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THIN DENSE CHROME BEARING INSERTION PROGRAM

Pyrowear 675 and Cronidur Wear Testing

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This report documents the results and conclusions of an extension to the Thin Dense Chrome Insertion Program. Prior results are reported in WL–TR–97–2053 (R97AEB141).

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13. ABSTRACT *(Maximum 200 words)*

This portion of the Thin Dense Chrome Insertion Program evaluated two new corrosion-resistant materials for use in F101 and F110 main shaft bearings: Cronidur 30 and Pyrowear 675. Contamination, wear, and corrosion resistance were assessed through selected subscale and full-scale tests. Subscale tests evaluated the wear characteristics and corrosion resistance. Full-scale tests demonstrated contamination resistance at normal F110–GE–129 operating conditions with exposure to abnormal aluminum oxide contamination levels. Cronidur 30 demonstrated improved corrosion resistance relative to M50 in salt water and tap water in subscale corrosion testing. Pyrowear 675 also demonstrated improved corrosion resistance relative to M50 but was not as good as Cronidur 30. Both Cronidur 30 and Pyrowear 675 demonstrated reduced wear resistance relative to M50 material in subscale testing. In full-scale testing, both materials exhibited outer race shoulder and cage pocket wear greater than M50. Based on these results, both new bearing materials were deemed to be too great of risk for immediate application to the F101 and F110 engines. Possibly, bearing alloy development or race treatments can be used to improve wear resistance, but such assessment was beyond the scope of this contract.

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MRC	Jim Clayton George Cozzens Ron Spitzer
FALEX	Brian Holtkamp

1.0 Summary

This report describes effort performed under an extension to the Thin Dense Chrome Insertion Program. Prior work under this contract (03/01/92 through 12/01/96) was reported in WL–TR–97–2053 (R97AEB141), "Thin Dense Chrome Bearing Insertion Program" Final Report, March 1997. Subsequently, the program was extended to evaluate two new corrosion-resistant materials for future use in F101 and F110 military engine main-shaft bearing applications. The added objectives included evaluation of contamination-induced wear and corrosion resistance of Cronidur 30 and Pyrowear 675 bearing materials.

To achieve these objectives, a select group of subscale and full-scale tests were completed. Subscale tests evaluated the wear characteristics and corrosion resistance of material specimens. Full-scale tests demonstrated the contamination resistance of the materials at normal F110–GE–129 operating conditions with exposure to abnormal amounts of aluminum oxide contaminant. M50 bearing material was used as the baseline during these evaluations.

Cronidur 30 material demonstrated improved corrosion resistance relative to M50 bearing material in salt water and tap water in subscale corrosion testing. Pyrowear 675 material also demonstrated improved corrosion resistance relative to M50 bearing material but was not as good as Cronidur 30.

Both the Cronidur 30 and Pyrowear 675 bearing materials demonstrated reduced wear resistance relative to M50 material in subscale wear testing. In full-scale testing, both materials exhibited outer race shoulder and cage pocket wear greater than that of M50.

Based on the results of these evaluations, Cronidur 30 and Pyrowear 675 were deemed high risk for immediate F101 and F110 applications. Further alloy development or race treatments could improve wear resistance, but such assessment is beyond the scope of this contract.

2.0 Introduction

GE Aircraft Engines (GEAE) completed this effort under contract F33615–92–C– 2208. The Thin Dense Chrome Bearing Insertion Program was initiated in March 1992 and was performed under the guidance of Jon Dell, USAF Project Engineer. The objective was to develop a material/process specification for applying thin dense chrome (TDC) to aerospace-quality bearings and to conduct testing to substantiate insertion of TDC coated bearings into F101 and F110 military engines. After extensive testing, it was concluded that TDC coated bearings are too high risk for F101 and F110 engine applications.

Additional tasks were added to the program as part of a contract modification, dated September 27, 1995. The tasks included evaluation of the corrosion resistance and wear characteristics of two corrosion-resistant bearing materials: Cronidur 30 and Pyrowear 675.

2.1 Wear and Corrosion Resistance Program Description

The effort reported herein consisted of two main elements: rig wear tests (contamination-endurance tests) and corrosion-resistance evaluation (material specimen tests).

GEAE completed rig wear tests of two Pyrowear 675 ball bearings with M50 balls, two Cronidur 30 ball bearings with Cronidur 30 balls, and two Cronidur 30 ball bearings with M50 balls at normal F110–GE–129 engine operating conditions with exposure to aluminum oxide contaminant. The contamination-endurance rig test evaluated ball bearings of design and geometry similar to those of the F101/F110 No. 3B bearing. Test results were compared with previous M50 and M50NiL contamination-endurance rig tests.

GEAE completed subscale testing and evaluation of Pyrowear 675 and Cronidur 30 specimens. This included corrosion-resistance testing and wear testing of both materials. Test results were evaluated and compared with identical tests on other bearing materials.

2.2 Background

M50 is the material of choice for main-shaft ball and roller bearings in military engine applications at GEAE. It is favored for good fatigue and wear resistance but is limited by poor corrosion resistance. Cronidur 30 and Pyrowear 675 both have good corrosion resistance — attributed to high chromium content. The corrosion-resistance test used synthetic salt water and tap water and was intended to demonstrate the behavior of Cronidur 30 and Pyrowear 675 relative to M50. Both materials present a wear concern because of small carbides in the microstructures relative to M50. The contamination-endurance test and the Falex wear test were intended to demonstrate the behavior of the materials relative to M50 and M50NiL.

The contamination-endurance rig test simulates engine startup with severe contamination. Two ball bearings are tested at normal F110–GE–129 operating conditions with exposure to a large quantity of aluminum oxide contaminant. This rig test was developed to investigate the suspected shoulder wear concerns on M50NiL within a short period of test time.

The contamination level and exposure in the tests conducted on Cronidur 30 and Pyrowear 675 were intended to be as severe as in the previous tests conducted on M50 and M50NiL bearings and were intended to demonstrate the relative shoulder-wear resistance. In the previous tests, the No. 3 ball bearing with M50 races and a silver-plated cage was tested for 126 hours and did not show any shoulder wear. Raceway spalling did occur at 126 hours in this baseline M50 test.* The No. 3 ball bearing with bare M50NiL races, no coatings, and a silver-plated cage had apparent shoulder wear after 10 hours. These prior tests form the baseline for evaluation of Cronidur 30 and Pyrowear 675 bearings.

2.3 Cronidur 30 Technical Description

Cronidur 30 is a high-nitrogen steel produced by the pressurized electro-slag remelt (PESR) process. The material was developed for bearing use by a consortium consisting of FAG, VSG, and the University of Bochum. FAG has exclusive rights to the use of this material for bearing, gear, and ballscrew applications. FAG has demonstrated by extensive testing that Cronidur 30 has greater corrosion resistance than 440C or TDC plated M50 and a longer fatigue life than M50 or M50NiL.

2.4 Pyrowear 675 Technical Description

Pyrowear 675 is a carburizing stainless steel that was originally developed by Carpenter Technology Corporation in response to a need for increased corrosion resistance and fracture strength in bearings and gears. MRC developed a heat treat and carburizing process that makes Pyrowear 675 an ideal material for high-performance jet engines requiring bearings to operate at high speeds and elevated operating temperatures. The dual-property capabilities of Pyrowear 675 make it a candidate for integral bearing/structural components where rolling contact and structural fatigue strength are required. Testing of Pyrowear 675 by MRC has demonstrated that rolling contact fatigue endurance is several times better than that of M50.

2.5 Technical Approach Summary

The primary objective of this effort was to compare the wear resistance of Cronidur 30 and Pyrowear 675 to M50 and M50NiL.

The contamination-endurance test was used to provide a measure of the wear resistance of a bearing material. Excessive wear during this test is an indication that general insertion into field applications should not be recommended. The material may still be acceptable for specific bearing applications where contamination is minimal.

Additional specimen tests were also conducted to evaluate Cronidur 30 and Pyrowear 675 resistance to contamination-induced wear relative to that of M50 and M50NiL.

* WL–TR–97–2053 (R97AEB141), "Thin Dense Chrome Bearing Insertion Program" Final Report, March 1997, page 89.

3.0 Full-Scale Contamination-Endurance Rig Testing

3.1 Test Setup and Operation

Contamination-endurance tests were conducted at the GEAE Component Test Center. Two bearings were tested simultaneously under the same axial load, shaft speed, and lube-supply temperature.

Rig operation simulated the F110–GE–129 No. 3 ball bearing startup with severe contamination and full-speed operating conditions. A hydraulic cylinder and load cell were used to apply an axial load of 6000 ±100 lbf. No radial load or intentional unbalance were applied to the bearing. The outer race temperature, regulated by oil-supply temperature and monitored by thermocouples, was maintained at 375 ±25°F. The oil was MIL–L–7808J. The shaft speed was set at 14,250 ±250 rpm. Figure 1 shows the test rig arrangement.

Aluminum oxide particles, 200 mg at 75-μm diameter, were mixed with a small amount of the lubrication oil. Two samples of oil contaminated with suspended aluminum oxide were prepared separately and injected by the two oil jets, at the beginning of the test, directly into the two test bearings. The aluminum oxide particles were then filtered out of the oil system using a 40–50 μm filter during subsequent running. No additional contamination was injected during the remaining rig operation. This procedure was the same for each test.

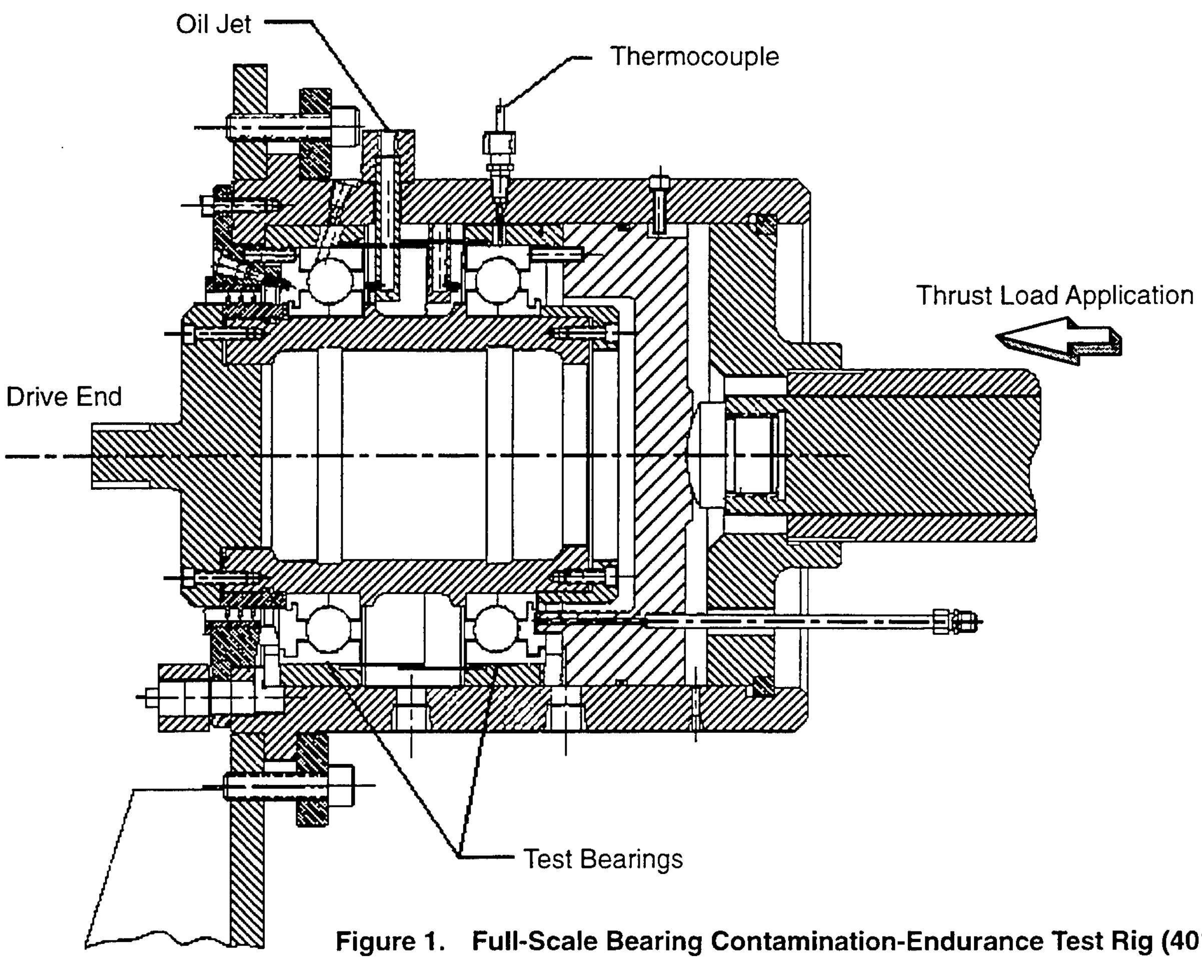


Figure 1. Full-Scale Bearing Contamination-Endurance Test Rig (4013417–860)

The first shutdown and bearing inspection were planned to occur after 40 hours of run time. Early shutdown could be instigated by abnormal rig operating noise, vibration, outer race temperature, or debris observed on the magnetic chip detector. Ultimately, the rig could be permitted to run for 1000 hours if the bearings did not show signs of contamination damage or wear in excess of previous equivalent M50 tests.

Four new bearings were purchased to conduct full-scale contamination-endurance tests. Two bearings consisted of Cronidur 30 races with Cronidur 30 balls from FAG, and two bearings consisted of Pyrowear 675 races with M50 balls. Figure 2 shows one of the Cronidur 30 bearings. Two subsequent bearings were purchased from FAG with Cronidur 30 races and M50 balls. Table 1 is a summary of the bearing tests. To differentiate the bearings, the full Cronidur 30 bearings are referred to as "purebred," and the mixed material bearings with M50 balls are referred to as "hybrid" in subsequent sections of this report.

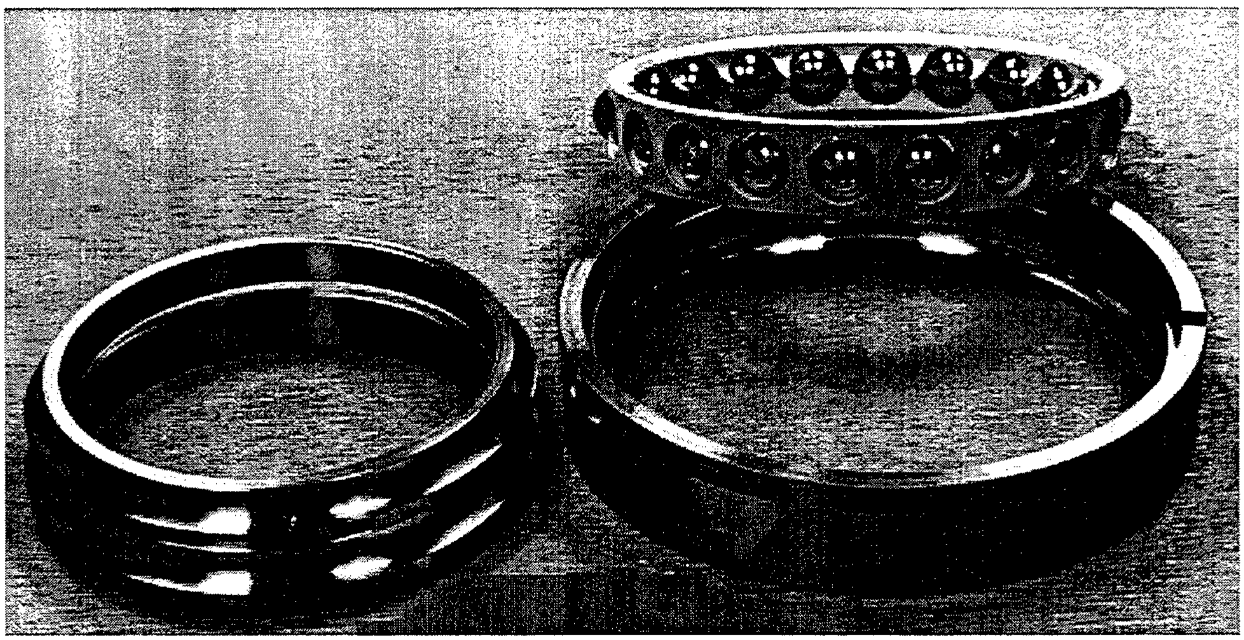


Figure 2. Cronidur 30 "Hybrid" (S/N FCAB0971) – Bearing Pretest Condition

Table 1 Contamination-Endurance Tests – Test Bearing Summary

Supplier	Part No.	Serial No.	Race Material	Ball Material	Rig Location
FAG	597059	FCAA7069	Cronidur 30	Cronidur 30	Drive End
FAG	597059	FCAA7068	Cronidur 30	Cronidur 30	Opposite Drive End
FAG	597248	FCAB0971	Cronidur 30	M50	Drive End
FAG	597248	FCAB0972	Cronidur 30	M50	Opposite Drive End
MRC	9126UK123	MDAGK040	Pyrowear 675	M50	Drive End
MRC	9126UK123	MDAGK041	Pyrowear 675	M50	Opposite Drive End

3.2 Cronidur 30 "Purebred" Results

The full-scale Cronidur 30 "purebred" bearings consisted of Cronidur 30 races with Cronidur 30 balls as supplied by FAG. The geometry is similar to that of the F110 No. 3 ball bearing, GEAE P/N 9732M10P20. Both bearings were visually inspected prior to installation, and no visible damage was found. One bearing, FAG P/N 597059, S/N FCAA7069, was installed on the drive side; the second bearing, S/N FCAA7068, was installed opposite the drive side in the same rig.

The rig was operated according to the procedure outlined in Section 3.1 but was shut-down after 10 minutes because of abnormal operating noise. The magnetic chip detectors revealed debris, a characteristic of wear. Scanning electron microscopy (SEM) confirmed the presence of Cronidur 30 curls and flakes. The rig was disassembled for inspection of the bearings.

Both bearings showed similar evidence of wear initiation. The balls had scratches, and some could be felt with a 0.030-inch radius scribe. The cage rail outer surfaces had circumferential scratches and local dark streaks. The cage pockets had aluminum oxide imbedded in the silver. The outer raceway curvatures had some pitting and denting on the puller groove side (the loaded side). The outer race shoulders showed some circumferential polishing. The inner raceway also had pitting and denting on the loaded half. Figures 3 and 4 show the bearings at this midtest point.

The rig was reassembled and continued operation without any additional contamination injected. After a few hours, the rig was shut-down by the operator due to unusual noise. With a total of 3.92 hours of operation, the contamination-endurance rig test of the two Cronidur 30 bearings with Cronidur 30 balls was considered complete.

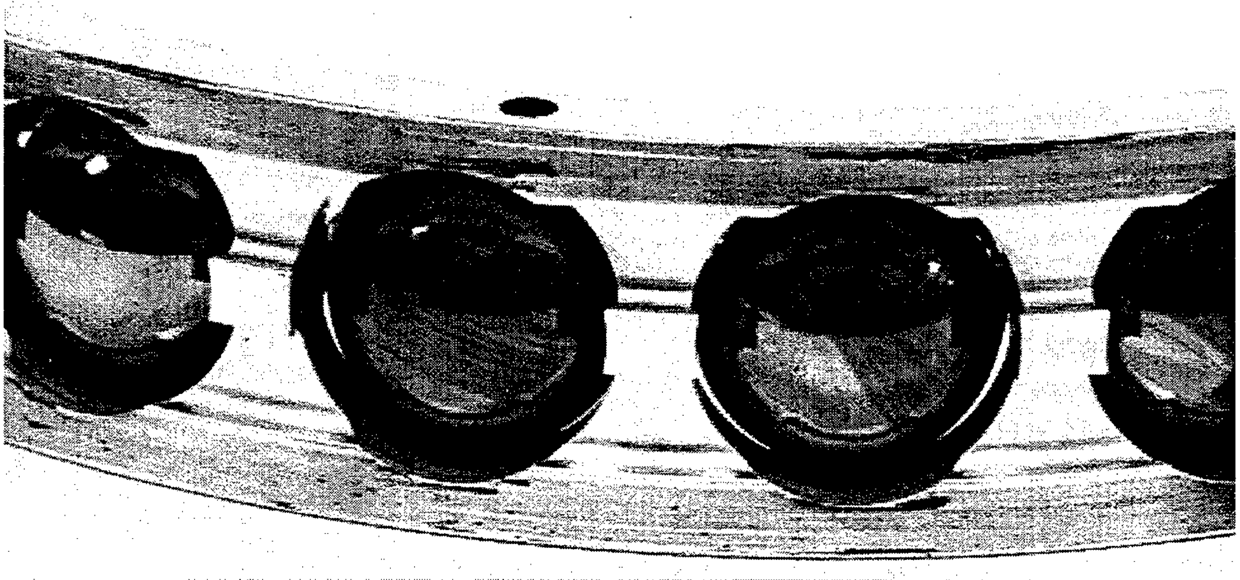
At teardown, the condition of the two bearings was reviewed. Several balls in one bearing, S/N FCAA7068, were severely worn — the worst ball being ellipsoid in shape. Table 2 lists ball diameter measurements. A few balls had debris denting. The second bearing, S/N FCAA7069, did not experience this severe wear but did have scratches on the balls. The cage rail outer surfaces had local dark streaks. The outer race of both bearings had some wear on the cage guiding shoulders. The outer race shoulders were measured before and after the test to reveal a radial wear depth of 0.001 inch. The loaded half of the inner race had fine pitting and denting. The raceway-to-shoulder corner appears distorted and raised. Figures 5 through 14 show the posttest "purebred" bearings.

Both bearings had shoulder wear to a depth of 0.001 inch on the outer race shoulders, and both had the local dark streaks on the cage rail outer surfaces. The excessive damage to the balls was a concern. Both bearings were subjected to material evaluation to further examine the microstructure. The wear characteristic of the Cronidur 30 "purebred" bearing was deemed unacceptable.

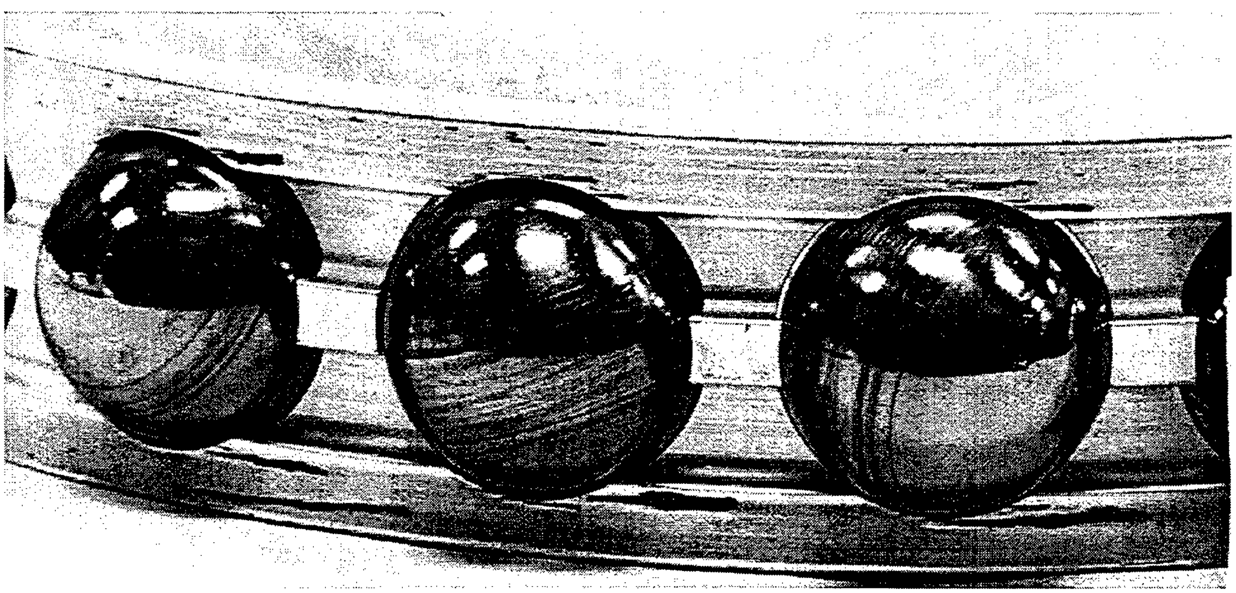
3.3 Cronidur 30 "Hybrid" Results

The full-scale Cronidur 30 "hybrid" bearings consisted of Cronidur 30 races with M50 balls as supplied by FAG. M50 balls were used in an attempt to obviate the ball wear witnessed in the previous test (Section 3.2). The bearing geometry is similar to that of the F110 No. 3 ball bearing, GEAE P/N 9732M10P20. Both bearings were visually inspected prior to installation, and no visible damage was found. One bearing, FAG P/N 597248 S/N FCAB0971, was installed on the drive side; the second bearing, S/N FCAB0972, was installed opposite the drive side in the same rig.

