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FINAL TEST REPORT FOR ETP-0474, EVALUATION OF ELECTROLESS NICKEL COATINGS TO ACHIEVE INTERFERENCE FIT IN THE RSRM WITHOUT FRETTING

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1. INTRODUCTION

Part of the redesign of the SRMs for the Space Shuttle involved the substitution of three new capture cylinders for three of the previously used cylinders. These new cylinders mate with the old standard case segments in each of the three field joints. The new capture cylinders contain an integral capture latch on the tang end which mates with a case clevis during stackup at KSC. The capture cylinders also contain a groove in the capture latch to provide for a third O-ring in the joint and are designed to achieve a metal-to-metal interference fit between the capture latch and the mating clevis.

An unexpected fretting problem has occurred on the tang capture feature and the inner clevis leg interference fit surfaces on flight hardware since STS-26. Varying degrees of fretting damage have been found on the case segments from different flight motors. Fretting is a wear phenomena that occurs when two tightly fitting metal surfaces are subject to cyclic relative motion of extremely small amplitudes (generally <0.010-inch) in the absence of adequate lubrication. It is adhesive ("cold" - welding) in nature and vibration is its essential causative factor. This problem has manifested itself on the flight motors as a series of pits and axial gouges on the inside diameter (ID) surfaces of the inner clevis legs and the outside diameter (OD) surfaces of the tang capture features. The problem occurs in varying degrees of severity in all of the field joints. It is not believed that fretting is a flight safety issue. However, it could become a reusability issue if left unattended.

Fretting has been encountered in other industries for many years and measures that will prevent or reduce it have been devised. These include: elimination or reduction of vibration (amplitudes and/or frequencies), elimination of slip, improved lubrication between parts, increased surface separation, increased interference, inducing residual compressive stresses in the surfaces of the mating parts, and employing non-fretting interference shims.

Looking at each of these separately; vibration and slip occur in varying degrees and magnitudes in the field joints (as part of the roll-out, launch, flight, splashdown, flotation, and/or tow back) and are difficult to define or eliminate. Improved lubrication is something that was evaluated since it would be the simplest change to incorporate, but little or no improvement was found[1*]. Increasing surface separation would defeat the purpose of the interference fit. The effect of increasing the interference fit is unknown. Additional shot peening and/or surface rolling to impart residual compressive stresses in the joints undoubtedly would alter the characteristics and finish of the sealing surfaces of the motor cases. Also, experimental data[2] indicate that the tangs and clevises already have residual compressive stress fields on their surfaces yet fretting occurs. These stresses probably result from the case machining and the glass beading used to clean these surfaces.

From the foregoing reasoning it would appear that the only viable remedy to the fretting problem is one which involves applying a dissimilar material which resists fretting in the interference region. Another fretting problem involving the RSRM cases was solved using this approach[1].

An extension of this approach will evaluate electroless nickel coatings which could be applied in a narrow band, of the capture tangs and/or clevises of case segments which would mate in the field joints. Electroless nickel has a low coefficient of friction, and would provide a dissimilar metal in the joint. One concern with this approach is that there may be a possibility of encountering hydrogen-embrittlement, which can occur when metallic coatings are deposited from aqueous solutions. Electroless nickel coating processes include a 350° to 400°F bake for at least three hours to provide for hydrogen embrittlement relief.

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[*] See References.

The intent of this testing was to evaluate the fretting performance of electroless nickel with the view of restoring or building up the sealing surfaces of clevises to achieve the required interference fit without encountering fretting. A cylindrical test specimen configuration and methods for testing fretting susceptibility were proposed in ETP-0474[3]. However, it was mentioned, in Section 2.0 of ETP-0474, that the number of test specimens used, and the configurations of these specimens could be modified from those described, and would be at the discretion of the Metallurgical and/or the Mechanical Property Characterization Sections. The scope of this evaluation did change as information was gained from some of the early testing. As it turned out, only four of the six test specimens which had coatings applied to them were evaluated.

This report will summarize the results obtained from testing the various combinations of electroless nickel coatings evaluated for mitigation and/or elimination of the RSRM fretting problem.

2. OBJECTIVES

The first objective was to evaluate the cylindrical test specimens and testing methods for their ability to simulate the fretting phenomena.

Assuming that the first objective was achieved, the primary objective of this evaluation was to examine a combination of electroless nickel coatings, applied by standard processing techniques, with the view of identifying one which could be used to build up the sealing surfaces of clevises to achieve a metal-to-metal interference fit without fretting.

3. EXECUTIVE SUMMARY

1. The cylindrical test specimens were capable of generating fretting damage, however, the interference fits between mating specimen halves could not be controlled to generate reproducible test results.

2. The various electroless nickel coating materials evaluated were susceptible to fretting when evaluated in accordance with the test parameters used, and the testing was discontinued.

4. CONCLUSIONS

It was concluded that electroless nickel coatings were not good candidate materials for mitigating or eliminating fretting of D6AC steel motor cases.

5. MATERIALS AND EQUIPMENT USED

1. Cylindrical D6AC fretting specimens with and without various combinations of electroless nickel coatings applied.

2. Conoco HD calcium grease 2, per STW5-2942.

3. Axial torsion Servohydraulic Universal Test Machine, Model No. 6469-104, manufactured by Lebow Associated, Inc.

4. Transducer, Model No. 632.01, manufactured by MTS Systems Corp.

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8. Strain Conditioning Unit, Model 2100, manufactured by Measurements Group.

9. LVDT, Model No. GCD-121-125, manufactured by Shaevitz Engineering Co.

6. TEST ITEM DESCRIPTION

The first generation test specimens for characterizing the susceptibility of a material to fretting were designed as cylindrical male/female couples. Figure 1 shows the configuration of this test specimen. These specimens were fabricated from production D6AC steel per STW4-2606 or S183007 heat treated in accordance with STW7-2608 or S183008.

