ROLLING CONTACT FATIGUE LIFE OF CHROMIUM ION PLATED 440C BEARING STEEL

Biliyar N. Bhat
Materials and Processes Laboratory
NASA/MSFC
Marshall Space Flight Center, Alabama 35823
U.S.A.

Jack H. Davis
Department of Physics
The University of Alabama in Huntsville
Huntsville, Alabama 35899
U.S.A.

ABSTRACT

Rolling contact fatigue (RCF) test specimens of heat treated 440C bearing steel were chromium ion plated in thicknesses from 0.1 μm to 8.0 μm and tested in RCF tester using 700 ksi maximum Hertzian stress. Heavy coatings, greater than about 5 μm in thickness, peeled off or spalled readily, whereas thin coatings, less than 3 μm thick, were tenacious and did not come off. Furthermore, significant improvement in RCF life was obtained with thin chromium ion plated test specimens. The average increase in B_{10} life was 75% compared with unplated 440C. These preliminary results indicate that ion plating is a promising way to improve bearing life.

ROLLING CONTACT FATIGUE LIFE OF CHROMIUM ION PLATED 440C BEARING STEEL

Introduction

The high efficiency operation of the Space Shuttle Main Engine (SSME) appears to limit the service life of 440C steel bearings in the engine, especially those of the high pressure oxidizer turbopump (HPOTP). Bearing life enhancement is expected to contribute significantly to increased life and reliability of space transportation systems. To achieve this goal, efforts have been made to thoroughly understand the complexities of turbopump bearing service life.[1] Improved bearing materials with greater resistance to fatigue and wear are being developed through powder metallurgy techniques.[2] Furthermore, surface modification techniques such as ion plating and ion implantation appeared to offer potential for improving the fatigue life of bearing materials.[3] Ion plating, in particular, seemed to have several positive qualities, the most important of which are outstanding film adhesion and deposition on all sides of the substrate (including some coverage into cavities), whereas normal vacuum deposition and ion implantation give the usual line-of-sight coverage. Other qualities are fine grain structure, low coefficient of friction and improved mechanical properties. The latter two qualities of ion plated coatings make it attractive for application in turbopump bearings. Therefore, a study of ion plating 440C with chromium was conducted. This paper presents some preliminary results obtained in that study.

Ion Plating Procedure

Chromium was selected for ion plating 440C steel because of its common use in electroplating steel for corrosion resistance. Furthermore, 440C steel contains about 16-18 wt. % chromium, thus providing a continuity in chemistry which is an important consideration in obtaining a good bond. The test specimen used in this study and the heat treatment are shown in Figure 1. The apparatus used for ion plating is shown schematically in Figure 2. Chromium is melted by an electron beam and vaporized. Some chromium atoms are ionized in the plasma glow discharge formed by the ionized argon gas, accelerated by the applied electric potential and deposited on the 440C rolling contact fatigue (RCF) test specimen. The specimen rod axis was mounted coaxially with the jar axis to produce a symmetric uniform coating. The specimen was initially sputter-cleaned in situ to remove the oxide layer before the electron beam was turned on to vaporize chromium. Plating thickness was varied so that the effect of plating thickness on RCF life could be determined. The plating thickness was calculated based on weight gain during plating. Argon pressure during plating was typically 15-30 μm. Substrate temperatures using an infrared pyrometer varied between 200°C-300°C. Table 1 gives a summary of the test specimens ion plated with chromium in this program. Estimated plating thickness varied from 0.1 μm to 8.0 μm. Coating appearance was variable, from nearly invisible and bright to bluish, grey and dark[4].

Metallurgical Analysis

All RCF test specimens were examined under a stereo viewer. Where the coatings were very thin (< 1 μm) it was difficult to tell that the specimens were coated. Dark coatings were generally porous and were readily scratched by knife. Good, thin coatings were not scratched by knife. One such specimen (No. 5) was sectioned, electroless nickel plated, mounted in epoxy, polished, etched and examined under optical microscope. A thin ion plated chromium layer was observed (Figure 3). The plating was uniform and followed the surface contours. There was a good bond between the chrome plating and the surface, especially with the carbides.

