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FATIGUE LIVES AT 600° F OF 120-MILLIMETER-BORE BALL BEARINGS OF AISI M-50, AISI M-1, AND WB-49 STEELS

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16. Abstract

Groups of 120-millimeter bore angular-contact ball bearings made from consumable-electrode vacuum melted AISI M-50, AISI M-1, and WB-49 steels were fatigue tested with a synthetic paraffinic oil in a low oxygen environment at a bearing outer-race temperature of 600° F (588 K). The experimental lives of the bearings made from the AISI M-50 and AISI M-1 steels exceeded the AFBMA predicted (catalog) life by factors in excess of 13 and 6, respectively. The experimental life of the WB-49 bearings was less than half the AFBMA predicted (catalog) life. An apparent correlation exists between the rolling-element fatigue life of carbides (incidence, size, shape, and location) and the type of alloying element. For all three materials tested, the mode of failure was classical subsurface initiated rolling-element fatigue.

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SUMMARY

Groups of 120-millimeter bore angular-contact ball bearings made from consumable-electrode vacuum melted AISI M-50, AISI M-1, and WB-49 steels were fatigue tested with a synthetic paraffinic oil (synthesized hydrocarbon oil) at a bearing outer-race temperature of 600° F (588 K). Test conditions were a speed of 12 000 rpm and a thrust load of 5800 pounds (25 800 N) producing a maximum Hertz stress of 323 000 psi (233 000 N/cm^2) on the bearing inner race.

Fatigue-life results were evaluated with respect to failure appearance, alloying elements, and metallurgical structure. All experimental results were obtained with the same batch of lubricant. For a given material, all components of the test bearings were from the same heat of material.

The experimental life of the bearings made from the AISI M-50 and AISI M-1 steels exceeded the AFBMA predicted (catalog) life by factors in excess of 13 and 6, respectively. As a result, for these two materials, no derating of bearing life is required. The experimental life of the WB-49 bearings was, however, less than half AFBMA predicted life. Hence, this material would have to be derated. For all three materials tested the mode of failure was classical subsurface initiated.

An apparent correlation exists between rolling-element fatigue life and carbides (incidence, size, shape, and location) as affected by the amount and type of alloying element.

INTRODUCTION

Advances in airbreathing turbojet engines have dictated that bearing materials and lubricants operate at higher temperatures, higher speeds, and higher loads. The first

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generation of a supersonic transport (SST) turbine engine mainshaft bearings will operate at a bearing temperature of 425° F (492 K) and at a maximum speed of 1.3 million DN. (DN is the bearing bore in millimeter multiplied by shaft speed in rpm.) It is anticipated that more advanced engine designs may require that bearings operate at temperatures between 500° and 550° F (534 and 561 K) and speeds of approximately 2 million DN. Projection of these trends to the 1990's would predict bearing temperatures to 600° F (588 K) and bearing speeds of 3 to 4 million DN producing higher bearing operating stresses.

Several bearing alloys are available for operation between 350° and 750° F (450 and 672 K) (ref. 1). The most common of these is AISI M-50. In most turbojet applications, this material is used exclusively. The material has the capability of maintaining a hardness above Rockwell C 58 to temperatures of approximately 600° F (588 K) (ref. 1). Tests at temperatures from 400° to 600° F (478 to 588 K) with 120-millimeter bore angular-contact ball bearings produced fatigue lives in excess of 13 times the AFBMA predicted (catalog) life (refs. 2 and 3).

Another material which maintains satisfactory hardness at the temperatures of interest is AISI M-1 (ref. 1). In preliminary tests at 600° F (588 K) with 25-millimeter bore angular-contact ball bearings lives, twice the AFBMA predicted (catalog) life were achieved without failure (refs. 4 and 5).

A material that was developed for high-temperature bearing use is WB-49 (ref. 6). This material has the reported potential of maintaining a hardness greater than Rockwell C 58 to 900° F (755 K) (ref. 1). The amount of rolling-element fatigue data with this material is limited. The first fatigue data generated with this material were reported in references 7 and 8 for room temperature conditions. In general, fatigue life increased with increasing hardness for this material. However, there was no direct comparison with other materials. A similar material to WB-49 in composition and microstructure is Hypercut M-42. At a temperature of 150° F (340 K), M-42 produces a fatigue life of only 10 percent that of M-50 (refs. 9 and 10).

Reference 10 indicates that a trend exists toward decreased rolling-element fatigue life with increased total weight percent of alloying elements such as molybdenum, chromium, vanadium, tungsten, and cobalt. Because of the higher amounts of alloying elements in the WB-49 and M-1 steels with respect to the M-50 steel, it would be expected that M-50 would produce the longest life, followed by M-1 and WB-49. From reference 9, AISI M-1 has approximately 40 percent the life of AISI M-50 at 150° F (340 K) where hardnesses are nearly equal. However, these alloying elements promote the retention of hardness at high temperature. At 600° F (588 K) M-1 and WB-49 may have higher hardnesses. From references 7 and 8 increased life is obtained with higher hardness. This factor may help to offset the reduction in life observed with greater amounts of alloying elements.

The objectives of the research reported herein were (1) to determine in 120-millimeter angular-contact ball bearings the life expectancy with AISI M-50, AISI M-1, and WB-49 bearing steels at 600° F (588 K); (2) to compare these results with AFBMA predicted (catalog) life; and (3) to compare the relative lives with these three high-temperature bearings steels.

Tests were conducted in a high-temperature bearing tester at an outer-race temperature of 600° F (588 K) in a low-oxygen environment with 120-millimeter bore angular-contact ball bearings made of consumable-electrode vacuum-melted (CVM) AISI M-50, AISI M-1, or WB-49. Test conditions were a speed of 12 000 rpm and a bearing thrust load of 5800 pounds (25 800 N) which produced a maximum Hertz stress on the inner race of 323 000 psi (223 000 N/cm^2). Fatigue-life results were evaluated with respect to failure appearance, alloying elements, and metallurgical structure. All experimental results were obtained using one batch of lubricant. For a given material, all components of the test bearings were from the same heat. All bearing fatigue tests were conducted by the General Electric Company, Cincinnati, Ohio, under contract to NASA.

APPARATUS, SPECIMENS, AND PROCEDURE

High-Temperature Fatigue Tester

The high-temperature fatigue tester used in these tests is shown in figure 1 and was initially described in reference 11. Essentially, the tester is a test shaft to which are attached the two test bearings. Loading is supplied through a system of 10 springs which thrust load both bearings. The test rig is driven by a flat belt on a crowned spindle (not shown in the figure). Lubrication is provided to the test bearing through a jet-feed lubrication system by a pump immersed in a temperature controlled oil reservoir.

Instrumentation was provided for automatic shutoff by monitoring bearing temperatures, oil temperature, bearing vibration, nitrogen flow rate, and pressure. Should any of these parameters vary from those programmed for the test conditions, the test was shut down. Oxygen content within the bearing housing assembly was monitored during operation. An infrared pyrometer was used to measure inner-race temperature through a sight tube aimed at the inner race of the first test bearing.

Thrust load to the bearings was applied and calibrated through a force gage attached to the load plate and the connector. (This gaging system is not shown in the schematic diagram). The lubricant was preheated to 250° F (394 K) by use of a salt or oil bath in order to achieve adequate pumpability. Heat generation in the test bearings was sufficient to raise the temperature from 250° F (394 K) to 600° F (588 K). Test temperature stabilization was normally achieved within 1/2 hour after the test was started. Control of the operating temperature was achieved by using an automatic water-oil heat exchanger.

