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A NEW CRITERION FOR PREDICTING ROLLING-ELEMENT FATIGUE LIVES OF THROUGH-HARDENED STEELS

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A NEW CRITERION FOR PREDICTING ROLLING-ELEMENT FATIGUE LIVES OF THROUGH-HARDENED STEELS

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ABSTRACT

A carbide factor was derived based upon a statistical analysis which related rolling-element fatigue life to the total number of residual carbide particles per unit area, median residual carbide size, and percent residual carbide area. An equation was experimentally determined which predicts material hardness as a function of temperature. The limiting temperatures of all of the materials studied were dependent on initial room temperature hardness and tempering temperature. An equation was derived combining the effects of material hardness, carbide factor, and bearing temperature to predict rolling-element bearing life.

INTRODUCTION

Heat treatment can significantly influence several rolling-element bearing material properties. Most bearing procurement specifications do not designate heat treatment but rather call for certain material characteristics such as grain size and hardness, which are controlled by the heat treat cycle. Hardness is the most influential heat treat induced variable in rolling-element fatigue. [1-3]. A relationship has been proposed in [4] which approximates the effect of bearing material hardness on fatigue life.

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$$L_2/L_1 = e^{m(R_{c2}-R_{c1})} \tag{1}$$

where L_1 and L_2 are the bearing ten-percent life at bearing hardnesses of R_{c1} and R_{c2}, respectively, and m is a material constant. It is assumed for the purpose of this relationship which was obtained for AISI 52100 that all components in the rolling-element bearings, that is rolling-elements and the races, are of the same hardness. It was further assumed that this equation can be extended to high-speed tool steels. In [5] a nomograph was constructed which was based on this equation and the basic assumption that the material hardness for the various bearing steels varied similarly with temperature. This assumption may or may not be correct.

While the studies of [1] indicated that in general as hardness increased life increased, for a given hardness, materials having different chemical compositions would give significant differences in life. There have been considerable number of studies performed to determine the fatigue lives of various bearing materials [1, 2, 6-8]. However, none of these studies maintained the close control on operating and processing variables such as material hardness, melting technique, and lubricant type and batch required for unbiased material evaluation.

A research program that was specifically performed for the purpose of comparing the rolling-element fatigue lives of several through hardened bearing steels under identical conditions was reported [9-11]. A trend was reported that indicated a decrease in rolling-element fatigue life with increased total weight percent alloying elements. There was a strong indication that there was interrelation between the affect of alloying elements such as molybdenum, chromium, vanadium, tungsten, and cobalt and the size and distribution of the metal carbides, which vary with alloy content and heat treatment.

The objective of the research described in this paper was to determine a criterion for the selection of rolling-element bearing materials based upon a material hardness and carbide factor which can be determined nondestructively and/or specified through heat treat procedure. The results reported herein have been based upon data which was initially reported in [12, 13].

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 [9, 10]. The resulting hardness, retained austenite, grain size, and cleanliness are shown in table II for each heat treatment lot of each material.

For the hardness tests the materials used in this investigation were consumable vacuum-melted AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49. These materials were from different ingots from those materials used in the fatigue tests. However, for the hardness tests, all specimens for each material with the exception of AISI M-50 were made from one vacuum-melted ingot. Two different vacuum-melted ingots of M-50 material were used. The specimens were heat treated according to the heat treat schedules contained in table III. Room temperature hardness, retained austenite, and grain size are also presented in this table.

PROCEDURE

Fatigue tests - The five-ball fatigue tester was used for all tests conducted. 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 [14] for analyzing rolling-element fatigue data were used for evaluating the test data. The results of these tests are tabulated in table II.

Hardness tests - 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 parallel flats were ground on each specimen. 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.

Carbide measurements - From each material lot of 25 to 30 tests, one ball was chosen at random. These balls were then mounted, metallographically polished, and etched. They were then examined on the Quantimet Image Analyzing Computer (QTM) for the total number of residual carbides in a unit area, residual carbide size, and percent residual carbide area in a unit area.

