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EFFECT OF DOUBLE VACUUM MELTING AND RETAINED AUSTENITE ON ROLLING-ELEMENT FATIGUE LIFE OF AMS 5749 BEARING STEEL

by Richard J. Parker and Robert S. Hodder*

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SUMMARY

AMS 5749 steel 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. The effects of double vacuum melting and retained austenite on the rolling-element fatigue life of AMS 5749 steel were determined in tests run in the five-ball fatigue tester. Groups of 1.27-cm (1/2-in.) diameter balls were tested at a maximum Hertz stress of 5520 MPa (800 000 psi), a contact angle of 30°, and a shaft speed of 10 000 rpm. Tests were run at a race temperature of 339 K (150° F) with a superrefined naphthenic mineral oil as the lubricant. Double vacuum melting (vacuum induction melting plus vacuum arc remelting, VIM-VAR) produced AMS 5749 material with a rolling-element fatigue life at least 14 times that of vacuum induction melting alone. The VIM-VAR AMS 5749 steel balls gave lives from 6 to 12 times greater than VIM-VAR AISI M-50 steel balls. The highest level of retained austenite, 14.6 percent, was significantly detrimental to rolling-element fatigue life relative to the intermediate level of 11.1 percent.

INTRODUCTION

Current aircraft turbine engine manufacturers' material specifications demand a double vacuum melted (VIM-VAR, for vacuum induction melt, vacuum arc remelt) AISI M-50 steel for mainshaft bearings. With this material ball bearing fatigue lives of nearly 100 times AFBMA predicted life have been obtained (ref. 1). Reduction in inclusion content, trace elements, and interstitial gas content due to double vacuum melting is considered responsible for a major portion of this life advancement (ref. 2).

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AISI M-50 also has the hot hardness and hardness retention ability for long life rolling-element bearing operation at temperatures up to 588 K (600° F) (ref. 3).

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. 4 and 5). 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. 5). Additional hot hardness data for AMS 5749 is shown in reference 6 where the material is identified as "a modified AISI 440C." Preliminary data presented in reference 2 and confirmed in unpublished supplemental work indicate that VIM-VAR AMS 5749 has a rolling-element fatigue life similar to that of VIM-VAR AISI M-50.

It is a well-established fact that, for reasons of dimensional stability, a low level of retained austenite is desirable for critical bearing components. Typical maximum levels are in the range of 2 to 5 percent. For this reason little work has been directed at fatigue life studies of steels exhibiting higher levels of retained austenite. However, some unpublished work with AISI M-50 has indicated that fatigue life may improve with increased retained austenite. AMS 5749 steel, because of its alloy content, tends to retain higher levels of austenite, but levels as low as 5 percent are attainable with suitable heat treatment. This characteristic allowed the development of appropriate test material with varied retained austenite while other characteristics such as hardness remained constant.

The objective of this research was to (1) compare the rolling-element fatigue life of AMS 5749 steel with AISI M-50 steel, (2) determine the effect of double vacuum melting (VIM-VAR) on the fatigue life of AMS 5749, and (3) determine the effect of retained austenite on the fatigue life of AMS 5749.

The objective was accomplished by running groups of AMS 5749 balls in five-ball fatigue testers. Groups of VIM-VAR AMS 5749 balls with different amounts of retained austenite and one group of VIM AMS 5749 balls were tested. In addition a group of VIM-VAR AISI M-50 balls was tested for comparison. Test conditions included a shaft speed of 10 000 rpm, a contact angle of 30°, a maximum Hertz stress of 5520 MPa (800 000 psi), and a temperature of 339 K (150° F).

TEST SPECIMENS

The 1.27-cm (1/2-in.) diameter, VIM-VAR AMS 5749 steel balls used in these tests were from a single heat of material. Likewise, the VIM AMS 5749 and the

VIM-VAR AISI M-50 balls were from single heats of the respective materials. The balls were heat treated according to the specifications given in table II.

All balls in lots A, B, and C (VIM-VAR material) were initially heat treated as one large group through and including the double temper as listed in table II for lot A. They were all finished to AFBMA grade 10 ball specifications at this time. These balls had a relatively high level of retained austenite, 14.6 percent average. The large group was divided into the three lots. Lot A was tested as is at the high level of retained austenite as shown in table III. Lot B was given an additional tempering cycle to reduce this level and refinished to grade 10 specifications. Lot C was given three additional tempering cycles and also refinished. The reduced levels of retained austenite for lots B and C averaged 11.1 and 6.3 percent, respectively.

