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# AN EVALUATION OF GALLING-RESISTANT MATERIALS FOR THE A-10 GAU-8/A GUN MOUNTS

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Final Report for Period August 1983 - May 1984

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Laboratory procedures were developed to duplicate the fretting and galling that occurs in the 17-4PH stainless steel spindle and 4340 steel pillow block of the A-10 GAU-8/A gatling gun. The procedures were then used to evaluate galling-resistant materials, coatings, and lubricants for incorporation into replacement gun mounts. The program involved duplicating the reciprocal lateral sliding motion of the mount spindle in its mating pillow block and applying an impact load in synchonization with the sliding.

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A short-term solution was found which improved baseline material wear life by a factor of two; it involved applying either AFSL-41 or MIL-L-46010 dry film lubricant and MIL-G-81827 high pressure grease to mating parts. Two long-term solutions were identified which extended specimen life by over an order of magnitude. In one case, the 17-4PH spindle material was replaced by H11 steel. The other case involved plating baseline materials with 0.0015 inch-thick electroless nickel. Both long-term solutions also incorporated the dry film and grease. Unsatisfactory results were achieved with hard chrome, improperly applied dry film, and polyimide and polyamide resins.

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## PREFACE

This report was prepared by the Materials Engineering Branch (AFWAL/MLSE), Systems Support Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 2418, "Aerospace Structural Materials," Task 241807, "Systems Support," Work Unit 24180703, "Engineering and Design Data."

The work reported herein was performed during the period August 1983 to May 1984 by the author, 2Lt Torsten M. Rhode (AFWAL/MLSE). The report was released by the author in May 1984.

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## INTRODUCTION

Flight tests were performed at Nellis AFB, NV, to evaluate the effectiveness of an experimental gun-gas diverter (designated the XPD) used on the GAU-8/A gatling gun installed in A-10 aircraft. During the test program, inspections of the aircraft with and without the XPD diverter revealed severe galling of the inboard aft gun mounts. Results of an Air Force-wide inspection of bare-barrelled gun mounts revealed the galling phenomenon was widespread, and it appeared that the XPD accelerated the galling. The galled mounts do not adversely affect the performance of the aircraft or the gun; however, the galling locks the gun into the mount and severely hinders gun removal for maintenance and inspection.

Of the two aft mounts used to hold the gun in place, only the inboard mount is affected by galling. This is due to the geometry of the system where the outboard spindle is immobilized by a threaded end cap; flexure of the airframe allows the inboard assembly to move. The galling of the mount is a function of high-recoil loads coupled with sliding reciprocating lateral movement of the inboard spindle in its mating pillow block.

Both the impact load and the lateral displacement act in phase with the firing of the gun at a frequency of 70 Hz. Bare-barrelled guns exhibit a displacement of about one-half the $\pm$0.040-inch displacement of XPD-equipped guns. Recoil loads for either configuration were about the same and were initially estimated to be alternating from a minimum of 0 ksi to a maximum of 2 or 3 ksi.

The Engineering & Design Data Group of the AFWAL Materials Laboratory agreed to carry out a test program which employed test parameters that duplicated those that caused the fretting and galling of the gun mount base materials. The program evaluated various materials, coatings, and lubricants in terms of their resistance to galling.

Since all guns would eventually be equipped with the XPD gun gas diverter, the test program focused on duplicating parameters measured on XPD-equipped guns.

This report outlines the laboratory techniques developed to duplicate the fretting and galling of A-10 GAU-8/A gun mount materials. It also includes an evaluation of galling-resistant materials, coatings, and lubricants for incorporation into replacement gun mounts.

## SECTION II

## TEST PROGRAM & PROCEDURES

The first phase of testing involved designing a test mechanism which could test samples under conditions which approximate actual gun mount conditions as closely as possible. For this task, an MTS 50,000 lb, 20,000 in-lb tension-torsion machine was used. The goal of the test was in no way centered around designing specimens which duplicated the geometry of the actual mount; instead, duplicating the displacement and impact load cycle was of paramount importance. Preliminary research indicated that the critical parameters for fretting and galling corrosion are, in order of precedence, amplitude of slip, magnitude of the normal load, and frequency of movement. [1,2] The test configuration duplicated the slip amplitude and normal loads, while equipment limitations allowed a test frequency of only 20 Hz as compared to the actual gunfire frequency of 70 Hz.

Special grips and specimen configurations were designed to exploit the synchronous axial loading and radial twisting of the test machine's lower grip. Figure 1 depicts the test set-up and Figure 2 depicts the configuration of test specimens.

The round disk-shaped specimen had a raised lip 0.1-inch thick, which was one test surface. This disk was bolted to a holder clamped in the machine's lower grip, which was driven by the machine actuator. A flat plate specimen was bolted to a holder in the fixed top grip to form the other surface. A universal joint was used as part of the top grip to ensure a level contact surface between the lip of the disk and the top plate.

