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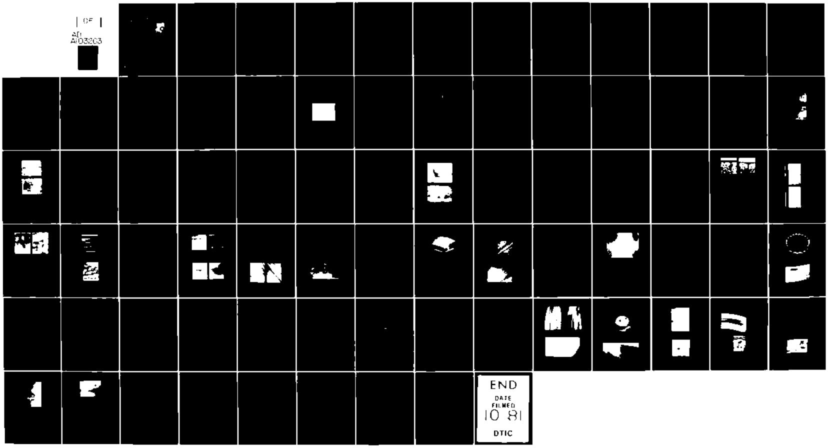

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EVALUATION OF POWDER PROCESSED TURBINE ENGINE BALL BEARINGS

United Technologies Corporation
Pratt & Whitney Aircraft Group
Government Products Division
P.O. Box 2691
West Palm Beach, Florida 33402

June 1981

Final Report for Period 19 May 1980 - 30 September 1980

Approved for Public Release; Distribution Unlimited

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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20. Abstract *(Continue on reverse side if necessary and identify by block number)*

Rolling element fatigue life testers, as well as full-scale bearing testers, were used to develop a highly rolling contact fatigue resistant powder processed material (P/M) for use in aircraft turbine engine bearings. Ball and rod elemental tests were conducted, for screening purposes, on three P/M alloys; M-50, T-15 and CRB-7. The best results were realized with the P/M CRB-7 material, a 14 percent chrome corrosion resistant alloy, which demonstrated a B10 life almost twice that of the baseline, conventionally processed VIM-VAR M-50. Twenty full-scale 140 mm ball bearings were

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20. **Abstract** *(Continued)*

subsequently fabricated from P/M CRB-7 alloy. The B10 life realized with these bearings was equivalent to that expected from these same bearings had they been made from conventional VIM-VAR M-50 material. This good result was achieved in spite of an inner ring land wear problem which was alleviated by plating the lands with hard nickel.

FOREWORD

This report describes the work performed by Pratt & Whitney Aircraft Group under U.S. Air Force Contract F33615-76-C-2009, Project No. 3048. This report is submitted in accordance with Section II, Exhibit A of the contract and Sequence No.A007 of DD Form 1423, and covers work performed from 19 May through 30 September 1980.

The Government Technical Manager for this program was Dale R. Schulze of the Air Force Aero Propulsion Laboratory, WPAFB (telephone 512-255-5568). The project was conducted at Pratt & Whitney Aircraft Group under the direction of John Miner, Component Technology Manager; Paul Brown, Principal Investigator, and Glen Bogardus, Program Manager. Engineering assistance was provided by Robert Cohen, with metallurgical support by Otis Chen. Gerald McCarthy of United Technologies Research Center provided the transmission electron microscopy documentation.

Acknowledgement is accorded to the technical and coordination assistance contributed by the following companies: Carpenter Technology Corporation for the powder metal processing, TRW Bearing Division for fabrication of the rolling elements and bearings, and the Tribon Bearing Company for the testing of the full scale bearings.

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INTRODUCTION

1.1 BACKGROUND

The advance of aircraft turbine engine technology is forcing improvements in the state of the art of the design and fabrication of mainshaft bearings. Engine configurations and economic considerations require bearing designs to be capable of operating in an environment of higher speeds, loads, and temperatures and for longer periods of time creating the need for increased rolling contact fatigue resistance. New materials or processes which would extend bearing life through improvement in both rolling contact fatigue performance and corrosion resistance would thus benefit the industry.

Powder metal technology provides an extremely attractive and promising approach for satisfying these requirements and has further merit because of its cost reduction potential. A principal source of rolling contact fatigue failure in present high quality M-50 alloy bearings for aircraft engines is the occurrence of undesirably large carbide formations in the metal matrix. These act as points of weakness under the highly cyclic loading experienced in bearing operation, and ultimately become the origin of fine cracks which lead to spalling and bearing failure. The use of powder metal processing promises to produce alloys with uniform carbide distribution and to minimize carbide size. Carbide size would be limited to the dimensions of the powder particles and would not change in size as a result of subsequent processing. Although the potential of powder metal for rolling contact bearings has been recognized for several years, it has only been within the relatively recent past that the necessary purity of the powder product has been realized to a level that makes it attractive for use in the subject application.

Powder metallurgy is a well established process for use in the manufacture of a multitude of critical parts, most notably in the automotive and aerospace industries. In spite of this good experience relatively little attention, prior to the conduct of the subject program, has been given to powder metallurgy techniques for the production of precision high performance rolling bearings. One of the reasons for this was the realization that rolling bearings cannot tolerate the use of anything less than 100% dense material. It was well known that powder metal parts were historically inferior in their mechanical properties due to residual porosity. This stigma was removed, however, with the development of Hot Isostatic Pressing (HIP) technology and related good field experience with high performance powder processed parts such as gas turbine disks for aircraft engine applications.

Several high speed M-series tool steels; e.g., M1, M2, M7 and M10, are being commercially produced with powder processing. Although not yet widely available on a commercial basis, powder processed M50 steel has also been produced. More exotic high temperature bearing materials, such as WADC-65, T-15, WB-49, BG-42 and CRB-7 (formerly EX-00007), which offer corrosion resistance in addition to hardness retention in the 850-1000°F temperature range, are also being produced through powder techniques.

1.2 OBJECTIVES

The basic objective of this program was to evaluate the rolling contact fatigue life capability of full scale gas turbine engine ball bearings manufactured from a selected powder processed high temperature bearing steel. It was anticipated that an improvement in performance over that of conventionally processed material would be demonstrated. Another objective was to select the bearing steel for this full scale test from among three candidate alloys to be evaluated for rolling contact fatigue resistance in a series of elemental laboratory tests.

1.3 PROGRAM APPROACH

A plan was developed for screening and testing various powder processed alloy candidates toward the goal of identifying the most promising material for manufacture into full scale bearings for subsequent B-10 life testing. The initial step involved review of historical data to identify the three best performing alloys from materials previously tested in the single ball fatigue machine as was reported in Reference 1. These alloys were then powder processed and evaluated in two different laboratory machines; the single ball rig and the RC rod element tester. The best performer was then selected for fabrication into full scale ball bearings with powder processing applied to the manufacture of the inner and outer races as well as to the balls. The bearings were then rig tested to determine their rolling contact fatigue B-10 life.

SECTION 2

ELEMENT TESTS

2.1 ALLOY SELECTION

Review of past single ball tester rolling contact fatigue data disclosed that of the many materials evaluated only two alloys had exhibited fatigue lives that equalled or surpassed that of M-50 alloy, the current standard for aircraft gas turbine use. These alloys are T-15, a high tungsten-cobalt tool steel with 4% chromium by weight, and a stainless steel alloy, CRB-7, which is 14% chromium. There is difficulty in assessing the relative performance of materials when the data being compared were acquired at different points in time spanning a period of years. The performance of the M-50 baseline material has changed over the years because of improvements in processing, manufacturing and quality control. For this reason the B-10 life data presented herein is identified with the calendar year of the test and on a relative or normalized scale to minimize confusion.

Balls manufactured from T-15 alloy were tested in 1965 in the single ball rolling contact fatigue test facility and the observed life of 15.57 million stress cycles was 1.77 times that of the longest lived M-50 steel tested up to that time as shown in Figure 1. At the time this data was obtained this life difference, although indicating a gain, was not considered high enough to warrant further evaluation of the material until now.

Single ball rolling contact fatigue tests are normally conducted with either of the two most widely used aircraft gas turbine engine oils; namely MIL-L-7808 or MIL-L-23699. Typical test results of these two oils in 1965 indicated there is no statistically significant difference in their performance, as shown in Figure 1, when used to evaluate M-50 alloy.

Many other candidate alloys were evaluated between 1965 and into the early 1970's and none of them exhibited fatigue life values that equalled the performance of M-50 or T-15. Notable among the many were

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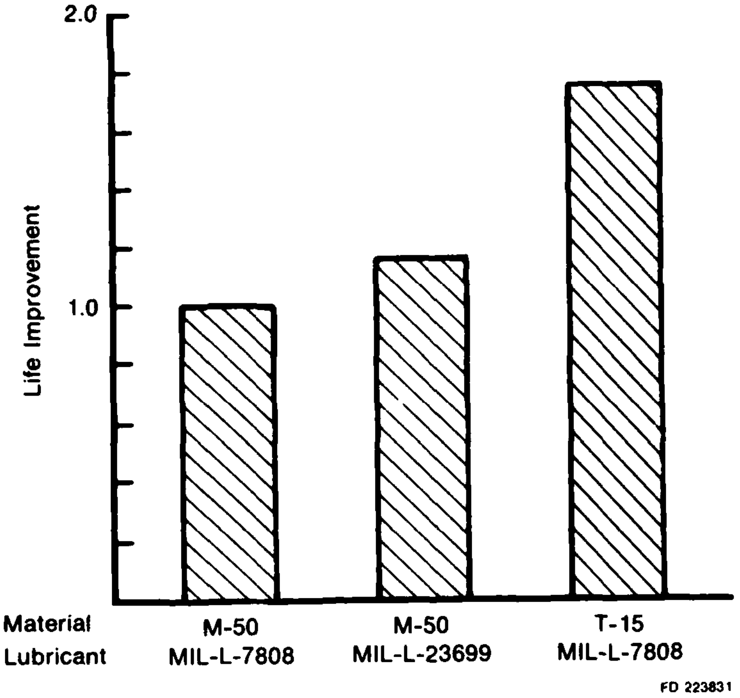

Figure 1. M-50 AND T-15 Alloy Life Improvement Comparison. The Single Ball Tester B-10 Life of T-15 is 1.77 Times That of M-50 in These 1965 Tests and no Statistically Significant Difference is Seen in The Performance of Two Widely Used Aircraft Oils.

WB-49, BG-42 and WADC-65 alloys which are compared to M-50 alloy B-10 life in Figure 2. WB-49 was tested in 1964 and its performance was 32% of the B-10 life of M-50, BG-42 alloy tested in 1968 had a B-10 life of only 71% of that of M-50 while WADC-65 tested in 1969 exhibited a fatigue life which was 64% of that of the baseline M-50 alloy.

An experimental alloy designated CRB-7, a material introduced in the mid '70's which is basically a stainless steel, produced a significant improvement in life results when tested in the single ball rigs. This is the only material, as provided from a laboratory heat, to equal or surpass current M-50 alloy performance and it produced the highest B-10 life in the history of single ball testing. This alloy was retested in 1975 but this time the balls were processed from a

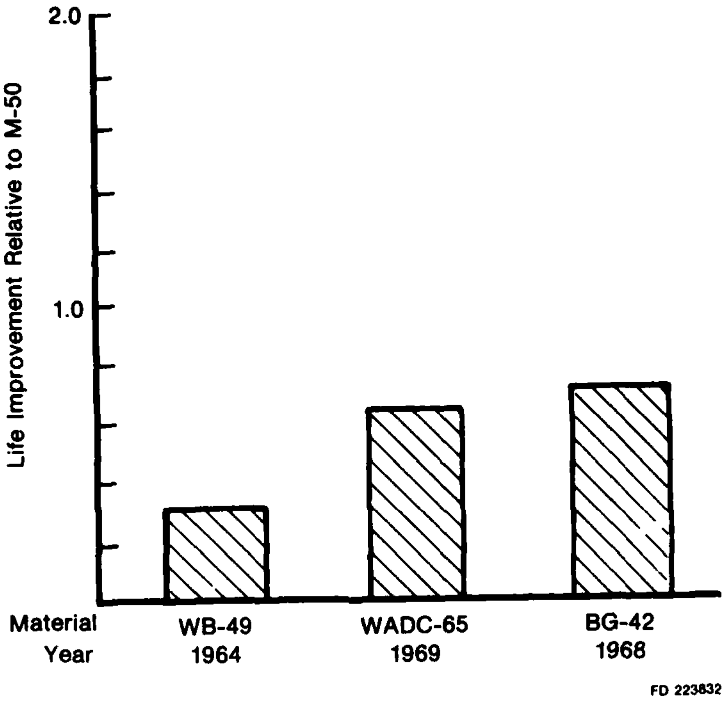

Figure 2. Life Improvement Comparison of Different Alloys. None of These Alloys Exceeded The Performance of M-50.

production quality ingot and produced fatigue life which eclipsed even the performance obtained from the laboratory heat ball lot. A comparison of these single ball fatigue life test results is presented in Figure 3.

On the basis of their single ball rolling contact fatigue test results, and other considerations, the three bearing alloys, M-50, T-15, and CRB-7, were selected for further evaluation in this powder metal development program. M-50 was chosen as the baseline material due to its widespread use in current service engines. In addition to their demonstrated fatigue life improvement, T-15 and CRB-7 also exhibited improved hot hardness and corrosion resistance beyond the levels available from AISI M-50 alloy steels. Available data on the hot hardness retention of these alloys is presented in Figure 4 and shows that T-15 and CRB-7 alloys are superior to that of M-50 and other stainless steels such as 14-4 and 440C.

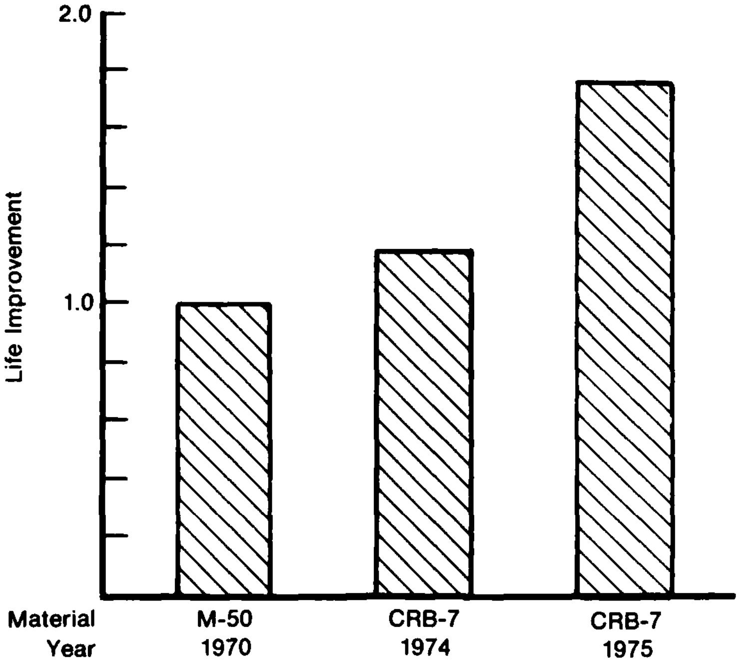

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Figure 3. M-50 and CRB-7 Life Improvement Comparison. The CRB-7 Alloy Produced The Best Life Rating in The History of Single Ball Rig Testing.

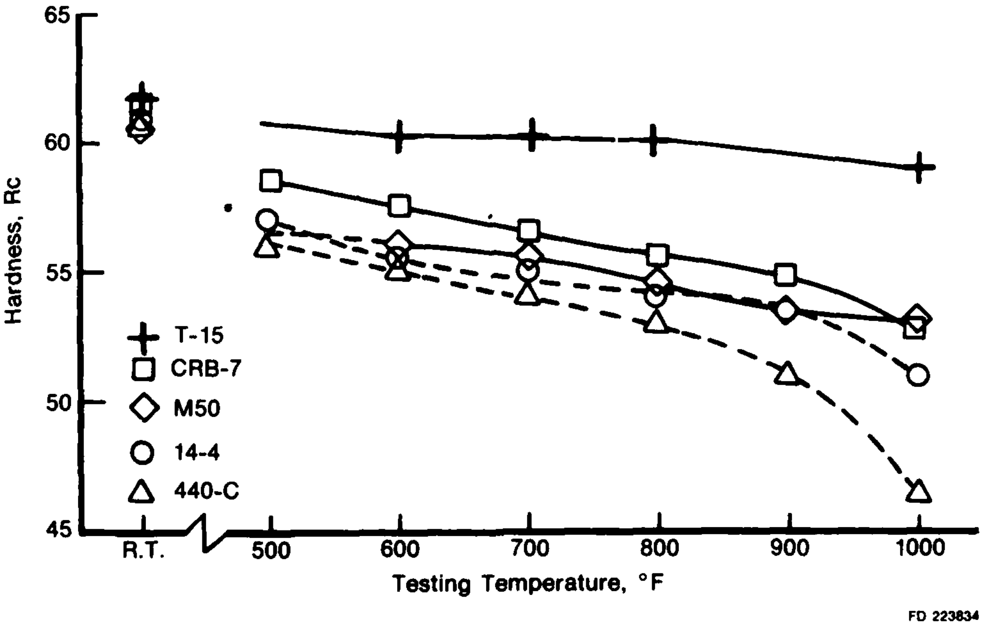

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Figure 4. Hot Hardness of Some Bearing Steels. Readings at Temperature After a 30-Min. Soak.