The rig was operated according to the procedure outlined in Section 3.1. The rig was shut-down after a few hours due to abnormal noise and spall-like flakes on the magnetic chip detector. With a total



S/N FCAA7068



S/N FCAA7069

Figure 3. Cronidur 30 "Purebred" Cage and Ball Midtest Wear

S/N FCAA7068

S/N FCAA7069

Figure 4. Cronidur 30 "Purebred" Outer Race Shoulder Midtest Wear

Table 2. Contamination-Endurance Test – Cronidur 30 Races with Cronidur 30 Balls (FAG P/N 597059, S/N FCAA7068)

Ball No.	Diameter, in			Radial Wear Depth, in
	Pretest	Posttest, Major	PostTest, Minor	
1	0.875	0.869	0.784	0.0455
2	0.875	0.866	0.861	0.0070
3	0.875	0.868	0.842	0.0165
4	0.875	0.869	0.864	0.0055
5	0.875	0.868	0.865	0.0050

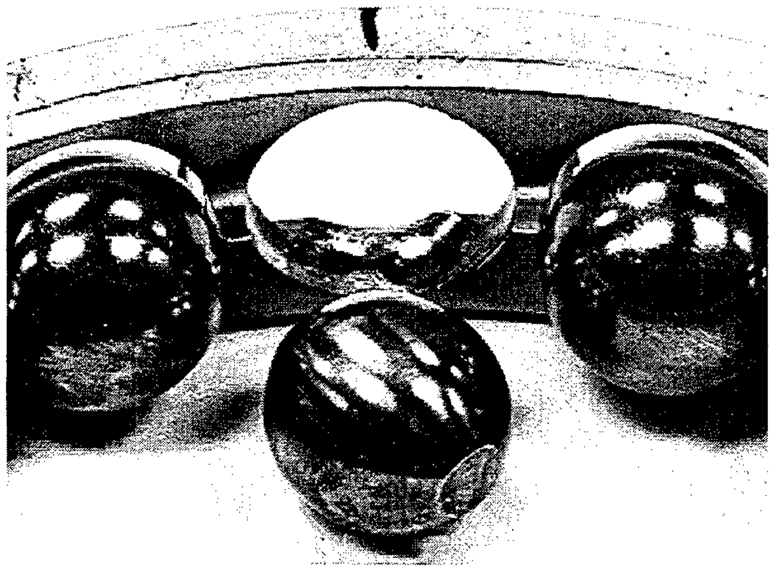


Figure 5. Cronidur 30 "Purebred" (S/N FCAA7068) Ball Ellipsoidal Wear

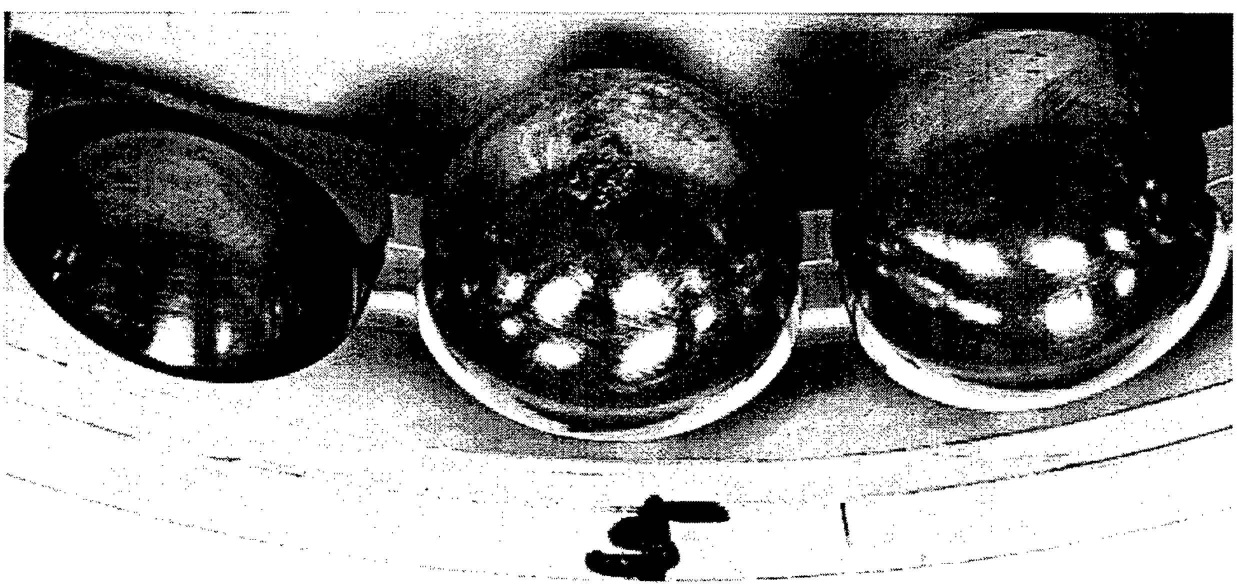


Figure 6. Cronidur 30 "Purebred" (S/N FCAA7068) Ball Debris Denting

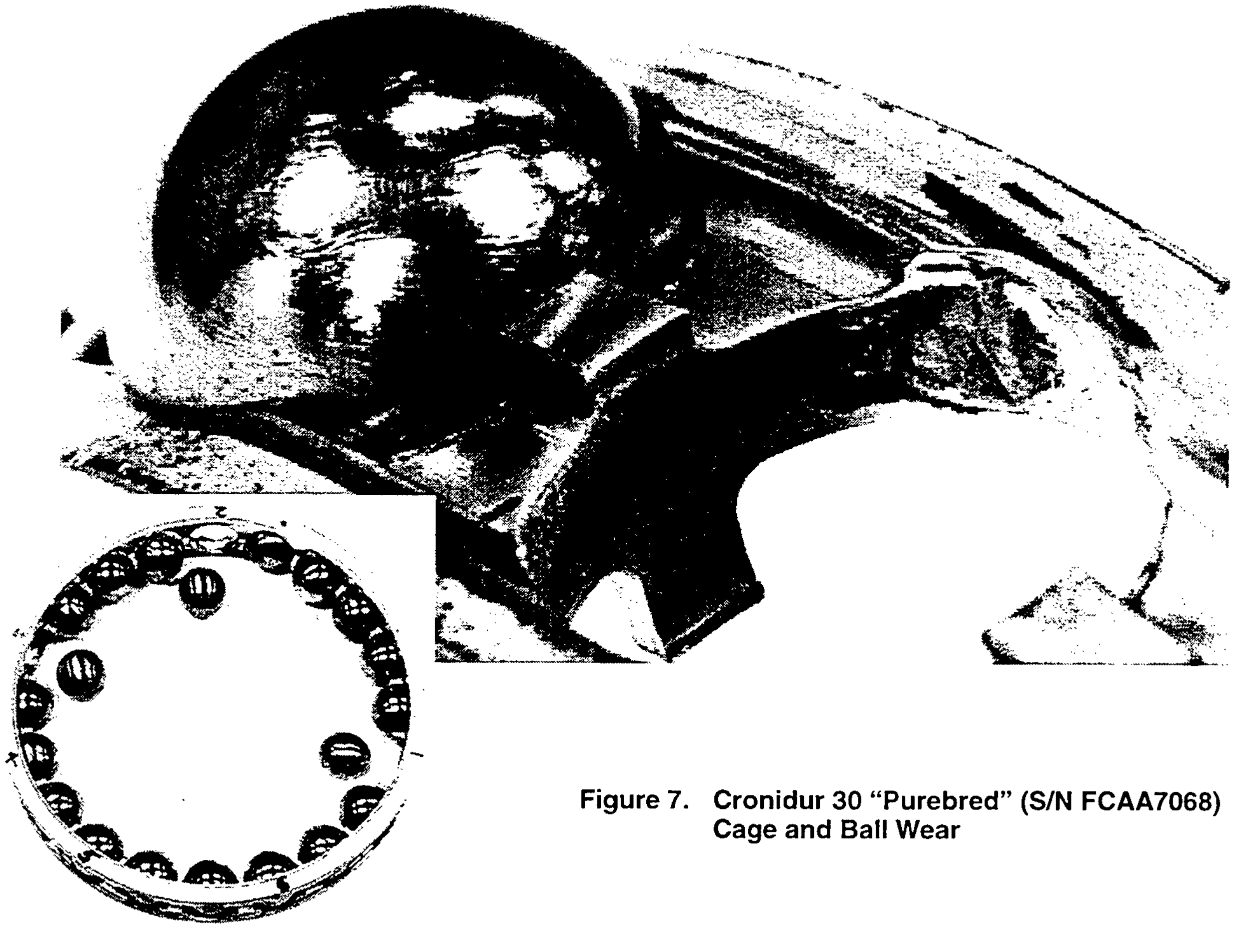


Figure 7. Cronidur 30 "Purebred" (S/N FCAA7068) Cage and Ball Wear

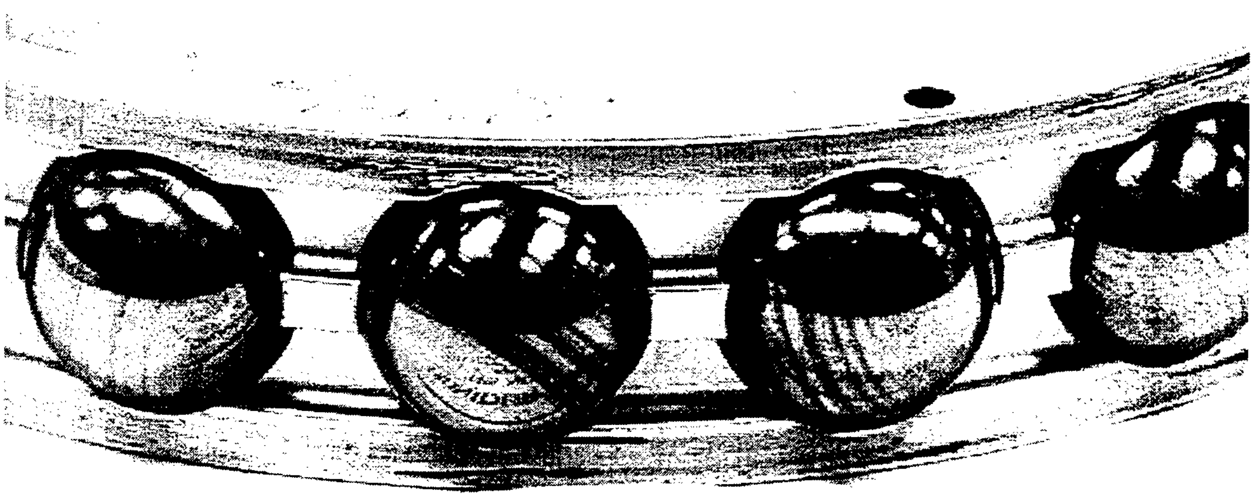


Figure 8. Cronidur 30 "Purebred" (S/N FCAA7069) Cage and Ball Wear

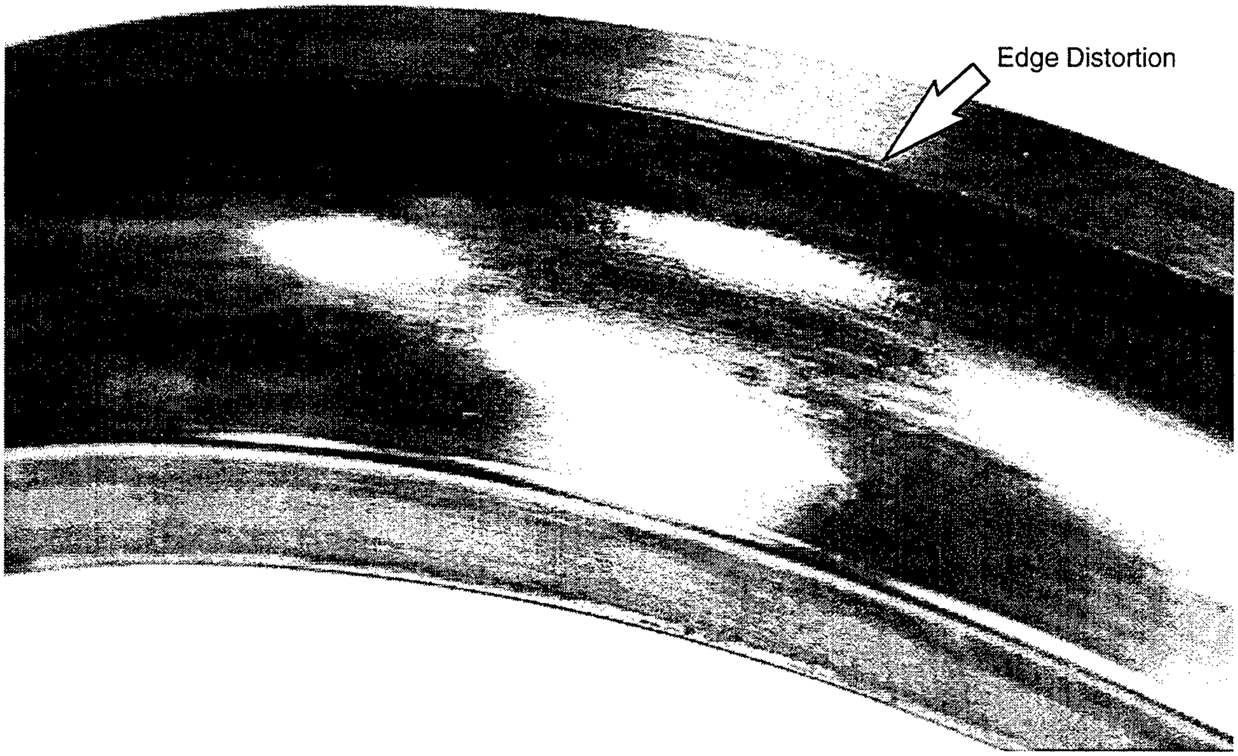


Figure 9. Cronidur 30 "Purebred" (S/N FCAA70680) Inner Race (Loaded Half) Posttest Condition

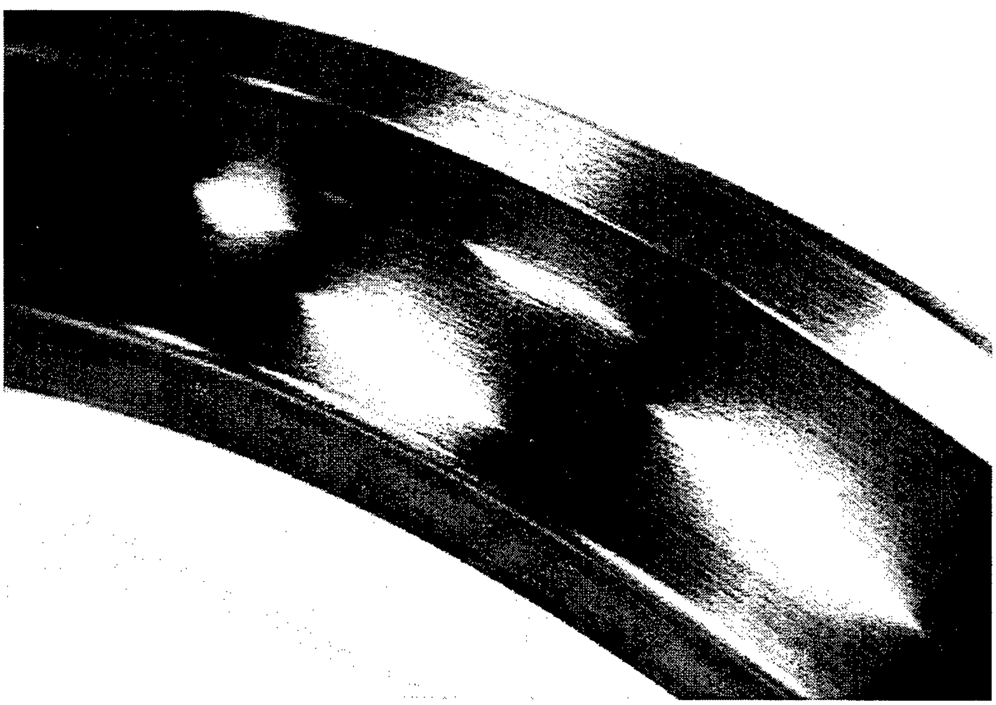


Figure 10. Cronidur 30 "Purebred" (S/N FCAA7068) Inner Race (Unloaded Half) Posttest Condition

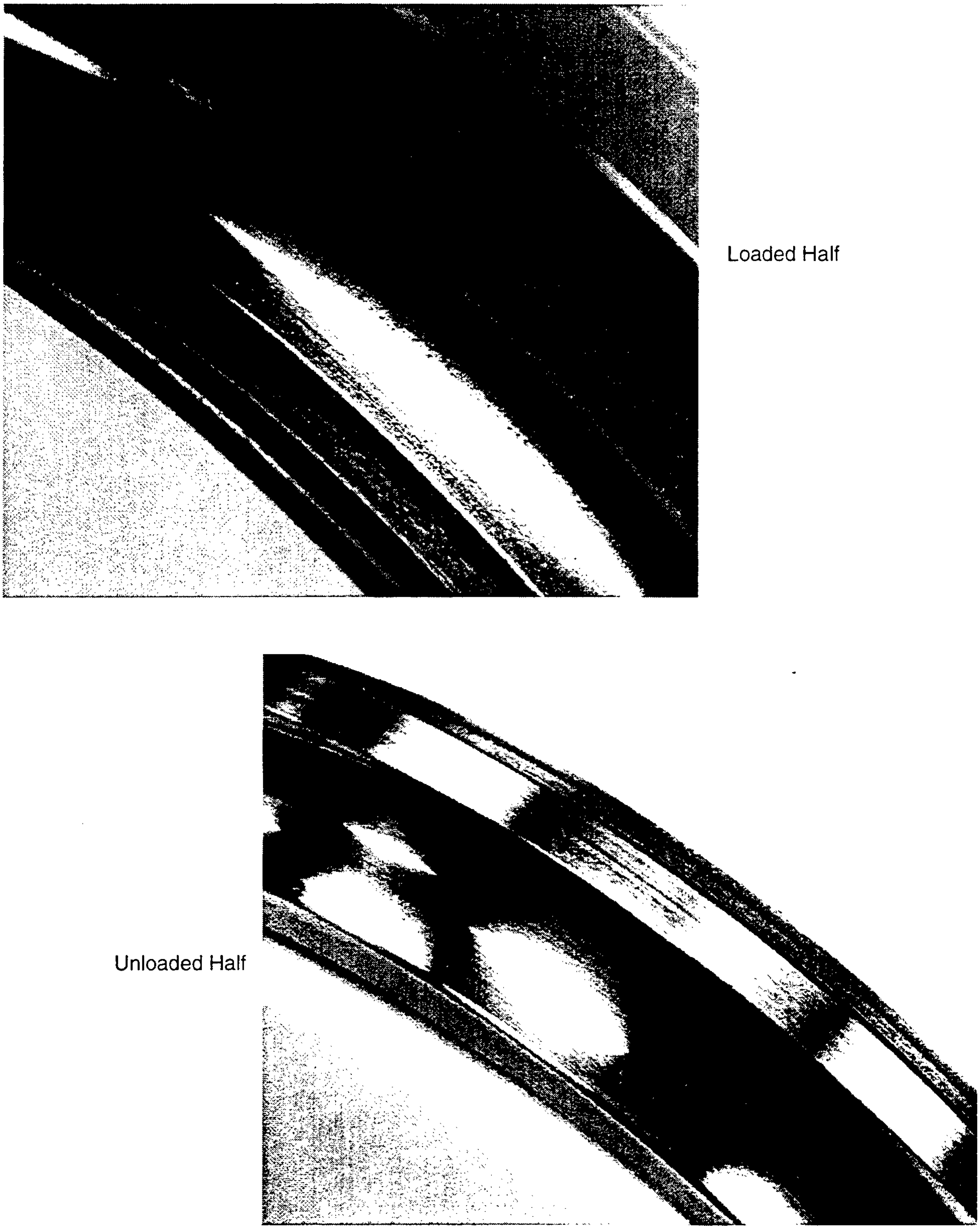


Figure 11. Cronidur 30 "Purebred" (S/N FCAA7069) Inner Race Posttest Condition

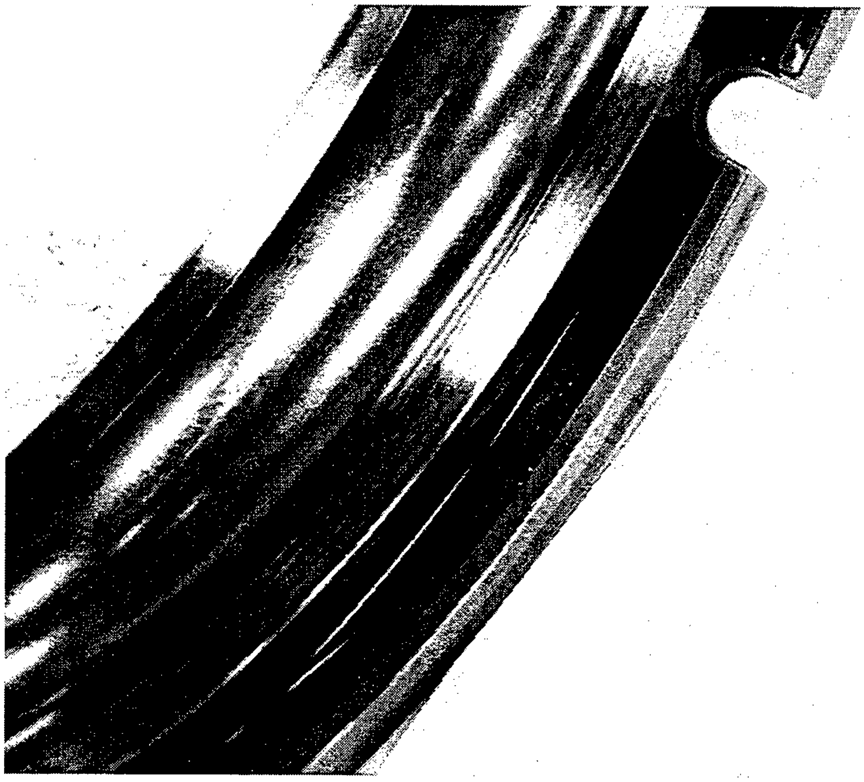


Figure 12. Cronidur 30 "Purebred" (S/N FCAA7068) Outer Race Shoulder Wear

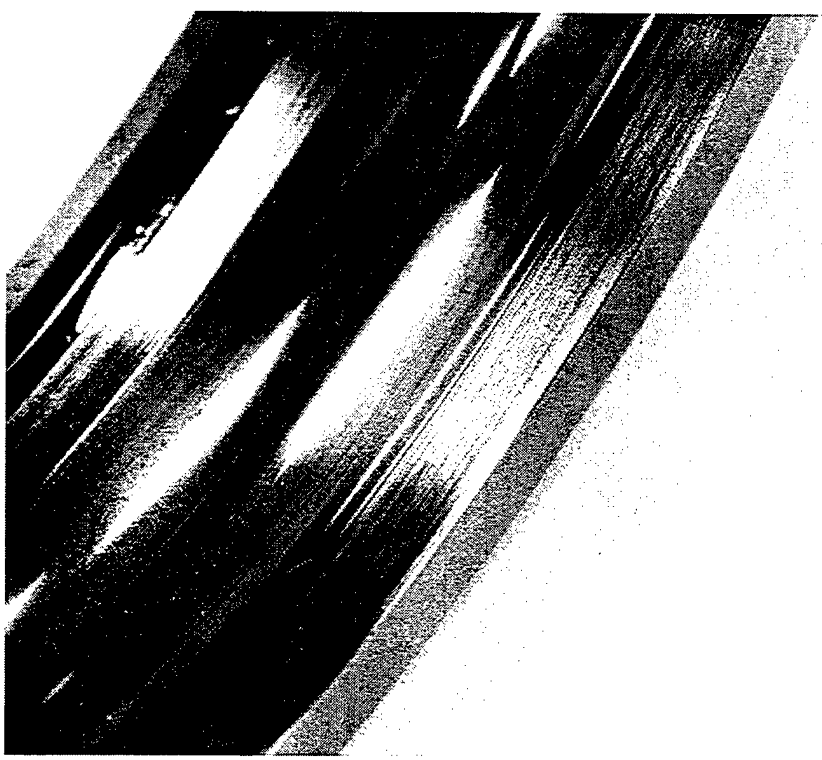


Figure 13. Cronidur 30 "Purebred"(S/N FCAA7069) Outer Race Shoulder Wear

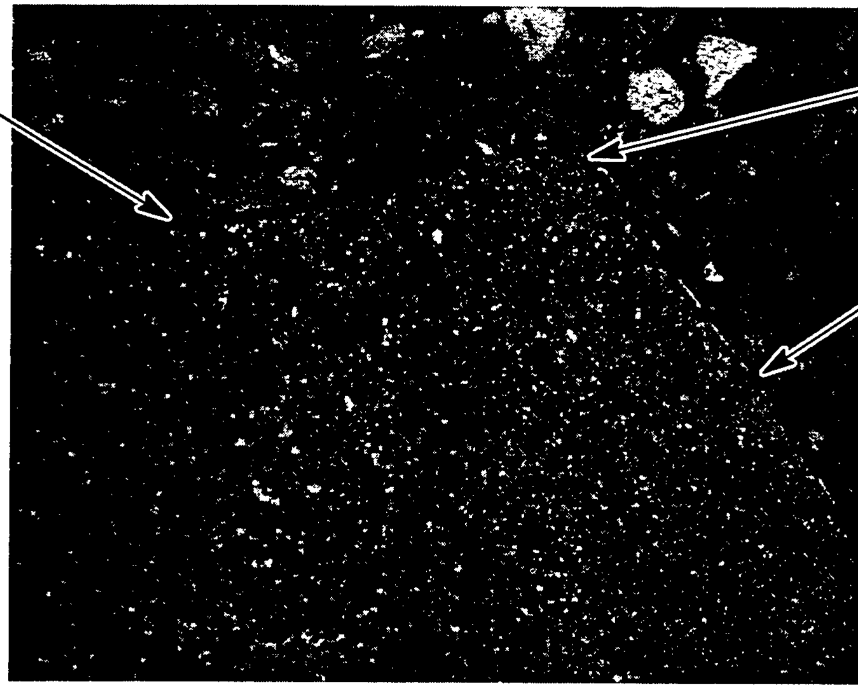


Figure 14. Cronidur 30 "Purebred" Inner Raceway Shoulder Wear/Distortion
Radial section of distortion on inner race shoulder (200X).