These specimens were designed to achieve a nominal 3-mil interference fit between the male and female portions. This corresponds to a nominal contact pressure of 30-ksi, which is the approximate contact pressure between the capture feature and the mating clevis leg in a pressurized (flight) motor.

7. PREPARATION OF SPECIMENS FOR TESTING

7.1. BASELINE SPECIMENS

Mating fretting specimens of uncoated D6AC steel had HD-2 grease applied to them and were tested against each other to evaluate the ability to simulate the fretting phenomena. These specimens were used to generate a baseline level of fretting for cylindrical specimens. This baseline performance was used to judge the success or failure of the electroless nickel coatings evaluated.

7.2. ELECTROLESS NICKEL PLATED SPECIMENS

To evaluate the electroless nickel coatings involved machining approximately 1-mil from the diameter of the male end of the baseline specimens depicted in Figure 1. This diameter was built up, with the electroless nickel coating to be evaluated. The coating thicknesses were targeted to be of such a size to achieve a predetermined amount of interference with the female portion of each test specimen.

7.3. DESCRIPTION OF THE VARIOUS ELECTROLESS NICKEL COATINGS

Four male and four female specimen components were sent to Witco Corp. for electroless nickel plating. These coatings were supplied in either the as-coated or coated and heat treated conditions, as described below.

7.3.1. AS-COATED

One of the electroless nickel coatings was applied in accordance with MIL-C-26074 per Class 1 - as plated, no subsequent heat treatment. (The bake for hydrogen embrittlement relief is not considered a heat treatment). All of the coated specimens received this hydrogen embrittlement relief bake. An exception to this specification was that the thickness of the coating was 0.3- to 0.5-mil, instead of 1.5-mils. The surfaces to be electroless nickel coated were glass beaded prior to plating.

7.3.2. HEAT TREATED COATING

The other electroless nickel coating was applied in accordance with MIL-C-26074 per Class 2 - heat treated to obtain maximum coating hardness. Again, an exception to this specification was that the thickness of the coating was 0.3- to 0.5-mil, instead of 1.5-mils. Again, the surfaces to be coated were glass beaded prior to plating.

The various electroless nickel coating combinations prepared for evaluation are described in Table I.

8. TEST EQUIPMENT, INSTRUMENTATION, AND TESTING

8.1. FIXTURING

The specimens were first cleaned by flushing them three times with methylethyl ketone (MEK). Next HD-2 grease was applied to both mating surfaces as specified in STW7-2999.

The specimens were then loaded into the grips of the Instron Servolhydraulic Test Machine as shown in Figure 2. The pins were secured with tape to ensure that they would not vibrate out during testing.

8.2. LOAD MEASUREMENTS

The load and extensometer were calibrated and recorded on a calibration chart. After the mating surfaces were properly aligned the specimen halves were pressed together. The load versus time was recorded on the chart. Any evidence of "plowed" metal on the male end of the specimen was noted.

8.3. DISPLACEMENT MEASUREMENTS

The function generator was set for a 2-Hz square wave and the position controller was set to cycle ± 20-mils from the current mean level. A MTS extensometer was mounted on the sample and the readout was zeroed. The oscilloscope was set up to monitor the strain and stroke channels and the cycle counter was set for 20,000-cycles.

8.4. TEMPERATURE AND ACOUSTIC MEASUREMENTS

The surface temperature of the female part was recorded, and the acoustic emission equipment was attached to the test specimen.

8.5. SPECIMEN TESTING

The wave-form generator was started, and the input signal on the position controller was adjusted until ± 20-mils of movement was achieved on the extensometer. If or when the load versus time plot showed a sharp increase in the load, the test was terminated immediately, and the specimens were examined for evidence of galling or fretting. Also, if the acoustic emission device indicated a sharp increase in signal, the test was terminated immediately, and the specimens were examined for evidence of galling or fretting. The load versus time was recorded on the chart for all cycles.

The temperature of the surface of the female part was measured every 500-cycles and the specimens were examined for any evidence of "plowed" metal. The test was considered a success if or when 20,000-cycles were achieved without evidence of galling or fretting.

Mating fretting specimens were tested against each other in accordance with the procedures described above to test the baseline specimens and to evaluate the performances of the various electroless nickel coatings.

9. DISCUSSION

Part of the redesign of the SRMs for the Space Shuttle involved the substitution of three new capture cylinders for three of the cylinders previously used. The new capture cylinders contain an integral capture latch on the tang end and are designed to achieve a metal-to-metal interference fit between the capture latch and the mating clevis.

An unexpected fretting problem has occurred on the tang capture feature and the inner clevis leg interference fit surfaces on flight hardware since STS-26. Varying degrees of fretting damage have been found on the case segments from different flight motors. This problem has manifested itself on the flight motors as a series of pits and axial gouges on the ID surfaces of the inner clevis legs and on the OD surfaces of the tang capture features. Figure 3 is a photograph showing an example of the fretting damage on the inner clevis leg of a RSRM case. This problem occurs in varying degrees of severity in all of the field joints. It should be noted that virtually no fretting has occurred on any of the static fired motors incorporating capture cylinders.

It would appear that the only viable remedy to the fretting problem is one which would involve applying a fretting resistant material to the interference region. For the RSRM case fretting problem, nickel which could be applied by electroless processing in a narrow band on the ID of the clevises of the case segments, which mate with capture feature tangs, was selected for evaluation. Such a coating could serve as a fretting resistant shim or lubricant. A combination of candidate electroless nickel coatings was proposed for evaluation in ETP-0474. A clindrical test specimen configuration and methods for testing fretting susceptibility were also proposed in ETP-0474. However, it was mentioned that the number of test specimens used, and the configuration of these specimens could be modified from those described, at the discretion's of the Metallurgical and/or Mechanical Property Characterization Sections.

