(NASA-TM-73698) ROLLING-ELEMENT FATIGUE LIFE OF AMS 5749 CORROSION RESISTANT, HIGH TEMPERATURE BEARING STEEL (NASA) 27 p HC A03/MF A01 CSCL 11F

N77-32287

Unclas
G3/26 49088

NASA TECHNICAL MEMORANDUM

NASA TM 73698

NASA TM 73698

ROLLING-ELEMENT FATIGUE LIFE OF AMS 5749 CORROSION RESISTANT, HIGH TEMPERATURE BEARING STEEL

by Richard J. Parker
Lewis Research Center
Cleveland, Ohio 44135

and

Robert S. Hodder
Latrobe Steel Co.
Latrobe, Pennsylvania

TECHNICAL PAPER to be presented at the
1977 Joint Lubrication Conference
cosponsored by the American Society of Lubrication Engineers
and the American Society of Mechanical Engineers
Kansas City, Missouri, October 3-5, 1977

E-9101

ROLLING-ELEMENT FATIGUE LIFE OF AMS 5749 CORROSION RESISTANT, HIGH TEMPERATURE BEARING STEEL

by R. J. Parker[1] and R. S. Hodder[2]

ABSTRACT

The rolling-element fatigue lives of AMS 5749 and AISI M-50 were compared in tests run in the five-ball fatigue tester and the rolling-contact (RC) fatigue tester. The effects of double vacuum melting and retained austenite on the life of AMS 5749 were determined in five-ball fatigue tests. The double vacuum melting process consisted of induction vacuum melting followed by vacuum arc remelting (VIM-VAR). In the five-ball tests, VIM-VAR AMS 5749 gave lives at least six times that of VIM-VAR AISI M-50. Similar tests in the rolling-contact (RC) fatigue tester showed no significant difference in the lives of the two materials. The rolling-element fatigue life of VIM-VAR AMS 5749 was at least 14 times that of vacuum induction melted AMS 5749. A trend toward increased rolling-element fatigue life with decreased retained austenite is apparent, but the confidence that the all experimental differences are significant is not great. The highest level of retained austenite, 14.6 percent, is, however, significantly detrimental to rolling-element fatigue life, relative to the intermediate level of 11.1 percent.

---

[1]NASA, Lewis Research Center, Cleveland, Ohio; Member ASME

[2]Latrobe Steel Co., Latrobe, Pennsylvania.

STAR Category 37

INTRODUCTION

Rolling-element bearings for aircraft turbine engine mainshaft applications are generally specified to be made of AISI M-50 steel. Current aircraft turbine engine manufacturers' material specifications require 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 [1]. Reduction in inclusion content, trace elements, and interstitial gas content is considered responsible for a major portion of this life advancement [2]. 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) [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 [4, 5]. This material, with typical chemical composition shown in Table 1, 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 improved over AISI 440C and similar to AISI M-50 [5]. Additional hot hardness data for AMS 5749 is shown in [6] where the material is identified as "a modified AISI 440C". Preliminary data presented in [2], indicates 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 requirements are 5 percent or 2 percent maximum. 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 development of appropriate test material with varied retained austenite present, while other characteristics such as hardness remained constant.

The objective of this research was (1) compare the rolling-element fatigue life of AMS 5749 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 rolling-element fatigue tests in the five-ball fatigue tester and the rolling-contact (RC) fatigue tester. In the five-ball fatigue tester, 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 were tested for comparison purposes. 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 340 K (150° F). In the RC tests, bars of VIM-VAR AMS 5749 were tested. Test conditions in the RC fatigue tester included a test bar speed of 10 000 rpm, a maximum Hertz stress of 4830 MPa (700 000 psi), and room temperature.

TEST SPECIMENS

Test Balls

The 1.27-cm (1/2-in.) diameter VIM-VAR AMS 5749 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 2(a). The retained austenite variation is shown in Table 3. The hardness of the three lots of VIM-VAR AMS 5749 was maintained at a constant 64±0.2 Rockwell C. All balls were finished to grade 10 specifications, including surface finish of 5.0×10^{-6} cm (2 μin.) rms or better.

Test Bars

The RC test bars were 7.62 cm (3.00 in.) long and 0.952 cm (0.375 in.) in diameter with a surface finish of 30×10^{-6} cm (12 μin.) rms or better. The three lots of VIM-VAR AMS 5749 were tested, with no difference intended, except to be representative of three separate material heats. The bars were heat treated according to the specifications given in Table 2(b). Hardnesses of the three lots E, F, and G were 61.2, 62.3, and 62.3, respectively. The retained austenite in these bars was not measured and the test bars have been discarded. But, based on the specific heat treatment used and previous experience with the material, the retained austenite level is assumed to be in the range of 4 to 5 percent.

APPARATUS AND PROCEDURE

In order to economically study rolling-element fatigue, accelerated fatigue tests are typically run on bench type fatigue testers. In this study, two types of testers were employed; the five-ball fatigue tester and the rolling-contact (RC) fatigue tester.

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester is shown in Fig. 1 and is described in detail in [7]. This fatigue tester consists essentially of an upper test ball pyramided upon four lower balls that are positioned by a separator and are free to rotate in an angular-contact raceway. System loading and drive are supplied through a vertical drive shaft, which grips the upper-test ball. For every revolution of the drive shaft, the upper-test ball receives three stress cycles from the lower balls.

