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ROLLING-ELEMENT FATIGUE LIFE OF AISI M-50 AND 18-4-1 BALLS

by Richard J. Parker and Erwin V. Zaretsky

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SUMMARY

Rolling-element fatigue tests were conducted with VIM-VAR AISI M-50, EFR 18-4-1, and VAR 18-4-1. Two groups of each material were subjected to slightly different heat treatments. Balls of 12.7-millimeter (1/2-in.) diameter of each material group were tested in the five-ball fatigue tester. Test conditions included a load of 1540 newtons (347 lbf), which gave a maximum Hertz stress of 5520 megapascals (800 000 psi), a shaft speed of 10 700 rpm, and a contact angle of 30°. Tests were run at a race temperature of 339 K (150° F) with a type II ester (MIL-L-23699) lubricant. A statistical comparison of the test results indicates that the rolling-element fatigue life of VIM-VAR AISI M-50 is not significantly different from EFR or VAR 18-4-1. The slight variations in heat-treatment procedures for each material resulted in statistically insignificant differences in rolling-element fatigue life.

INTRODUCTION

Rolling-element bearings for main-shaft applications of aircraft turbine engines are made primarily of either AISI M-50 or 18-4-1 steels. AISI M-50 has been used in such applications since about 1957 and is today the standard material used by American jet-engine manufacturers (ref. 1). The use of 18-4-1 for these applications is primarily by the European jet engine manufacturers. Both materials contain alloying elements to promote high hardness and good hardness retention at the high temperatures experienced by main shaft bearings. Both contain significant chromium and vanadium, but M-50 contains molybdenum, whereas 18-4-1 contains tungsten. Specific chemical compositions of the materials are shown in table I.

Significant progress in the melting processes of these high quality steels has been made in the past decade (refs. 1 to 3). Current material specifications call for very high quality steels with precise composition control and very low gas and inclusion content. Consumable-electrode vacuum melting (CVM), also known as vacuum-arc remelting (VAR), and electro-slag melting or remelting (ESR), also known as electro-flux remelting (EFR), have become the primary melting processes for these high quality bearing steels. The VAR process is predominantly used in the United States, and the EFR process is used primarily in Europe and the USSR.

Both processes start with an electrode made from a primary-air-melted or vacuum-induction-melted heat which is then remelted by an electric arc process in a water-cooled copper crucible. To protect the molten metal from contamination, a vacuum environment is used for the VAR process and a molten flux blanket is used for the EFR process. Both processes yield very clean materials with close control of chemistry and very low gas and inclusion content.

If the primary heat in the VAR process is vacuum-induction-melted (VIM), the process is called double-vacuum melting or, alternatively, VIM-VAR. The high quality, VIM-VAR AISI M-50 material has a much longer rolling-element fatigue life than VAR material in accelerated rolling-element-fatigue tests (refs. 3 and 4) and in ball-bearing tests (ref. 5). The EFR process with a VIM primary heat has also shown longer life than the VAR process with AISI M-50 in accelerated rolling-element fatigue tests (refs. 3 and 4), but the improvement was not as great as that with VIM-VAR.

In tests reported in reference 6 a comparison of melting practice was performed with an ShKh 15 ball bearing steel. Accelerated fatigue tests were run in a test rig similar to those of reference 4. Reference 6 shows that greater fatigue life is attained with the VAR and EFR processes than with the baseline air-melt steel from an electric furnace. Life of the VAR steel was slightly greater than that of the EFR steel.

American jet engine manufacturers currently specify VIM-VAR AISI M-50 for critical applications, while their European counterparts specify EFR 18-4-1. A direct comparison of the rolling-element fatigue lives of these two materials is not available in the open literature. Such information would be a valuable aide in the selection of replacement bearings in light of present cooperative American-European engine development and manufacturing programs, and the purchase of European-built engines by American airline companies and vice versa.

The research described in this paper compared the rolling-element fatigue lives of VIM-VAR AISI M-50 and EFR 18-4-1. In addition, VAR 18-4-1 was tested under the same closely controlled operating conditions. Groups of 12.7-millimeter (1/2-in.) diameter balls of each material were tested in the five-ball fatigue tester. All balls for each material were made from a single heat of the material. Test conditions included a load of 1540-newtons (347 lbf) giving a maximum Hertz stress of 5520 megapascals (800 000 psi), a shaft speed of 10 700 rpm, a contact angle of 30°, and a temperature of 339 K (150° F). A single batch of type II ester (MIL-L-23699) was used as the lubricant.

The 18-4-1 ball materials for these tests were provided by Kenneth L. Day of Rolls Royce Limited in Derby, England. The AISI M-50 ball material property measurements and photomicrographs were provided by Alex Nahm of the General Electric Company's Material and Process Technology Laboratory, Aircraft Engine Group, in Cincinnati, Ohio.

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, a type II ester (MIL-L-23699), has viscosities of 29 centistokes (29×10^{-6} m^2/sec) at 311 K (100° F) and 5.3 centistokes (5.3×10^{-6} m^2/sec) at 372 K (210° F). When the vibration instrumentation detects a fatigue failure on either the upper or a lower ball, it automatically shuts down the tester. This provision allows unmonitored operation and a consistent criterion for failure.

