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EFFECT OF CARBIDE SIZE, AREA, AND DENSITY ON ROLLING-ELEMENT FATIGUE

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and

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16. Abstract

A carbide parameter that can be used to predict rolling-element fatigue life was developed. The parameter is based on a statistical life analysis and incorporates the total number of particles per unit area, particle size, and percent carbide area. These were determined from Quantimet Image Analyzing Computer (QTM) examinations of random samples selected from eight lots of material previously tested in rolling fatigue. The carbide parameter is independent of chemical composition, heat treatment, and hardening mechanism of the materials investigated.

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SUMMARY

An analysis was undertaken to determine if a correlation exists among the number of carbide particles per unit area, median carbide size, and percent carbide area, and rolling-element fatigue. Specimens studied were obtained from a previous investigation that determined the rolling-element fatigue lives of eight consumable-electrode vacuum-melted steels: AISI 52100, AISI T-1, AISI M-42, AISI M-1, AISI M-2, AISI M-10, AISI M-50, and Halmo. Care was taken to maintain constant all variables that are known to affect rolling-element fatigue life. From each lot of material one sample was randomly selected and examined metallurgically on a Quantimet Image Analyzing Computer (QTM) for the total number of carbide particles per unit area, median carbide size, and percent carbide area. Based on the aforementioned data and a statistical analysis, a carbide factor C was derived that was capable of predicting the rolling-element fatigue lives of the materials investigated within an acceptable variance. The correlation coefficient for the prediction of combined material 10-percent life was found to be 0.87 and that of the individual material lots was found to be 0.83. The carbide parameter was independent of chemical composition, heat treatment, and hardening mechanism of the materials investigated.

INTRODUCTION

AISI 52100 has been the most commonly used rolling-element bearing material. However, in recent years tool steels have been used with increasing frequency as rolling-element bearing materials for service above 450 K (350° F) such as in turbojet engines. This transition from AISI 52100 to the tool steels has taken place because dimensional stability, retention of hot hardness, wear resistance, and oxidation resistance

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at elevated temperatures, which are particularly important in bearing steels, cannot be obtained in AISI 52100. Typical of the high-speed tool steels are AISI M-1, M-2, M-10, M-50 and Halmo. These alloys contain elements such as molybdenum, tungsten, and vanadium, which are all strong carbide formers. The alloy carbides that form not only provide increased hardness of the material, but also help to retain this hardness at elevated temperatures. The greater amount of hard alloy carbides in the high-speed tool steels make them more difficult to grind and finish than AISI 52100 (refs. 1 and 2). These materials are through-hardenable steels; that is, material hardness is attained throughout the part by heat treatment rather than by a case hardening procedure such as carburizing.

The investigators of references 3 and 4 reported that rolling-element fatigue life decreases as the total amount of alloying elements such as molybdenum, chromium, vanadium, tungsten, and cobalt increased. With the exception of cobalt, these alloying elements are all strong carbide formers. These hard alloy carbides may act as notch concentrators. If this is true, it may explain why AISI 52100 has a higher rolling-element fatigue life than the high-speed tool steels (refs. 3 and 4).

Although there have been a number of studies performed to investigate the effect of metallurgical variables such as hardness, thermal mechanical treatment, melting practice, and grain flow, on rolling-element fatigue life, there have been no systematic investigations into the effect of carbides. The objective of the research reported herein was to determine if a correlation exists among the number of carbide particles per unit area, carbide length, and percent carbide area, and rolling-element fatigue life. This correlation was compared with fatigue data obtained with eight materials on five-ball testers in a previous investigation (refs. 3 and 4).

Carbide data were obtained on a Quantimet Image Analyzing Computer (QTM). All specimens for each material were made from a single vacuum-melted ingot.

SYMBOLS

A	ratio of the percent area of carbides in lots 1 and 2
a	percent area of carbides
C	carbide factor
Co	weight percent cobalt in a material
e	Weibull slope that can be taken as approximately one for rolling-element fatigue
K	constant
L	life

L_{10} life at which there is a 90 percent probability of survival

M ratio of the median carbide size of lots 1 and 2

m median carbide size (length)

N ratio of the number of carbide particles per unit area of lots 1 and 2

n total number of particles per unit area

P probability of failure

S probability of survival (1 - P)

S_{Co} probability of survival due to the percent cobalt

S_{α} probability of survival due to the median carbide size

S_{μ} probability of survival due to the number of carbide particles per unit area

S_{ν} probability of survival due to the percent area of carbides

u location parameter that can be taken as zero in rolling-element fatigue

β characteristic life at which there is a 38 percent probability of survival if e is one

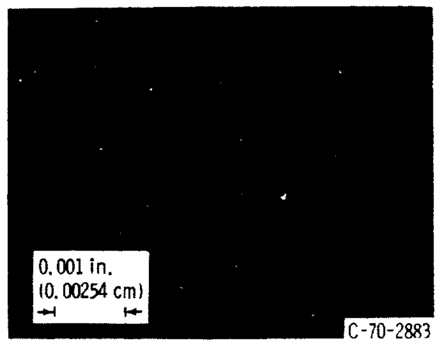
Test Specimens

The materials used in this investigation were consumable vacuum-melted (CVM) AISI 52100, AISI M-1, AISI M-2, AISI M-10, AISI M-42, AISI M-50, AISI T-1, and Halmo used in references 3 and 4. The chemical compositions of these materials are presented in table I. Photomicrographs of the individual materials are shown in figure 1. All the high-speed steels show typically larger carbides than AISI 52100. All specimens of each material were made from one vacuum-melted ingot and heat treated according to the heat-treatment schedules contained in table II. Room temperature hardness, retained austenite, and grain size are presented in table III. ASTM cleanliness ratings are given in table IV.