Rolling Contact Fatigue (RCF) Testing

RCF testing was done using the Polymet model RCF-1 machine which used two, 7.5 in. diameter loading discs (Figure 4). The specimen was loaded to a maximum Hertzian stress of 700,000 psi. The testing speed was 10,000 rpm. The number of revolutions were counted automatically by a revolution counter. The testing machine was shut down automatically by a failure sensor which picked up vibrations that increased sharply when the specimen failed by spalling. The number of revolutions to failure was noted. About eight tests were run with each specimen, four on each end. The data were plotted on a Weibull probability chart, which plotted cumulative percent failure versus number of cycles to failure (Figure 5). The B_{10} life was read off the chart. The results are summarized in Table 1. Some specimens had coatings that were too thick and readily spalled off. These samples were not tested any further. Specimen No. 1 (in Table 1) was not ion plated, but was simply sputter cleaned by argon. Auger analysis of this sample showed a chromium rich (40 wt. % Cr) surface layer, approximately 15 nm thick. Such a surface layer obviously provides a good transition layer for ion plating chromium. RCF testing produced typical wear tracks and spalls in the specimen. Figure 6 gives three examples. The spalls of both ion plated and standard specimens were examined in the scanning electron microscope (Figure 7). Failure mode appears to be the same in both cases.

Discussion

On examination of RCF test results (Table 1) chromium ion plating obviously helped to improve the RCF life of 440C steel test specimens. The ratio B_{10} (specimen)/B_{10} (standard) is listed in the last column of Table 1. This ratio varied from 1.07 to 2.86. The average was 1.75, indicating a 75% improvement in RCF life. The failure mode in RCF testing was by spalling (Figure 7). In this mechanism subsurface crack initiation occurs under high Hertzian stresses and the crack propagates to the surface resulting in spalling. The reason for the improvement in RCF life may be due to the fact that a thin chromium layer is likely to produce a more even distribution of contact stresses which results in a somewhat reduced maximum shear stress, thus extending the fatigue life. It is not clear how well the coating would perform under actual service conditions of the turbopump where some sliding motion is present and where lubrication is marginal. To answer this question it would be necessary to run cryogenic tests with ion plated bearings.
The preliminary results obtained in this study are encouraging. However, there is a considerable scatter in the B_{10} lives of ion plated specimens, taken as a whole. The reason for this scatter is not very clear. One possibility is that the ion plating process is not fully optimized yet. For instance, further optimization in electron beam current (which determines the rate of chromium evaporation) may be necessary. However, it does appear that the highest B_{10} lives are associated with thin coatings (0.1 μm and 0.2 μm, Table 1). This avenue should be pursued further to gain confidence in the imporved RCF life of ion plated 440C bearing steel.

Summary and Conclusions

RCF tests were conducted with chromium ion plated 440C bearing steel specimens. The results showed significant improvements in B_{10} life. The average improvement was 75% for all samples. Thin coatings, 0.1 to 0.2 μm thin, gave the best results, with B_{10} life improvements greater than 150%. Further process optimization and tests in cryogenic environments are necessary to qualify these coatings for use in the SSME turbopump bearings.

Acknowledgements

The technical support of F. J. Dolan, R. R. Rowe, and other personnel of Materials and Processes Laboratory, NASA-MSFC, and the advice and assistance of A. P. Biddle of Space Science Laboratory, NASA-MSFC, in setting up and operating the ion plating unit are gratefully acknowledged.

References

1. B. N. Bhat, "Fracture Analysis of HPOTP Bearing Balls," NASA-TM-82428, May 1981; B.N. Bhat and F. J. Dolan, "Past Performance Analysis of HPOTP Bearings", NASA-TM-92470, March 1982; B.N. Bhat and F.J. Dolan, "Analysis of Cryogenic Turbopump Bearing Service Life," unpublished report, May 1983.

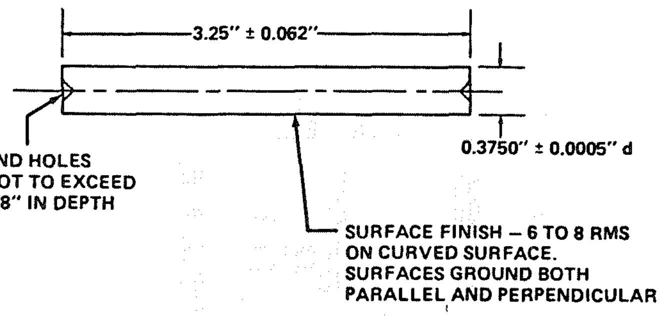
2. "Application of Powder Metallurgy Techniques to Produce Improved Bearing Elements for Liquid Rocket Engines," by TRW, Inc., Materials and Manufacturing Technology Center, Cleveland, Ohio. (NASA Contract NAS8-34763) Work in progress.