Test Balls

The specific chemical compositions of the individual batches of AISI M-50 and 18-4-1 steel are shown in table I. All M-50 balls were processed by double-vacuum melting; that is, a vacuum-induction melted ingot was vacuum arc remelted (VIM-VAR). The 18-4-1 balls were processed by either vacuum-arc remelting (VAR) of an air-melt ingot or electroflux remelting (EFR) of an air-melt ingot.

For each of the three material-process combinations, VIM-VAR M-50, VAR 18-4-1, and EFR 18-4-1, a group of 600 balls from a single material heat were formed and rough ground to approximately 13.2 millimeters (0.520 in.) in diameter. Half the balls in each group were then heat treated by each of two suppliers according to the specific heat treatment procedures listed in tables II and III. The effect on rolling-element fatigue life of the variations of heat treatments shown in these tables could then be evaluated. Hardnesses of all groups was carefully held between 62 and 63 Rockwell C, to eliminate hardness as a variable. The balls were then finish ground and lapped to 12.7 millimeters (0.500 in.) in diameter, AFBMA grade 10 specifications by one manufacturer.

Photomicrographs of each material group are shown in figures 2 to 4. The structures appear to be typical of that expected for each material. Hardness and retained austenite for each groups of materials is shown in table IV.

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 cheesecloth. After visual examination all specimens were coated with the test lubricant to prevent wear at startup. A new set of lower balls was used with each upper test-ball specimen. 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 examined visually for damage. If any damage was observed, the race would be replaced before further testing.

Method of Presenting Fatigue Results

The total test time for each specimen was recorded and converted to total stress cycles. The statistical method of reference 8 for analyzing rolling-element fatigue data was 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 is drawn through the plotted points, as determined by the method of least squares. From these plots the number of stress cycles necessary to fail any given portion of the specimen group may be determined. Where high reliability is of paramount importance, the main interest is in early failures. For comparison the 10-percent life on the Weibull plot was 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.

RESULTS AND DISCUSSION

Fatigue Life Results

Groups of 12.7-millimeter (1/2-in.) diameter balls of VIM-VAR AISI M-50, EFR 18-4-1, and VAR 18-4-1 were tested in the five-ball fatigue tester. Test conditions included a load of 1540 newtons (347 lbf), a maximum Hertz stress of 5520 megapascals (800 000 psi), a shaft speed of 10 700 rpm, and a contact angle of 30°. Tests were run at a race temperature of 339 K (150° F) with a type II ester (MIL-L-23699) lubricant.

Results of the fatigue tests are shown in the Weibull plots of figures 5 to 7 and are summarized in figure 8 and table V. At the 10-percent life level the longest lives were obtained with the VIM-VAR AISI M-50 (lot C) and the VAR 18-4-1 (lot F), both heat treated by supplier R. Lowest life was found with EFR 18-4-1 heat treated by supplier N (lot D).

From a preliminary comparison of the 10-percent lives, three results are apparent: (1) The lives of the VIM-VAR M-50 and the VAR 18-4-1 from supplier N were approximately equal. The same is true for those from supplier R. (2) For each supplier the life of EFR 18-4-1 was less than those of VIM-VAR M-50 and VAR 18-4-1. And (3) For the same materials, the heat treatment performed by supplier R gave longer lives than that by supplier N.

To determine the statistical significance in the 10-percent fatigue life differences, confidence numbers were determined by method of reference 8. The confidence number is the probability, expressed as a percentage, that the baseline test lot would give longer or shorter lives, as the case may be, than the particular test lot being considered. A confidence number greater than 95 percent, which is equivalent to a 2σ confidence level (twice the standard deviation), indicates a high degree of certainty that the observed results denote a significant difference in the lives of the materials.

Confidence numbers shown in table VI consider each test lot as a baseline for comparison with each other lot. Materials are arranged in order of descending 10-percent fatigue life. The only confidence numbers greater than 95 percent appear in the comparison of lot D and lots F and C; that is, the 10-percent fatigue life of the EFR 18-4-1 heat treated by supplier N is significantly less than that of either the VIM-VAR M-50 or the VAR 18-4-1, both heat treated by supplier R.

The variations in heat-treatment procedures, as shown in tables II and III, are slight differences in hardening, deep freeze, and tempering temperatures. Although materials heat treated by supplier R have greater fatigue life than those heat treated by supplier N, the life differences are not statistically significant. Additionally, no differences in the metallurgical structure of the 18-4-1 due to variations in heat treatments was noted. A slightly more coarse martensite structure is apparent in the M-50 heat treated by supplier N. Although this coarser martensite structure would be acceptable for aircraft bearings, it could possibly account for the somewhat lower life of that particular material lot.

As shown in table IV the 18-4-1 material had a higher level of retained austenite than the M-50. It is well established that, for reasons of dimensional stability, a low level of austenite is desirable for critical bearing components. Typical maximum levels are in the range of 2 to 5 percent. All the materials tested in this program except lot E are below the 5 percent maximum. The difference in the retained austenite levels between the M-50 and the 18-4-1 may have influenced the fatigue life results. Some unpublished work on M-50 has indicated that fatigue life may be greater with higher levels of retained austenite.

Considering the statistical comparison of the VIM-VAR M-50 and either the EFR or VAR 18-4-1 from both suppliers, the differences in fatigue life are not significant. As a result, it appears that bearings of either VIM-VAR M-50 or EFR 18-4-1 are interchangable as far as rolling-element fatigue considerations are concerned.