Available information on corrosion resistance does not exist on a common basis. Thus it is difficult to effect an absolute judgement in this regard, however, it is the opinion of many metallurgists that an alloy's chromium content governs the material's corrosion resistance. Thus, CRB-7 which has 14% chromium would have superior corrosion resistance compared to both M-50 and T-15, each contain only 4% chromium. The three alloys, M-50, T-15 and CRB-7, have chemical compositions which are significantly different as noted in Table 1. As a result they produce microstructures with marked differences in not only the number of carbides but in their distribution and morphology as well.

TABLE 1. ALLOY CHEMICAL COMPOSITION (WEIGHT PERCENT)

	C	Cr	Mo	V	W	Co	Cb	Si	Mn
CRB-7	1.1	14.0	2.0	1.0	---	---	0.3	0.3	0.4
T-15	1.6	4.0	---	5.0	12.0	5.0	---	0.3	0.3
M-50	0.8	4.0	4.2	1.0	---	---	---	0.2	0.2

2.2 POWDER PROCESSING AND CONSOLIDATION

The starting materials for the single ball program were conventionally processed ingots prepared either by Vacuum Induction Melting (VIM) or Vacuum Induction Melting-Vacuum Arc Remelting (VIM-VAR) techniques. Conversion of the ingots into powder was accomplished by initially melting the ingot by induction heating in a crucible in the upper section of the atomizing unit. After the metal became molten it was poured through an atomizing nozzle into another vacuum chamber located below the remelt chamber. The molten metal was discharged as refined droplets. They were solidified through cooling provided by high velocity inert gas and then dropped to the bottom of the chamber. Vacuum pumping acted continuously to maintain the chamber pressure well below atmospheric. This powder now contained carbides that were many times smaller than those that were present in the original mill ingot. The powders were later reconsolidated into new ingots at temperatures well below alloy melt temperature in order to ensure that no coalescence or growth of the alloy carbides occurred. By means of this process it was assured that the final product would exhibit refined carbides.

Powders smaller than 0.007 were retained and separation was accomplished by sieving the powders under an inert gas to prevent oxygen and nitrogen contamination of the powders. After the rough sieving, the various batches of powder were blended into a master blend to provide a homogeneous mixture. Particle size distribution shown in Table 2 indicated that the bulk of the powders were smaller than 0.0034 inch.

TABLE 2. BLENDED POWDERS PARTICLE SIZE DISTRIBUTION (WEIGHT PERCENT)

Mesh Size Wires Per Inch	Average Size Micro Meters (inches)	Alloys		
		M-50	T-15	CRB-7
- 80, +100	162.6 (0.0064)	1.0	1.0	3.0
-100, +140	127.0 (0.0050)	9.1	10.2	15.2
-140, +200	86.4 (0.0034)	16.8	17.6	21.1
-200, +325	58.4 (0.0023)	32.7	30.5	28.3
-325	43.1 (0.0017)	40.4	40.7	32.4
		100.0	100.0	100.0

Consolidation of the blended powders was accomplished by hot isostatic pressing (HIP) by heating the containers of powders to 2150°F under a gas pressure of 15,000 psi for four hours. The metallurgical examination revealed complete compaction of the powders, uniform microstructures of the individual alloys, and material cleanliness that was equal to that exhibited by the cleanest alloys produced by conventional vacuum melt processing. Processing continued with the removal of the containers, followed by forging and rolling operations. Sections were taken from each bar for chemical analysis to determine the nitrogen and oxygen content. The results are presented in Table 3.

TABLE 3. NITROGEN AND OXYGEN CONTENT OF P/M PROCESSED BEARING STEELS PARTS PER MILLION BY WEIGHT

	AISI M-50		AISIT-15		CRB-7	
	N	O	N	O	N	O
Avg. Powder Results	75	97	74	96	63	91
Avg. Barstock Results	90	95	95	110	75	100

Metallurgical examination of the bar specimens was conducted to determine the cleanliness and or the non-metallic inclusion content of the alloy per ASTM Standard E45. A JK rating (which derives its name from its sponsors, Jerkontoret, the Swedish Ironmasters Association) of 1/2 was assigned to each of the alloys. To put this cleanliness level in perspective, conventional vacuum melt material specifications allow a JK rating of 1. A typical photomicrograph of CRB-7 P/M alloy, that was taken at 100X for rating purposes, is shown in Figure 5. The M-50/T15 P/M alloys were similarily free of non-metallic contamination. Reference 1 contains additional photomicrographs taken at 500X and 1000X as part of the metallurgical examination.

Figure 5. Powder Metal Processed CRB-7 Alloy. This Processed Material Was Free of Non-Metallic Contamination as Were The Powder Metal Processed M-50 and T-15 Alloys.

2.3 BALL MANUFACTURE

Balls were rough formed by upset forging of short sections of the barstock in a set of forming dies. They were then ground to a uniform sphere prior to heat treatment. An investigation was conducted to determine the most satisfactory heat treatment schedule for achieving the requisite hardness levels of Rockwell C 62-63 in combination with acceptable grain size and retained austensite level. The heat treatment finally settled upon is presented for all three program alloys in Table 4.

TABLE 4. HEAT TREATMENT OF POWDER PROCESSED ALLOY BALLS

Alloy	M-50	T-15	EX00007
Preheat Temp. (°F)	1550	1550	1550
Austenitize Temp. (°F)	2050	2250	2100
Time at Temp. (Minutes)	6.25	6.25	20.0
Quench Temp. (°F)	1100	1100	1100
Mar Temp. (°F)	350	350	350
Stress Relief	300°F-1 Hr	300°F-1 Hr	300°F-1 Hr
Deep Freeze	-120°F-2 Hr	-120°F-2 Hr	-120°F-2 Hr
1st Temper	1000°F-3 Hr	1050°F-3 Hr	950°F-3 Hr
Deep Freeze	-120°F-2 Hr	-120°F-2 Hr	-120°F-2 Hr
2nd Temper	1000°F-3 Hr	1050°F-3 Hr	950°F-3 Hr

2.4 SINGLE BALL RIGS

Rolling contact fatigue B-10 life evaluation of the 15/16 inch diameter test balls was accomplished in the Single Ball Test Rigs. These rigs are configured as shown in Figure 6 and load the balls in compression between two rotating 130 degree Vee groove rings. The test ball, held in position by a stationary retainer with the ball flats aligned so rolling contact was limited to the spherical surface only, was driven by the lower hub. The upper hub acted as an idler through which the loading was accomplished by means of a hydraulic cylinder. Oil jets above and below the ball provided flood lubrication.

2.5 TEST PROCEDURE

The 15/16 inch diameter test balls were individually tested at a load of 1350 pounds to develop a maximum Hertz stress of 600,000 psi at the ball race contact area. This stress level was sufficient to cause spall failure within a few hours but was below the threshold of plastic deformation. The lubrication, MIL-L-7808G, was heated to 300°F and was supplied to the ball/race contact area by means of a

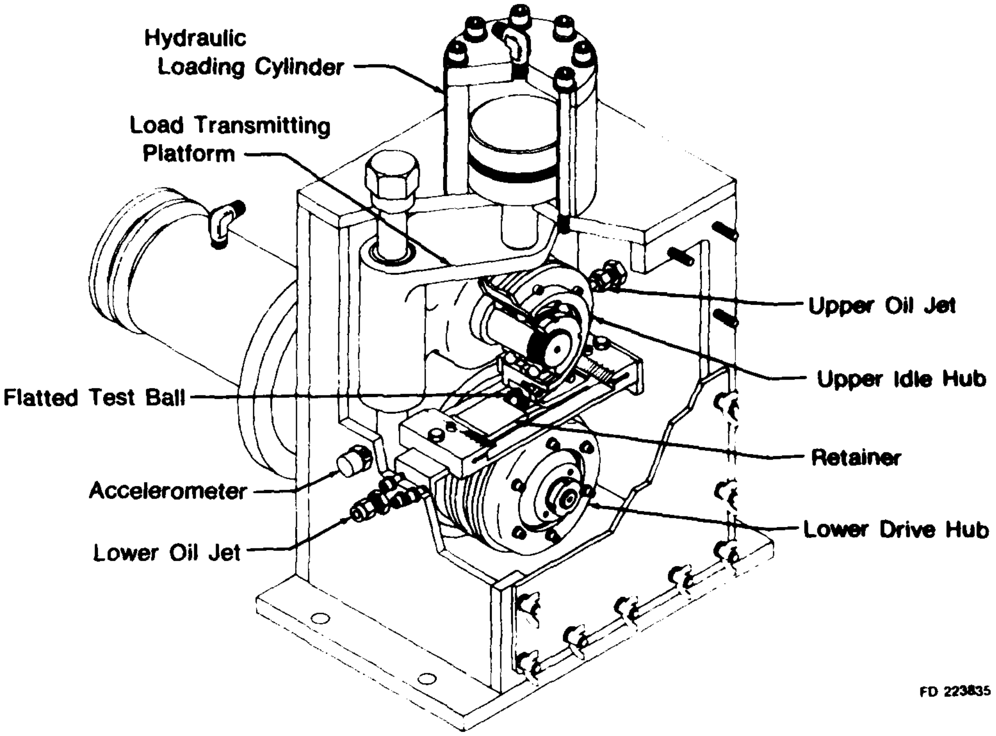


Figure 6. Single Ball Fatigue Test Rig. The Test Ball, Held in Position By The Stationary Retainer Was Driven by The Lower Hub. The Upper Hub Acted as an Idler Through Which The Loading Was Accomplished by Means of a Hydraulic Cylinder.

pair of oil jets. The vee test rings spun the test balls at 41,050 rpm. Vee ring race surfaces were honed to a nominal 5AA microinch finish. Ball failure by spalling of the surface or operation without failure for the predetermined run out time of 40 hours constituted completion of a test.

2.6 TEST RESULTS

A summary of the single ball B-10 life test results is provided in Table 5 for the program baseline material, VIM-VAR M-50, and the three powder processed alloys. The B-10 life value of the CRB-7 material exceeded that for the VIM-VAR M-50 by a factor of 1.83. Utilizing L.G. Johnson's method (Reference 2) for assigning a confidence level to this life difference, it was determined that there was 85%

confidence that the observed life difference was real. Based upon this performance it is apparent that the CRB-7 alloy has considerable potential for providing improved B-10 life performance in full scale bearings as compared to today's production bearings.

TABLE 5. SINGLE BALL FATIGUE LIFE RESULTS

Alloy	No. of Tests	$B\text{-}10 \times 10^{-6}$ Stress Cycles	$B\text{-}50 \times 10^{-6}$ Stress Cycles	Weibull Slope
Program Baseline VIM-VAR M-50	15	20.56	60.78	1.74
Powder Metal M-50	30	16.99	44.05	1.98
Powder Metal T-15	34	6.67	67.65	0.81
Powder Metal CRB-7	30	17.61	116.57	1.67

2.7 EVALUATION IN RC TESTERS

Concurrent with the single ball tests, an RC Disk Machine was used to generate fatigue life estimates of the same three powder processed materials: T-15, CRB-7 and M-50. The test specimens, which were fabricated from the same HIPPED billets used for ball manufacture, were cylindrical bars having a diameter of 9.525 millimeters (0.375 inches) and a finish of .15-.20 micrometers (608 microinches) RMS. A description of the RC tester and how it was employed in the evaluation of the subject powder processed alloys is described in Reference 3.

Ten tests were conducted with each material and all tests were terminated because of rolling contact fatigue spalling. In addition to the three powder processed materials, specimens of CEVM and VIM-VAR M-50 materials were also tested to provide comparative baseline data. The results of these tests are shown in Table 6. Powder processed CRB-7 again provided the longest life of all the materials, generally corroborating the results observed in the single ball test program.

TABLE 6. REFATIGUE TEST LIFE RESULTS

Alloy	RC Hardness	B-10 Life $\times 10^{-6}$ Cycles	B-15 Life $\times 10^{-6}$ Cycles	Weibull Slope
CEVM M-50	RC62	2.72	5.93	2.42
VIM-VAR M-50	RC62	3.89	9.54	2.10
P/M M-50	RC62	3.87	10.26	1.93
P/M T-15	RC64	4.05	8.50	2.54
P/M CR B-7	RC63	7.73	14.64	2.95

SECTION 3
FULL SCALE BEARING EXPLORATORY TESTS

3.1 MATERIAL SELECTION

The evaluation of the three powder processed alloys, CRB-7, T-15, and M-50 in the single ball rig and the RC tester programs demonstrated that the CRB-7 alloy produced B-10 lives that were respectively 1.8 and 2.0 times higher than the B-10 life obtained from VIM-VAR M-50 balls. Based on these favorable results, the CRB-7 powder processed alloy was selected for further evaluation but as applied to full scale bearings. A sufficient quantity of powder processed CRB-7 alloy was procured to allow manufacture of twenty, 140-mm bore ball bearings for subsequent testing.

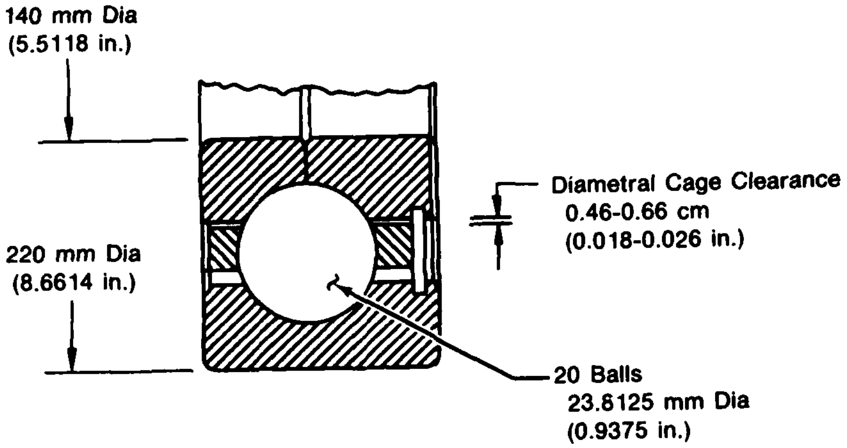
3.2 DESCRIPTION OF BEARING DESIGN

The design selected for use in the endurance program was a 140 mm bore split inner ring angular contact ball bearing. This design is normally used in pairs to form a tandem thrust bearing in the TF33P-7 engine application in many of the military transports. The bearing speed reaches 1.44 million DN (bearing bore diameter measured in millimeters multiplied by the shaft speed). To accelerate the testing of the endurance bearing, the test speed was increased to 1.75 million DN.

This bearing, described in detail in Figure 7, had a split inner ring with a silver plated, AMS 6415 steel cage that was one piece, fully machined, and inner ring guided. This bearing design had a complement of twenty balls of 0.9375 inch diameter which was the same size as those tested earlier in the single ball screening program.

3.3 BEARING FABRICATION

Applying the same processing techniques used to provide ball material, Carpenter Technology produced from vacuum induction melt (VIM) ingots, sieved powder in a quantity sufficient to make twenty sets of inner and outer rings. Samples of the sieved powder of the



Ring Material	CRB-7 P/M	Cage Material	AMS 6415
Hardness	Rc 62-64	Hardness	Rc 28-33
Ball Material	CRB-7 P/M	Plating	AMS 2412
Hardness	Rc 62-64		

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Figure 7 Design of The 140mm Bore Endurance Ball Bearing. This Bearing Has The Same Geometry as That of The Main Ball thrust Bearing in The TF33P-7, a Widely Used Transport Engine.

master blend resulting from the combining of five laboratory process lots were measured for particle size distribution and the results, Table 7, indicated some variation from that achieved with the powder used to make the test balls, Reference 1. Approximately 7.2% of this quantity of powder was larger in size than +80 mesh compared to essentially 0.0% in this category for the powder used to make the test balls. The decision was made to accept this powder with its small amount of large particles because of the experimental nature of the program and related cost considerations. Chemical analysis of these powder lots are tabulated in Table 8.

The powders were consolidated to near theoretical density by hot isostatic pressing (HIP) of the container by simultaneous application of elevated temperature, 2150°F and an inert gas pressure of 15000 psi for 4 hours. After removal of the cans by machining, the resulting ingots were forged and rolled to the desired bar diameters.