Cylindrical test specimens had various combinations of electroless nickel coatings applied to them as shown in Table I. A summary of the test results obtained from the uncoated baseline and electroless nickel coated specimens, evaluated for mitigation and/or elimination of the RSRM fretting problem, follows.

9.1. TEST RESULTS FROM BASELINE CYLINDERICAL SPECIMENS

Testing was initiated using cylindrical specimens of uncoated (bare) D6AC steel which had been lubricated with HD-2 grease. These specimens were tested against each other to see if fretting could be generated. These specimens were designed to achieve a nominal 3-mil interference fit between the male and female portions, however, this was not always achieved. Three mils interference translates to a nominal contact stress of 30-ksi, which is the nominal stress in the field joints of a pressurized (flight) motor. Five such specimen pairs were tested.

The first specimen pair tested had an interference fit of only 1-mil instead of the desired 3-mils. This would have translated to a contact stress of 10-ksi. When this specimen was being tested, the load trace was observed to a be increasing and a clicking noise developed. After 13,137 cycles the test was terminated. The testing had also generated enough of a temperature rise to cause the HD-2 grease to smoke. When the couple was disassembled, a fretting like defect was found. Figure 4 is a photograph of this specimen showing the damage.

It was thought that the clicking noise was associated with the onset of fretting. The second specimen was fixtured with acoustic modules set to shut-down the test when the noise level exceeded the background level of the early stages of testing. This specimen pair had an interference fit of approximately 2-mils instead of the desired 3-mils. This would have translated to a contact stress of approximately 20-ksi. This specimen ran for only 1,396 cycles. When it was disassembled, it too exhibited a fretting-like defect. Figure 5 is a photograph of this specimen showing a close-up view of the damage on the female end of this specimen. This damage was more severe than what has been observed on flight hardware or in some of the other fretting tests.

The differences in performance between these two specimens, based on the number of cycles run, was probably due to differences in interference pressures and to the increased sensitivity used for monitoring the onset of fretting of the second specimen. It is believed that varying levels of joint interference's in the RSRMs is one of the factors which causes some joints to exhibit more fretting damage than others. It should also be pointed out that these first two specimens were tested without an alignment pilot which may have contributed to the differences in their performances. In any event, both of these test specimens developed a degree of fretting-like damage which was used for comparing the success or failure of the specimens containing the electroless nickel coatings.

The third specimen pair (No. 2) was retested after some of the damage was smoothed with emery paper. This specimens, reported as No. 2a, developed additional fretting damage after only an additional 356 cycles, and the testing was discontinued.

The fourth specimen pair (No. 3) had an interference fit of slightly over 3-mils. This specimen was run to 18,371 cycles when fretting occurred and testing was discontinued.

The last baseline specimen pair (No. 5 male and No. 6 female) had an interference fit of slightly under 3-mils. This specimen was run to 5,797 cycles when fretting occurred and testing was discontinued. The results of these tests are reported under Baseline Specimens in Table II.

9.2. TEST RESULTS FROM ELECTROLESS NICKEL PLATED CYLINDRICAL SPECIMENS

The first specimen pair tested (EN4) had both the male and female components electroless nickel plated and heat treated to achieve maximum hardness in the coating (Class II). This specimen pair had an interference fit of 3.5-mils which translates to a nominal contact stress of 35-ksi. The specimens were coated with HD-2 grease and tested in the same manner as the baseline specimens. The testing equipment sensed damage after only 200 cycles, and the test terminated. When the couple was disassembled, a broad area of damage was apparent to the coating and the steel. It was evident that a portion of the coating had become unbonded damaging the adjacent coating and the underlying D6AC steel substrate. This particular specimen exhibited the greatest amount of interference fit any specimen tested to this point, which could have contributed to its poor performance. The problem of controlling the interference fit, using this specimen configuration, was the major drawback of this design. Figure 6 is a photograph of this specimen showing the damage.

The second specimen pair tested (EN6) had a bare D6AC steel male component mated with an electroless nickel plated female component heat treated to achieve maximum hardness in the coating (Class II). This specimen pair had on interference fit of 2-mils which translates to a nominal contact stress of 20-ksi. This specimen was also coated with HD-2 grease and tested in the same manner as the baseline specimens. This specimen was run to 7,552 cycles when fretting occurred and testing was discontinued. When this specimen was disassembled, a more classical type of fretting was observed. Figure 7 is a photograph of this specimen showing the damage.

The third specimen pair tested (EN1) had both the male and female components electroless nickel plated and not heat treated (Class I). This specimen pair had an interference fit of 2-mils which translates to a nominal contact stress of 20-ksi. This specimen was tested in the same manner as the other cylindrical specimens, however, the test data were lost. When this specimen couple was disassembled, a broad range of damage was apparent to the coating and the steel, similar to what was observed in specimen EN4. Figure 8 is a photograph of this specimen showing the damage.

The fourth specimen pair tested (EN3) had a bare D6AC steel male component mated with an electroless nickel plated female component and not heat treated (Class I). This specimen pair also had an interference fit of 2-mils which translates to a contact stress of 20-ksi. This specimen was tested in the same manner at the other cylindrical specimens, however, the test data were also lost. When this specimens couple was disassembled, it also exhibited a broad range of damage to the coating and the steel. Figure 9 is a photograph of this specimen showing the damage.

At this point it was decided not to test the remaining specimens (EN2 and EN5) which had electroless nickel plated males, both heat treated and un-heat treated (Classes II and I, respectively), mated with bare D6AC female specimens. It was apparent that the electroless nickel coatings were not performing well. Also, the cost of fabricating the cylindrical specimens and the difficulties in controlling the interference fits directed the program away from this specimen configuration.

9.3. SUMMARY OF TEST RESULTS

In summarizing the results of these tests, it was concluded that electroless nickel coatings would probably not be viable candidates for mitigating or eliminating fretting in the RSRM field joints. Difficulties in applying such coatings and concerns about the unknown possibility of localized hydrogen embrittlement of the hardware were other considerations in backing away from this approach.

