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ROLLING-ELEMENT FATIGUE LIVES OF THROUGH-HARDENED BEARING MATERIALS

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ABSTRACT

Rolling-element fatigue tests were run with eight through-hardened bearing materials at 150° F. One-half inch diameter balls of each material were run in five-ball fatigue testers. Care was taken to maintain constant all variables known to affect rolling-element fatigue life. The longest lives at 150° F were obtained with AISI 52100. Ten-percent lives of the other materials ranged from 7 to 78 percent of that obtained with 52100. A trend is indicated toward decreased rolling-element fatigue life with increased total weight percent of alloying elements. Three groups of 120-mm bore ball bearings made from AISI M-1, AISI M-50, and WB-49 were fatigue tested at an outer-race temperature of 600° F. The 10-percent lives of the M-50 and M-1 bearings exceeded the calculated AFBMA life by factors of 13 and 6, respectively. The bearings with WB-49 races showed lives less than AFBMA life. The results of the bearing tests at 600° F correlate well with the results of the five-ball fatigue data at 150° F.

[1]Member ASME.

INTRODUCTION

AISI 52100 steel has been the most common material for rolling-element bearings. Initially this high-carbon chromium steel was produced by basic electric arc melting. Subsequently, vacuum melting processes such as consumable electrode vacuum melting (CVM)[1][2] have improved dynamic load carrying capacity and reliability of bearings made from AISI 52100.

Because of a decrease in hardness with increasing temperature, AISI 52100 has been limited to applications where the maximum temperature generally will not exceed 350° F. At about this temperature the hardness drops below R_c 58 which is considered a minimum hardness for rolling-element bearing components under normal loading conditions.[2]

For applications above 350° F, such as for advanced turbine engines, bearing alloys suitable for higher temperatures must be considered. These alloys contain elements such as molybdenum, tungsten, and vanadium to promote the retention of hardness at high temperatures. Typical of these alloy steels are those shown in Table 1. Each of these materials is a through-hardenable steel wherein the hardness is attained by heat treatment rather than a case-hardening procedure such as carburizing.

Based on the hot hardness minimum of R_c 58, these steels have upper-temperature limits ranging from 600° F to about 900° F. Typically, these steel alloys are more difficult to grind and finish than AISI 52100.[2]

AISI M-50 has been the most widely used of these steel alloys for rolling-element bearing applications. The major jet engine manufacturers use this material for rolling-element bearings.[3] In addition, much experimental work has been performed with AISI M-50.[2 to 8]

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[2]Refers to references at end of text.

There has been a considerable number of studies performed to determine the rolling-element fatigue lives of various bearing materials.[2 to 12] However, none of these studies maintained the required close control of operating and processing variables such as material hardness, melting technique, and lubricant type and batch for a completely unbiased material comparison. It is necessary to compare these materials in rolling-element fatigue tests or actual bearing tests. The more standard mechanical tests such as tension and compression tests or rotating beam tests are not correlatable with rolling-element fatigue results.[7]

The objective of the research described in this paper was to compare the rolling-element fatigue lives of eight materials AISI 52100, -M-1, -M-2, -M-10, -M-50, -M-42, -T-1, and Halmo under closely controlled operating conditions.

Groups of one-half-inch diameter balls of each material were tested in the five-ball fatigue tester. All balls for each material were made from one ingot of consumable-electrode vacuum-melted material.

Fatigue tests at 600° F with angular-contact ball bearings (120-mm bore) made from AISI M-50, AISI M-1, and WB-49 are reported in [13 and 14]. These fatigue life results are compared with those from the five-ball fatigue tests which were initially described in [15 and 16].

TEST SPECIMENS

Groups of AFBMA grade 10 balls of one-half-inch diameter were fabricated from each of the materials having the chemical compositions shown in Table I with the exception of the WB-49 material. All balls for each material were made from one consumable-electrode vacuum-melted ingot.

Three lots of each material were separately heat treated, but one specific heat treatment specification was used for each material. Details of heat treatments are given in [15 and 16]. The resulting hardness retained austenite, grain size, and cleanliness are shown in Table II for each heat treatment lot of each material.

FIVE-BALL FATIGUE TESTER

The five-ball fatigue tester was used for all tests conducted. The test assembly, shown in Fig. 1, consists of an upper 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. For every revolution of the drive shaft, the upper ball receives three stress cycles. Instrumentation provides for automatic failure detection and shutdown. Lubrication is provided by means of a once-through mist lubrication system.

PROCEDURE

In each of the tests, all five balls of the five-ball system were from the particular material lot being tested. From 25 to 30 five-ball tests were run for each material lot. Each test was suspended when either an upper or a lower ball failed or when a cutoff time of 100 hours was reached. The statistical methods of [17] for analyzing rolling-element fatigue data were used for evaluating the test data.

HARDNESS TESTING

The hardness of the materials was measured at both room and elevated temperatures using a standard hardness tester fitted with an inerted electric furnace. Hardness tests were performed using a 150-kilogram load and a

Rockwell "C" diamond indentor. Ball specimens from the same heats as those fatigue tested herein were selected at random for hardness testing. Two 1/4-inch parallel flats were ground on each ball. The grinding was done at a very slow feed rate with a copious supply of coolant to prevent overheating of the test specimens.

