NASA TECHNICAL MEMORANDUM

NASA TM X-73591

NASA TM X-73591

(NASA-TM-X-73591) FRETTING OF AISI 9310 AND SELECTED FRETTING RESISTANT SURFACE TREATMENTS (NASA) 24 p HC A02/MF A01 CSCL 11D G3/37
N77-24494
Unclas
26164

FRETTING OF AISI 9310 AND SELECTED FRETTING RESISTANT SURFACE TREATMENTS

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TECHNICAL PAPER to be presented at the Annual Meeting of the
American Society of Lubrication Engineers
Montreal, Canada, May 3-5, 1977

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E-9069

ABSTRACT

Fretting wear experiments were conducted with uncoated AISI 9310 mating surfaces, and with combinations incorporating a selected coating to one of the mating surfaces. Wear measurements and SEM observations indicated that surface fatigue, as made evident by spallation and surface crack formation, is an important mechanism in promoting fretting wear to uncoated 9310. Increasing humidity resulted in accelerated fretting, and a very noticeable difference in nature of the fretting debris. Of the coatings evaluated, aluminum bronze with a polyester additive was most effective at reducing wear and minimizing fretting damage to the mating uncoated surface, by means of a self-lubricating film that developed on the fretting surfaces. Chromium plate performed as an effective protective coating, itself resisting fretting and not accelerating damage to the uncoated surface.

INTRODUCTION

Fretting is commonly observed on the assembly interfaces of mechanical power transmission components. Typical examples include spline couplings (ref. 1), bearing/housing interfaces (ref. 2), and gear/flange interfaces. The fretting action can be caused by shaft misalignments as in the case of spline wear, or by mechanical strain differences between mating components, as for gear/flange interfaces. In any event, the occurrence of fretting is marked by surface damage that may include crack initiation (ref. 3), pitting (ref. 4), and debris generation. The consequences often include degradation of component fatigue life, loss of critical assembly tolerance, and fouling of moving components by debris. Both the extent of fretting damage and the mechanisms of fretting are affected by a number of factors including slip amplitude, relative humidity, temperature, fretting frequency, normal load, and the materials comprising the fretting pair.

Increasing slip amplitude invariably results in increased fretting wear, with a transition amplitude identified above in which greatly accelerated wear is observed (refs. 5 and 6), and characteristics of unidirectional sliding wear mechanisms predominate. Under fretting conditions in which fatigue crack initiation is a concern, a critical slip amplitude (lower than the wear transition amplitude) that causes a maximum degradation in fatigue life of the fretting components is also reported (refs. 7 and 8).

Relative humidity is known to influence the fretting of steel components, as illustrated by the experimental results of Feng and Uhlig (ref. 9). Waterhouse (ref. 10) suggests that relative humidity influences the oxidation of iron wear debris, resulting in softer debris for higher levels of humidity and reduced fretting damage.

Feng and Uhlig also studied the influence of fretting frequency on wear of mild steel, and observed reduced wear with increased frequency up to about 17 Hz. For higher frequencies, little change in fretting wear was observed. Feng and Uhlig attribute their results to a surface corrosion mechanism. Hurricks (ref. 11) points out that other factors may be significant in frequency experiments, including strain rate sensitivity of adhering junctions, and stress corrosion associated with surface fatigue cracks.

There is considerable debate as to the relationship between fretting wear experiments and fretting fatigue studies. It is commonly held that fretting accelerated fatigue is brought on by the early initiation of surface cracks where slip is occurring. Nichioka and Hirakawa (ref. 12) attribute crack initiation to the combination of contact stresses superimposed on the alternating fatigue stresses, with cracks being initiated where friction induced stresses are highest. Where pitting and nonpropagating cracks are observed, initial crack growth under fretting conditions is insufficient to provide critical sized cracks that may propagate under the alternating fatigue stress after growing outside the stress concentration zone of the contact region. This strongly suggests that the pitting and subsurface crack propagation leading to fretting wear of many materials (ref. 4 and 13) is really the same mechanism as that leading to the formation of propagating fatigue cracks when alternating microscopic fatigue stresses are superimposed on the contact stress state.

The purpose of this investigation is to evaluate some surface treatment and coating combinations particularly applicable to fretting encountered at gear/flange interfaces. While a major concern is the potential for initiating fatigue cracks, the investigation is primarily a fretting wear study. However, the fretting wear measurements are heavily supplemented bv microscopy studies to determine the extent to which pitting and crack initiation and propagation contributed to the wear. The baseline material was untreated AISI 9310, a standard gear steel. Surface nitride and surface carburize treatments were evaluated, and the coatings examined included electroplated Cr, electroplated Ag, plasma sprayed Al-bronze and polyimide.