3. "Ion Plating" by R.F. Hochman and D.U. Mattox; "Ion Implantation" by R.F. Hochman, Metals Handbook, Volume 5, American Society for Metals (1982).

4. Jack H. Davis, "Aluminum and Chromium Ion Plating Studies for Enhancement of Surface Properties," NASA CR-162051 and NASA CR-161851, University of Alabama in Huntsville, AL, August 11, 1981 and August 18, 1982.

EH531

A. RCF TEST SPECIMEN



B. HEAT TREATMENT OF RCF TEST SPECIMEN

AFTER ROUGH MACHINING, HEAT TREATMENT IS CARRIED OUT AS FOLLOWS:

A. AUSTENITIZE AT 1930° ± 30°F FOR ONE HOUR AT TEMPERATURE.

B. HARDEN (OIL QUENCH 120° – 150°F OIL TEMP.).

C. TEMPER ONE HOUR MIN. AT 325° + 25°F – 0°F

D. COOL IN AIR TO 70° ± 10°F (ROOM TEMP.)

E. COLD SOAK IN LIQUID NITROGEN FOR 30 MINUTES.

F. TEMPER ONE HOUR MINIMUM AT 325° + 25°F – 0°F

FINAL HARDNESS – TYPICALLY Rc 59–61

FIGURE 1. RCF TEST SPECIMEN CONFIGURATION AND HEAT TREATMENT

EH532

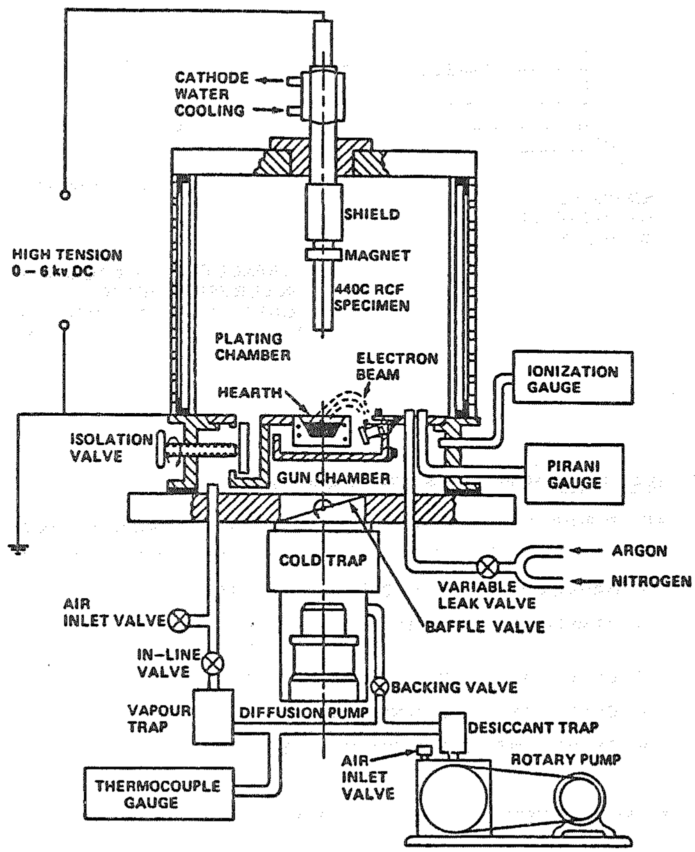


FIGURE 2. ION PLATING APPARATUS WITH AN ELECTRON BEAM GUN (SCHEMATIC)