TABLE 7. SIZE DISTRIBUTION CRB-7 BLENDED POWDER

Mesh Size Wires per Inch		Average Size		Weight %
		Micro Meters	(Inches)	
	+ 60	246.4	0.0097	0.1
- 60,	+ 80	210.8	0.0083	7.1
- 80,	+100	162.6	0.0064	6.0
-100,	+140	127.0	0.0050	14.7
-140,	+200	86.4	0.0034	19.4
-200,	+325	58.4	0.0023	23.2
-325		43.1	0.0017	29.5
				100.0

TABLE 8. CHEMICAL COMPOSITION OF CRB-7 BLENDED POWDERS
WEIGHT PERCENT - ELEMENTS

Alloy	C	Cr	Mo	V	Cb	Si	Mn	Ni	P	S	Cu
Powder Lot											
A1264	1.03	13.76	2.0	1.05	0.33	0.35	0.51	0.23	0.012	0.003	0.03
A1265	1.07	13.79	2.01	1.07	0.32	0.37	0.47	0.16	0.014	0.003	0.04
A1266	1.04	13.73	1.98	1.05	0.32	0.36	0.48	0.17	0.014	0.003	0.04
A1267	1.02	13.83	1.99	1.07	0.33	0.31	0.49	0.20	0.012	0.003	0.03
A1268	1.02	13.75	1.98	1.05	0.33	0.32	0.49	0.20	0.012	0.003	0.03
Master Blend											
#142	1.09	14.39	2.18	1.13	0.39	0.31	0.48	0.18	0.010	0.003	0.03

Metallurgical examination was conducted on specimens taken from the bars to determine the nitrogen and oxygen content, Table 9, and the cleanliness and or its non-metallic inclusion content per ASTM Standard E45. A JK rating of 1/2 was assigned which typifies that achieved with the cleanest of vacuum melt bearing steel alloys. See Figure 8 for micrographs of the worst fields of inclusions. Micrographs of the etched samples, Figure 9, shows that the microstructure of the CRB-7 alloy sample was homogeneous with the refined carbides uniformily dispersed. Maximum carbide size was estimated to be 0.0001 inch.

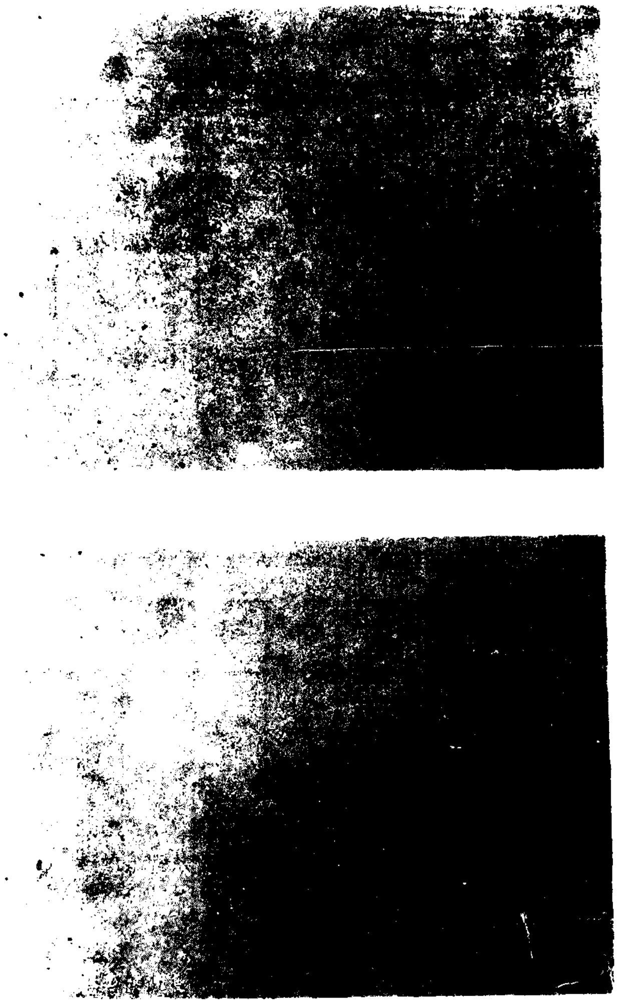

Figure 8. Powder Metal Processed CRB-7 Alloy. The J-K Rating For This Material Was Better Than One-Half Which Compares to a Rating of 1 For Modern VIM-VAR M-50. These Photos Show The Worst Fields of View For The Bar Stock Form of This Material.

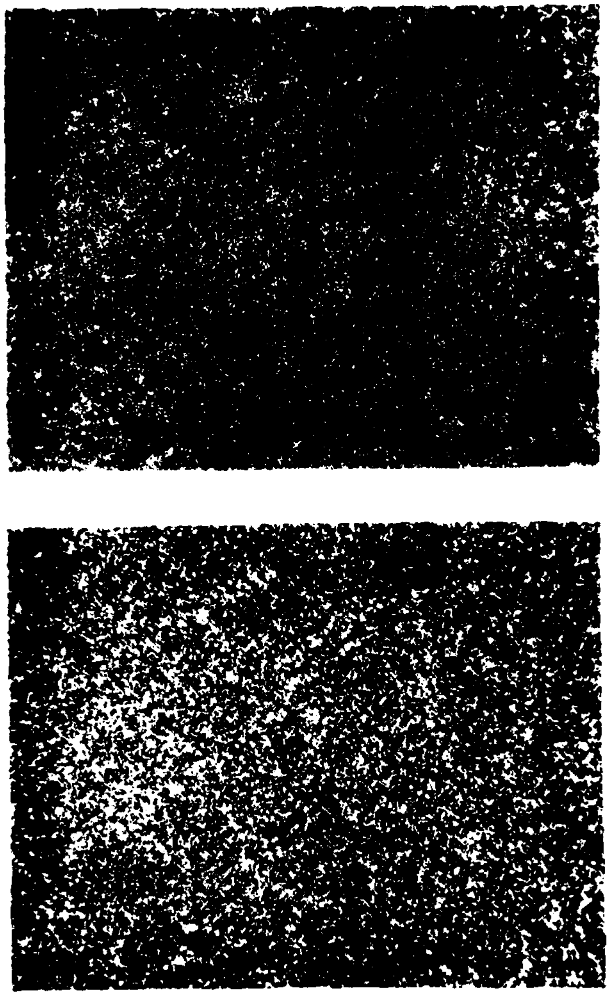

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Figure 9. Powder Metal Processed CRB-7 Alloy. Photomicrographs of The Etched Samples Showing The Homogeneous Distribution of The Refined Carbides.

TABLE 9. NITROGEN AND OXYGEN CONTENT
OF FINISHED CRB-7 BARS

Identification	Size Inch Dia.	N % Weight	0 ppm
C943-2A	3 1/2	0.007/0.007	145/139
C943-3A	3 1/2	0.007/0.007	157/140
C944X-1A	3 1/2	0.007/0.007	144/159
C944A-1A	2 1/2	0.007/0.007	161/153
C945-2A	2 1/2	0.007/0.007	162/155
C945-3A	2 1/2	0.007/0.007	144/159

Following this metallurgical examination, twenty 140 mm bore ball bearings were fabricated by the TRW Bearing Division, Jamestown, New York. Using the powder processed forged and rolled bar material, the inner and outer rings were rough forged to the required bearing size. After ring fabrication the bearings were assembled with balls from the same powder process and fabrication lot as used in the element fatigue program. Bearings were inspected on receipt and found acceptable for testing in the endurance program.

3.4 TEST RIG

Endurance evaluation of the CRB-7 P/M alloy test bearings was conducted using the bearing test rig shown in Figure 10. It consisted of a cylindrical housing with an annular thrust loading system on the drive end. In operation, the hydraulic loading piston applied an axial load to the rear test bearing outer ring housing. The load path was through the rear bearing to the common shaft, to the front bearing and thence to the rig case. Thus two bearings were operated simultaneously under identical test conditions. A multiheaded gear box was powered through a transmission gearbox which in turn was driven by an electric motor. This system provided the capability to operate four rigs simultaneously. Instrumentation to measure operating temperatures and vibration levels described in Table 10 was installed to permit continuous monitoring of the test rigs during the endurance tests. Controls were installed in the various rig support systems which permitted unattended operation of the rigs. A self-contained micro-processor controlled the data acquisition and recording of critical bearing and oil system parameters.

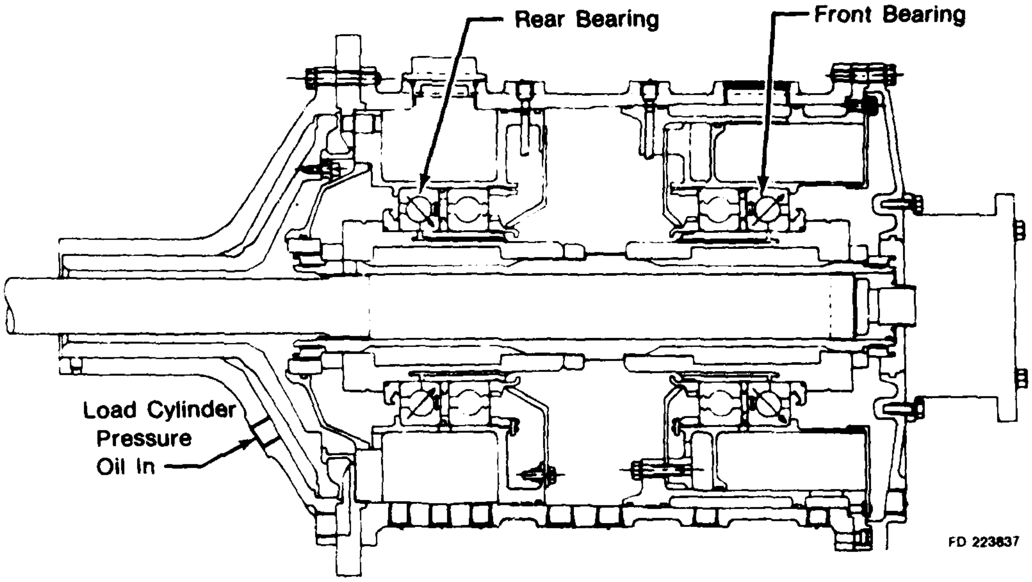

Figure 10. Bearing Endurance Test Rig. Two Bearings Are Tested Simultaneously With Thrust Loading Accomplished by Applying Oil Pressure to The Load Cylinder.

TABLE 10. INSTRUMENTATION FOR BEARING ENDURANCE TEST

Measurement	Instrumentation
Independent Test Bearing Parameters	
Applied Axial Load	Pressure Tap at Hydraulic Load Cylinder Supply Port with Pressure Gage Readout
Oil Flow to Test Bearing	Transducer Installed in Individual Test Bearing Supply Lines
Oil Supply Temperature	Thermocouples installed in Oil Supply Lines with Direct Recording System Readout
Dependent Test Bearing Parameters	
Outer Ring Temperature	Thermocouple Installed in Bearing Housing, Contacting Bearing Outer Ring with Direct Recording System Readout
Discharge Oil Temperature	Thermocouples Installed in Discharge Oil Sumps with Direct Recording System Readout
Vibration	Accelerometers Mounted in the Vertical and Horizontal Planes on Test Rig with Vibration Displacement Meter Readout with Automatic Rig Shutdown Provision

The test rig and external lubrication system consisted of four oil circulating loops. One loop with a 3 micron filter installed, provided 20 pounds per minute flood lubrication to each test bearing. The other three loops, that are serviced by a common micron filter, supplied lubricating oil to the test bearing thrust loading piston, the multiheaded rig drive gear box, and the drive system gearbox/transmission.

The bearing lubricant was a synthetic oil which conformed to MIL-L-7808G and is the same lubricant used in United States Air Force aircraft and also by P&WA in the testing of turbine engines and components supplied to the Air Force.

3.5 TEST PROCEDURES

The 140 mm bore CRB-7 powder metal endurance bearing operating test conditions were established on the assumption that the test condition thrust load would produce the same theoretical B-10 life, 308 hours, see Figure 11, that would be expected for the same geometry bearing made from VIM-VAR M-50 material. Test conditions employed in this test were: thrust load 7840 pounds; oil flow, 20 pounds per minute with MIL-L-7808G lubricant at 250°F; and a bearing speed of 12,500 rpm or 1.75 million DN.

It was planned to run the initial group of bearings for 5 hours to ascertain that all of the test facility systems; i.e., instrumentation, lubrication, loading and automatic controls were functioning correctly. After the installation of eight of the test bearings in the rigs, the stand lubrication system was activated and the oil circulated through the rigs and gearbox. The startup conditions were normal and the bearing instrumentation readings were acceptable and the operating conditions were set. After approximately two hours, an automatic shutdown of the test facility occurred as initiated by a rise in rig vibration. Disassembly of all the rigs revealed various degrees of inner ring land wear and cage bore distress on all of the test bearings.

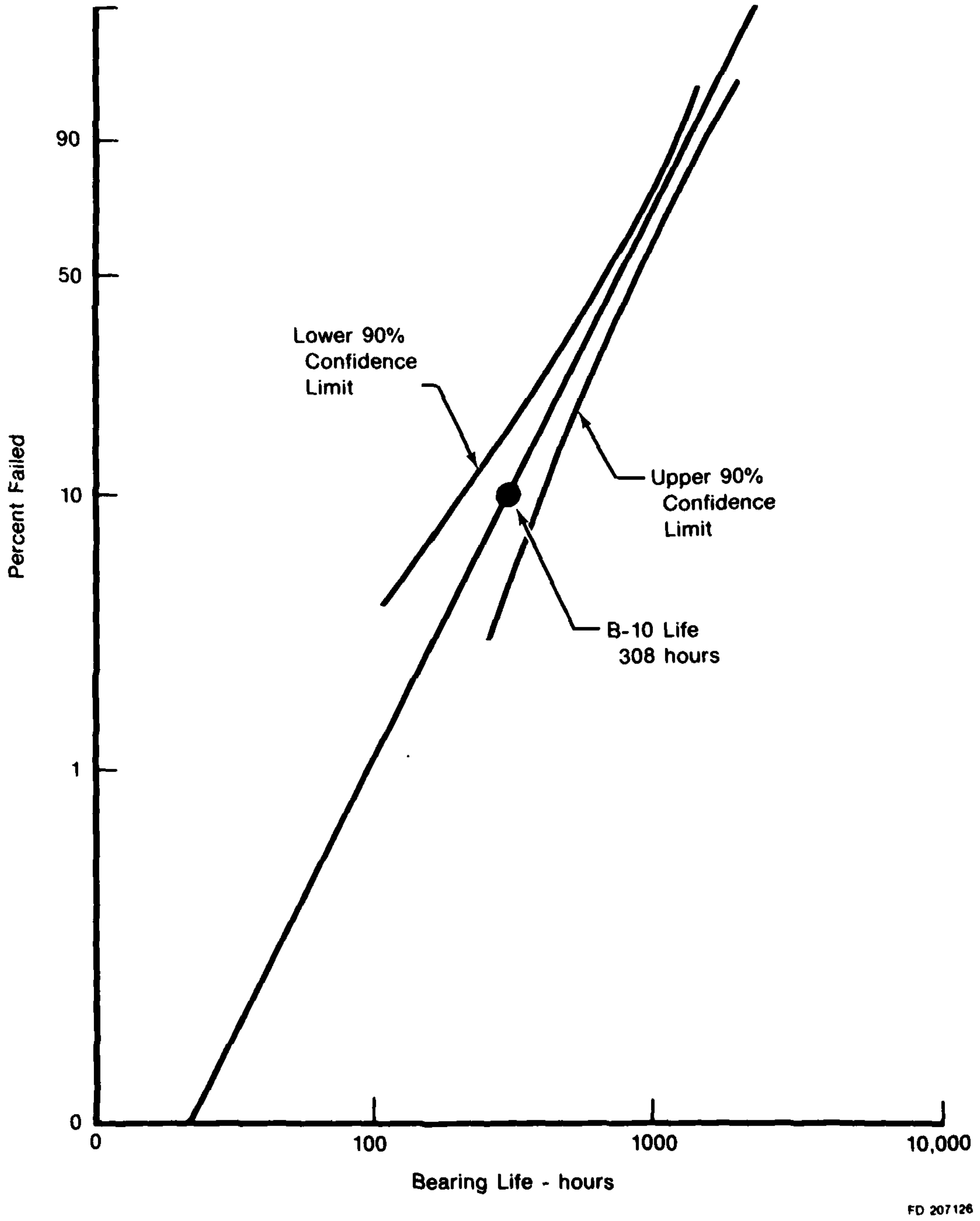

Figure 11. Weibull Prediction For VIM-VAR M-50 Ball Bearing. Thrust Loaded 140mm Bore Bearing Under 7840 lb Load.