The fatigue data contained herein were obtained in five-ball fatigue testers and were reported in references 3 and 4. Groups of 12.7-millimeter (1/2-in.) diameter balls of each material were tested at a maximum Hertz stress of 5.52×10^{9} newtons per square meter (800 000 psi), a contact angle of 30°, and a shaft speed of 10 300 rpm. Tests were run at a race temperature of 340 K (150° F) with a super-refined naphthenic mineral oil as the lubricant. The results are summarized in table V. 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 cutoff time of 100 hours was reached.

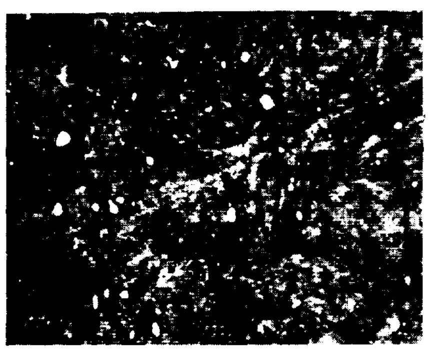
Lot A

Lot B

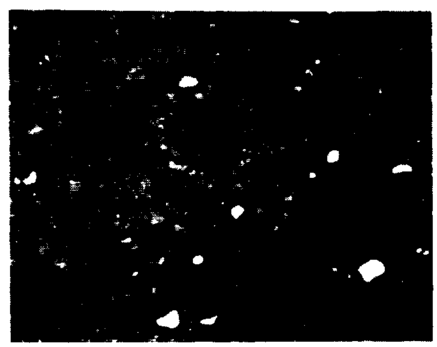


Lot C

(a) AISI 52100 steels.



Lot A



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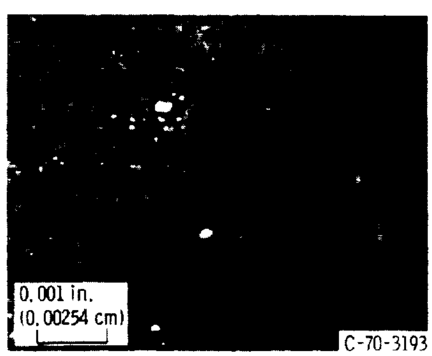
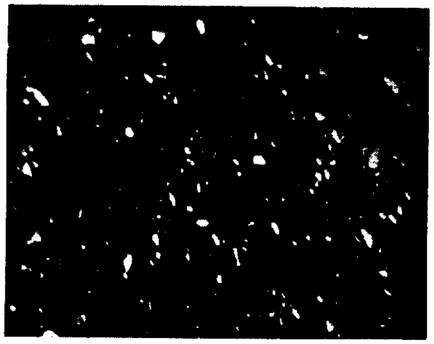


Lot C

(b) Halmo steel.

Figure 1. - Photomicrographs of materials; 2 percent Nital etch.



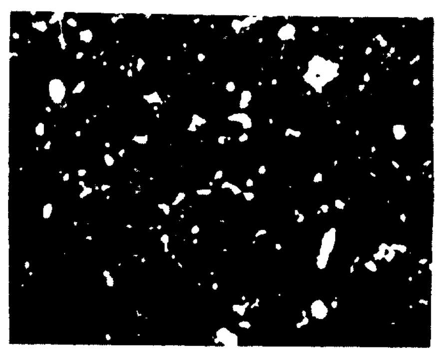
Lot A

Lot B

Lot C

(c) AISI T-1 steel.

Lot A



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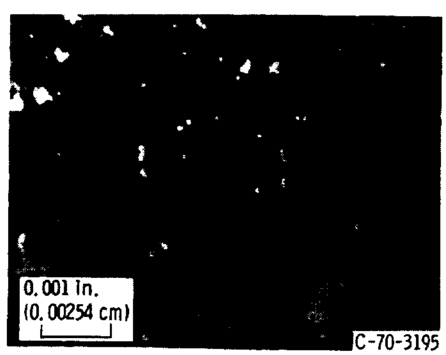
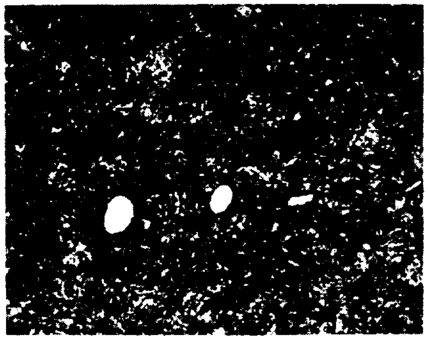


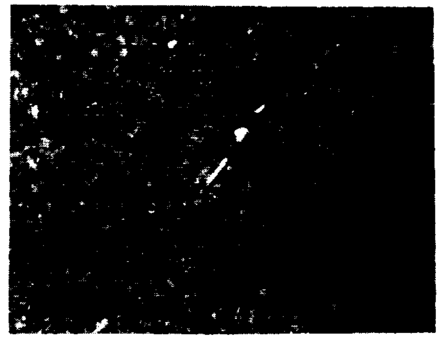
Lot C

(d) AISI M-42 steel.

Figure 1. - Continued.



