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ROLLING-ELEMENT FATIGUE LIVES OF FOUR M-SERIES STEELS AND AISI 52100 AT 150° F

by Richard J. Parker, Erwin V. Zaretsky, and Marshall W. Dietrich

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Rolling-element fatigue studies were performed with 1/2-inch- (12.7-mm-) diameter balls of AISI M-1, M-2, M-10, M-50, and 52100. Tests were run in five-ball fatigue testers at 800 000 psi (5.52×10^{9} N/m^{2}) and at a temperature of 150° F (340 K). Care was taken to maintain constant all the variables known to affect rolling-element fatigue life. The longest lives were obtained with AISI 52100. Ten-percent lives of the other materials ranged from 27 to 68 percent of that obtained with AISI 52100. Lives of different heat treatment lots of the same material differed by factors as great as two. There was no significant difference among the ability of AISI M-50, M-10, and M-2 to maintain hardness at elevated temperatures.

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SUMMARY

Rolling-element fatigue studies were performed with five consumable-electrode vacuum-melt steels. Groups of 1/2-inch- (12.7-mm-) diameter balls of each material were run in five-ball fatigue testers. Test conditions included a maximum Hertz stress of 800 000 psi (5.52×10^9 N/m^2), a contact angle of 30°, a shaft speed of 10 300 rpm, a super-refined naphthenic mineral oil lubricant, and a temperature of 150° F (340 K). Care was taken to maintain constant all variables known to affect rolling-element fatigue life. The longest rolling-element fatigue lives were obtained with AISI 52100. The 10-percent lives of the other four materials ranged from 27 to 68 percent of that obtained with AISI 52100. The statistical confidence that the 10-percent lives of AISI M-1 and M-2 are less than that of AISI 52100 is greater than 99 percent. The lives of AISI M-10 and M-50 were better than AISI M-1 and M-2 but significantly less than that of AISI 52100. Lives of different heat treatment lots of the same material differed by factors as great as two.

Contrary to previously published work, there appears to be no significant difference among the abilities of AISI M-50, M-10, and M-2 to maintain hardness at elevated temperatures. AISI M-1 indicates a higher temperature potential than these three materials of about 100° F (56 K).

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) (ref. 1) have improved the 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 will not exceed 350° F (450 K). At about this temperature, the hardness drops below R_c58 which is considered a minimum hardness for rolling-element bearing components (refs. 2 and 3).

For applications above 350° F (450 K), such as for advanced turbine engines, bearing alloys suitable for higher temperatures must be considered. These alloys contain elements such as molybdenum, tungsten, silicon, and vanadium to promote the retention of hardness at high temperatures. Typical of these alloy steels are AISI M-1, M-50, M-10, and M-2. Based on the hot hardness minimum of R_c58, AISI M-50 should have an upper temperature limit of about 600° F (589 K) (ref. 2). Likewise, AISI M-1, M-2, and M-10 may be useful well above the limit of AISI 52100. However, even if the hardness remains satisfactory, at temperatures above 800° F (700 K) the oxidation resistance becomes marginal for these steels.

These "M" series steel alloys are all more difficult to grina and finish than AISI 52100 (ref. 2). However, the hot hardness characteristics of AISI M-50, for example, have been so advantageous that this steel is being specified for many current turbine engine bearings.

There has been a considerable number of studies performed to determine the fatigue lives of various bearing materials (refs. 2 and 4 to 9). However, none of these studies maintained the required close control on operating and processing variables such as material hardness, melting technique, and lubricant type and batch for a valid material comparison.

The objective of this research was to compare the relative rolling-element fatigue lives of AISI 52100, M-1, M-2, M-10, and M-50 steels under closely controlled operating conditions. All materials were in the form of 1/2-inch- (12.7-mm-) diameter grade 10 balls and were prepared by the consumable-electrode vacuum-melt (CVM) technique (ref. 10).

The previous objective was accomplished by running groups of balls of each of the materials as upper and lower balls in five-ball fatigue testers. Test conditions included a drive shaft speed of 10 300 rpm, a contact angle of 30°, a maximum hertz stress of 800 000 psi (5.52×10^9 N/m^2), and a temperature of 150° F (340 K). All fatigue testing was conducted at SKF Industries, Inc., King of Prussia, Pennsylvania under NASA contract NAS 3-11617. All hardness testing was done at NASA Lewis Research Center.

TEST SPECIMENS

Groups of AFBMA grade 10 balls of 1/2-inch- (12.7-mm-) diameter were fabricated from each of the materials having the chemical compositions shown in table I. All balls of each material were made from one consumable-electrode vacuum-melted ingot. The

TABLE I. - CHEMICAL COMPOSITION OF TEST MATERIALS

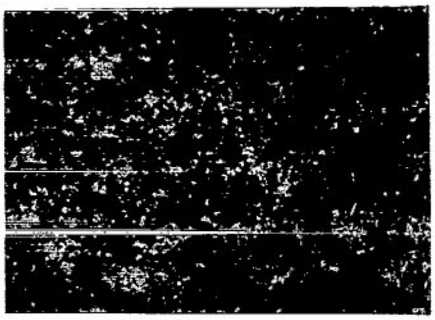
Material	Heat treatment lot	Chemical composition, percent (balance is Fe)						
		C	Mn	Si	Cr	V	W	Mo
AISI 52100	A	1.09	0.36	0.24	1.46	<0.05	----	<0.05
	B	1.07	.36	.22	1.48	<.05	----	<.05
	C	1.08	.34	.24	1.45	<.05	----	<.05
AISI M-50	A	0.81	0.23	0.24	5.03	1.03	----	4.00
	B	.79	.24	.24	4.93	1.05	----	3.98
	C	.84	.24	.22	4.90	1.04	----	4.02
AISI M-10	A	0.92	0.23	0.20	4.38	1.83	----	7.49
	B	.89	.25	.20	4.40	1.85	----	7.06
	C	.90	.27	.20	4.44	1.84	----	7.22
AISI M-1	A	0.82	0.24	0.25	3.89	1.20	1.26	7.68
	B	.82	.26	.20	3.93	1.18	1.27	7.63
	C	.89	.21	.20	4.02	1.09	1.40	7.88
AISI M-2	A	0.87	0.20	0.28	4.38	1.80	6.31	4.06
	B	.86	.21	.24	4.39	1.82	6.43	4.08
	C	.87	.20	.22	4.33	1.82	6.40	4.05

slight variation in composition from one lot to another of the same material is probably due to error in measurement. The balls were heat treated according to the schedules shown in table II. Each material was processed in three separate heat treatment lots; each lot was given the same heat treatment.

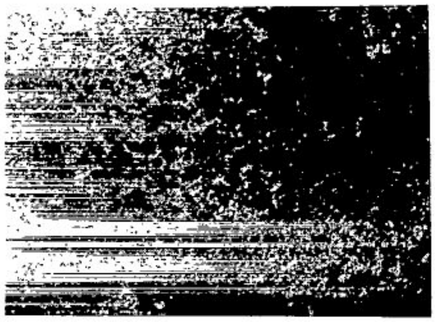
Photomicrographs of each material are shown in figures 1 to 5. The structures appear to be typical of each material. Larger carbides are seen in each of the M-series steels than in the AISI 52100. Hardness, retained austenite, and grain size of each material lot are shown in table III. ASTM cleanliness ratings are shown in table IV.