[1] Materials Evaluation Under Fretting Conditions, ASTM STP 780, August 1982.

[2] Corrosion Engineering, Fontana and Greene, McGraw-Hill, pg. 88-90, 1967.

Operation of the machine was planned to simulate firing of XPD-equipped guns. The test rig was capable of operating at alternating impact stresses of any value from 0 to 40 ksi; the maximum and minimum loads were programmable. Displacement was set to ±0.04 inch. Figure 3 depicts a comparison between actual firing and test conditions.

Timers were incorporated into the control cycle to simulate a "gun firing spectrum" for A-10 training and test flights. Such a "spectrum" involved firing a 110-round burst, pausing for one minute, firing another burst, and repeating this cycle 15 times before stopping and allowing the mounts to cool to ambient temperature.

Baseline specimens were prepared to duplicate actual gun mount materials. The spindle of production gun mounts is made of 17-4 PH stainless steel (33-38 Rockwell C (Rc)) Tufftrided to a surface hardness of 63 Rc. Tufftriding is a liquid salt bath nitriding process in accordance with AMS-2755. A manganese phosphate coating is applied to the Tufftrided surface. Production pillow blocks are machined as a matched set with a spindle of 4340 steel heat treated to 33-38 Rc and shot-peened to a hardness of 58 Rc. A 0.0003 - 0.0005-inch-thick electroless nickel coating is then applied to the bearing surface. The lubricant applied to production mounts is DOD-L-25681, a composition of molybdenum disulfide suspended in a silicone oil (methyl phenyl polysiloxane) designed for use in slow-speed sliding applications at temperatures up to 750°F.

Testing the baseline materials involved establishing a "threshold galling stress," a stress at which galling and fretting similar to that found on service mounts would initiate between 12,000 and 20,000 cycles. After the threshold galling stress was established, that stress was used to evaluate the materials and lubricants listed in Table 1.

## SECTION III

## RESULTS AND DISCUSSION

Preliminary research cast suspicion on the 1 to 3 ksi value which was initially estimated to be the impact stress in the service mount, because it was felt that galling of the severity found on the actual mounts would only occur at much higher stresses (see Figure 4). Testing validated that conclusion, and a "threshold galling stress" of 20 ksi was experimentally determined. Later reinstrumentation of field aircraft provided a more realistic figure of impact loads of 13 - 16 ksi, which substantiated the lab test procedure and findings.

The results of testing are also listed in Table 1. The program had two objectives -- identify a short-term "quick fix" for aircraft in the field, a fix which could be carried out by field maintenance personnel, and secondly, identify a long-term permanent solution. Depot-level modifications to the aircraft gun mounts were not ruled out for the long-term repair.

A possible short-term repair for the mounts was found which in some cases could extend mount life beyond 25,000 rounds, an interval which is a regular gun maintenance interval. This extension of mount life would allow the gun to be fired with minimal damage until the permanent fix could be incorporated (Figure 5).

The proposed temporary repair involves applying AFSL-41 dry film lubricant to production mount surfaces, baking it for one hour at 480°F, and applying MIL-G-81827 high pressure grease. This combination was shown in laboratory tests to improve wear life by a factor of two over straight baseline configurations, but the improvement was closely linked to procedures used in applying the dry film. Vapor degreasing with 1,1,1 trichloroethane was vital, followed by a mild grit blast. The surface was then treated with the dry film, sprayed, dipped or brushed to a thickness of 0.0002-0.0005 inch. After one-half hour of air-drying, the part was baked for one hour after the part reached a temperature of 480°F. At no time in the procedure was the specimen touched with the fingers or wiped with cloths containing lanolin.

Lab tests showed that all aspects of the application procedure had to be carefully followed to ensure adhesion of the dry film. Any variation in degreasing or baking procedures produced sub-standard results (Figure 6).

Two proposed long-term repairs for the gun mounts were found. One involved plating mating mount surfaces with a thick electroless nickel coating; the other involved replacing the 17-4PH spindle material with H11 steel and leaving the pillow block as currently produced. Of the two proposed long-term solutions, both exhibited excellent wear characteristics to 250,000 rounds with the H11 mount performing marginally better than the electroless nickel coated mount.

The electroless nickel specimens were prepared as follows: the surfaces were machined to a very smooth finish, 15-20 RMS. They were then shot-peened to increase the surface hardness to 58 Rc. An electroless nickel coating 0.0015-inch-thick was applied, and the parts were heated for one hour at 750°F. The AFSL-41 dry film was then applied exactly as outlined above and high pressure grease was also used on mating surfaces.

The H11 specimen was heat treated as per MIL-H-6875, triple-tempered to 47-52 Rc. It was then treated in accordance with a "Melonite" process, a proprietary process of the Kolene Corporation, Detroit, Michigan. The sample was then treated with the AFSL-41 dry film and the high-pressure grease exactly as outlined above.