For all three lots the hardness was maintained at approximately 64 Rockwell C. As a result of refinishing to grade 10 specifications, including a surface finish of 5.0×10^{-6} cm (2 μin.) rms or better, the balls of lots B and C were decreased 0.0002 cm (0.000080 in.) below the nominal 1.27-cm (0.500-in.) diameter. This slight size difference is not considered to be a significant factor in the five-ball tests used in this study. The hardnesses and retained austenite levels of the VIM AMS 5749 and the VIM-VAR M-50 balls are also shown in table III.

APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester was used for all tests conducted. The apparatus is shown in figure 1 and is described in detail in reference 7. This fatigue tester consists essentially of an upper test ball pyramided on 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 receives three stress cycles from the lower balls. The upper test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and lower balls function in a manner similar to the cage and the balls in a bearing.

Lubrication is provided by a once-through, mist lubrication system. The lubricant was a superrefined naphthenic mineral oil with a viscosity of 79×10^{-6} m^2/sec (79 cS) at 311 K (100° F) and 8.4×10^{-6} m^2/sec (8.4 cS) at 372 K (210° F). Vibration instrumentation detects a fatigue failure on either the upper or the lower ball and automatically shuts down the tester. This provision allows unmonitored operation and a consistent criterion for failure.

Fatigue Testing

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

Method of Presenting Fatigue Results

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

For purposes of comparison the 10-percent or 50-percent lives on the Weibull plot were used. The 10-percent life is the number of upper-ball stress cycles within which 10 percent of the specimens can be expected to fail; this 10-percent life is equivalent to a 90-percent probability of survival.

Confidence numbers, which indicate the statistical significance of the fatigue life results were calculated by the method given in reference 9. A confidence number is the probability, expressed as a percentage, that lot B, which is used as 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

Fatigue Results

The rolling-element fatigue lives of VIM and VIM-VAR AMS 5749, and VIM-VAR AISI M-50 were compared in tests run in the five-ball fatigue tester. Groups of

1.27-cm (1/2-in.) diameter balls of each material were tested at a maximum Hertz stress of 5520 MPa (800 000 psi), a contact angle of 30°, and a shaft speed of 10 000 rpm. Tests were run at a race temperature of 339 K (150° F) with a superrefined naphthenic mineral oil as the lubricant.

The results of the fatigue tests are shown in the Weibull plots of figures 2 to 4. A summary Weibull plot is shown in figure 5, and the results are further summarized in table IV.

Effect of Retained Austenite

The comparison of the 10-percent lives of the three lots of VIM-VAR AMS 5749 does not present a clear effect of retained austenite on fatigue life. The intermediate level (lot B, 11.1 percent) gave the longest life with apparent statistical significance when compared with the highest level, where the confidence number is 97 percent, or greater than 2σ confidence. For the lowest level of retained austenite (lot C), the confidence number is 87 percent. Thus, it is apparent that the high level of retained austenite, 14.6 percent (lot A), is significantly detrimental to the 10-percent fatigue life. Therefore, an optimum level of retained austenite is suggested for maximum fatigue life. However, because of the limits imposed by dimensional stability, such levels are probably not practical for bearings for critical applications such as in aircraft turbine engines.

It should be noted that an unusually high Weibull slope exists in the lot B failure distribution. The reason for this high slope along with the relatively long life of this lot is not understood; however, it is of interest to note that relatively early failures did not occur at the 11.1 percent retained austenite level. Thus, the 50-percent life data suggest a trend toward increased life with decreased retained austenite level. However, where high reliability is of importance, the main interest is in early failures, which is indicated best by the 10-percent life data.

Effect of Vacuum Arc Remelting

The results of fatigue tests with the VIM AMS 5749 balls are shown in figure 3. These data are compared with the VIM-VAR data in figure 5 and in table IV. At the 10-percent life level the improvement in life with the double vacuum melting process, VIM-VAR, is from 14 to 28 times that of the VIM process alone with AMS 5749 steel. The VAR process undoubtedly promotes additional cleanliness and uniformity of the VIM ingot and, as a result, much superior fatigue life.