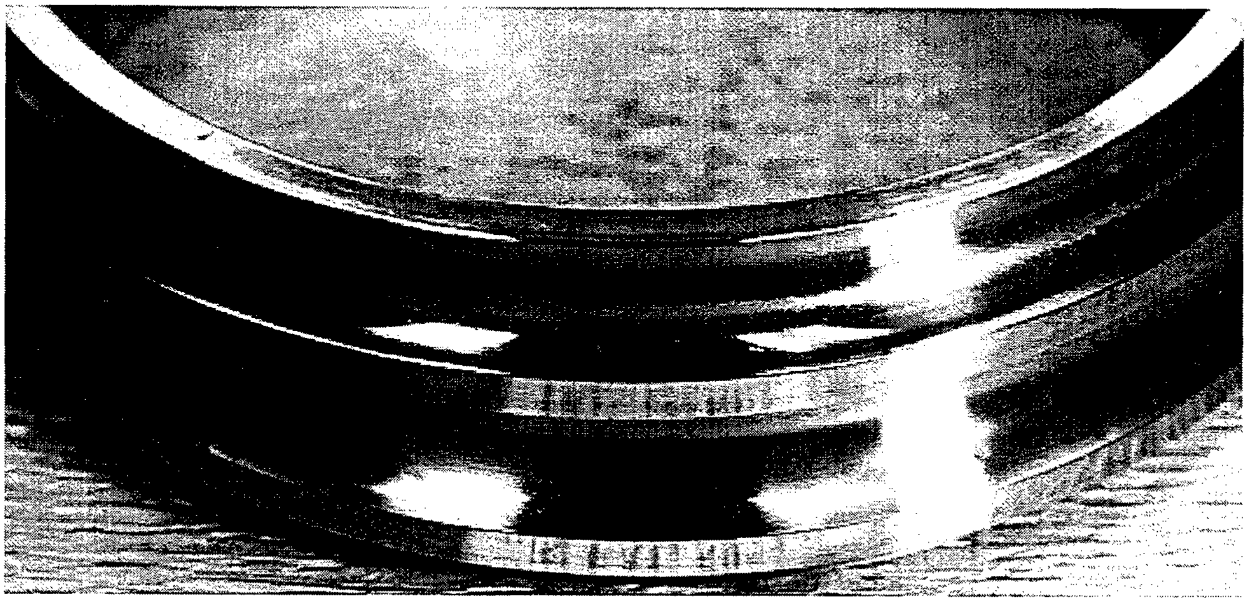
of 4.03 hours of testing, the contamination-endurance rig test of two Cronidur 30 full-scale bearings with M50 balls was considered complete.

At teardown, the condition of the two bearings was reviewed. On the inner raceway, they exhibited microspalling on the loaded half. The damage was in a narrow band, about 0.10-inch wide, positioned about the middle of the raceway, and was relatively shallow. The microspalling on one bearing, S/N FCAB0971, was continuous while the second bearing, S/N FCAB0972, exhibited intermittent microspalling. Microspalling was not present on the outer race curvature of either bearing, but both had a wide shiny band and some fine pitting toward the loaded portion. The outer race cage-riding shoulders had light polishing and fine scratches. The cage rail outer surfaces had local dark streaks, and the balls had light circular scuffing. Figures 15 through 18 show the after-test conditions of the Cornidur 30 "hybrid" bearings.

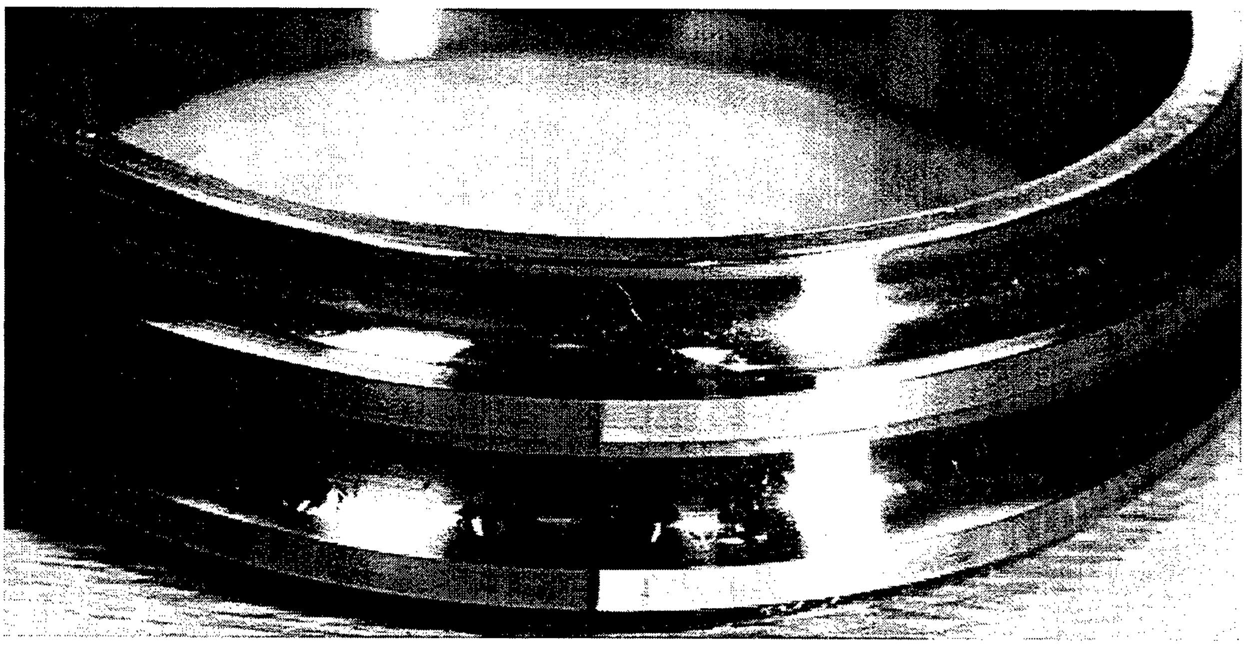
Both bearings had shoulder wear as indicated by light polishing and fine scratches on the outer race shoulders and local dark streaks on the cage rail outer surfaces. Both bearings underwent material evaluation to further examine the microstructure. The wear characteristic of the Cronidur 30 "hybrid" bearing was deemed unacceptable.

3.4 Pyrowear 675 "Hybrid" Results

The full-scale Pyrowear 675 "hybrid" bearings consisted of Pyrowear 675 races with M50 balls as supplied by MRC. The bearing geometry is similar to that of the F110 No. 3 ball bearing, GEAE P/N 9732M10P16. Two-dimensional nonconformances were identified by MRC. The puller-side contact angle was 37.5° versus the requirement of 33.5° to 36.5°. The inner ring width was 1.4011 to 1.4034 inch versus the requirement of 1.405 to 1.410 inch. Both nonconformances were accepted



S/N FCAB0971



S/N FCAB0972

Figure 15. Cronidur 30 "Hybrid" Inner Race Shoulder Wear

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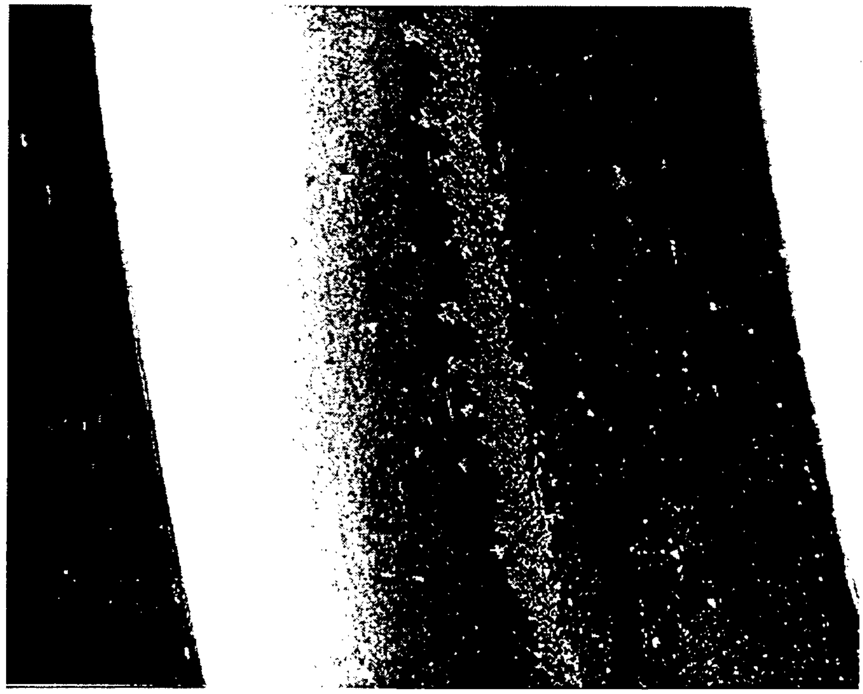
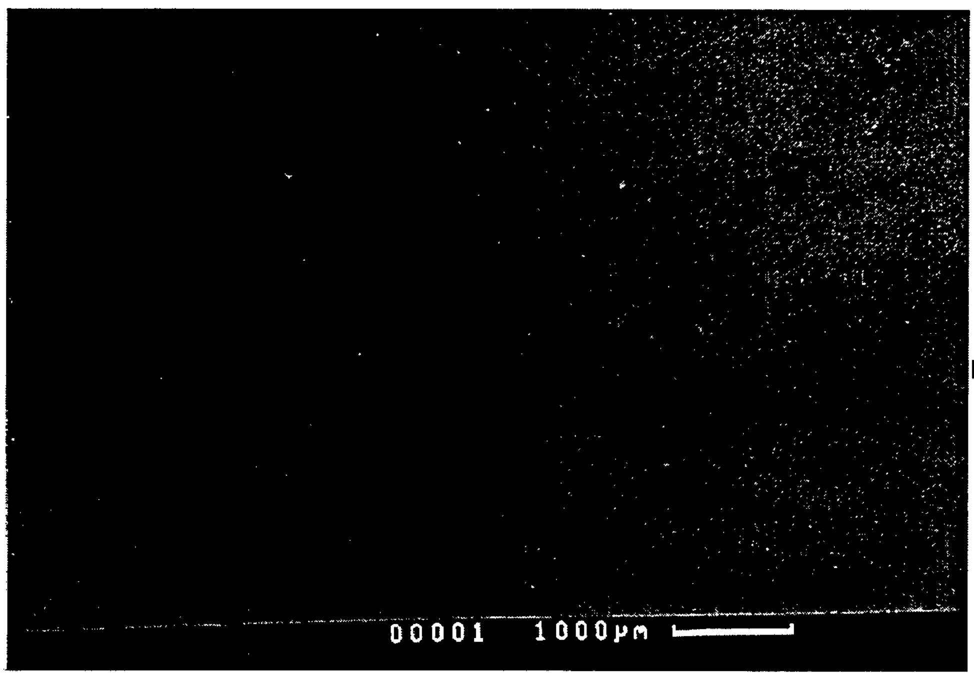
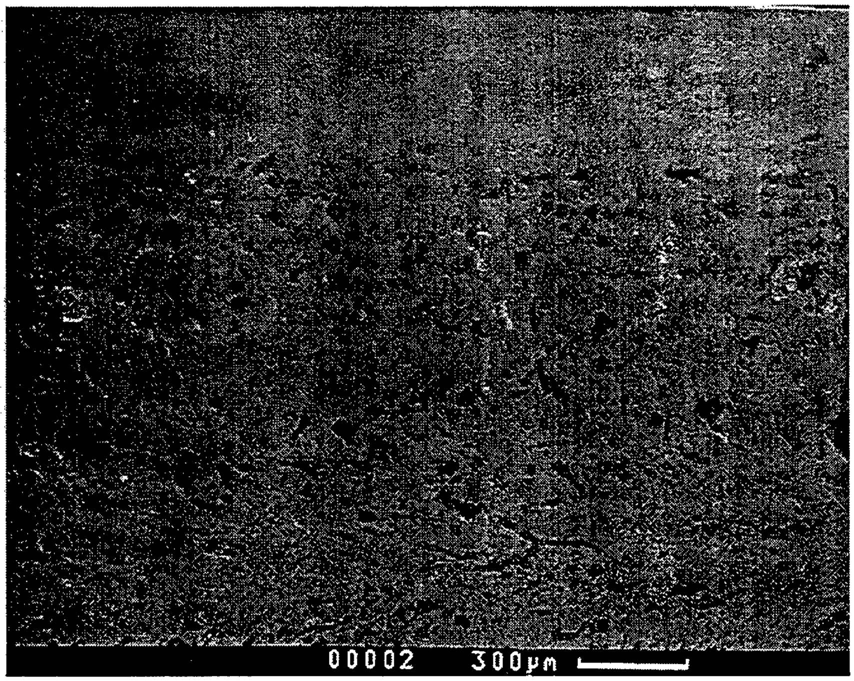




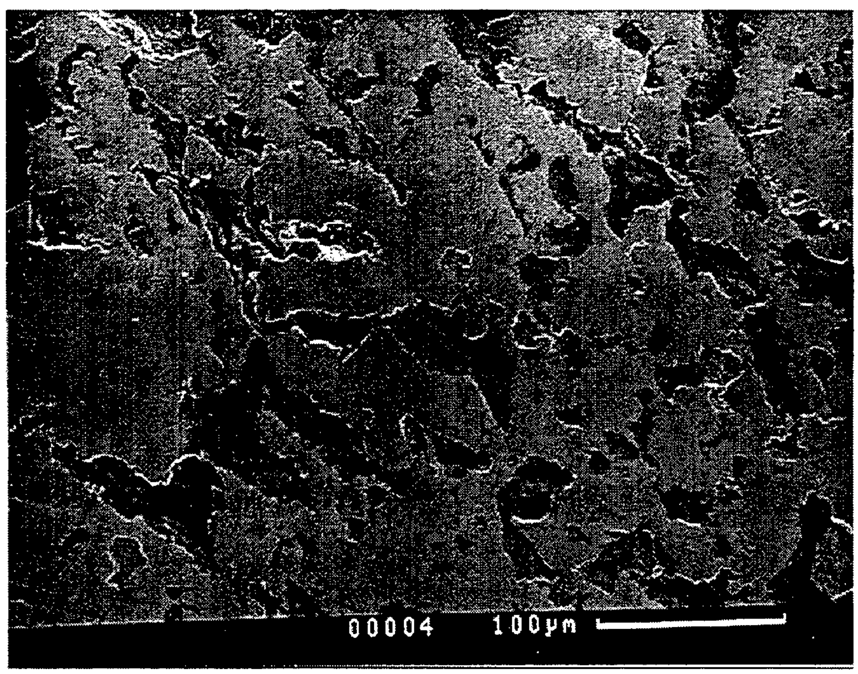
Microspalling

14X (SEM)

Figure 16. Cronidur 30 "Hybrid" Inner Raceway Microspalling *(Page 1 of 3)*



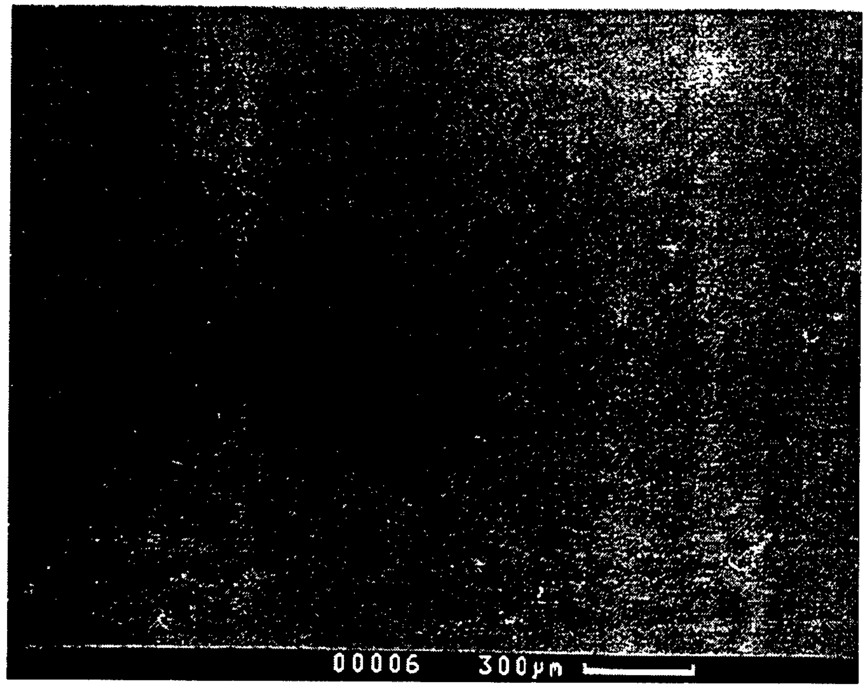
50X (SEM)

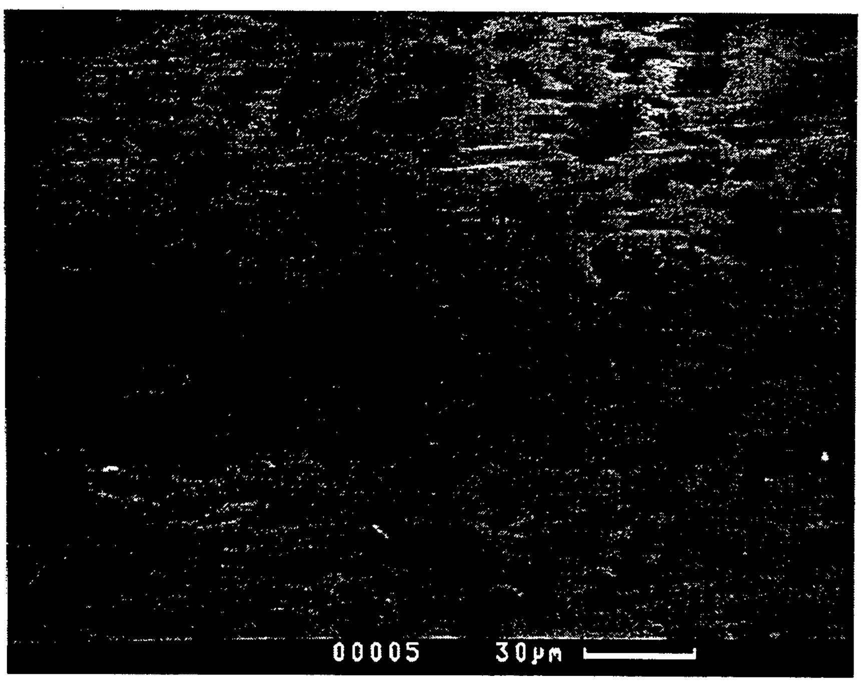


250X (SEM)

Figure 16. Cronidur 30 "Hybrid" Inner Raceway Microspalling *(Page 2 of 3)*

50X (SEM)

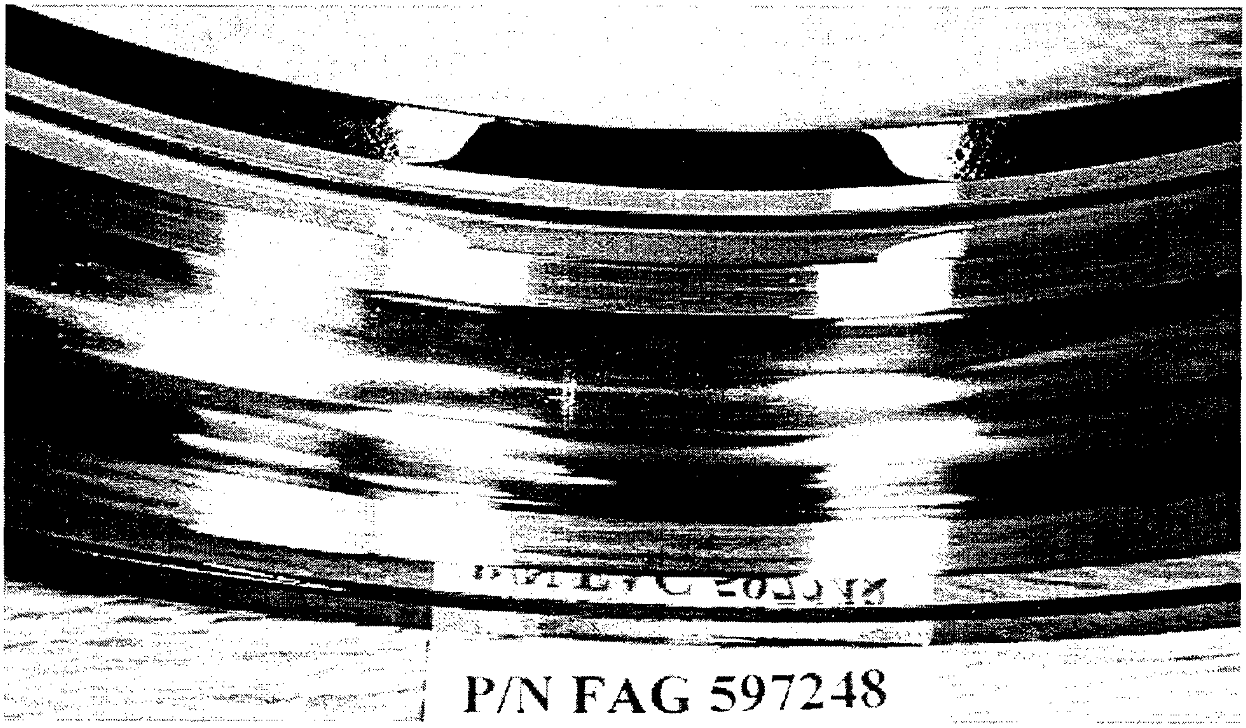




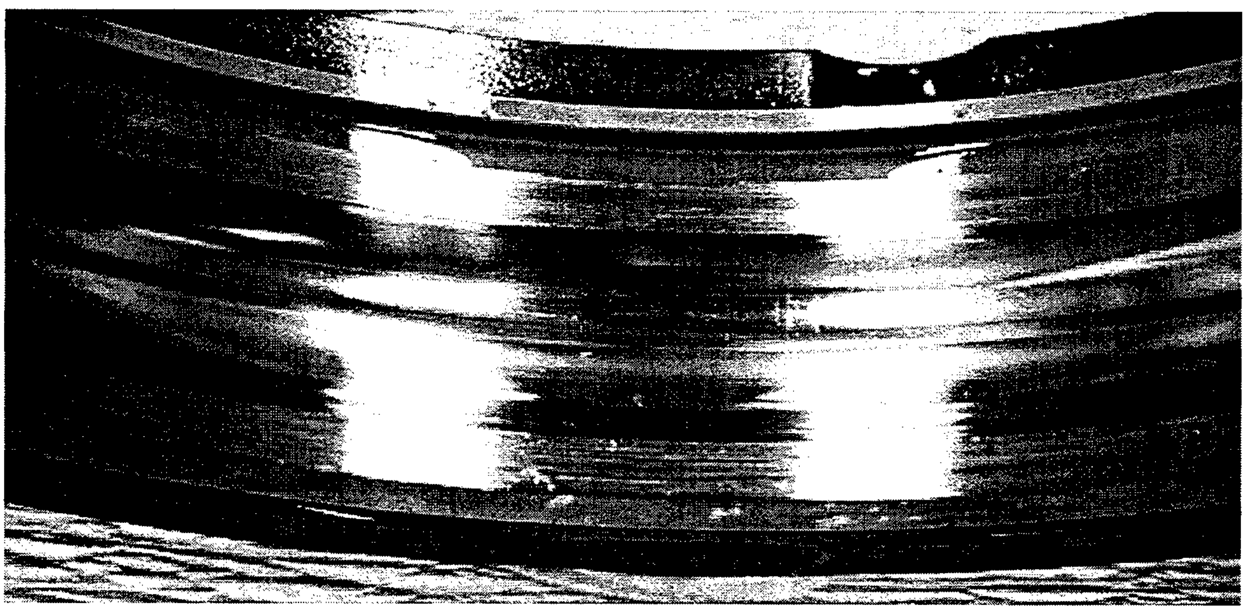
Surface dents from test contamination

500X (SEM)