Hardness measurements were taken immediately after an equilibrium temperature was reached before the heat input was increased for the next higher temperature. Approximately 1/2 hour elapsed before equilibrium was reached at each test temperature. Temperature was increased in increments of about 100° F.

RESULTS AND DISCUSSION

Fatigue Results at 150° F

Eight steels (AISI 52100, M-1, M-2, M-10, M-50, M-42, T-1, and Halmo) were tested in the five-ball fatigue tester. Groups of 1/2-inch diameter balls of each of these materials were tested at a maximum Hertz stress of 800,000 psi, a contact angle of 30°, and a shaft speed of 10,300 rpm. Tests were run at a race temperature of 150° F with a super-refined naphthenic mineral oil as the lubricant.

The results of the fatigue tests with each heat treatment lot of 52100 are shown in the Weibull plots in Fig. 2. Both upper- and lower-test ball fatigue failures were considered in determining the five-ball system life in the Weibull analysis. Each of the other seven materials were analyzed in this manner. Only the Weibull plots for 52100 are shown.

The 10-percent lives for each material lot are shown in Table III. A 2 to 1 ratio in the 10-percent lives of two lots of the same material is observed with both 52100 and M-10. (It should be recalled that the only difference between lots of the same material is that they were heat treated separately.) The different values of fatigue life among the material lots cannot be attributed to the slight variations in the material properties shown in Table II such as hardness, grain size, retained austenite, and cleanliness since no clear trends are apparent. These slight material property differences may be a result of slight variations in execution of the heat treatment, or they may be scatter in the property measurements. The variation in 10-percent fatigue lives between material lots may also be normal scatter in rolling-element fatigue data. Based upon previous experience, a 2 to 1 ratio in fatigue lives among lots of the same material should not be unexpected.

An analysis which considered upper-ball failures as failures and lower-ball failures as suspensions was also performed. Including lower-ball failures as failures seems to yield a consistently but slightly lower life of each group. No significant difference between the two analyses was indicated.

Material Comparison

The tests with all three heat treatment lots of each material were grouped together in order to compare the fatigue lives of the various materials. A Weibull analysis was performed on the combined results for each material. The Weibull plot for 52100 is shown in Fig. 3 as an example. Results for each material are shown in Table IV. Ten-percent lives of the materials are shown in Fig. 4. A direct comparison shows that at the 10-percent life level, the material with the longest fatigue life is 52100. Halmo gave the next highest 10-percent life, which was about 78-percent of that of 52100. The shortest life material was M-42 which gave a 10-percent life of only 7 percent of that of 52100. All of the other materials gave lives ranging from 27 to 68 percent of that of 52100.

Because of the large number of failures (63 to 87) in the combined groups, relatively small differences in lives can be significant. To determine the significance of these fatigue results, the confidence numbers shown in Table IV were calculated by the methods of [17]. The 10-percent life of 52100 is used as a reference. These confidence numbers indicate the percentage of the time that the 10-percent life obtained with a group of 52100 balls will be greater than that of a group of balls of one of the other materials. The confidence numbers for M-1, M-2, T-1, and M-42 exceed 95 percent (the 2-sigma confidence level). These results indicate that the differences in fatigue lives between 52100 and these four materials are significant. The results for M-10, M-50 and Halmo show less confidence in the fatigue life differences. These life differences are not statistically significant.

The fatigue spalls on the balls of all eight materials were similar in appearance. The failures appeared to be of the same origin, classical subsurface rolling-element fatigue.

Effect of Alloying Elements

It is interesting to note that the materials containing the greatest weight percentage of alloying elements are those with the lowest fatigue lives. This effect is shown in Fig. 5, where relative 10-percent lives are plotted against total weight percent of the alloying elements tungsten, chromium, vanadium, molybdenum, and cobalt. Individually, each element shows no consistent effect on fatigue life. The possible exception is tungsten which is present in significant quantities in the four lowest lived materials, M-1, M-2, T-1, and M-42. The effect, therefore, seems to be a cumulative one. When present in high percentages, these alloying elements appear to be detrimental to rolling-element fatigue life.

These alloying elements are essential for attaining the required hardness as well as the retention of hardness at elevated temperature. Chromium, tungsten, molybdenum, and vanadium are carbide formers [13]. The other major alloying element, cobalt, is not considered to be a major carbide former, although it may contribute incidentally to the formation of other metal carbides. There are considerable differences in the size, shape, and distribution of these metal carbides in the various materials. It seems reasonable that the differences in fatigue life could be largely attributed to the incidence of these metal carbides. In a sense, this has been indicated in the work performed on ausforming of M-50 [5]. The prime function of the ausforming process is to refine the material structure as well as to disperse the carbides more uniformly and reduce their tendency toward critical segregation. Significant improvement in fatigue life was obtained by the thermomechanical working, without any modification of the basic chemistry.