Lubrication is provided by a once-through, mist lubrication system. The lubricant was a super-refined naphthenic mineral oil with a viscosity of 79 centistokes at 311 K (100^{o} 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.

Rolling-Contact (RC) Fatigue Tester

The RC fatigue tester is shown in Fig. 2. The test bar is mounted in a precision chuck and driven by an electric motor. Two 19.1 cm- (7.50 in.-) diameter rollers with a crown radius of 0.64 cm (0.25 in.) are loaded against the test bar with a micrometer threaded turnbuckle and calibrated load cell. The concentrated Hertzian contact between the rollers and the test bar is lubricated by drip feeding. The lubricant used in these tests was a MIL-L-7808F with a viscosity of 15.2 centistokes at 311 K (100° F). The test bar is rotated at 10 000 rpm, thus receiving 20 000 stress cycles per minute from the pair of rollers. Vibration instrumentation detects a fatigue failure and terminates the test.

Fatigue Testing Procedure

In the five-ball tests, a new set of five balls was used for each test of the group of 21 to 40 tests for each material lot. Each test was suspended when a fatigue failure occurred on either a lower or an upper test ball or when a preset cutoff time was reached.

In the RC tests, a single bar was used for four or five tests by moving it to various axial positions in the chuck. Each test was run to fatigue failure.

Method of Presenting Fatigue Results

The statistical methods of [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. 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-percent and 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. The failure index indicates the number of specimens that failed out of those tested.

Confidence numbers were calculated by methods of [8], which indicates the statistical significance of the fatigue life results. A confidence number is the probability, expressed as a percentage, that a given lot used as baseline, 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, 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 and the rolling-contact fatigue tester. In the five-ball 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 340 K (150° F) with a super-refined naphthenic mineral oil as the lubricant. In the RC tests, bars of VIM-VAR AMS 5749 were tested at a maximum Hertz stress of 4830 MPa (700 000 psi), a test bar speed of 10 000 rpm, and room temperature with a MIL-L-7808F lubricant.

The results of the fatigue tests are shown in the Weibull plots of Figs. 3 to 6. Summary Weibull plots are shown in Figs. 7 and 8, and the results are summarized in Tables 4 and 5.

Effect of Retained Austenite

The comparison of the 10-percent lives of the three lots of VIM-VAR AMS 5749 balls in the five-ball tester does not present a clear effect of retained austenite on fatigue life. As shown in Table 4 and Fig. 3, the intermediate level (11.1 percent) gave the longest life with apparent statistical significance when compared to the highest level where the confidence number is 95 percent or 2σ confidence. For the lowest level of retained austenite, the confidence number is 87 percent. Thus it is apparent that the high level of retained austenite, 14.6 percent, is significantly detrimental to the 10-percent fatigue life, relative to the 11.1 percent level.

At the 50-percent life level, a trend toward increased life with decreased retained austenite is suggested. 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 this retained austenite level. Considering the life rankings at both the 10-percent and the 50-percent life levels, a trend toward increased rolling-element fatigue life with decreased retained austenite may be suggested, but the confidence that all the experimental differences are significant is not great.

Effect of Vacuum Arc Remelting

The results of fatigue tests with the VIM AMS 5749 balls are shown in Fig. 4. This data is compared with the VIM-VAR data in Fig. 7 and in Table 4. 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, which is a consumable-electrode-vacuum-arc remelting 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 [2]. The life improvements with the improved AISI M-50, although 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 relative to 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 in the five-ball tester are shown in Fig. 6. The data is compared with that of the VIM-VAR AMS 5749 in Fig. 7 and Table 4. 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 to all three lots of AMS 5749.

The results of the fatigue tests in the rolling-contact (RC) fatigue tester with three lots of VIM-VAR AMS 5749 bars are shown in Fig. 5. Ten-percent lives are very similar and indicate no significant life differences among the three material heats as shown in Table 5.

The data for the three lots were combined and treated as a single lot of 36 fatigue failures for comparison with similar data with VIM-VAR AISI M-50 test bars from [9]. In [9] four separate heats (lots) of VIM-VAR AISI M-50 were tested in RC tests under conditions identical to those reported herein for the AMS 5749 bars. The data from these four lots were also combined and heated as a single lot of data of 48 fatigue failures.

The results of the combined lot analyses for both materials is summarized in Table 5. The combined 10-percent life with VIM-VAR AMS 5749 is only slightly greater than that with VIM-VAR AISI M-50. The confidence number is only 76 percent, which indicates a statistically insignificant difference.

The difference between the RC test results and those from the five-ball tests warrants further discussion. In the five-ball tests, AMS 5749 was much superior to AISI M-50, whereas in the RC tests, the difference between the two materials was insignificant.

The hardness of the RC bars of both materials was nearly identical. The AISI M-50 balls were only slightly lower (Table 3) than the AMS 5749 balls. This difference of less than one point Rockwell C is not expected to induce such a large fatigue life difference.

As noted in Table 3, 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 to 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. However, these retained austenite levels were significantly greater than that of the AISI M-50. Thus the possibility exists that the life difference between the VIM-VAR AMS 5749 and the VIM-VAR AISI M-50 may be partly due to the retained austenite difference.