Test Bearings

The test bearings were ABEC-5 grade, split inner-race 120-millimeter bore angular-contact ball bearings having a nominal contact angle of 20°. The inner and outer races were manufactured from one heat of consumable-electrode vacuum-melted (CVM) steel, and the balls were manufactured from a second heat. However, both CVM heats were from the same master heat of air-melted material. For the purpose of the research reported herein a heat is defined as being from one CVM ingot, even though the ingots are made from the same air-melted master heat. Consequently, it was expected that the chemical analysis of the two heats used in the bearings should be essentially identical.

Each bearing contained fifteen 13/16-inch (2.06-cm) diameter balls. The cage, a one-piece outer-land riding type, was made of a nickel base alloy (AMS 4892) (table I) having a nominal Rockwell C hardness of 33. The inner- and outer-race curvatures were 54 and 52 percent, respectively. All components with the exception of the cage were within ±0.5 point Rockwell C. This assured a nominal differential hardness in all bearings (i.e., the ball hardness minus the race hardness, commonly called ΔH) of zero.

The surface finish on the races was 2 to 3 microinch (51 to 76 nm) rms. On the balls the surface finish was 1 to 2 microinch (25 to 51 nm) rms.

Bearing Materials

Three bearing materials were investigated at 600° F (588 K). These were AISI M-50, AISI M-1, and WB-49. The chemical analysis of all materials including the retainer material is shown in table I. The specific heat treat cycles are presented for each material in table II.

AISI M-50. - AISI M-50 is a martensitic high-speed tool steel, which has been used in critical bearing applications for the past decade. The steel was developed primarily for use as a high strength, high wear resistant tool steel. It has inherently high hardness and good compressive strength. Its operational temperature capability is in excess of 600° F (588 K).

The material as presently available is produced by the consumable-electrode vacuum remelting (CVM) process, using either an air melted or an induction vacuum-melted electrode. The photomicrographs in figure 2 illustrate the typical microstructure of the material. The M-50 is characterized by a finer grained martensitic matrix (with relatively uniform, small and well dispersed alloy carbides) than the other two materials evaluated. The material has good through hardenability. For the test bearings, the material hardness was controlled at room temperature to Rockwell C 63±1 for the rings and Rockwell C 63±0.5 for the balls.

AISI M-1. - AISI M-1 is also a high-speed tool steel which has been under investigation as a potential high-temperature bearing material for a number of years. As indicated in the photomicrographs in figure 3, this material tends to have rather large carbides which agglomerate or band. Since these massive carbides will act as nuclei for fatigue failures, assuming they are located in the critical stress region, they may tend to reduce the rolling-element fatigue life. The material hardness for the test bearings was controlled to Rockwell C 63±1 for the rings and Rockwell C 63±0.5 for the balls.

WB-49. - WB-49 is a material developed specifically for high temperature bearing applications (ref. 6). It contains considerably more alloying elements than either the M-50 or the M-1 material. The inherent difficulty with this material is the tendency toward rather massive carbide segregation such as that shown in the photomicrograph in figure 4 which, at least in the present case, could not be sufficiently broken up during forging to eliminate their effect as stress raisers.

The WB-49 rings were heat treated to a room temperature hardness of Rockwell C 64±0.5. The WB-49 bearings used M-1 tool steel balls from the same heat as that for the AISI M-1 bearings. Previous experience (ref. 12) has shown that WB-49 balls could not be manufactured without producing incipient microcracking. As a result, balls made from WB-49 had extremely short fatigue lives.

Hardness Testing

The hardness of the materials was measured at both room temperature and elevated temperatures using a Rockwell hardness tester fitted with an electric furnace. Tests were performed using a 150-kilogram (1471-N) load and a Rockwell C diamond indenter. Consequently, the test results can be directly related to standard room temperature Rockwell hardness measurements. Specimens from the same heats as those that were fatigue tested were selected at random for hardness testing. 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. However, previous experience (ref. 10) has indicated that a 1/2-point Rockwell C loss in hardness can occur because of tempering during the grinding process.

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. The results of these measurements for the three materials used in this investigation, AISI M-50, AISI M-1, and WB-49, are shown in figure 5. From these data at 600° F (588 K) the

AISI M-50 hardness is approximately Rockwell C 58. For the AISI M-1 and WB-49 the hardnesses at 600° F (588 K) are approximately equal at Rockwell C 60.5. For standard heat treatment the hardness at 600° F for the tests reported herein are probably near maximum for each of these three materials at this temperature.

Test Lubricant

A synthetic paraffinic oil (synthesized hydrocarbon oil) was used as the test lubricant. A standard ASTM chart showing the viscosity-temperature relation of this fluid is presented in figure 6. Properties of the synthetic paraffinic oil are given in table III. This lubricant is a 100-percent paraffinic fluid with relatively high viscosity at high temperature (fig. 6). It contains an antiwear additive and an antifoam agent. It was necessary to maintain this fluid in a low oxygen environment (less than 0.1 percent oxygen by volume) at 600° F (588 K) in order to prevent oxidation.

Using a two disk rolling-element apparatus and an X-ray measuring technique (ref. 2), the film parameter Λ was determined under conditions which simulated the contact temperature, load, and speed of the 120-millimeter angular-contact ball bearing. At 600° F (588 K) the value of Λ was approximately 1.8 with this lubricant at the inner-race ball contact (ref. 2) where

$$\Lambda = \frac{h}{\sigma}$$

$$\sigma = \left(\sigma_1^2 + \sigma_2^2\right)^{1/2}$$

and where

h	minimum film thickness, in. (cm)
σ	composite surface roughness, in. (cm) rms
σ_1, σ_2	surface roughness of contacting bodies, in. (cm) rms

Method of Presenting Fatigue Results

The statistical methods of reference 13 for analyzing rolling-element fatigue data were used to obtain a plot of the log-log of the reciprocal of the probability of survival as a function of the log of bearing inner-race revolutions to failure (Weibull coordinates).

For convenience, the ordinate is graduated in statistical percent of bearings failed. From a plot such as this, the number of bearing inner-race revolutions necessary to fail any given portion of the bearing 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 inner-race revolutions at which 10 percent of the bearings 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 bearing failures out of those tested.

RESULTS AND DISCUSSION

Fatigue Tests

Groups of 120-millimeter bore angular-contact ball bearings made from consumable-electrode vacuum-melted (CVM) AISI M-50, AISI M-1, and WB-49 steels were tested. Test conditions were a thrust load of 5800 pounds (25 000 N), which produced maximum Hertz stresses of 323 000 and 267 000 psi (223 000 and 184 000 N/cm^2) on the inner and outer races, respectively; a speed of 12 000 rpm; and a synthetic paraffinic oil as the lubricant. The lubricant had an antiwear additive and an antifoam agent. The outer-race temperature was 600° F (588 K). The inlet oil temperature was 545° to 565° F (558 to 564 K). The bearing test chamber and the lubricant sump were kept under a low oxygen environment (less than 0.1 percent of volume) in order to prevent the oil from oxidating.