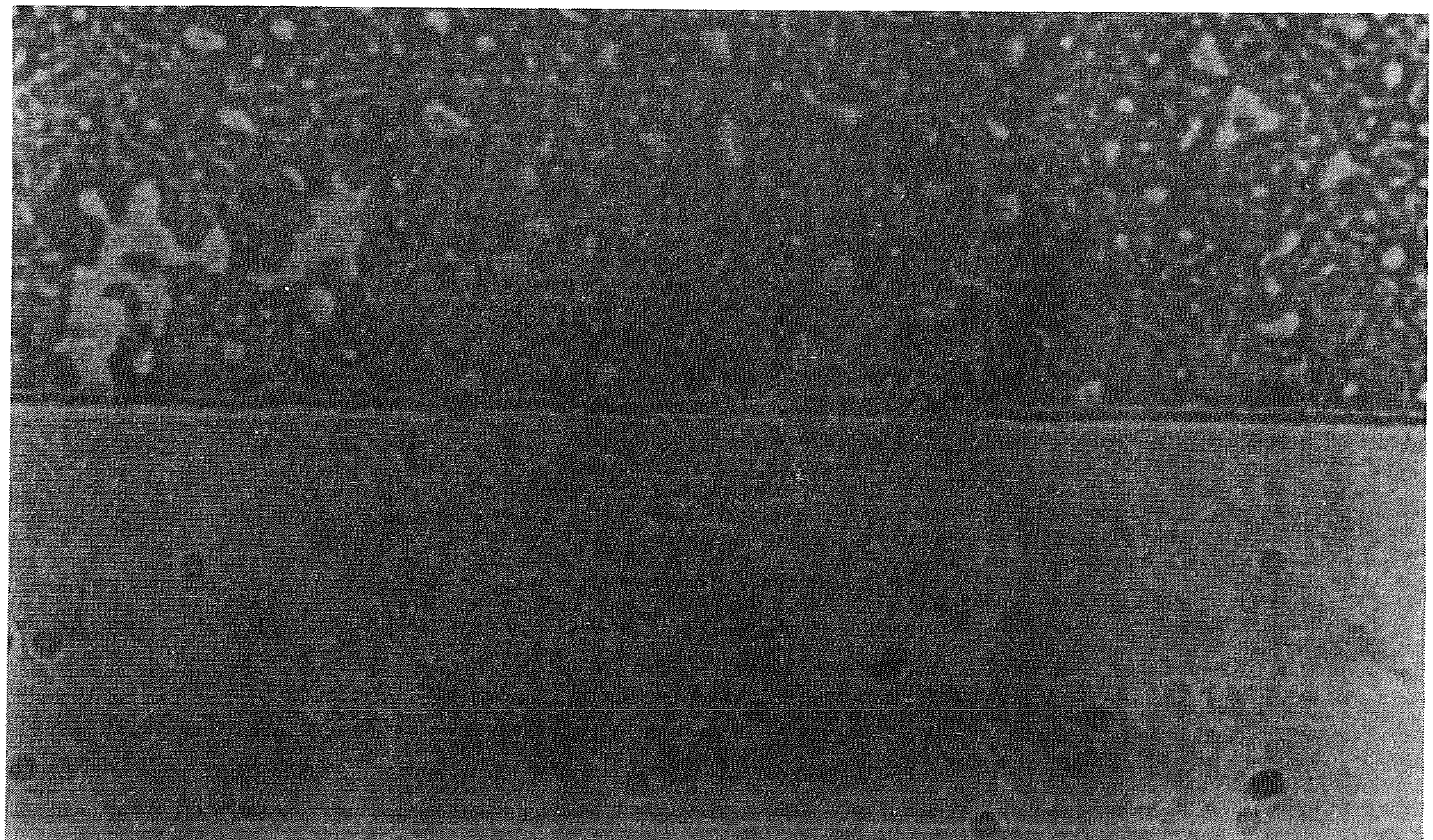


FIGURE 3. - PHOTOMICROGRAPH OF ION PLATED 440C RCF TEST SPECIMEN (NO. 6).