It may be expected that the superiority of AMS 5749 in the five-ball tests may be attributed to its better corrosion and oxidation resistance when compared to AISI M-50. Corrosion and oxidation resistance may be more significant in the five-ball tests than in the RC tests because of the greater sliding and higher stress in the concentrated contact of the five-ball tests. These effects have not been confined experimentally.

SUMMARY OF RESULTS

The rolling-element fatigue lives of AMS 5749 and AISI M-50 were compared in tests run in the five-ball fatigue tester and the rolling-contact (RC) fatigue tester. In the five-ball tests, 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. These tests were run at a race temperature of 340 K (150° F) with a super-refined naphthenic mineral oil as the lubricant. In the RC tests, bars were run at a maximum Hertz stress of 4830 MPa (700 000 psi), a test bar speed of 10 000 rpm, and room temperature with a MIL-L-7808F lubricant. The effects of double vacuum melting and retained austenite on the rolling-element fatigue life of AMS 5749 were also determined in the five-ball tests. The following results were obtained:

1. Double vacuum melted (VIM-VAR) AMS 5749 steel balls gave lives from 6 to 12 times that of VIM-VAR AISI M-50 steel balls in the five-ball fatigue tester. Similar tests in the rolling-contact (RC) fatigue tester showed no significant difference in the lives of the two materials.

2. 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.

3. A trend toward increased rolling-element fatigue life with decreased retained austenite is apparent, but the confidence that all the experimental differences are significant is not great. The highest level of retained austenite, 14.6 percent is, however, significantly detrimental to rolling-element fatigue life, relative to the intermediate level of 11.1 percent.

REFERENCES

1. Bamberger, E. N., Zaretsky, E. V., and Signer, H., "Endurance and Failure Characteristics of Main-Shaft Jet Engine Bearings at 3×10^6 DN," Journal of Lubrication Technology, Trans ASME, Series F, Vol. 98, 1976, pp. 580-585.
2. Schlatter, R., "Double Vacuum Melting of High Performance Bearing Steels," Industrial Heating, Vol. 41, 1974, pp. 40-55

3. Zaretsky, E. V. and Anderson, W. J., "Rolling-Element Bearing Life From 400° to 600° F," NASA TN D-5002, 1969.

4. Johnson, B. L., "High Temperature Wear Resisting Steel," U.S. Patent No. 3, 167, 423, Jan. 1965.

5. Johnson, B. L., "A Stainless High Speed Steel for Aerospace Applications," Metal Progress, Vol. 84, 1964, pp. 116-118.

6. Chevalier, J. L., Dietrich, M. W., and Zaretsky, E. V., "Hot Hardness Characteristics of Ausformed AISI M-50, Matrix II, WD-65, Modified AISI 440C, and Super Nitralloy," NASA TN D-7244, 1973.

7. Carter, T. L., Zaretsky, E. V., and Anderson, W. J., "Effect of Hardness and Other Mechanical Properties on Rolling-Contact Fatigue Life of Four High-Temperature Bearing Steels," NASA TN D-270, 1960.

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

9. Schlatter, R. and Stroup, J. P., "Improved M50 Aircraft Bearing Steel Through Advanced Vacuum Melting Processes," Journal of Vacuum Science and Technology, Vol. 9, 1972, pp. 1326-1333.

TABLE 1. - TYPICAL CHEMICAL

COMPOSITIONS OF TEST MATERIALS

Material	Chemical composition, percent by weight[a]					
	C	Si	Mn	Cr	Mo	V
AMS 5749	1.15	0.30	0.50	14.5	4.0	1.2
AISI M-50	0.85	0.25	0.35	4.0	4.25	1.0
AISI 440C	1.00	0.50	0.50	17.0	0.5	---

[a]Balance Fe.

TABLE 2. - HEAT TREATMENT OF THE TEST MATERIALS

(a) Test Balls

Heat treatment	Material				
	AMS 5749 Lot				AISI M-50
	A	B	C	D	
Preheat	1088 K (1500° F)				
Harden	In salt at 1423 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 hour				811 K (1000° F) for 2 hours
Deep freeze	200 K (-100° F) for 15 minutes				183 K (-130° F) for 1.5 hours
Temper	797 K (975° F) for 2 hours; air cool to room temperature; repeat				811 K (1000° F) for 2 hours
Temper	--	797 K (975° F) for 2 hours; air cool to room temperature	797 K (975° F) for 2 hours; air cool to room temperature; repeat twice	--	797 K (975° F) for 2 hours; air cool to room temperature

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

TABLE 2. - Concluded.

(b) Test bars

Heat treatment	Material	
	AMS 5749 lots E, F, and G	AISI M-50 (from [9])
Preheat	1116 K (1550° F)	1116 K (1550° F)
Harden	1380 K (2025° F) 30 min. in salt[a]	1394 K (2050° F) 3 min. in salt
Quench	839 K (1050° F) in salt	839 K (1050° F) in salt
Air cool	To room temperature	To room temperature
Temper	422 K (300° F) for 1 hour	839 K (1050° F) for 2 hours
Deep freeze	200 K (-100° F) for 15 min.	----------------------------
Temper	797 K (975° F) for 2 hours; air cool to room temperature; repeat	839 K (1050° F) for 2 hours
Temper	----------------------------	839 to 850 K (1050° to 1070° F) for 2 hours

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

TABLE 3. - 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 4. - FATIGUE RESULTS WITH 1.27-CM- (1/2-INCH-) DIAMETER BALLS RUN IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30^{o}; shaft speed, 10 000 rpm; temperature, 340 K (150^{o} F).]