The VIM-VAR process has also been shown to produce AISI M-50 steel superior to that produced by air-melt VAR, air-melt electroslag remelting, or VIM electroslag remelting (ref. 2). The life improvements with the improved AISI M-50, although very significant, have not been as large as these results with AMS 5749.

It should also be noted that the slopes of the Weibull lines through the VIM-VAR AMS 5749 data are very high compared with that of the VIM data, indicating greater uniformity and homogeneity of the double vacuum melted steel.

Comparison with VIM-VAR AISI M-50

The results of the fatigue tests with VIM-VAR AISI M-50 balls are shown in figure 4. The data are compared with those of the VIM-VAR AMS 5749 in figure 5 and table IV. At the 10-percent life level, VIM-VAR AMS 5749 gave lives from 6 to 12 times greater than AISI M-50. Confidence numbers are greater than 99 percent when compared with all three lots of AMS 5749.

This large superiority of AMS 5749 over AISI M-50 was unexpected in view of the data of reference 2, which showed fatigue lives of the two materials essentially equal in tests in the rolling-contact (RC) fatigue rig. The hardness of the AISI M-50 balls was only slightly lower than that of the AMS 5749 balls (table III). This difference of less than 1 point Rockwell C is not expected to cause such a large fatigue life difference.

As noted in table III, the retained austenite content of the AISI M-50 balls was 2.1 percent. The influence of the difference in retained austenite from the higher levels of the three lots of AMS 5749 and that of the AISI M-50 is not known. Because of the relatively small differences in fatigue life with the three levels of retained austenite, one would not expect that the large difference in life between the two materials could be attributed to retained austenite differences alone. However, since these retained austenite levels were significantly greater than that of the AISI M-50, the possibility exists that the observed life differences between the two materials may be partly due to retained austenite differences.

It may be expected that a portion of the superiority of AMS 5749 in the five-ball tests may be attributed to its greater corrosion and oxidation resistance. Although rolling-element fatigue in controlled fatigue tests such as these has been considered a subsurface originated phenomenon, with the cleaner double vacuum melted materials, fewer inclusions and subsurface defects are present, thus any surface effects may take on added significance.

Corrosion or oxidation resistance may be more significant in the five-ball tests than in the rolling contact (RC) rig tests of reference 2 because of the greater sliding and higher stress in the concentrated contact of the five-ball tests. These effects have not been confirmed experimentally.

SUMMARY OF RESULTS

The effects of double vacuum melting and retained austenite on the rolling-element fatigue life of AMS 5749 steel were determined in tests run in the five-ball fatigue tester. Groups of 1.27-cm (1/2-in.) diameter balls were tested at a maximum Hertz stress of 5520 MPa (800 000 psi), a contact angle of 30°, and a shaft speed of 10 000 rpm. Tests were run at a race temperature of 339 K (150° F) with a superrefined naphthenic mineral oil as the lubricant. The following results were obtained:

1. Vacuum induction melted, vacuum arc remelted (VIM-VAR) AMS 5749 steel gave rolling-element fatigue lives at least 14 times that of vacuum induction melted (VIM) AMS 5749.
2. The VIM-VAR AMS 5749 steel balls gave lives from 6 to 12 times greater than the VIM-VAR AISI M-50 steel balls.
3. The longest rolling-element fatigue life was obtained at 11.1 percent retained austenite. The highest level of retained austenite, 14.6 percent, was significantly detrimental to rolling-element fatigue life.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 2, 1977,
505-04.

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TABLE I. - TYPICAL CHEMICAL COMPOSITIONS

OF TEST MATERIALS

Material	Chemical composition, wt % (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	17.0	.5	---

[a] Balance iron.