The 52100 material has generally smaller and more uniformly dispersed carbides than the other materials tested. The longer life of 52100 under these test conditions at 150° F supports the contention that the incidence, size, and distribution of the metal carbides is very influential in the rolling-element fatigue life of bearing steels.

Hardness at Elevated Temperature

A commonly accepted minimum hardness at operating temperature for rolling-element bearing components is Rockwell C 58. At a hardness below this value, brinelling of the bearing races can occur and plastic deformation during operation can be excessive.

It has been observed that the temperature at which a material's hardness drops below Rockwell C 58 is dependent on the initial room temperature hardness. Fig. 6 shows data from two specimens of M-1 with room temperature hardnesses of R_c 63 and 66. A constant difference of 3 to 4 Rockwell C points was observed between the hardnesses of the two specimens as temperature was increased from room temperature to about 900° F. These data imply that an upward or downward shift in hardness versus temperature curve may be justified such that the useful maximum temperature for a given material at a given room temperature hardness may be determined.

The materials tested in this program were of slightly different room temperature hardnesses (Table II). An adjustment in the hardness versus temperature curves is necessary for a meaningful comparison of the material's hardness retention capabilities.

The hardness at elevated temperature as adjusted from measured hardness for each of the materials is shown in Fig. 7. The common room temperature hardness is Rockwell C 62.5. As expected, all seven other materials maintain hardness above Rockwell C 58 at higher temperatures than does 52100. The temperature difference is at least 200° F. Surprisingly, there was very little difference among the hardness-temperature curves of the seven materials investigated in this program. M-42 appears to form the upper limit of hardness retention capabilities of these materials. These data suggest that the room temperature hardness has more effect on the maximum useful temperature than the alloy composition of the material. The influence of time at elevated temperature may differ among the materials tested. Further testing on room temperature hardness effect and the time effect is warranted.

Bearing Fatigue Tests at 600° F

Groups of 120-mm bore angular-contact ball bearings made from CVM AISI M-50, AISI M-1, and WB-49 were tested in a high-temperature fatigue tester [18] at an outer-race temperature of 600° F [13 and 14]. All inner and outer races were made from a single heat of each respective material. The balls for the M-1 and M-50 bearings were made from a second heat of each material. Because of difficulties in fabricating WB-49 balls [19], M-1 balls were used with the WB-49 races. The nominal room temperature hardness of all balls and races was Rockwell C 63.

Shaft speed was 12,000 rpm, and thrust load was 5800 pounds which produced maximum Hertz stresses of 323,000 and 267,000 psi at the inner and outer races, respectively. A synthetic paraffinic oil with antiwear and antifoam additives was used. The bearing test chamber and the lubricant sump were kept under a low oxygen environment (less than 0.1 percent oxygen by volume).

All bearings were run to fatigue failure of a race or ball or to a cutoff time of 500 hours (750 hours for the M-1 bearing tests). The failure mode for bearings of all three materials was classical rolling-element fatigue, apparently originating subsurface in the zone of maximum resolved shearing stress. A typical fatigue spall on an M-1 bearing inner race is shown in Fig. 8. An unfailed M-50 bearing run for 500 hours is shown in Fig. 9.

Fatigue life results with the three materials are shown in the Weibull plots in Fig. 10. The calculated AFBMA standard life (catalog life) at this load is also given for comparative purposes. The results are summarized in Table V. The experimental lives of the M-50 and the M-1 bearings exceeded the AFBMA life by factors of 13 and 6, respectively.

The M-1 bearings produced much more scatter in their fatigue life results. Accordingly, at the 10-percent life level, the M-1 bearings show about one-half the life of the M-50 bearings. (The 10-percent life level or even lower must be used for comparative purposes in high reliability applications.) The bearings with WB-49 races showed lives lower than AFBMA life and a 10-percent life only about 3 percent of that of the M-50 bearings.

Confidence numbers for the M-1 and WB-49 data when compared to the M-50 data are 67 and 99 percent, respectively. Thus the difference between the 10-percent lives of M-1 and M-50 is considered insignificant. In the case of the WB-49 bearings, the difference is significant.

The magnitudes of the life differences seen in these bearing tests at 600° F correlate well with the five-ball fatigue test results. Relative 10-percent fatigue lives are shown in Fig. 11. Using the M-50 10-percent life as a comparison, the M-1 data for the five-ball fatigue tests and the bearing tests agree remarkably well. WB-49 and M-42, both alloys containing relatively high percentages of cobalt and similar in microstructure, show reasonably good agreement between the five-ball fatigue tests and the bearing tests. These results indicate that the alloying element effect (or carbide effect) on rolling-element fatigue life exists at 600° F as well as at 150° F.