TABLE II. - HEAT TREATMENT OF TEST MATERIALS

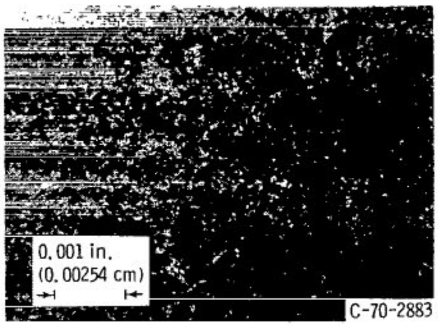
Heat treatment	Test material				
	AISI 52100	AISI M-1	AISI M-2	AISI M-10	AISI M-50
Preheat	-------------------	1400° to 1550° F (1033 to 1118 K)	1400° to 1600° F (1033 to 1144 K)	1400° to 1550° F (1033 to 1118 K)	1400° to 1550° F (1033 to 1118 K)
Harden	1540° to 1560° F (1116 to 1121 K)	$2200^{\circ}\pm10^{\circ}$ F (1477 ± 5 K)	$2225^{\circ}\pm10^{\circ}$ F (1491 ± 5 K)	$2200^{\circ}\pm10^{\circ}$ F (1477 ± 5 K)	$2100^{\circ}\pm10^{\circ}$ F (1423 ± 5 K)
Quench	In oil at 100° to 130° F (311 to 327 K)	In molten salt at 1000° to 1050° F (811 to 839 K)			
Air cool	To room temperature	To $<150^{\circ}$ F (339 K)			
Deep freeze	-100° F (200 K) for 4 hr	---------------	---------------	---------------	---------------
Temper	350° F (450 K) for 6 hr	$1100^{\circ}\pm10^{\circ}$ F (866 ± 5 K) for 2 hr	$1125^{\circ}\pm10^{\circ}$ F (880 ± 5 K) for 2 hr	$1075^{\circ}\pm10^{\circ}$ F (853 ± 5 K) for 2 hr	$1025^{\circ}\pm10^{\circ}$ F (825 ± 5 K) for 2 hr
Deep freeze	-100° F (200 K) for 3 hr	-110° to -150° F (194 to 172 K) for $1\frac{1}{2}$ to 2 hr			
Stabilize	350° F (450 K) for 2 hr	$1100^{\circ}\pm10^{\circ}$ F (866 ± 5 K) for 2 hr	$1125^{\circ}\pm10^{\circ}$F ($880\pm5$ K) for 2 hr	$1075^{\circ}\pm10^{\circ}$ F (853 ± 5 K) for 2 hr	$1025^{\circ}\pm10^{\circ}$ F (825 ± 5 K) for 2 hr
Air cool	To 100° F (311 K)	To room temperature			
Stabilize	350° F (450 K) for 2 hr	$1000^{\circ}\pm10^{\circ}$ F (811 ± 5 K) for 2 hr	$1000^{\circ}\pm10^{\circ}$ F (811 ± 5 K) for 2 hr	$975^{\circ}\pm10^{\circ}$ F (797 ± 5 K) for 2 hr	$975^{\circ}\pm10^{\circ}$ F (797 ± 5 K) for 2 hr
Air cool	To room temperature				



(a) Lot A.

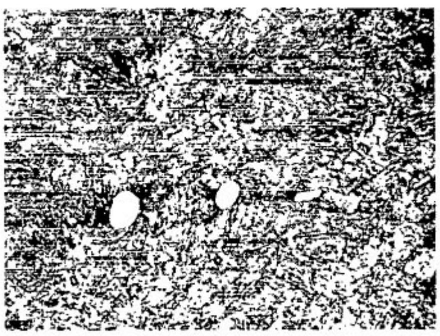


(c) Lot C.



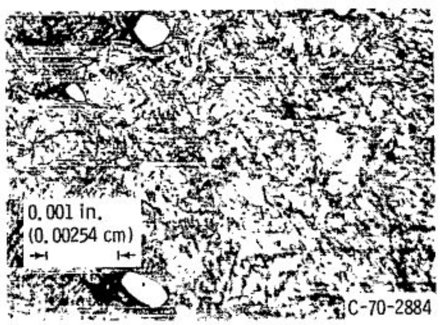
(b) Lot B.

Figure 1. - Photomicrographs of AISI 52100 steels; 2 percent Nital etch.



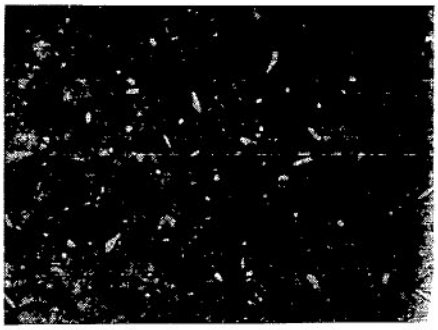
(a) Lot A.

(b) Lot B.



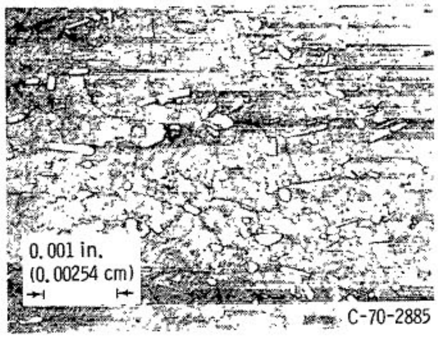
(c) Lot C.

Figure 2. - Photomicrographs of AISI M-50 steels; 2 percent Nital etch.



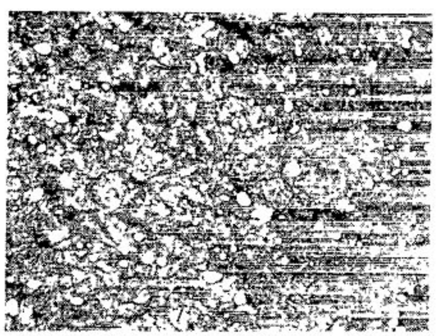
(a) Lot A.

(b) Lot B.

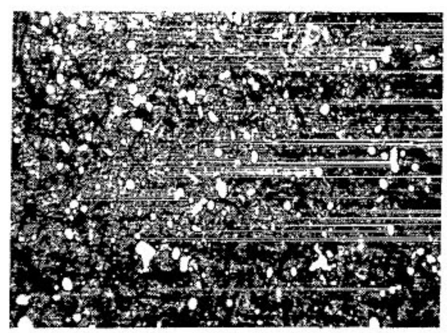


(c) Lot C.