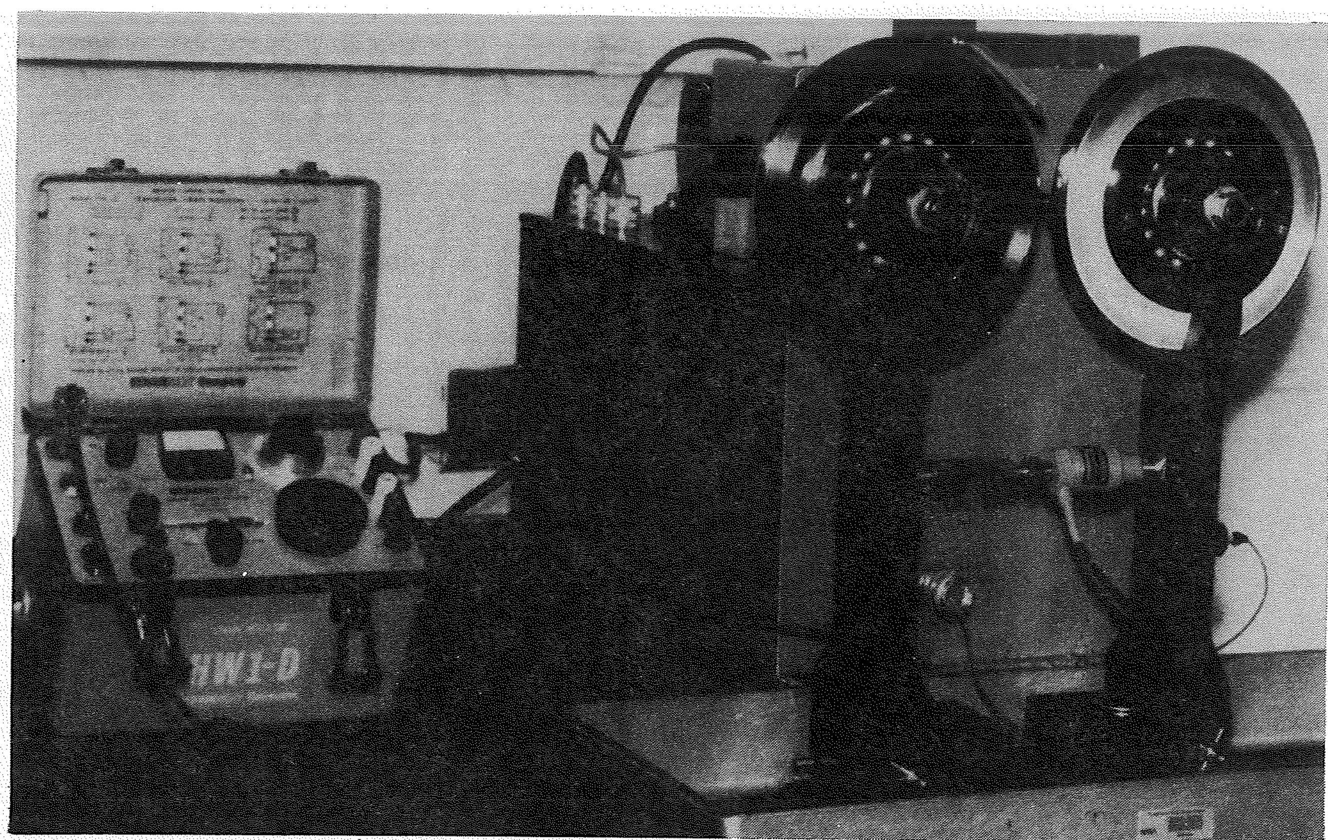


FIGURE 4. - ROLLING CONTACT FATIGUE TESTER (POLYMET MODEL RCF-1).