Five areas were examined on each sample. Four were near the surface and 90° apart. The fifth was in the center of the sample. The values of the five readings were then averaged to obtain what was considered the value of the variables for the sample in question. To obtain the value of the variables for the different materials, the fifteen readings for the three samples of each material were averaged to obtain what was considered the average value of the variables for the material in question. To be consistent with the terminology used in describing the L_{10} life, these average material values will be referred to as the combined values.

RESULTS AND DISCUSSION

Hardness tests - Hot hardness measurements were made for groups of specimens of AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49. The results of these measurements are shown in figures 1 and 2. These normalized data show that regardless of the initial hardness, the hot hardness of the individual materials show the same functional dependence. That is, the changes in hardness with increasing temperature of AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49 are all independent of initial hardness. These plots also illustrate that the changes in hardness of these materials are independent of material composition.

The data of figure 2 when plotted on log-log coordinates can be represented by a straight line having the form

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^{\beta} \tag{2}$$

where

$(Rc)_T$	Rockwell C hardness at operating temperature
$(Rc)_{RT}$	Rockwell C hardness at room temperature
ΔT	change in temperature, $T_T - T_{RT}$
T_T	operating temperature, ^oF
T_{RT}	room temperature, ^oF
α	temperature proportionality factor, $(^oR)^{-\beta}$
β	exponent

For AISI 52100 between 70^o and 500^o F

$$(Rc)_T = (Rc)_{RT} - 3.4\times10^{-4}\ \Delta T^{1.6} \tag{3}$$

For the other materials studied between 70^o and 1000^o F,

$$(Rc)_T = (Rc)_{RT} - 5.4\times10^{-4}\ \Delta T^{1.4} \tag{4}$$

The general nature of the equation can be understood from the tempering characteristics of high-speed steels and AISI 52100. These materials are precipitation hardening alloys [15]. As the temperature of the material is raised, it begins to overage and soften. When the operating temperature nears the tempering temperature, this process is accelerated and the hardness decreases more rapidly. As the test temperature is raised beyond the tempering temperature, the precipitation hardening precipitate particles increase in size and decrease in number and the material begins to spheroidize [15, 16]. At this point, the greatest decrease in hardness occurs and the hardness of the material tends to decrease toward the fully annealed condition.

The difference in hot hardness capability between the AISI 52100 and the high-speed steels can be explained by the difference in the precipitation hardening phase. In AISI 52100, the precipitate is an iron carbide ($Fe_{2.4}C$) called epsilon carbide, whereas in the high-speed steels the precipitates are VC, W_2C, and/or Mo_2C [5]. This, it would be expected that all materials which obtain their hot hardness from the precipitation of W_2C or Mo_2C would have similar hot hardness characteristics as the high-speed steels show to 812 K (1000° F). Similarly, those materials which obtain their hot hardness from the precipitation of epsilon carbide would be expected to have the same hot hardness characteristics as AISI 52100 up to 450 K (350° F). Materials having different hardening mechanisms would, of course, be expected to have different curves.

In this study, the materials tested were exposed to elevated temperatures only long enough (30 min) to make hardness measurements after having reached a predetermined equilibrium temperature (approximately 30 min). The effects of exposure to elevated temperatures for longer periods of time were not studied as a part of the research reported herein. However, time at temperature is just as important a factor as temperature itself with regard to hot-hardness characteristics. In fact, in heat treating practice, these two factors are considered interchangeable. That is, if the heat treating temperature is reduced, an identical structure can be obtained by increasing the exposure time at the lower temperature. High speed steels tested up to 1100° F showed no change in room temperature hardness. However, if the material were taken up to 1200° F, a hardness change was observed.

Carbide effects - From the data of [9-11] it was speculated that an interrelation existed among median residual carbide size, number of residual carbide particles per unit area and the percent area of residual carbides and rolling-element fatigue life. Residual carbides are those carbides that do not go completely into solution during austenitizing and are a function of the alloying elements and heat treatment. This is opposed to the hardening carbide precipitates, which precipitate upon aging at the tempering temperature. The carbides referred to in the rest of the paper will be the residual carbides.