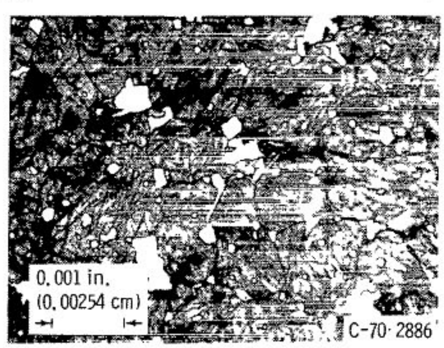
Figure 3. - Photomicrographs of AISI M-10 steels; 2 percent Nital etch.



(a) Lot A.

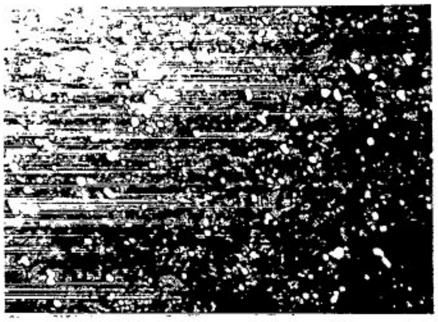


(b) Lot B.

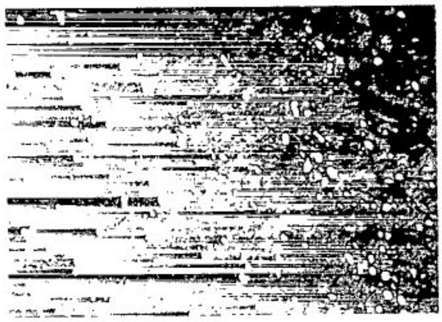


(c) Lot C.

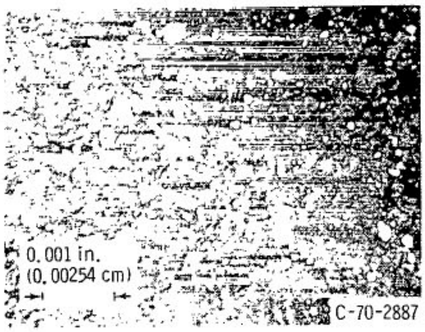
Figure 4. - Photomicrographs of AISI M-1 steels; 2 percent Nital etch.



(a) Lot A.



(b) Lot B.



(c) Lot C.

Figure 5. - Photomicrographs of AISI M-2 steels; 2 percent Nital etch.

TABLE III. - PROPERTIES OF TEST MATERIALS

Material	Heat treatment lot	Average hardness, R_c	Retained Austenite, volume percent	Austenitic grain size[a]
AISI 52100	A	62.5	4.90	13
	B	62.0	4.10	13
	C	62.5	.80	13
AISI M-50	A	62.6	1.90	10.3
	B	62.2	2.90	9
	C	62.3	1.50	10
AISI M-10	A	62.2	1.10	9
	B	62.0	2.40	6
	C	61.8	1.60	6
AISI M-1	A	63.3	2.90	10
	B	63.4	3.30	9
	C	63.5	1.00	8
AISI M-2	A	63.4	1.70	6
	B	63.4	2.40	10
	C	63.4	2.30	9

[a]ASTM E 112-63.

TABLE IV. - MATERIAL CLEANLINESS RATINGS

Material	Heat treatment lot	Cleanliness rating[a]	
		Class[b]	Type
AISI 52100	A	B1	Heavy
	B	D1	Thin
	C	D1	Thin
AISI M-50	A	B1	Heavy
	B	D2	Heavy
	C	D1	Heavy
AISI M-10	A	D3	Heavy
	B	D2	Heavy
	C	D1	Thin
AISI M-1	A	B2	Heavy
	B	A1	Heavy
	C	A2	Heavy
AISI M-2	A	B1	Heavy
	B	D1	Thin
	C	D1	Heavy

[a]ASTM E45-63, Method A (table shows predominate inclusion class and type).
[b]Inclusion classes: A, sulfides; B, alumina; C, silicates; D, globular oxides.

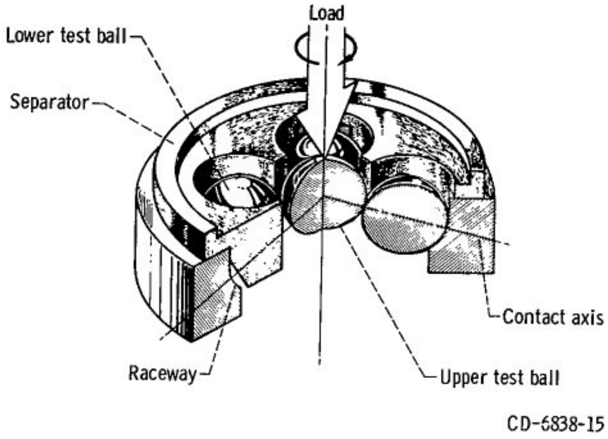


Figure 6. - Five-ball test assembly.

APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The five-ball fatigue tester was used for all tests conducted. The test assembly, shown in figure 6, consists of an upper-test ball pyramided on four lower-test 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-test ball received three stress cycles. The upper-test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and the lower-test balls function in a manner similar to the cage and the balls in a bearing. Lubrication is provided by a once-through, mist-type lubrication system.

Fatigue Testing

In each of these tests, all five balls 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-test ball failed, a lower-test ball failed, or when a cut-off time of 100 hours was reached.

Hardness Testing

The hardness of the materials was measured at both room and elevated temperatures using a standard hardness tester fitted with an electric furnace. Ball specimens from the same heats as those fatigue tested herein were selected at random for hardness testing. Two 1/4-inch (6.4-mm) 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 any overheating of the test specimens.

Hardness measurements were taken after reaching an equilibrium temperature before increasing the heat input for the next higher temperature. Approximately 1/2 hour elapsed before equilibrium was reached at each test temperature.

Method of Presenting Fatigue Results

The statistical methods of reference 11 for analyzing rolling-element fatigue data were used to obtain a log-log plot 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. 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 life on the Weibull plot was used. The 10-percent life is the number of upper-ball stress cycles at 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 system failures out of those tested. The five-ball system was considered failed when a fatigue spall occurred on either the upper or lower test balls. Analyses were also performed considering only upper-ball failures with lower-ball failures being considered as suspensions.

RESULTS AND DISCUSSION

Fatigue Results

Five steels (AISI 52100, M-1, M-2, M-10, and M-50) were tested in the five-ball fatigue tester. Groups of 1/2-inch- (12.7-mm-) diameter balls of each of these materials were tested at a maximum Hertz stress of 800 000 psi (5.52×10^9 N/m^2), a contact angle of 30°, and a shaft speed of 10 300 rpm. Tests were run at a race temperature of 150° F (340 K) with a super-refined naphthenic mineral oil as the lubricant.

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 heat treatment specification was used for each material.