SUMMARY

Eight consumable-electrode vacuum-melted steels were fatigue tested in five-ball fatigue testers at 150° F. Groups of one-half-inch diameter balls of each material were tested at a maximum Hertz stress of 800,000 psi, a shaft speed of 10,300 rpm, a contact angle of 30° and with a super-refined naphthenic mineral oil lubricant. Care was taken to maintain constant all variables known to affect rolling-element fatigue life. Three groups of 120-mm bore angular-contact ball bearings made from AISI M-1, M-50, and WB-49 were fatigue tested at an outer-race temperature of 600° F. Shaft speed was 12,000 rpm, and thrust load was 5800 pounds which produced a maximum Hertz stress on the bearing inner-race of 323,000 psi. The bearings were lubricated with a synthetic paraffinic oil containing an antiwear additive and were tested in a low oxygen environment. The following results were obtained:

1. The longest fatigue lives at 150° F were obtained with AISI 52100. The 10-percent fatigue lives of M-1, M-2, M-42, and T-1, were significantly less than that of 52100. Differences in the 10-percent lives of Halmo, M-50, M-10 and 52100 were not statistically significant.

2. A trend is apparent toward decreasing rolling-element fatigue life with increased total weight percent of alloying elements molybdenum, chromium, vanadium, tungsten, and cobalt. The size and distribution of the metal

carbides, which vary with alloy content, appear to be primary factors in rolling-element fatigue life.

3. The experimental lives at 600° F of bearings made from M-50 and M-1 exceeded the calculated AFBMA standard life by factors of 13 and 6, respectively. The bearings with WB-49 races showed lives less than AFBMA life.

4. The results of the bearing tests at 600° F correlate remarkably well with the results of the five-ball fatigue tests at 150° F.

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TABLE I. - CHEMICAL COMPOSITION OF BEARING STEELS

Material	Alloying element, percent by weight (balance Fe)											
	C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Cu
52100	1.05	0.26	0.27	0.006	0.006	-----	1.38	----	----	----	----	----
Halmo	.56	1.12	.36	.008	.003	-----	4.84	0.53	5.18	----	----	----
M-50	.82	.22	.18	.006	.012	0.02	4.03	.98	4.26	0.02	0.04	0.04
M-10	.86	.21	.21	.008	.015	-----	3.93	1.85	8.18	----	----	----
T-1	.68	.22	.30	.010	.012	17.52	3.95	1.14	.09	.93	.05	.03
M-1	.81	.24	.28	.008	.009	1.57	3.70	1.20	8.92	----	----	----
M-2	.85	.27	.16	.008	.012	6.39	4.22	1.92	4.81	----	----	----
M-42	1.10	.17	.15	.007	.012	1.66	3.77	1.15	9.51	7.99	----	----
WB-49	.06	.32	.74	.008	.004	6.82	4.22	1.86	3.76	5.29	.08	----

TABLE II. - PROPERTIES OF THE TEST MATERIALS RUN IN

FIVE-BALL FATIGUE TESTER

Material	Heat treatment lot	Average hardness, Rc	Retained austenite, volume percent[a]	Austenitic grain size[b]	Cleanliness rating[c]	
					Class[d]	Type
52100	A	62.5	4.90	13	B1	Heavy
	B	62.0	4.10	13	D1	Thin
	C	62.5	.80	13	D1	Thin
Halmo	A	60.8	0.60	8	D2	Heavy
	B	60.8	1.00	8	D1	Heavy
	C	61.1	1.70	8	D2	Heavy
M-50	A	62.6	1.90	10	B1	Heavy
	B	62.2	2.90	9	D2	Heavy
	C	62.3	1.50	10	D1	Heavy
M-10	A	62.2	1.10	9	D3	Heavy
	B	62.0	2.40	6	D2	Heavy
	C	61.8	1.60	6	D1	Thin
T-1	A	61.4	7.30	11	B1	Heavy
	B	61.4	5.20	9	D1	Thin
	C	61.0	9.50	10	D1	Heavy
M-1	A	63.3	2.90	10	B2	Heavy
	B	63.4	3.30	9	A1	Heavy
	C	63.5	1.00	8	A2	Heavy
M-2	A	63.4	1.70	6	B1	Heavy
	B	63.4	2.40	10	D1	Thin
	C	63.4	2.30	9	D1	Heavy
M-42	A	61.8	1.00	9	A1	Thin
	B	61.3	4.40	10	D1	Heavy
	C	61.3	4.90	8	D1	Heavy

[a]Determined from the integrated peak intensities of (220) γ and (200) α planes.
[b]ASTM E 112-63.
[c]ASTM E 45-63, Method A (Table shows predominate inclusion class and type.)
[d]Inclusion classes; A-Sulfides, B-Alumina, C-Silicates, D-Globular Oxides.

TABLE III. - FATIGUE RESULTS WITH GROUPS OF ONE-HALF-INCH DIAMETER BALLS RUN IN FIVE-BALL FATIGUE TESTERS. MAXIMUM HERTZ STRESS, 800,000 PSI; CONTACT ANGLE, 30°, SHAFT SPEED, 10,300 RPM; RACE TEMPERATURE, 150° F.