It was speculated that abormalities in one of the rigs and or the rig lubrication system may have introduced dirt or abrasive debris which could then have caused the distress observed on the test bearings.

To explore this possibility, the lubrication system was throughly cleaned and flushed, and the system then refilled with new oil. The oil was then circulated through the system for twenty-four hours. The oil was subsequently drained, the 3 micron absolute filter element replaced and the system refilled with new oil.

Available 140 mm bore M-50 P/M bearings which had been fabricated by another vendor were installed in the test rigs. These bearings (see Table 11 for a design comparison with the P/M CRB-7 geometry) had previously been tested in another research program with individual bearings having accummulated as much as 175 hours of test time. After completing 5 hours at the program endurance conditions, the bearings were examined and no evidence of wear on the inner ring lands or cage bore surfaces was noted.

One of the M-50 P/M bearings was then replaced by a zero time CRB-7 P/M bearing and the previously used P/M M-50 alloy bearings were reinstalled in the other seven rig locations. After 3.75 hours at endurance conditions the test was terminated due to an increase in pressure across the 3 micron bearing oil filter. Upon disassembly the CRB-7 P/M alloy bearing was observed to have measurable amounts of wear on the inner ring land surface with accompanying cage distress. All of the other 7 bearings, of P/M M-50 material, were noticeably free of any such wear.

TABLE 11. COMPARISON OF 140mm BORE POWDER METAL BEARING DESIGNS

Material	Research Bearing	A/F Contract Bearing
Rings and Balls	P/M M-50	P/M CRB-7
Cage, Silver plated	AMS 6414	AMS 6415
Number of Balls	19	20
Ball Diameter, Inch	1.0	0.9375
Pitch Diameter, Inch	7.087	7.061
Cage Dia. Clearance, Mils	18-26	18-26

3.6 RESULTS OF EXPLORATORY TESTS

A visual examination was conducted with binocular assistance on the eight bearings run in the initial test. This revealed various degrees of wear on the inner ring lands and the mating cage bore surfaces. The inner ring land surfaces were worn uniformly in depth, axially, radially and circumferentially. One bearing with the greatest ring/cage clearance, see Figure 12, was measured and found to have the ring lands worn to a depth of approximately 0.070 inch. In addition, the inner race ball groove surface was worn due to contact with the cage ball-retention lugs. See Table 12 for a tabulated summary of post-test visual observations made on the test bearings.

The nature of the wear observed on the program bearings had the appearance of the abrasive type that can be generated by hard particles bridging any oil film between the OD land surface and the inner ring and the bore surface of the cage. This type of wear has been seen before on service engine bearings and in most instances has been attributed to dirt particles suspended in the oil. However, as described earlier, after a complete oil system cleanup and the successful running of P/M M-50 alloy bearings, a P/M CRB-7 alloy bearing that was run next still experienced the same type of distress as observed in the first test. It was then concluded that the problem was not due to dirt in the oil system from sources outside the test bearing itself.

At this point in the investigation thoughts turned to manufacturing processes employed in the fabrication and finishing of the test bearing components and the influence these might have had on the wear phenomena at hand. Certain experience with similar cage and inner ring land wear problems experienced in commercial service engines supported this thought. In one instance abrasive particles of alumina and silica were found imbedded in the silver plate of the cage. The source was determined to be the abrasive slurry used in the final finishing step in the manufacture of the cage. Elimination of this step eliminated the wear experienced with this bearing in the service engine. In another instance of excessive wear occurring on

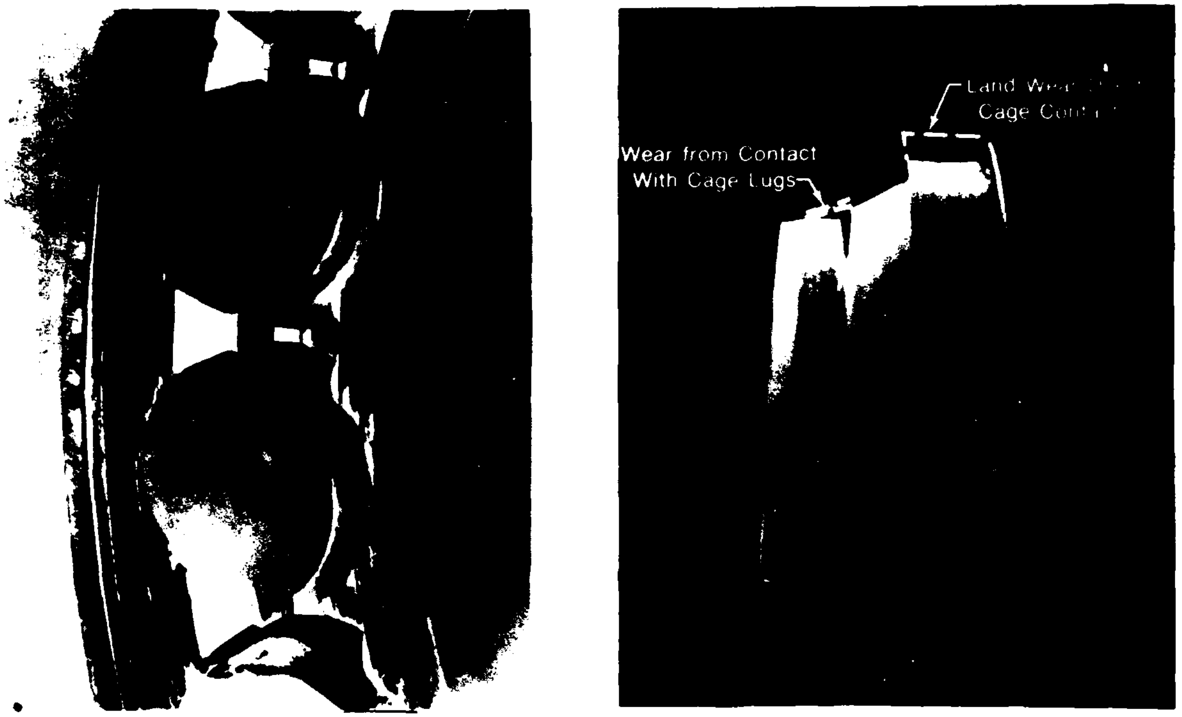

Figure 12. Powder Metal Processed CRB-7 Alloy Bearing Wear. (Left) Pitting Shown on This Cage Bore Surface is The Worst Case, But Similar in Appearance to All Other CRB-7 Bearing Cages Tested. (Right) Inner Ring Wear Was Extensive, And This Was the Worst Case; 0.070 in. of Material Was Worn From The Land.

TABLE 12. POST TEST VISUAL INSPECTION SUMMARY FOR P/M CRB-7 BEARINGS

S/N	General Condition	Inner Ring		Outer Ring	Cage		
		Groove	Lands	Groove	Balls	Pocket	Bore
R1	Clean-except for darkened area, IR/NPG face outer edge (due to cage rub)	Groove worn by cage lug contact	Worn by cage	Good	Good	Good	Eroded 360° heavy, 5-8 Pockets, blackened OD, some 5-8 pockets
R2	Clean-except for straw colored area, IR/NPG face outer edge (due to cage rub)	No cage lug contact	Worn by cage	Good	Normal but with minor scratches	Good	Local patches of erosion 1/2 in. long 18 in number both sides
R3	Clean-no discoloration	Slight by cage lug contact	Worn by cage	Good	Good	Good	Erosion 360° on both sides
R4	Hint of discoloration on balls and races	Worn heavily by cage lug contact	Heavy wear by cage	Good	Worn with flats on equator	Wear unusually heavy	Erosion 360° both sides
R5	Clean-no discoloration	Good, no cage contact	Worn by cage	Good	Good	Good	Erosion 180° both sides
R6	Clean-no discoloration	Good, no cage contact	Worn by cage	Good	Good	Good	Erosion, 270° both sides

TABLE 12. POST TEST VISUAL INSPECTION SUMMARY FOR P/M CRB-7 BEARINGS

S/N	General Condition	Inner Ring		Outer Ring	Cage		
		Groove	Lands	Groove	Balls	Pocket	Bore
R7	Clean-no staining or discoloration, balls and races	Slight cage lug contact	Heavy wear by cage	Good	Good	Good	Eroded 360°, both sides
R8	Clean-no staining or discoloration, balls and races	Slight groove from cage lug contact	Heavy wear by cage	Good	Good	Normal	Eroded 360°, both sides
R9	Clean	Good	Good	Good-only component showing some contact path	OK	Normal	Erosion 360°, both sides
R10	Clean-no staining	Good	Worn by cage	Good	Good	Slightly more wear	Erosion, both sides

the inner ring land and cage bore surfaces of a service engine ball bearing, the source of the difficulty was traced to a less than desirable as manufactured *surface* texture on that inner ring land surface. As a result of these service experiences and the unusual nature of the wear observed on the subject program bearings an extensive wear investigation effort was launched in an attempt to provide some solution to the problem at hand.

SECTION 4

MODIFIED BEARING TESTS

4.1 WEAR INVESTIGATION

Extensive effort was expanded jointly by the TRW Bearing Division and by Pratt & Whitney Aircraft toward identification of the probable cause(s) of the wear distress of the P/M CRB-7 bearings and to provide a solution and or an alternate course of action that would permit the planned bearing endurance testing to continue. Three approaches were taken: (1) metallurgical examination of the inner rings and cages for possible contamination; (2) identification of the nature of the inner ring land surface texture and, if not considered acceptable, the development of a desirable texture, and (3) coating the inner ring surface with an alternate material.

4.1.1 Metallurgical Examination

Two P/M CRB-7 bearing sets were examined by TRW Bearing Division. One set was from that group which had experienced wear distress while being endurance tested and the other was from a program bearing with zero test time. The inner rings and cages of both sets were sectioned to permit further examination. The inner ring hardness for both sets was determined to be Rc 62 and was within the blueprint specification of Rc 62-64. Microhardnesses were determined as a function of depth from the ring surface and results were in close agreement with the overhaul hardness. The hardness of the cage from the tested bearing was Rc 28 and the blueprint specifies Rc 28-33. Micrographs of the tested bearing inner ring acquired at 800X shown in Figure 13 were analyzed. The carbide structure was found to be acceptable with no abnormalities visible.

This analysis also revealed that the dendritic structure associated with the as-atomized powder had been eliminated. These observations indicate that proper consolidation, working and heat treatment temperatures had been achieved in processing the material.

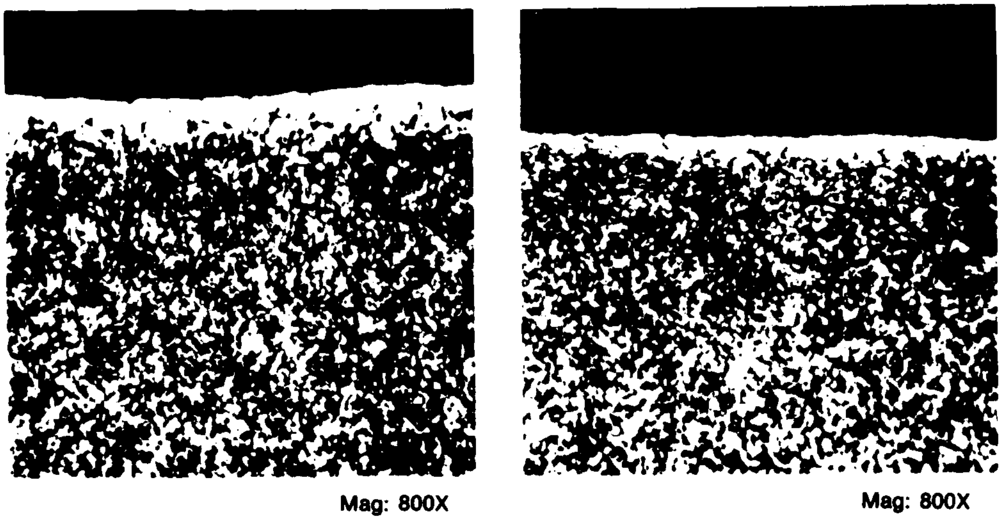

Figure 13. Microstructure of a Tested Powder Process CRB-7 Bearing Inner Ring. No Abnormally Large Carbides Were Observed in Either The Unworn Surface (Left) or The Worn Surface (Right).

Micrographs of the polished and nital etched cage sections presented in Figure 14 revealed a tempered martensite microstructure, which supports the hardness data. Also, no excessive amounts of any contaminants were observed to be present at the silver plate and steel interface.

Studies of the silver plated untested cage revealed particles lying on and partially embedded in its surface as shown in Figure 15. These particles were identified as aluminum and silicon oxides by means of microprobe examination.

Examination of a photomicrograph of the silver plate OOD surface of the non-worn region of the tested cage also revealed evidence of the presence of foreign particles along with a group of multi-directional scratches. Microprobe traces made on this cage surface indicated again that the particles were mainly aluminum and silicon oxides. The multi-directional surface scratches and the presence of foreign particles were concluded to have come from a polishing/tumbling operation and the particles were most likely remnants of the polishing media.

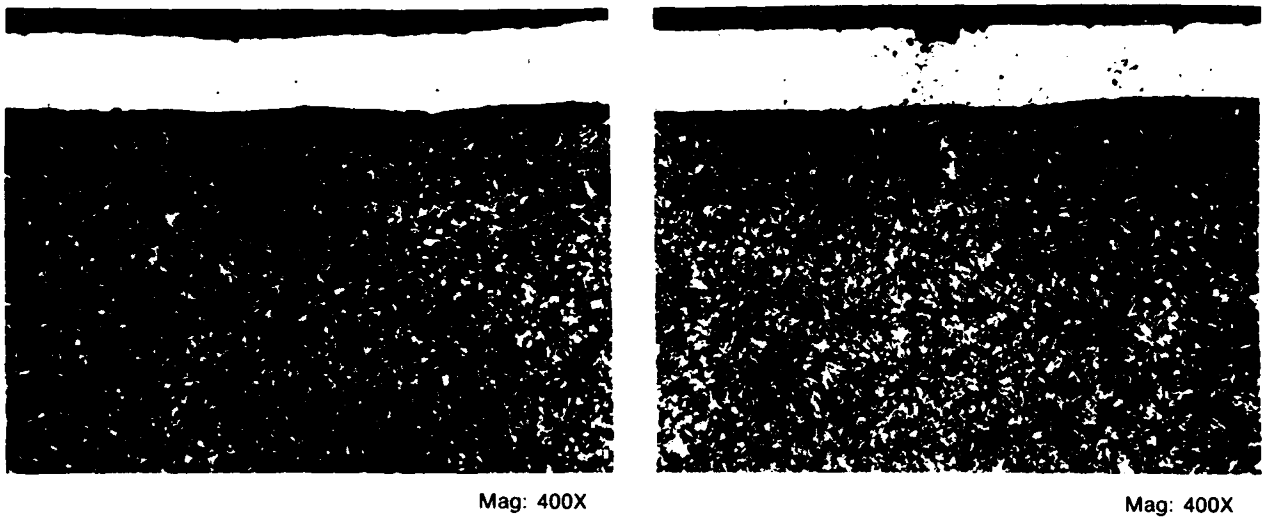

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Figure 14. Cage Interface Micrographs. No Excessive Amounts of Any Contaminants Were Observed To Be Present Along The Silver Plate And Steel Interface on Either The Untested Cage (Left) or The Tested Cage (Right).