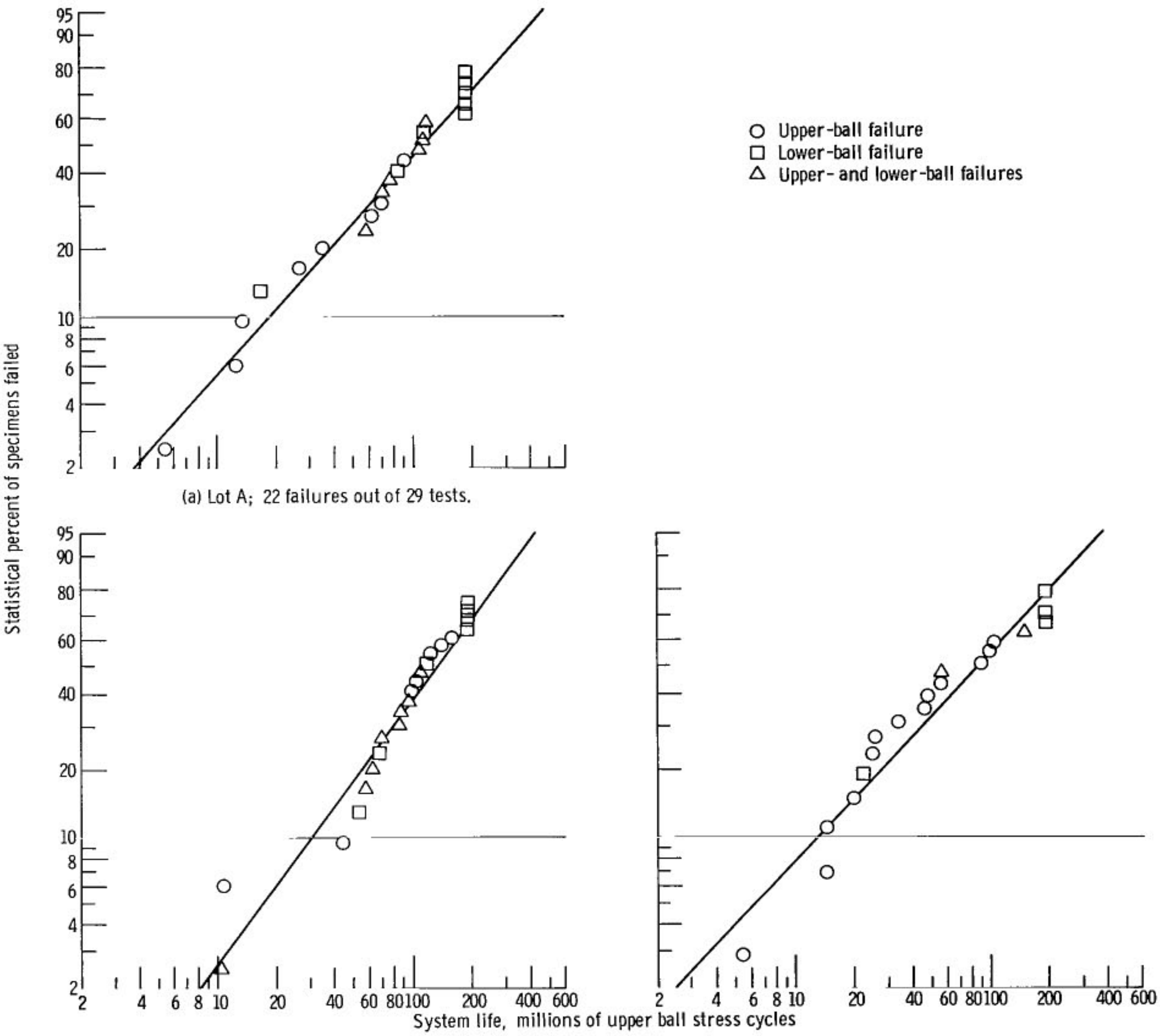
The results of the fatigue tests with each heat treatment lot of each material are shown in the Weibull plots of figures 7 to 11. Both upper- and lower-test ball fatigue failures were considered, in determining the five-ball system life in the Weibull analysis.

The 10-percent lives for each material lot are shown in table V. A 2 to 1 ratio in the 10-percent lives of two lots of the same material is observed with both AISI 52100 and AISI M-10. (It should be recalled that the only difference between lots of the same material is that they were heat treated separately.) These differences in fatigue lives cannot be attributed to the slight differences in the material properties shown in tables III and IV 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 differences in 10-percent fatigue lives between material lots may also be normal scatter in rolling-element fatigue data. The 2 to 1 ratio in fatigue lives among the lots of the same material is not unexpected based on previous experience.

Also tabulated in table V are the results of analyses considering upper-ball failures as failures and lower-ball failures as suspensions. Including lower-ball failures as failures seems to yield a consistently but slightly lower life of each group. No significant differences between the two analyses are indicated.

Material Comparison

The tests with all three heat treatment lots of each material were grouped together to compare the fatigue lives of the various materials. A Weibull analysis was performed on the combined results for each material. The results are shown in table VI. Ten-percent lives of the materials are shown in figure 12. A direct comparison shows that,



(a) Lot A; 22 failures out of 29 tests.

(b) Lot B; 22 failures out of 29 tests.

(c) Lot C; 19 failures out of 25 tests.

Figure 7. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI 52100 consumable-electrode vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F (340 K).

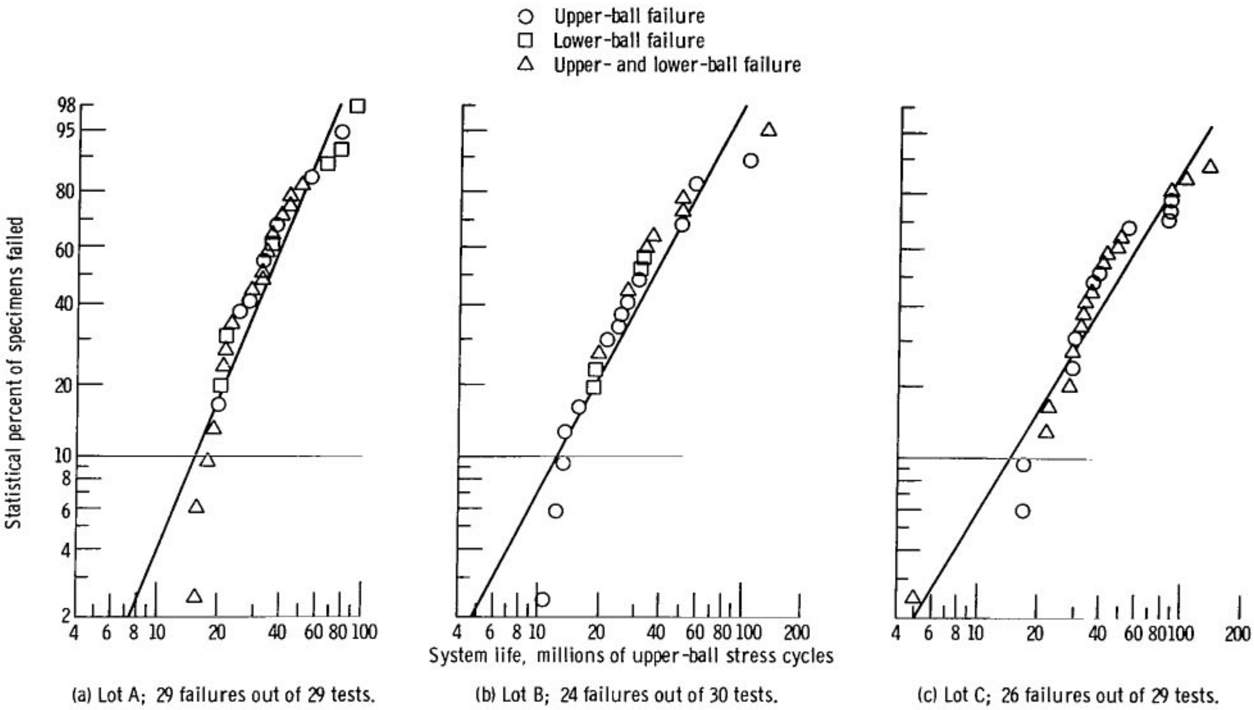


Figure 8. - Rolling-element fatigue life of 1/2-inch (12.7-mm-) diameter AISI M-50 consumable-electrode vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^{9} N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F (340 K).