If the carbides in a material are the nucleation site of an incipient fatigue failure, then the probability of survival S for a lot or specimens or a single specimen is a function of the product of the probabilities of survival due to the median carbide size, S_α, the number of carbide particles per unit area, S_μ, and the percent area of carbides, S_ν. This relationship can be expressed as

$$S = S_\alpha \cdot S_\mu \cdot S_\nu \tag{5}$$

All of the alloying elements mentioned above are carbide formers, with the exception of cobalt. The exact effect cobalt may have upon rolling-element fatigue is not clear. It has been suggested that cobalt may decrease the fracture toughness of the material [15]. In addition, a Russian paper [17] suggested that the nonuniformity of the material increased due to the presence of cobalt. The exact meaning of nonuniformity was not clear. From the text it appeared that nonuniformity referred to the carbide distribution through the material and/or the size distribution of the carbides in the material. If the fracture toughness was decreased, the carbides segregated, or the size distribution shifted toward the large end, the fatigue life would be reduced. The probability of survival being a function of the amount of cobalt in the structure can be represented by S_{Co}. Equation (1) would then be modified as follows:

$$S = S_{\alpha} \cdot S_{\mu} \cdot S_{\nu} \cdot S_{Co} \tag{6}$$

If there are two specimens or lots, whereby each of the probabilities discussed above are different, then:

$$\begin{aligned} S_2 &= S_{\alpha_2} \cdot S_{\mu_2} \cdot S_{\nu_2} \cdot S_{Co_2} \\ S_3 &= S_{\alpha_3} \cdot S_{\mu_3} \cdot S_{\nu_3} \cdot S_{Co_3} \end{aligned} \tag{7}$$

where the designations 2 and 3 are used in order to relate the following equations to equation (1). Assume that M is the ratio of the median carbide size of lots 2 and 3, N is the ratio of the number of carbide particles per unit area of lots 2 and 3, A is the ratio of the percent area of carbides in lots 2 and 3, and $(Co)_2$, and $(Co)_3$ are the weight percent cobalt in lots 2 and 3, respectively. Let:

$$N = n_3/n_2$$

$$M = m_3/m_2$$

$$A = a_3/a_2$$

where

a percent area of carbides

m the median carbide size (length)

n the total number of carbides per unit area

The probability of survival for each of the factors in lot 3 can be expressed in terms of the probability of survival for each of the factors in lot 2. Considering carbide size only, it is reasonable to assume that as the carbide size m decreased, the probability of survival increases. If the percent area of carbides remains constant but the carbide size decreases, then the total number of carbides per unit area increases. Therefore, the probability of survival would be directly proportional to the ratio of the number of carbides per unit area. The factor which remains is the percent area of carbides. If carbides are a critical factor then it is reasonable to assume that the probability of survival decreases as the percent area of carbide increases. All of the above factors, of course, are related. As for the cobalt, all that is known is that as percent weight cobalt increases life decreases. The aforementioned can be expressed statistically as follows

$$S_{\alpha_3} = S_{\alpha_2}^{M} = S_2^{K_1 M}$$

$$S_{\mu_3} = S_{\mu_2}^{1/N} = S_2^{K_2/N} \tag{8}$$

$$S_{\nu_3} = S_{\nu_2}^{A} = S_2^{K_3 A}$$

$$S_{Co_3} = S_{Co_2}^{Co} = S_2^{K_4 Co}$$

where K_1, K_2, K_3, and K_4 are constants. From equations (7) and (8) S_2 can be expressed in terms of S_2 as follows:

$$S_3 = S_2^{K_1 M} \cdot S_2^{K_2/N} \cdot S_2^{K_3 A} \cdot S_2^{K_4 Co} = S_2^{(K_1 M + K_2/N + K_3 A + K_4 Co)} \tag{9}$$

By using Weibull analysis [18]:

$$(1 - P) = \exp - \left(\frac{L - u}{\beta}\right)^e \tag{10}$$

where

P	probability of failure
e	Weibull slope which can be taken as being approximately one for rolling-element fatigue
β	characteristic life at which there is a 38 percent probability of survival where $e \approx 1$
L	life
u	location parameter which can be taken as being zero in rolling-element fatigue
$S = 1 - P$	probability of survival