TABLE II. - HEAT TREATMENT OF THE TEST MATERIALS

Heat treatment	Material				
	VIM-VAR AMS 5749			VIM AMS 5749 (Lot D)	VIM-VAR AISI M-50
	Lot A	Lot B	Lot C		
Preheat	1089 K (1500° F)				
Harden	In salt at 1422 K (2100° F)[a]				1403 K (2065° F)
Quench	In oil at 339 K (150° F)				In molten salt at 825 K (1025° F)
Air cool	To room temperature				To below 339 K (150° F)
Temper	422 K (300° F) for 1 hr				811 K (1000° F) for 2 hr
Deep freeze	200 K (-100° F) for 15 min				183 K (-130° F) for 1.5 hr
Temper	797 K (975° F) for 2 hr, air cool to room temperature, repeat				811 K (1000° F) for 2 hr
Temper	-----	797 K (975° F) for 2 hr; air cool to room temperature	797 K (975° F) for 2 hr; air cool to room temperature; repeat twice	-------------	797 K (975° F) for 2 hr; air cool to room temperature

[a] Current recommendation 1394 K (2050° F) in salt.

TABLE III. - HARDNESS AND RETAINED AUSTENITE OF THE TEST MATERIALS

Material	Lot	Hardness, Rockwell C	Retained austenite, percent
VIM-VAR AMS 5749	A	63.8	14.6
	B	64.2	11.1
	C	64.1	6.3
VIM AMS 5749	D	63.1	13.1
VIM-VAR AISI M-50	---	63.3	2.1

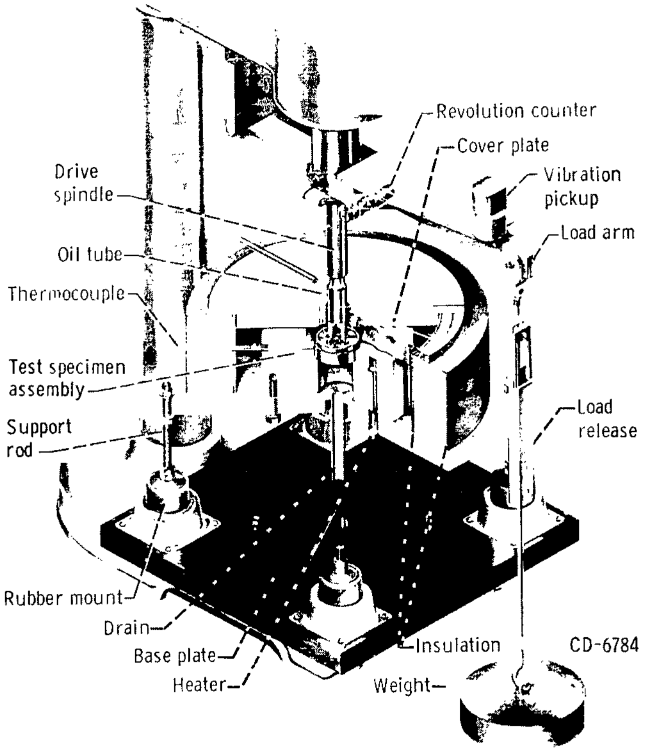
TABLE IV. - FATIGUE RESULTS WITH 1.27-CM- (1/2-IN.-) DIAMETER BALLS RUN IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; temperature, 339 K (150° F), lubricant, superrefined naphthenic mineral oil.]

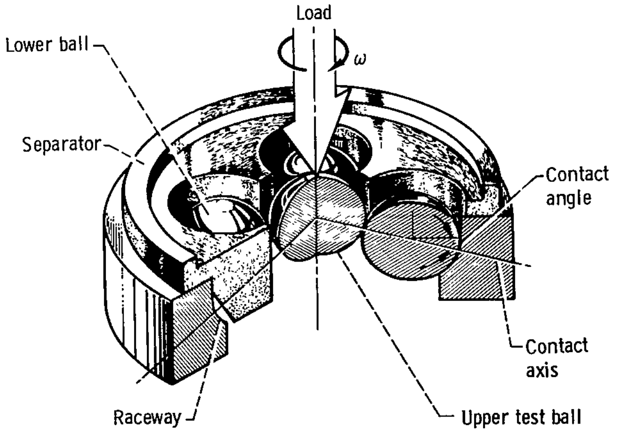
Material	Lot	Fatigue life, millions of upper ball stress cycles		Slope	Failure index[a]	Confidence number,[b] percent
		10-Percent life	50-Percent life			
VIM-VAR AMS 5749	A	56.7	120	2.50	31 Out of 40	97
	B	112	164	4.94	20 Out of 30	---
	C	66.4	192	1.77	10 Out of 21	87
VIM AMS 5749	D	3.9	26.3	0.99	29 Out of 30	>99
VIM-VAR AISI M-50	---	8.9	36.6	1.33	34 Out of 40	>99

[a] Indicates number of failures out of total number of tests.