Lot A



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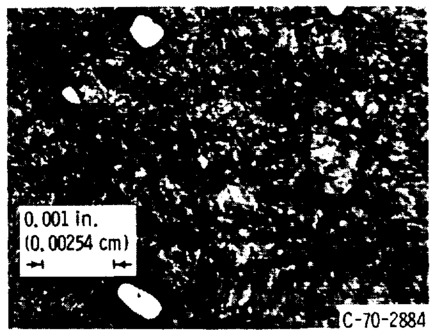
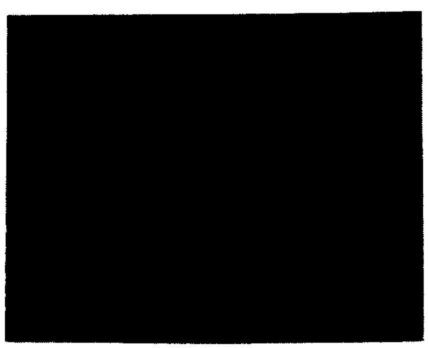


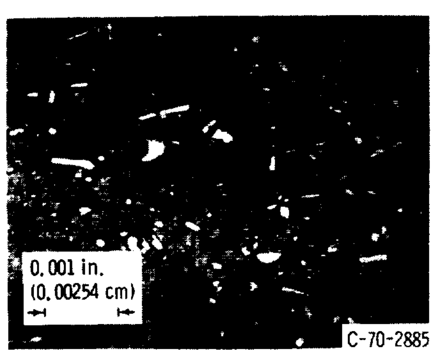
Lot C

(e) AISI M-50 steels.



Lot A

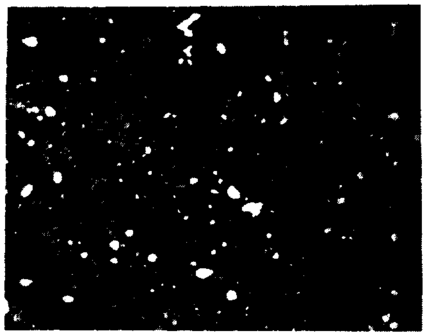
Lot B



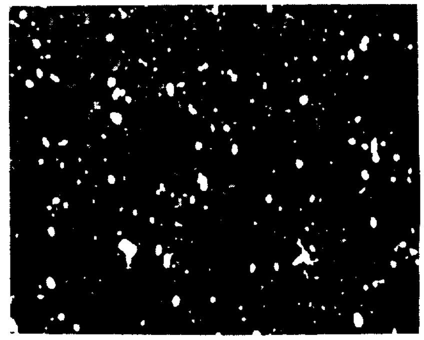
Lot C

(f) AISI M-10 steels.

Figure 1. - Continued.



Lot A



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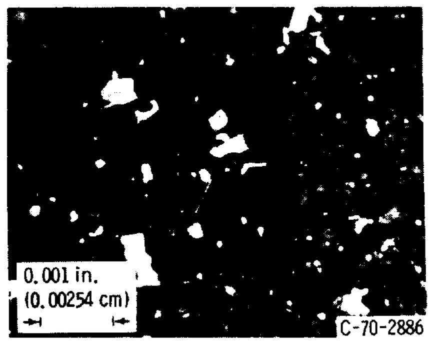
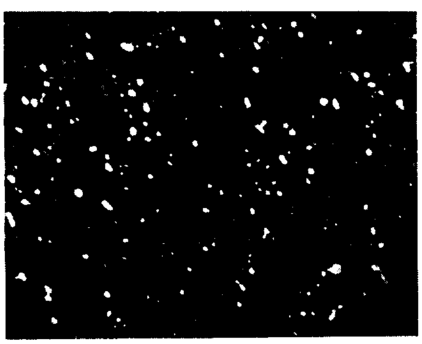
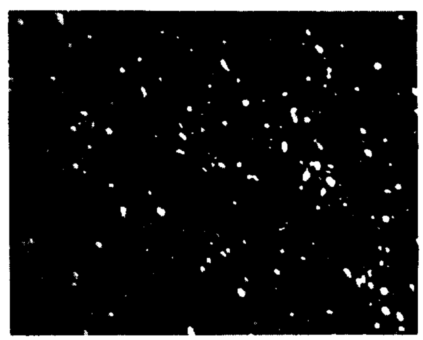


Lot C

(g) AISI M-1 steels.



Lot A



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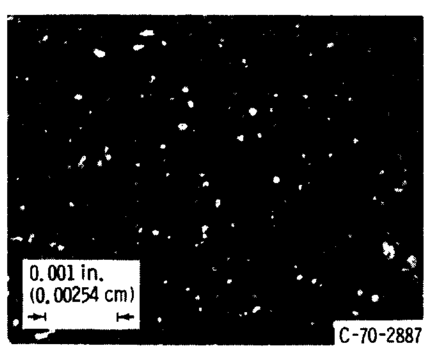

Lot C

(h) AISI M-2 steels.

Figure 1. - Concluded.

The test results of the three lots of each material were combined, and a Weibull analysis was performed on the combined results to determine the 10-percent fatigue life of the various materials. This life will be referred to in this report as the combined 10-percent life.

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 particles in a unit area, particle size, and percent carbide area in a unit area.