SUMMARY OF RESULTS

Groups of 12.7-millimeter (1/2-in.) diameter balls of VIM-VAR AISI M-50, EFR 18-4-1, and VAR 18-4-1 were tested in the five-ball fatigue tester. Rolling-element fatigue tests were conducted on two groups of each of the three materials that were subjected to slightly different heat treatments by two suppliers. Test conditions included a load of 1540 newtons (347 lbf), a maximum Hertz stress of 5520 megapascals (800 000 psi), a shaft speed of 10 700 rpm, and a contact angle of 30°. Tests were run at a race temperature of 339 K (150° F) with a type II ester (MIL-L-23699) lubricant. The following results were obtained:

1. Based on a statistical comparison of the test results, the rolling-element fatigue life of VIM-VAR AISI M-50 is not significantly different from that of EFR or VAR 18-4-1.
2. The slight variations in heat-treatment procedures used by the two suppliers for each material gave statistically insignificant differences in rolling-element fatigue life.

Lewis Research Center,
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505-04.

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TABLE I. - SPECIFIC CHEMICAL COMPOSITIONS OF THE TEST MATERIALS

Material	Melting practice	Heat treatment supplier	Test lot	Chemical composition, wt %							
				C	Si	Mn	Cr	V	Mo	W	Fe
AISI M-50	VIM-VAR	N	A	0.86	0.39	0.20	4.11	1.15	4.27	----	Bal.
		R	C	.88	.23	.21	4.06	1.20	4.33	----	Bal.
18-4-1	EFR	N	D	0.70	0.18	0.18	4.33	1.08	0.28	18.2	Bal.
		R	B	.70	.40	.18	4.34	1.05	.25	18.2	Bal.
	VAR	N	E	0.74	0.37	0.18	4.14	1.10	0.36	18.8	Bal.
		R	F	.73	.44	.18	4.20	1.10	.35	18.8	Bal.

TABLE II. - HEAT TREATMENT OF VIM-VAR AISI M-50 BALLS

Procedure	Supplier	
	N	R
Preheat	[a]1115 (1550) in salt	1123 (1562) in salt for 20 min
Harden	1403 (2065) in salt	1373 (2012) in salt for 3 min
Quench	811 (1000) in salt and air cool to 339 (150^{o}) or lower	813 (1004) in salt for 5 min, air cool
Temper	811 (1000) for 2 hr and air cool	813 (1004) for 2 hr and air cool
Deep freeze	183 (-130) for $1\frac{1}{2}$ hr	203 (-94) for 30 min in trichloroethylene
Temper	811 (1000) for 2 hr and air cool	813 (1004) for 2 hr and air cool
Temper	797 (975) for 2 hr and air cool	813 (1004) for 2 hr and air cool

[a]Temperatures, K (^{o}F).

TABLE III. - HEAT TREATMENT OF VAR 18-4-1

AND EFR 18-4-1

Procedure	Supplier	
	N	R
Preheat	[a]1115 (1550) in salt	1123 (1562) in salt for 20 min
Harden	1533 (2300) in salt	1523 (2282) in salt for 3 min
Quench	811 (1000) in salt and air cool to 339 (150°) or lower	833 (1040) in salt for 5 min, air cool
Deep freeze	83 (-310) for 2 hr	None
Temper	839 (1050) for 2 hr and air cool	833 (1040) for 2 hr and air cool
Deep freeze	83 (-310) for 2 hr	203 (-94) for 30 min in trichloroethylene
Temper	839 (1050) for 2 hr and air cool	833 (1040) for 2 hr and air cool
Temper	839 (1050) for 2 hr and air cool	833 (1040) for 2 hr and air cool

[a]Temperatures, K (°F).

TABLE IV. - HARDNESS AND RETAINED AUSTENITE

OF THE TEST MATERIALS

Material	Melting practice	Heat-treatment supplier	Test lot	Hardness, Rockwell C	Retained austenite, percent
AISI M-50	VIM-VAR	N	A	63.0	0.4
		R	C	62.5	.7
18-4-1	EFR	N	D	62.6	3.6
		R	B	62.1	2.8
	VAR	N	E	62.8	6.7
		R	F	63.0	4.6

TABLE V. - FATIGUE LIFE RESULTS WITH AISI M-50 AND 18-4-1 BALLS

RUN IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5520 MPa (800 000 psi); contact angle, 30°; shaft speed, 10 700 rpm; temperature 339 K (150° F).]

Material	Melting process	Heat-treatment supplier	Test lot	Fatigue life, millions of stress cycles		Slope	Failure index[a]
				L_{10}	L_{50}		
AISI M-50	VIM-VAR	N	A	5.50	14.0	2.01	40 out of 40
		R	C	10.4	32.3	1.66	40 out of 40
18-4-1	EFR	N	D	3.20	13.2	1.33	40 out of 40
		R	B	5.26	33.2	1.02	38 out of 40
	VAR	N	E	4.50	25.4	1.09	40 out of 40
		R	F	10.4	38.2	1.45	39 out of 39