The H11/4340 combination completed a 250,000 cycle test with negligible wear (Figure 8).

An alternate dry film designated MIL-L-46010A was also evaluated on baseline materials to compare its effectiveness with the AFSL-41. Its performance was essentially similar to the AFSL-41, and its performance is also closely linked to strict adherence to application procedures outlined in the associated specification. The optimal baking schedule for the MIL-L-46010A is 400°F for 1 hour after the part reaches that temperature. Unlike the AFSL-41, which allows an air cure to provide minimum (and in this application, unsatisfactory) wear properties, the MIL-L-46010A has no such provision for air curing, even for minimum performance properties.

Aside from the proposed fixes described above, some other material/lubricant combinations yielded unexpected results. One test evaluated use of the AFSL-41 dry film and a lubricant designated MIL-G-83414, a grease formulated for use on the 20-mm guns on AC-130 gunships. In lab tests, however, the MIL-G-83414 dissolved the dry film; the test specimens were severely galled after only 6440 cycles.

In another test, similar damage occurred after 7000 cycles to specimens treated with the same dry film and grease which was the proposed short-term solution. The specimens were not vapor-degreased or baked, however (Figure 6).

Hard chrome plating on mating parts also proved to be an unsatisfactory solution. The plating was badly damaged by 25,000 cycles (Figure 9). A curious sidelight to this result is the fact that metallographic examinations found similar microhardnesses and thicknesses for the chrome and the electroless nickel. [3]

[3] Evaluation Report on Analysis of Test Specimens, AFWAL/MLS 84-31, dtd 11 Apr 84 submitted by Mr George Saul.

Tests of Torlon 4203-L, a polyamide, revealed unsatisfactory results. After 7000-9000 cycles, the Torlon pitted, gouged, and cold-flowed to such a degree that the material was judged to be unacceptable for use as a replaceable compliant bushing (Figure 10).

Vespel SP-1, a polyimide, was also evaluated to test its resistance to cold flow and wear. It, too, was judged unacceptable, since it exhibited similar wear characteristics as the Torlon (Figure 11).

## SECTION IV

## CONCLUSIONS AND RECOMMENDATIONS

Both the thick 15 inch) electroless nickel coating and the H11 spindle with a dry f ubricant and grease provided a specimen life of five to ten times that any other material or lubricant combination.

The dry film alone ncreased service life over baseline samples two to four times when appl d properly, and is considered to be an important part of the proposed lo -term solution.

The proposed dry a and lubricant short-term solution can only be considered a temporar stop-gap" fix to be applied to mounts until they can be reworked and nickel-plated.

Performance of the polyimide or polyamide materials (Vespel and Torlon) was judged to be unsatisfactory for use in this application. The materials degraded more rapidly than any other tested combination of materials.

Application of either long term fix to existing galled mounts is a procedure which can be incorporated quite easily into current maintenance and repair procedures. Galled mounts are currently machined to remove the galled area. The spindle's diameter is reduced due to the machining process and the bearing is bored out. A sleeve of the original material is then pressed over the 17-4PH spindle, dry film and grease is applied, and the assembly is returned to service.

Existing procedures could easily be modified to substitute application of either long-term proposal. In one instance, an H11 sleeve could be press-fit onto the spindle; in the other, nickel-coated sleeves could be press fit onto the spindle and into the pillow block with good results.

Instead of fitting a sleeve of the original material to galled mounts, the process could be modified to substitute application of an electroless nickel-coated sleeve and bushing or an H11 sleeve prepared in accordance with the procedures outlined previously.

Table 1. Materials and test results.

| Material Treatment | Compressive Stress (KSI) | First Evidence of Galling (Cycles) | Total Cycles | Temp Rise (°F) | Comments |
|---|---|---|---|---|---|
| Baseline [4] | 1.5 | 9000 | 18,550 | 2 | Small pits and flakes. Minimal wear. |
| | 1.75 | 9000 - 10,000 | 21,800 | 4 | Essentially similar to previous test. |
| | 3 | 6200 | 25,000 | 5 | Rust, pitting, and mild flaking of low severity. |
| | 4 | 8500 | 25,000 | 8 | Similar to above. |
| | 6 | 6900 | 25,000 | 8 | Metal transfer noted at 6900 cycles. Pitting and gouging more severe than previous tests. |
| | 8 | 6700 | 25,000 | 5 | No appreciable increase in severity. |
| Baseline | 20 | 9100 | 25,000 | 2 | Metal Curling from surface. Appreciable increase in severity. Appearance similar to actual mount. |

[4] Baseline Materials:

Spindle: 17-4 PH Stainless Steel
33-38 Rc, 63 RMS
150 ksi Tensile Strength
Tufftride: .0001 - .0015 in thick
63 Rc
Mn Phosphate Ctg