[b] Probability that lot B (baseline) has a 10-percent fatigue life greater than that of the particular lot being considered.



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



(b) Five-ball test assembly.

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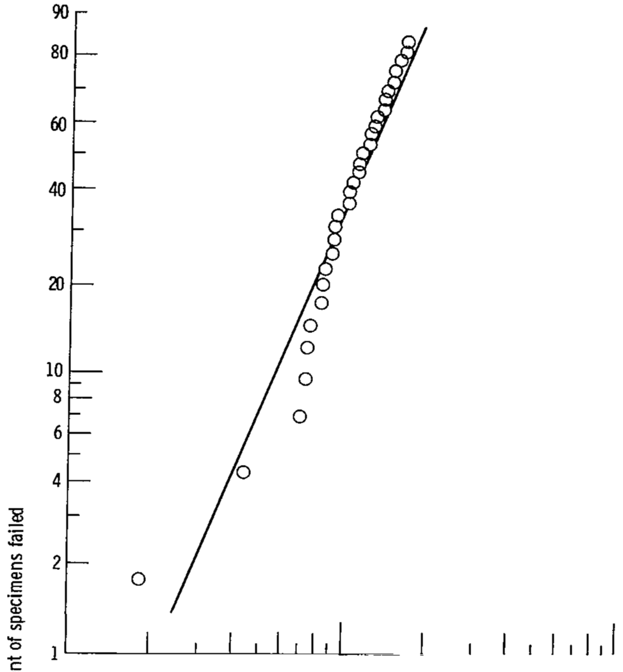
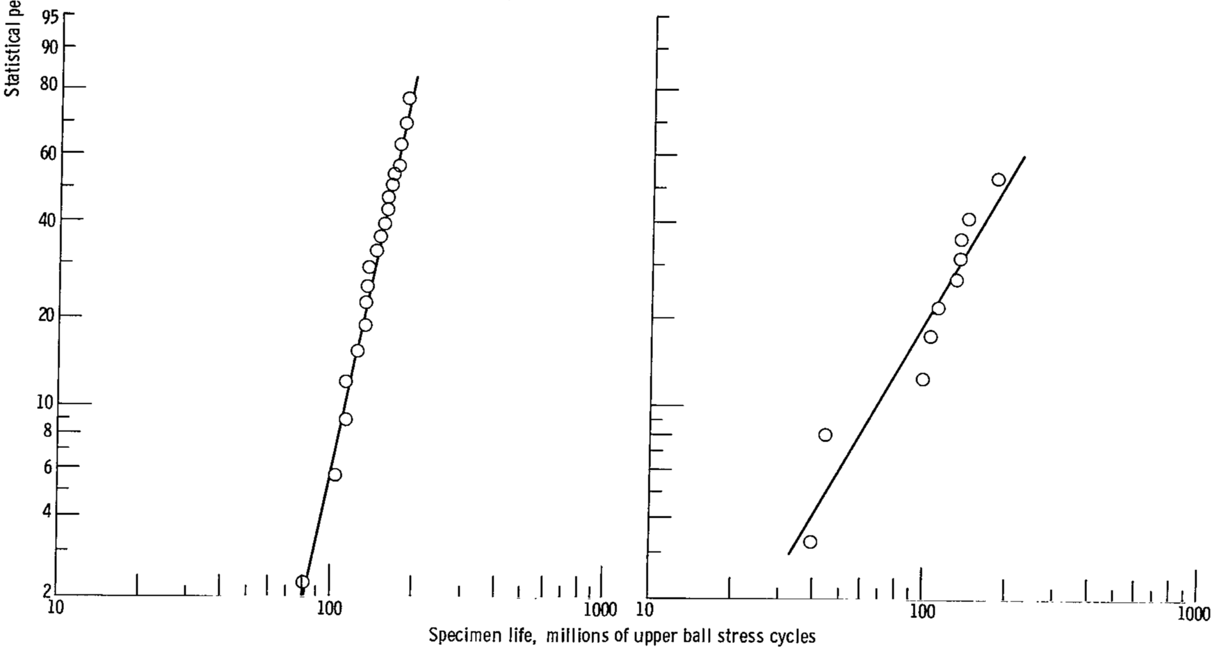
Figure 1. - Test apparatus.