10. REFERENCES

1. W.O. Schaffnit, M.D. Blair, and B.K. Christensen, "Evaluation of Various Lubricants and Materials to Mitigate or Eliminate Fretting Between the RSRM Case Segments and Their Handling Rings," TWR 61186, 6 November 1990.

2. E. B. S. Pardue, Technology for Energy Corp., "Morton Thiokol, Inc. Residual Stress Summary," TEC Report R-88-049, Case 053 Sequences 1 through 4, locations 1 through 9 and F, 29 November 1988.

3. W.O. Schaffnit, "Evaluation of Electroless Nickel Coating of RSRM Joints to Eliminate Fretting," ETP-0474, March 1989.

TABLE I

Fretting/Galling Evaluation of Electroless Nickel Coated D6AC Specimens

Set Number	Specimen Half	Coating Description	Interference Target, inch	Assembly Test	Cyclic Test
1	Male	Coated and Hydrogen Embrittlement Relieved (Class 1)	0.003	X	X
	Female	Coated and Hydrogen Embrittlement Relieved (Class 1)			
2	Male	Coated and Hydrogen Embrittlement Relieved (Class 1)	0.003	X	X
	Female	Uncoated			
3	Male	Uncoated	0.003	X	X
	Female	Coated, Hydrogen Embrittlement Relieved (Class 1)			
4	Male	Coated, Hydrogen Embrittlement Relieved and Baked (Class 2)	0.003	X	X
	Female	Coated, Hydrogen Embrittlement Relieved and Baked (Class 2)			
5	Male	Coated, Hydrogen Embrittlement Relieved and Baked (Class 2)	0.003	X	X
	Female	Uncoated			
6	Male	Uncoated	0.003	X	X
	Female	Coated, Hydrogen Embrittlement Relieved and Baked (Class 2)			

TABLE II. PERFORMANCE OF UNPLATED AND ELECTROLESS NICKEL PLATED MATERIALS EVALUATED USING CYLINDRICAL SPECIMENS

Specimen Identification		Material Trade	Manufacturer/Supplier	Material or Method of Application to D6AC	Thiokol's Fretting Tests				
Male	Female	Name		Fretting Specimens	Interference Fit, mils	Initial Pressure Load, lbs.	Average Cyclic Load, lbs.	No. of Cycles (to fretting)*	Performance
Baseline Specimens									
1	1	D6AC Steel	LTV Steel Co./Ladish	D6AC vs. D6AC	1**	4,000	±4,000	13,137	Fretted D6AC
2	2	D6AC Steel	LTV Steel Co./Ladish	D6AC vs. D6AC	1.96	2,320	±2,100	1,396	Fretted D6AC
2a	2a	Repeat of 2 after smoothing damage with emery paper	LTV Steel Co./Ladish	D6AC vs. D6AC	<1.96	1,740	±2,000	356	Fretted D6AC
3	3	D6AC Steel	LTV Steel Co./Ladish	D6AC vs. D6AC	3.29	3,475	±2,400	18,371	Fretted D6AC
5	6	D6AC Steel	LTV Steel Co./Ladish	D6AC vs. D6AC	2.03	2,350	±2,150	5,797	Fretted D6AC
Electroless Nickel Plated Specimens									
EN1	EN1	Electroless Nickel Class 1	Witco Corp.	Plated male,*** Plated female***	2.00	Not Reported	Not Reported	Not Reported	Fretted D6AC and electroless nickel
EN2	EN2	Electroless Nickel Class 1	Witco Corp.	Plated male,*** Bare D6AC female	Not Tested				
EN3	EN3	Electroless Nickel Class 1	Witco Corp.	Bare D6AC male, Plated female***	2.00	Not Reported	Not reported	Not Reported	Fretted D6AC and electroless nickel
EN4	EN4	Electroless Nickel Class 2	Witco Corp.	Plated male,**** Plated female****	3.50	4,200	±4,000	200	Fretted D6AC and electroless nickel
EN5	EN5	Electroless Nickel Class 2	Witco Corp.	Plated male,**** Bare D6AC female	Not Tested				
EN6	EN6	Electroless Nickel Class 2	Witco Corp.	Bare D6AC male, Plated female****	2.00	2,600	±2,400	7,552	Fretted D6AC and electroless nickel

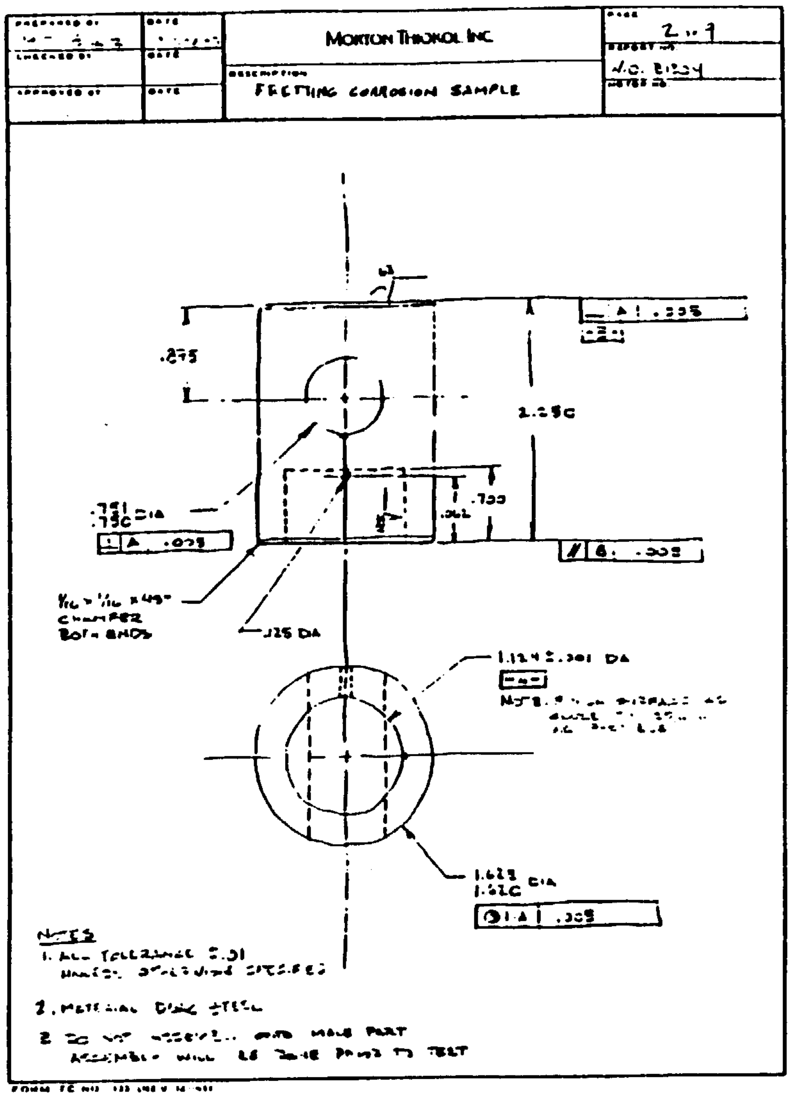
NOTE: All specimens were lubricated with HD-calcium grease 2 per STW7-2999. Specimens 1 and 2 were run without alignment pilot.