Material	Heat treatment lot	Life, millions of upper ball stress cycles		Slope	Failure index[a]
		B_{10}	B_{50}		
52100	A	18.5	114	1.04	22 out of 29
	B	30.1	130	1.29	22 out of 29
	C	12.9	84	1.00	19 out of 25
Halmo	A	22.0	74	1.56	25 out of 30
	B	12.9	57	1.26	28 out of 30
	C	12.9	68	1.14	26 out of 30
M-50	A	15.3	35	2.29	29 out of 29
	B	12.3	36	1.73	24 out of 30
	C	14.2	48	1.55	26 out of 29
M-10	A	19.4	65	1.56	26 out of 30
	B	8.3	46	1.11	30 out of 30
	C	13.1	42	1.62	29 out of 30
T-1	A	6.6	50	0.92	26 out of 30
	B	8.4	59	.97	26 out of 30
	C	8.5	74	.87	23 out of 30
M-1	A	8.2	43	1.13	29 out of 30
	B	5.9	37	1.02	29 out of 30
	C	6.7	33	1.18	29 out of 29
M-2	A	5.8	35	1.05	28 out of 30
	B	5.5	26	1.23	28 out of 29
	C	4.2	31	.95	29 out of 30
M-42	A	1.0	6.6	0.97	30 out of 30
	B	1.7	8.9	1.12	27 out of 30
	C	1.4	5.8	1.33	30 out of 30

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

TABLE IV. - COMBINED FATIGUE RESULTS (THREE LOTS OF EACH MATERIAL COMBINED)

Material	Life, millions of upper ball stress cycles		Slope	Failure index[a]	Relative B_{10} life	Confidence number percent[b]
	B_{10}	B_{50}				
52100	21.2	109	1.15	63 out of 83	1.0	---
Halmo	16.4	66	1.35	79 out of 90	.78	76
M-50	14.4	39	1.89	79 out of 88	.68	89
M-10	13.2	50	1.40	85 out of 90	.62	91
T-1	8.6	59	.98	75 out of 90	.41	98
M-1	7.6	38	1.18	87 out of 89	.36	>99
M-2	5.7	30	1.13	85 out of 89	.27	>99
M-42	1.4	7.0	1.18	87 out of 90	.07	>99

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

[b]Percentage of time that the 10-percent life with a group of AISI 52100 balls will be greater than that of a group of one of the other materials.

TABLE V. - FATIGUE LIFE RESULTS FOR 120-MM BORE ANGULAR-CONTACT BALL BEARINGS AT 600° F. DATA FROM [13 AND 14].

(THRUST LOAD, 5800 LBS; SPEED, 12,000 RPM)

Material	Experimental life, millions of inner-race revolutions		Weibull slope	Failure index[a]	Confidence number[b]
	10-Percent life	50-Percent life			
M-50	182	513	1.8	6 out of 26	---
M-1	89	2331	0.6	6 out of 24	67
WB-49[c]	6	26	1.3	28 out of 30	>99

[a]Number of fatigue failures out of number of bearings tested.

[b]Percentage of time that 10-percent life obtained with AISI M-50 bearings will have the same relation to the 10-percent life of the bearings made from other material.

[c]Bearings had AISI M-1 balls.

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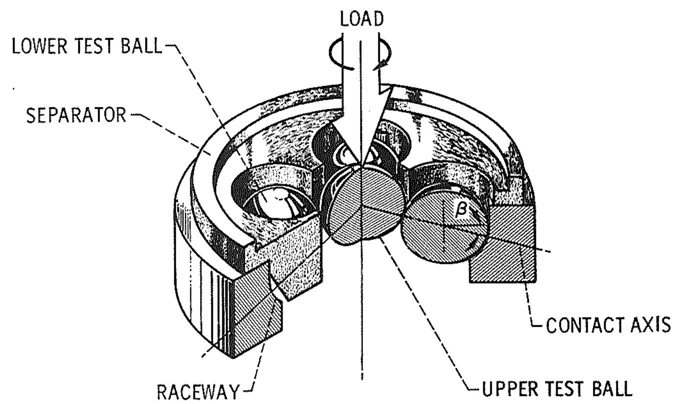

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Figure 1. - Five-ball fatigue test assembly.