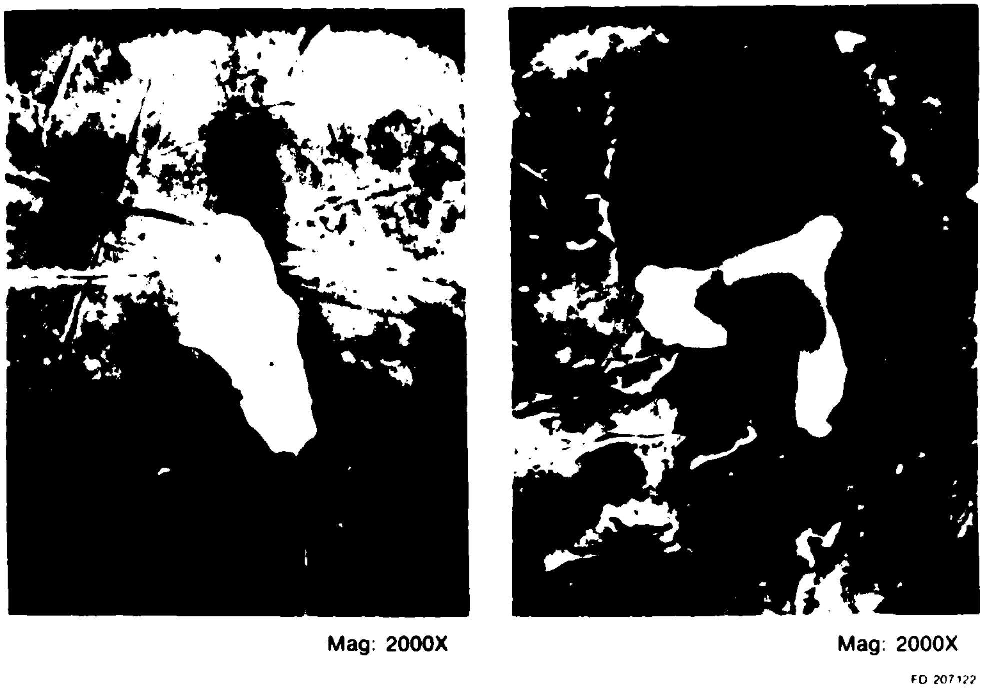

Figure 15. Oxide Particles on The Cage Silver Plated Surface. Aluminum And Silicon Oxides Were Observed Lying on A[illegible] Partly Imbedded in The Silver Plate of an Untested Cage

On the ID bore of the tested cage, where abrasion and adhesive wear occurred, two types of surfaces are visible, one having a matte finish and the other a raised blackened finish as seen in Figure 16. Associated micrographs indicated that the matte finish surface was the silver plate and the blackened finish was CRB-7 alloy smeared onto the silver plate. The roughened and blackened regions are smeared areas that experienced both abrasive and adhesive wear.

Micrographs show that granular particles of CRB-7 alloy were transferred to the silver plate and then abraded by oxides and/or carbides. Hard oxides were also present as evidenced by Figure 17, which shows a 10 micron silicon oxide particle.

The worn surface of the inner ring was also examined by SEM/x-ray. The x-ray spectrum revealed the presence of the elements that comprise CRB-7 alloy in addition to some silicon, but no silver was in evidence.

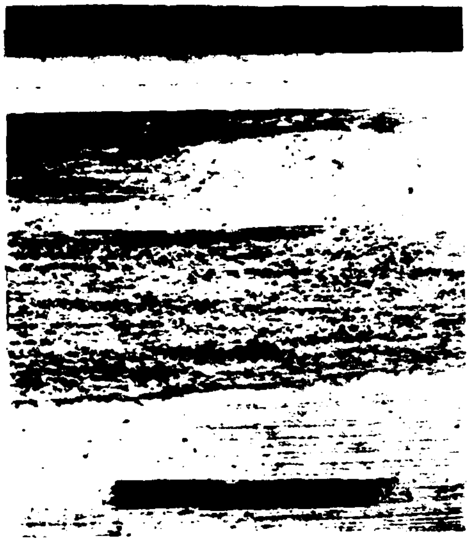

Figure 16 Cage Bore Surface With Abrasive And Adhesive Wear. Darkened Surface Areas Are Regions Where CRB-7 Alloy Was Smeared Onto The Silver Plate.

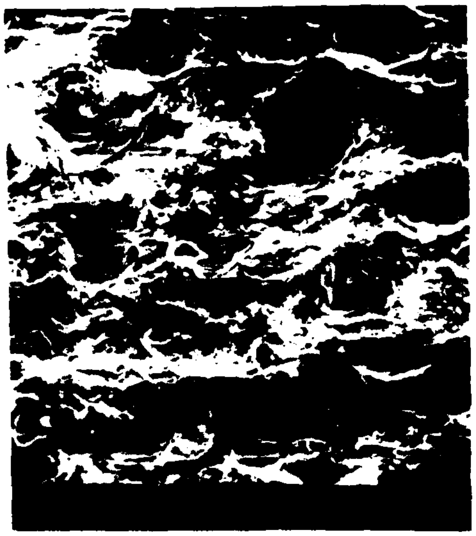

Figure 17. Silicone Oxide Particle on Cage Bore Surface. Presence of 10 micron Silicon Oxide Particle Was Observed Among The Granular Particles of CRB-7 Transferred to The Silver Plate.

At higher magnifications metal carbides are visible as seen in Figure 18 (left). The carbon maps in Figure 18 (right) show that the whole wear surface is contaminated by carbon, as well as presenting evidence of the presence of carbide particles as illustrated in Figure 19.

In other analytical examinations of the bearing cages the silver plate was determined to be 0.001 inch thick which is within blueprint specifications. Traces of copper on the untested cage provided evidence that the proper copper strike was also used as required by the designated AMS 2412 silver plate and the cage base material was also determined to be satisfactory.

At this stage of the investigation the tentative conclusion was drawn that the excessive wear of the CRB-7 inner rings was apparently caused by alumina and silica particles that were present in/on the silver plate of the cage prior to testing. These particles most likely were introduced during tumbling of the silver plated cage in a medium containing alumina and silca polishing stones. Fragments of the stones were pressed onto the soft silver and effectively held there until the bearing test started. It was speculated that these particles then abraded the inner ring surface, exposing and removing carbides as well as removing the CRB-7 matrix. Deposits of the CRB-7 were transferred onto the silver plated cage to interrupt lubricant flow and accelerate wear. These deposits were further abraded by carbides now left in some relief on the inner ring. To explore this contention what remained to be done was the manufacture of a cage that was free of the silica and alumina particles followed by rig testing to see if the wear was alleviated in any way. This in fact was done and the results are presented in Section 4.5.

In addition to the role played by the imbedded alumina and silica it was also considered likely that the texture on the inner race land was possibly less than optimum and could have played a role in the wear that occurred. A study was launched to assess the nature of this texture and how it compared to that which existed on bearings that were operating satisfactorily.

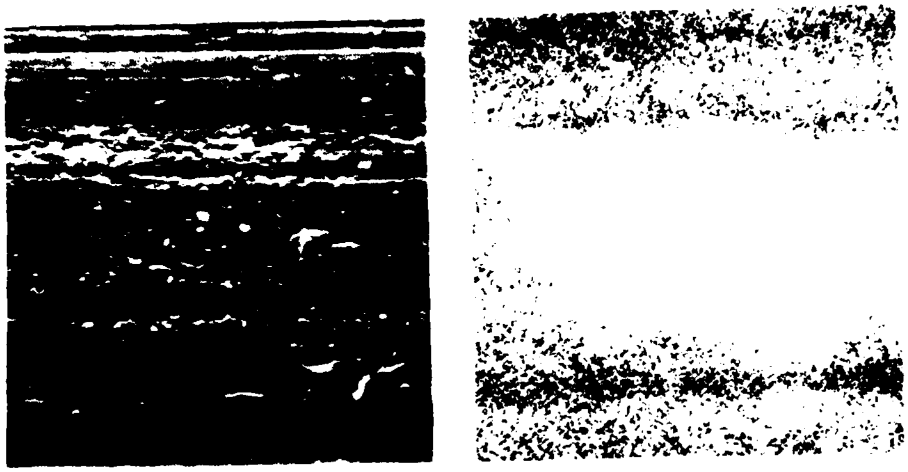

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Figure 18. Worn Surface of Tested Inner Ring.
(Left) Area of Fine Carbide Particles is Shown in Micrograph.
(Right) Carbide Dot Map Indicates Wear Surface is
Contaminated by Carbon.

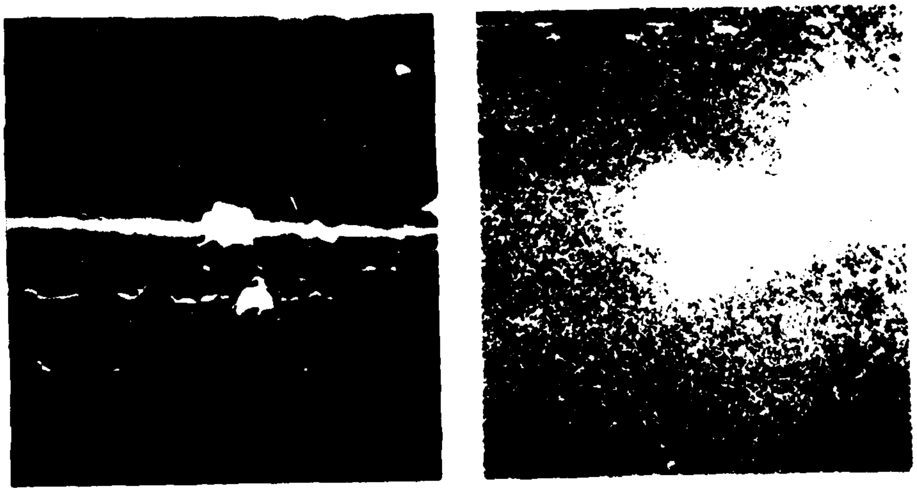

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Figure 19. Worn Surface of Tested Inner Ring.
(Left) Higher Magnification Shows Carbide Particles.
(Right) Carbon Dot Map Confirmed Presence of Carbon.

4.1.2 Surface Texture Examination

Use of a transmission electron microscope (TEM) allows indirect non-destructive examination of a bearing surface by studying replications of the surface texture. Studies of replications by TEM are utilized when it is desirous and important that the condition of the original sample surface remain unchanged. Such replicas of the CRB-7 ring land unrubbed surface shown in Figure 20, were compared to those of a museum M-50 alloy bearing surface depicted in Figure 21. This specific conventionally processed, non-powder-metal M-50 museum piece has a desirable land texture. Experience with this bearing in service engines had been free of any wear difficulties on the inner ring land and cage bore surfaces. When the texture of the land was altered through deletion of a nital acid etch, done for cost reduction purposes, wear problems were immediately experienced. This acid etch is applied to the finish ground surface of the M-50 bearing to check for local surface tempering damage otherwise known as grinding burns. Reinstatement of the acid etch step in the processing of this production bearing resulted in a return to the same good wear experience realized in service prior to removal of this process.

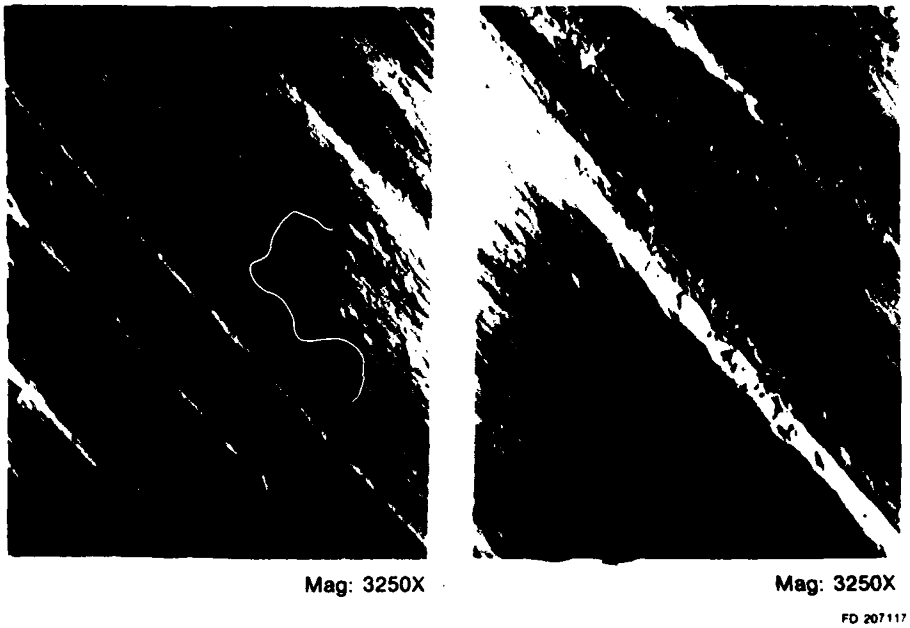

Figure 20. Unrubbed CRB-7 Ring Land Surface. Absence of Desirable "Moonscape" Textured Surface Was Apparent in Both Micrographs of an Unrubbed Ring Land Surface.

As a result of this production bearing experience it was considered desirable at this juncture in the P/M CRB-7 program to develop an acid etch based procedure that would produce a land texture similar to that of the M-50 museum piece. The nital acid etch, which uses an etchant solution composed of 4% by volume of nitric acid and 96% by volume of alcohol, when applied to the CRB-7 rings was found not to produce any visible change in the surface appearance or its texture. Thus, CRB-7 being a more highly alloyed material than M-50, was determined to require the development of a new more erosive etchant that would provide a surface texture that would have a visual appearance similar to that shown in Figure 21. Toward this end a series of candidate etchants were compiled as shown in Table 13.

Figure 21. Typical M-50 Bearing Surface Properly Textured "Moonscape" Surface Which is Believed to Contribute to The Retention of The Lubricant at The Cage/inner Ring Interface, is Observed in The Micrograph.

TABLE 13. SUMMARY OF RESULTS FROM ETCHANT TRIALS

Etchant	Immersion	Results
50 ml Acetic Acid/ 50 ml Nitric Acid	1 minute	Mild Attack
45 ml Glycerine/ 15 ml Nitric Acid/ 30 ml Hydrochloric Acid	45 seconds	Severe; Carbides, Grain Boundaries Visible
PWA #73: Nickel Chloride/ Nitric Acid	15 minutes	Little Effect
	45 minutes	Severe; Carbides, Grain Boundaries Visible
Vilella's Reagent: 5 ml Hydrochloric Acid/ 1 Gram Picric Acid Powder/ 100 ml Ethyl or Methyl Alcohol	30 seconds	Moderate Attack, Favorable Texture
	1 minute	Less Favorable
	2 minutes	Severe; Carbides, Grain Boundaries Visible

These etchants were selected based on recommendations of Carpenter and by means of a separate literature search. To provide speciments for use in developing the etchant process, sections were cut from a previously tested and worn inner ring that had unrubbed areas suitablefor the etching trials. A typical specimen is shown in Figure 22. For each selected etchant process a specimen was treated and then examined by TEM techniques to assess the resultant texture. Results of those studies are shown in Table 13.

The Vilella's etchant with a 30 second immersion produced the surface shown in Figure 23 which compares favorably with the target texture in Figure 21. This same etchant was then applied to the land surfaces of a P/M CRB-7 bearing for subsequent rig testing. The results of tests conducted on this bearing are presented in section 4.4 of this report. In addition to this texture etchant study, a concurrent effort was made to identify a treatment in the form of a coating for the inner race P/M CRB-7 lands that might be more wear compatible with the mating silver plated bore surface of the cage.

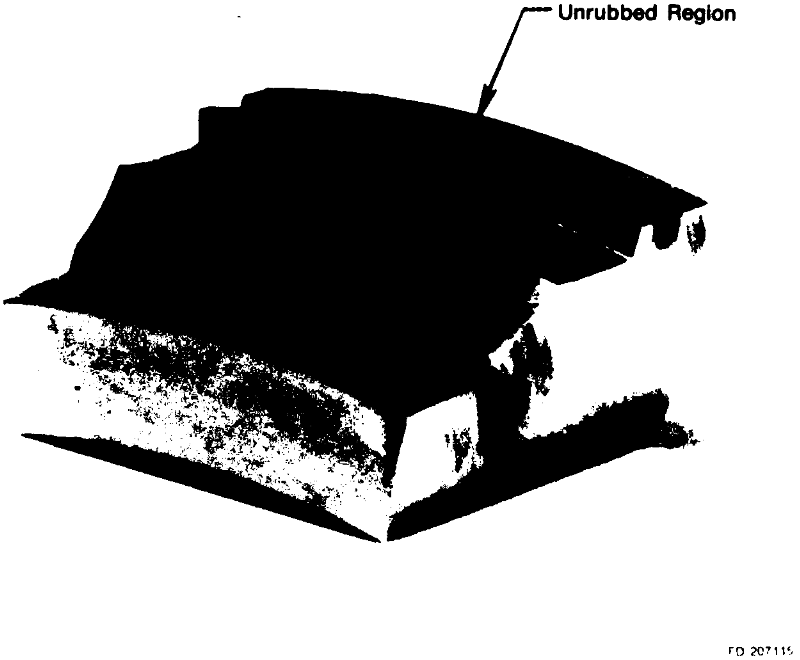

Figure 22. Surface Texture Study Specimen. Unrubbed Surface Was Utilized From Inner Ring Section Cut From Worn Bearings.

4.2 NICKEL COATING ON LAND SURFACE

A study was conducted by the materials laboratory to determine what alternate material could be coated on to the ring land surface. Due to the high shaft speed, 12,500 rpm, the temperature and oil environment, it was recommended to adapt a plating repair technique normally used to salvage worn rig shafts. The shafts are ground undersize, then nickel plated per AMS 2423 and ground to blueprint. This process produces a surface hardness in the Rc 59-60 range which was considered compatible with the needs of this experimental program. A technique for satisfactorily masking the inner ring ball groove was developed that produced a continuous nickel plate surface on the land without causing any damage to the ball groove. The success of this effort led to the manufacture of a set of rings, as described in the next section, which were subsequently rig tested.