* Based on visible appearance of fretting.

** Measured out to three places only with Vernier calipers.

*** Components of specimens EN1, EN2, and EN3 which were electroless nickel plated were baked to provide hydrogen embrittlement relief.

**** Components of specimens EN4, EN5, and EN6 which were electroless nickel plated were baked to provide hydrogen embrittlement relief and heat treated to achieve maximum hardness in the coating.



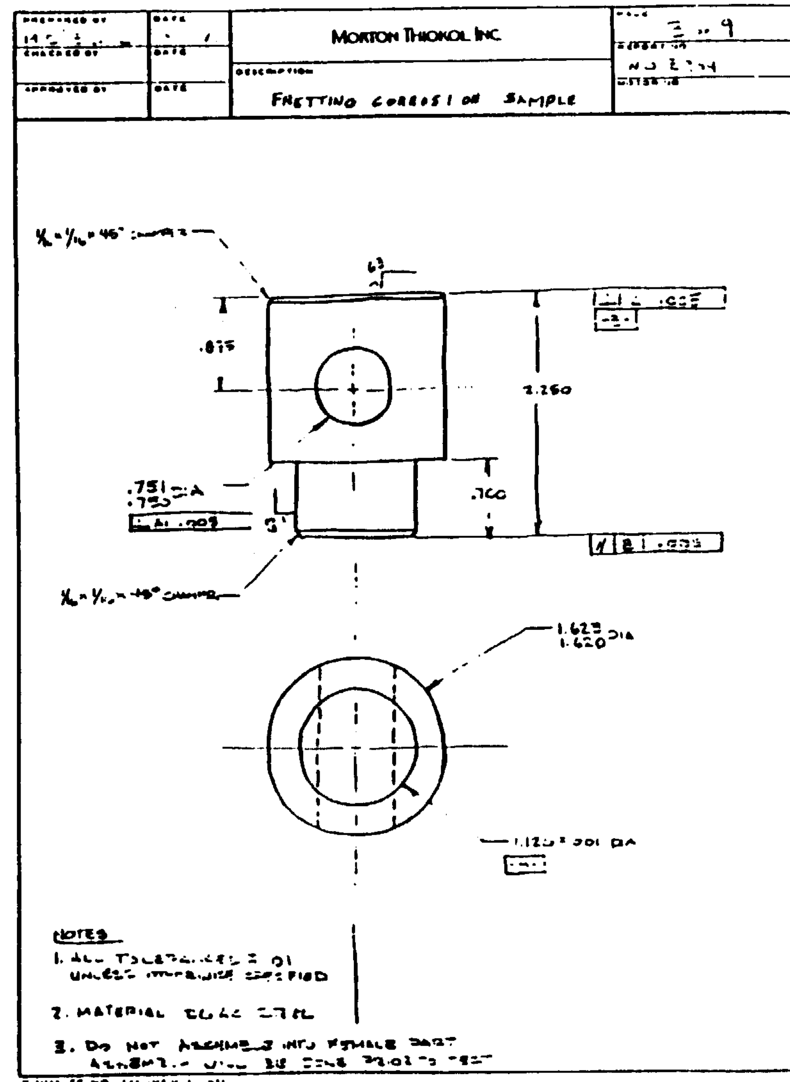


Figure 1. Shows Configuration of First Generation Test Specimen for Characterizing Fretting.