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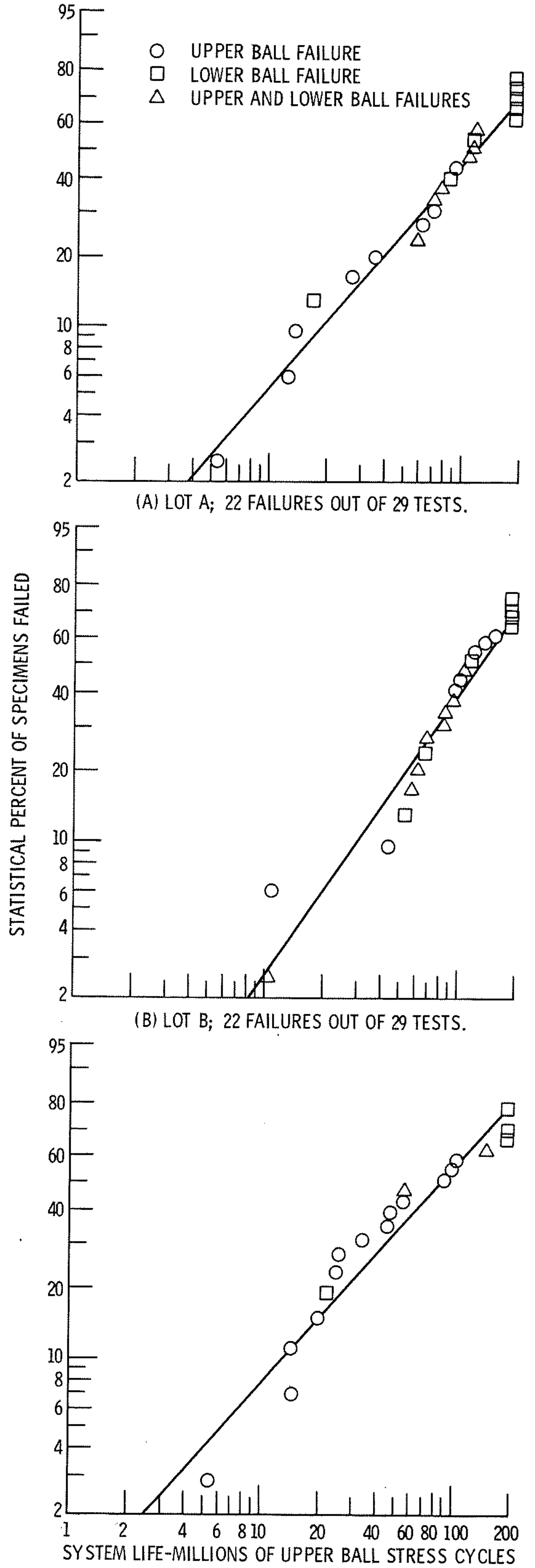

(C) LOT C; 19 FAILURES OUT OF 25 TESTS.

Figure 2. - Rolling-element fatigue life of one-half inch diameter AISI 52100 consumable-electrode vacuum melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi; shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F.

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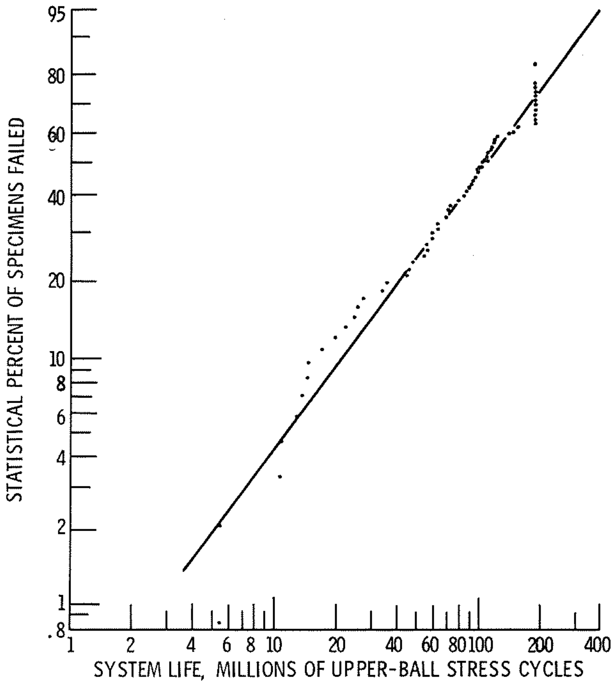

Figure 3. - Rolling-element fatigue life of the three lots of AISI 52100 balls combined. Failure index, 63 out of 83.

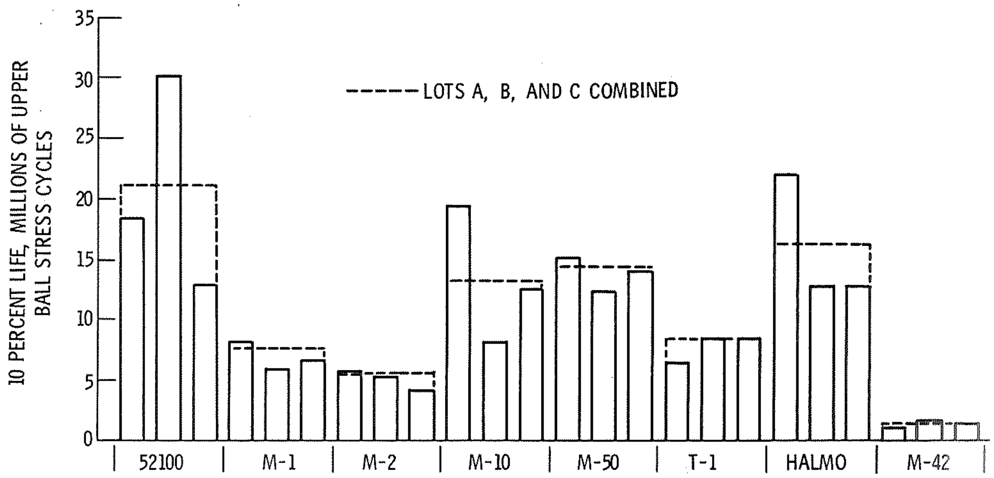

Figure 4. - 10-Percent fatigue lives at 150° F of individual material lots and of three lots of each material combined..