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

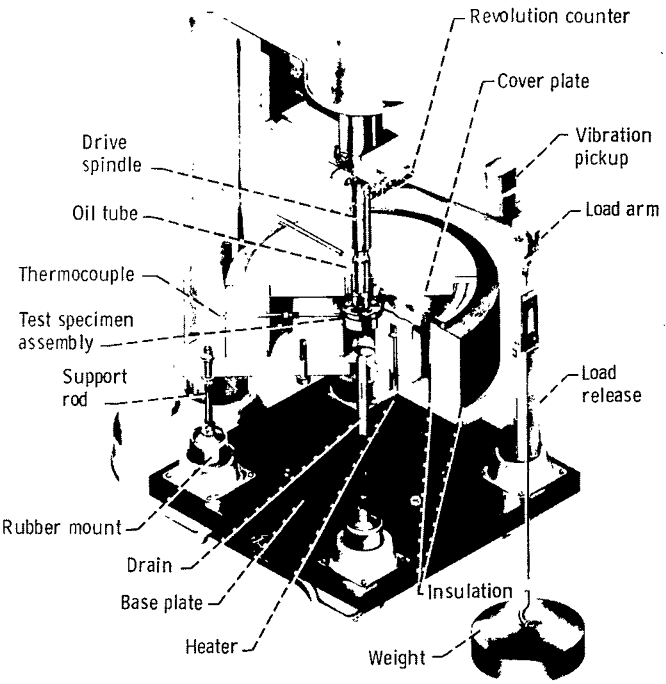
TABLE VI. - STATISTICAL CONFIDENCE IN THE 10-PERCENT

FATIGUE LIFE RESULTS WITH AISI M-50 AND 18-4-1 BALLS

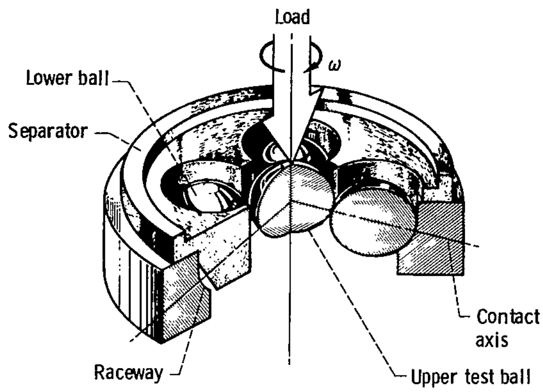
RUN IN FIVE-BALL FATIGUE TESTER

Material	Melting process	Heat-treatment supplier	Test lot	Ten-percent life,[a] millions of stress cycles	Baseline test lot[b]					
					F	C	A	B	E	D
					Confidence number, %					
18-4-1	VAR	R	F	10.4	--	50	90	82	89	99
M-50	VIM-VAR	R	C	10.4	50	--	92	87	91	99
M-50	VIM-VAR	N	A	5.50	90	92	--	53	63	84
18-4-1	EFR	R	B	5.26	82	87	53	--	58	74
18-4-1	VAR	N	E	4.50	89	91	63	58	--	68
18-4-1	EFR	N	D	3.20	99	99	84	74	68	--

[a]Materials listed in descending order of life in five-ball fatigue tester.
[b]The confidence number is the probability, expressed as a percentage, that the baseline test lot would give longer or shorter lives, as the case may be, than the particular lot being considered.

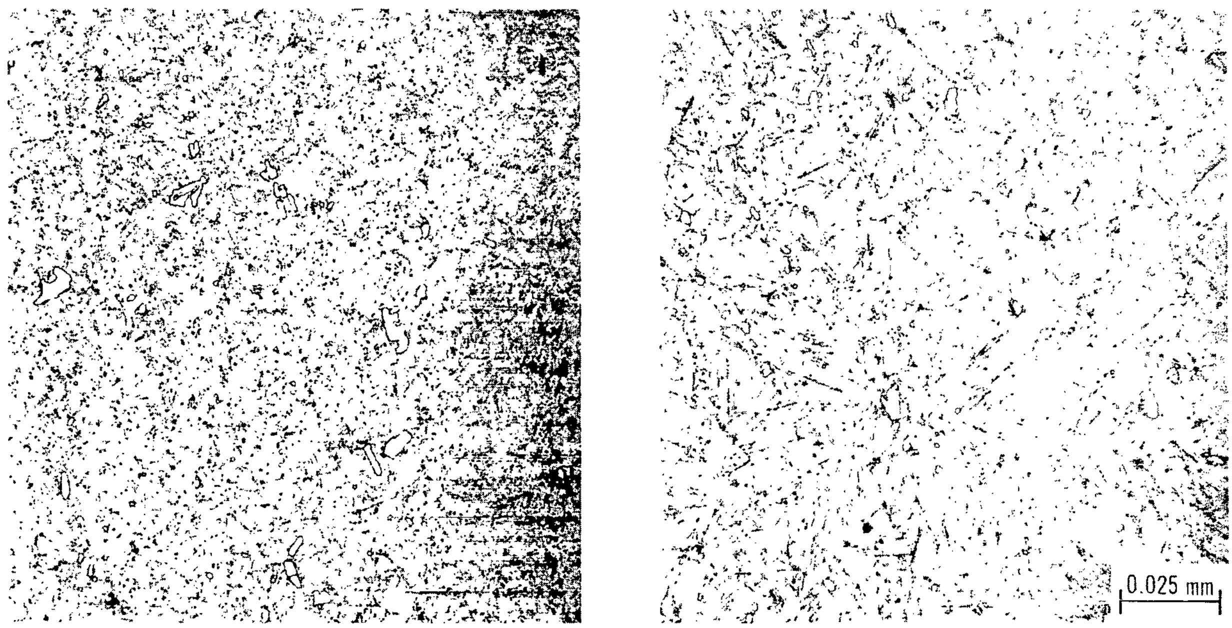


(a) Cutaway view of five-ball fatigue tester.