Equation (8) can be rewritten as follows:

$$S = \exp - (L/\beta) \tag{11}$$

or

$$\ln S = -(L/\beta)$$

In figure 3, there is shown a Weibull plot of two hypothetical groups of specimens denoted as groups 2 and 3, respectively, from equation (11).

$$\ln S_3 = -\left(\frac{L_2}{\beta_3}\right) \tag{12a}$$

and

$$\ln S_2 = -\left(\frac{L_3}{\beta_3}\right) \tag{12b}$$

If equation (12b) is divided by equation (12a) then

$$\frac{L_3}{L_2} = \frac{\ln S_2}{\ln S_3} \tag{13}$$

Since $S_3 = S_2^{(K_1M+K_2/N+K_3A+K_4Co)}$ from equation (9) then

$$\frac{L_3}{L_2} = \frac{\ln S_2}{(K_1M + K_2/N + K_3A + K_4Co)\ln S_2} \tag{14}$$

Let C' be the carbide factor where

$$C' = \frac{1}{(K_1M + K_2/N + K_3A + K_4Co)} \tag{15}$$

Therefore,

$$C' = \frac{L_3}{L_2} \tag{16}$$

In [9-11] AISI 52100 is the material which produced the highest life values. Therefore, let the values for the carbide factor C be normalized with respect to the average values of the AISI 52100 material shown in table II. That is let;

$$C' = \frac{1}{\frac{K_1m_3}{0.26} + \frac{718K_2}{n_3} + \frac{K_3a_3}{9.54} + K_4Co} \tag{17}$$

Assume that

$$K_1 = K_2 = K_3 \tag{18}$$

Equation (17) can be rewritten as

$$C' = \frac{1}{K_1\left(\frac{m}{0.26} + \frac{718}{n} + \frac{a}{9.54} + \frac{K_4}{K_1} Co\right)} \tag{19}$$

where the subscript 3 has been dropped. From the data of table 4, K_1 and K_4 can be empirically determined. They were found to be 1/3 and 4/3 for K_1 and K_4, respectively.

In figure 4 the relative material L_{10} lives are plotted against the carbide factor C. (The L_{10} life is that time at which there is a 90 percent probability of survival for a bearing or group of bearings.) There appears to be a reasonable correlation between the carbide factor C and relative life. The correlation coefficient [19] was calculated for the data of figure 4. For the individual groups of data and the combined groups the confidence number was found to be 0.87 and 0.83, respectively. This means that the carbide factor C can give a reasonable prediction of relative life under identical conditions of material hardness and lubrication mode. Thus, the carbide parameter seems to transcend such variables as heat treatment, chemical composition, and hardening mechanism to predict the lives of individual lots. The carbide parameter may also be applicable to conventional fatigue (i.e., bending, rotating-bending, etc.). However, application of the carbide parameter should be confined to either high-speed tool steels or AISI 52100 (L series tool steels).

Combined effects - There appears to be two distinct criteria in the selection of a through-hardened rolling-element material. First, rolling-element fatigue life is a function of material hardness. Second, life is a function of carbide size, area and number as represented by the carbide factor. These two criteria can be combined to both determine and evaluate without extensive testing the fatigue life of a bearing material or groups of materials. From equation (1), let L_1 be the bearing life calculated according to [20]. Hence

$$L_1 = \left(\frac{C}{P}\right)^n \tag{20}$$

where C is the basic load rating of the bearing and P is the equivalent load [20]. Assume, based upon experience, that the basic load rating is based upon a material hardness of Rockwell C 60. As a result, equation (1) can be written

$$L_2 = e^{m[(Rc)_{RT}-60]}\left(\frac{C}{P}\right)^n \tag{21}$$

Combining equations (2) and (21) where $T_{RT} = 70^{\circ}$ F,

$$L_2 = e^{m\{[(Rc)_{RT}-60]-\alpha(T_T-70)^{\beta}\}}\left(\frac{C}{P}\right)^n \tag{22}$$