(a) Lot A; retained austenite, 14.6 percent; failure index, 31 out of 40.



(b) Lot B; retained austenite, 11.1 percent; failure index, 20 out of 30. (c) Lot C; retained austenite, 6.3 percent; failure index, 10 out of 21.

Figure 2. - Rolling-element fatigue life of 1.27-cm (1/2-in.) diameter VIM-VAR AMS 5749 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft-speed, 10 000 rpm; race temperature, 339 K (150° F).

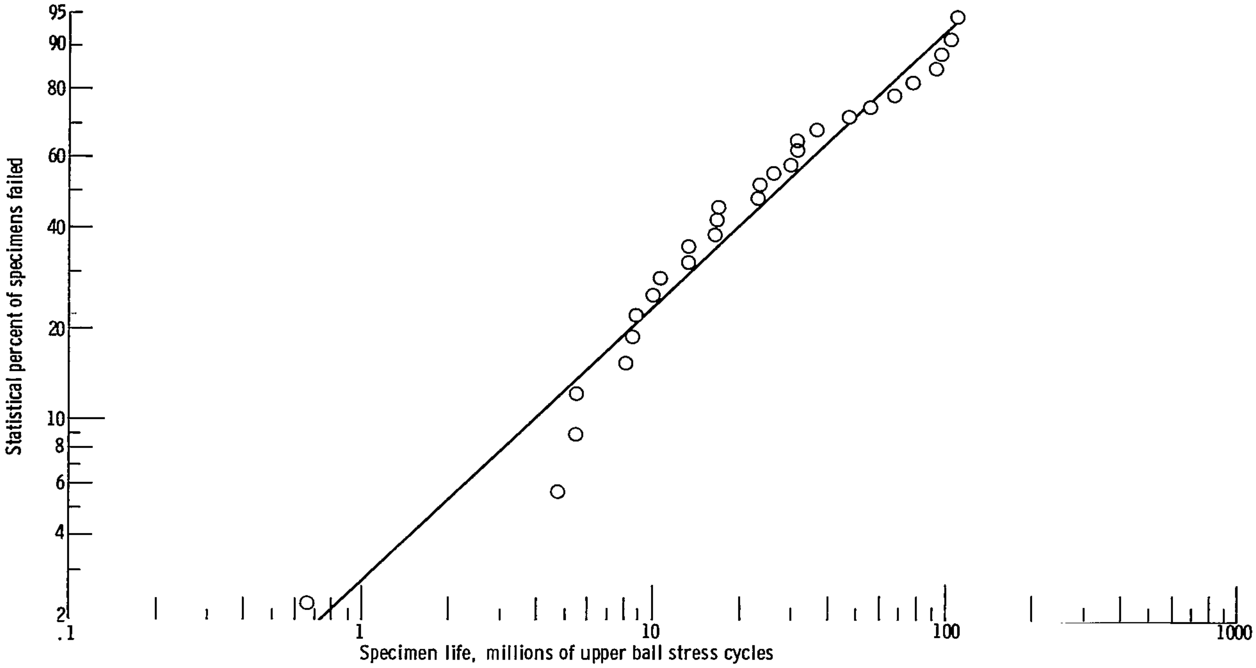


Figure 3. - Rolling-element fatigue life of 1.27-cm (1/2-in.) diameter VIM AMS 5749 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; race temperature, 339 K (150° F); failure index, 29 out of 30.