APPARATUS

A schematic diagram of the fretting rig is shown in figure 1. Linear oscillatory motion is provided by an electromagnetically driven vibrator with the frequency controlled by a variable oscillator. Peak to peak fretting amplitude is monitored by means of a capacitance proximity probe. The load is applied to the specimens by placing precision weights on a pan which is hung from the load arm.

The fretting specimens consist of an upper, stationary, 4.76-millimeter-radius, hemispherical tip in contact with a lower flat surface which is driven by the vibrator.

A dry air environment was provided by flowing air through an absorption drier and then into the experimental chamber. In this way moisture content was kept in the range 10 to 100 parts per million. When a moisture-saturated environment was desired, the air was bubbled through a water-filled column and then blown into the chamber. Intermediate humidity levels are achieved by combining dry air and saturated air flows, and monitoring relative humidity.

PROCEDURE

The preparation of the specimen surfaces before a fretting experiment depended on the type of coating or surface treatment applied to the surface.

The bare AISI 9310 surfaces were hand lapped with levigated alumina and then washed in tap water with a polishing cloth to remove the alumina. Following the washing, the specimens were rinsed in absolute ethanol, rinsed in distilled water, and then set aside to dry.

The flat plasma-sprayed surfaces were machine lapped, with approximately 75 to 105 micrometers (3 to 5 mils) of coating being removed in the process. In this way the very rough as-sprayed coating was smoothed so that, disregarding the surface pores, the root-mean-square roughness of the coating was about 0.5 micrometer (20 μin.). The lapped surface was then ultrasonically cleaned in absolute ethanol, rinsed in ethanol, rinsed in distilled water, and allowed to dry.

The surfaces with polymer-bonded coatings and those with the various surface treatments were washed in tap water, rinsed in ethanol, and rinsed in distilled water before being subjected to fretting.

Following the surface preparation treatment, the specimens were assembled into the grips according to the desired combination. The test chamber was then purged with the selected atmosphere for 15 minutes.

The fretting exposure was initiated by adding the required weight to the load pan to bring the contact force to the desired level, usually 1.47 newtons. The amplitude of the fretting motion was 35 micrometers (0.0014 in.), and the frequency of the fretting motion was 163$\pm$1 hertz. The standard duration of the fretting exposure was 10^6 cycles.

Following each fretting experiment, the fretting scars on both surfaces were photomicrographed to record the size and features of the wear scars and the debris accumulation. The loose debris was then rinsed off with ethyl alcohol, and a light-section microscope was used to measure the maximum depth and diameter of the wear scars on both surfaces. Wear volumes were calculated by applying spherical cap approximations to the wear scar geometry.

In principle, the light-section measurement technique consists of directing a plane beam of light obliquely (with a 45° angle of incidence) at the specimen surface. The reflected light beam is viewed through an optical microscope. If a plane surface is viewed, the light beam appears as a straight line across the field of view; if a hemispherical surface is viewed, the light beam appears as a smooth curve. Wear or surface distress due to fretting action shows up as deviations from the smooth profile of the surrounding surface. With the surrounding surface profile used as the datum, wear depth measurements may be made by means of a built-in crosshair system. The diameter of the wear area may be measured by manipulation of an indexed micrometer stage translation. Wear depth measurements are accurate to within 0.5 micrometer, and diameter measurements are accurate to about 20 micrometers. The smallest wear scars examined in this investigation had a nominal depth of about 0.5 micrometer and a diameter of roughly 80 micrometers. Thus, these wear scars represented the practical limit of resolution for the light-section technique, with an uncertainty in wear volume, resulting from measurement of about 50 percent. The wear volume uncertainty due to measurement techniques for the typical wear scars in this investigation was of the order of 10 percent.

MATERIALS

The primary material that served as the subject of this investigation was AISI 9310 steel, the nominal composition of which is given in table I. The 9310 steel was in a cold drawn, annealed condition, and the hardness was measured to be 12 on the Rockwell C scale.

Selection of coatings and surface treatments studied in this evaluation was based on many considerations. The carburized and nitride surface treatments were included because they are standard treatment often applied to gear components, and their performance would naturally be of interest. The surface platings selected are typical of approaches commonly employed to reduce fretting wear. Aluminum bronze-polyester, and polyimide surface coatings were included because of their good performance in fretting wear studies of Ti-6Al-4V surfaces (ref. 14).

Several of the AISI 9310 specimens were carburize case hardened to a depth of 500 to 700 micrometers (0.020 in. to 0.030 in.), and the hardness of the carburized surface was 53 on the Rockwell C scale. A surface nitride treatment was applied to other specimens, and the affected depth was approximately 500 micrometers (0.020 in.). The hardness of the nitrided surface was 42 on the Rockwell C scale.

Two electroplated surface coatings were evaluated in this study. Chromium plate was applied to a thickness of 12 to 25 micrometers (0.0005 in. to 0.001 in.), and silver plate was applied to a thickness of roughly 12 micrometers (0.0005 in.). Both surfaces were cleaned of oxides and etched prior to plating. The silver plate was applied to a palladium flash which was first put down on the 9310 steel surface.