Quantimet Image Analyzing Computer (QTM)

The Quantimet Image Analyzing Computer (QTM) contains a microscope with normal optics. This microscope is mounted on an electronic unit containing a camera equipped with a special vidicon tube receiving the microscope image, a detector scanning it, and a computer converting the detector values into measured units and indicating them on a meter. On a television screen the microscope image is reproduced and at the same time shows the measuring operations being carried out. The QTM's capacity of recording and calculating various phases of a picture is based on the difference in optical intensity, color, size, or topography. It is necessary to ensure that the objects to be measured appear considerably darker or lighter than their environment. The principle measurement in the QTM is that the picture projected on to the camera is scanned electronically by a detector reacting to varying optical intensity. A square is projected on the television screen that shows the scanned area; this square may be varied in size according to the requirements of the operator. By means of a discriminator, a minimum value of optical intensity is positioned in order to be recorded. Areas below this intensity will appear on the screen as very light spots. The size of the discriminated area in percent of the measured surface can be read directly on a meter. The number of particles in the field of view can also be read directly on a meter. The QTM is also fitted with a discriminator that allows the mean and median sizes of the particles to be determined if the largest particle is known. The largest particle can be obtained by simply measuring the largest particle in the field of view on the television screen.

Before any measurements were taken, the QTM was electronically calibrated. To assure that the instrument was functioning properly, the particles being counted electronically were also counted manually and were compared to insure consistency.

Five areas were examined on each sample. Four were near the surface and 90° apart. The values of the five readings were then averaged to obtain what was considered the value of the variables for the sample in question. A typical variation in the five readings can be seen in table VI for AISI M-50, lot C. To obtain the value of the variables for the different materials, the 15 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 10-percent life, these average material values will be referred to as the combined values.

The blank frame size used was 30 by 22 centimeters, and the magnification was $\times 1900$. This magnification is approximately three times that of the micrographs of figure 1. Thus, at any one time an area of 1.83×10^{-4} square centimeter was being examined. For QTM analysis, the samples were electrolytically etched at about 2 volts with Murakami's reagent (10 percent KOH, 10 percent $K_3Fe(CN)_6$, 80 percent H_2O). This made the carbides etch black and the matrix white so that the QTM could distinguish the carbides.

RESULTS AND DISCUSSION

The results of references 3 and 4 showed an interrelation between the total percent weight of alloying elements tungsten, chromium, vanadium, molybdenum, and cobalt, and fatigue life. From these data it was theorized that an interrelation existed among median carbide size, number of carbide particles per unit area, and the percent area of carbides and rolling-element fatigue life. In other words, any of the carbides in a material, which are a function of the alloying elements and heat treatment, could be the nucleation site of an incipient fatigue failure. If this be the case, then the probability of survival S for a lot of specimens or of 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. If these variables are independent, this relation can be expressed as

$$S = S_\alpha \cdot S_\mu \cdot S_\nu \tag{1}$$

It was found that there was a gross difference between the mean and median carbide sizes whereby the median size was more representative of the size distribution.

All of these alloying elements are carbide formers, with the exception of cobalt. The exact effect cobalt may have on rolling-element fatigue is not clear. It has been suggested that cobalt may decrease the fracture toughness of the material (ref. 5). In addition, a Russian paper (ref. 6), suggested that the nonuniformity of the material increased because of 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 if the size distribution shifted toward the larger 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:

$$S = S_\alpha \cdot S_\mu \cdot S_\nu \cdot S_{Co} \tag{2}$$

If there are two specimens or lots whereby each of these probabilities are different, then

$$\left.\begin{aligned} S_1 &= S_{\alpha_1} \cdot S_{\mu_1} \cdot S_{\nu_1} \cdot S_{(Co)_1} \\ S_2 &= S_{\alpha_2} \cdot S_{\mu_2} \cdot S_{\nu_2} \cdot S_{(Co)_2} \end{aligned}\right\} \tag{3}$$

Assume that M is the ratio of the median carbide size of lots 1 and 2, N is the ratio of the number of carbide particles per unit area of lots 1 and 2, A is the ratio of the percent area of carbides in lots 1 and 2, and $(Co)_1$, and $(Co)_2$ are the weight percent cobalt in lot 1 and 2, respectively. Let

$$N = \frac{n_2}{n_1}$$

$$M = \frac{m_2}{m_1}$$

and

$$A = \frac{a_2}{a_1}$$

where a is the percent area of carbides, m is the median carbide size (length), and n is the total number of carbides per unit area. The probability of survival for each of the factors in lot 2 can be expressed in terms of the probability of survival for each of the factors in lot 1. Considering carbide size only, it is reasonable to assume that, as the carbide size m decreases, 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 proportional to the number of carbides per unit area. The factor that remains is the percent area of carbides. If carbides are a critical factor, it is reasonable to assume that the probability of survival decreases as the percent area of carbide increases. As for the cobalt, all that is known is that, as weight percent of cobalt increases, life decreases. The aforementioned can be expressed statistically as follows:

$$\left.\begin{aligned} S_{\alpha_2} &= S_{\alpha_1}^{M} \\ S_{\mu_2} &= S_{\mu_1}^{1/N} \\ S_{\nu_2} &= S_{\nu_1}^{A} \\ S_{Co_2} &= S_{Co_1}^{Co} \end{aligned}\right\} \tag{4}$$

From equation (3)

$$S_{\alpha_1} = \frac{S_1}{S_{\mu_1} \cdot S_{\nu_1} \cdot S_{Co_1}} = S_1^{K_1}$$

Similarly,

$$S_{\mu_1} = S_1^{K_2}$$

$$S_{\nu_1} = S_1^{K_3}$$

$$S_{Co_1} = S_1^{K_4} \tag{5}$$

where K_1, K_2, K_3, and K_4 are constants. Equating equations (4) and (5) results in

$$\left.\begin{aligned} S_{\alpha_2} &= S_1^{K_1 M} \\ S_{\mu_2} &= S_1^{K_2/N} \\ S_{\nu_2} &= S_1^{K_3 A} \\ S_{Co_2} &= S_1^{K_4 Co} \end{aligned}\right\} \tag{6}$$

From equations (3) and (6) S_2 can be expressed in terms of S_1 as follows:

$$\begin{aligned} S_2 &= S_1^{K_1 M} \cdot S_1^{K_2/N} \cdot S_1^{K_3 A} \cdot S_1^{K_4 Co} \\ &= S_1^{(K_1 M + K_2/N + K_3 A + K_4 Co)} \end{aligned} \tag{7}$$

By using Weibull analysis (ref. 7)

$$(1 - P) = \exp - \left(\frac{L - u}{\beta}\right)^e \tag{8}$$

where P is the probability of failure; e is the slope, which can be taken as being one for rolling-element fatigue; β is the characteristic life at which there is a 38 percent probability of survival (where $e \approx 1$); L is life; and u is the location parameter, which can be taken as being zero in rolling-element fatigue.