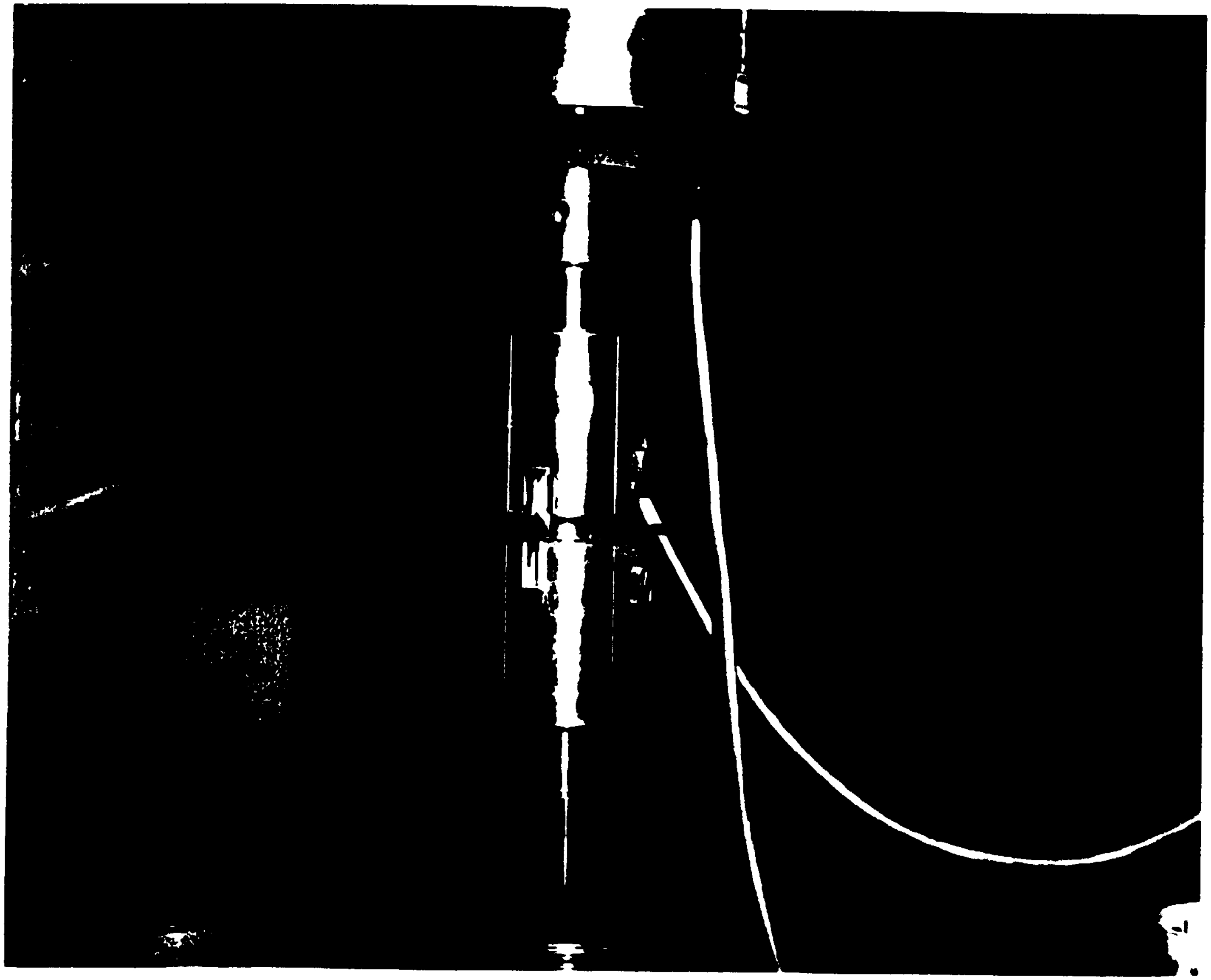


Figure 2. Photograph Showing Cylindrical Fretting Specimen (Arrow) Installed In Instron Machine For Testing. 107760-2