Material	Lot	Fatigue life, millions of upper ball stress cycles		Slope	Failure index[a]	Confidence number, percent[b]
		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, expressed as a percentage, that lot B (baseline) has a 10-percent fatigue life greater than that of the particular lot being considered.

TABLE 5. - FATIGUE RESULTS WITH TEST BARS OF AMS 5749 AND AISI M-50 IN THE ROLLING-CONTACT (RC) FATIGUE TESTER

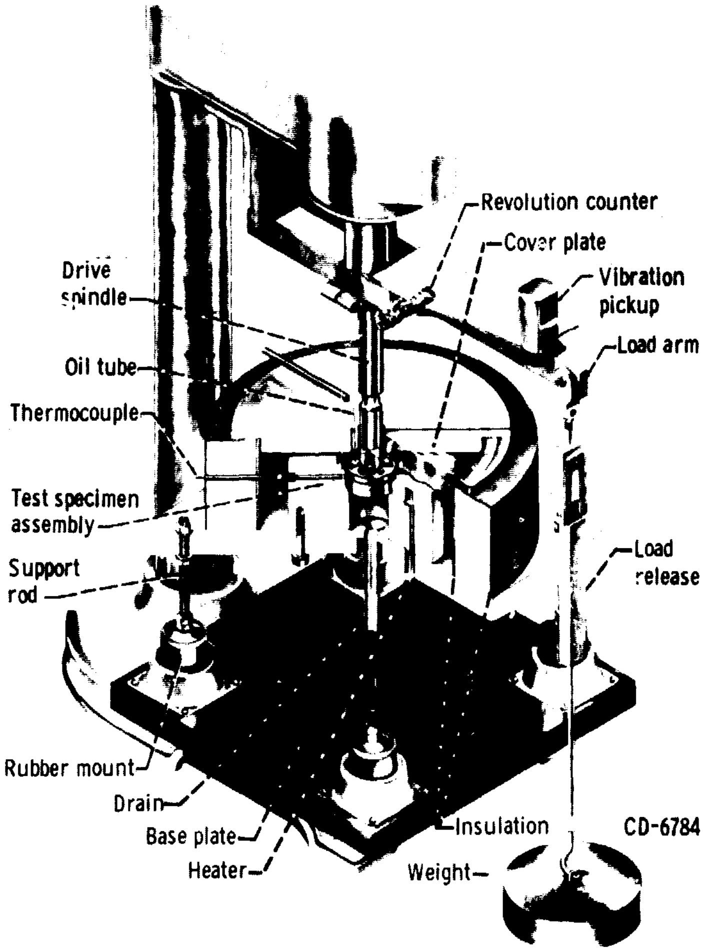
[Maximum Hertz stress, 4830 MPa (700 000 psi); test bar speed, 10 000 rpm; room temperature.]

Material	Lot	Fatigue life, millions of stress cycles		Slope	Failure index[b]	Confidence number, percent[c]
		10-Percent life	50-Percent life			
VIM-VAR AMS 5749	E	3.25	8.62	1.94	12 out of 12	61
	F	4.74	9.88	2.57	12 out of 12	74
	G	5.46	10.08	3.08	12 out of 12	85
	E, F, and G combined	4.75	9.55	2.67	36 out of 36	76
VIM-VAR AISI M-50[a]	-----------	3.70	7.01	2.95	48 out of 48	--

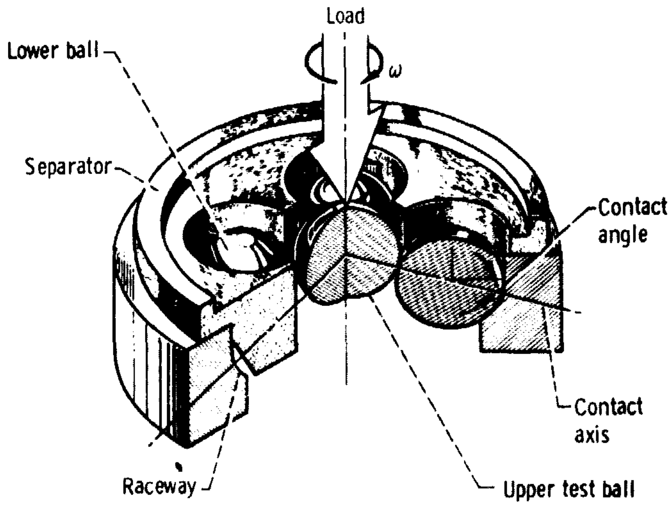
[a]Data from [9], four lots combined.

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

[c]Probability, expressed as a percentage, that the 10-percent life with the VIM-VAR AISI M-50 bars is less than or greater than, the particular lot of VIM-VAR AMS 5749 being considered.



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



(b) Five-ball test assembly.

Figure 1. - Test apparatus.