It should be noted that

$$S = (1 - P) = \text{Probability of survival}$$

Equation (8) can be rewritten as follows:

$$S = \exp - \left(\frac{L}{\beta}\right) \tag{9}$$

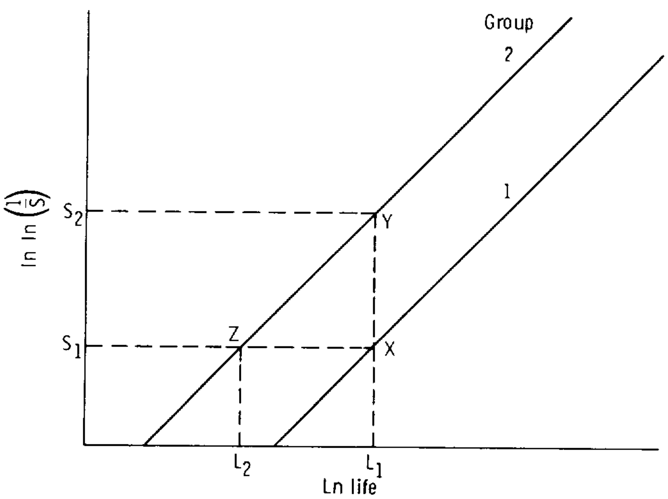

Figure 2. - Weibull plot of probability of survival as function of life.

or

$$\ln S = -\left(\frac{L}{\beta}\right)$$

In figure 2, there is shown a Weibull plot of two hypothetical groups of specimens denoted as groups 1 and 2, respectively. From equation (7) for point Y in figure 2

$$\ln S_2 = -\left(\frac{L_1}{\beta_2}\right) \qquad (10a)$$

For point Z in figure 2

$$\ln S_1 = -\left(\frac{L_2}{\beta_2}\right) \qquad (10b)$$

If equation (10b) is divided by equation (10a), then

$$\frac{L_2}{L_1} = \frac{\ln S_1}{\ln S_2} \qquad (11)$$

Since $S_2 = S_1^{(K_1M+K_2/N+K_3A+K_4Co)}$ from equation (7), then

$$\frac{L_2}{L_1} = \frac{\ln S_1}{\left(K_1 M + \frac{K_2}{N} + K_3 A + K_4 Co\right) \ln S_1} \tag{12}$$

Let C be the carbide factor where

$$C = \frac{1}{\left(K_1 M + \frac{K_2}{N} + K_3 A + K_4 Co\right)} \tag{13}$$

Therefore,

$$C = \frac{L_2}{L_1} \tag{14}$$

In references 3 and 4 AISI 52100 is the material that 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 VII under the heading "combined." That is let

$$C = \frac{1}{\frac{K_1 m_2}{0.26} + \frac{718\ K_2}{n_2} + \frac{K_3 a_2}{9.54} + K_4 Co} \tag{15}$$

and assume that

$$K_1 = K_2 = K_3 \tag{16}$$

Equation (15) can then be rewritten as

$$C = \frac{1}{K_1\left(\frac{m}{0.26} + \frac{718}{n} + \frac{a}{9.54} + \frac{K_4}{K_1}\ Co\right)} \tag{17}$$

where the subscript 2 has been dropped. From the data of tables I and VII, K_1 and K_4 were empirically determined. Values of 1/3 and 4/3 were selected for K_1 and K_4, respectively, and found to be satisfactory.

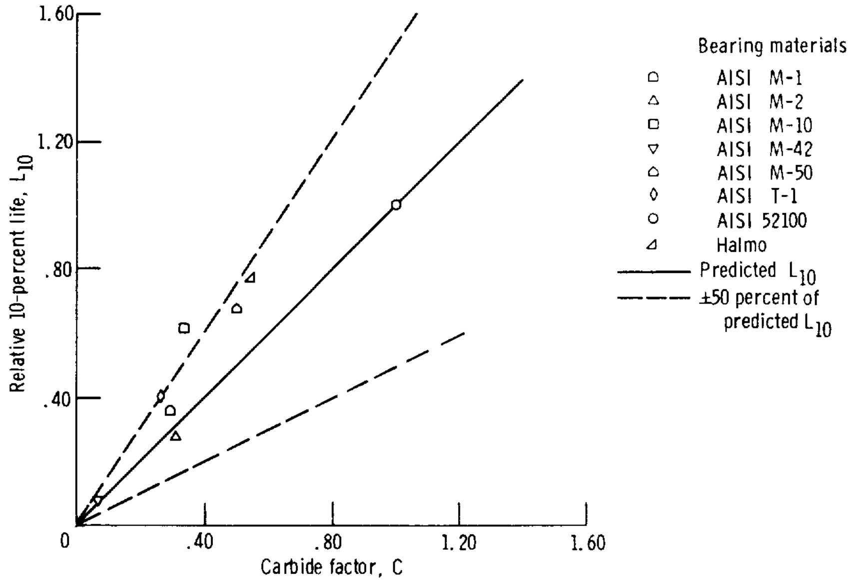

Figure 3. - Combined 10-percent life for eight bearing materials as function of carbide factor.