(b) Five-ball test assembly.

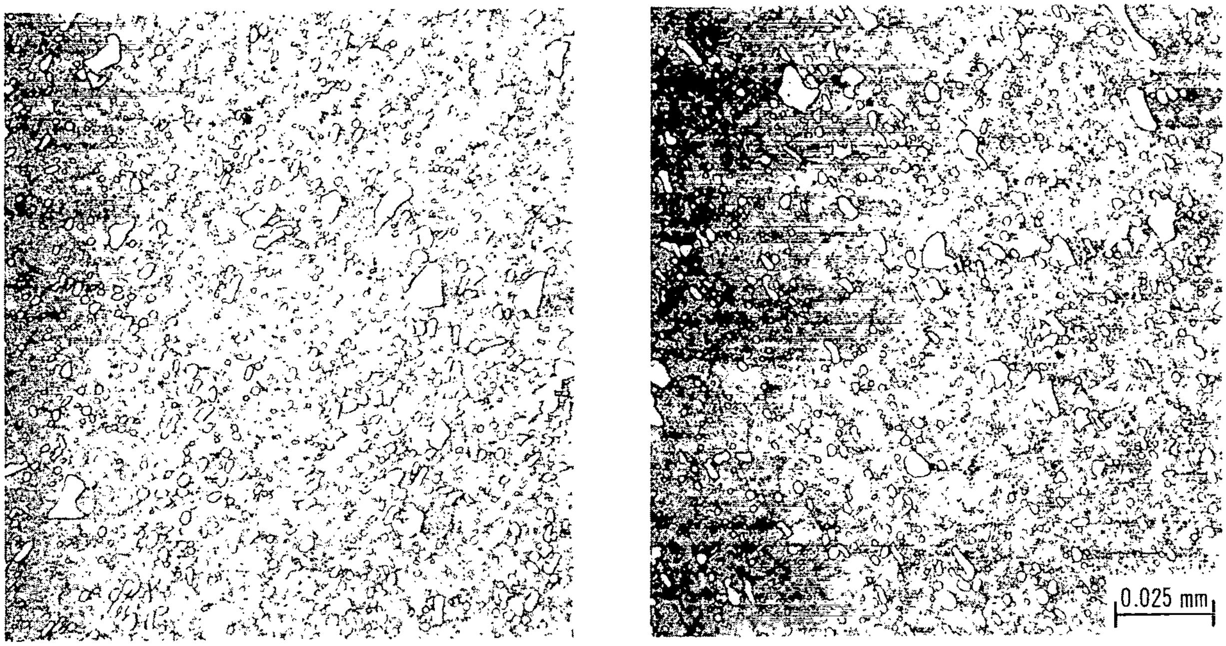
Figure 1. - Test apparatus.



(a) Lot C; heat treated by supplier R.

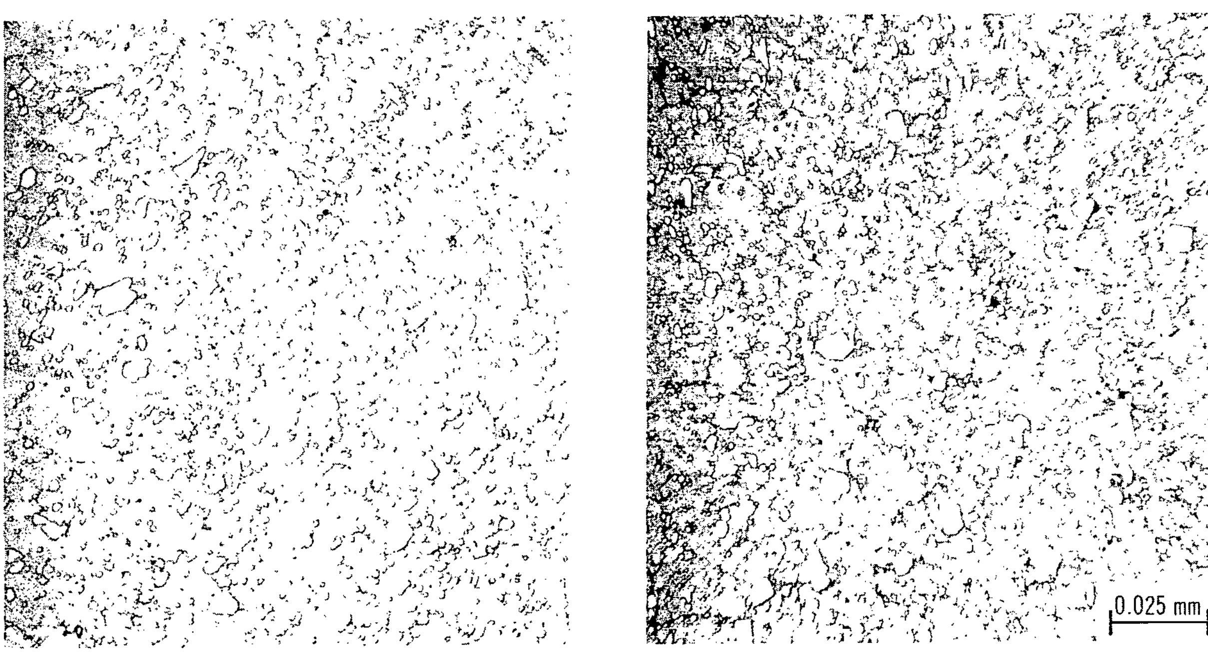
(b) Lot A; heat treated by supplier N.