The aluminum bronze-polyester coating was applied by a plasma spray technique. Composition of the aluminum bronze was copper-10 percent aluminum, which was cosprayed with 10 percent (by volume) of an aromatic polyester. The thickness of the coating, as sprayed, was 200 to 250 micrometers (about 0.010 in.).

The polyimide coating was solution-sprayed onto the 9310 surface according to the procedure described in detail in reference 15. Briefly, the coatings were applied to a final thickness of about 20 micrometers, baked for 1 hour at 100° C to volatilize the thinner, and then baked for 1 hour at 300° C to cure the polymer. The choice of polyimide was based on its combination of mechanical and low friction and wear (ref. 16).

RESULTS AND DISCUSSION

Fretting of AISI 9310 Steel

The effect of amplitude on the fretting wear of uncoated AISI 9310 in contact with uncoated AISI 9310 is shown in figure 2. Up to an amplitude of about 25 micrometers, the fretting wear volume remains at a nearly constant, relatively low value. In the 30 to 35 micrometer amplitude range, a transition is observed beyond which the wear increases linearly with increased amplitude. This observation is in qualitative agreement with the results of Halliday and Hirst on mild steel (ref. 5), but they observed a transition to occur at about 70 micrometers. Material, frequency, and loading differences might account for this disagreement.

SEM studies show that, though the wear rate does begin to increase in the 25 to 35 micrometer amplitude range, the fretting mechanisms causing surface damage are still qualitatively similar to those predominating at lower amplitudes. Figure 3 summarizes the types of surface damage observed as the fretting amplitude was increased from 7.5 micrometers up to 62 micrometers. The surfaces examined showed signs of crack initiation and "exfoliation." Thus, for applications in which one of the mating components is subject to significant fatigue loading, variations in slip amplitude alone (at least above 7.5 micrometers) would not be expected to have an important effect on observed fretting fatigue life. Fretting fatigue results generally show that fatigue life is in fact negligibly affected by slip amplitude beyond the 5 to 10 micrometer range (ref. 6).

Measured wear volume as a function of fretting exposure (number of cycles) is shown in figure 4. Beyond 3×10^4 cycles, the fretting wear volume is roughly proportional to (number of cycles)$^{1/2}$. This type of proportionality implies that the instantaneous wear rate is inversely proportional to the accumulated wear:

$$V = C_1 N^{1/2} = C_2 t^{1/2}$$

$$\Rightarrow V^2 = C_2^2 t$$

so

$$\mathring{V} = \frac{C}{V}$$

where $\mathring{V}$ is the wear rate, V is the instantaneous wear volume, N the number of cycles, and t the time of fretting exposure. Thus, the fretting wear process for 9310 steel does not follow an Archard type wear equation, generally descriptive of adhesive wear. Rather, it is consistent with a surface fatigue mechanism as the wear rate controlling process. Fretting wear of 9310 steel, under the conditions imposed in this study, is envisioned to proceed via fatigue induced spallation of material (accelerated by corrosive mechanisms), with the frictional shear stress at the surface as the primary driving force. The surface frictional shear stress is given by

$$\tau_f = \mu \frac{L}{A}$$

where L is the applied load, A the instantaneous area of contact (wear scar surface area), and μ is the coefficient of friction. The contact load L is assumed to be uniformly distributed over the entire contact area (with the assistance of fine accumulated debris). The number of cycles (N_C) required to cause a spallation is approximated by

$$N_C \;\alpha\; \frac{1}{\tau_f{}^m}$$

If each spallation is of a shallow depth d, and of approximately the same volume, then

$$\mathring{v} \propto \frac{f}{N_C},\ f = \text{frequency}$$

$$=> \mathring{V} \;\alpha\; \frac{F(\mu L)^m}{A^m} \;\dot{\propto}\; \frac{1}{V}$$

provided $m \doteq 1$. The approximation $m \doteq 1$ is reasonable since the spallations are caused by low cycle fatigue with corrosion as a contributory effect. It should be emphasized that this argument, not being a solid if-and-only-if argument, does not exclude the possibility of other mechanisms, in particular corrosion and three body abrasion. The micrographs in figures 3 and 5 show significant surface cracking and spallation up to at least 10^6 cycles, indicative of fatigue, with a finer scale process, possibly corrosion combined with 3 body abrasion (no striations or scratches can be seen) after 12×10^6 cycles.