In figure 3 the relative material 10-percent life is plotted against the carbide factor C having the combined life of AISI 52100 as L_1 in equation (14). (The 10-percent life is that time at which there is a 90-percent probability of survival for a bearing or group of bearings.) In figure 4 individual lot life normalized to the combined life of AISI 52100 is plotted against the carbide factor C. In both figures 3 and 4 the solid line represents the theoretically predicted relative 10-percent life obtained by calculating C from equation (17) and substituting it into equation (14). The dashed lines in figures 3 and 4 represent a plus or minus 50 percent deviation from the theoretically predicted values. In both of these figures there appears to be a reasonable correlation between the carbide factor C and relative life. The correlation coefficient (ref. 8) was calculated for the data of figures 3 and 4. For both sets of data it 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, load, and lubrication mode. Thus, the carbide factor appears to transcend such variables as heat treatment, chemical composition, and hardening mechanism to predict the lives of individual lots. Of course, heat treatment and composition determine the carbide area, size, and number. The carbide parameter may also be applicable to conventional fatigue (i.e., bending, rotating-bending, etc.).

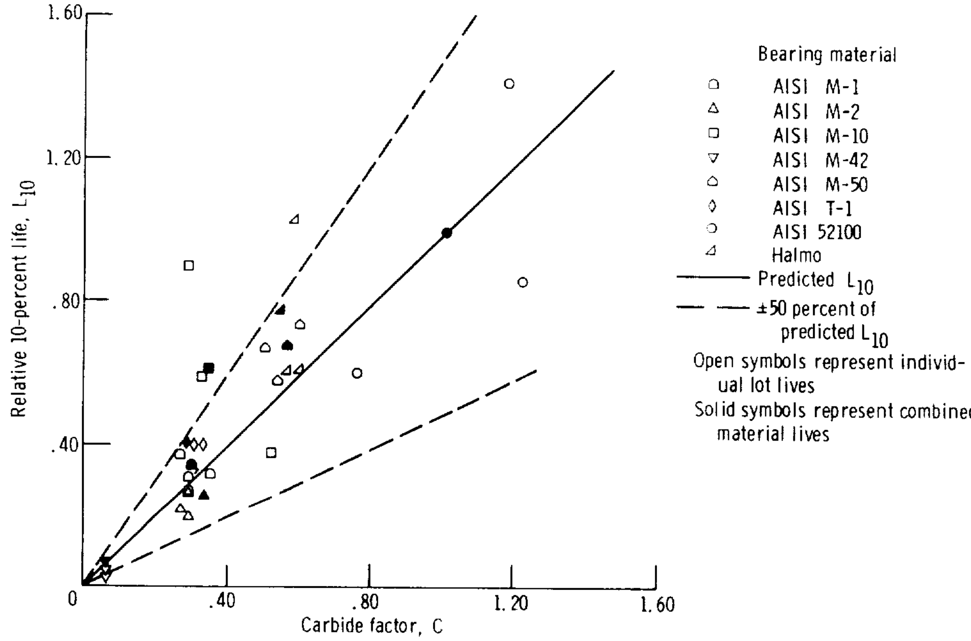

Figure 4. - Individual and combined 10-percent life for eight bearing materials as a function of the carbide factor, C.

SUMMARY OF RESULTS

An analysis was undertaken to determine if a correlation exists among the number of carbide particles per unit area, median carbide size, and percent carbide area and rolling-element fatigue. Specimens studied were obtained from a previous investigation which determined the rolling-element fatigue lives of eight consumable-electrode-vacuum-melted steels: AISI 52100, AISI T-1, AISI M-42, AISI M-1, AISI M-2, AISI M-10, AISI M-50, and Halmo. Care was taken to maintain constant all variables that are known to affect rolling-element fatigue life. From each lot of material, one sample was randomly selected and examined metallurgically on a Quantimet Image Analyzing Computer (QTM) for the total number of carbide particles per unit area, median carbide size, and percent carbide area. The following results were obtained:

1. Based on the aforementioned data and a statistical analysis, a carbide factor C was derived that was capable of predicting the rolling-element fatigue lives of the materials investigated within an acceptable variance. The correlation coefficient for the prediction of combined material 10-percent life was found to be 0.87; that of the individual material lots was found to be 0.83.

2. The carbide parameter was independent of chemical composition, heat treatment, and hardening mechanism of the materials investigated.

Lewis Research Center,
National Aeronautics and Space Administration,
and
U.S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, April 6, 1972,
132-15.