E-9101

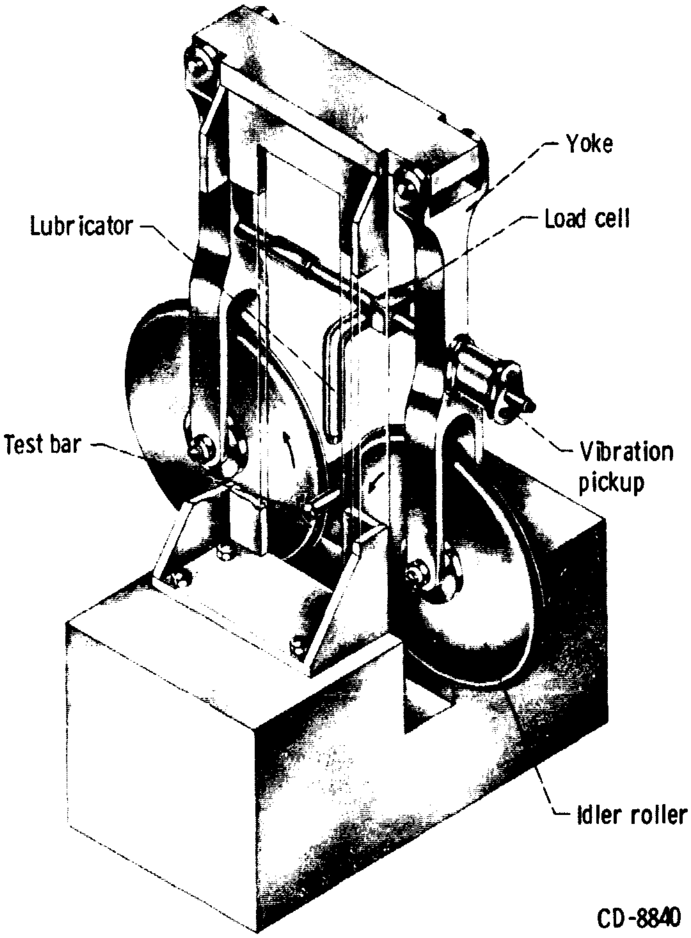
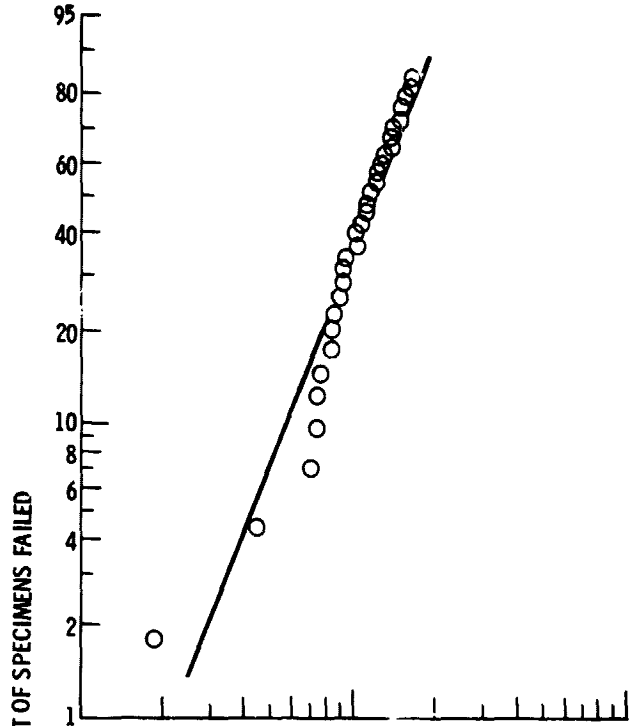
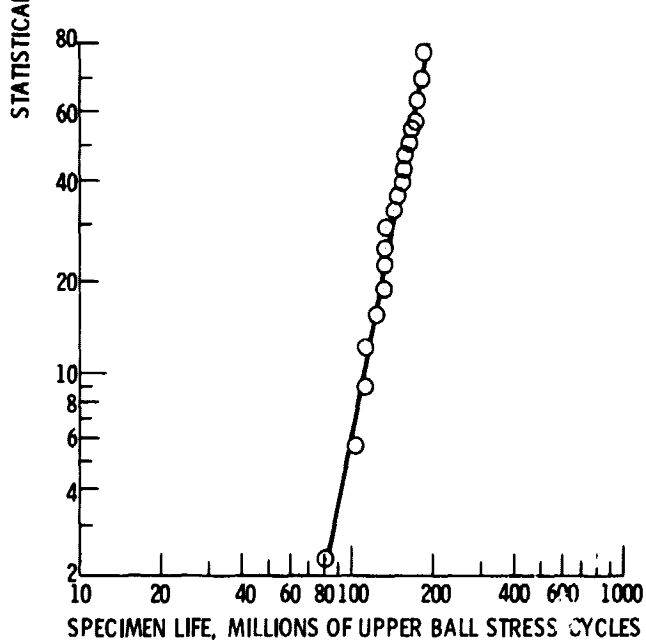


Figure 2. - Rolling-contact (RC) fatigue tester.