Figure 16. Cronidur 30 "Hybrid" Inner Raceway Microspalling *(Page 3 of 3)*

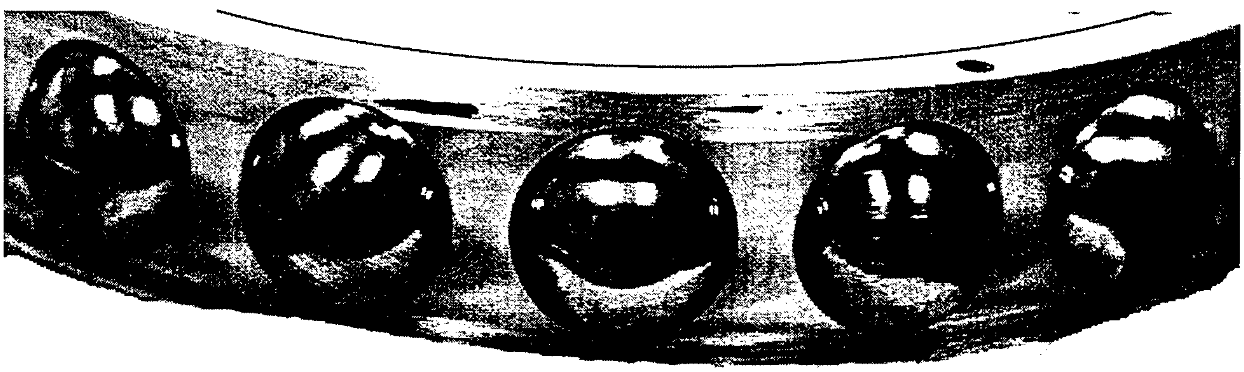


S/N FCAB0971

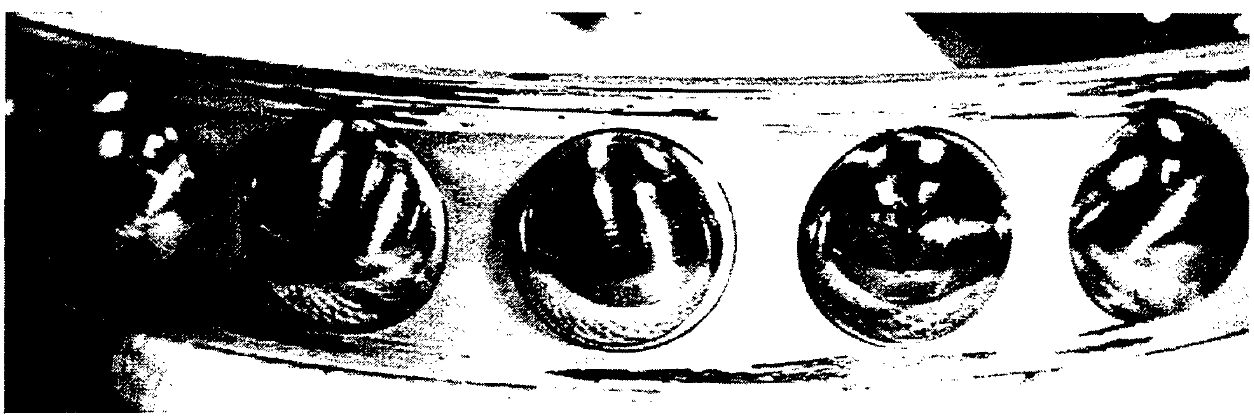


S/N FCAB0972

Figure 17. Cronidur 30 "Hybrid" Outer Race Shoulder Wear



S/N FCAB0971



S/N FCAB0972

Figure 18. Cronidur 30 "Hybrid" Cage and Ball Wear

because they would have no effect on bearing performance in the contamination-endurance rig test. Both bearings were visually inspected prior to installation, and no visible damage was found. One bearing, MRC P/N 9126UK123 S/N MDAGK040, was installed on the drive side; the second bearing, S/N MDAGK041, was installed opposite the drive side in the same rig.

The rig was operated according to the procedure outlined in Section 3.1. The test was shut-down after 4.4 hours to pull the magnetic plugs, and all three had fine debris typical of a contamination test. The rig was restarted but continued to produce chips and was finally shut-down due to high heat generation as indicated by the temperature rise of the bearing outer races. With a total of 8.48 hours of testing, the contamination-endurance rig test of two Pyrowear full-scale bearings with M50 balls was considered complete.

At teardown, the condition of the two bearings was reviewed. Both exhibited essentially the same severe wear on the outer race cage guiding shoulders. The inner race cage riding shoulders were also worn from contact with the cage. Table 3 lists outer and inner race cage riding shoulder wear measurements. There was no visible evidence of ball or raceway surface spalling on either race. The cage-rail outer surfaces had heavy wear — measured to a radial depth of 0.006 inch on S/N

MDAGK040 and 0.0035 inch on S/N MDAGK041. The cage rail inner surfaces had circumferential scratches from contact with the inner race shoulders. The cage pockets were worn in the circumferential direction with raised material on the outer edges of the pockets in one circumferential direction. The balls had concentric, circular, scratch patterns about a single axis. Figures 19 through 22 show the after-test conditions of the Pyrowear 675 "hybrid" bearings.

Table 3. Pyrowear 675 "Hybrid" Contamination-Endurance Test Shoulder Wear Depth (MRC P/N 9126UK123, S/N MDAGK040 and MDAGK0441)

S/N Location		Drawing Required Diameter, in	Posttest Actual Diameter, in	Radial Wear Depth, in
Outer Race Shoulders				
MDAGK040	Forward	7.035 Max.	7.192–7.194	0.0785–0.0795
	Aft		7.196–7.200	0.0805–0.0825
MDAGK041	Forward		7.148–7.157	0.0565–0.0610
	Aft		7.174–7.177	0.0695–0.0710
Inner Race Shoulders				
MDAGK040	Forward	6.241 Min.	6.1832–6.1849	0.0280–0.0289
	Aft		6.1815–6.1859	0.0275–0.0297
MDAGK041	Forward		6.2200–6.2220	0.0095–0.0105
	Aft		6.2170–6.2190	0.0110–0.0120

According to MRC, the full scale bearings supplied for the contamination-endurance test had the races aged using a 925°F temper cycle. This is believed to have no impact on the performance in this test. Subscale tests indicated that the specimens tempered at 600°F and 900°F had approximately the same wear depth; see Subsection 5.3.

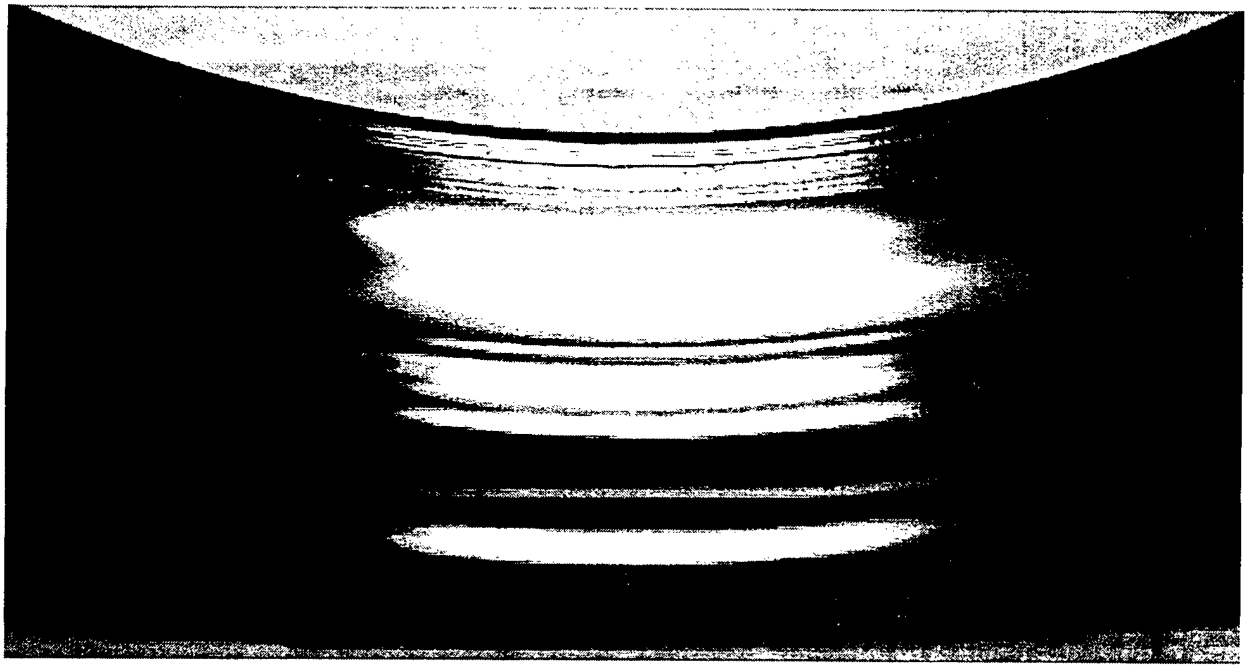
Both bearings had shoulder wear as indicated by the severe wear on the outer race cage guiding shoulders and cage rail outer surfaces. The bearings underwent material evaluation to further examine the microstructure. The wear characteristic of the Pyrowear 675 "hybrid" bearing was deemed unacceptable.

3.5 Cronidur 30 and Pyrowear 675 Material Evaluation

Destructive analyses after the No. 3 ball bearing contamination-endurance rig tests compared the microstructure of Cronidur 30, Pyrowear 675, and M50NiL bearings.

Microstructure analyses of radial cut sections of the bearing races compared the microstructures of Cronidur 30 and Pyrowear 675. The Cronidur 30 microstructure consisted of very fine-grain martensite and was void of eutectic carbides. Fine nitrides are visible in the microstructure at 500× in Figure 23. The electron-dispersive spectra (EDS) are illustrated in Figure 24.

The Pyrowear 675 microstructure consisted of a carburized case morphology that is readily visible at around 100× (Figure 25). The case carbide microstructure of M50NiL is similar (Figure 26) but smaller, typically not visible at magnifications less than 500×. Grain boundary network carbides are evident in the carburized Pyrowear 675 raceway case in Figure 27. Grain boundary network carbides are typically only observed in M50NiL bearings in the race corner regions, where the carbon



S/N MDAGK040

S/N MDAGK041

Figure 19. Pyrowear 675 "Hybrid" Outer Race Shoulder Wear

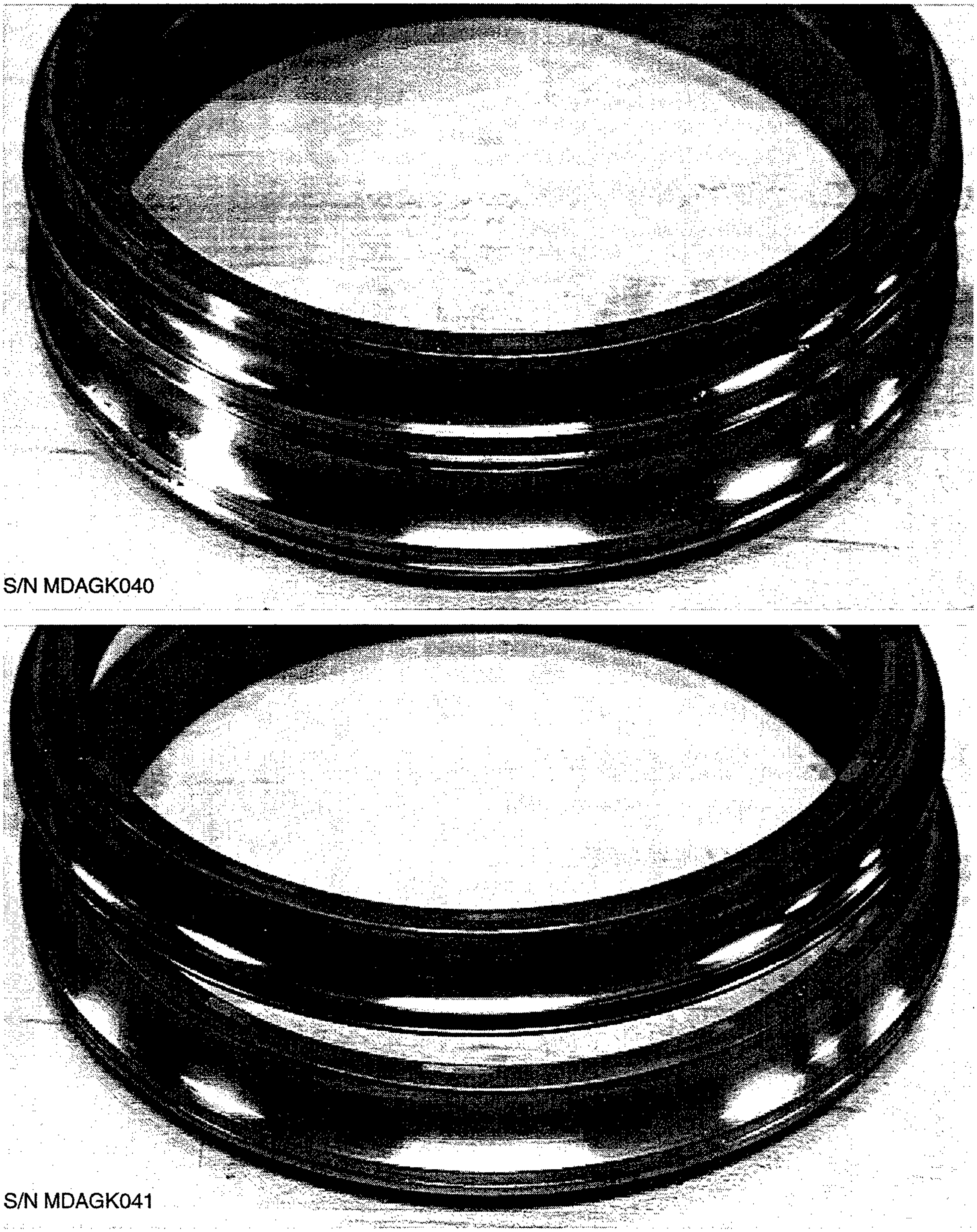
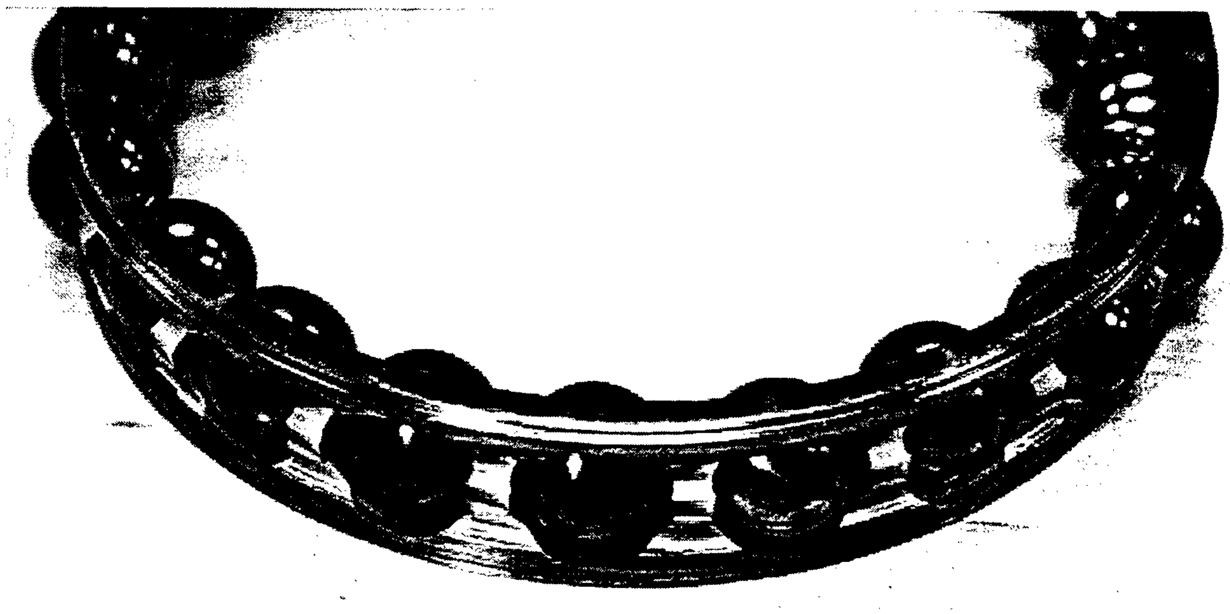
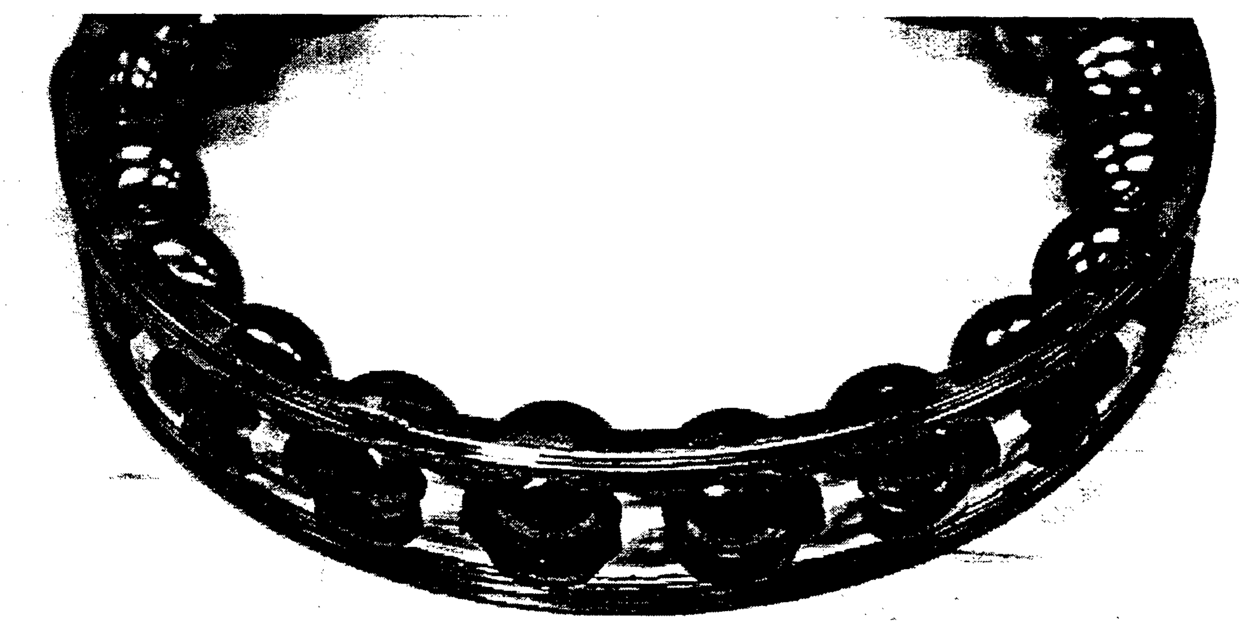


Figure 20. Pyrowear 675 "Hybrid" Inner Race Shoulder Wear



S/N MDAGK040



S/N MDAGK041

Figure 21. Pyrowear 675 “Hybrid” Cage and Ball Wear

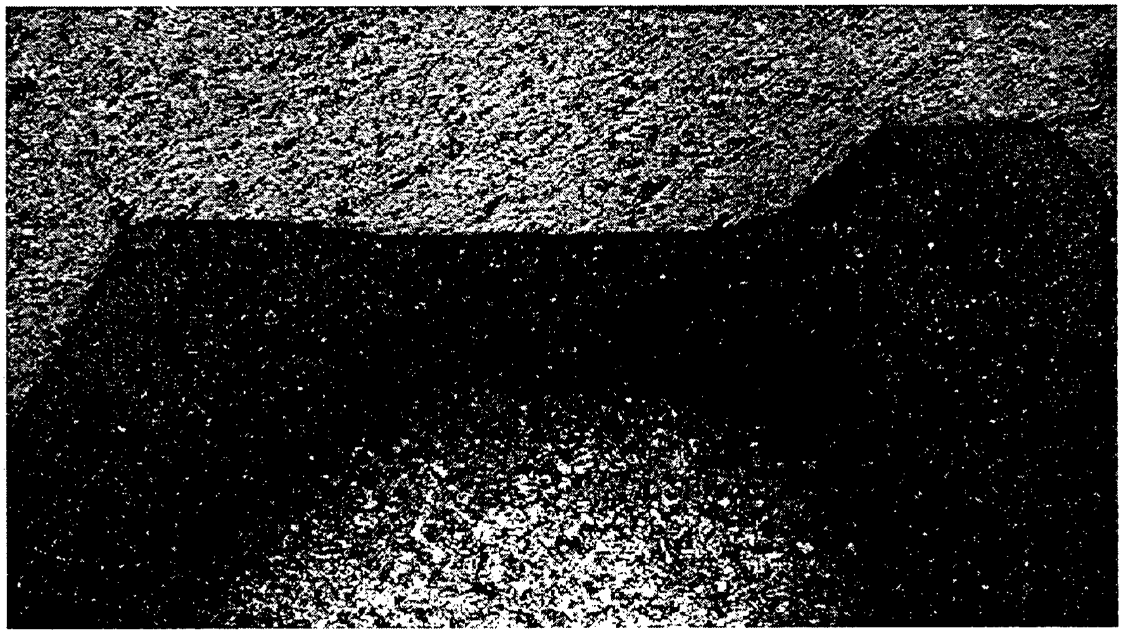


Figure 22. Radial Section of Pyrowear 675 "Hybrid" (S/N MDAGK041) Inner Race Showing Depth of Shoulder Wear (25X)