EH408A

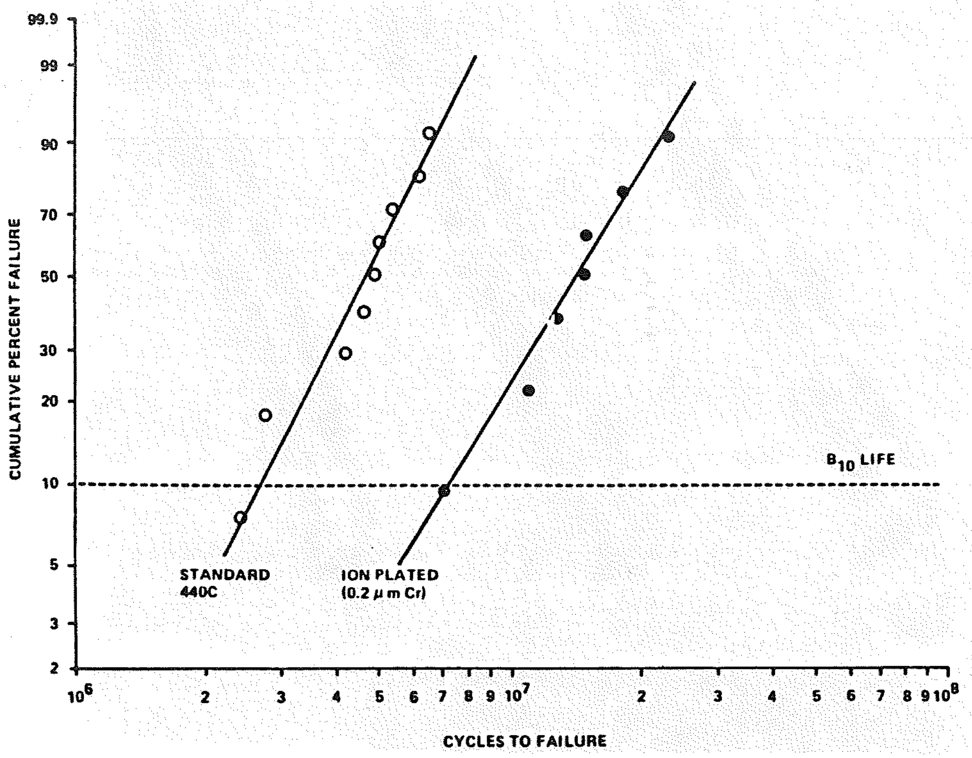


FIGURE 5. WEIBULL PLOT OF RCF TEST RESULTS FOR STANDARD AND CHROMIUM ION PLATED 440C

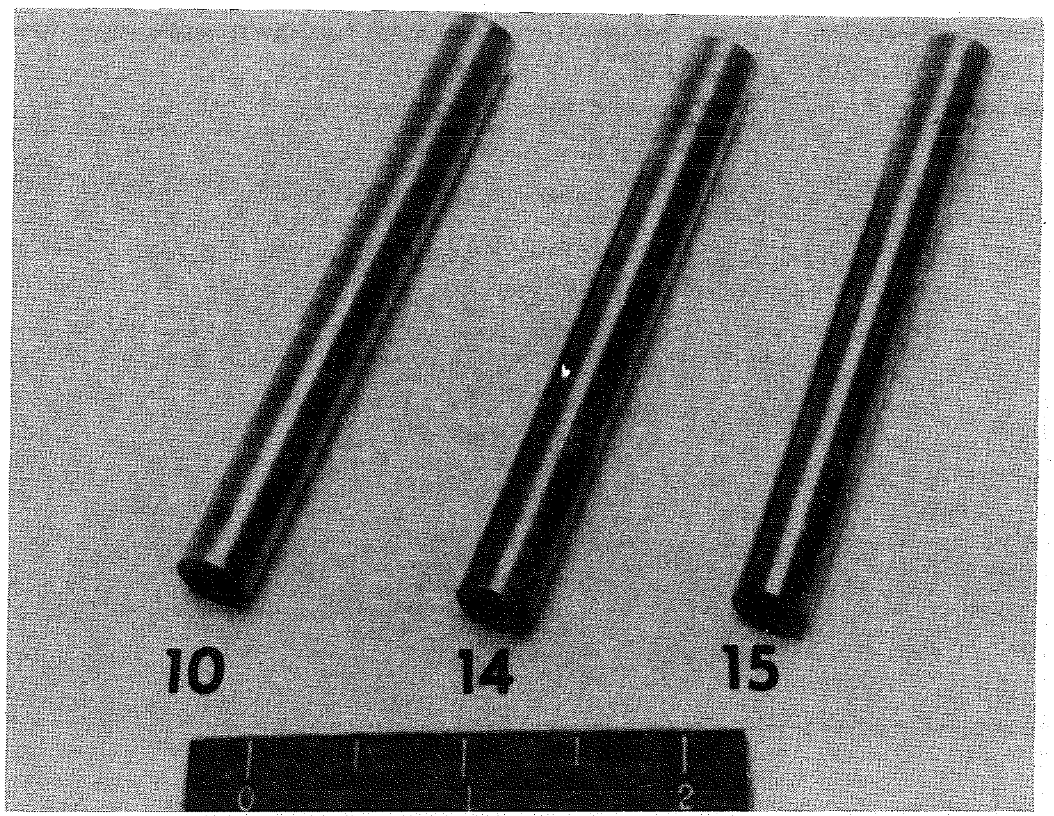


FIGURE 6. - RCF TEST SPECIMENS - AFTER TESTING. NOTE WEAR TRACKS AND SPALLS. (NUMBERS REFER TO SPECIMEN NUMBERS IN TABLE 1.)