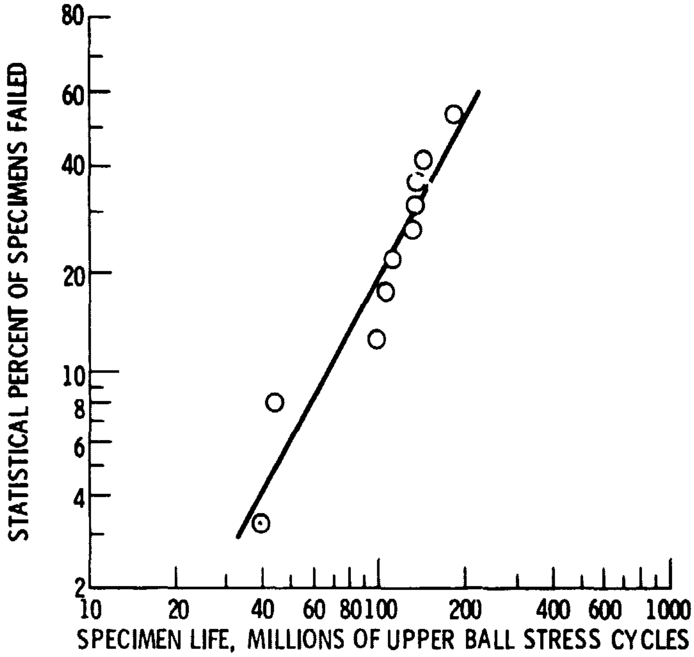


(a) LOT A; RETAINED AUSTENITE, 14.6%; FAILURE INDEX, 31 OUT OF 40.



(b) LOT B; RETAINED AUSTENITE, 11.1%; FAILURE INDEX, 20 OUT OF 30.

Figure 3. - Rolling-element fatigue life of 1.27-cm- (0.500-inch-) diameter VIM-VAR AMS 5749 steel balls in the five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; race temperature, 340 K (150° F.



(c) LOT C; RETAINED AUSTENITE, 6.3%; FAILURE INDEX, 10 OUT OF 21.

Figure 3. - Concluded.

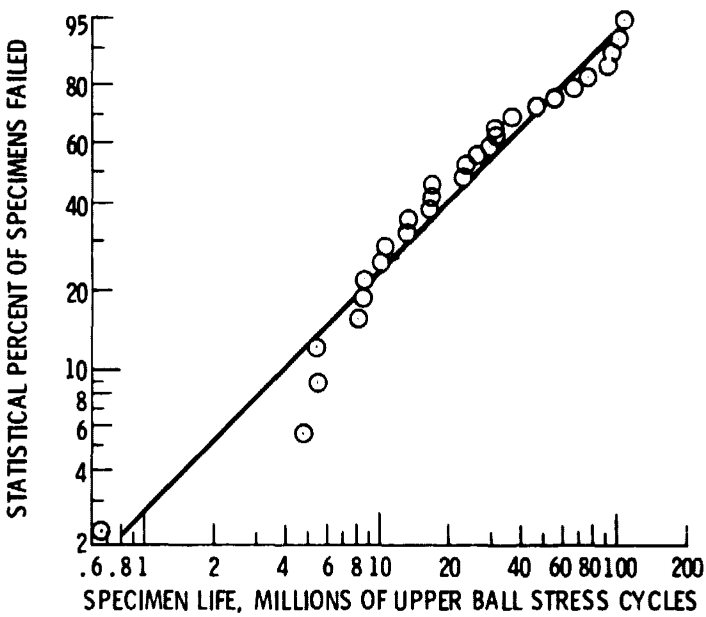
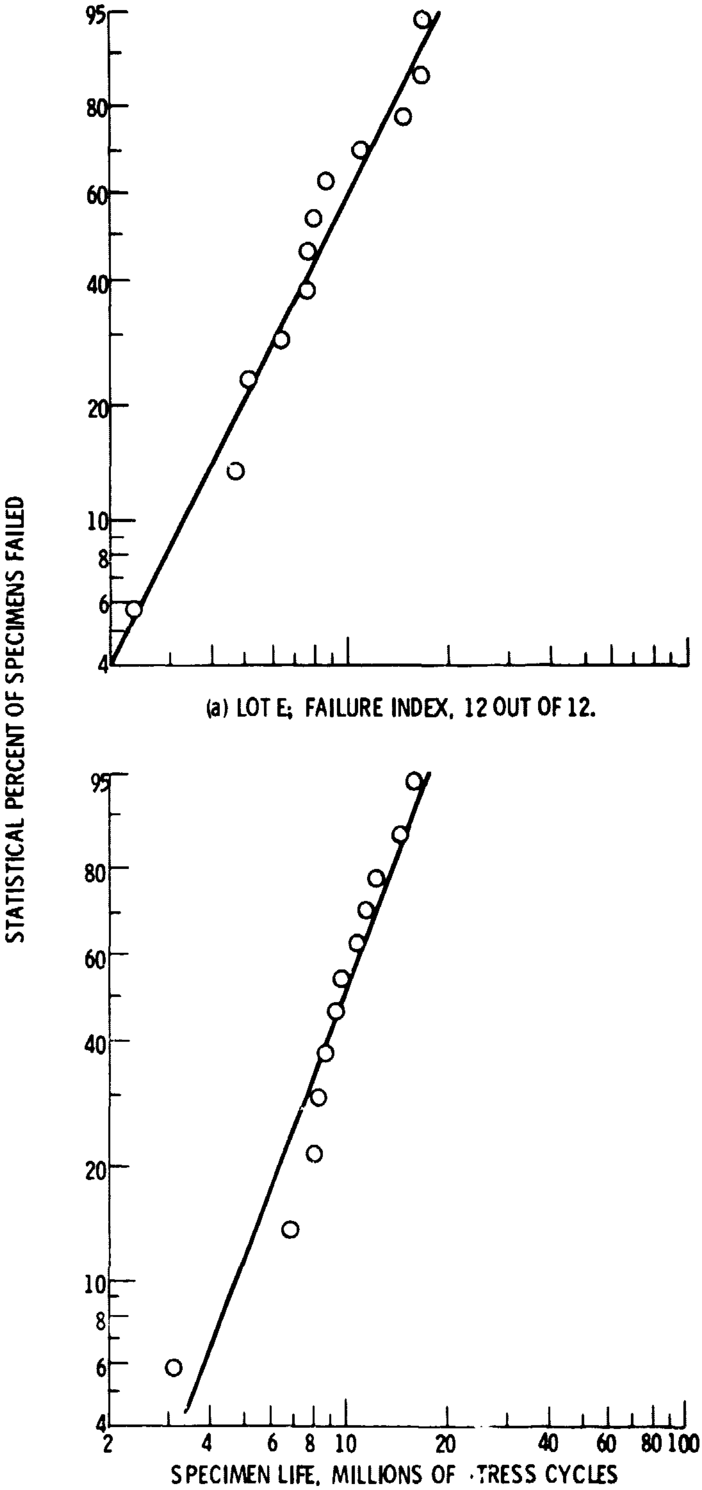