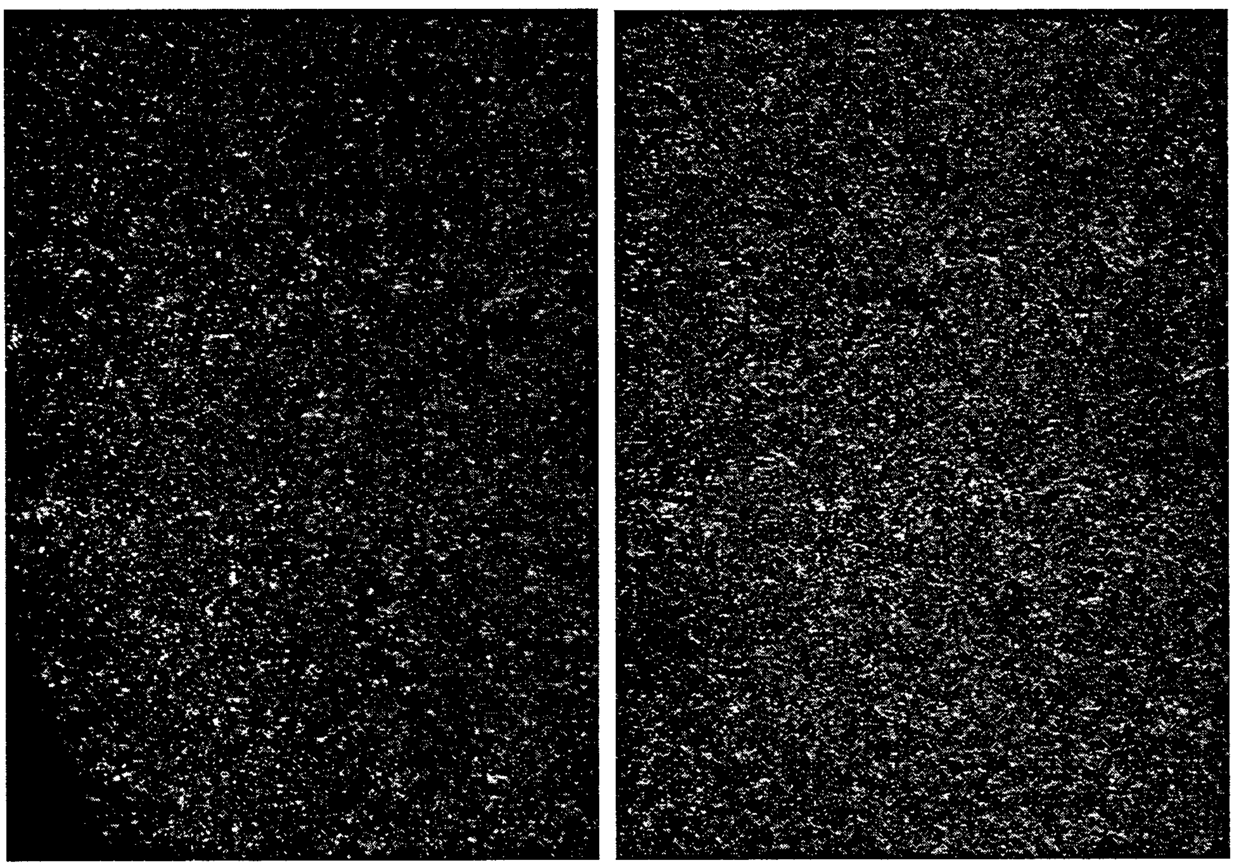


Figure 23. Cronidur 30 Inner Race Microstructure (500X)

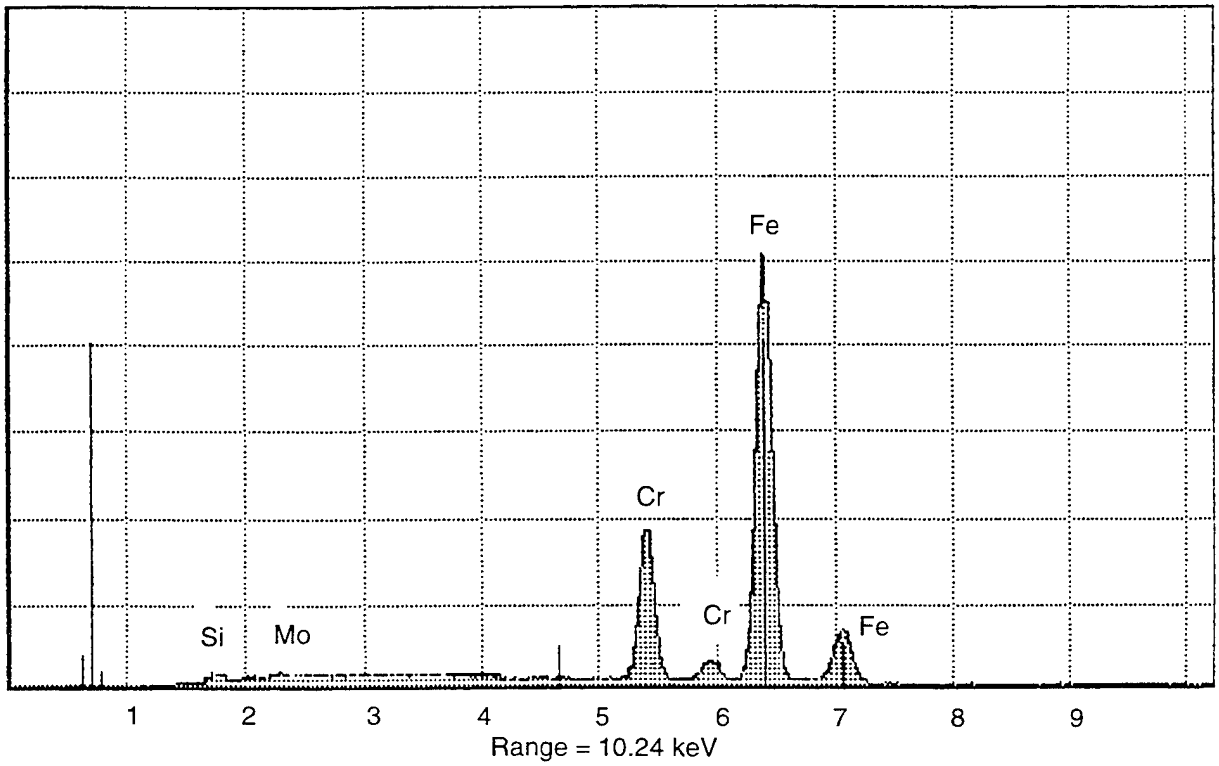


Figure 24. SEM EDS of Cronidur 30 Inner Race

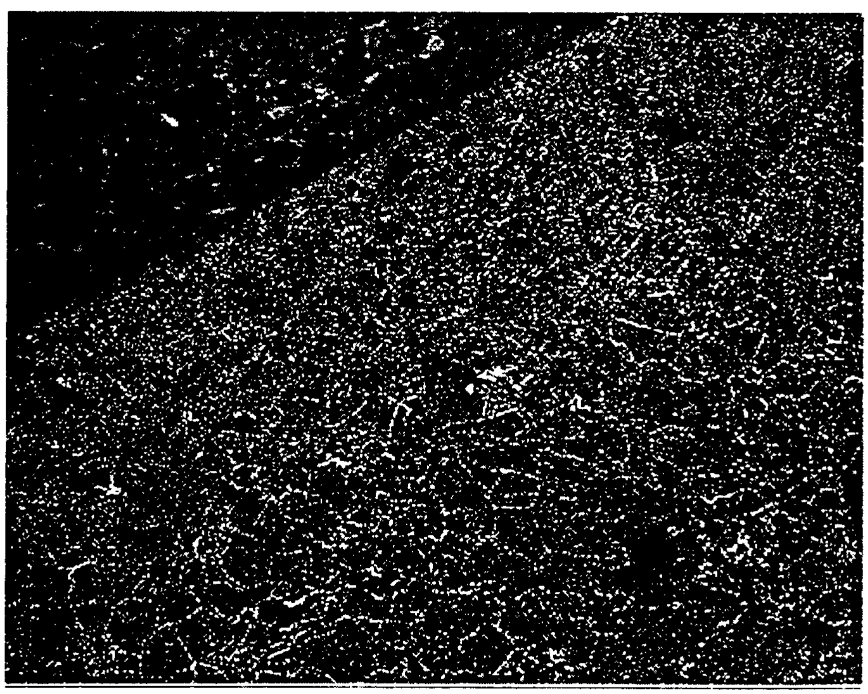


Figure 25. Pyrowear 675 Inner Raceway Case Carbide Morphology (100X)
Network grain boundary carbides are present.

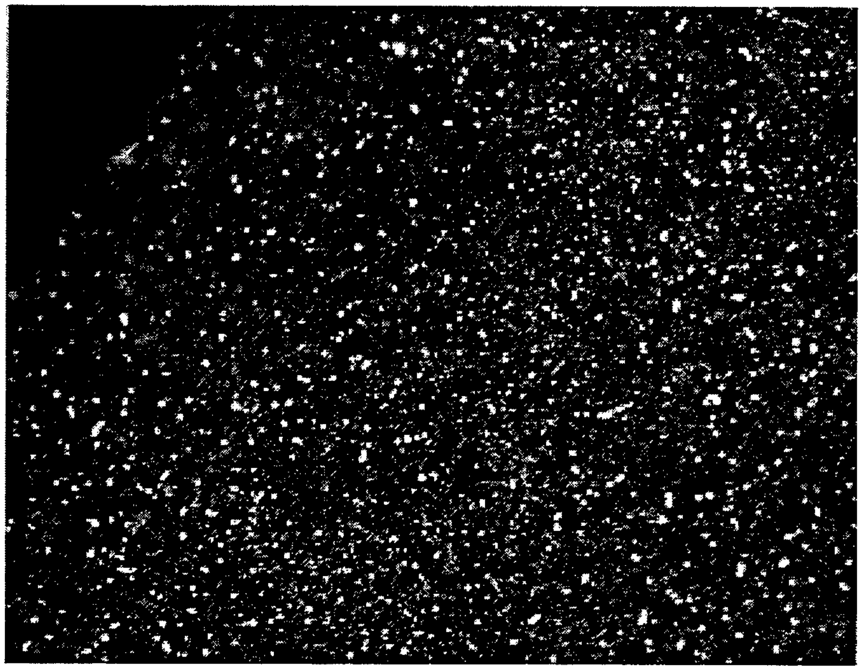


Figure 26. Typical M50NiL Carburized Carbide Morphology (1000X)
From commercial M50NiL 3B bearing.

saturation is at its highest during the carburizing cycle. The outer race case carbide morphology is shown in Figure 28.

Measurement of the Pyrowear 675 material hardness showed case depth to be consistent with the typical requirements for a 3B bearing made of M50NiL. Figure 29 shows carburized case depth in the inner raceway, and Figure 30 is a plot of the microhardness measurements (inner and outer races).

The microstructure of a Cronidur 30 ball was analyzed. A metallographic section through the center of the ball was polished and etched in order to evaluate the microstructure. The ball microstructure appears to have more retained austenite and larger austenitic grains compared to the race microstructure, and fewer nitrides are observed in the ball microstructure (Figures 31 through 34). FAG reported that these balls came from an earlier version of Cronidur 30 and do not represent the latest heat treat process. The nonoptimal heat treatment may be related to the poor wear resistance of the balls. However, the races were supplied to the current, optimal heat treat process.

The Pyrowear 675 bearings had M50 balls, so microstructure analysis was not performed on the balls of these bearings.

SEM analysis of sections of the bearing cage from a Pyrowear 675 bearing and a Cronidur 30 bearing was done to evaluate the wear products embedded in the silver plating. The energy dispersive spectra analysis of the Pyrowear 675 wear products embedded in the silver plate revealed wear particles of

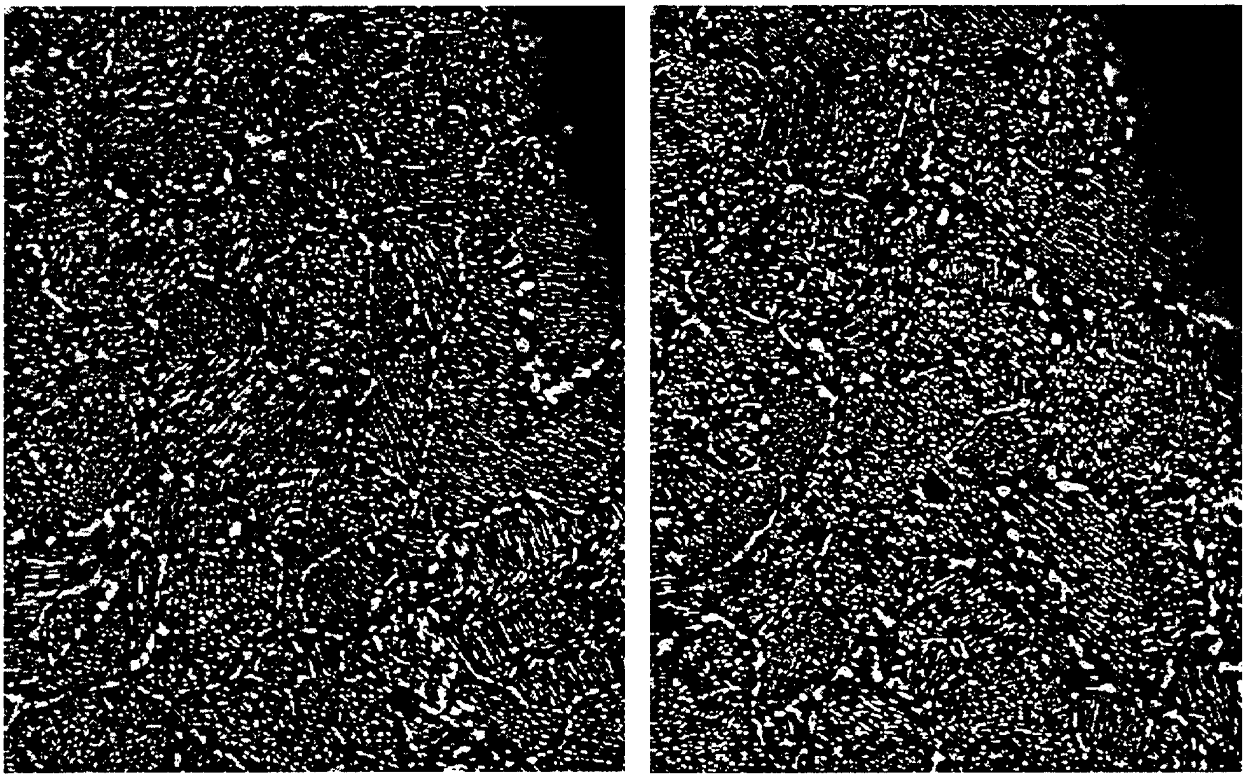


Figure 27. Pyrowear 675 Inner Raceway Case Carbide Morphology (500X)
Network grain boundary carbides are present.

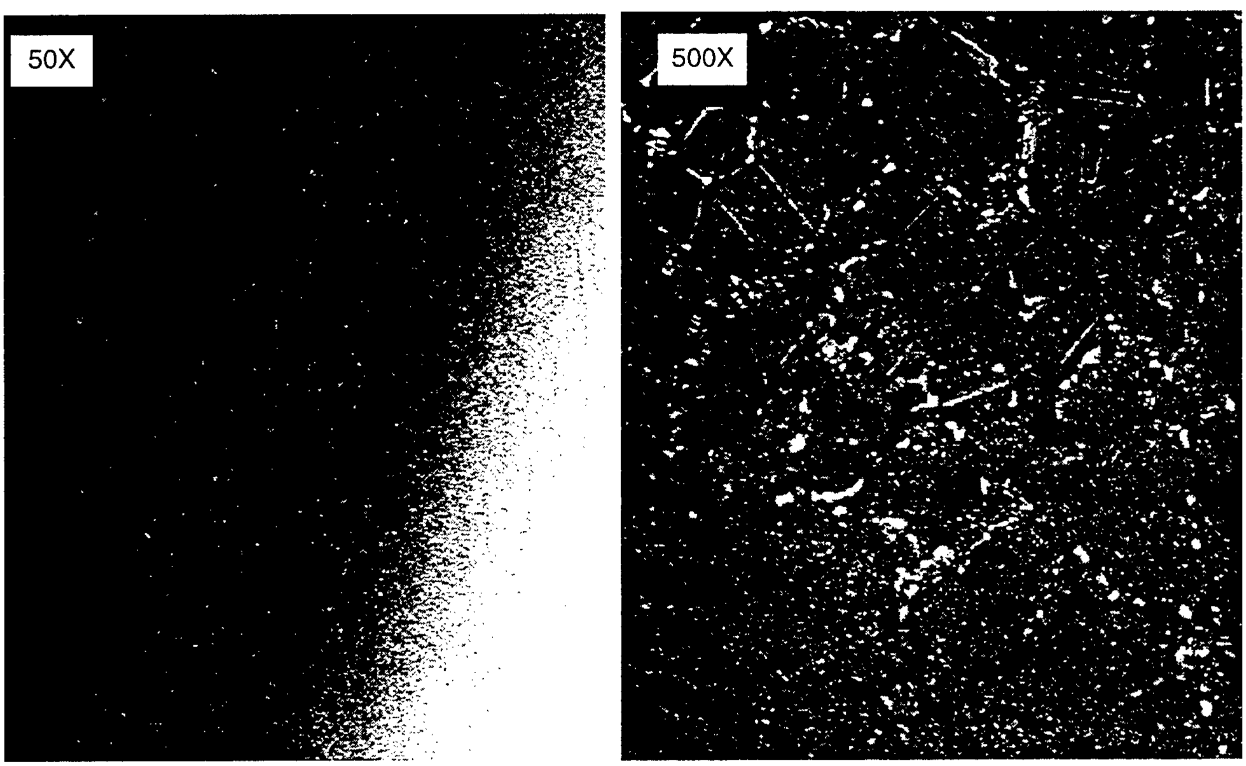


Figure 28. Pyrowear 675 Outer Raceway Case Carbide Morphology

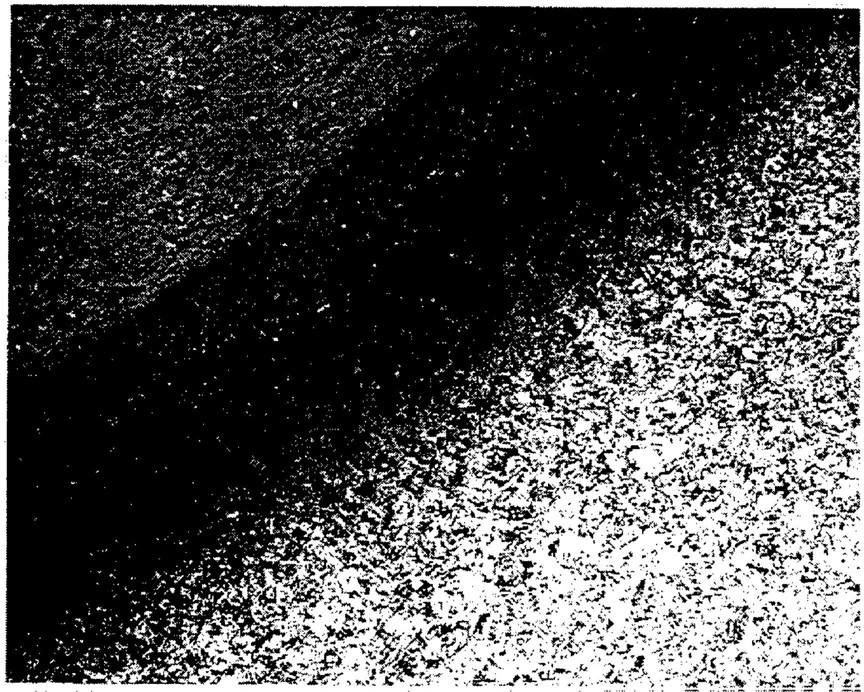


Figure 29. Pyrowear 675 Inner Raceway Carburized Case Depth (25X)

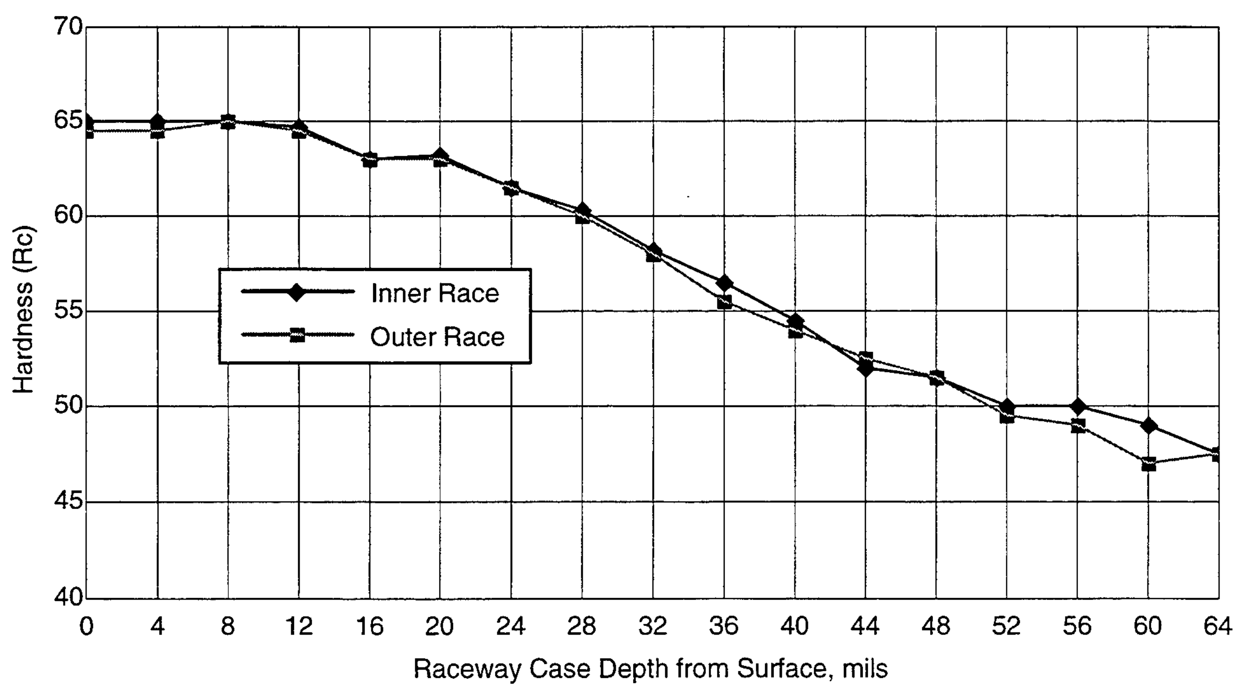


Figure 30. Microhardness Case Depth Profiles of Outer and Inner Races Following Pyrowear 675 Contamination-Endurance Test

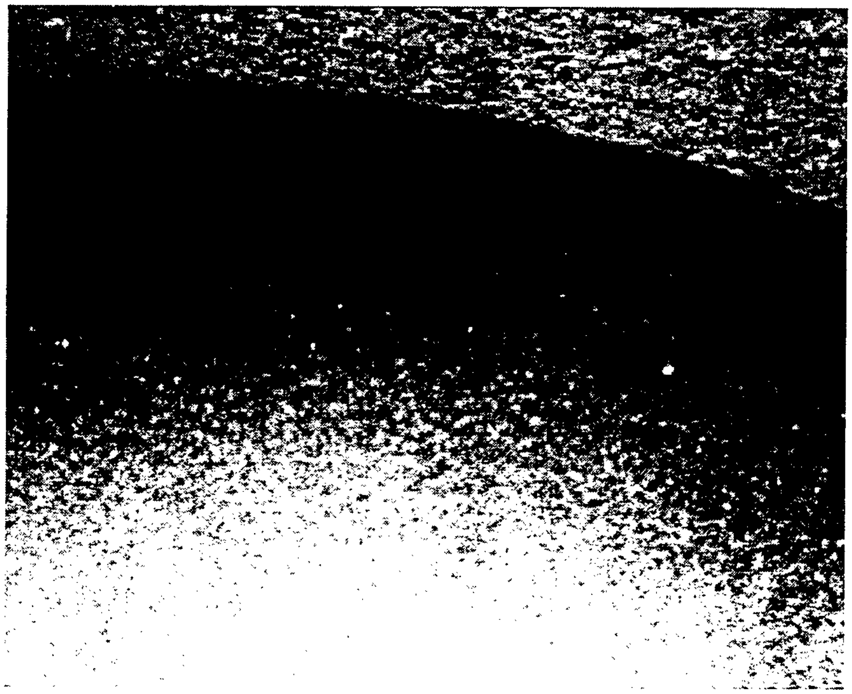


Figure 31. Cronidur 30 Ball Etched Microstructure (25X)