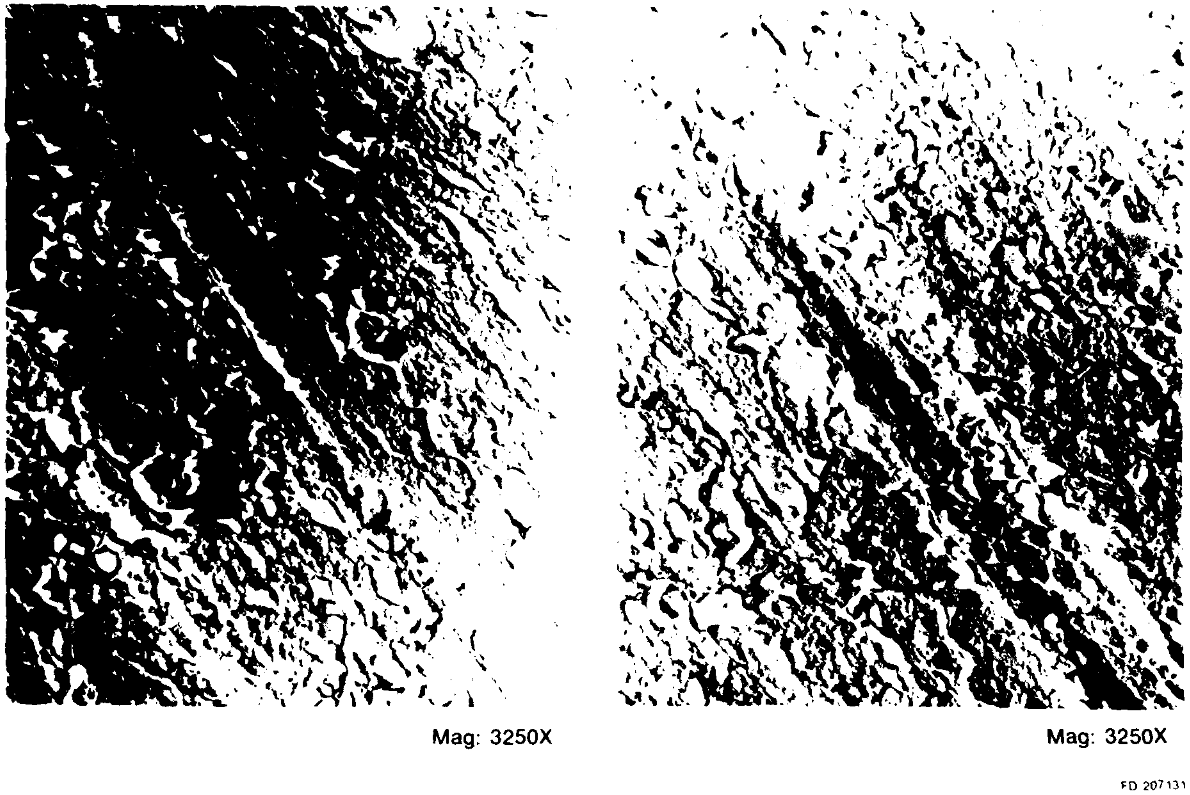

Figure 23. Vilella Etched Specimen. Surface Treated For 30 Seconds. Texture Developed by This Etchant Compares Favorably With Target Texture in Figure 21.

4.3 BEARING MODIFICATIONS

As a consequence of the results of the wear investigation and related land surface coating work, several program bearings were modified for subsequent rig testing. This testing would hopefully reveal at least one solution to the wear problem, providing a fix that would then permit the rolling contact fatigue testing of the P/M CRB-7 bearings to continue. There were four modification steps introduced at this point in the program which are described in the following.

One modification made was replating of the silver on the cages of all those program bearings that had not yet seen any test time. This was accomplished at the TRW Bearing Division's facility by removing the silver from the cages and replating with AMS 2412 silver followed by check balancing. This replating work was done to provide a cage surface free of any imbedded alumina and silica which was found in notable amounts on the original cages. One of these cages was reassembled in one of the P/M CRB-7 bearings that had not yet been rig tested. This was the first bearing of those tested in the next portion of this program.

Another modification pursued was the development of an improved surface texture on the program bearing inner race lands. Various acid etch process techniques were explored to accomplish this and the Vilella's etchant, with a 30 second immersion, produced the best results. This treatment, when applied to a set of P/M CRB-7 bearing rings, produced the texture shown in the TEM photograph in Figure 24. This compares favorably with the target texture shown for the conventionally processed M-50 bearing in Figure 20. These specially textured rings were then assembled with their mating outer ring and ball set, along with a resilvered cage. This bearing assembly was the second of those tested in this portion of the program.

Yet another bearing was made available to the program but of an alternate material, SAE 52100 steel. This bearing was of a geometry identical to the P/M CRB-7 version. By assembling this bearing with one of the resilvered cages and rig testing under the same conditions

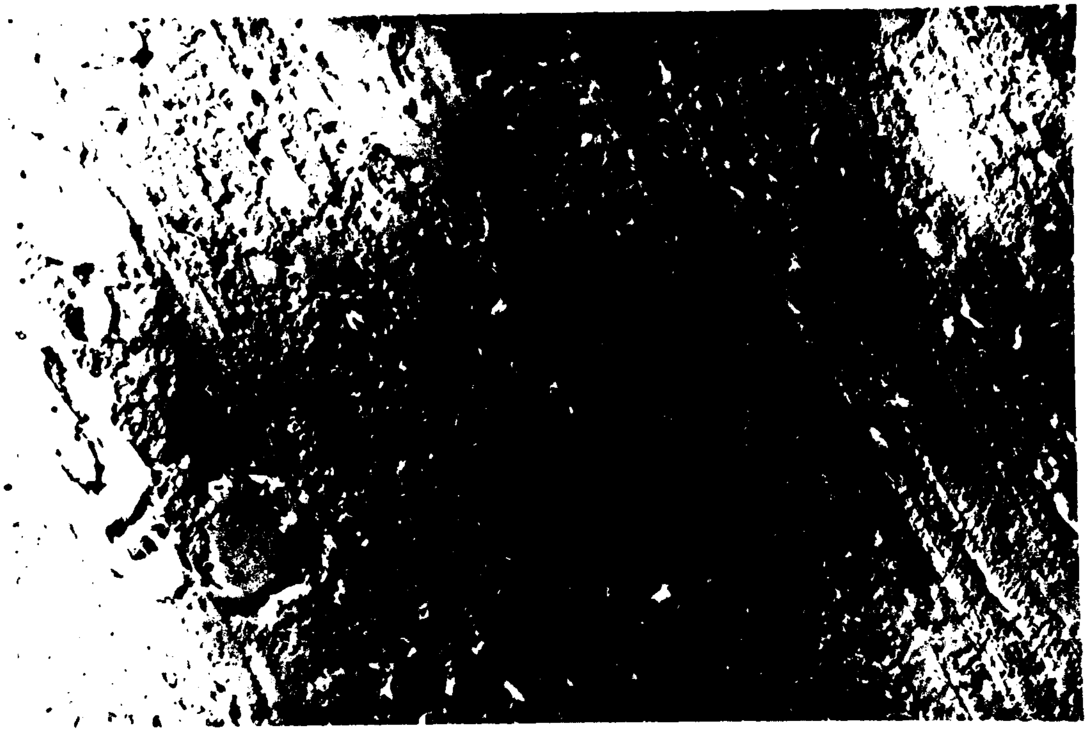

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Figure 24. Vilella Etched Inner Ring. Surface Treated For 30 Seconds. Texture Essentially The Same as That Produced on The Specimen in Figure 23.

it was anticipated that the results would assist in identifying the role that the bearing material may have been playing in the land wear process. This was the third bearing of those tested in this portion of the program.

The fourth modification evaluated in this section of the program is that which provded an alternate material on the P/M CRB-7 land surfaces in the form of a hard nickel coating. A set of P/M CRB-7 bearing inner rings were ground undersize on the lands to a depth of 0.008 to 0.010 inch. After masking the ring bores, end faces and ball grooves, the nickel was plated on the land surfaces per AMS 2423. These lands were then ground to blueprint dimensions to a finish of 10 microinches AA. These rings were assembled with their mating components, along with a resilvered cage, and was the fourth and final bearing tested in this portion of the program.

4.4 TESTING OF THE MODIFIED BEARINGS

Each of the four modified bearings was tested separately and at the same test conditions employed during the intial testing that had produced the sever land wear. As the initial tests had produced significant wear distress in less than five hours of testing, this was the time limit chosen for screening the wear characteristics of the modified bearings. The bearing chosen for test was mounted in one of the eight rig test positions in the normal manner, with conventional M-50 bearings mounted in the remaining seven. At the end of each test the bearings were removed from the rigs and examined for wear.

4.5 WEAR TEST RESULTS

4.5.1 P/M CRB-7 Bearing with Resilvered Cage

After approximately two hours of testing at the program conditions the test was terminated because of excessive darkening of the oil noticed during a routine check. Upon removal of the P/M CRB-7 test bearing from the rig it was observed that severe wear had occurred on the lands. This wear, measured to be 0.019 inches deep, along with the distress pattern observed on the bore of the cage, was similar to that which had been observed on the bearings tested earlier in the program. The M-50 bearing removed from the same rig, and the other six M-50 bearings run in the other three rigs,were all found to be free of any visual wear and/or distress as a result of this test.

4.5.2 Improved Surface Texture Bearing

After one hour of operation on the P/M CRB-7 bearing with the specially textured inner ring lands, testing was stopped to allow for visual examination. It was observed that the puller grooved inner ring land was worn uniformily to a depth of .004 inch while only local polishing was evident on the non-puller grooved ring. The cage was found to have distress on that portion of its bore surface that was in contact with the worn puller grooved inner ring. This land and cage wear, though less in magnitude, was similar to that observed on the

P/M CRB-7 bearings previously tested. The bearing was reinstalled and after one additional hour was removed. No additional wear was observed. After a third hour of testing, both inner lands were found worn to a uniform depth of 0.006 to 0.007 inch with the cage now exhibiting distress on both portions of its land surfaces. None of the other seven conventional bearings of M-50, mounted in the other rig locations, suffered any visual distress from this test.

4.5.3 Alternate Ring Land Material Bearing

The bearing with SAE 52100 ring and ball material, and the same geometrical design as the P/M CRB-7 bearing, was assembled with a resilvered cage and was successfully tested for five hours under the same test conditions as previously used. No evidence of distress was noted on either the inner ring land surfaces or on the cage bore. The seven conventional M-50 bearings, mounted in the remaining locations in the test rigs, also did not suffer any distress as a result of this test.

4.5.4 Nickel Plated Rig Land Material Bearing

After five hours of testing the CRB-7 P/M bearing that had nickel plated inner ring lands and a resilvered cage, only minimal distress was observed during post test inspection. The testing of this combination of alternate surface material was successfully extended to 25 hours at the same test conditions. Using a surface analyzer, an axial stylus trace across the inner ring lands indicated the wear to be less than 0.00085 inch. The condition of the cage after seven hours of this testing can be seen in the photograph in Figure 25. The condition of the inner ring lands after 25 hours of testing can be seen in the photograph in Figure 26.

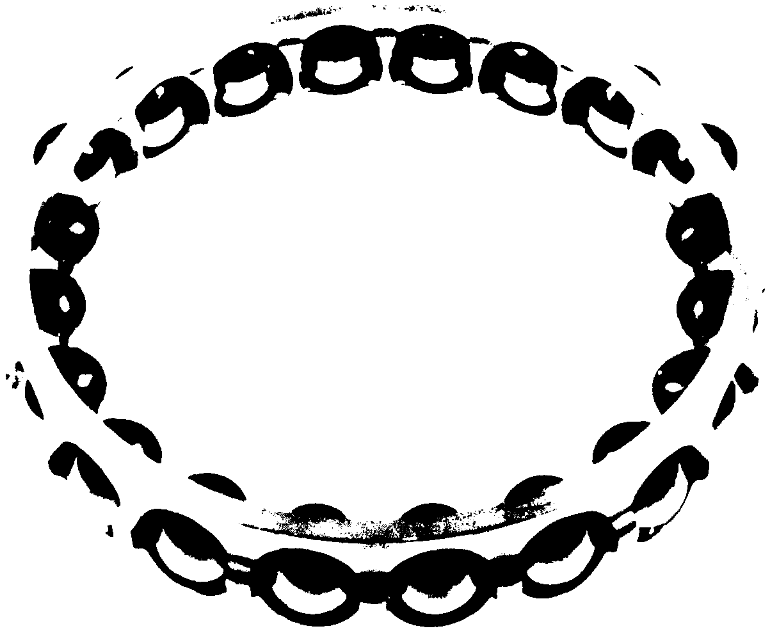

Figure 25. Replated Cage after 7 Test Hours. No Evidence of Cage Distress by Contact With Nickel Plated Inner Rings Was Observed.

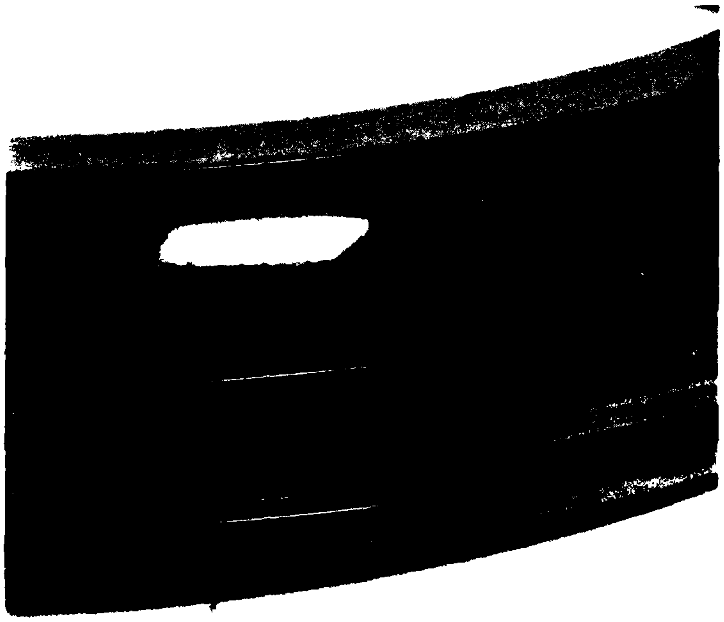

Figure 26. Nickel Plated Inner Ring After 25 Test Hours. Minimal Distress Was Seen Upon Bearing Inspection.

SECTION 5

FULL SCALE BEARING TESTS

5.1 ENDURANCE BEARING MODIFICATIONS

Based on the good test results obtained with the nickel plated inner ring land bearing, as combined with a replated cage, the remaining untested full scale bearings, as well as the previously tested bearings with only minimal inner ring/cage distress, were similarly modified. Those components that had zero test time included eight sets of matched races and balls and seven cages. Refurbishable components that had accumulated various amounts of test time included four sets of matched races and balls and five cages. This made a total of 12 complete nickel plated land bearings available to the endurance program.

5.2 ENDURANCE TEST PROCEDURE

The test conditions used in the endurance program for the modified P/M CRB-7 bearings were the same as those employed during both the initial endurance test and succeeding wear investigation tests. These conditions were as follows:

Speed	1.75 million DN (12,500 rpm)
Lubrication	20-25 PPM MIL-L-7808H Exxon Turbo Oil at 250°F
Bearing Outer Ring Temperature	500°F maximum allowable
Thrust Load	7840 pounds

After the first 25 hours at the test conditions it was planned to interrupt the testing in order to visually examine the bearings for evidence of any possible wear or distress. Prior to this test, the stand oil system was drained, flushed, and then refilled with new lubricant.

5.3 ENDURANCE TEST RESULTS

Eight modified CRB-7 P/M bearings were installed in the four rigs; No. 1, No. 2, No. 3 and No. 5, and the planned 25 hour test program was initiated. After 2.6 hours the test was interrupted due to an increase in vibration and noise in No. 2 rig. The test bearings were removed, examined and found to be in satisfactory condition. The gear box spool shaft for No. 2 rig was then removed and the support bearings, which felt rough when rotated manually, were replaced. An attempt to resume running proved unsuccessful with high vibration again encountered. The two P/M CRB-7 test bearings, S/N R13 and R14, were then removed from No. 2 rig. Visual examination revealed evidence of skidding damage. This rig was reassembled with available M-50 bearings. Testing was resumed with vibration on all five rigs then settling out at normal levels. The planned 25 hours of testing was accumulated without incident and the bearings were removed for inspection. Each of the six test bearings were found to be in good condition and reinstalled for continued evaluation. The two M-50 bearings in No. 2 rig were also found to be in acceptable condition. They were subsequently replaced with two other modified P/M CRB-7 test bearings, S/N R6 and R10. The test was resumed and after accumulating 157.4 hours at the test conditions, the program was interrupted due to an increase in vibration levels on No. 1 rig. Visual inspection of the bearings in this rig revealed that the front position test bearing, S/N R11, had a spalled ball. A zero time modified bearing, S/N 17, was installed in its place and the fatigue endurance program resumed.