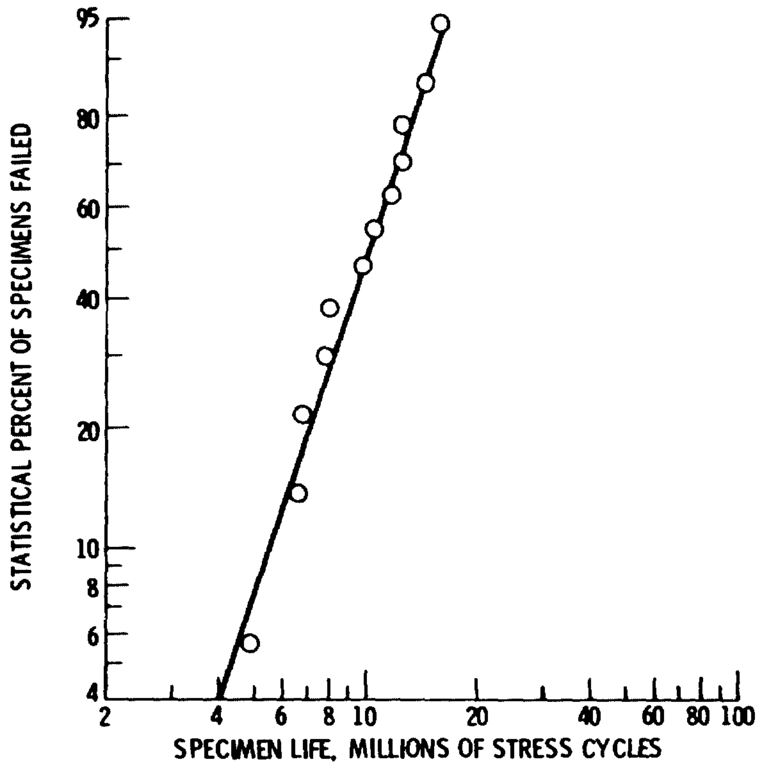
Figure 4. - Rolling-element fatigue life of 1.27-cm- (0.500-in.-) diameter VIM AMS 5749 steel balls in the five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; race temperature, 340 K (150° F); failure index, 29 out of 30.



(a) LOT E; FAILURE INDEX, 12 OUT OF 12.

(b) LOT F; FAILURE INDEX, 12 OUT OF 12.

Figure 5. - Rolling-element fatigue life of VIM-VAR AMS 5749 test bars in the rolling-contact fatigue tester. Maximum Hertz stress, 4830 MPa (700 000 psi); test bar speed, 10 000 rpm; room temperature.



(c) LOT G; FAILURE INDEX, 12 OUT OF 12.

Figure 5. - Concluded.