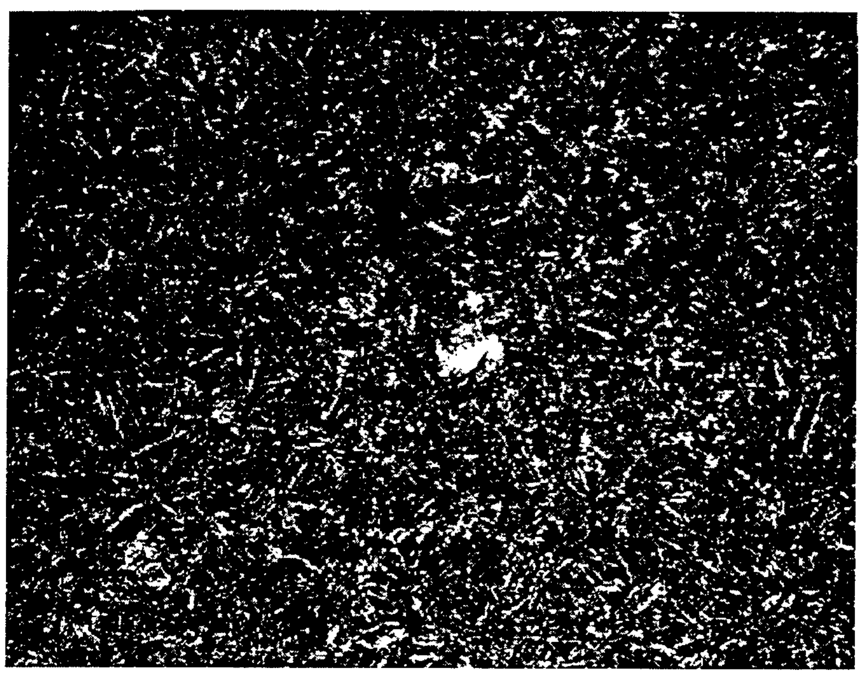


Figure 32. Cronidur 30 Ball Microstructure (250X)

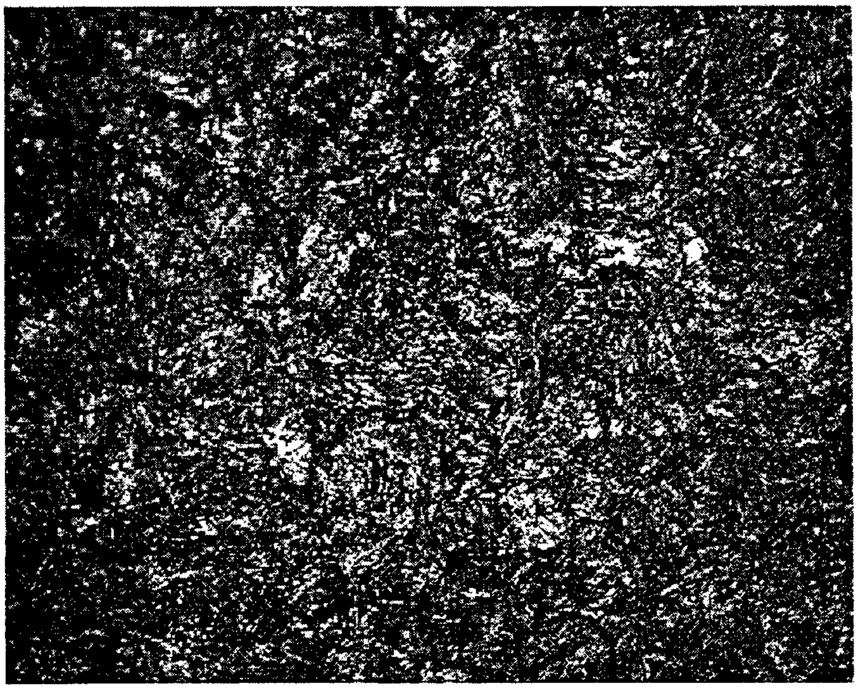


Figure 33. Cronidur 30 Ball Microstructure Near Surface (500X)

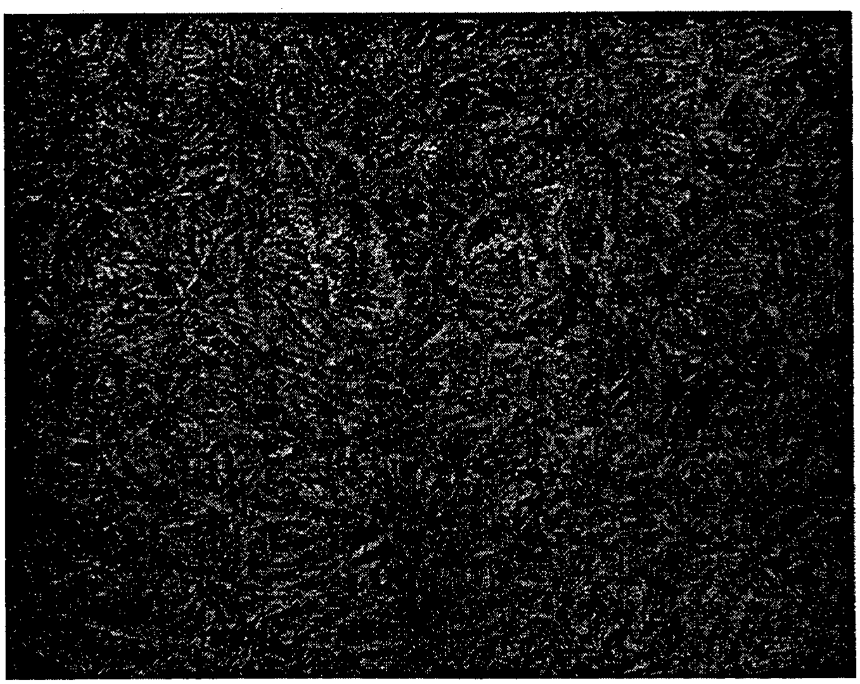


Figure 34. Cronidur 30 Ball Microstructure in Center Region (500X)

Pyrowear 675 and mechanically alloyed particles rich in chromium and vanadium (Figures 35 through 39).

SEM EDS analysis of the Cronidur 30 wear products embedded in the silver plating indicated wear particles of Cronidur 30 and mechanically alloyed particles, rich in chromium and silicon (Figures 40 through 44). These embedded wear products are very similar to those found in cages from shoulder-worn M50NiL bearings — from this same test and from field-service bearings. The M50NiL wear products are high in chromium, vanadium, and silicon (Figures 45 through 47).

In both materials, the wear damage induced during the 3B contamination-endurance test is believed to be related to the microstructure. Previous contamination-endurance rig testing of M50 and M50NiL bearings consistently showed that M50 has superior shoulder-wear lapping resistance compared to M50NiL. This is believed to be due to the larger primary melt eutectic carbides in the M50 structure. The wear resistance of Cronidur 30 and Pyrowear 675 is similar to that of M50NiL due to the absence of primary melt eutectic carbides in the microstructures.

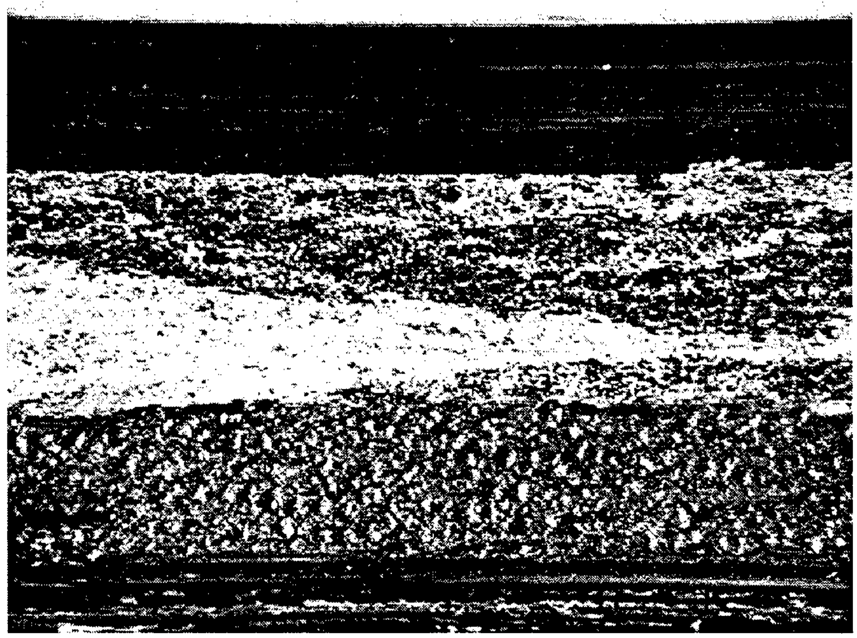


Figure 35. Cage Outer Diameter from Pyrowear 675 "Hybrid" Bearing Contamination-Endurance Test (12.5X)

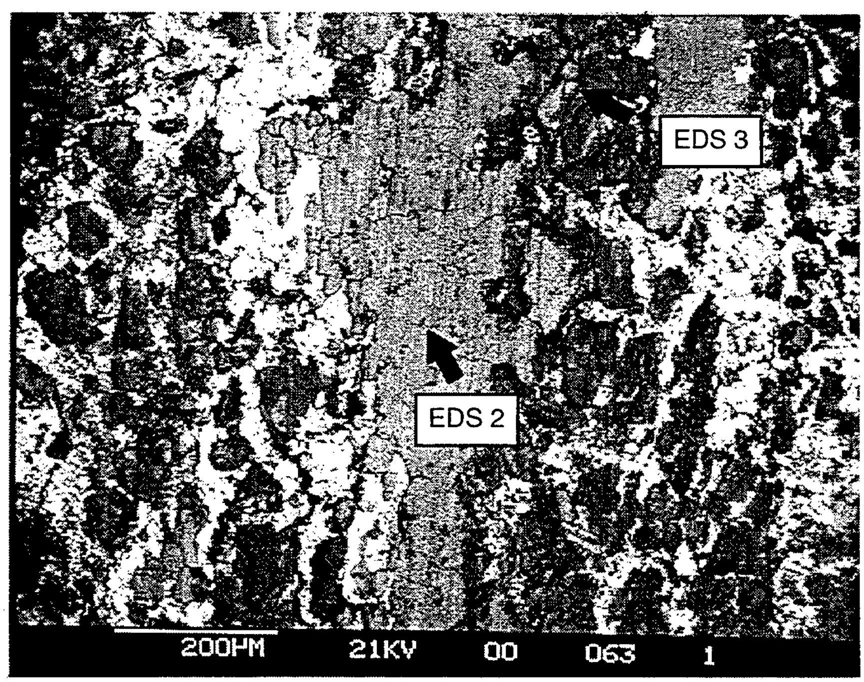


Figure 36. SEM Photograph of Bearing Cage Outer Diameter (110X)
Arrows indicate areas of EDS analysis.

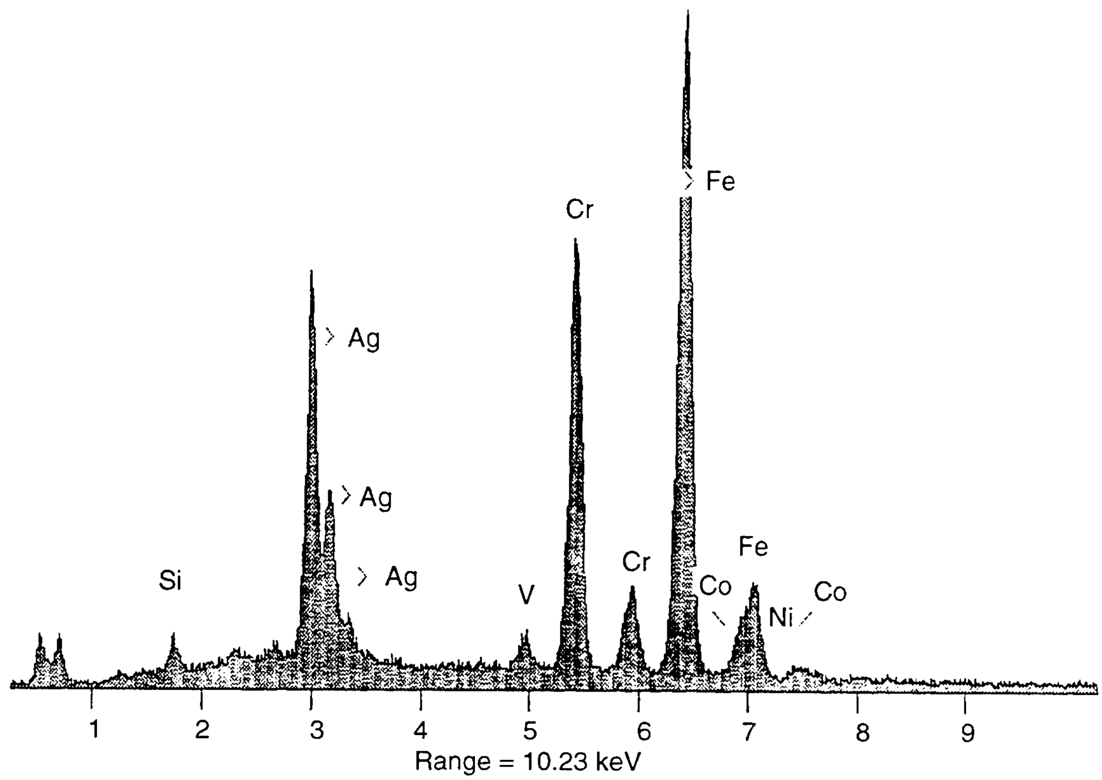


Figure 37. EDS Signature of Frame Analysis of Fig. 36

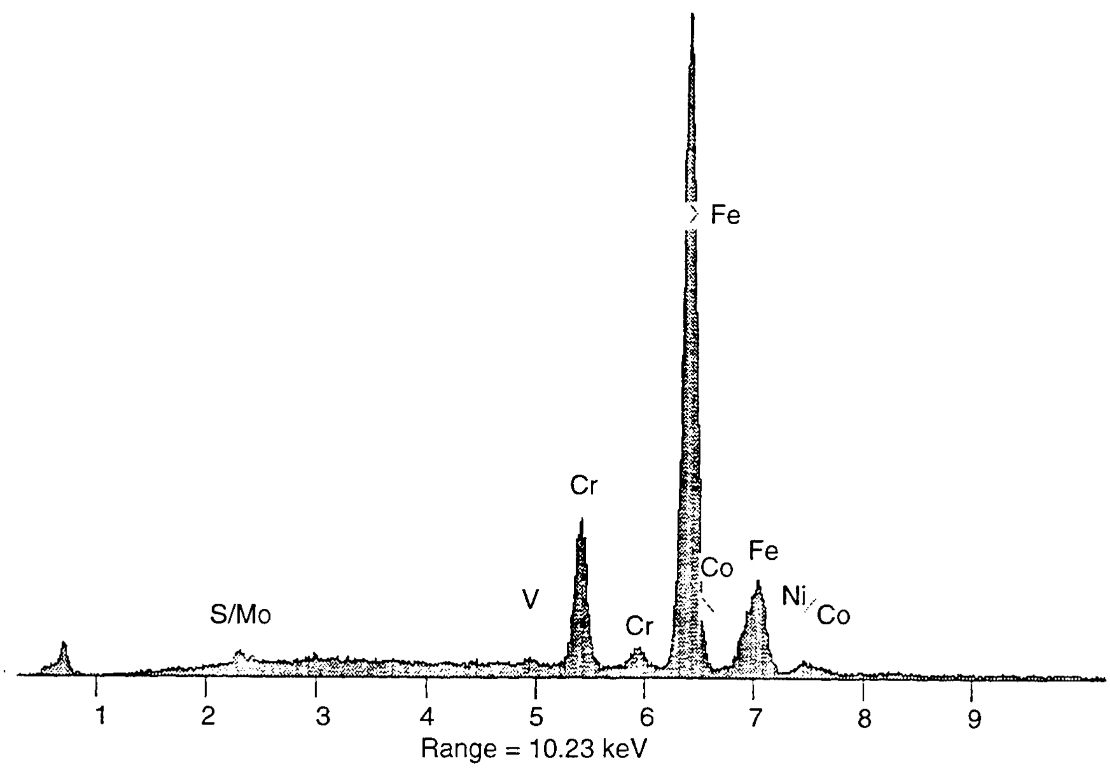


Figure 38. EDS 2 (Fig. 36) Signature Indicating Pyrowear 675 Wear Particles

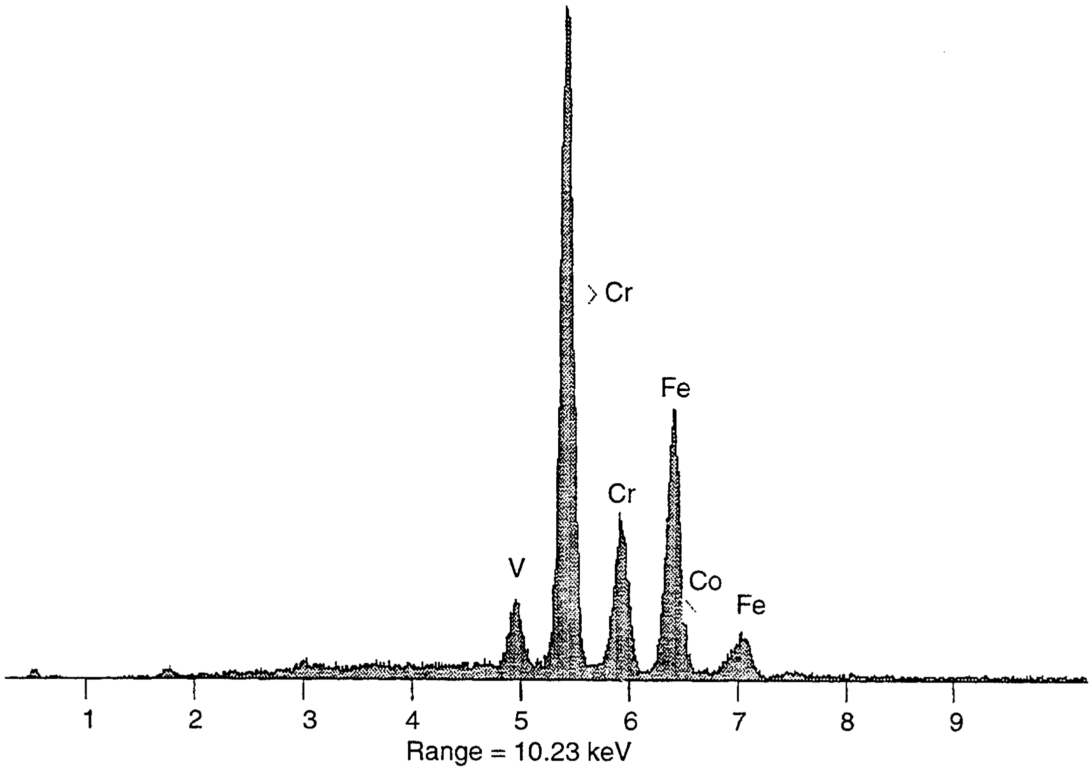


Figure 39. EDS 3 (Fig. 36) Signature Indicating Elevated Chromium and Vanadium in the Wear Product with Reduced Iron Content

Figure 40. Cage Outer Diameter from Cronidur 30 "Purebred" Bearing Contamination-Endurance Test (12.5X)

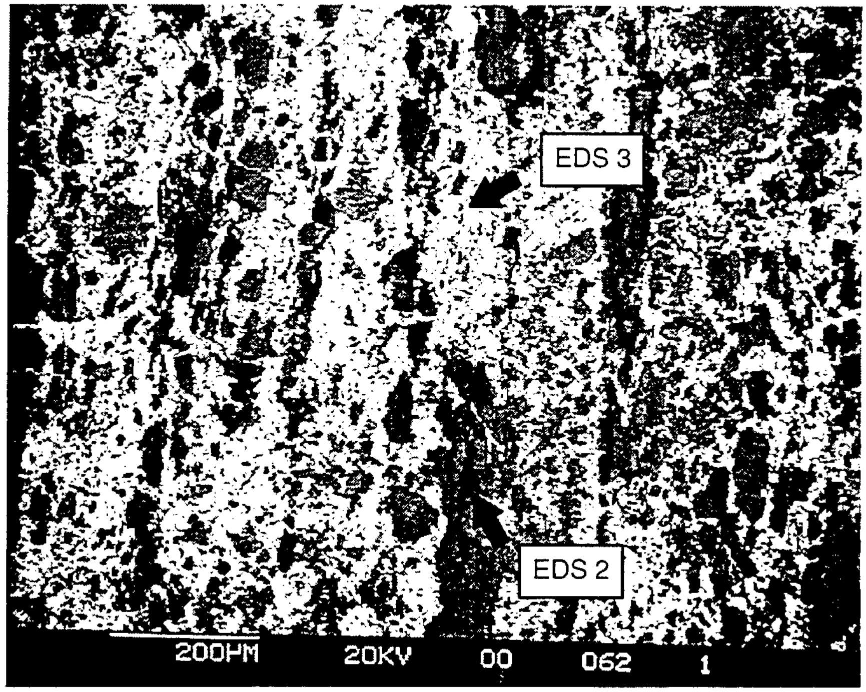


Figure 41. SEM Photograph of Bearing 3B Cage Outer Diameter (100X)
Arrows indicate areas of EDS analysis.