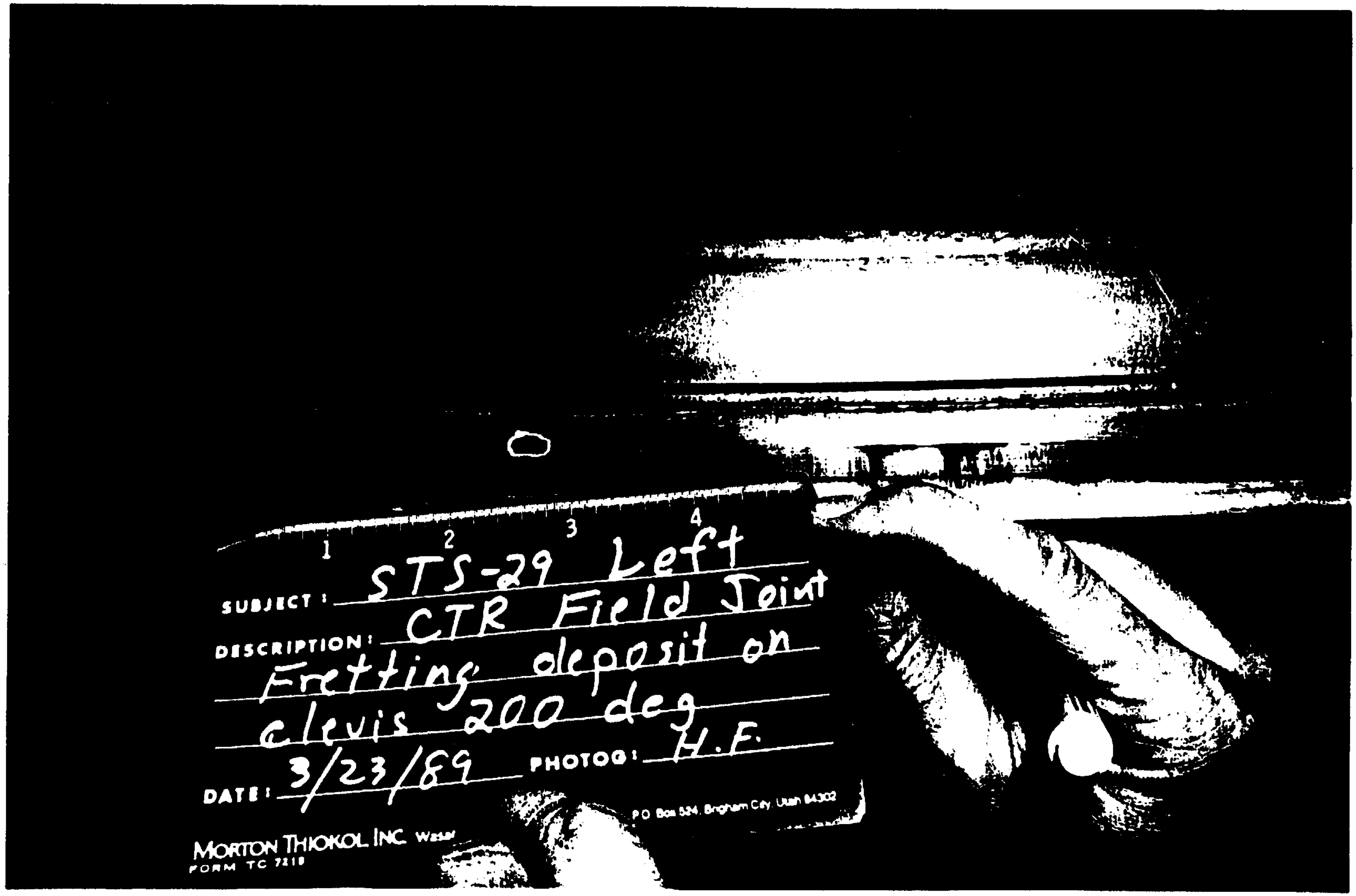


Figure 3. Photograph Showing Examples of Fretting Damage on the Inner Clevis Leg of a RSRM Case. 109495-2

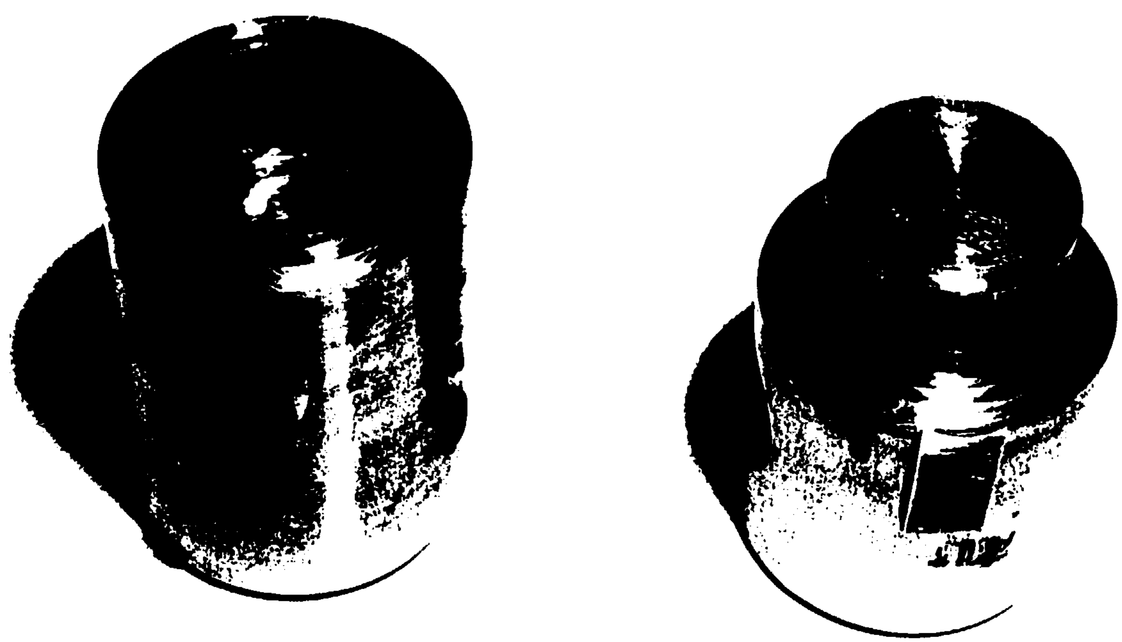


Figure 4. Photograph of Baseline D6AC Specimen No. 1 Showing Fretting-Like Damage (Arrows), Generated in Cylindrical Fretting Specimen, Which Occurred After 13,137 Cycles. **107760-1**

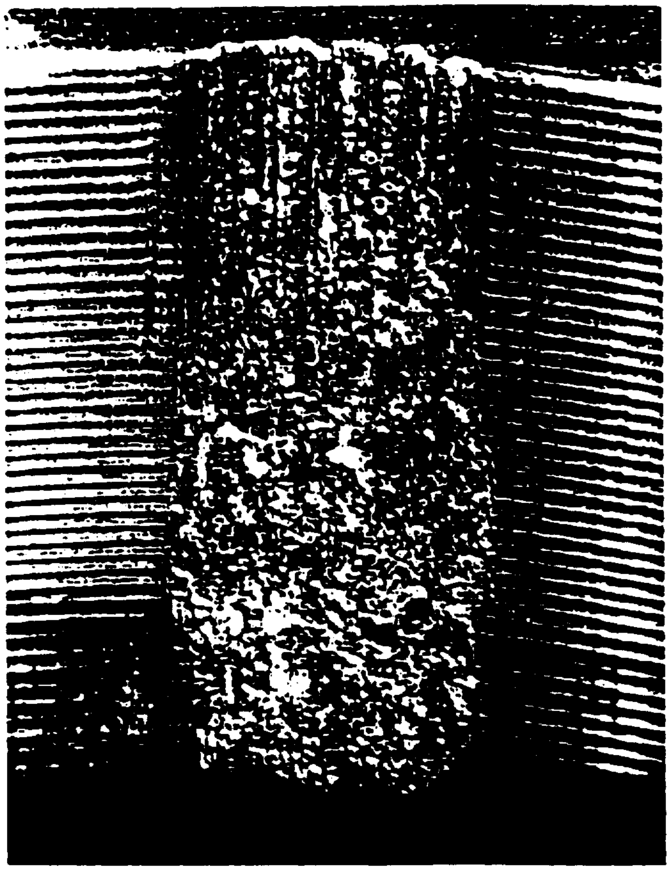


Figure 5. Photograph of Baseline D6AC Specimen No. 2 Showing a Closeup View of Severe Fretting Damage on the ID of the Female Specimen Which Occurred After 1,396 Cycles.