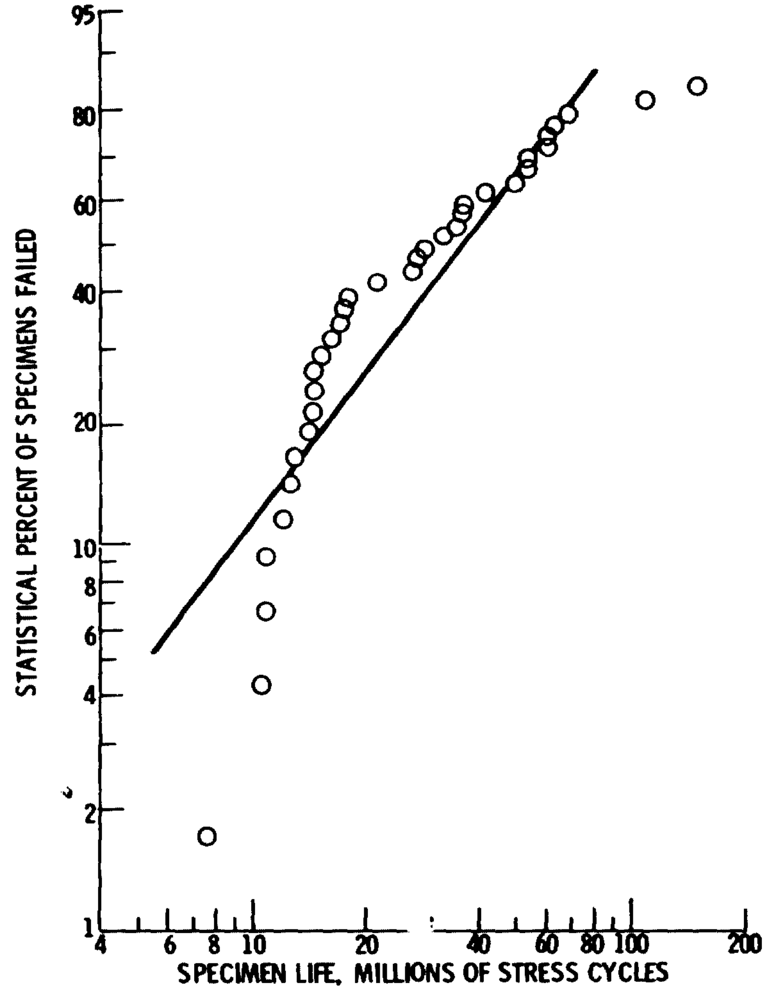


Figure 6. - Rolling-element fatigue life of 1.27-cm- (0.500-in.-) diameter VIM-VAR AISI M-50 steel balls in the five-ball fatigue tester. Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 000 rpm; race temperature, 340 K (150° F); failure index, 34 out of 40.

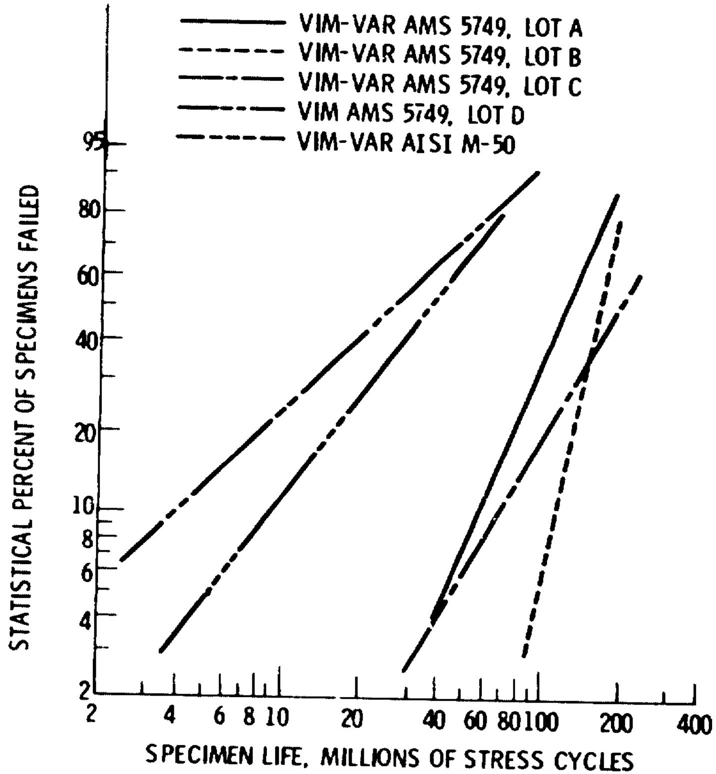


Figure 7. - Summary of rolling-element fatigue data with AMS 5749 and AISI M-50 balls in the five-ball fatigue tester.

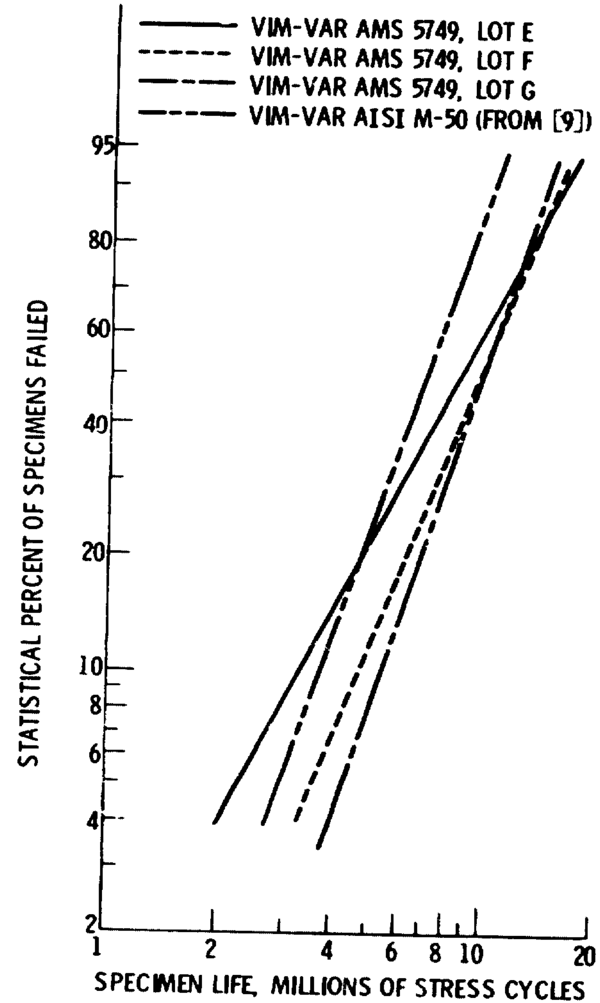


Figure 8. - Summary of rolling-element fatigue data with AMS 5749 and AISI M-50 bars in the rolling-contact fatigue tester.