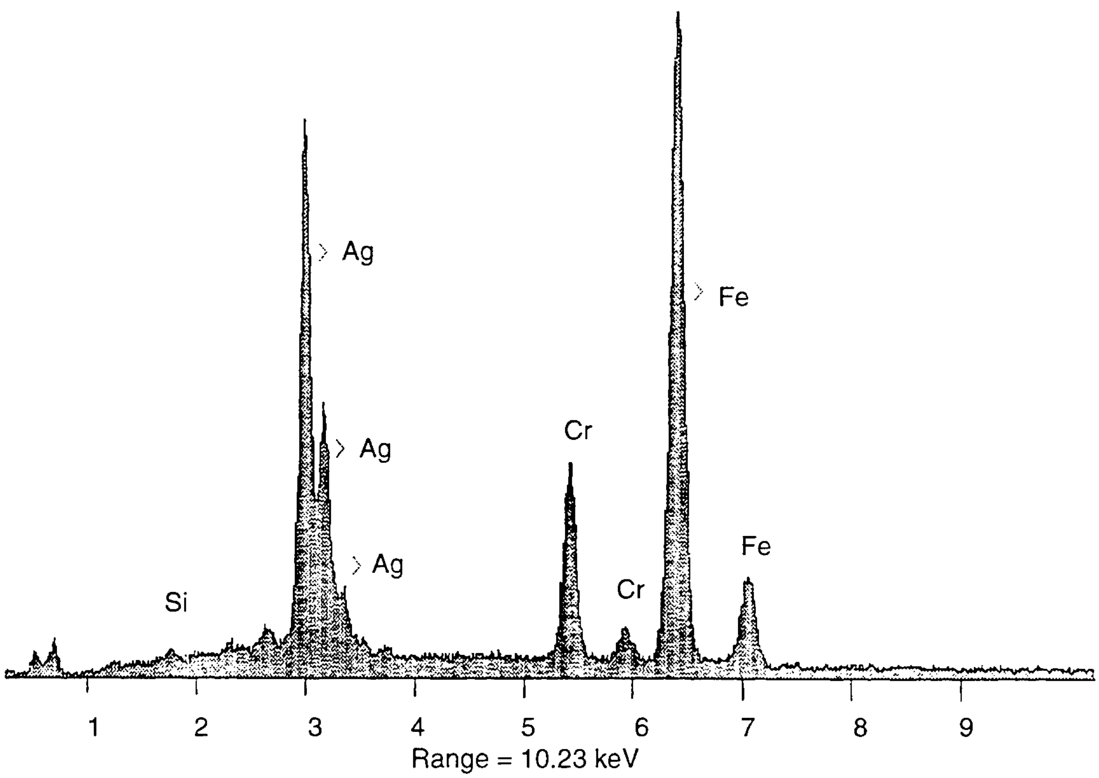


Figure 42. EDS Signature of Frame Analysis of Fig. 41

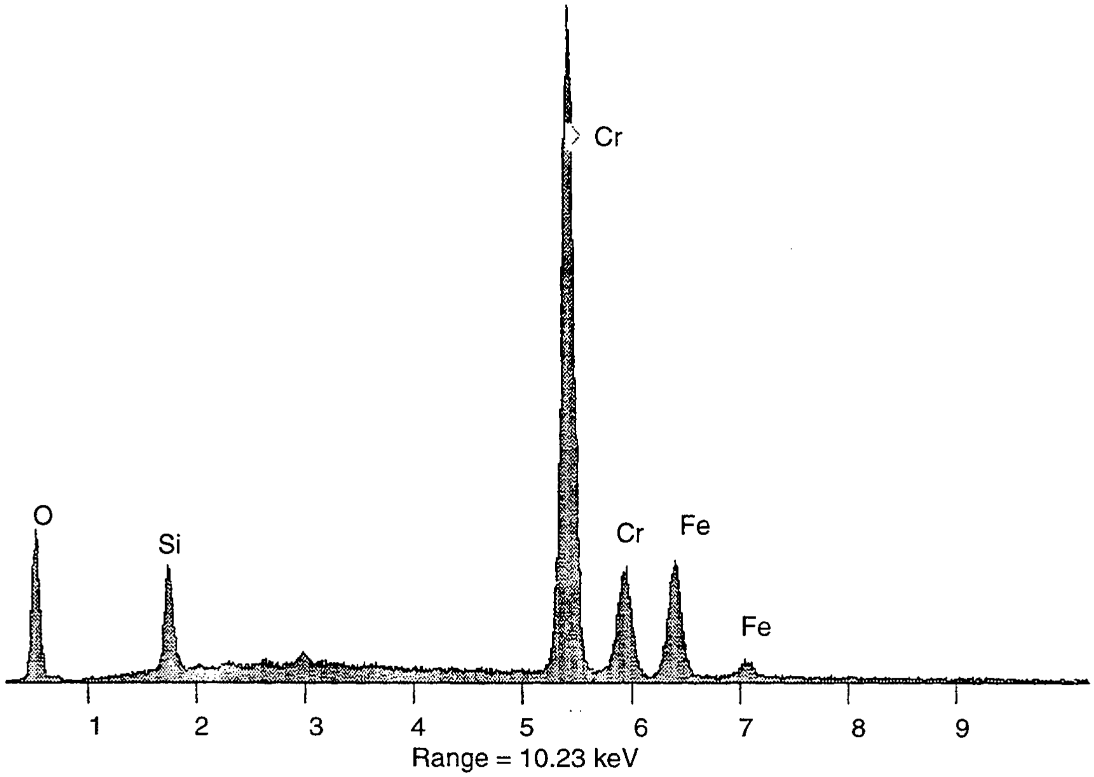


Figure 43. EDS 2 (Fig. 41) Signature Showing Elevated Chromium, Silicon, and Oxygen in the Wear Product

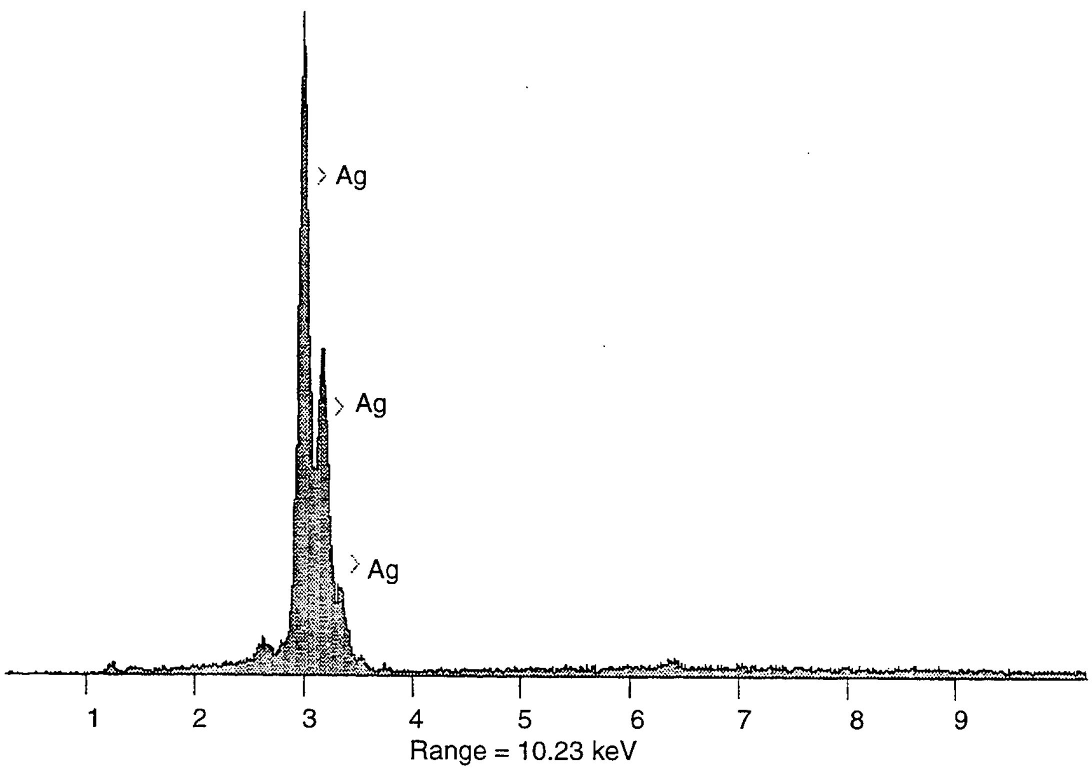


Figure 44. EDS 3 (Fig. 41) Signature Indicates Silver Plating

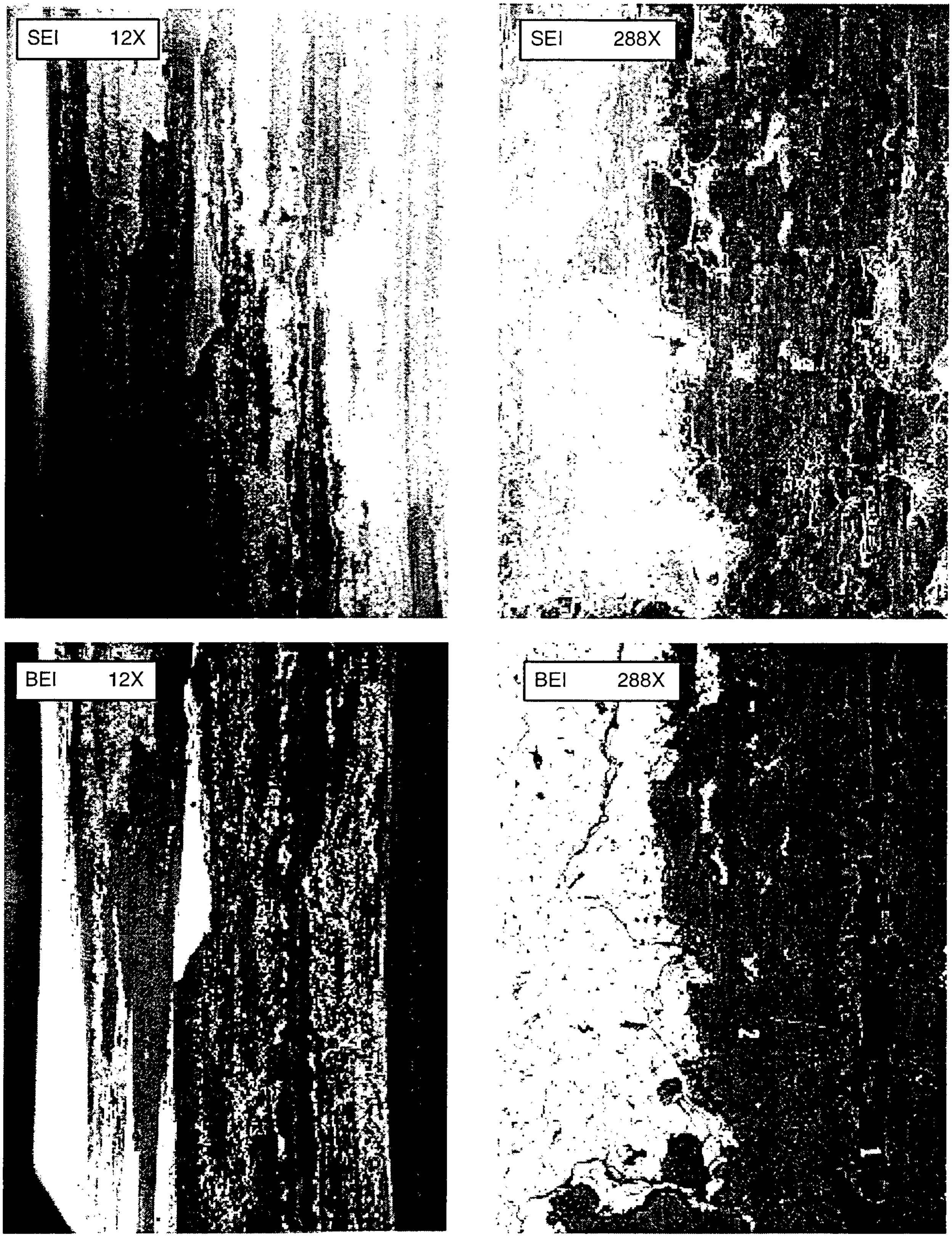


Figure 45. SEM Photographs of M50NiL Bearing Cage Outer Diameter

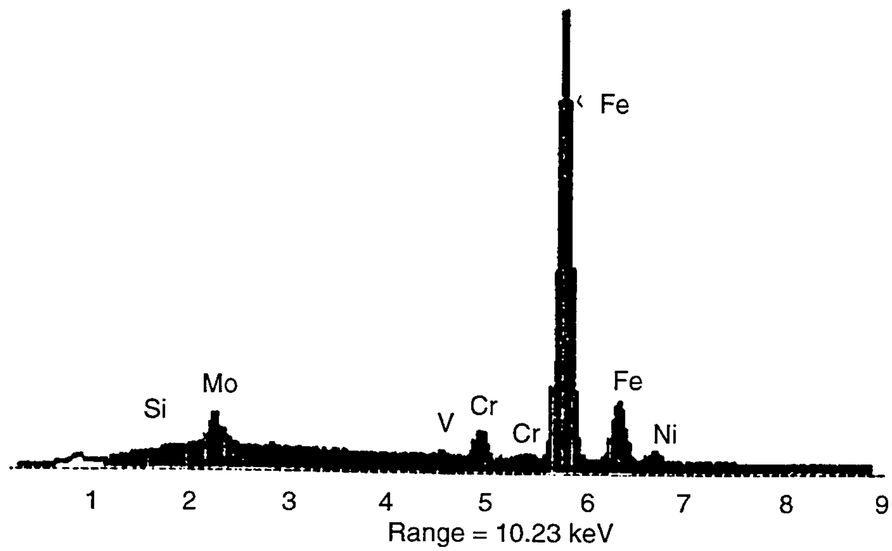


Figure 46. EDS Spectra for Cage Land Wear Products Typical of M50NiL

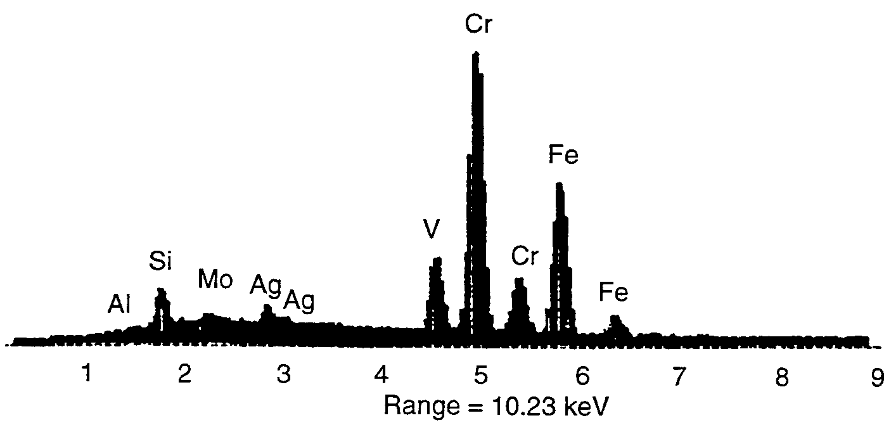


Figure 47. EDS Spectra Showing High Cr, Si, and V Wear Debris

4.0 Subscale Corrosion-Resistance Testing

4.1 Background

Issues with TDC coating made it evident that we would be focusing on the high-chrome tool steels for potential next-generation bearing materials for military engine applications. It was decided that since corrosion resistance is a key performance parameter, it would be wise to assess the relative corrosion resistance of two of the leading high-chrome tool steels: Pyrowear 675 and Cronidur 30.

Relative corrosion resistance was compared for M50, Pyrowear 675 with a 600°F temper, Pyrowear 675 with a 900°F temper, and Cronidur 30. The lower tempering of the Pyrowear 675 was thought to possibly increase corrosion resistance compared to that of the 900°F temper, where further secondary hardening would occur at the likely expense of some of the matrix chromium. Corrosion can be caused by a multitude of environments — including degraded engine oils, moisture in the air, and finger prints from handling. The purpose of this testing was to simply rank the relative corrosion resistance of these three alloys in two environments: tap water and synthetic sea water. M50NiL was not tested; it has a chemistry similarity to that of M50 and thus a similar lack of corrosion resistance.

4.2 Procedure

Rolling-contact-fatigue rods (3/8-inch diameter by 3-inch long) were placed in a plastic fixture that held them upright while keeping them from contacting one another. Synthetic sea water was made according to ASTM Specification D1141–90. The specimens were placed in the plastic fixture and partially submerged in either tap or synthetic sea water. The exposed portions of the samples were then sprayed with the appropriate solution, and the entire setup was covered with plastic wrap to keep the humidity high within the microtest environment. All tests were performed at room temperature. Inspections were made daily, and the test was discontinued after 23 days of exposure.

4.3 Results

Localized corrosion was evident on the M50 and Pyrowear 675 specimens within the first 2 days of exposure, in both solutions. Of the four specimens, the M50 material exhibited the greatest amount of corrosion. Very little difference existed between the 600° and 900°F tempered Pyrowear 675 specimens.

The relative ranking remained the same after 9 days of exposure, and a difference was evident between the Pyrowear 675 specimens in the tap water solution. The 600°F tempered Pyrowear 675 specimen was exhibiting less corrosion than the 900°F tempered specimen, as expected.

After 23 days of exposure, the M50 specimen was almost covered in corrosion, and the Pyrowear 675 specimens displayed a fair amount of corrosion. The Cronidur 30 material, on the other hand, was showing very little corrosion. The 600°F tempered Pyrowear 675 still exhibited less corrosion than the 900°F tempered Pyrowear 675 specimens in the tap water solution. Figures 48 and 49 show the specimens after 23 days of exposure in tap water and synthetic sea water solutions, respectively.

4.4 Conclusion

From this testing, it is apparent that, although the Pyrowear 675 material offers an improvement in corrosion resistance over M50, Cronidur 30 is superior in corrosion resistance.

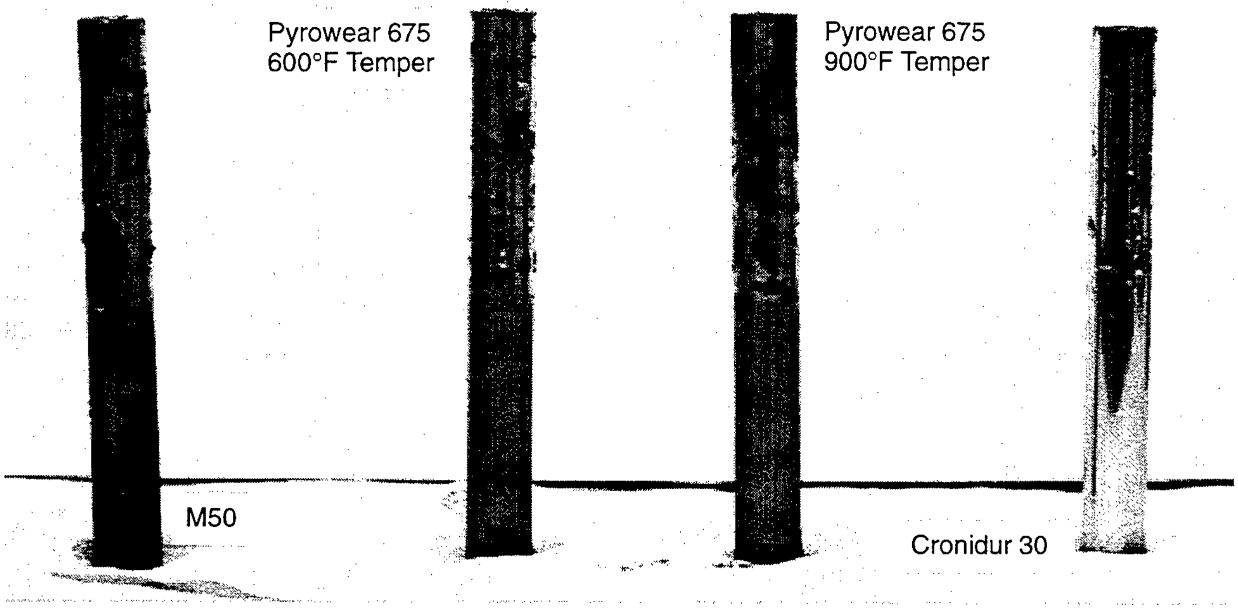


Figure 48. Corrosion Resistance Test: Tap Water

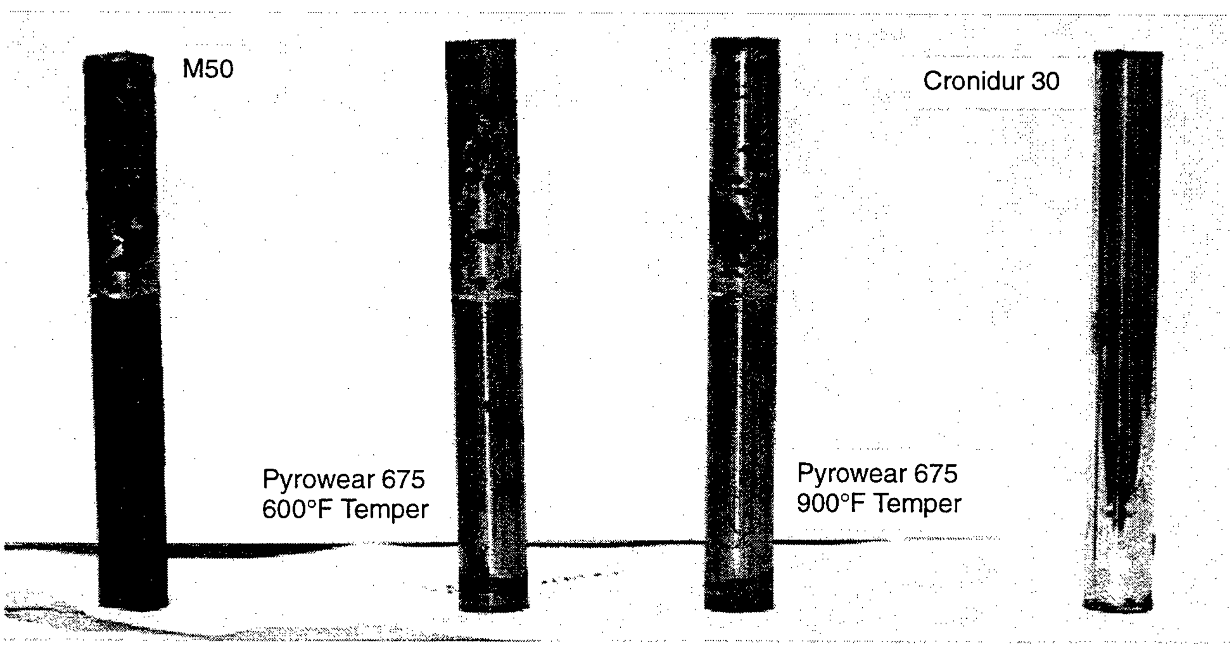


Figure 49. Corrosion Resistance Test: Synthetic Sea Water

5.0 Subscale Wear-Resistance Testing

5.1 Background

Experience has indicated that another key performance parameter of bearing material is abrasive wear resistance, particularly as it applies to the shoulders of the bearing subject to contact with the silver-plated cage. Embedded hard debris, such as alumina or silica, in the silver plate can result in excessive shoulder wear.

As part of a screening test, thrust-washer testing was performed at the Falex Corporation. The results were compared to existing M50 and M50NiL data. The test procedure followed ASTM D3702. The specifics of this testing are described below.

5.2 Procedure

This test involves two thrust-washer-shaped specimens brought into contact under set conditions of speed and load for a predetermined period of time. One washer is made of fully hardened Pyrowear 675 or Cronidur 30 bearing material, to simulate the stationary outer race. It has an outer diameter of 2.128 inch, an inner diameter of 1.500 inch, and is 0.370-inch thick. It is ground to a surface finish of 12 to 16 Ra, contains eight slots approximately 0.0625-inch deep by 0.0625-inch wide with broken corners at the edges of the slots. The purpose of the slots is to aid in getting the contaminated oil in between the two thrust washers. The second washer is to simulate the cage. It is 2.00-inch outer diameter by 1.650-inch inner diameter by 0.185-inch thick and is made of silver-plated 4340 material. The test rig rotates this second washer and loads it against the stationary washer. A schematic of the thrust-washer specimens is shown in the Falex report (Appendix). The specifics of this testing are listed below:

Load:	25 lbf
Speed:	1,750 rpm
Duration	20 minutes
Conditions:	Run specimens submerged in doped oil
Oil:	Mil–L–23699 (50 cm^3 per test)
Contamination:	Al_2O_3 (0.5 grams in 50 cm^3 of oil), 30 to 45-µm diameter
Test Temperature:	Initially at ambient, typical operation at 275°F (392°F maximum)

Posttest wear measurements were taken in each of the eight segments to determine the amount of material worn away as a result of the testing. These data were compared to both M50Nil and M50.

5.3 Results

In prior Falex thrust-washer testing, M50NiL material wore at a rate roughly two to three times that of M50 material. Although the wear rate in this most recent series of tests for the M50NiL material is less severe than in tests conducted in prior years, it is still twice that of the prior M50 wear-rate data. Thus, although the data within this series of testing will be directly compared to the M50NiL data run under this program, it is still of value to compare all of these data to the prior M50 data in order to assess where the candidate materials fall relative to both M50 and M50NiL.

Analyses of these data indicate that Cronidur 30 experienced greater wear than did the M50NiL material in this test. Based on M50NiL experience, this would indicate the need for some sort of shoulder treatment, such as a carburization or TiN coating of the Cronidur 30.

Pyrowear 675, on the other hand, appears to offer greater wear resistance than M50NiL, although it does not appear to be as wear resistant as M50. Table 4 and Figures 50 and 51 summarize the results. The total wear of eight segments of M50 material was roughly 9 mils after similar prior testing. Average Pyrowear 675 total wear was on the order of 13.5 mils for both the 600°F tempered and the 900°F tempered specimens. This is not totally surprising since the Pyrowear 675 case material contains carbides that are visible at 200× magnification, unlike the Cronidur 30 and M50NiL materials where the carbides are difficult to resolve even at 500× magnification. On the other hand, M50 contains large primary carbides from the melting and solidification of the alloy, and large carbides significantly contribute to wear resistance. It is important to note that the rather large spread in Pyrowear 675 wear data may indicate sensitivity to process or microstructural conditions.