Figure 2. - VIM-VAR AISI M-50 steel; 3 percent Nital etch.



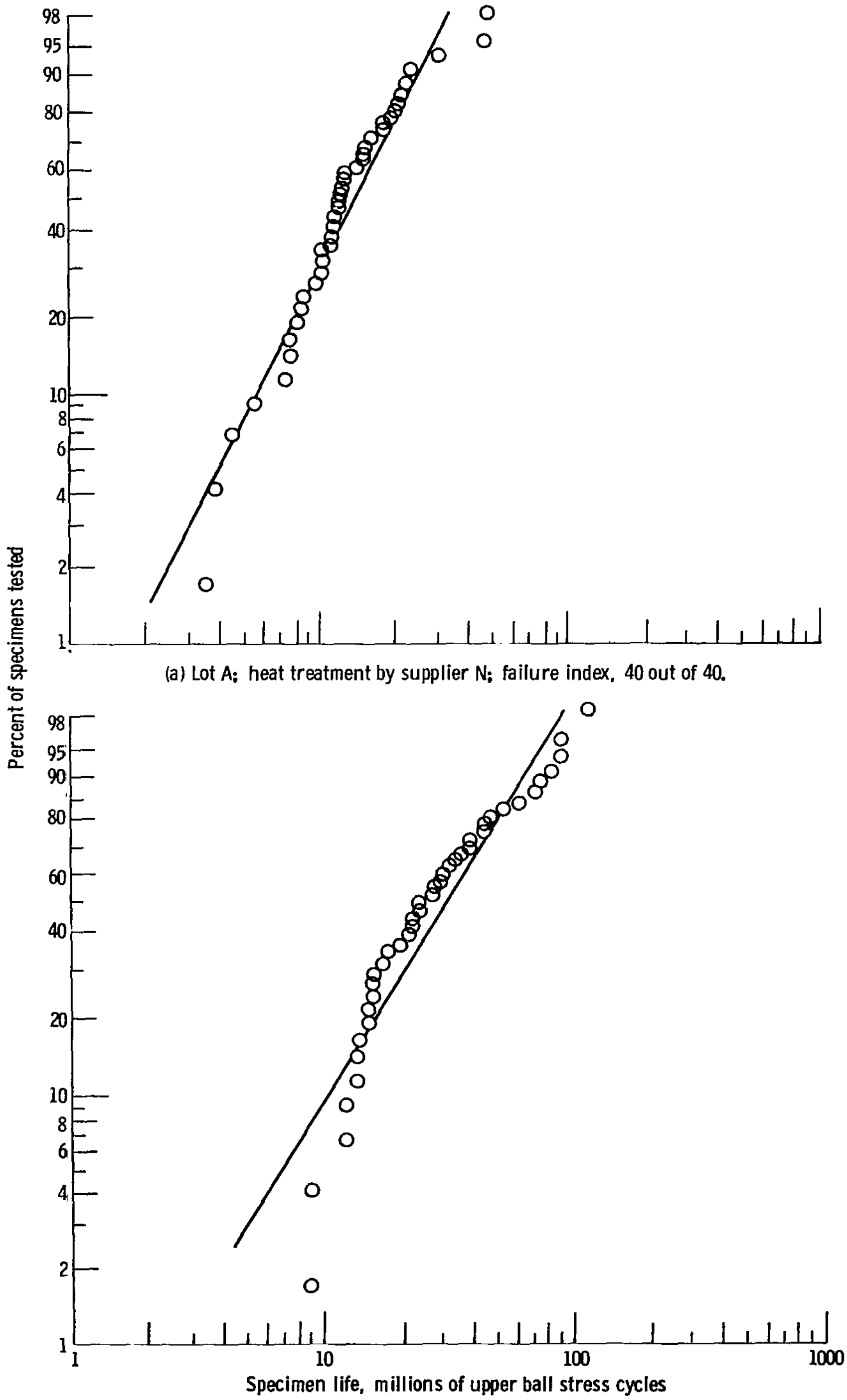
(a) Lot B; heat treated by supplier R. (b) Lot D; heat treated by supplier N.

Figure 3. - EFR 18-4-1 steel; 3 percent Nital etch.