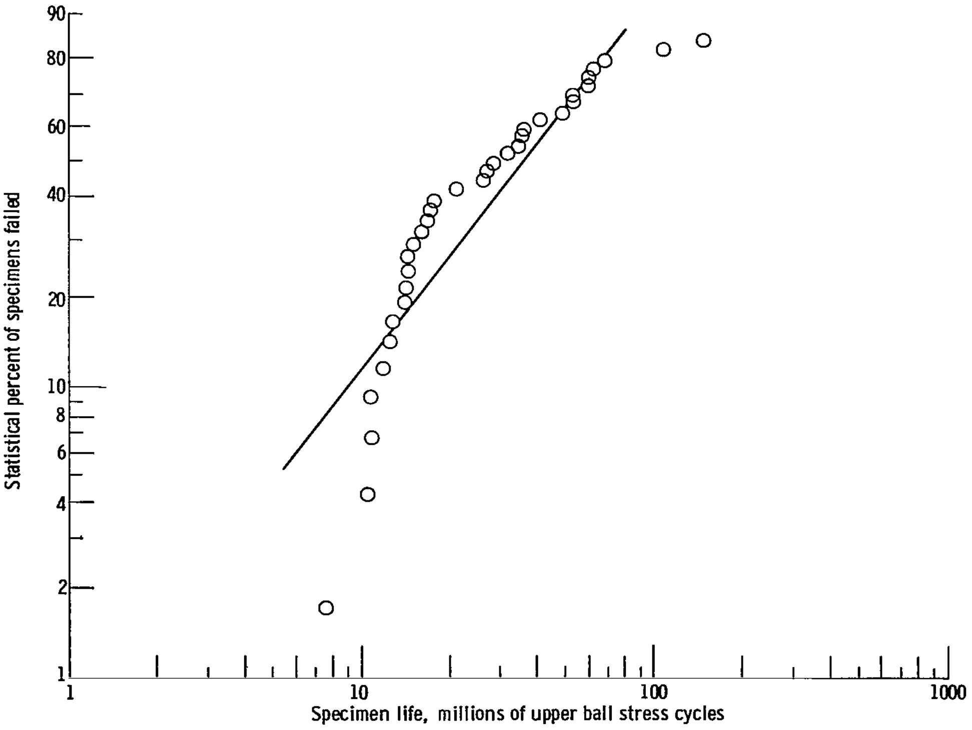


Figure 4. - Rolling-element fatigue life of 1.27-cm (1/2-in.) diameter VIM-VAR AISI M-50 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; race temperature, 339 K (150° F); failure index, 33 out of 40.

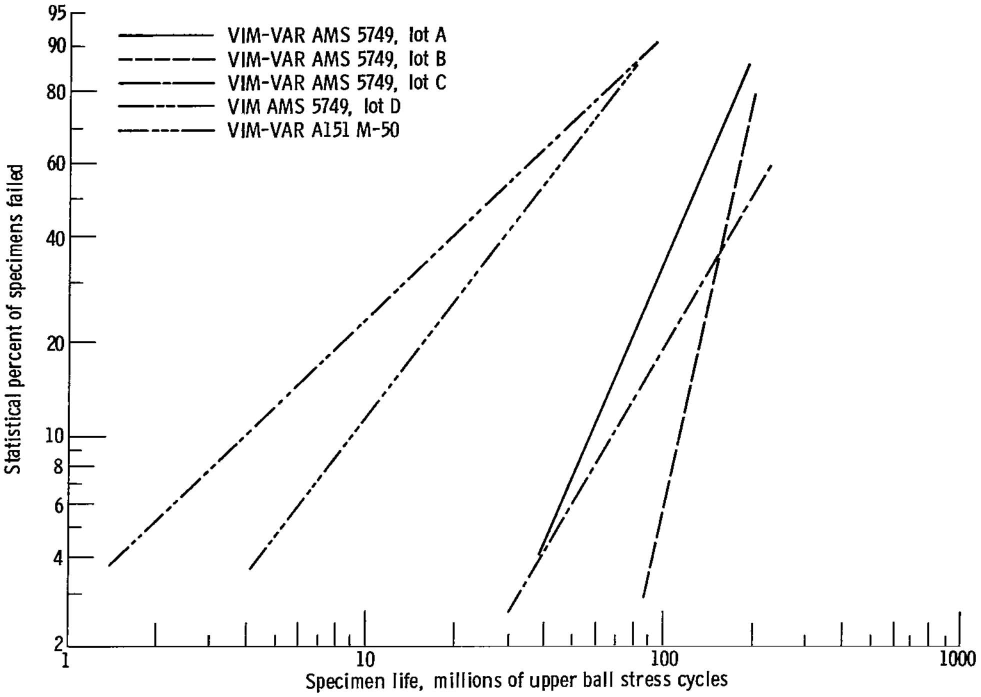


Figure 5. - Summary of rolling-element fatigue data with AMS 5749 and AISI M-50 balls in five-ball fatigue tester.

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16. Abstract

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