Fatigue-life results for 26 bearings tested with the bearings made from M-50 material are shown in figure 7(a). The failure index (i.e., the number of fatigue failures out of the number of bearings tested) was six out of 26. The AFBMA predicted (catalog) life at this load condition is also given for comparative purposes. These data are summarized in table IV. The location of the failure is summarized in table V. Because of the lack of sensitivity of the test rig shutoff system, a spall can develop on more than one component of the bearing before the rig shuts down.

Typical fatigue spalls occurring on the balls of a M-50 bearing are shown in figure 8. Metallurgical examination of all failures (where one element failed) indicated that the fatigue spalls were of subsurface origin, initiating in the zone of resolved maximum shearing stresses. A cross section of a failed ball is shown in the photomicrograph of figure 9. The subsurface initiated spall is characterized by a plurality of subsurface cracks emanating below the surface and propagating into a crack network. Eventually these develop into a typical fatigue spall or pit. An inner-race failure is shown in figure 10. A bearing run to the suspension of a test (500 hr) is shown in figure 11.

The fatigue lives of the bearings made from AISI M-1 steel are shown in figure 7(b). For this group of bearings there were six fatigue failures out of 24 bearings tested. As with the M-50 material, the fatigue failures were of a subsurface origin emanating from the zone of resolved maximum shearing stresses. Typical fatigue failures with the M-1 bearings are shown in figure 12. The M-1 bearings that were run to suspension (750 hr) are identical in appearance to the M-50 bearings shown in figure 11.

The fatigue scatter with M-1 bearings, of which the inverse of the Weibull slope is a measure, is rather large relative to the M-50 bearing. Generally, for SAE 52100 steel, a Weibull slope of 1.1 is considered to be normal. From reference 13 the probably error for the slope can be ±20 percent for both the M-1 and M-50 material.

The results obtained with the bearings made from the WB-49 material are shown in figure 7(c). Because of problems in fabricating balls made from WB-49 steel, the balls in these bearings were made of M-1 steel from the same batch as those balls run with the M-1 balls. Out of the 30 bearings tested, 28 failed by fatigue. The probable error of the Weibull slope for this set of bearings is ±9 percent. A representative failure is shown in figure 13.

From table V there was only one M-1 ball failure unaccompanied by a race failure. This occurred in combination with failure of the second bearing of the pair; this second bearing suffered a race failure after approximately 7 hours. As a result the M-1 ball failure can be attributed to debris from the mating bearing. The other ball failures were in combination with an inner- and/or outer-race failure. In these cases it may be speculated that the race failure occurred before the ball failure because of the generally longer lives these balls exhibited in the M-1 bearings.

The confidence that can be placed in the experimental results was determined statistically using the methods given in reference 13. Each test bearing group was compared with the M-50 results. Confidence numbers for the 10-percent life were calculated and are presented in table IV. The confidence number for M-1 of 67 percent means that 67 out of 100 times the 10-percent life of the M-1 bearings will be less than that of M-50 bearings. A 68-percent confidence is approximately equal to a one-sigma deviation, which, for statistical purposes, is considered to be insufficient to conclude that there is any difference in 10-percent life between the materials. Hence, from these data, the fatigue-life difference between the M-50 and M-1 steels can be considered to be statistically insignificant at 600° F (588 K). However, the difference between the WB-49 and both the M-50 and M-1 materials is statistically significant (a 95-percent confidence number is equivalent to a two-sigma deviation). For the M-50 and M-1 bearings run with the synthetic paraffinic oil, the experimental bearing 10-percent life exceeds the AFBMA predicted (catalog) life by a factor in excess of 13 and 6, respectively. As a result, for these two materials no derating of bearing life is required. However, the WB-49 was less than half the AFBMA predicted (catalog) life. Hence, this material would have to be derated.

METALLURGICAL VARIABLES

References 9 and 10 report a trend of decreasing rolling-element fatigue life and increasing total combined percentages of alloying elements, specifically tungsten, chromium, vanadium, molybdenum, and cobalt. This relationship is shown in figure 14. From table I, the total percentage of these alloying elements for the materials used in this investigation is also shown in this figure for comparative purposes. From these data, relative lives based on the percentage of alloying elements for the bearings made from AISI M-50, AISI M-1, and WB-49 were predicted and are given in table VI. Also given for these materials are the relative experimental lives. A good correlation is indicated between the two, which reinforces those data of references 9 and 10.

The general microstructure of three materials appears to be quite similar, consisting primarily of tempered martensite. The most obvious difference among them, however, is the size, frequency, and density of the metal carbides. X-ray difraction measurements have shown retained austenite levels to be less than 3 percent for all materials.

There is a more pronounced delineation of the prior austenitic grain boundaries in the M-1 and WB-49 than with the M-50 material. This may be due in part to the higher austenitizing temperatures as shown in table II (2175° and 2200° F) (1464 and 1478 K) versus 2025° F (1381 K) for the M-50. This would improve the degree of solutioning and consequent reprecipitation of the alloy carbides into the grain-boundary areas. It is known that vanadium carbides in particular will react in this manner (ref. 14).

It would also appear that the majority of the visible carbides in the M-1 and WB-49 are those originally present in the as-cast conditions. The smaller more uniformly dispersed carbides are most likely those which are solutioned and reprecipitated during the subsequent heat treatments.

Since it seems reasonable to consider the possibility that the difference in fatigue life could be largely attributed to the incidence, size, shape, and location of the carbides, it is appropriate to briefly review the makeup of these carbides in terms of the alloying elements on each of the three materials. Specifically the carbide formers, such as, chromium, vanadium, tungsten, and molybdenum, are of interest.

The other major alloying element, cobalt, is not considered to be a major carbide former, although it may contribute incidentally to the formation of other alloy carbides.

In any steel requiring the high hardnesses of those in the present study, the presence of sufficient amounts of carbon is necessary. However, because of the relatively small differences in the amount of carbon in the various bearing alloys, it is not considered as a variable in the present case.

Chromium

Considering the amounts of chromium and carbon in the three materials, two chromium carbides are expected to occur: Cr_7C_3 and $Cr_{23}C_6$ (refs. 15 to 18). Since $Cr_{23}C_6$ has some solubility in other carbide-forming elements and iron (ref. 19) it is called the $M_{23}C_6$ type of carbide, where M denotes the metal atom in the carbide. This is the most stable chromium carbide and is usually observed in steels that have been tempered extensively.

At the normal austenitizing temperatures of the three bearing steels, nearly all of the chromium carbide should go into solution in austenite (ref. 19), and the total carbon from this carbide is therefore available to the martensite formed during the subsequent quenching of the steel. Consequently, most of the chromium carbides are precipitated in either the grain boundaries or as small spheroidal particles uniformly dispersed throughout the matrix. In view of the nearly equal amounts of chromium in the three steels, the incidence and location of the chromium carbides should be common to all the subject materials.

Vanadium

Vanadium is a strong carbide former and is known to form a NaCl type of carbide which is identified as either VC or V_4C_3 (refs. 18, 20, and 21). However, the carbide usually observed in the steel has been found to have an intermediate composition. It has been suggested (ref. 18) that the probable reason for the difference in the reported compositions of the vanadium carbide is that VC and V_4C_3 form solid solutions. For instance, to form the VC carbide, 1 percent vanadium combines with 0.235 percent of the carbon, and, in the formation of V_4C_3, 1 percent of the element combines with 0.177 percent of the carbon.