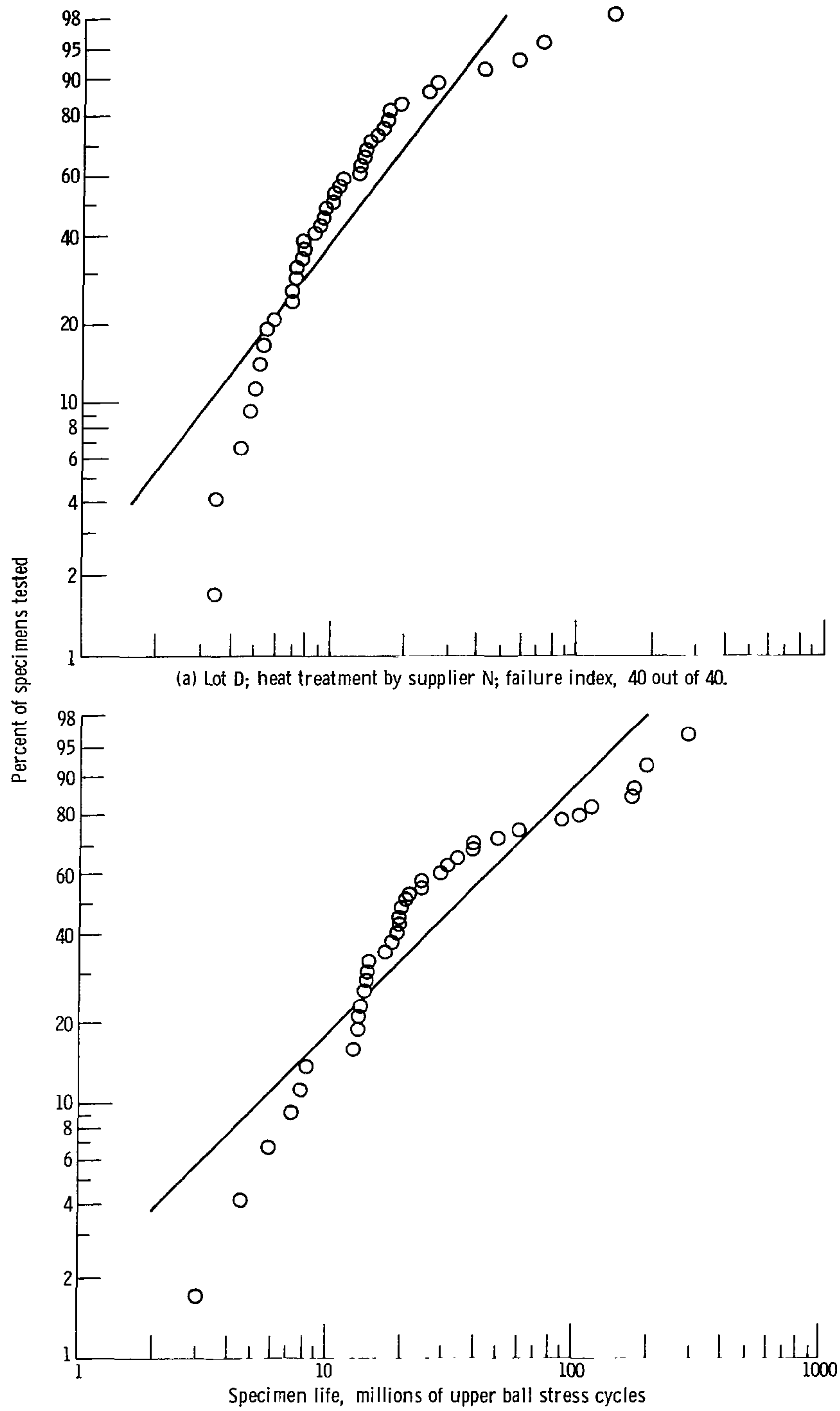
(a) Lot E; heat treated by supplier N. (b) Lot F; heat treated by supplier R.

Figure 4. - VAR 18-4-1 steel; 3 percent Nital etch.



(b) Lot C; heat treatment by supplier R; failure index, 40 out of 40.