From equation (16),

$$L_3 = C'L_2 \tag{23}$$

Combining equations (22) and (23) and letting $L_A = L_3$ where L_A is the expected bearing life at a 90 percent probability of survival

$$L_A = C'e^{m\{[(Rc)_{RT}-60]-\alpha(T_T-70)^{\beta}\}}\left(\frac{C}{P}\right)^n \tag{24}$$

Finally,

$$L_A = kC'e^{m\{[(Rc)_{RT}-60]-\alpha(T_T-70)^{\beta}\}}\left(\frac{C}{P}\right)^n \tag{25}$$

where k is a factor which combines processing and environmental factors which can affect bearing life [5]. For AISI 52100 steel $m = 0.1$ [4]. Values of m for other bearing materials have not been experimentally determined. However, they can reasonably be assumed to also equal 0.1. Values for α and β can be obtained from the section entitled - "Hardness tests." For ball and roller bearings n is equal to 3 and 10/3, respectively.

SUMMARY

Research was conducted to determine the effect of carbide size, area, and number on bearing fatigue life with eight consumable-electrode vacuum-melted steels, which were fatigue tested in the five-ball fatigue tester at 150° F. Hardness measurements were conducted on five of the eight materials to temperatures of 1000° F. The following results were obtained:

1. A carbide factor was derived based upon a statistical analysis which related rolling-element fatigue life to the total number of residual carbide particles per unit area, median residual carbide size, and percent residual carbide area.

2. An equation was experimentally determined which predicts material hardness as a function of temperature. The limiting temperatures of the materials studied were dependent on initial room temperature hardness and tempering temperature.

3. An equation was derived combining the effects of material hardness, carbide factor, and bearing temperature to predict rolling-element bearing life.

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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	1.06	.32	.74	.008	.004	6.82	4.22	1.86	3.76	5.29	.08	----

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

Material	Heat treatment lot	Average hardness, R_c	Retained austenite, volume percent[a]	Austenitic grain size[b]	Cleanliness rating[c]		Life, millions of upper ball stress cycles		Slope	Failure index[e]	Carbide factor C'
					Class[d]	Type	B_{10}	B_{50}			
52100	A	62.5	4.90	13	B1	Heavy	18.5	114	1.04	22 out of 29	1.22
	B	62.0	4.10	13	D1	Thin	30.1	130	1.29	22 out of 29	1.17
	C	62.5	.80	13	D1	Thin	12.9	84	1.00	19 out of 25	.76
	Combined	----	----	--	--	-----	21.2	109	1.15	63 out of 83	1.00
Halmo	A	60.8	0.60	8	D2	Heavy	22.0	74	1.56	25 out of 30	0.58
	B	60.8	1.00	8	D1	Heavy	12.9	57	1.26	28 out of 30	.64
	C	61.1	1.70	8	D2	Heavy	12.9	68	1.14	26 out of 30	.69
	Combined	----	----	--	--	-----	16.4	66	1.35	79 out of 90	.63
M-50	A	62.6	1.90	10	B1	Heavy	15.3	35	2.29	29 out of 29	0.60
	B	62.2	2.90	9	D2	Heavy	12.3	36	1.73	24 out of 30	.54
	C	62.3	1.50	10	D1	Heavy	14.2	48	1.55	26 out of 29	.50
	Combined	----	----	--	--	-----	14.4	39	1.89	79 out of 88	.56
M-10	A	62.2	1.10	9	D3	Heavy	19.4	65	1.56	26 out of 30	0.36
	B	62.0	2.40	6	D2	Heavy	8.3	46	1.11	30 out of 30	.39
	C	61.8	1.60	6	D1	Thin	13.1	42	1.62	29 out of 30	.35
	Combined	----	----	--	--	-----	13.2	50	1.40	85 out of 90	.37
T-1	A	61.4	7.30	11	B1	Heavy	6.6	50	0.92	26 out of 30	0.26
	B	61.4	5.20	9	D1	Thin	8.4	59	.97	26 out of 30	.33
	C	61.0	9.50	10	D1	Heavy	8.5	74	.87	23 out of 30	.30
	Combined	----	----	--	--	-----	8.6	59	.98	75 out of 90	.29
M-1	A	63.3	2.90	10	B2	Heavy	8.2	43	1.13	29 out of 30	0.32
	B	63.4	3.30	9	A1	Heavy	5.9	37	1.02	29 out of 30	.34
	C	63.5	1.00	8	A2	Heavy	6.7	33	1.18	29 out of 29	.38
	Combined	----	----	--	--	-----	7.6	38	1.18	87 out of 89	.33
M-2	A	63.4	1.70	6	B1	Heavy	5.8	35	1.05	28 out of 30	0.36
	B	63.4	2.40	10	D1	Thin	5.5	26	1.23	28 out of 29	.36
	C	63.4	2.30	9	D1	Heavy	4.2	31	.95	29 out of 30	.35
	Combined	----	----	--	--	-----	5.7	30	1.13	85 out of 89	.36
M-42	A	61.8	1.00	9	A1	Thin	1.0	6.6	0.97	30 out of 30	0.07
	B	61.3	4.40	10	D1	Heavy	1.7	8.9	1.12	27 out of 30	.07
	C	61.3	4.90	8	D1	Heavy	1.4	5.8	1.33	30 out of 30	.07
	Combined	----	----	--	--	-----	1.4	7.0	1.18	87 out of 90	.07