The vanadium carbide has slight solubility for other carbide forming elements in the steel and therefore is called an MC carbide (ref. 19). At the usual austenitizing temperatures only a part of this carbide is dissolved in the austenite. The residual carbide then remains essentially in its massive as-cast form and may contribute to the heavy carbide masses observed in the WB-49 and to a lesser extent in the M-1. A beneficial effect of the residual vanadium carbide is that it does allow the steel to be heated to high austenitizing temperatures without causing pronounced grain growth.

In the case of tool steels, the residual vanadium carbides also serve to improve wear resistance. Although this factor is not applicable nor necessary to bearing steels, it does explain why this alloying element is present to such a relatively large percentage in the three subject steels. They are, after all, basically tool steels, including the

WB-49, which, while ostensibly developed as a bearing steel, was formulated with a tool steel criterion.

Tungsten and Molybdenum

These two strong carbide formers probably represent the major difference in the chemistries between M-50 and M-1 or WB-49. As a result they may account for most of the massive carbide segregation seen in M-1 and WB-49. Tungsten and molybdenum are expected to behave similarly in the three steels. Both alloying elements form the same type of carbide in which the metallic elements are interchangeable. Several investigators report that MC, M_2C, M_6C, and $M_{23}C_6$ occur in tungsten or molybdenum steels (refs. 15, 18, 20, and 22). The metal-to-carbon ratio in the steel and the austenitizing temperature seem to be the factors controlling the formation of these carbides (refs. 20 and 22). It has also been shown (refs. 20 and 22) that M_2C is mainly responsible for the secondary hardening reaction in tungsten or molybdenum steels. This transition carbide is formed on tempering the quenched steels. Later it is transformed into M_6C, which is believed to be the most stable carbide. The usual compositions listed for M_6C are $Fe_4(W, Mo)_2C$ and $Fe_3(W, Mo)_3C$. Although this is principally a tungsten molybdenum complex carbide, it has some solubility for other carbide-forming elements in the steel.

At the austenitizing temperatures of the three subject steels, an appreciable portion of the tungsten and molybdenum carbides are expected to remain undissolved in the austenite (ref. 19). Consequently, in addition to not contributing to the age-hardening reactions that take place during tempering of the hardened steel, they remain as the massive carbides observed in the microstructures of the WB-49 and M-1 material.

In view of the preceding, it does not seem unreasonable to speculate whether the structure of the material, specifically the incidence, shape, size, and location of the carbides, is perhaps much more influential in terms of rolling-element fatigue performance than any other metallurgical consideration. In a sense this has been indicated in the work performed on ausforming of M-50, (refs. 23 and 24) where significant improvements in fatigue life have been obtained on M-50 material by thermomechanical working, without any modification of the basic chemistry. The prime function of the ausforming is to refine the structure as well as to disperse the carbides more uniformly and reduce their tendency toward critical segregation.

SUMMARY OF RESULTS

Groups of 120-millimeter bore angular-contact ball bearings made from consumable-electrode vacuum melted AISI M-50, AISI M-1, and WB-49 steels were fatigue tested with a synthetic paraffinic oil at a bearing outer-race temperature of 600° F (588 K). Test conditions included a speed of 12 000 rpm and a thrust load of 5800 pounds (25 800 N) producing a maximum Hertz stress of 323 000 psi (233 000 N/cm^2) on the bearing inner race.

1. The experimental life of the bearings made from the AISI M-50 and AISI M-1 steels exceeded the AFBMA predicted (catalog) life by factors in excess of 13 and 6, respectively.

2. The experimental life of the WB-49 bearings was less than half AFBMA predicted (catalog) life.

3. An apparent correlation exists between rolling-element fatigue life and carbides (incidence, size, shape, and location) as affected by the amount and type of alloying element.

4. For all three materials tested the mode of failure was classical subsurface initiated rolling-element fatigue.

Lewis Research Center,
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TABLE I. - CHEMICAL ANALYSIS OF BEARING MATERIALS

Materials	Components	Element, wt. %											
		C	Mn	P	S	Si	Cr	Mo	V	Ni	W	Co	Fe
AISI M-50	Rings and balls	0.80	0.24	0.008	0.003	0.18	3.95	4.46	0.93	-----	----	----	Bal.
AISI M-1	Balls for WB-49 and M-1 bearings	.80	.28	.020	.005	.29	3.74	8.71	1.11	-----	1.53	----	Bal.
WB-49	Rings	1.06	.44	.004	.008	.32	4.22	3.76	1.86	0.08	6.82	5.29	Bal.
AMS 4892[a]	All retainers	.06	.74	-----	-----	3.69	----	----	----	65.28	----	----	0.66

[a] Also contains 28.78 percent copper.

TABLE II. - HEAT TREATMENT CYCLES FOR BEARINGS[a]

Material	Preheat		Austentize		Quench sequence	Tempering cycles		
	°F	K	°F	K		Step a	Step b	Step c
AISI M-50	700 1200 1550	644 933 1115	2025±15	1380±8.3	Quench to 1000° F (811 K) in 250° F (395 K) oil; air cool to room temperature	1025° F (824 K) for 2 hr; air cool; -120° F (189 K) for 3 hr	1025° F (824 K) for 2 hr; air cool; -120° F (184 K) for 3 hr	1025° F (824 K) for 3 hr; air cool
AISI M-1	1500	1088	2150±15	1450±8.3	Liquid nitrogen quench	-100° F (200 K) for 1 hr; 1000° F (811 K) for 2 hr	-100° F (200 K) for 1 hr; 1000° F (811 K) for 2 hr	---------------------
WB-49	700 1550	644 1115	2200±15	1476±8.3	Air cool	1025° F (824 K) for 3 hr; oil quench; -120° F (189 K) for 2 hr	1025° F (824 K) for 2 hr; oil quench; -120° F (828 K) for 2 hr	1025° F (824 K) for 2 hr; oil quench

[a] Does not include stress relief treatments during final grinding.

TABLE III. - PROPERTIES OF SYNTHETIC PARAFFINIC OIL

Kinematic viscosity, cs, at -	
100° F (311 K)	443.3
210° F (372 K)	39.7
400° F (478 K)	5.8
Flash point, $^\circ$F (K)	515 (542)
Fire point, $^\circ$F (K)	600 (588)
Autoignition temperature, $^\circ$F (K)	805 (814)
Pour point, $^\circ$F (K)	-35 (236)
Volatility (6.5 hr at 500° F (533 K)), weight percent	14.2
Specific heat at 500° F (533 K), Btu/(lb)($^\circ$F) (J/(kg)(K))	0.695 (2.91×10^3)
Thermal conductivity at 500° F (533 K), Btu/(hr)(ft)($^\circ$F) (J/(m)(sec)(K))	70×10^{-3} (0.12)
Specific gravity at 500° F (533 K)	0.71
Additives	Antiwear agent Antifoam agent

TABLE IV. - FATIGUE-LIFE RESULTS FOR 120-MILLIMETER BORE ANGULAR-CONTACT BALL BEARINGS MADE FROM THREE HIGH-TEMPERATURE BEARING STEELS

[Thrust load, 5800 lbf (25 800 N); speed, 12 000 rpm; temperature, 600° F (588 K). All materials consumable-electrode vacuum melted.]