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TABLE I. - CHEMICAL COMPOSITION OF TEST MATERIALS

Material	Heat-treatment lot	Chemical composition, percent (balance Fe)							
		C	Mn	Si	Cr	V	W	Mo	Co
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	.45	< .05	-----	< .05	----
Halmo	A	0.54	0.38	0.97	6.03	0.63	-----	4.93	----
	B	.57	.36	.97	5.98	.63	-----	4.82	----
	C	.57	.37	.97	5.95	.64	-----	4.96	----
AISI T-1	A	0.70	0.24	0.25	3.43	1.02	17.02	-----	----
	B	.70	.25	.35	3.45	1.03	17.05	-----	----
	C	.70	.22	.35	3.48	1.04	16.90	-----	----
AISI M-42	A	1.13	0.20	0.10	4.02	1.09	1.51	7.88	8.40
	B	1.12	.20	.11	3.49	1.09	1.53	7.92	8.38
	C	1.12	.21	.14	3.92	1.07	1.49	7.86	8.42
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	----

TABLE II. - HEAT TREATMENT OF TEST MATERIALS

Heat treatment	AISI 52100	Halmo	AISI T-1	AISI M-42	AISI M-1	AISI M-2	AISI M-10	AISI M-50
Preheat	----------------	1062 to 1088 K (1450° to 1500° F)	1088 to 1118 K (1500° to 1550° F)	1118 to 1144 K (1550° to 1600° F)	1033 to 1118 K (1400° to 1550° F)	1033 to 1144 K (1400° to 1600° F)	1033 to 1118 K (1400° to 1550° F)	1033 to 1118 K (1400° to 1550° F)
Harden	1116 to 1121 K (1540° to 1560° F)	1394 to 1450 K (2050° to 2150° F)	1533 ±11 K (2300° ±20° F)	1464 to 1477 K (2175° to 2200° F)	1477 ±5 K (2200° ±10° F)	1491 ±5 K (2225° ±10° F)	1477 ±5 K (2200° ±10° F)	1423 ±5 K (2100° ±10° F)
Quench	In oil at 311 to 327 K (100° to 130° F)	In oil to 339 K (150° F)	In molten salt to <811 K (1000° F)	In molten salt to 866 to 922 K (1100° to 1200° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)
Air cool	To room temperature	----------------	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)
Deep freeze	200 K (-100° F) for 4 hr	----------------	----------------	----------------	----------------	----------------	----------------	----------------
Temper	450 K (350° F) for 6 hr	805 to 816 K (990° to 1010° F) for 2 hr	894 ±11 K 1150° ±20° F) for 2 hr	816 to 828 K (1010° to 1030° F) for 2 hr (twice)	866 ±5 K (1100° ±10° F) for 2 hr	880 ±5 K (1125° ±10° F) for 2 hr	853 ±5 K (1075° ±10° F) for 2 hr	825 ±5 K (1025° ±10° F) for 2 hr
Air cool	----------------	To room temperature	To <339 K (150° F)	To room temperature (twice)	To room temperature	To room temperature	To room temperature	To room temperature
Deep freeze	200 K (-100° F) for 3 hr	189 K (-120° F) for 2 hr	189 K (-120° F) for 2 hr	194 to 172 K (-110° to -150° F) for 2 hr	194 to 172 K (-110° to -150° F) for 1$\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for 1$\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for 1$\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for 1$\frac{1}{2}$ to 2 hr
Stabilize	450 K (350° F) for 2 hr	805 to 816 K (990° to 1010° F) for 2 hr	894 ±11 K (1150° ±20° F) for 2 hr	894 K (1150° F) for 2 hr	866 ±5 K (1100° ±10° F) for 2 hr	880 ±5 K (1125° ±10° F) for 2 hr	853 ±5 K (1075° ±10° F) for 2 hr	825 ±5 K (1025° ±10° F) for 2 hr
Air cool	To 311 K (100° F)	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature
Stabilize	450 K (350° F) for 2 hr	----------------	811 to 825 K (1000° to 1025° F)	816 K (1010° F) for 2 hr	811 ±5 K (1000° ±10° F) for 2 hr	811 ±5 K (1000° ±10° F) for 2 hr	797 ±5 K (975° ±10° F) for 2 hr	797 ±5 K (975° ±10° F) for 2 hr
Air cool	To room temperature	----------------	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature

TABLE III. - PROPERTIES OF TEST MATERIALS

TABLE V. - CARBIDE PARAMETER, PREDICTED RELATIVE TEN PERCENT LIFE, AND ACTUAL RELATIVE 10-PERCENT LIFE

Material	Lot	Predicted relative 10-percent life, C, percent	Actual relative 10-percent life, percent (a)
52100	A	122	87
	B	117	142
	C	76	61
	Combined	100	100
Halmo	A	58	104
	B	64	61
	C	69	61
	Combined	63	78
AISI T-1	A	26	31
	B	33	40
	C	30	40
	Combined	29	41
AISI M-42	A	7	5
	B	7	8
	C	7	7
	Combined	7	7
AISI M-50	A	60	74
	B	54	58
	C	50	67
	Combined	56	68
AISI M-10	A	36	91
	B	39	39
	C	35	60
	Combined	37	62
AISI M-1	A	32	39
	B	34	28
	C	38	32
	Combined	33	36
AISI M-2	A	36	27
	B	36	26
	C	35	20
	Combined	36	27

[a]Refs. 3 and 4.