[a]Determined from the integrated peak intensities of $(220)\gamma$ and $(200)\alpha$ planes.
[b]ASTM E 112-63.
[c]ASTM E45 63, Method A (table shows predominate inclusion class and type).
[d]Inclusion classes: A-Sulfides, B-Alumina, C-Silicates, D-Globular oxides.
[e]Indicates number of failures out of total number of tests.

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TABLE III. - TEST MATERIAL PROPERTIES AND HEAT TREATMENT FOR TEMPERATURE-HARDNESS TESTS

Material	Room temperature hardness, Rockwell C	Retained austenite, percent by volume[a]	Austenitic grain size, ASTM	Heat treatment, ^{o}F						
				Preheat	Austenitize	Quench	First temper	Subzero cooling	Second temper	Third temper
AISI					(30 min)	Oil:	(60 min)		(60 min)	
52100	59.7	<2	12		1500 to	125	250		450	
	62.3	12.8			1600				350	
	63.4	15.6							320	
	64.6	18.4							250	
	65.1	11.8							None	
AISI				Salt:		Oil:	(120 min)		(120 min)	
M-1	62	2.8	8-	1450,	2200	120	1100		1100	
	62.4	3.2					1050		1050	
	64	7.2					1000		1000	
AISI				Salt:		Oil:	(120 min)		(120 min)	(40 min)
M-50	58.9	1.8	8-	1450,	2050	120	1100		1100	None
(Group A)	59.2	2.2					1050		1050	None
	61.8	----					1000		1000	1025
AISI				Salt:		Salt:	(120 min)	(90 to 120 min)	(120 min)	(120 min)
M-50	60	----	9.9	1450,	2050	1000	b	-110 to -150	b	b
(Group B)	62.4	----				Air:				
	62.5	----				150				
	63	----								
	63.4						975		975	975
Halmo				Salt:		Oil:	(120 min)		(120 min)	
	56.3	2.6	6 to 7	1450,	2100	120	1100		1100	
	60.1	3.6					1050		1050	
	62.4	4.4					1000		1000	
WB-49				Salt:	Salt:	Salt:	(120 min)		(120 min)	(40 min)
	54.3	<1	8+	1500,	2225,	1225,	1025		1025	1250
	58.1	<1			6 min	6 min				1200
	62.7	<1								1150
	67.6	5.0								None

[a]Obtained by X-ray diffraction.
[b]Tempered between 975° and 1050° F. Exact heat treatment unknown.