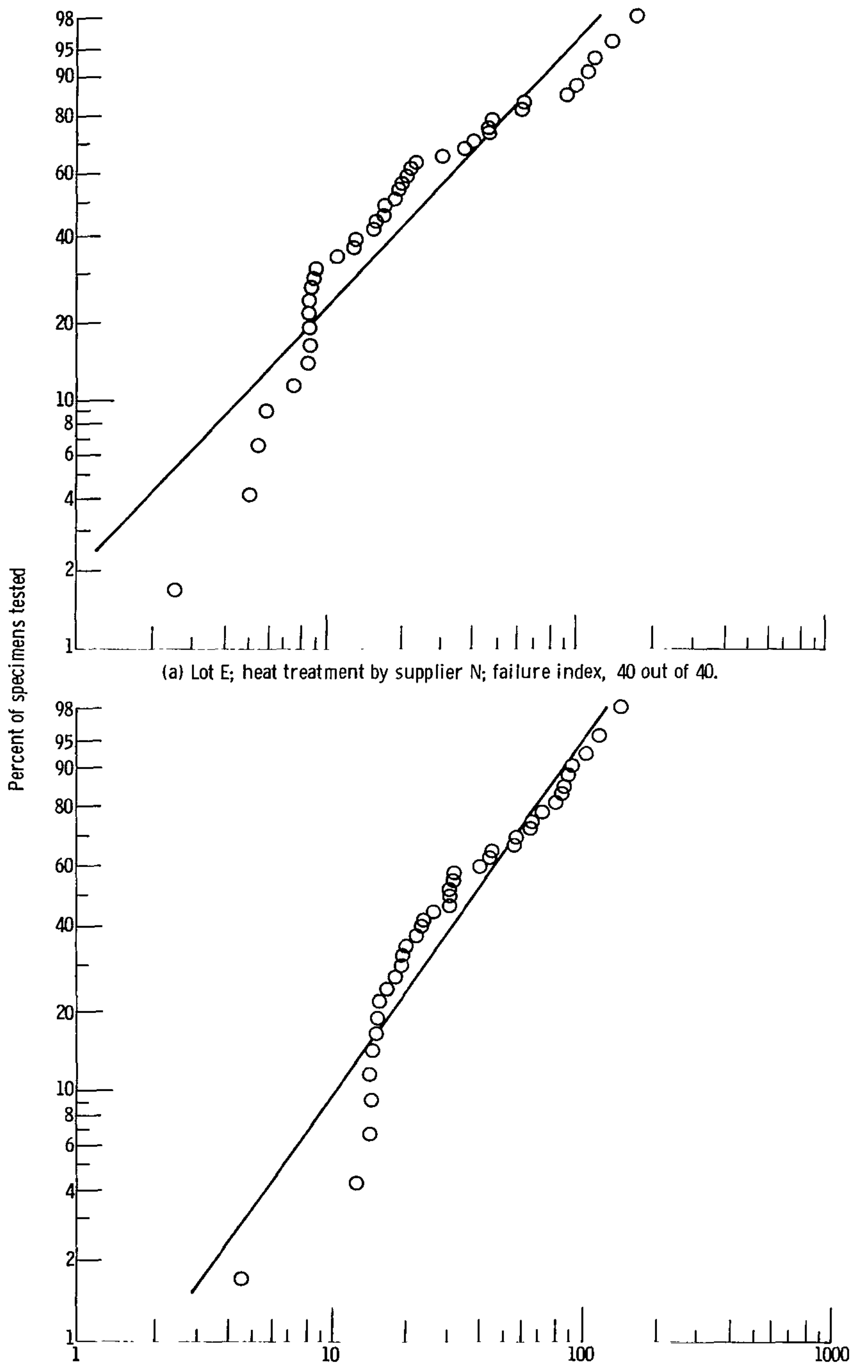
Figure 5. - Rolling-element fatigue life of VIM-VAR AISI M-50 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 megapascals (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°; temperature, 339 K (150° F).



(a) Lot D; heat treatment by supplier N; failure index, 40 out of 40.

(b) Lot B; heat treatment by supplier R; failure index, 38 out of 40.

Figure 6. - Rolling-element fatigue life of EFR 18-4-1 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 megapascals (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30; temperature, 339 K (150° F).



(b) Lot F; heat treatment by supplier R; failure index, 39 out of 39.

Figure 7. - Rolling-element fatigue life of VAR 18-4-1 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 megapascals (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°; temperature, 339 K (150° F).

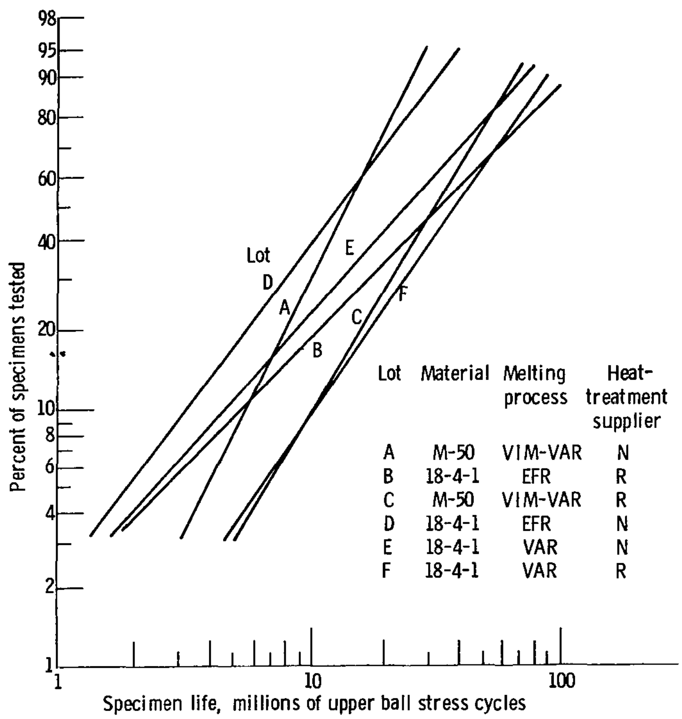


Figure 8. - Rolling-element fatigue life of VIM-VAR AISI M-50, EFR 18-4-1, and VAR 18-4-1 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520 megapascals (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°; temperature, 339 K (150° F).

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16. Abstract

Rolling-element fatigue studies were conducted with VIM-VAR AISI M-50, EFR 18-4-1, and VAR 18-4-1. Groups of 12.7-mm (1/2-in.) diameter balls of each material were tested in the five-ball fatigue tester. Test conditions included a load of 1540 N (347 lbf) giving a maximum Hertz stress of 5520 MPa (800 000 psi), a shaft speed of 10 700 rpm, and a contact angle of 30°. Tests were run at a race temperature of 339 K (150° F) with a type II ester (MIL-L-23699) lubricant. The rolling-element fatigue life of VIM-VAR AISI M-50 was not significantly different from that of EFR 18-4-1 or VAR 18-4-1 based on a statistical comparison of the test results.

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