Pillow Block: 4340 Steel, 125 RMS
Electroless nickel coating
.0003 - .0005 in. thick
on shot peened surface
(58 Rc)

Lubricant: DOD-L-25681

Table 1. Materials and test results. (continued)

| Material Treatment | Compressive Stress (KSI) | First Evidence of Galling (Cycles) | Total Cycles | Temp Rise (°F) | Comments |
|---|---|---|---|---|---|
| Baseline Materials, Dry film Not baked, Specimen not vapor degreased, MIL-G-83414 | 20 | 3160 | 6440 | 35 | Rapid initiation of pits. Rapid rise in temp. By far, most severe wear to date. |
| Baseline Materials, Dry film Not baked, Specimen not vapor degreased, MIL-G-81827 | 20 | 5000 | 7000 | 33 | Almost identical to above. |
| Baseline Materials, DOD-L-25681, Dry Film Not baked, Specimen not vapor degreased. | 20 | 11,000 | 25,000 | 0 | Wear less severe than baseline. |

Table 1. Materials and test results. (continued)

| Material Treatment | Compressive Stress (KSI) | First Evidence of Galling (Cycles) | Total Cycles | Temp Rise (°F) | Comments |
|---|---|---|---|---|---|
| Baseline Materials, vapor degreased, Baked Dry Film, MIL-G-81827 | 20 | 13,500<br>10,000<br>14,000 | 25,000<br>25,000<br>100,000 | 2 | Mild pitting, some metal transfer; least severe wear of 20-ksi specimens to date one specimen was run to 100,000 cycles to duplicate baseline wear |
| Baseline Materials, No shot-peening, Hard Chrome Plate, vapor degreased, Baked Dry Film, MIL-G-81827 | 20 | 12,000 | 25,000 | 5 | Poor adherence of dry film. Chipping, flaking, pitting, and removal of chrome plate. Deep gouges by 25,000 cycles. |
| Baseline Materials, Shot peening, Electroless Nickel .0015" Thick, vapor degreased, Baked Dry Film MIL-G-81827 | 20 | N/A | 100,000 | 2 | No wear visible at 100,000 cycles. |

Table 1. Materials and test results. (continued)

| Material Treatment | Compressive Stress (KSI) | First Evidence of Galling (Cycles) | Total Cycles | Temp Rise (°F) | Comments |
|---|---|---|---|---|---|
| SAME | 20 | 110,000 | 250,000 | 2 | Circumferential scratches visible at 110,000 cycles. Mild pits and gouges to test completion. |
| 52100 Steel, vapor degreased Baked Dry Film, MIL-G-81827 | 20 | 12,000 | 50,000 | 4 | At 25,000 cycles, wear similar to baseline/dry film combination. At 50,000 cycles., pitting, gouging similar to most severe wear achieved. |
| Torlon 4203-L MIL-G-81827 | 20 | 9,000<br>8,000 | 10,000<br>9,800 | 0 | Cold flow, galling, and gouging noted. |
| Vespel SP-1 MIL-G-81827 | 20 | 1,100 (Cold flow) | 1,290 | 0 | Cold flow and gouging almost immediate |
| Baseline (4340) Pillow Block H11 Steel Spindle Baked Dry Film, MIL-G-81827 | 20 | 69,660 | 250,000 | 2 | Some slight galling evident at 69,660 was polished out by 150,000 cycles. Minimal wear at 250,000 cycles. |
| Baseline Materials MIL-L-46010 Dry Film MIL-G-81827 Grease | 20 | 17,000 | 100,000 | 2 | Performance essentially similar to AFSL-41 dry film |