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TABLE IV. - NUMBER OF CARBIDES, CARBIDE SIZE, AND PERCENT CARBIDE AREA AS DETERMINED BY THE QTM

Material	Lot	Average number of carbide particles, a*	Median carbide size, m, in microns	Average carbide area in percent, n*
52100	A	722	0.16	8.18
	B	734	.14	10.06
	C	700	.48	10.38
	Combined	718	.26	9.54
Halmo	A	326	0.59	7.16
	B	338	.54	5.44
	C	323	.38	6.08
	Combined	329	.51	6.23
AISI T-1	A	335	1.96	29.92
	B	344	1.39	17.20
	C	542	1.71	21.16
	Combined	413	1.69	19.76
AISI M-42	A	316	1.58	10.88
	B	411	1.85	12.00
	C	390	1.67	10.72
	Combined	372	1.70	11.23
AISI M-50	A	324	0.57	5.79
	B	263	.67	3.13
	C	180	.46	2.04
	Combined	255	.57	3.65
AISI M-10	A	234	1.10	10.08
	B	510	1.50	12.12
	C	408	1.49	10.80
	Combined	394	1.36	11.06
AISI M-1	A	340	1.43	15.50
	B	389	1.37	16.86
	C	520	1.69	17.20
	Combined	416	1.50	16.52
AISI M-2	A	332	1.16	15.70
	B	580	1.42	17.10
	C	351	1.25	15.94
	Combined	421	1.28	16.25

*Measured in an area of 1.83×10^{-4} cm^2.

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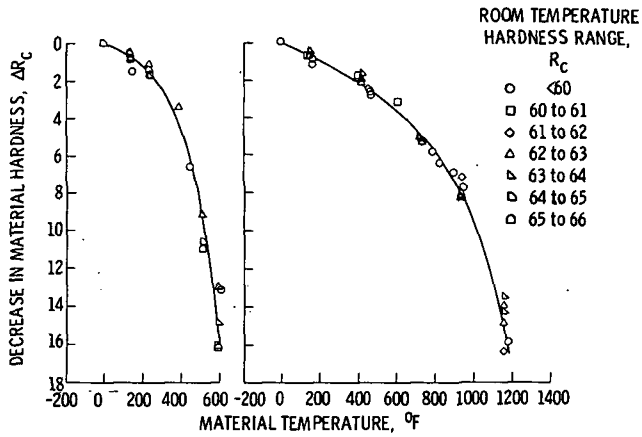
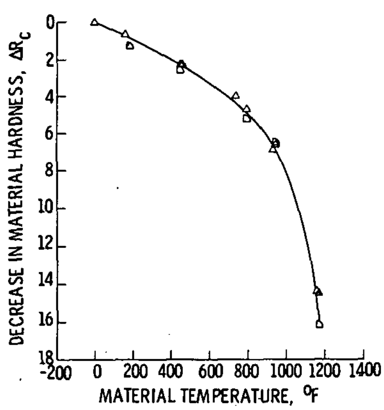
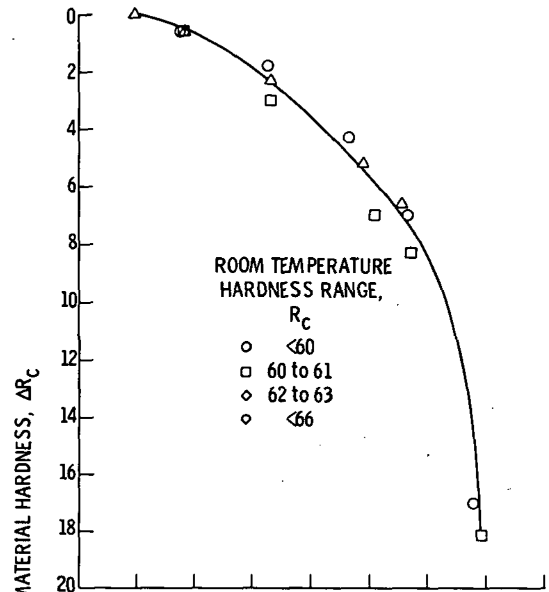


(a) AISI 52100. (b) AISI M-50.