TABLE II. - HEAT TREATMENT OF TEST MATERIALS

Heat treatment	AISI 52100	Halmo	AISI T-1	AISI M-42	AISI M-1	AISI M-2	AISI M-10	AISI M-50
Preheat	---------------	1062 to 1088 K (1450° to 1500° F)	1088 to 1118 K (1500° to 1550° F)	1118 to 1144 K (1550° to 1600° F)	1033 to 1118 K (1400° to 1550° F)	1033 to 1144 K (1400° to 1600° F)	1033 to 1118 K (1400° to 1550° F)	1033 to 1118 K (1400° to 1550° F)
Harden	1116 to 1121 K (1540° to 1560° F)	1394 to 1450 K (2050° to 2150° F)	1533 ±11 K (2300° ±20° F)	1464 to 1477 K (2175° to 2200° F)	1477 ±5 K (2200° ±10° F)	1491 ±5 K (2225° ±10° F)	1477 ±5 K (2200° ±10° F)	1423 ±5 K (2100° ±10° F)
Quench	In oil at 311 to 327 K (100° to 130° F)	In oil to 339 K (150° F)	In molten salt to <811 K (1000° F)	In molten salt to 866 to 922 K (1100° to 1200° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)	In molten salt to 811 to 839 K (1000° to 1050° F)
Air cool	To room temperature	---------------	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)	To <339 K (150° F)
Deep freeze	200 K (-100° F) for 4 hr	---------------	---------------	---------------	---------------	---------------	---------------	---------------
Temper	450 K (350° F) for 6 hr	805 to 816 K (990° to 1010° F) for 2 hr	894 ±11 K 1150° ±20° F) for 2 hr	816 to 828 K (1010° to 1030° F) for 2 hr (twice)	866 ±5 K (1100° ±10° F) for 2 hr	880 ±5 K (1125° ±10° F) for 2 hr	853 ±5 K (1075° ±10° F) for 2 hr	825 ±5 K (1025° ±10° F) for 2 hr
Air cool	---------------	To room temperature	To <339 K (150° F)	To room temperature (twice)	To room temperature	To room temperature	To room temperature	To room temperature
Deep freeze	200 K (-100° F) for 3 hr	189 K (-120° F) for 2 hr	189 K (-120° F) for 2 hr	194 to 172 K (-110° to -150° F) for 2 hr	194 to 172 K (-110° to -150° F) for $1\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for $1\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for $1\frac{1}{2}$ to 2 hr	194 to 172 K (-110° to -150° F) for $1\frac{1}{2}$ to 2 hr
Stabilize	450 K (350° F) for 2 hr	805 to 816 K (990° to 1010° F) for 2 hr	894 ±11 K (1150° ±20° F) for 2 hr	894 K (1150° F) for 2 hr	866 ±5 K (1100° ±10° F) for 2 hr	880 ±5 K (1125° ±10° F) for 2 hr	853 ±5 K (1075° ±10° F) for 2 hr	825 ±5 K (1025° ±10° F) for 2 hr
Air cool	To 311 K (100° F)	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature
Stabilize	450 K (350° F) for 2 hr	---------------	811 to 825 K (1000° to 1025° F)	816 K (1010° F) for 2 hr	811 ±5 K (1000° ±10° F) for 2 hr	811 ±5 K (1000° ±10° F) for 2 hr	797 ±5 K (975° ±10° F) for 2 hr	797 ±5 K (975° ±10° F) for 2 hr
Air cool	To room temperature	---------------	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature	To room temperature

TABLE III. - PROPERTIES OF TEST MATERIALS

Material	Heat-treatment lot	Average hardness, RC number	Retained austenite, vol. %	Austenitic grain size[a]
AISI 52100	A	62.5	4.90	13
	B	62.0	4.10	13
	C	62.5	.80	13
Halmo	A	60.8	0.60	8
	B	60.8	1.00	8
	C	61.1	1.70	8
AISI T-1	A	61.4	7.30	11
	B	61.4	5.20	9
	C	61.0	9.50	10
AISI M-42	A	61.8	1.00	9
	B	61.3	4.40	10
	C	61.3	4.90	8
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 E112-63.

TABLE IV. - MATERIAL CLEANLINESS RATINGS

Material	Heat treatment	Cleanliness rating[a]	
		Class (b)	Type
AISI 52100	A	B1	Heavy
	B	D1	Thin
	C	D1	Thin
Halmo	A	D2	Heavy
	B	D1	Heavy
	C	D2	Heavy
AISI T-1	A	B1	Heavy
	B	D1	Thin
	C	D1	Heavy
AISI M-42	A	A1	Thin
	B	D1	Heavy
	C	D1	Heavy
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.

TABLE V. - CARBIDE PARAMETER, PREDICTED RELATIVE TEN PERCENT LIFE, AND ACTUAL RELATIVE 10-PERCENT LIFE

Material	Lot	Predicted relative 10-percent life, C, percent	Actual relative 10-percent life, percent (a)
52100	A	122	87
	B	117	142
	C	76	61
	Combined	100	100
Halmo	A	58	104
	B	64	61
	C	69	61
	Combined	63	78
AISI T-1	A	26	31
	B	33	40
	C	30	40
	Combined	29	41
AISI M-42	A	7	5
	B	7	8
	C	7	7
	Combined	7	7
AISI M-50	A	60	74
	B	54	58
	C	50	67
	Combined	56	68
AISI M-10	A	36	91
	B	39	39
	C	35	60
	Combined	37	62
AISI M-1	A	32	39
	B	34	28
	C	38	32
	Combined	33	36
AISI M-2	A	36	27
	B	36	26
	C	35	20
	Combined	36	27

[a]Refs. 3 and 4.

TABLE VI. - VALUES FOR AISI M-50, LOT C

Number[a] of carbide particles, n	Median carbide size, m, μm	Carbide[a] area in percent, a
170	0.34	1.90
140	.60	1.60
85	.56	1.25
215	.38	2.30
290	.43	3.15
Average		
180	0.46	2.04

[a]Actual area measured, 1.83×10^{-4} cm^2.

TABLE VII. - NUMBER OF CARBIDES, CARBIDE SIZE, AND PERCENT CARBIDE AREA AS DETERMINED BY THE QUANTITATIVE IMAGE ANALYZING COMPUTER (QTM)

Material	Lot	Average[a] number of carbide particles, n	Median carbide size, m, μm	Average[a] carbide area, a, percent
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

[a]Actual area measured, 1.83×10^{-4} cm^2.

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