at the 10-percent life level, the material with the longest fatigue life is AISI 52100. AISI M-50 gave the next highest 10-percent life, which was about 68 percent of that of AISI 52100. The shortest life material was AISI M-2, which gave a 10-percent life of about 27 percent of that of AISI 52100.

Because of the large number of failures (63 to 87) in the combined groups, life ratios of 3 or 4 to 1 can be significant. To determine the significance of these fatigue results, the confidence numbers shown in table VI were calculated by methods of reference 11. The AISI 52100 10-percent life is used as a reference. These confidence numbers indicate the percentage of the time that the 10-percent life obtained with a group of AISI 52100 balls will be greater than that of a group of balls of one of the other materials. The confidence numbers for AISI M-1 and M-2 exceed 99 percent. For AISI M-10 and M-50, the confidence numbers are 91 and 89 percent, respectively. These results indicate that the differences in fatigue lives between AISI 52100 and either AISI M-1 or M-2 are significant. The results for AISI M-10 and M-50 show less confidence in the fatigue life differences, but these differences appear to be significant.

AISI M-1 and M-2 contain somewhat higher percentages of alloying elements such as molybdenum, vanadium, chromium, and tungsten which give them better hot-hardness characteristics than the other materials. The higher percentages of alloys may also

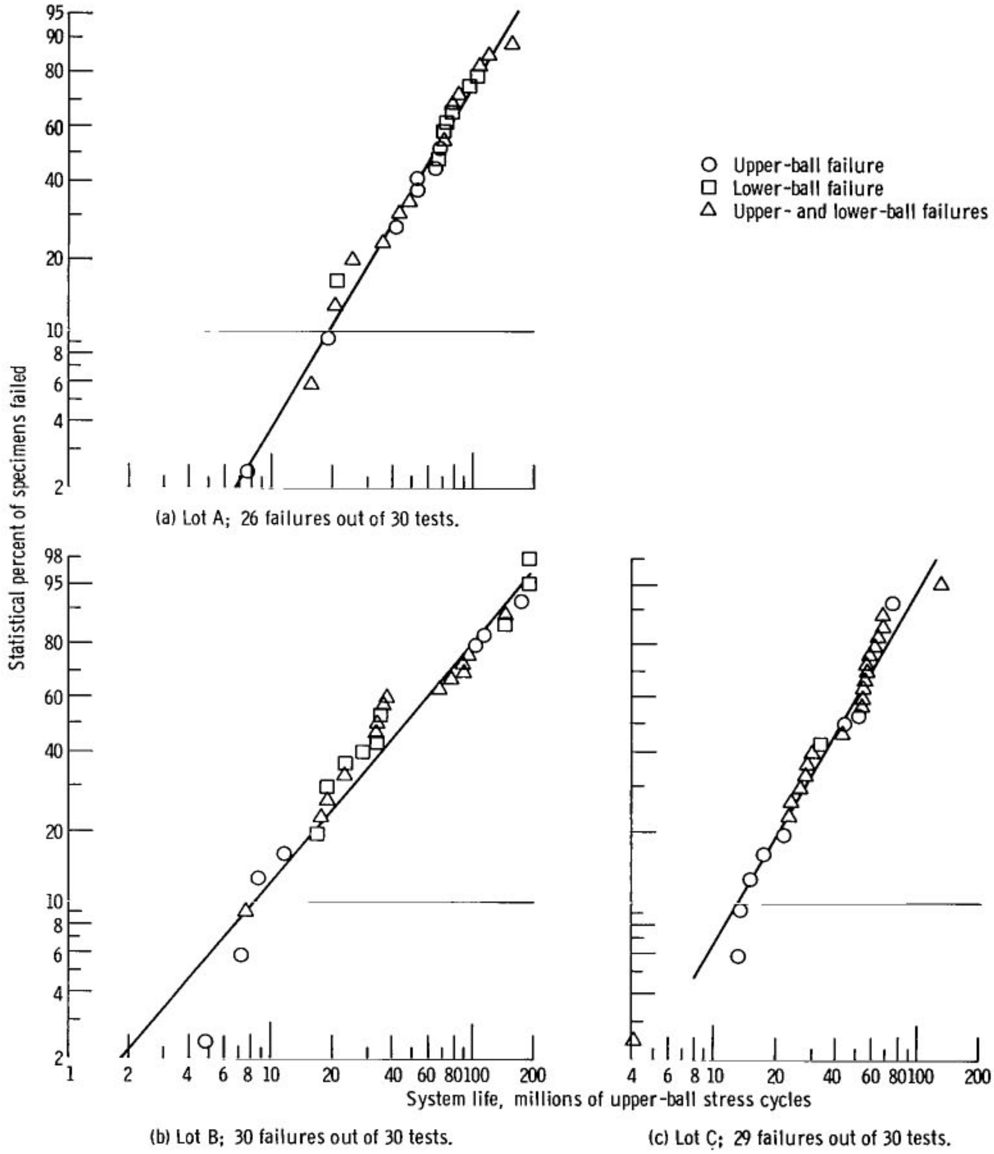
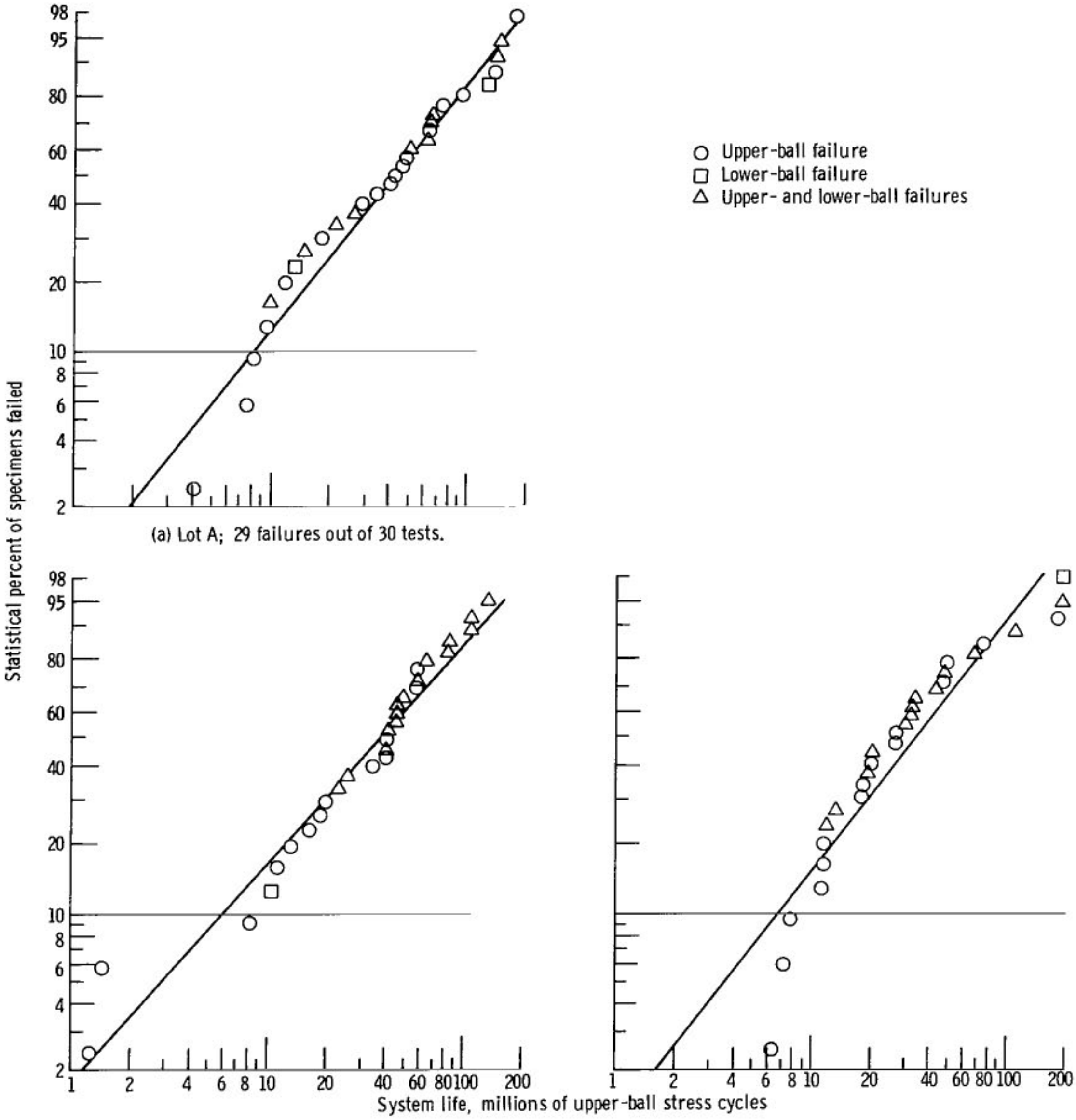