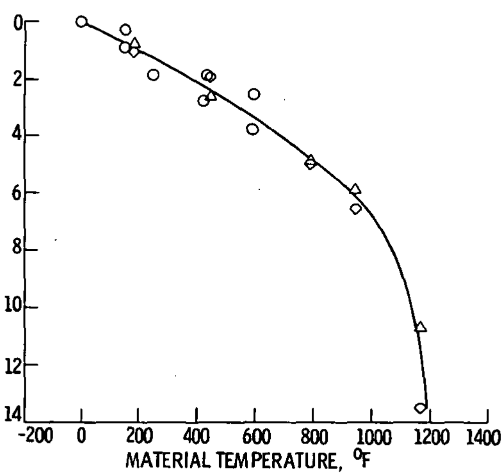


(c) AISI M-1.

Figure 1. - Normalized short-term hardness data for five bearing steels.



(d) HALMO.



(e) WB-49.

Figure 1. - Concluded.

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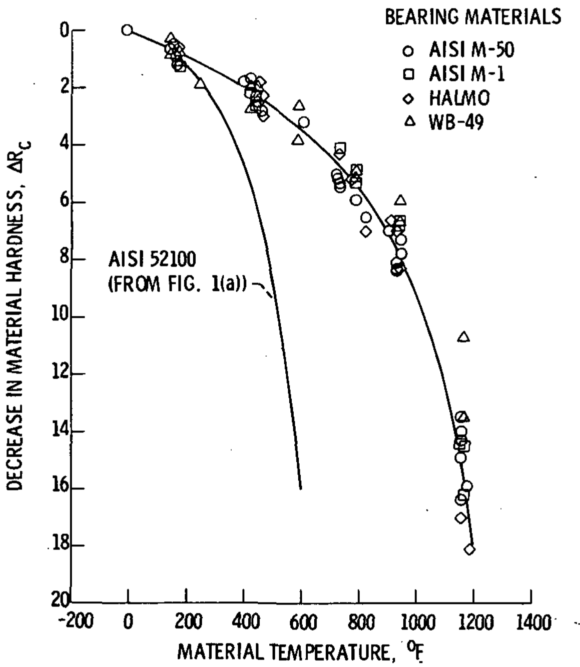

Figure 2. - Combined normalized short-term hardness data for five bearing steels.

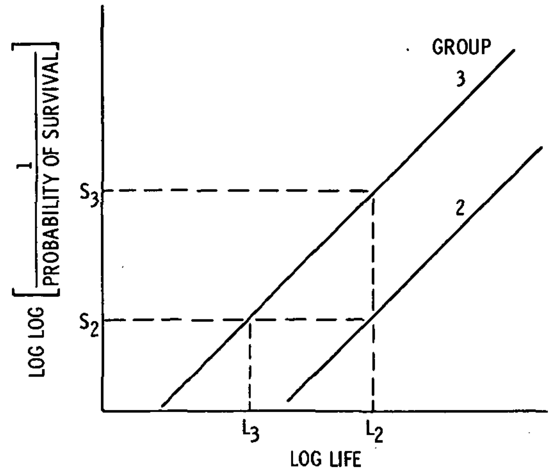

Figure 3. - Weibull plot of probability of survival versus life.

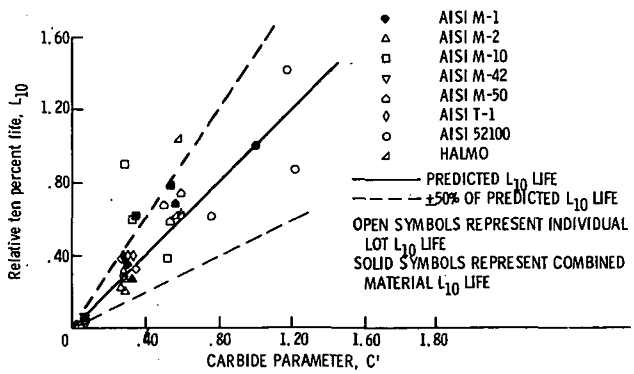

Figure 4. - Individual and average ten percent life, L_{10}, for eight bearing materials as a function of the carbide parameter, C'