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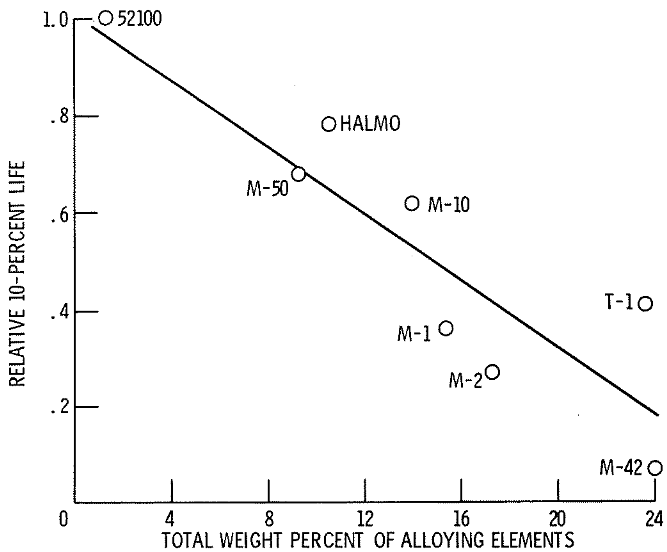

Figure 5. - Effect of total weight percent of alloying elements tungsten, chromium, vanadium, molybdenum, and cobalt on rolling-element fatigue life at 150° F.

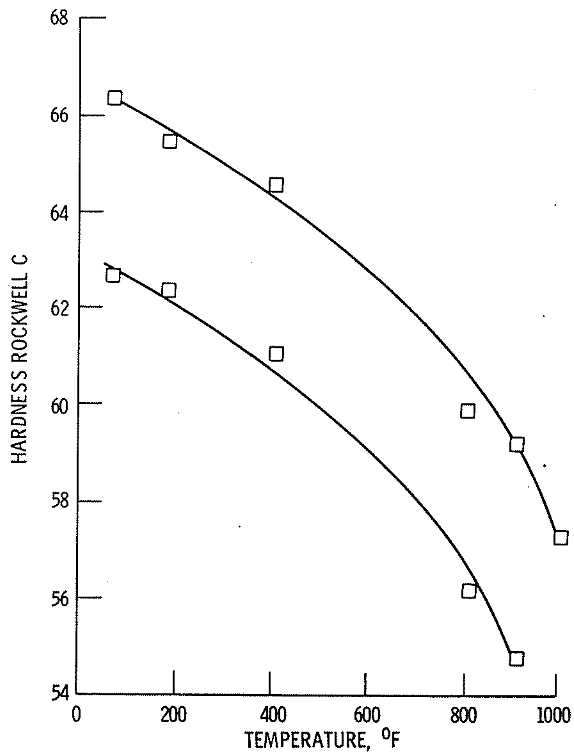

Figure 6. - Hardness (Rockwell C) as a function of temperature for AISI M-1 specimens at two different room temperature hardnesses.

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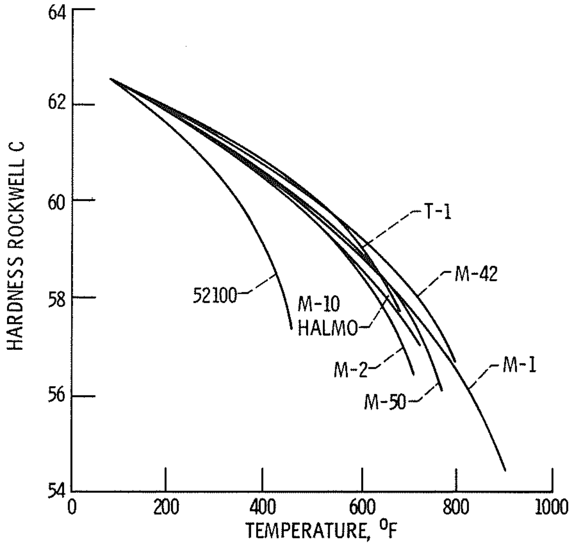
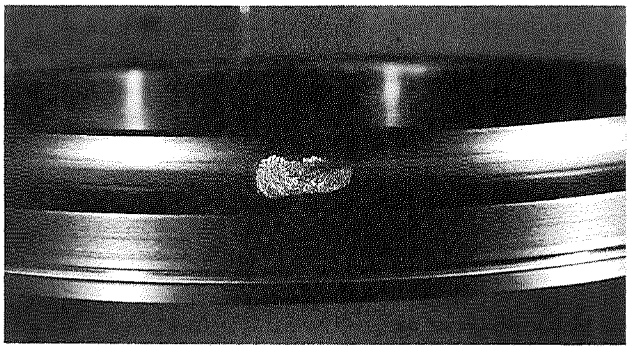


Figure 7. - Hardness as a function of temperature for the eight materials adjusted to a room temperature hardness of Rockwell C 62.5.