Material	Experimental life, millions of inner-race revolutions		Weibull slope	Failure index	Confidence number at 10-percent life level	AFBMA predicted 10-percent (catalog) life, millions of inner-race revolutions	Ratio of experimental 10-percent life to AFBMA-predicted life
	10-Percent life	50-Percent life		(a)	(b)		
AISI M-50	182	513	1.8	6 out of 26	---	13.4	~13.6
AISI M-1	89	2331	.6	6 out of 24	67	13.4	~6.7
WB-49[c]	6	26	1.3	28 out of 30	>99	13.4	~0.4

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

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

[c] Bearings had AISI M-1 balls.

TABLE V. - FAILURE LOCATION FOR 120-MILLIMETER BORE ANGULAR-CONTACT BALL BEARINGS MADE FROM THREE HIGH-TEMPERATURE BEARING STEELS

Material	Failure index (a)	Failure location					
		Inner race	Outer race	Ball	Inner and outer races	Inner race and ball	Inner-outer races and ball
AISI M-50	6 out of 26	3	-	2	-	1	-
AISI M-1	6 out of 24	--	-	3	-	3	-
WB-49	28 out of 30	13	1	1	1	6	6

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

TABLE VI. - COMPARISON BETWEEN ACTUAL AND PREDICTED ROLLING-ELEMENT FATIGUE LIFE BASED UPON PERCENT WEIGHT OF ALLOYING ELEMENTS

Bearing steel	Total weight percent of alloying elements[a]	Predicted relative life[b]	Actual relative life[c] at 600° F (588 K)
AISI M-50	9.24	1	1
AISI M-1	15.09	.7	.5
WB-49	21.95	.4	.03

[a] Alloying elements are tungsten, chromium, vanadium, molybdenum, and cobalt. Carbon is not included in these percentages.

[b] Comparison predicted all three materials to be of equal hardness (see fig. 14).

[c] See table IV.

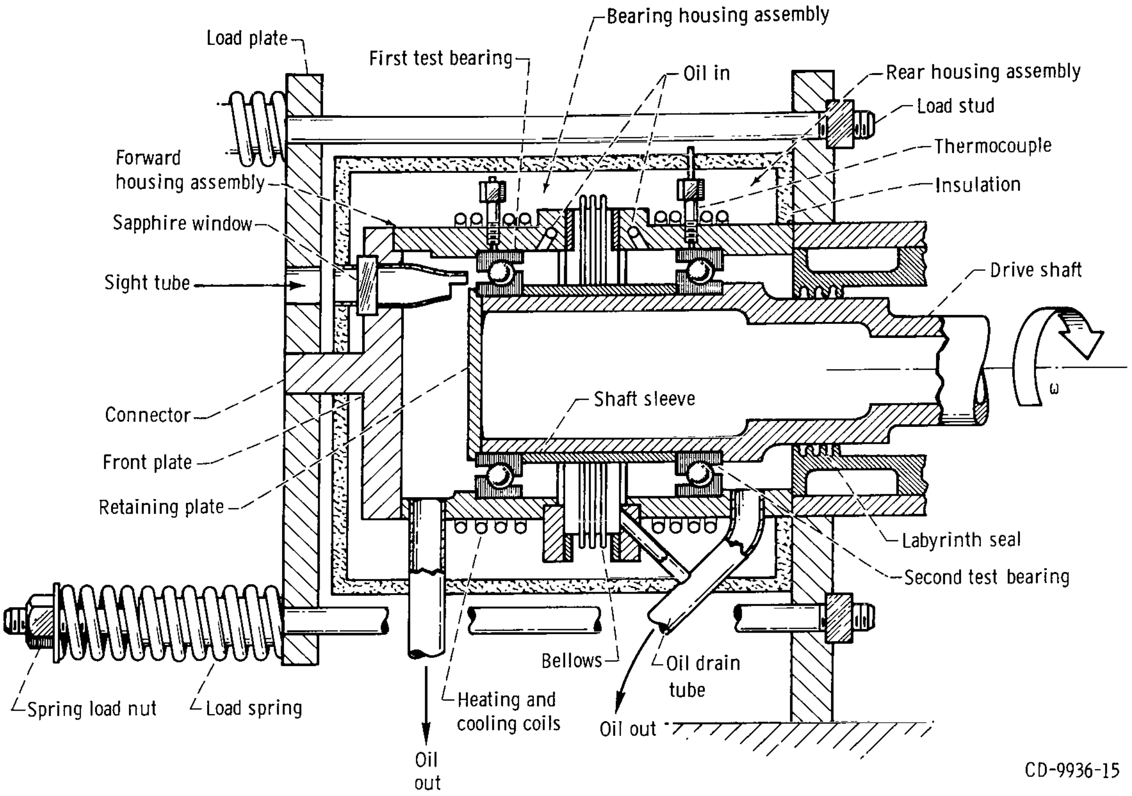
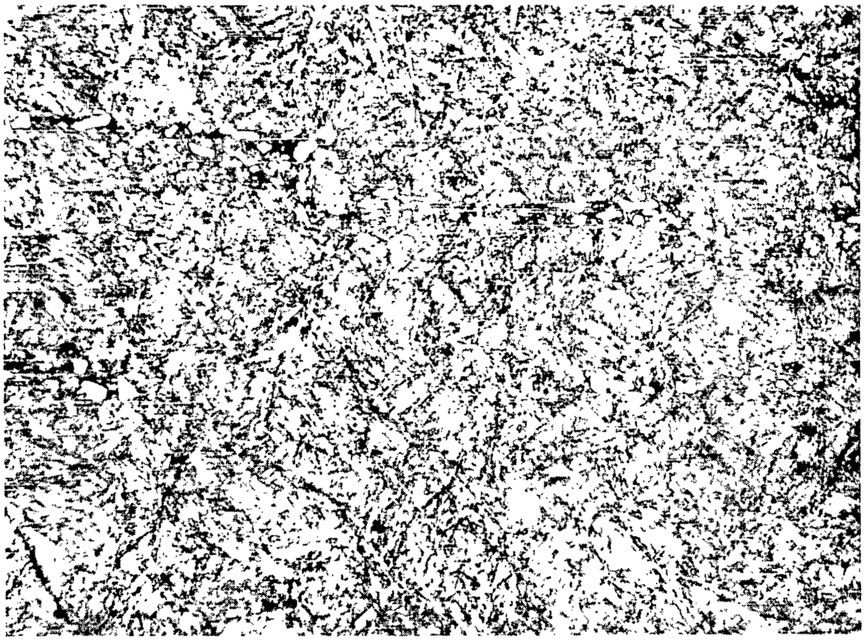
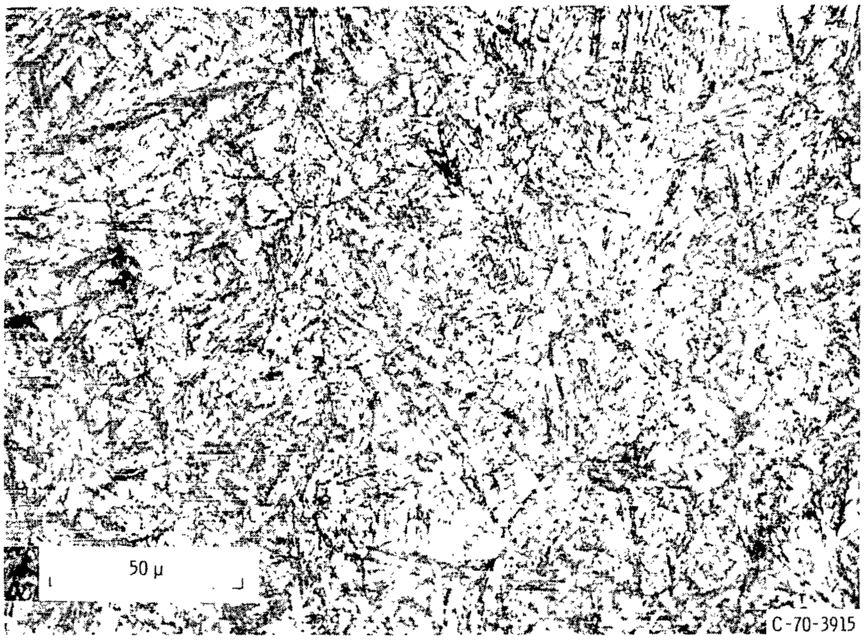


Figure 1. - High-temperature bearing fatigue test apparatus.