Figure 9. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI M-10 consumable-electrode vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^{9} N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F (340 K).

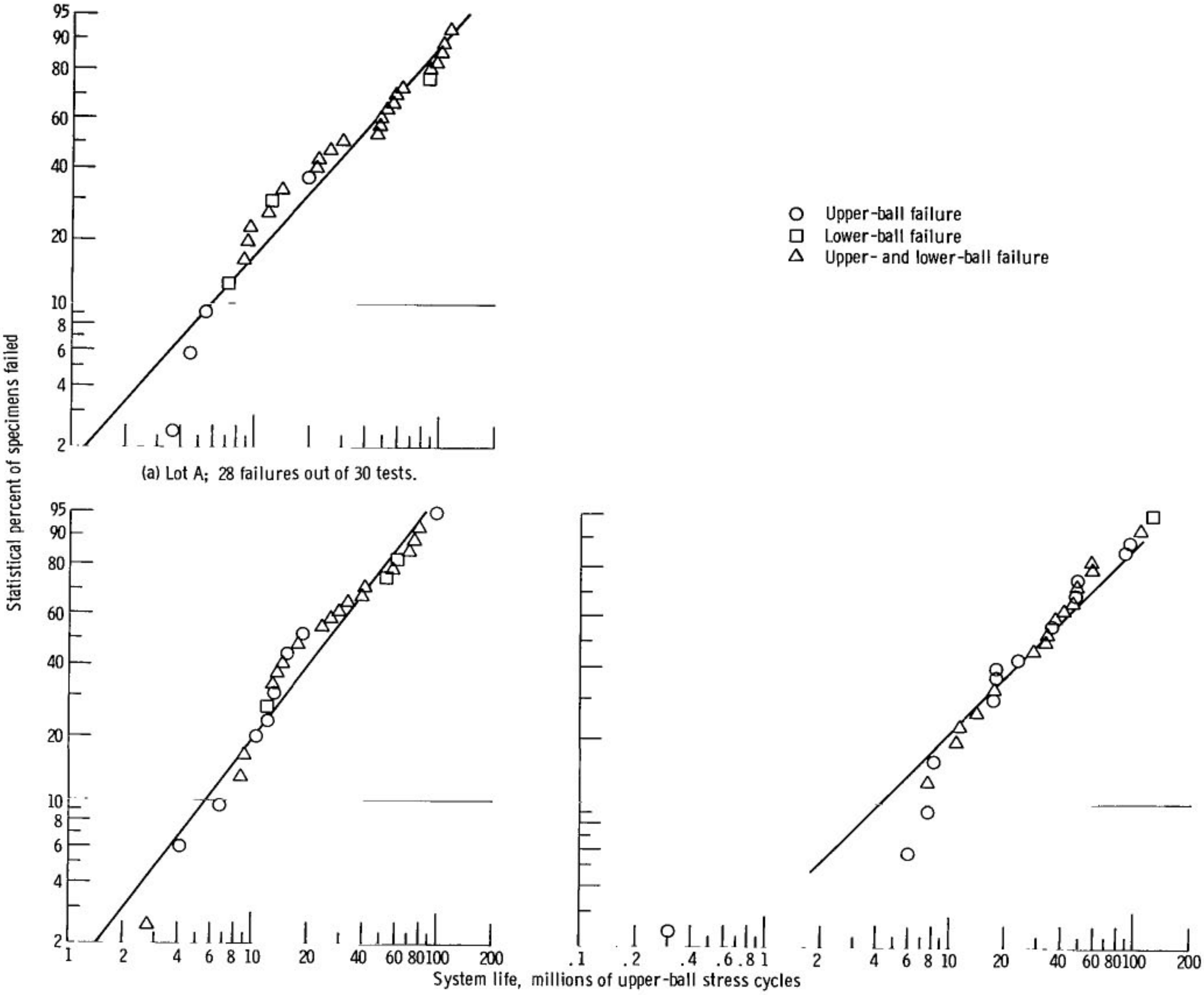


(a) Lot A; 29 failures out of 30 tests.

(b) Lot B; 29 failures out of 30 tests.

(c) Lot C; 29 failures out of 29 tests.