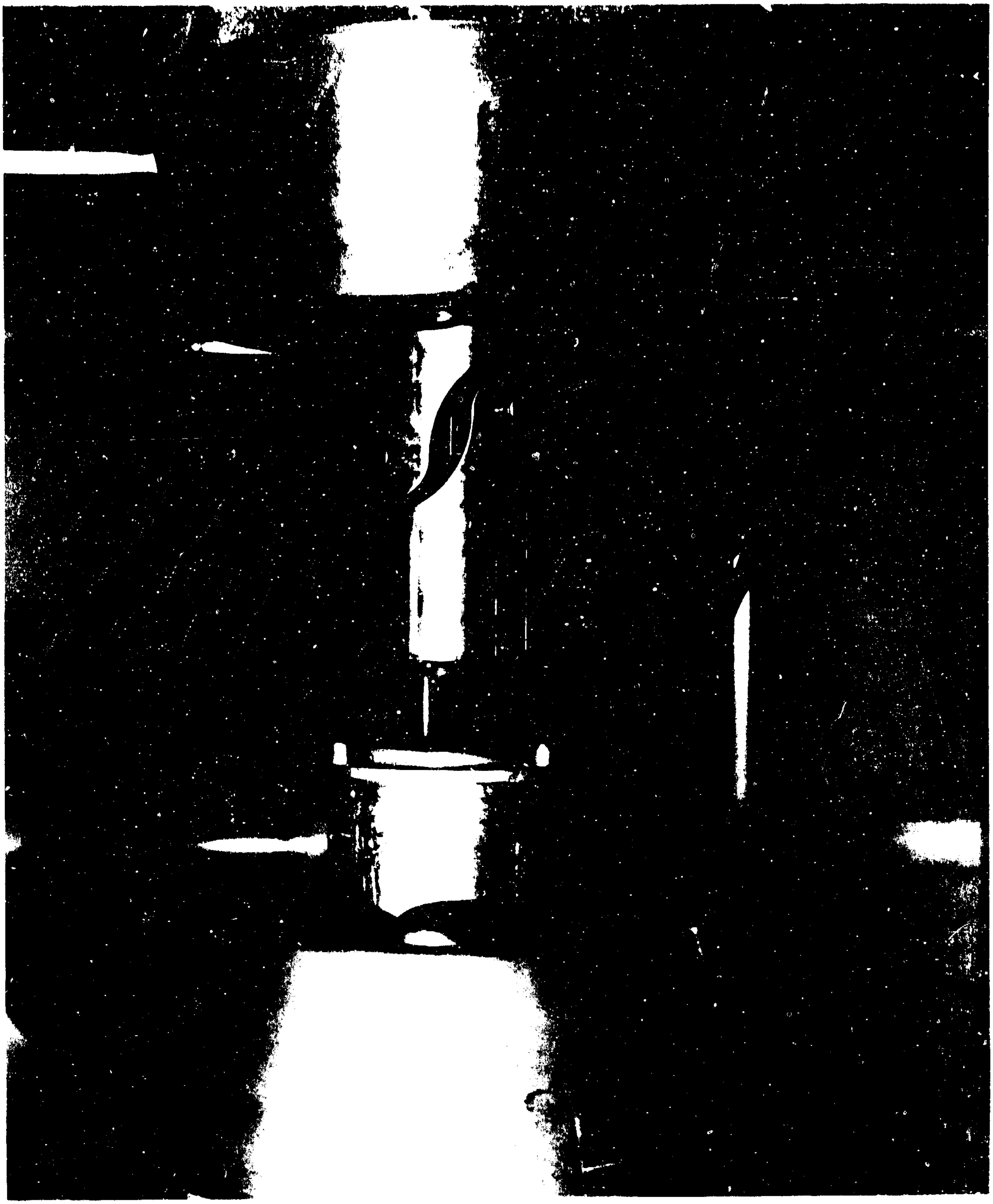
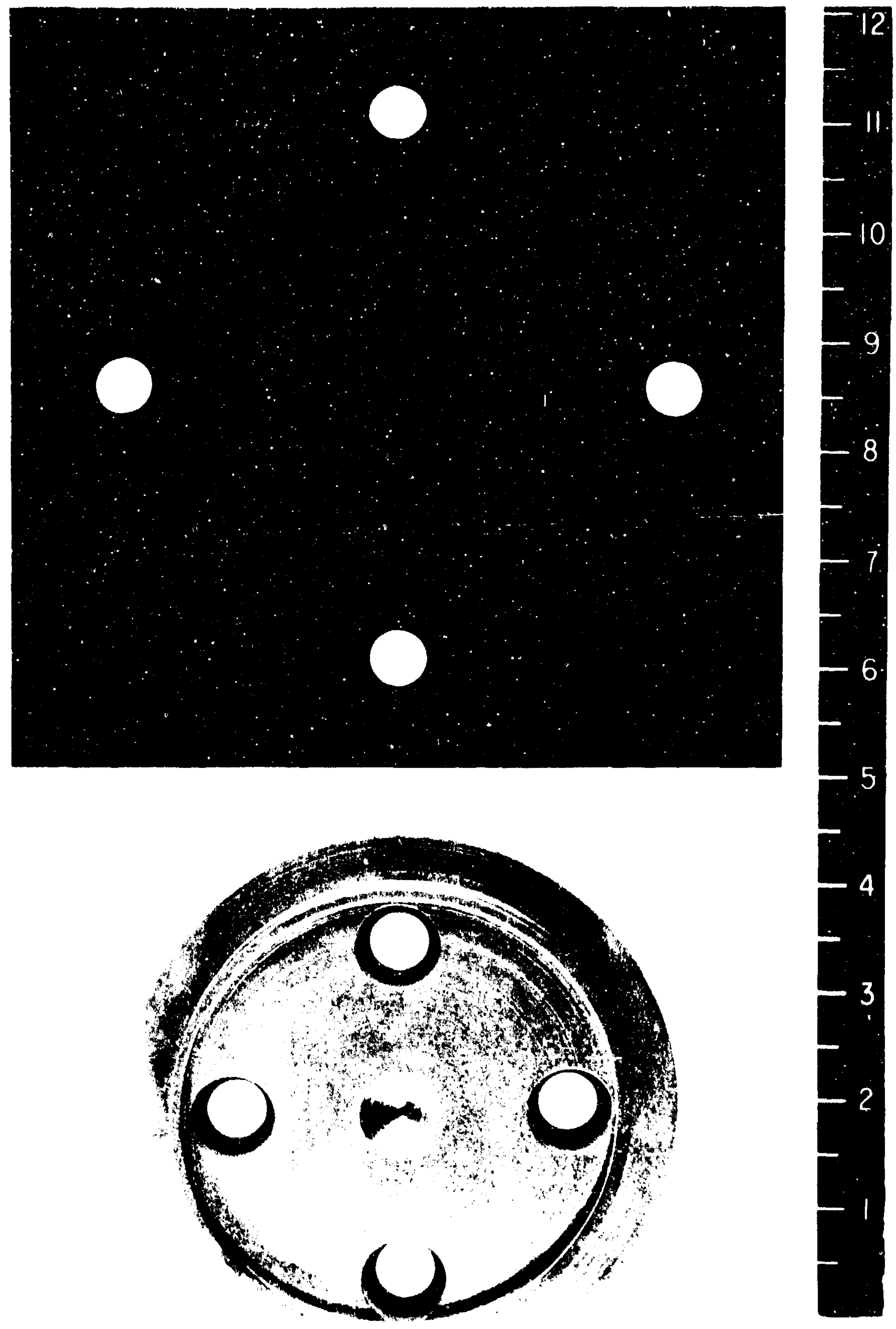