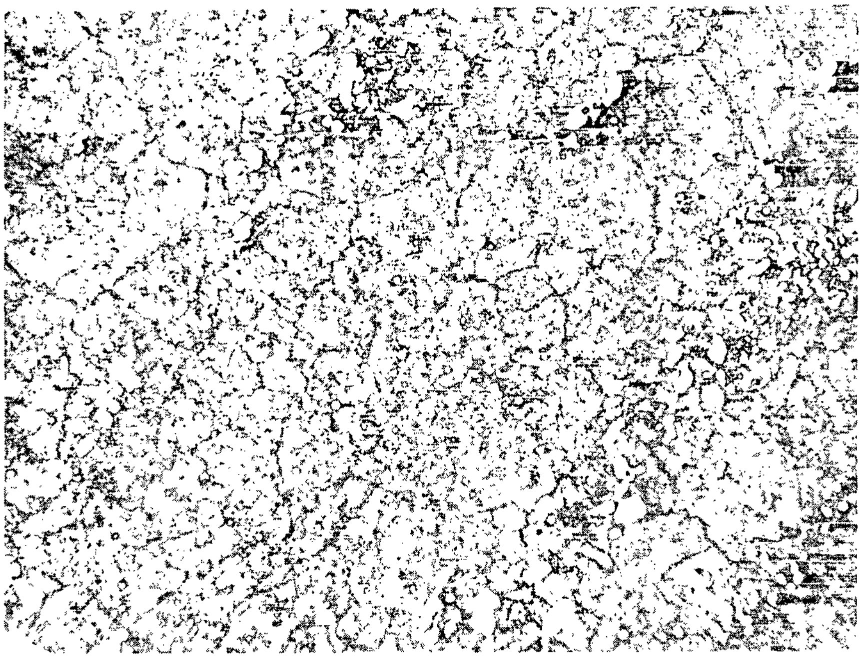


(a) Race material.

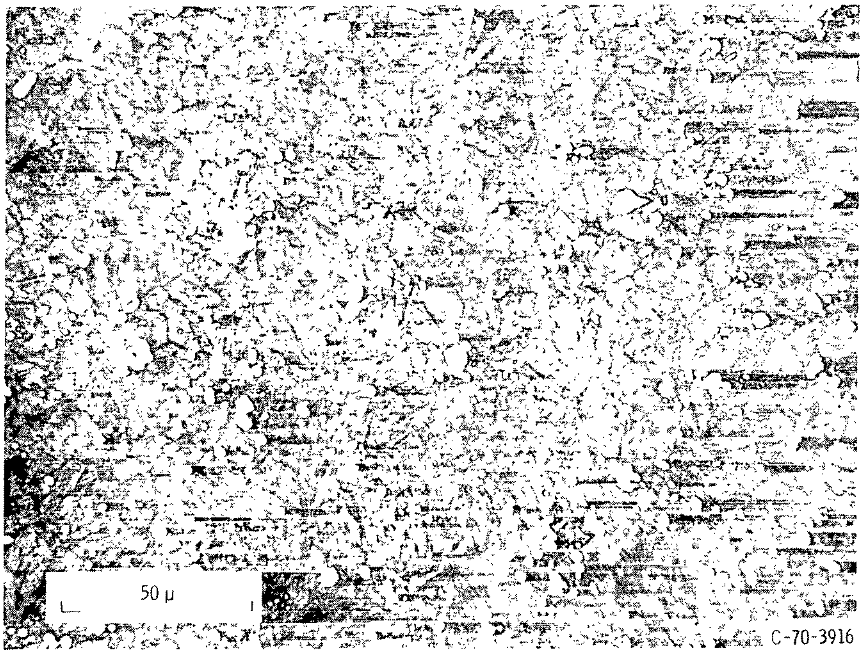


(b) Ball material.

Figure 2. - Microstructure of CMV AISI M-50 steel. Etchant, 5 percent nital.



(a) Race material.



(b) Ball material.

Figure 3. - Microstructure of CMV AISI M-1 steel. Etchant, 5 percent nital.

Figure 4. - Microstructure CVM WB-49 steel used for bearing races. Etchant, 5 percent nital.

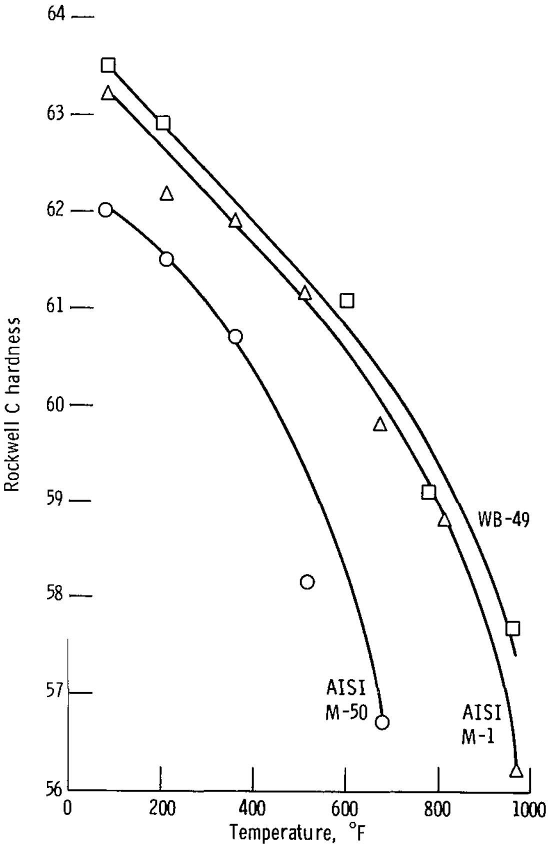


Figure 5. - Hardness as function of temperature for bearing test materials.