Figure 10. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI M-1 consumable-electrode vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); contact angle, 30°; shaft speed, 10 300 rpm; temperature, 150° F (340 K).



(a) Lot A; 28 failures out of 30 tests.

(b) Lot B; 28 failures out of 29 tests.

(c) Lot C; 29 failures out of 30 tests.

Figure 11. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI M-2 consumable-electrode vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^{9} N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F (340 K).

TABLE V. - FATIGUE RESULTS WITH GROUPS OF 1/2-INCH- (12.7-MM-) DIAMETER BALLS RUN IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); contact angle, 30°; shaft speed, 10 300 rpm; temperature, 150° F (340 K).]

Material	Heat treatment lot	Lower- and upper-ball failures				Upper-ball failures only			
		Life, millions of upper-ball stress cycles		Slope	Failure index[a]	Life, millions of upper-ball stress cycles		Slope	Failure index[a]
		L_{10}	L_{50}			L_{10}	L_{50}		
AISI 52100	A	18.5	114	1.04	22 out of 29	21.0	139	1.00	14 out of 29
	B	30.1	130	1.29	22 out of 29	31.5	161	1.15	15 out of 29
	C	12.9	84	1.00	19 out of 25	14.5	83	1.08	15 out of 25
AISI M-50	A	15.3	35	2.29	29 out of 29	17.0	36	2.54	23 out of 29
	B	12.3	36	1.73	24 out of 30	13.4	41	1.67	20 out of 30
	C	14.2	48	1.55	26 out of 29	14.2	48	1.55	26 out of 29
AISI M-10	A	19.4	65	1.56	26 out of 30	20.5	78	1.42	19 out of 30
	B	8.3	46	1.11	30 out of 30	9.9	61	1.04	21 out of 30
	C	13.1	42	1.62	29 out of 30	13.2	43	1.60	28 out of 30
AISI M-1	A	8.2	43	1.13	29 out of 30	8.8	46	1.14	27 out of 30
	B	5.9	37	1.02	29 out of 30	6.2	39	1.02	28 out of 30
	C	6.7	33	1.18	29 out of 29	6.9	33	1.21	28 out of 29
AISI M-2	A	5.8	35	1.05	28 out of 30	6.7	39	1.07	25 out of 30
	B	5.5	26	1.23	28 out of 29	5.7	27	1.21	25 out of 29
	C	4.2	31	.95	29 out of 30	4.2	32	.93	27 out of 30

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

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

Material	Lower- and upper-ball failures						Upper-ball failures only				
	Life, millions of upper-ball stress cycles		Relative L_{10} life	Slope	Failure index[a]	Confidence number,[b] percent	Life, millions of upper-ball stress cycles		Slope	Failure index[a]	Confidence number,[b] percent
	L_{10}	L_{50}					L_{10}	L_{50}			
AISI 52100	21.2	109	1.0	1.15	63 out of 83	---	23.2	122	1.14	44 out of 83	---
AISI M-50	14.4	39	0.68	1.89	79 out of 88	89	15.3	42	1.88	69 out of 88	85
AISI M-10	13.2	50	0.62	1.40	85 out of 90	91	14.4	57	1.36	68 out of 90	87
AISI M-2	5.7	30	0.27	1.13	85 out of 89	>99	6.0	32	1.12	77 out of 89	>99
AISI M-1	7.6	38	0.36	1.18	87 out of 89	>99	8.0	39	1.18	83 out of 89	>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.

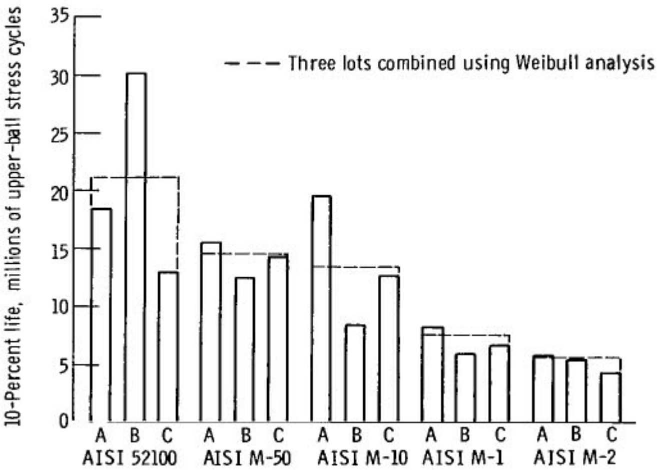


Figure 12. - Comparison of 10-percent fatigue lives of five bearing steels at 150° F (340 K).

affect the materials' resistance to rolling-element fatigue.

The analyses considering lower-ball failures as suspensions (table VI) show similar results to those previously discussed.

The fatigue spalls on the balls of all five materials were similar in appearance. Examination of the spalls revealed that they were subsurface in origin.

Hardness at Elevated Temperature

The measured hardness at elevated temperatures of each of the materials investigated herein is shown in figure 13. Hardness, as expected, decreases with increasing temperature. A commonly accepted minimum hardness at operating temperature for 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.

AISI 52100 has been considered useful to temperatures of about 350° F (450 K).

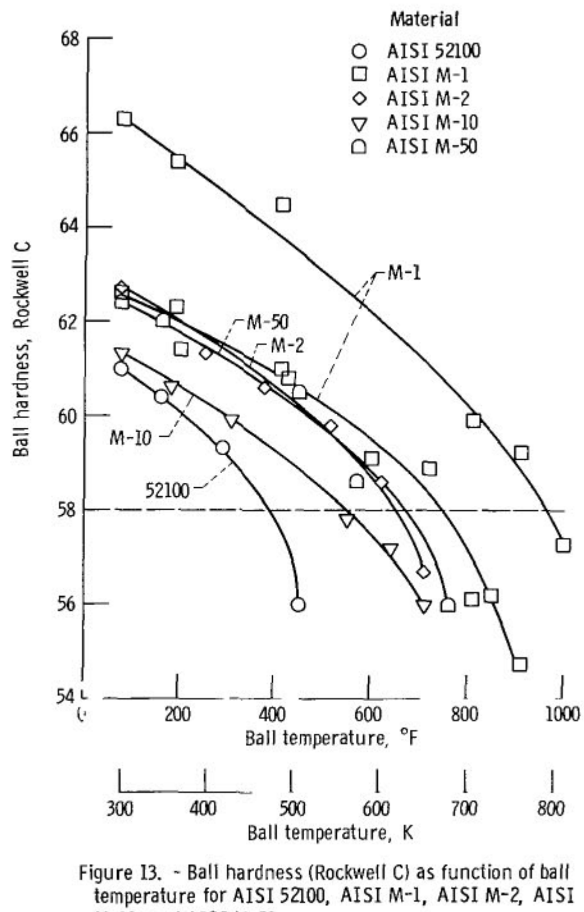


Figure 13. - Ball hardness (Rockwell C) as function of ball temperature for AISI 52100, AISI M-1, AISI M-2, AISI M-10, and AISI M-50.