FIGURE 1. Test set-up.



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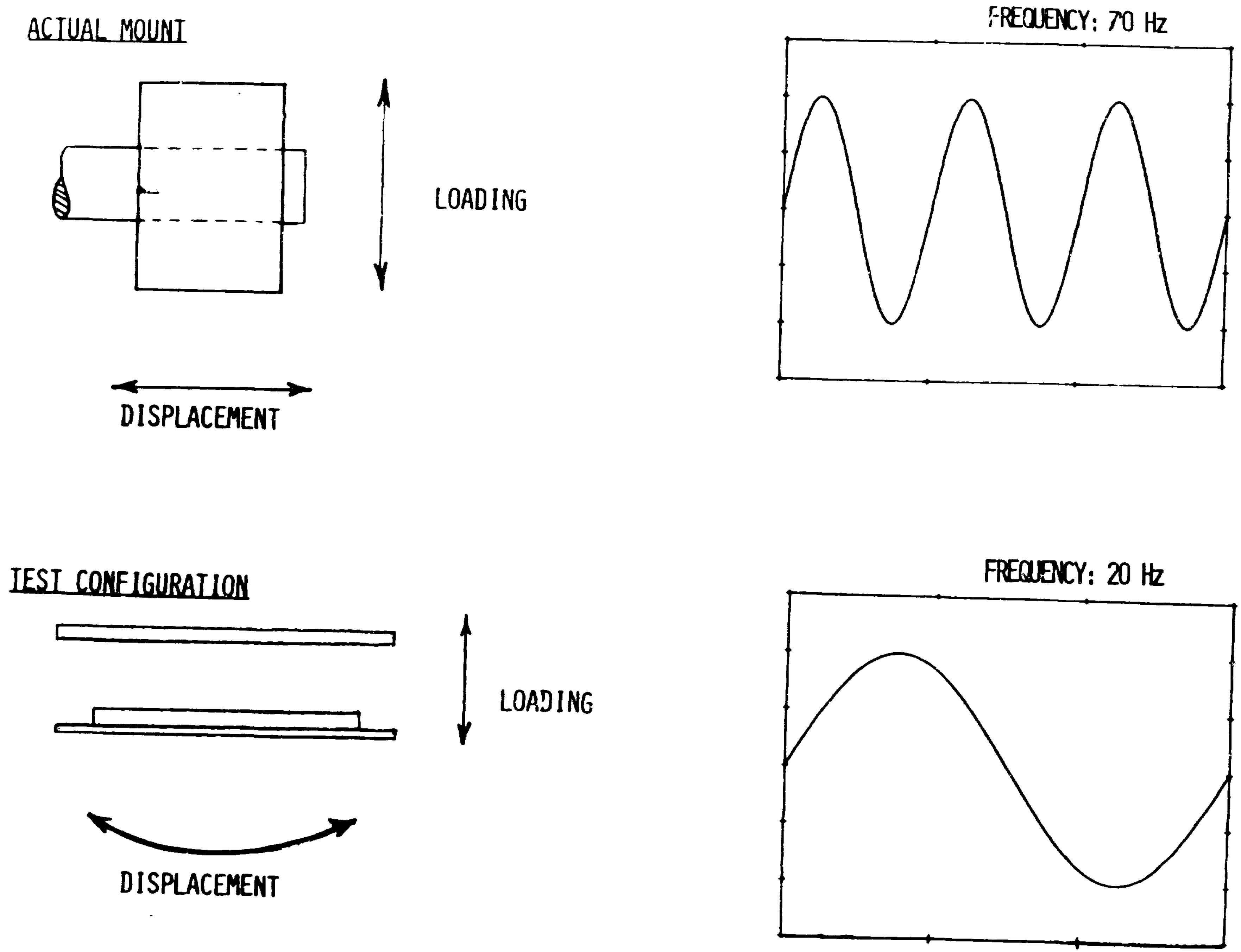