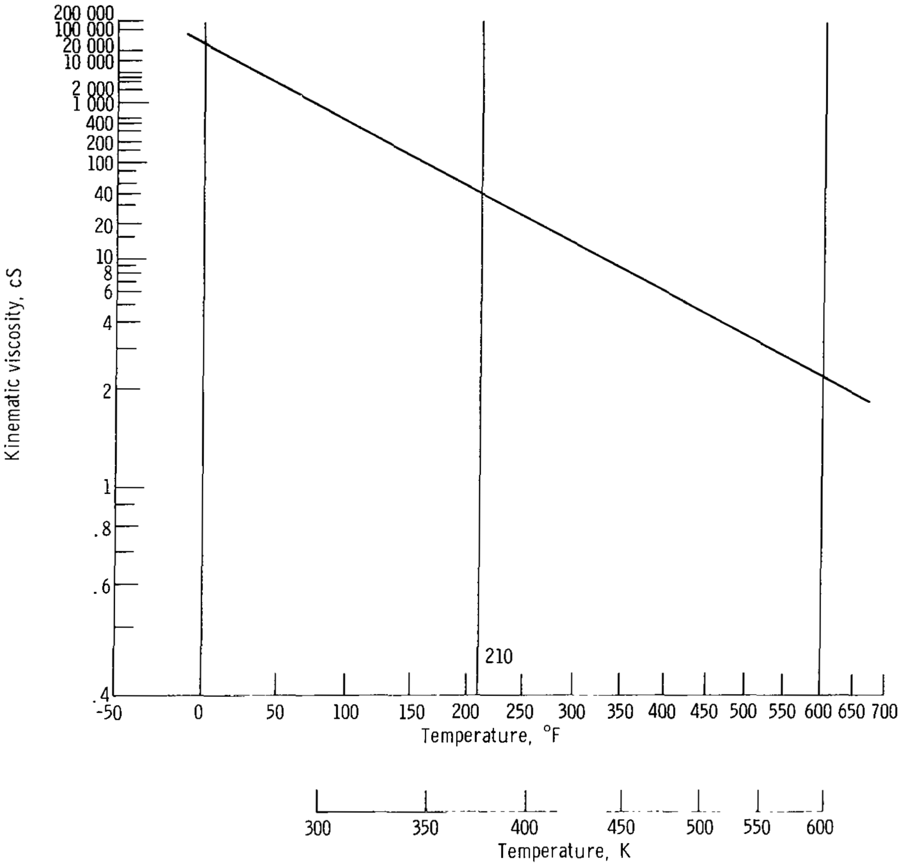
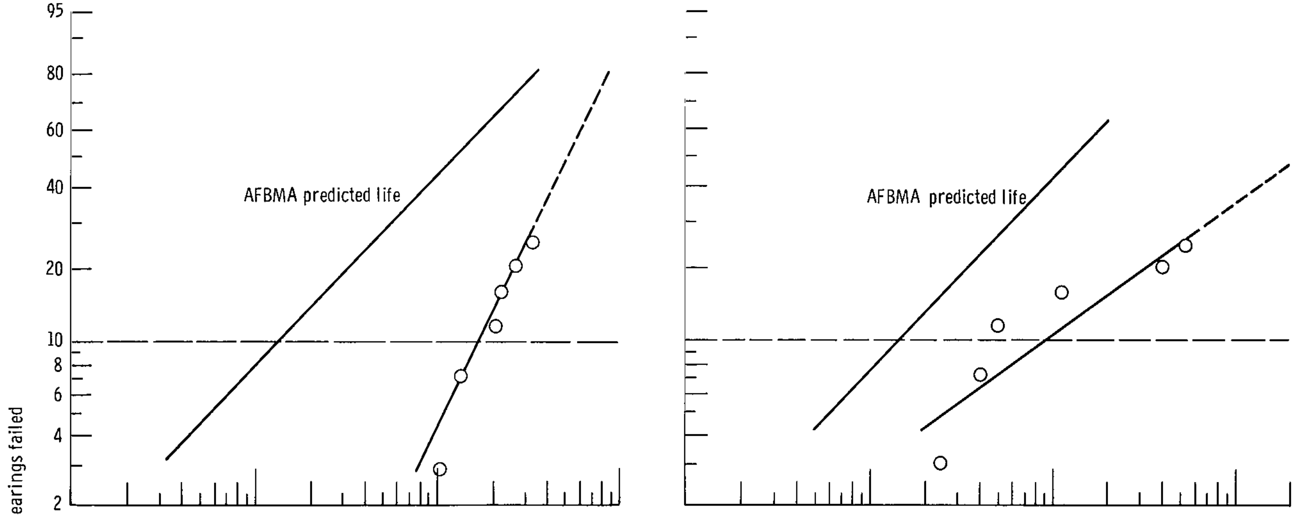
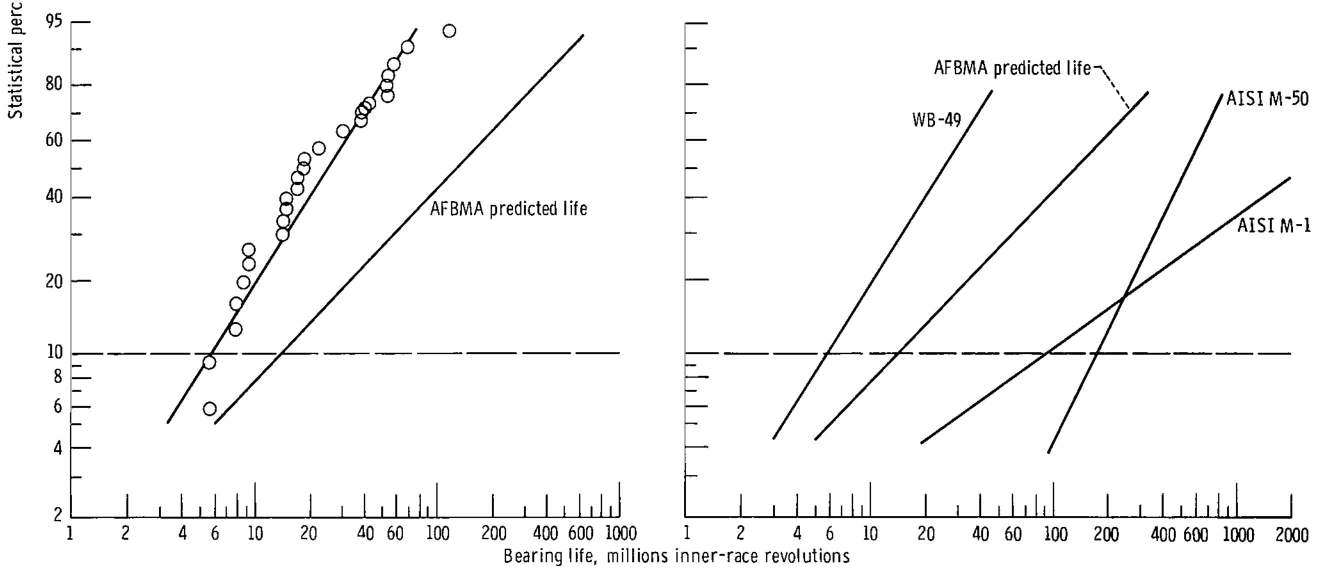


Figure 6. - ASTM chart of lubricant kinematic viscosity of synthetic paraffinic oil as a function of temperature.



(a) Material, AISI M-50; failure index, 6 out of 26.

(b) Material, AISI M-1; failure index, 6 out of 24.



(c) Material, WB-49 with AISI M-1 ball compliment. Failure index, 28 out of 30.

(d) Summary.

Figure 7. - Rolling-element fatigue life of 120-millimeter bore angular-contact ball bearings made from three high-temperature bearing steels. Thrust load, 5800 pounds (25 800 N); speed, 12 000 rpm; temperature, 600° F (588 K); low oxygen environment.