However, the data presented in figure 13 would suggest that AISI 52100 steel can be functional at temperatures to nearly 400° F (478 K). However, from table II the tempering temperature was 350° F (450 K). Were the temperature to remain at 400° F (478 K) for any appreciable length of time beyond that which it took to perform the hardness measurements, a further decrease in the material hardness would be expected.

In order to obtain these hardness data, two parallel flats were ground on each ball specimen to be measured. For the initial hardness measurements presented in table III for the AISI 52100 steel, an average Rockwell C hardness of 62.3 was reported. These measurements were taken on 1/8-inch (3.2-mm) flats. However, for all hardness measurements reported in figure 13 the flats were increased in diameter to 1/4 inch (6.4 mm).

Even though the grinding of the flats was done at a very slow feed rate with a copious supply of coolant, a certain amount of tempering of the AISI 52100 steel apparently occurred. As a result, the room temperature hardness of the steel had dropped to a Rockwell C hardness of 61. It is speculated, however, that the curve for the AISI 52100 steel can be shifted up 1 point Rockwell C for comparison purposes.

However, as the tempering temperature is approached, this upward shift may not be valid. For the M-series materials, where the tempering temperatures exceed 1000° F (811 K) (table II), such a shift may have more validity.

In order to verify this, ball specimens of two hardness levels of AISI M-1 steel from the same heat of material as the balls fatigue tested were checked for hardness as a function of temperature. These data are shown in figure 13. For the AISI M-1 steel, the higher hardness specimen had a room temperature Rockwell C hardness of approximately 66; where the lower hardness specimen had a hardness of approximately 63. A constant difference of 3 to 4 points Rockwell C separates the two curves throughout the range of temperature investigated.

The room temperature hardnesses for AISI M-10, M-1, and M-2 shown in figure 13 indicate that there was some tempering due to grinding of less than 1 point Rockwell C. The tempering temperature for these materials were all greater than 1000° F (811 K). The data for the AISI M-50 shown in figure 13 shows no tempering due to grinding.

In reference 3 the maximum operating temperatures for AISI M-50 were reported to be approximately 600° F (589 K); for AISI M-10, 800° F (700 K); and AISI M-1 and M-2, 900° F (755 K). In order to compare the hardness retention capabilities of these materials on the basis of the present hardness data, the various curves for the M-series steels were adjusted to the same room temperature hardness, that being 62.5. These curves are presented in figure 14. From these data and those in figure 13 it can be seen that the M-50 material maintains a hardness of Rockwell C 58 to temperatures in excess of 650° F (615 K). The AISI M-1 steel has a potential to approximately 750° F (672 K) where the material hardness drops below 58. The AISI M-2 steel has approximately the

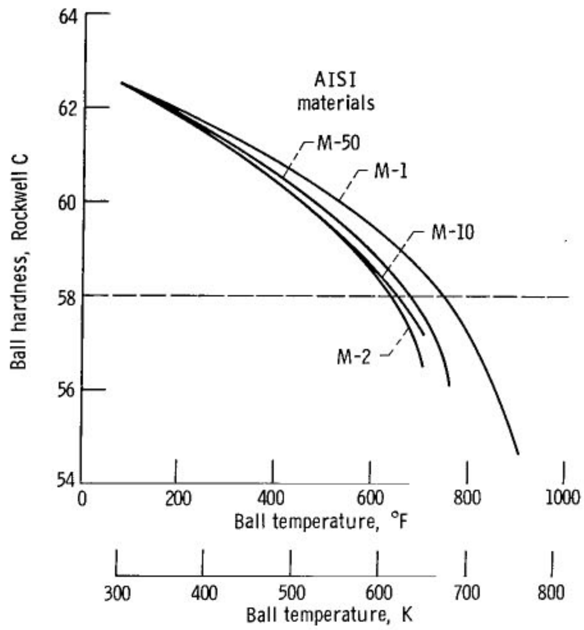


Figure 14. - Hardness adjusted to common room temperature value for AISI M-1, M-2, M-10, and M-50.

same hot hardness curve as the AISI M-10 where at a temperature of approximately 650° F (615 K) its hardness drops below 58.

These data indicate that, contrary to previously published work on the M-series steels, there appear to be no significant differences among three of these material (AISI M-50, M-10, and M-2) in their ability to maintain hardness at elevated temperature. On the other hand the AISI M-1 material indicates an approximately 100° F (56 K) higher temperature potential than these three materials.

GENERAL COMMENTS

The data presented in the previous section clearly shows the superiority of AISI 52100 over the other materials at the same hardness in rolling-element fatigue resistance. These data are at moderate temperatures, approximately 150° F (340 K). The choice of an "M" series steel offers no advantage over AISI 52100 on the basis of fatigue life assuming that the hardness of AISI 52100 is approximately the same as the "M" series steel at operating temperature. At about 350° F (450 K), the hardness of AISI 52100 drops below the accepted minimum hardness for rolling-element bearings, Rockwell C 58. The "M" series alloys retain acceptable hardness to higher temperatures. In general, as hardness of the components in a rolling-element bearing decreases, fatigue life decreases (refs. 6, 12, and 13). It is apparent then, that as bearing temperatures approach 350° F (450 K) the choice of an alloy steel such as AISI M-50 is advantageous. As a practical matter the maximum obtainable hardness with AISI M-50 is approximately Rockwell C 63. With AISI M-1 steel, the maximum obtainable hardness is in the range of 65 to 66 Rockwell C. As a result, for temperatures above 700° F (644 K) it may be necessary to specify AISI M-1.

SUMMARY OF RESULTS

Rolling-element fatigue studies were performed with five consumable-electrode vacuum-melt steels. Groups of 1/2-inch- (12.7-mm-) diameter balls of each material were run in five-ball fatigue testers at a maximum Hertz stress of 800 000 psi (5.52×10^{9} N/m^2), a contact angle of 30°, and a shaft speed of 10 300 rpm. The tests were run at a temperature of 150° F (340 K) with a super-refined naphthenic mineral oil lubricant. Care was taken to maintain constant all variables that are known to affect rolling-element fatigue life. The following results were obtained:

1. The longest fatigue lives were obtained with AISI 52100. The 10-percent lives of the other four materials ranged from 27 to 68 percent of that of AISI 52100.
2. The fatigue lives of the AISI M-1 and M-2 materials were significantly less than the fatigue life of AISI 52100. At the 10-percent level, the confidence that the group of AISI 52100 balls is better in rolling-element fatigue resistance than the AISI M-1 or M-2 balls is greater than 99 percent.
3. The fatigue lives of AISI M-50 and M-10 were similar. The confidence that AISI 52100 is better in rolling-element fatigue than these two materials is approximately 90 percent.
4. Lives of different heat treatment lots of the same material differed by factors as great as two.
5. The fatigue failures on the test balls of all five materials were similar and were subsurface in origin.
6. Contrary to previously published work, there appears to be no significant difference among the ability of AISI M-50, M-10, and M-2 to maintain hardness at elevated temperatures. AISI M-1 indicates a higher temperature potential than these three materials of about 100° F (56 K).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 3, 1970,
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