Figure 3. Comparisons between actual mount and test conditions.

Figure 4. Typical galled service mount. (MAG: 2X)

FIGURE 5. Proposed short-term solution after 100,000 cycles. This sample was run until significant galling similar to most severe galling of service mount was evident. (MAG: 7X)

FIGURE 6. Baseline materials with improperly applied dry film after 7000 cycles.

FIGURE 7. Most severe area of wear track of one long-term proposal (Electroless Nickel .0015-inch thick) after 250,000 cycles. Wear of specimen characterized as .05-inch-wide groove covering less than 40% of contact area.

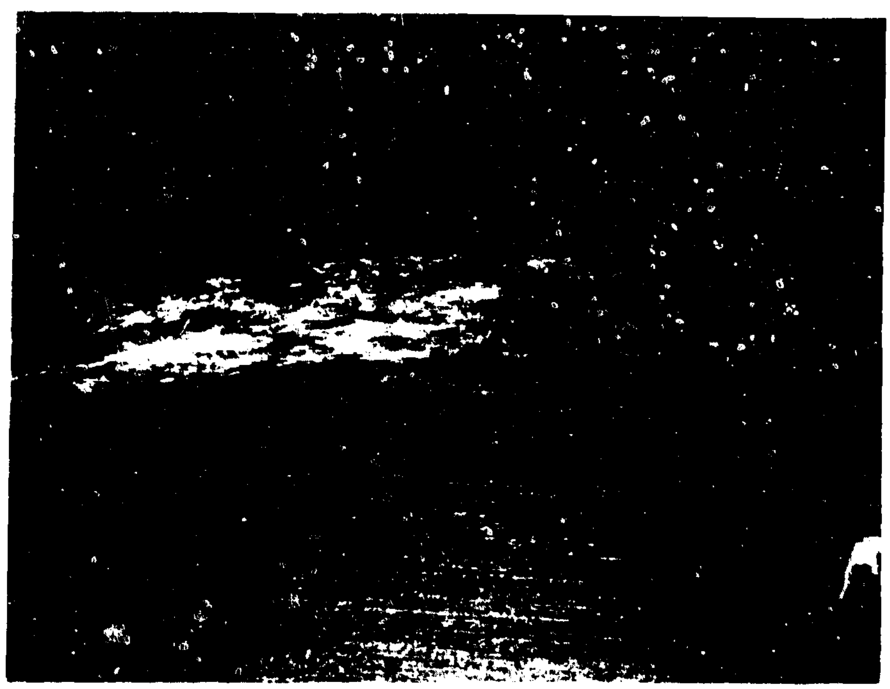

FIGURE 8. Alternate long-term proposal (H11 steel) after 250,000 cycles (MAG: 7X)