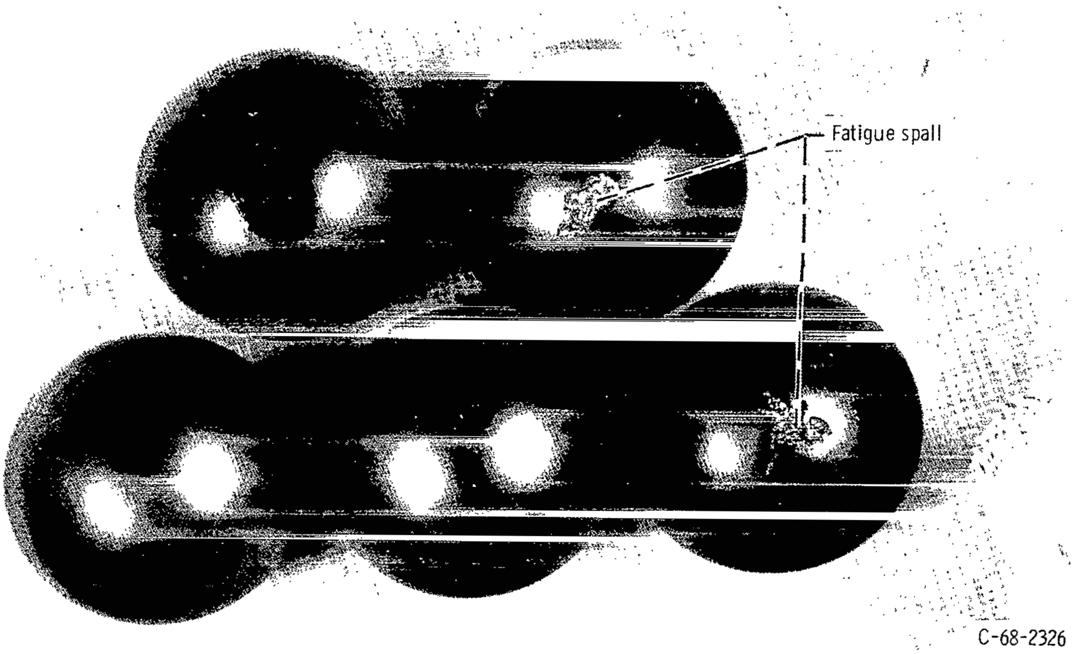


Figure 8. - Typical fatigue spalls on bearing balls run with synthetic paraffinic oil. Material, AISI M-50 steel; thrust load, 5800 pounds (25 800 N); speed, 12 000 rpm; temperature, 600° F (588 K); low-oxygen environment; running time, 375 hours (270×10^6 inner-race revolutions).

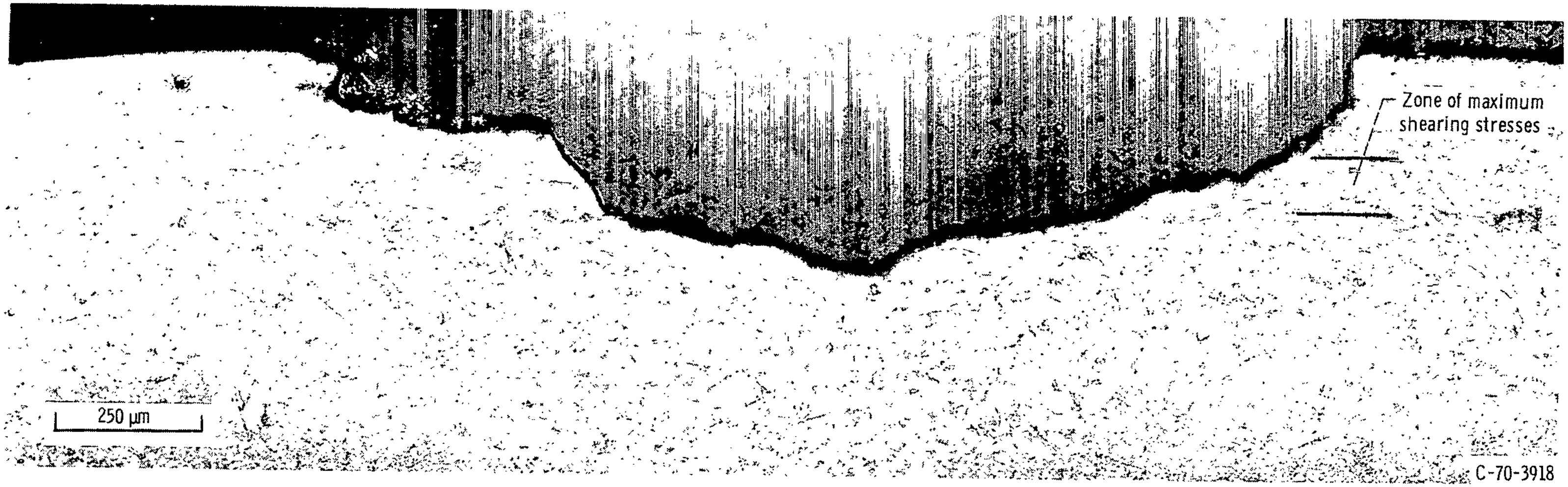


Figure 9. - Representative fatigue spall in AISI M-50 ball. Zone of maximum shearing stresses, 0.007 to 0.011 inch (0.018 to 0.028 cm) below surface. Etchant, 3 percent nital.

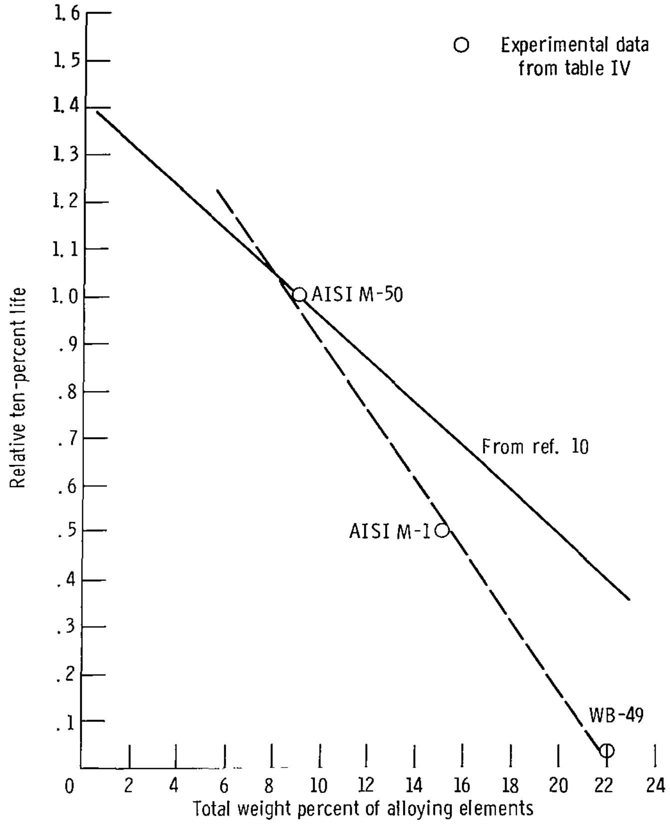


Figure 14. - Relationship between total weight percent of alloying elements, tungsten, chromium, vanadium, molybdenum, and cobalt, on rolling-element fatigue life.

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