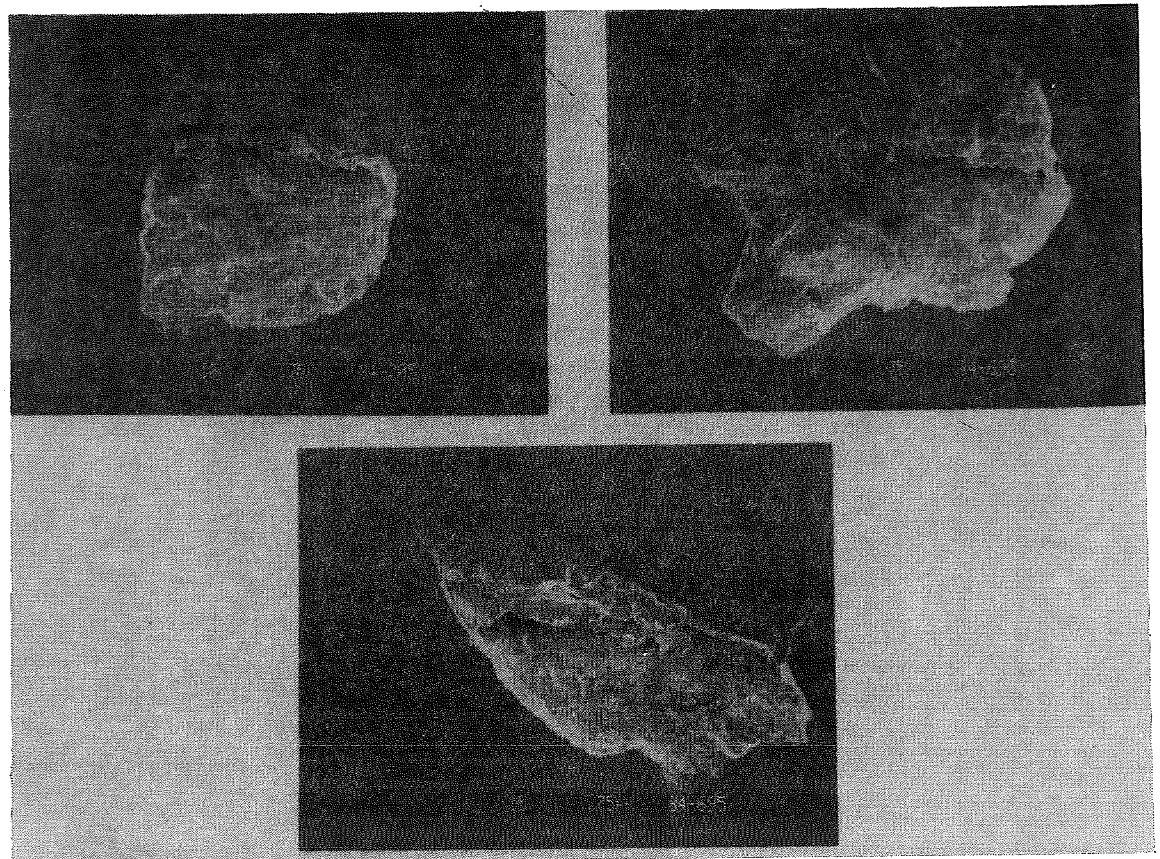


FIGURE 7. - TYPICAL SPALLS IN ION PLATED (NOS. 10, 14) AND UNPLATED (NO. 15) RCF TEST SPECIMENS.

TABLE 1: SUMMARY OF TEST SPECIMENS

Sample Number	Average Coating Thickness (μm)	Color of Coating	Comments	RCF Test Results	
				B_{10} Life (Cycles)	B_{10} (Specimen) / B_{10} (Standard 440C)
1	0.0	Light gold	Sputter-cleaned, but not ion plated		
2	4.5	Grey to dark	Thick coating, peeled off during RCF test		
3	8.0	Dark	Coating easily scratched by knife; not tested		
4	6.0	Bright	Coating peeled off during RCF test		
5	5.0	Bright	Easily scratched, not tested		
6	0.2	Bright	Good coating; RCF tested	$7.2X10^6$	2.57
7	6.6	Dark	Readily scratched, coating peeled off during RCF test		
8	6.0	Grey	Readily scratched, not tested		
9	1.0	Blackish	RCF tested	$3.6X10^6$	1.29
10	3.0	Bluish	RCF tested	$5.0X10^6$	1.79
11	0.1	Bright	RCF tested	$8.0X10^6$	2.86
12	2.0	Bluish	RCF tested	$3.0X10^6$	1.07
13	0.9	Bright	RCF tested	$4.2X10^6$	1.5
14	0.4	Bright	RCF tested	$3.4X10^6$	1.21
15	0.0	Bright	Standard 440C specimen	$2.8X10^6$	----
				AVG.	1.75