Table 4. Wear Test Results Reported by the Falex Corporation

Material	Age Temp (°F)	Specimen	Wear in mils (Measured by Falex)								Segment Wear, mils			
			1	2	3	4	5	6	7	8	Total of 8	Max	Min	Mean
Pyrowear 675	900	0604331B	2.3	2.6	2.6	2.5	2.4	2.2	2.2	2.3	19.10	2.60	2.20	2.39
		0604334B	1.1	1.1	1.0	1.1	1.0	1.0	1.1	1.1	8.50	1.10	1.00	1.06
		0604336B	1.1	0.9	1.1	0.9	1.2	1.4	1.7	1.5	9.80	1.70	0.90	1.23
		0604338B	1.9	1.8	2.0	2.2	2.1	1.6	2.0	1.9	15.50	2.20	1.60	1.94
	600	0604332A	1.6	1.5	1.5	1.4	1.4	1.4	1.6	1.5	11.90	1.60	1.40	1.49
		0604335A	2.4	2.1	1.7	1.5	1.6	1.9	2.1	2.4	15.70	2.40	1.50	1.96
		0604337A	2.2	2.2	1.7	1.2	1.6	1.6	1.9	2.1	14.50	2.20	1.20	1.81
		0604330A	1.9	1.6	1.4	1.3	1.3	1.3	1.8	2.0	12.60	2.00	1.30	1.58
C30	N/A	604235	3.0	3.1	3.0	3.0	3.1	3.2	2.7	2.8	23.90	3.20	2.70	2.99
		604237	3.0	2.8	2.9	2.6	2.7	3.1	2.2	2.7	22.00	3.10	2.20	2.75
		604239	3.1	3.0	3.3	3.5	3.5	3.3	3.7	3.0	26.40	3.70	3.00	3.30
		604241	2.4	2.3	3.0	2.6	2.7	2.5	2.6	2.4	20.50	3.00	2.30	2.56
		604243	2.3	2.1	1.9	2.1	2.2	2.3	2.6	2.1	17.60	2.60	1.90	2.20
M50–NiL	N/A	604236	2.4	2.2	2.9	2.2	2.6	2.3	2.4	2.6	19.60	2.90	2.20	2.45
		604238	2.5	2.5	2.1	2.0	2.0	2.3	2.3	2.4	18.10	2.50	2.00	2.26
		604240	2.1	2.3	2.1	2.2	2.1	1.9	2.2	2.2	17.10	2.30	1.90	2.14
		604242	2.0	1.8	2.5	2.2	1.9	2.0	2.4	2.2	17.00	2.50	1.80	2.13
		604244	1.9	1.6	1.5	2.0	2.2	2.1	2.1	1.9	15.30	2.20	1.50	1.91

5.4 Conclusions

This subscale wear testing indicated that Cronidur 30 has wear properties similar if not a little inferior to those of M50NiL. Pyrowear 675 is somewhere between M50 and M50NiL, but it is not known if further work on developing a more wear-resistant case is warranted. Full-scale rig or engine tests with the developed wear-resistant case in the shoulders are needed to indicate how this material would perform in a full-scale contaminated environment.

The wear test reports from Falex Corporation are replicated as an appendix to this report.

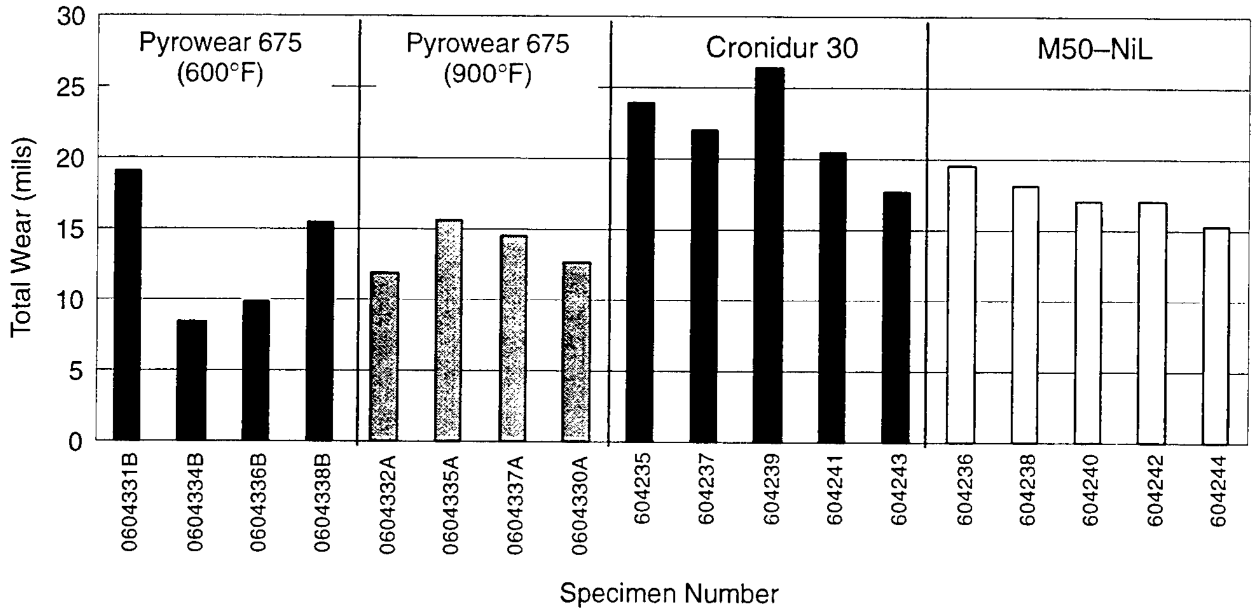


Figure 50. Total Wear from Specimens (Results Reported by Falex Corporation)

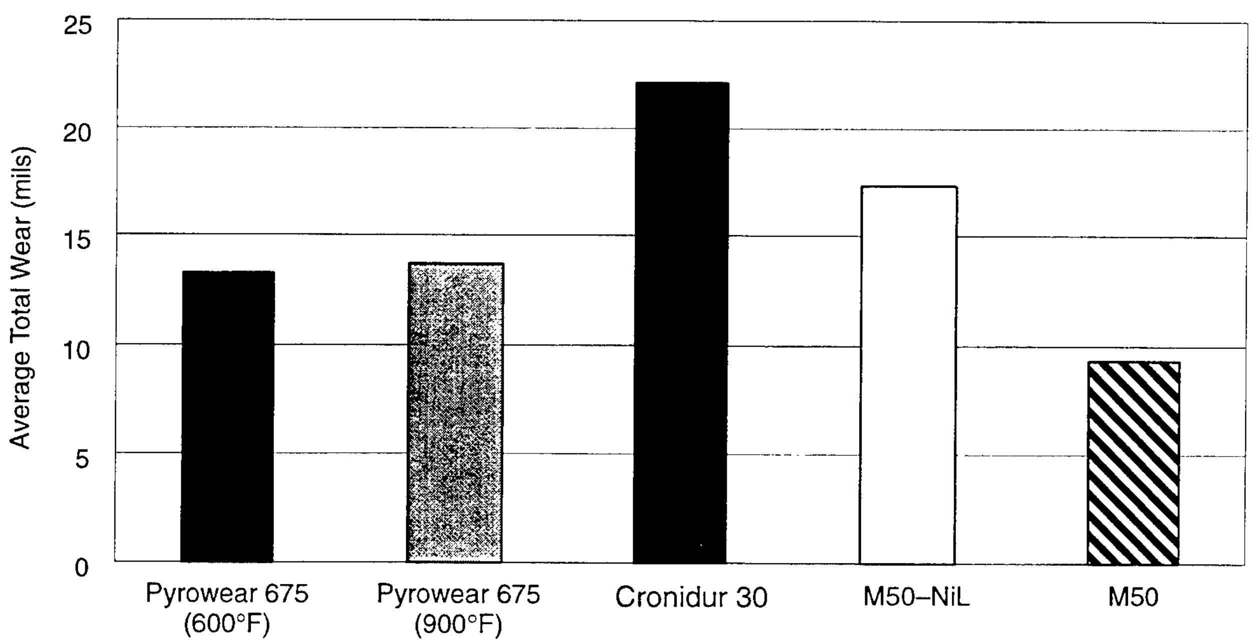


Figure 51. Average Total Wear from Specimens (Results Reported by Falex Corporation) Compared with Historical Results

6.0 Conclusions

The primary objective, to compare the wear resistance of Cronidur 30 and Pyrowear 675 to M50 and M50–NiL, was successfully achieved.

The corrosion benefit of these high-chrome steel materials was clearly demonstrated in the subscale corrosion-resistance tests. Cronidur 30 showed the best corrosion resistance to synthetic salt water and tap water. Pyrowear 675 with either 600°F or 900°F temper showed improved corrosion resistance relative to M50 but was not as good as Cronidur 30.

The wear characteristics were demonstrated by Falex wear tests. Cronidur 30 exhibited more wear than M50–NiL, and Pyrowear 675 had wear someplace between M50 and M50–NiL.

The potential for shoulder wear with Cronidur 30 and Pyrowear 675 was demonstrated by full-scale bearing contamination-endurance tests. This testing provides a rough measure of the shoulder wear resistance of a bearing material. The wear induced by this test with the Cronidur 30 bearing with Cronidur 30 balls indicated high ball wear in addition to shoulder wear. The test with the Cronidur 30 bearing with M50 balls indicated a potential raceway microspalling problem in addition to shoulder wear. The wear seen on the Pyrowear 675 bearing with M50 balls indicated severe shoulder wear.

The shoulder wear during the full-scale contamination-endurance test of both bearing materials is believed to be related to the microstructure. Previous contamination-endurance rig testing of M50 and M50NiL bearings consistently showed that M50 has superior shoulder-wear lapping resistance compared to M50NiL. This is believed to be due to the larger primary melt eutectic carbides in the M50 structure. The wear resistances of Cronidur 30 and Pyrowear 675 are similar to that of M50NiL because they have no primary melt eutectic carbides in the microstructures.

7.0 Recommendations

Cronidur 30 and Pyrowear 675 showed improved corrosion resistance relative to M50 and are still attractive for future bearing applications. The potential for shoulder wear, as demonstrated in specimen and full-scale rig testing through the use of injected hard-particle contamination, precludes the immediate introduction of either material into military jet engine applications. Prior to introduction of Cronidur 30 or Pyrowear 675, the following material developments and tests are recommended.

Further alloy development is warranted to improve the shoulder wear resistance. The impact on bearing endurance, contamination resistance, and corrosion resistance would need assessment.

Corrosion-resistance testing of Cronidur 30, Pyrowear 675, 52100, M50, and M50NiL in thermally degraded oil (to increase the acidity of the oil and thus represent field experience) is recommended. The synthetic sea water and tap water tests completed by this program were merely to assess the relative corrosion resistance of the materials and not to demonstrate behavior in field use.

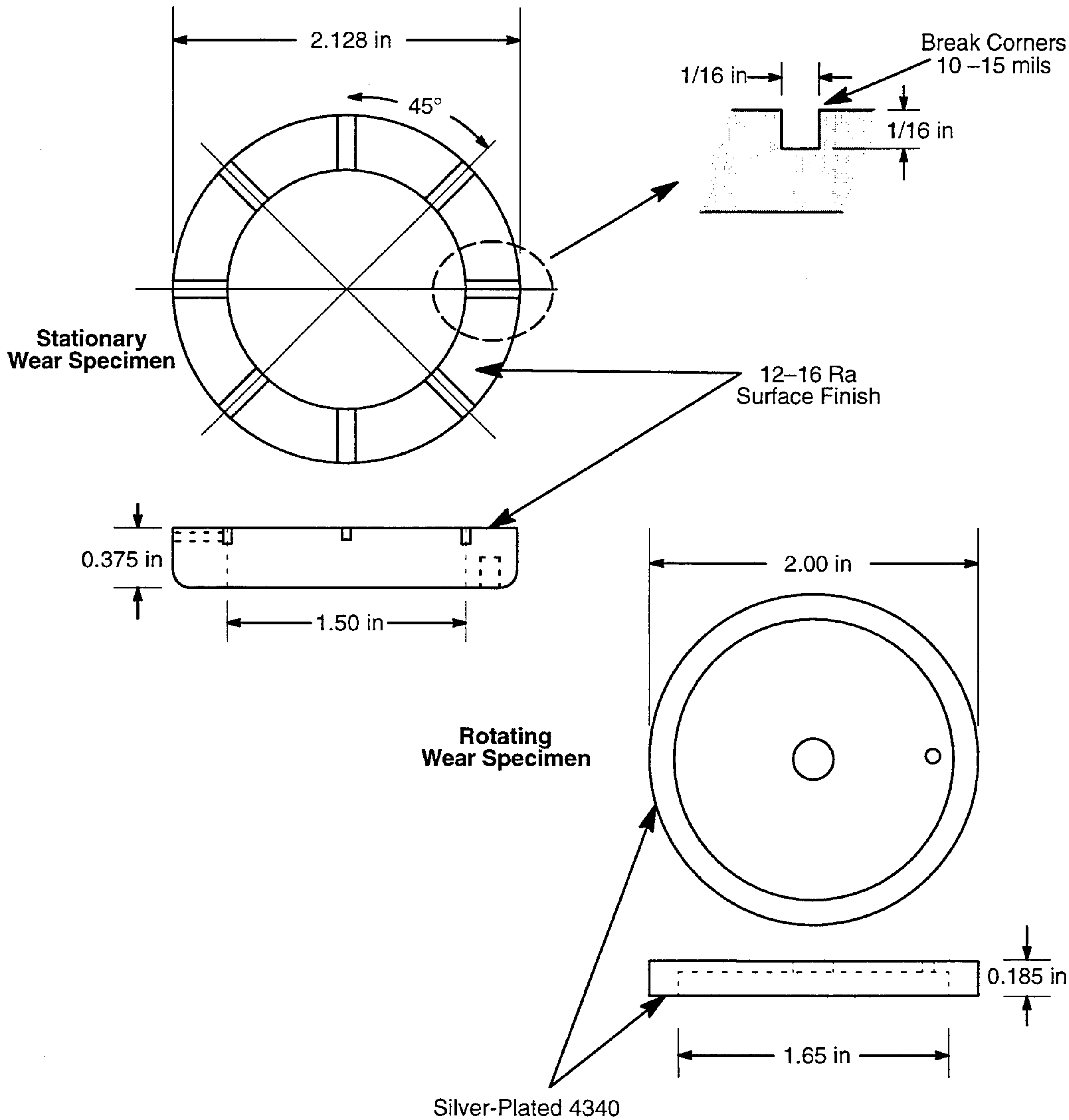
Several contamination-endurance tests on full-scale bearings of Cronidur 30, Pyrowear 675, M50, and M50NiL are recommended to statistically rank the wear resistance of the materials relative to M50 and M50NiL. This program only ran a few bearings to investigate the relative shoulder-wear resistance of the materials.

Subscale fatigue tests with contamination are recommended to characterize the potential for raceway spalling. Such tests were not done as part of this program.

Full-scale endurance tests without contamination are recommended to ensure sufficient bearing fatigue life. Such tests were not done as part of this program.

Appendix – Falex Wear Tests

Falex Corporation in Aurora, IL is the world's largest manufacturer of test equipment specializing in evaluation of friction, wear, abrasion, and lubrication. The test results described herein were reported to GEAE by Brian M. Holtkamp, Director, Falex Testing Services. Specimen geometry is illustrated in the schematics below. Wear-test results are tabulated on the following pages. *CoF* indicates the dynamic coefficient of friction (μ), the dimensionless ratio of the friction force (F) between the revolving washer and the stationary washer to the normal force (N) pressing the bodies together. Segment thickness change (wear) is listed under the heading Δt.



Machine: Falex Multispecimen Model 6 Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed: 0 to 1750 rpm Initial Temperature: Ambient Duration: 20 Minutes Load: 25 lbf				Upper Material: Ag-Coated 4340 Upper Material AA#: 1513 Fluid (Amount): Mobil Jet II with Al (50 cm^3) Fluid AA#: 1516			
Test Date		08/27/97		08/27/97		08/27/97	
Test Number		0604–235		0604–236		0604–237	
Lower Material		Cronidur 30		M50NiL		Cronidur 30	
Lower Material AA#		1514		1515		1514	
Mass Loss, Upper (g)		0.0431		0.0641		0.0572	
Mass Loss, Lower (g)		0.3199		0.2769		0.3029	
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.232	0.0030	0.244	0.0024	0.188	0.0030
5 Minutes	2	0.161	0.0031	0.156	0.0022	0.158	0.0028
10 Minutes	3	0.158	0.0030	0.158	0.0029	0.144	0.0029
15 Minutes	4	0.143	0.0030	0.148	0.0022	0.134	0.0026
20 Minutes	5	0.141	0.0031	0.145	0.0026	0.128	0.0027
Average	6	0.151	0.0032	0.152	0.0023	0.141	0.0031
	7		0.0027		0.0024		0.0022
	8		0.0028		0.0026		0.0027
Final Fluid Temp, °C		102		103		98	

Machine: Falex Multispecimen Model 6 Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed: 0 to 1750 rpm Initial Temperature: Ambient Duration: 20 Minutes Load: 25 lbf				Upper Material: Ag-Coated 4340 Upper Material AA#: 1513 Fluid (Amount): Mobil Jet II with Al (50 cm^3) Fluid AA#: 1516			
Test Date		08/28/97		09/02/97		09/02/97	
Test Number		0604–238		0604–239		0604–240	
Lower Material		M50NiL		Cronidur 30		M50NiL	
Lower Material AA#		1515		1514		1515	
Mass Loss, Upper (g)		0.0211		0.0351		0.0243	
Mass Loss, Lower (g)		0.2576		0.3618		0.2386	
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.293	0.0025	0.306	0.0031	0.241	0.0021
5 Minutes	2	0.154	0.0025	0.176	0.0030	0.160	0.0023
10 Minutes	3	0.146	0.0021	0.159	0.0033	0.149	0.0021
15 Minutes	4	0.144	0.0020	0.153	0.0035	0.138	0.0022
20 Minutes	5	0.146	0.0020	0.145	0.0035	0.144	0.0021
Average	6	0.148	0.0023	0.158	0.0033	0.148	0.0019
	7		0.0023		0.0037		0.0022
	8		0.0024		0.0030		0.0022
Final Fluid Temp, °C		103		104		100	

Machine: Falex Multispecimen Model 6 Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed: 0 to 1750 rpm Initial Temperature: Ambient Duration: 20 Minutes Load: 25 lbf				Upper Material: Ag-Coated 4340 Upper Material AA#: 1513 Fluid (Amount): Mobil Jet II with AI (50 cm^3) Fluid AA#: 1516			
Test Date Test Number Lower Material Lower Material AA# Mass Loss, Upper (g) Mass Loss, Lower (g)		09/02/97 0604–241 Cronidur 30 1514 0.0198 0.2834		09/02/97 0604–242 M50NiL 1515 0.0273 0.2280		09/02/97 0604–243 Cronidur 30 1514 0.0820 0.2337	
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.286	0.0024	0.265	0.0020	0.273	0.0023
5 Minutes	2	0.173	0.0023	0.154	0.0018	0.139	0.0021
10 Minutes	3	0.158	0.0030	0.143	0.0025	0.173	0.0019
15 Minutes	4	0.147	0.0026	0.145	0.0022	0.156	0.0021
20 Minutes	5	0.144	0.0027	0.147	0.0019	0.153	0.0022
Average	6	0.156	0.0025	0.147	0.0020	0.155	0.0023
	7		0.0026		0.0024		0.0026
	8		0.0024		0.0022		0.0021
Final Fluid Temp, °C		104		102		101	

Machine: Falex Multispecimen Model 6 Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed: 0 to 1750 rpm Initial Temperature: Ambient Duration: 20 Minutes Load: 25 lbf				Upper Material: Ag-Coated 4340 Upper Material AA#: 1513 Fluid (Amount): Mobil Jet II with AI (50 cm^3) Fluid AA#: 1516			
Test Date Test Number Lower Material Lower Material AA# Mass Loss, Upper (g) Mass Loss, Lower (g)		09/03/97 0604–244 M50NiL 1515 0.0528 0.2303					
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.241	0.0019				
5 Minutes	2	0.161	0.0016				
10 Minutes	3	0.147	0.0015				
15 Minutes	4	0.143	0.0020				
20 Minutes	5	0.141	0.0022				
Average	6	0.148	0.0021				
	7		0.0021				
	8		0.0019				
Final Fluid Temp, °C		100					

Machine: Falex Multispecimen Model 6, Lever-Loaded Version Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed:	0 to 1750 rpm			Upper Material:	Ag-Coated 4340		
Initial Temperature:	Ambient			Upper Material AA#:	1794		
Duration:	20 Minutes			Fluid (Amount):	Mobil Jet II with Al (50 cm^3)		
Load:	25 lbf			Fluid AA#:	1797		
Test Date		01/06/98		01/06/98		01/06/98	
Test Number		0604–330		0604–331		0604–332	
Lower Material		Pyrowear 675 (600°F)		Pyrowear 675 (900°F)		Pyrowear 675 (600°F)	
Lower Material AA#		1795		1796		1795	
Mass Loss, Upper (g)		0.0391		0.0367		0.0495	
Mass Loss, Lower (g)		0.1841		0.2674		0.1695	
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.279	0.0019	0.296	0.0023	0.263	0.0016
5 Minutes	2	0.167	0.0016	0.179	0.0026	0.160	0.0015
10 Minutes	3	0.157	0.0014	0.161	0.0026	0.155	0.0015
15 Minutes	4	0.148	0.0013	0.154	0.0025	0.146	0.0014
20 Minutes	5	0.142	0.0013	0.151	0.0024	0.142	0.0014
Average	6	0.154	0.0013	0.161	0.0022	0.151	0.0014
	7		0.0018		0.0022		0.0016
	8		0.0020		0.0023		0.0015
Final Fluid Temp, °C		96.5		100.7		96.4	

Machine: Falex Multispecimen Model 6, Lever-Loaded Version Method: Large Slotted Thrust Washer (0.911-in Mean Test Radius)							
Speed:	0 to 1750 rpm			Upper Material:	Ag-Coated 4340		
Initial Temperature:	Ambient			Upper Material AA#:	1794		
Duration:	20 Minutes			Fluid (Amount):	Mobil Jet II with Al (50 cm^3)		
Load:	25 lbf			Fluid AA#:	1797		
Test Date		01/10/98		01/12/98		01/12/98	
Test Number		0604–334		0604–335		0604–336	
Lower Material		Pyrowear 675 (900°F)		Pyrowear 675 (600°F)		Pyrowear 675 (900°F)	
Lower Material AA#		1796		1795		1796	
Mass Loss, Upper (g)		0.0171		0.0328		0.0095	
Mass Loss, Lower (g)		0.1195		0.2593*		0.1370	
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.260	0.0011	0.294	0.0024	0.263	0.0011
5 Minutes	2	0.162	0.0011	0.294	0.0021	0.159	0.0009
10 Minutes	3	0.156	0.0010	0.155	0.0017	0.153	0.0011
15 Minutes	4	0.150	0.0011	0.152	0.0015	0.149	0.0009
20 Minutes	5	0.148	0.0010	0.152	0.0016	0.145	0.0012
Average	6	0.154	0.0010	0.188	0.0019	0.152	0.0014
	7		0.0011		0.0021		0.0017
	8		0.0011		0.0024		0.0015
Final Fluid Temp, °C		99.4		102.0		99.4	
* Lower specimen chipped during removal from table after test segment.							

Machine:	Falex Multispecimen Model 6, Lever-Loaded Version						
Method:	Large Slotted Thrust Washer (0.911-in Mean Test Radius)						
Speed:	0 to 1750 rpm			Upper Material:	Ag-Coated 4340		
Initial Temperature:	Ambient			Upper Material AA#:	1794		
Duration:	20 Minutes			Fluid (Amount):	Mobil Jet II with Al (50 cm^3)		
Load:	25 lbf			Fluid AA#:	1797		
Test Date		01/13/98		01/13/98			
Test Number		0604–337		0604–338			
Lower Material		Pyrowear 675 (600°F)		Pyrowear 675 (900°F)			
Lower Material AA#		1795		1796			
Mass Loss, Upper (g)		0.0251		0.0289			
Mass Loss, Lower (g)		0.2243		0.2335			
Interval	**Segment**	**CoF**	**Δt, in**	**CoF**	**Δt, in**	**CoF**	**Δt, in**
0 Minutes	1	0.291	0.0022	0.255	0.0019		
5 Minutes	2	0.165	0.0022	0.162	0.0018		
10 Minutes	3	0.158	0.0017	0.152	0.0020		
15 Minutes	4	0.152	0.0012	0.150	0.0022		
20 Minutes	5	0.155	0.0016	0.151	0.0021		
Average	6	0.158	0.0016	0.154	0.0016		
	7		0.0019		0.0020		
	8		0.0021		0.0019		
Final Fluid Temp, °C		102.5		102.5			