At this point in the program only one of the twelve program bearings remained without at least a minimum amount of test time on it. Based on the performance of the bearings thus far it was determined to be most cost effective to interrupt the testing at the 500 hour point, remove a high time bearing and substitute the zero time bearing and resume testing. The No. 5 rig was subsequently removed from the test facility and disassembled. It was observed that one of the bearings, S/N R18, had sustained a fatigue type failure consisting of a single ball spall with resulting inner raceway damage. This same bearing also exhibited inner ring land wear similar in appearance to that observed during previous testing. The other test bearing, S/N R19, from the rig was examined and reinstalled as it was found to be in good condition with no distressed areas in evidence. The last available modified bearing, S/N R20, was then mounted in that location in No. 5 rig from which the failed bearing had been removed and the test program was resumed.

Testing was next interrupted after 942 hours had been accumulated on the longest time bearings. The cause was high vibration on two of the four rigs. Teardown and inspection of these two rigs revealed that S/N R15 bearing, with 942 hours in No. 3 rig, had a spalled outer raceway and that S/N R19 bearing in No. 5 rig, also with 942 hours, had a spalled ball. At this point, with the concurrence of the Air Force Project Monitor, it was decided that the endurance portion of the program was complete. This decision was made for cost effectiveness reasons and it was determined that any additional failure data that might be realized from testing the unfailed bearings to the previously established limit of 1000 hours would not alter the B-10 life significantly.

At the termination of the fatigue endurance program, 7491.2 hours had been accumulated on the twelve modified bearings at the test program conditions of 1.75 million DN and 7830 pound thrust load.

5.4 ANALYSIS OF RESULTS

The results of the endurance test portion of the program, as conducted on the modified P/M CRB-7 ball thrust bearings, are summarized in Table 14. A total of four rolling contact fatigue failures were classified as such from among the twelve bearings tested. Utilizing existing Wiebull analysis computer program procedures and using the test times of 157.4, 500.0, and 942.0 hours associated with the four failures, a B-10 life of 249 hours and a slope of 1.23 was calculated. This compared favorably with the predicted or theoretical B-10 life of 308 hours with an ideal slope of 2.0 as calculated for an equivalent VIM-VAR M-50 alloy bearing. The results of the two Weibul analyses are shown in Figure 27, and indicate that as the 90% confidence bands overlap there is no significant difference between the B-10 life of the CRB-7 powder metal alloy and the theoretical B-10 life for the M-50 bearing.

TABLE 14. POWDER METAL CRB-7 BEARING POST TEST VISUAL INSPECTION SUMMARY

General Condition	Test Time (Hr.)	Inner Ring		Outer Ring		Cage	
		Groove	Land Wear	Groove	Balls	Pocket	Bore
R6 Clean, No Discoloration	917	Good	0.006" (Nickel Plate Chip per 1/8"x1" PG* Half)	Good	Good	Good	Erosion 110 ° of circumference, S/N Side Only
R10 Clean, No Staining	917	Good, Some Etch Damage From Plating on Top Edge Of NPG* Side	.001	Good	Good	Slight Wear	Erosion, 40°, Both Sides
R11 Clean, Ball Spall	157.4	Good	.004	Good	5/16" Spall on Ball	Good	Erosion, 90°, Both Sides
R12 Clean, No Staining	942	Good, Some Staining Near Shoulder From Plating	.007	.010" Pit (not spalled)	Good	Good	Erosion, 110° Both Sides
R13 Clean, but Skid Damage Evident	2.6	Ball Contact on NPG Side, Shoulder	Negligible Plating	Good to Excellent Stains	Shallow Surface	Medium to Heavy Wear Characteristic of Skidding	No Erosion Damage Anywhere, Good Condition

TABLE 14. POWDER METAL CRB-7 BEARING POST TEST VISUAL INSPECTION SUMMARY (Cont.)

General Condition	Test Time (Hr.)	Inner Ring		Outer Ring		Cage	
		Groove	Land Wear	Groove	Balls	Pocket	Bore
R14 Clean, Unusually so, including no fretting on bore	2.6	NPG Side Slight Skid Damage	Negligible	Good to Excellent	Good to Excellent	Good	Erosion, 20°, S/N Side Only
R15 Clean, Spalled OR	942	Good	Negligible	1/8" Spall	Good	Good	Erosion, 90°, S/N Side Only
R16 Clean, No Staining	942	Good, Some Plate Stains	0.007	Good	Good	Good	Erosion, 90° Both Sides
R17 Some Staining-(Looks like it may have been reverse loaded at some time) OR pits unusual shiny bottomed	784.6	Wide Ball Contact Path-Within .050 inch of Shoulder, PG Side	0.001	Pit .020" and Many Smaller Pits but Not Spalled	Dark Bands on Balls But Not Scored or Scratched	Good	Erosion, 90° S/N Side
R18 Staining on Balls #6 Ball Spalled	500	Contact Path on NPG Side, PG Side Has Skid Damage	0.007	Minor Debris Dents	All Darkly Stained, with Few Local Clean Spots, 1/4" Spall on Ball	Medium to Heavy Wear	Erosion, 110° Both Sides

TABLE 14. POWDER METAL CRB-7 BEARING POST TEST VISUAL INSPECTION SUMMARY (Concl.)

General Condition	Test Time (Hr.)	Inner Ring		Outer Ring		Cage	
		Groove	Land Wear	Groove	Balls	Pocket	Bore
R19 Clean but With Skid Damage, Ball Spall	942	Contact on 180° Sector NPG Side, Skid Damage with Wide Track on PG Side	.004	Debris Dents	Pronounced Ball Banding, Single Band on Most	Ball Contact with retention lug	Erosion, 150° both sides
R20 Clean-No Staining	442	Normal Tracks	Negligible	Good to Excellent	Good	Good	Erosion, 60°, S/N Side Only

*PG - The split inner ring half carrying the thrust load and featuring a puller groove.
NPG - The other half of the inner ring without the puller groove which is the non-loaded side.

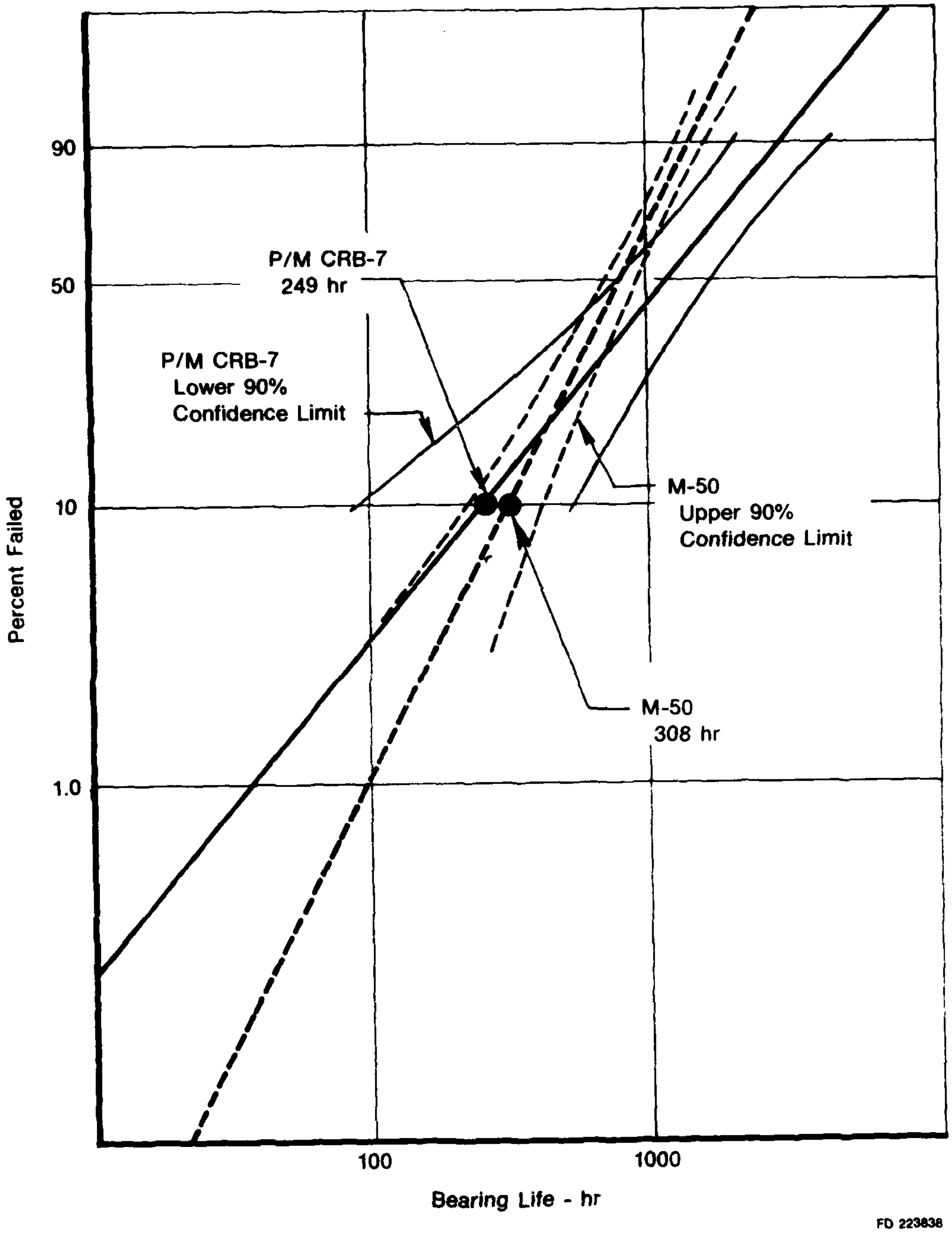

Figure 27. Weibull Analysis Comparison of P/M CRB-7 And M-50 Alloy. A B-10 Life of 49 Hours Was Determined For The P/M CRB-7 Alloy And Compares Favorably With The 308 Hours of The M-50 Alloy.

In addition to Weibull analysis of the fatigue data, certain other metallographic studies were conducted on the test bearings as well as hardness checks, quantitative chemical analysis, spectographic analysis and electron x-ray examination all in addition to the normal visual evaluation at different degrees of magnification from 1X to 60X. Some general impressions are offered before more detailed analytical information is presented for certain of the individual bearings tested.

Study of the four spalled bearings did not reveal any fundamental or pervasive deficiency in the metallurgical quality of the powder processed CRB-7 mateial that could provide an all encompassing explanation for the rolling contact fatigue failures. The inner ring land wear problem was still in evidence by virtue of some measurable amounts of material having been removed by interaction with the cage bore for almost every bearing tested. As much as 0.007 inch of uniform land wear had occurred, with this larger amount usually associated with the longer time bearings. Damage to the cage bore surface was also in evidence on all but one of the endurance bearings, the damage having the appearance of erosion pits in the silver plate. In many instances the erosion was so severe that it had penetrated the 0.001 to 0.002 inch thickness of silver plate and produced pitting in the substrate AMS 6415 steel cage material. All physical, chemical and metallurgical studies conducted on the cage, its plating and the P/M CRB-7 land surfaces revealed no deficiencies that would provide a clue as to the cause of this wear damage. The remaining bearing surfaces, such as the outer and inner ring ball grooves, and the external surfaces of the rings and cage and the ball pocket surfaces all were in good condition with only one or two notable exceptions as described in Table 14. More of the specifics for those bearings that were removed from the program for spalling or other reasons are discussed in the ensuing paragraphs in the order of their removal.

Bearings R13 and R14, that were removed after 2.6 hours of testing, were examined and it was noted that each bearing apparently had experienced a loss of axial thrust load as evidenced by the presence of ball tracking at the bottom of the inner race grooves as shown in Figure 28. Skidding distress was evidenced by the appearance of the balls is shown in Figure 29. Negligible wear of the nickel plated inner ring lands and only minor wear of the mating cage bore was observed.

Bearing R11 was removed after 157.4 test hours due to a spalled ball which is depicted in Figure 30. The inner ring lands experienced measurable wear up to 0.004 inch in depth. The mating cage land surfaces were locally distressed over a 90° sector in a manner similar to that experienced previously on the initial tests of the unmodified endurance bearings. The spalled ball was submitted to the materials laboratory for metallurgical examination. Binocular examination of the spall revealed rolling contact progression. Nital and microetch inspection of the subject ball, excluding the spalled area, revealed no indications of rehardening, abnormal tempering or segregation. The spall was located adjacent to the equator established during the ball fabrication forging. Chemical and spectrographic analyses identified the ball material as being similar to CRB-7 material. Hardness measurements on a machined flat of the ball produced readings of Rc 61.7 to 62.5, which are within the blueprint requirements. Metallographic examination of sections through the apparent spall origin revealed numerous transgranular cracks emanating from one end of the spall as can be seen in Figure 31. A number of localized deformation bands, or so called "butterflies" visible in Figure 32, were found adjacent to the spalled area with some micro-porosity evident in the vicinity of these butterflies. Kevex, or electron x-ray examination of both a butterfly and the surrounding material, as shown in Figure 33, revealed their makeup to be similar. This structure is believed to be work-hardened ferrite resulting from the breakdown of martensite.

Bearing R-18 was removed after 500 test hours due to a ball spall approximately 1/8 by 3/16 inch in size as shown in Figure 34. All of the balls were darkly stained with several having local clean spots.

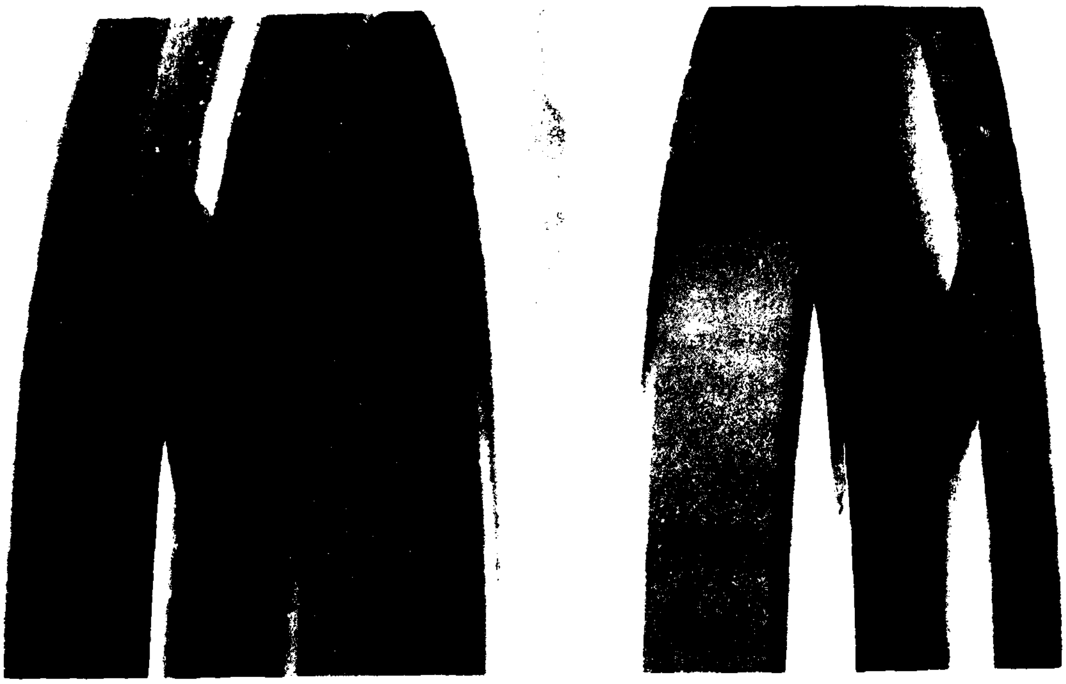

Figure 28. Ball Tracking at Bottom of the Inner Race Groove. This Bearing, S/N R13, Apparently Operated at a Low Thrust Load Resulting in Bearing Skid Distress.