C-70-3919

Figure 8. - Typical fatigue spall on inner race of an M-1 bearing run at 600° F. Thrust load, 5800 pounds; speed, 12,000 rpm; running time, 71 hours, from [13 and 14].

E-5081

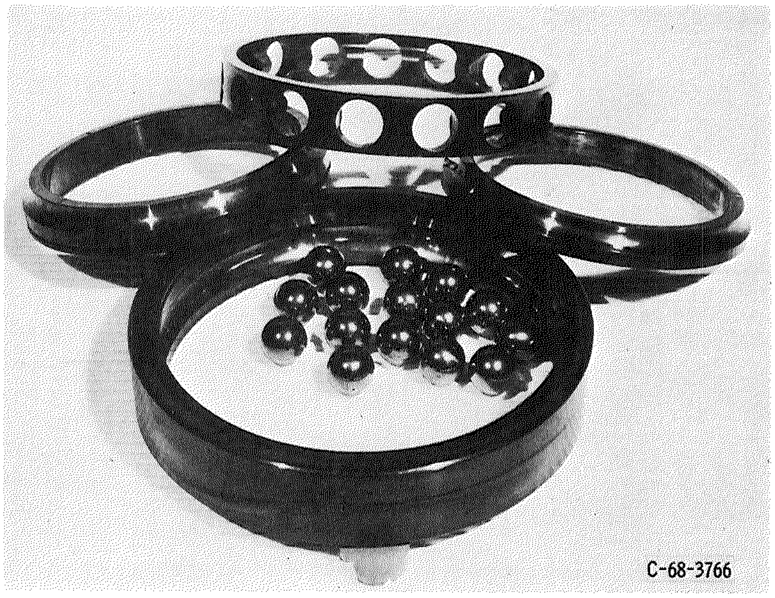


Figure 9. - Unfailed 120-mm bore ball bearing made of M-50 run for 500 hours at 600° F. Thrust load, 5800 pounds; speed, 12,000 rpm; lubricant synthetic paraffinic oil; from [13 and 14].

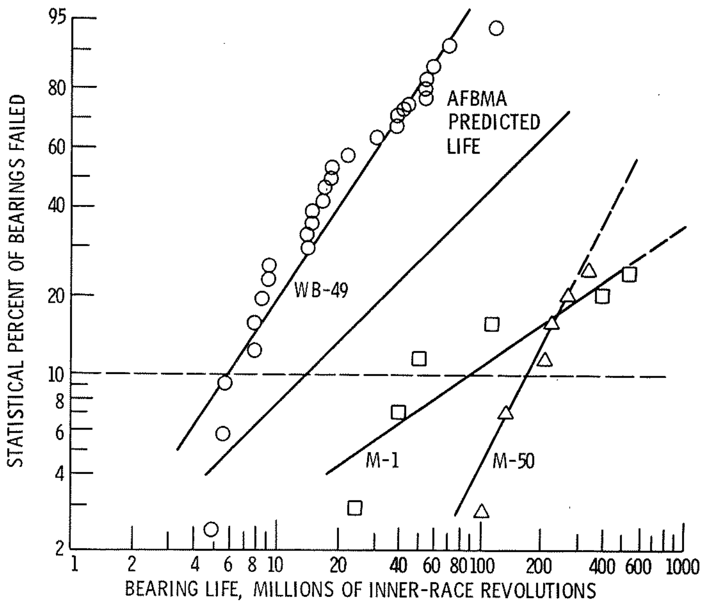


Figure 10. - Rolling-element fatigue life of 120-mm bore angular contact ball bearings made from three materials. Thrust load, 5800 pounds; speed, 12 000 rpm; temperature, 600° F; data from [13 and 14].

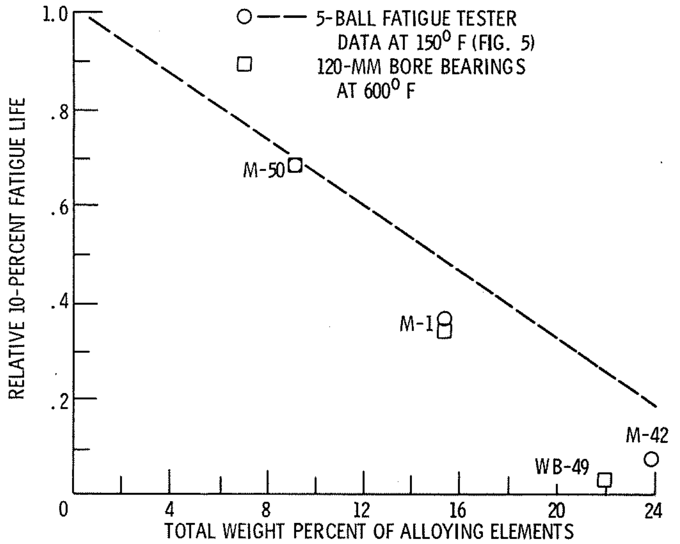


Figure 11. - Effect of total weight percent of alloying elements on fatigue life of 120-mm bore bearings at 600° F.