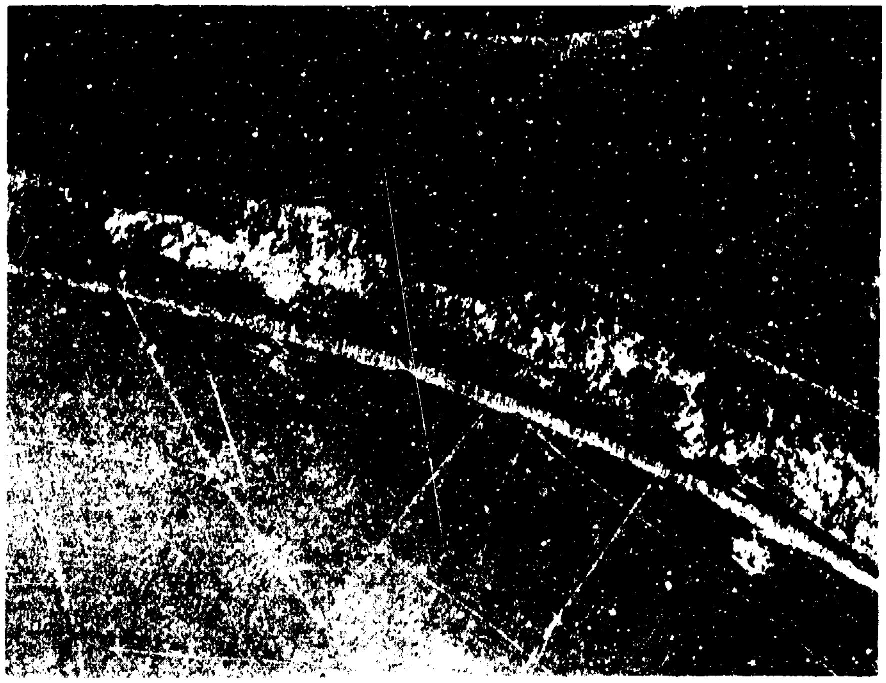

FIGURE 9. Hard chrome plating after 25,000 cycles. (MAG: 7X)

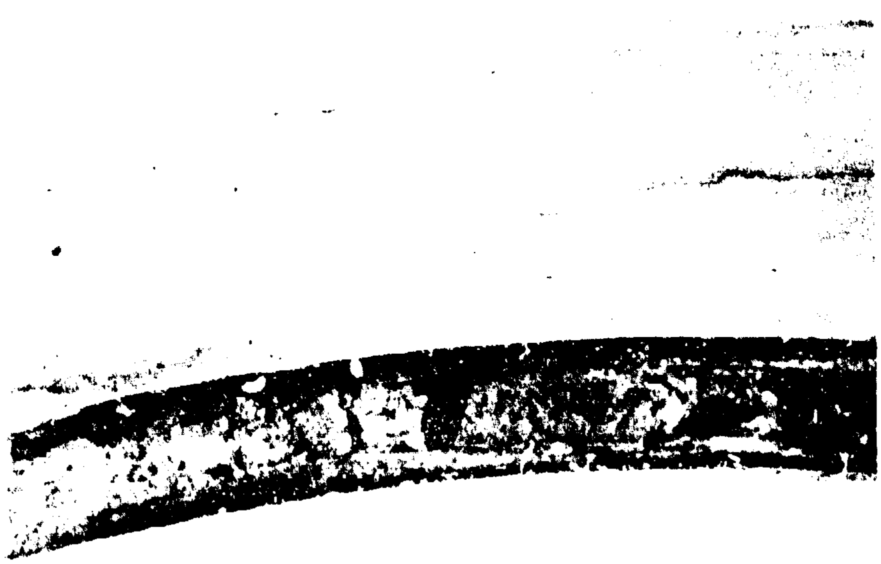

FIGURE 10. Torlon 4203L after 9,000 cycles. Notice wear track .01-inch-deep.

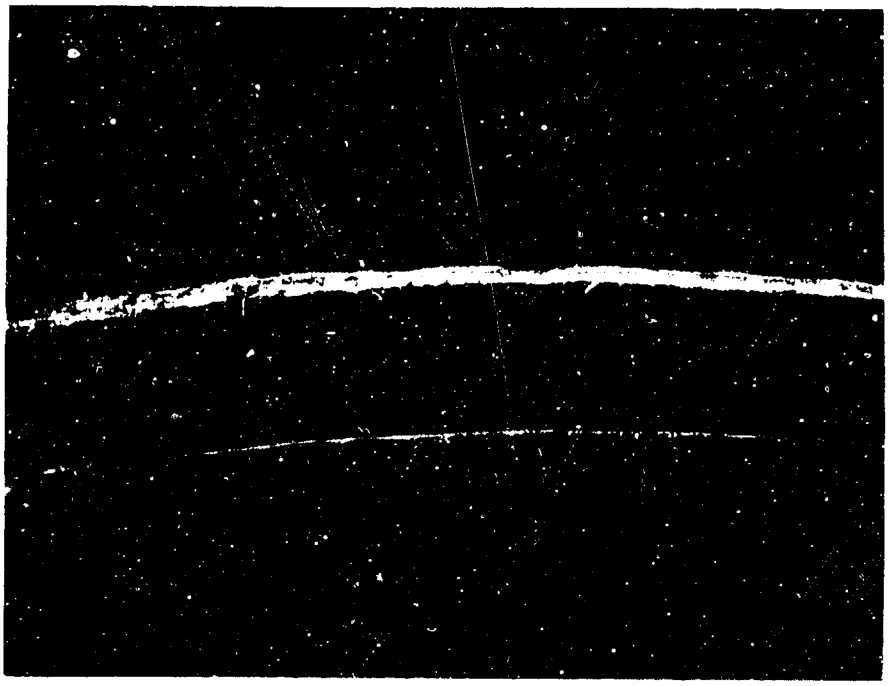

FIGURE 11. Vespel SP-1 after 1290 cycles (Mag 7X).



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