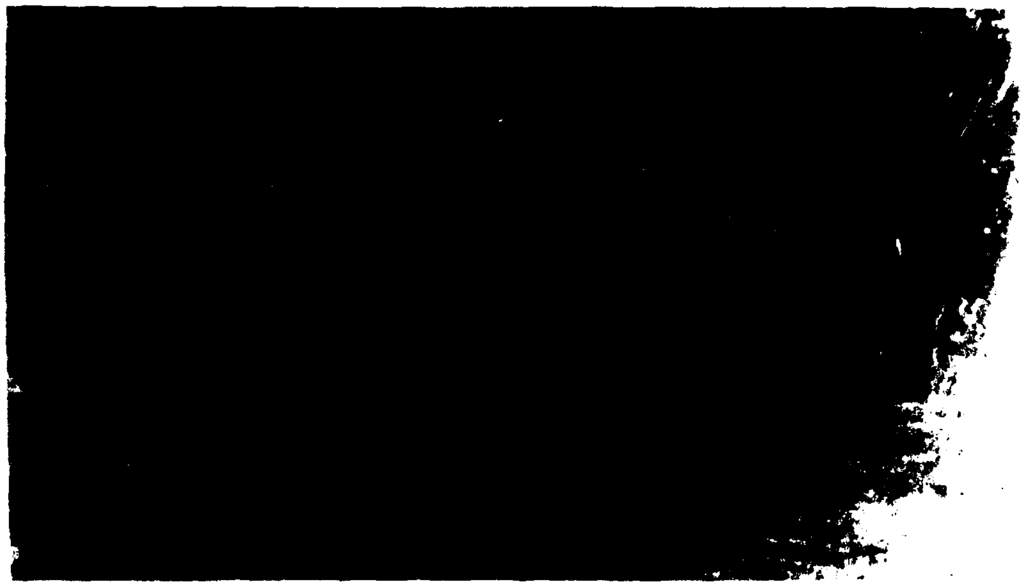

Figure 29. Ball Skid Distress. Appearance of Ball Surface From Bearing, S/N R13, That Apparently Operated at a Low Thrust Load.

Figure 30. Ball Spall after 157.4 Test Hours, Bearing S/N R11. Spall Was Located Adjacent to The Equator Established During Ball Fabrication Forging.

Figure 31. Photomicrograph of Ball Section Through Spall. Numerous Transgranular Cracks Emanated From Apparent Spall Origin.

Figure 32. "Butterfly" Formation Located Adjacent to Spall. Porosity Was Observed in Areas Adjacent to The "Butterfly."

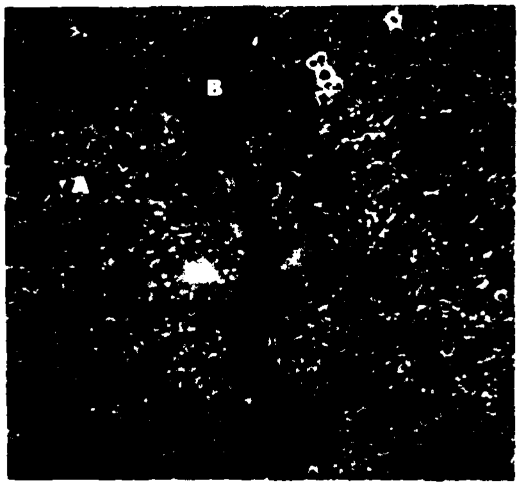

Figure 33. Micrograph of "Butterfly" Area. The Material in The "Butterfly," "B", Was Found to be Similar to Adjacent "A" Material. Structure is Believed to be Work Hardened Ferrite Resulting From The Breakdown of Martensite.

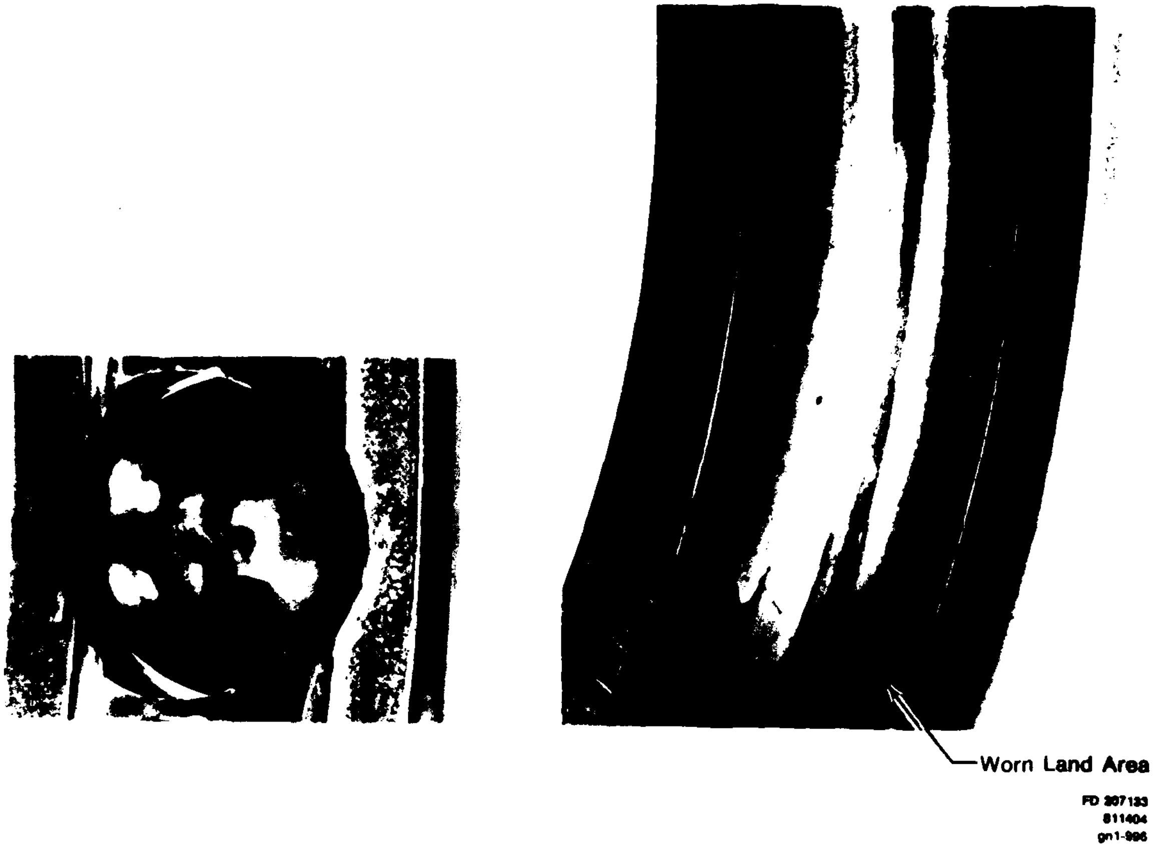

Figure 37. Outer Race Pit Found During Post Test Examination, Bearing S/N R17. Material Was Plucked or Pulled From The Surrounding Structure With The Pit Bottom Being Shiny. Pit Did Not Have The Normal Appearance of a Spall.

The axial thrust loaded inner race groove also indicated skid damage type distress as depicted in Figure 35. Land wear to a depth of 0.007 inch was measure on both inner ring halves. The cage bore surfaces also exhibited the erosive wear appearance, like that observed previously on the unmodified test bearings, and extended over 110° of the circumference.

Bearing R19 was removed after 942 test hours due to a ball spall, approximately 3/8 by 3/4 inch in size as can be seen in Figure 35. In addition, a section of nickel plating, 1/8 by 1.0 inch, was missing from the non-puller groove inner ring. Land surface wear of the inner rings was less than 0.004 inch in depth. Examination of the cage bore revealed typical erosive wear type damage over as much as 150° of the surface. Bearing R15 was removed after 942 test hours due to an outer race spall shown in Figure 36, which was approximately 1/8 inch in size. Negligible inner ring land wear was observed. Cage bore surface appearance was typical of that previously seen and extended for a 90° arc but on one side only.

Figure 35. Ball Spall after 942 Test Hours, Bearing S/N R19. Heavy Tracking Was Also Observed on The Spalled Ball in This Bearing.

Figure 36. Outer Race Spall Found after 942 Test Hours, Bearing S/N R15.The Wear Track is Oriented Vertically in This Photo.

While examining the outer race of the bearing R17 during the post test analysis, a pit approximately 0.020 inch in size was discovered and is depicted in Figure 37. This bearing had accumulated 784.6 test hours when the vibration indicator signalled for rig shutdown. Though this pit was believed to be a spall, more detailed optical examination indicated otherwise. The bottom of the pit was quite shiny and uncharacteristic of the rough, stricted appearance usually associated with a spall that had been initiated by rolling contact fatigue. Its appearance also gave the impression that the material originally there had been plucked out somehow. Although the cause or source of the action that produced this pit is not clear at this time it was considered that it could not be classified as a legitimate case of rolling contact fatigue. For purposes of Weibull analysis, this bearing was then treated as a suspension and not as a failure.

Figure 37. Outer Race Pit Found During Post Test Examination, Bearing S/N R17. Material Was Plucked or Pulled From The Surrounding Structure With The Pit Bottom Being Shiny. Pit Did Not Have The Normal Appearance of a Spall.

If it had been treated as a failure, the effect would have been to increase the resulting B-10 life for the P/M CRB-7 material. The magnitude of the increase, however, would not have altered the basic conclusion drawn from the overall results of this program.

Analysis of Lubricant Samples

In addition to post test analysis of the bearings the lubricant was also studied. Two samples of the MIL-L-7808H lubricant as used in the final 200 hours of the endurance test program were submitted to the Air Force Lubricant Branch for evaluation. A gas chromatography analysis conducted there indicated that both samples conformed to the Humble 1-M-1 lubricant specification which is the correct vendor supplier code number for the oil supplied to this program. Further, a spectrographic analysis (SOAP) indicated that there were no significant wear trends identifiable. It was concluded from a separate Ferrographic examination that the lubricant was servicable as it contained only a modest amount of metallic debris.

SECTION 6

DISCUSSION

The fact that the P/M CRB-7 ball bearings tested in this program produced a B-10 life equivalent to the industry standard VIM-VAR M-50 is highly encouraging considering the pioneering nature of this effort. The significance of this result can perhaps be best appreciated by looking back in time to that point when the alloy 52100 was the standard production bearing material for aircraft gas turbine use. In the mid to late 1950's the tool steel M-50 was first introduced experimentally for such applications and its B-10 life was found to be generally in the range of 10% to 50% of that for 52100 material of that day. Improvements in M-50 resulting from heat treat and quality control changes, and the introduction of vacuum melting processes paid off with a material that, today, provides a life more than two orders of magnitude better than what was initially available with that alloy. Although it is not being claimed that the same levels of improvement with P/M CRB-7 alloy can be realized in the next decade or two, some considerable measure of improvement can be expected since it is obvious that a solid foundation has been laid as evidenced by the work presented herein. One area where life improvement potential exists, for instance, is with the use of smaller particle size powder. In programs applying P/M processing to superalloys for gas turbine disks, a two-fold increase in fatigue strength came about through reducing particle size from the 80 mesh to the 325 mesh level. The smaller particles, besides compacting more readily, retain a lower percent of oxygen. This latter fact could favorably impact bearing steels that experience improved rolling contact fatigue resistance when the steel is free of oxides.

Some note should be made regarding the consistency of the ranking achieved by the two element testers used in this program. The single ball testers and the RCF machines both ranked P/M CRB-7 the best, P/M M50 and VIM-VAR M-50 as equivalent and in second place. The only notable difference occurred with the P/M T-15 material, the single ball tester ranking it a poor third and the RCF tester showing it equivalent to the M-50 materials. It is beyond the scope of this report to speculate in detail as to the cause of this difference in the results obtained on the two machines. Suffice it to state that care in preparing the specimens, resulting in good homogeneity, contributed much to obtaining consistent results from the two testers.

The encouraging results with the element testers were somewhat offset by the unanticipated wear problem experienced with the 140 mm P/M CRB-7 ball bearings. The nickel plating of the inner rings allowed the continuation of the rolling contact fatigue endurance program but did not entirely eliminate the wear problem. It was speculated that the nickel plate and the P/M CRB-7 material wore due to a lack of proper lubrication at the bearing test speeds combined with a possible cage resonance condition. This combination of factors may have produced local cage pitting damage similar to that caused by the collapse of cavitation bubbles. The bubbles can be created by large local pressure fluctuations in the lubricating film. These hydrodynamically erosive pressures may have then released material from both surfaces, the harder ring particles released becoming embedded in the soft silver plate on the cage bore. These hard particles so embedded could then remove more material from the inner ring land surface by an abrasive machining action.

In spite of the existence of erosion damage on the bore of every cage run in the P/M CRB-7 bearing tests, four of the twelve bearings experienced negligible wear on the mating inner ring land surfaces. Why this occurred is not understood. It is apparent, however, that some uncontrolled parameter or parameters played a role in producing no wear on one hand and objectionable levels on the other. Surface texture was one such uncontrolled parameter of the nickel plated lands. The land surfaces were finish ground to the required AA roughness level but may have had a texture variability from piece to piece that was perhaps responsible for the wide range of wear results experienced. It was beyond the scope of this program to conduct surface texture studies on the nickel coated lands and to develop any kind of surface texture specification for the bearings tested. It is quite likely, however, that such a development would have provided a consistent solution to the wear problem experienced on this program and would yield a generic technology gain for the aircraft bearing industry as a whole.

Another facet of this wear problem may be reflected in the test results obtained with the one 52100 bearing evaluated in this program. This bearing, with geometry identical to the P/M CRB-7 bearings, did not suffer any wear difficulties either on the inner ring lands or on the cage bore. TEM texture studies of the ring land surface of this bearing revealed an appearance similar to that of the M-50 bearings that also ran without wear difficulties. This fact adds further credence to the concept that texture control is important to the durability of high performance rolling element bearings.

This discussion would not be completed without some speculation as to the role that materials and their metallurgical structure might have played in this wear phenomena. The CRB-7 alloy is fundamentally a member of a high chrome, tool and bearing steel family populated by such materials as 440C, BG42 and WD65, all of which have widely acknowledged high resistance to wear. The CRB-7 alloy could be expected to perform similarly and in fact does so in machine tool applications. The next logical thought is to question the powdered structure of the CRB-7 alloy as used in the test bearings. Another similarly processed alloy of M-50 material has been tested in ball thrust bearings of the same 140 mm size and of similar geometry and under identical test conditions. These P/M M-50 bearings experienced none of the wear difficulties of the program CRB-7 bearings. This fact and, the other fact mentioned earlier that high chrome bearing steels of the same class as the CRB-7 alloy have tested well without such a wear problem, do not support any contention that the powder processed form of the material tested on the CRB-7 alloy in the bearing rings are intrinsically responsible in the current program. Thus, it appears at this juncture that the cause of the land wear problem is not due to a single parameter and a satisfactory solution must come from a study that would evaluate a combination of several parameters such as improved lubrication, cage resonance control and optimized inner ring land texture.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The innovative use of powder processing for bearing manufacture coupled with development of a new bearing steel has produced the following:

- Metallurgical studies demonstrated that powder processing can provide steels with cleanliness levels that are equal to or exceed those already established for double vacuum melted steels.
- Single ball tests of powder processed CRB-7 alloy yielded a B-10 life of 1.83 times that observed for VIM-VAR M-50 and 2.21 times better than that obtained on tests of powder processed M-50 material.
- RCF machine testing substantiated these single ball fatigue rig results.
- The B-10 fatigue life of the powder processed CRB-7 bearings was equal to that calculated for the same bearing fabricated from VIM-VAR M-50 alloy. Weibull analysis indicated that there was a 90% confidence that there was no significant difference between the two materials.
- Factors contributing to the inner ring land, cage bore wear difficulty experienced in this program are believed to be lack of proper land texture and marginal lubrication. Cage resonance may have also played a role.
- Use of hard nickel plating added substantially to the wear life of the inner ring lands to the extent that the rolling contact fatigue B-10 life tests could be conducted.

7.2 RECOMMENDATIONS

Powder processing of CRB-7 alloy has produced life improvements compared to that of the conventionally processed form of this material as demonstrated in single element rolling contact fatigue tests. The full scale bearing tests produced a B-10 life which is comparable to the theoretical M-50 life rating. Further investigation of the powder processed CRB-7 alloy is warranted and the Contractor recommends that the following be pursued:

- Optimize powder particle size and alloy heat treatment procedures, which have strong potential for making further life gains, and verify with ball fatigue tests.
- Evaluate fatigue life performance and hot isostatically pressed (HIP) balls. If encouraging results are obtained, the next logical step would be to experimentally evaluate HIP'd near net shaped ball bearing rings for cost saving and material conservation.
- Rework two of the powder processed CRB-7 bearings that survived the endurance test program by incorporating radial oil holes in the inner races to improve cage land lubrication and discourage cavitation damage, and rig test to verify.
- Apply existing analytical modeling techniques to the design of a replacement cage for the CRB-7 bearing that will not have a resonant frequency at the endurance test speed, fabricate and rig test to verify cavitation wear free operation.
- Conduct a comprehensive inner ring land texture optimization study and apply to reworked powder processed CRB-7 bearings that survived the endurance tests, and rig test to demonstrate wear life improvement.

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