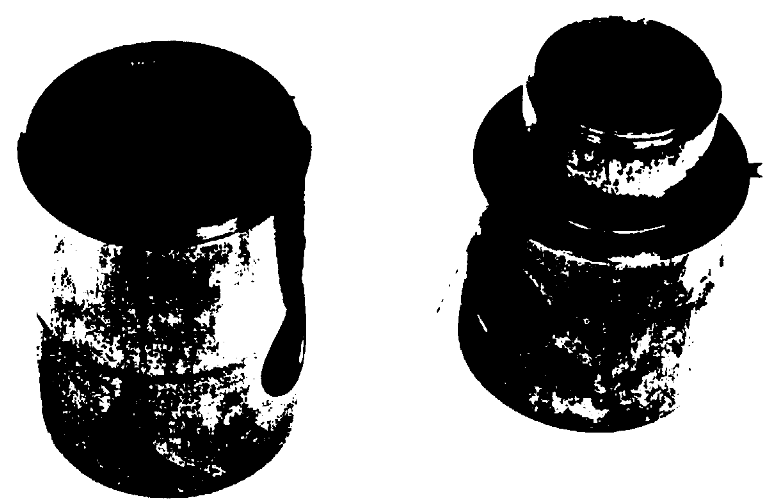


Figure 6. Photograph of Electroless Nickel Plated Specimen No. EN4 Showing Fretting-Like Damage (Arrows), Generated in Cylindrical Fretting Specimen, Which Occurred After Only 200 Cycles. 147361-1

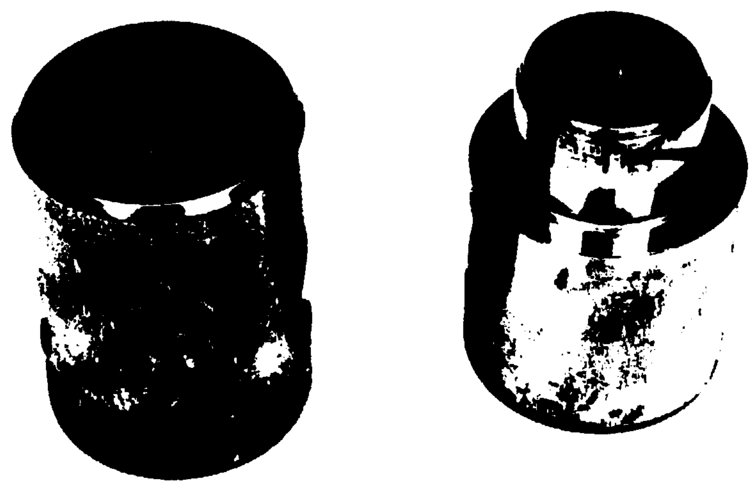


Figure 7. Photograph of Electroless Nickel Plated Specimen No. EN6 Showing Fretting-Like Damage (Arrows), Generated in Cylindrical Fretting Specimen, Which Occurred After 7,552 Cycles. **147361-2**

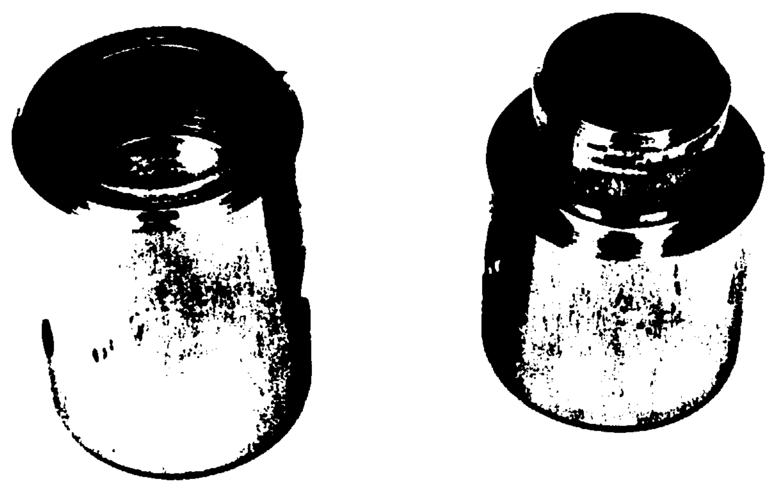


Figure 8. Photograph of Electroless Nickel Plated Specimen No. EN1 Showing Fretting-Like Damage (Arrows), Generated in Cylindrical Fretting Specimen. 147361-3

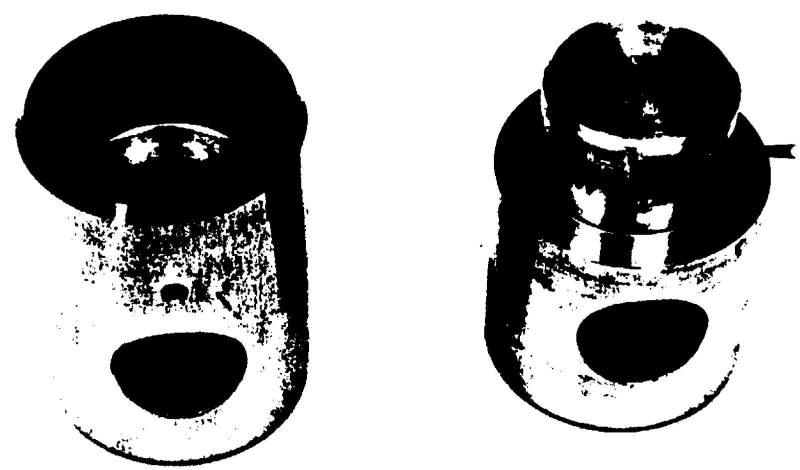


Figure 9. Photograph of Electroless Nickel Plated Specimen No. EN3 Showing Fretting-Like Damage (Arrows), Generated in Cylindrical Fretting Specimen. **147361-4**

SPACE SHUTTLE

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