
Ball diameter, mm (in.)	9.5250 (0.375)
Number of balls	15
Radial clearance under 49-N (11-lb) load, mm (in.)	0.087 - 0.099 (0.0034 - 0.0039)
Shim thickness, mm (in.)	0.229 (0.009)
ABEC tolerances	7
Inner curvature, percent of ball diameter	52.75 - 53.25
Outer curvature, percent of ball diameter	51 - 51.5
Specific dynamic capacity, N (lb)	17 868 (4017)
Surface roughness, μm (μin.) rms	
Balls	0.05 (2)
Raceways	0.10 (4)

TABLE III. - HEAT TREATMENT OF AMS 5749 TEST MATERIAL

Heat treatment	Bearing races	Bearing balls	RC rig test bars
Preheat[a]	1089 K (1500° F) 5 min	1089 K (1500° F) 5 min	1118 K (1500° F)
Harden[a]	1380 K (2025° F) 20 min	1380 K (2025° F) 20 min	1394 K (2050° F)
Quench[a]	866 K (1100° F) 5 min; air cool to room temperature	866 K (1100° F) 5 min; air cool to room temperature	839 K (1050° F) air cool to room temperature
Temper	450 K (350° F) 5 min; air cool	450 K (350° F) 5 min; air cool	422 K (300° F) 1 hr; air cool
Deep freeze	189 K (-120° F) 2 hr; air warm	189 K (-120° F) 2 hr; air warm	200 K (-100° F) 15 min; air warm
Temper	797 K (975° F) 2 hr; air cool; repeat twice	797 K (975° F) 2 hr; water quench	797 K (975° F); 2 hr; air cool; repeat
Deep freeze	------------------	189 K (-120° F) 2 hr; air warm	----------------
Temper	------------------	797 K (975° F) 2 hr; water quench; repeat; air cool	----------------

[a]In molten salt bath.

TABLE IV. - HARDNESS AND RETAINED AUSTENITE OF AMS 5749 BEARING COMPONENTS AND RC RIG TEST BARS

Component	Hardness, Rockwell C	Retained austenite, percent
Bearing balls	60.0	<3
Bearing races	60.5	6
Lot A bars	61.8	7
Lot B bars	61.2	12
Lot C bars	61.9	7

TABLE V. - AMS 5749 BEARING LIFE TEST RESULTS

[Shaft speed, 42 000 rpm; thrust load, 4890 N (1100 lb); oil-in temperature, 366 K (200° F).]

Bearing number	Bearing life, hr	Result
R1	89.4	No failure
R2	89.4	Inner race spall
R3	598.8	↓
R4	598.8	↓
R5	1012	↓
R6	1012	↓
R7	46.0	↓
R8	46.0	↓
aR9	106.0	No failure
aR10	106.0	Inner race spall

[a]Improved EHD film condition.

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15. Supplementary Notes

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16. Abstract

Endurance tests with ball bearings made of VIM-VAR AMS 5749 corrosion resistant bearing steel resulted in fatigue lives much lower than were predicted. Metallurgical analysis revealed an undesirable carbide distribution in the races. Accelerated fatigue tests in the RC rig showed that large, banded carbides could reduce rolling-element fatigue life by a factor of approximately four. The early spalling failures on the bearing raceways were attributed to the large carbide size and banded distribution.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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