Fretting experiments conducted in moisture saturated air produced results dictinctly different from those seen in dry air. First, the wear volume is increased by a factor of from 5 to 8 after 10^6 fretting cycles. Second, adherent buildups of material, apparently oxidized debris, are observed in and around the contact areas as may be seen in figure 6. It is apparent that the presence of moisture significantly alters the rheological properties of the debris causing it to become "sticky" and cohesive, forming the observed layered deposits. Waterhouse (ref. 10) addresses the influence of moisture on the oxidation of iron based debris, with debris generated in the presence of moisture being softer than that generated in dry air. It is felt that the accelerated wear observed for the case of AISI 9310 steel when fretted in saturated air is primarily the result of more rapid corrosion. Experiments conducted in air at a controlled 40 percent relative humidity showed a fretting wear volume of 20 to 25×10^{-5} mm^3, slightly higher than that measured for dry air.

Performance of Coatings and Surface Treatments

The results of fretting experiments involving coated or treated AISI 9310 steel in contact with untreated 9310 are summarized in figure 7. Fretting was conducted in both dry air and moisture saturated air. For purposes of performance evaluation, the fretting wear of untreated 9310 steel against untreated 9310 steel in dry air and saturated air is indicated on the figure.

No wear was measured on the carburized 9310 surface after fretting against untreated 9310 steel. However, extensive transfer to the carburized surface took place with the final contact situation being one of 9310 steel against 9310 steel. Wear to the untreated surface was indistinguishable from baseline wear under dry air conditions. Figure 8 shows the presence of considerable oxidized debris embedded in the fretting surface, with the presence of fine surface cracks indicating incipient spallation. Striations also visible on the surface suggest that abrasion by embedded debris particles was also contributory. Under saturated air conditions, wear to the untreated surface was 3 to 4 times the baseline. Again, very heavy metallic transfer to the carburized surface occurred. It is proposed that under fretting conditions the hard carburized material could more readily displace the protective surface oxides in the presence of moisture, and promote more extensive adhesion between the surfaces than took place under dry air conditions. The untreated material, being the weaker of the two, would then be expected to transfer to the carburized surface.

The results obtained with nitrided 9310 steel in contact with untreated 9310 steel also showed transfer of material to the nitrided surface in all cases when fretting was conducted in dry air. Wear to the untreated surface was slightly higher than the dry air baseline. Under saturated air conditions however, transfer to the nitrided surface was seen about 50 percent of the time, with wear occurring otherwise. Fretting wear to the untreated surface in saturated air was much lower than the corresponding baseline.

Low wear to the hard chromium plate was observed after fretting in dry air, and some transfer of 9310 steel to the chromium plated surface took place. Wear to the uncoated surface was slightly higher than the dry air baseline. When fretting was conducted in saturated air however, the chromium plate was observed to wear, and wear to the uncoated surface was reduced. The fretted chromium plate showed a nearly featureless surface, while on the mating 9310, "islands" of transferred chromium could be seen (fig. 9). It is hypothesized that the transferred chromium was in an oxidized form, and being embedded in the uncoated 9310 steel surface, promoted a 2-body abrasive action to the chromium plate.

Under dry air fretting conditions, Ag plate performed as a sacrificial coating, itself undergoing wear while the opposing uncoated surface showed considerably reduced fretting damage compared to the baseline. SEM and x-ray dispersion analysis indicated that a thin, nonuniform deposit of Ag was present on the uncoated 9310 steel surface after fretting in dry air as may be seen in figure 10. Fretting under a moisture saturated air environment did not result in a significant difference in the performance of the Ag plate; it still worked as a sacrificial coating, but more wear to the uncoated 9310 steel surface was seen than under dry air conditions. Considerably greater experimental scatter occurred.

Like the Ag plate, the aluminum bronze-polyester performed as a sacrificial coating with results similar to those described in reference 14 for the fretting of Ti-6Al-4V. Wear to the uncoated 9310 steel surface was reduced by nearly an order of magnitude in both dry and saturated air. Microscopic examination of the uncoated surface (fig. 11) revealed that a thin adherent film accomodated most of the fretting action. Based on x-ray dispersion analysis of the fretted region on the uncoated specimen, it was concluded (by elimination) that the adherent film must be mostly polyester. The fretting damage features visible on either surface were of a benign nature-absent were fatigue spalls and surface cracks.

The polyimide coating (evaluated against Ti-6Al-4V in ref. 15) resulted in marginally reduced wear to the uncoated AISI 9310 steel mating surface, but itself a sacrificial coating, underwent rather rapid wear. Microscopic examination of the fretted surfaces revealed oxidized debris embedded in the polyimide coating, and evidence of abrasive wear to the uncoated surface. It was thus concluded that the predominant wear mechanism to the uncoated surface was 2-body abrasion, with gradual disintegration of the coating as it became overloaded with debris.

CONCLUSIONS

From the fretting studies conducted on 9310 steel, and the assessment of several candidate "anti-fret" coatings applied to one of the mating surfaces, the following conclusions are drawn:

1. Up to at least 10^6 cycles, the fretting of AISI 9310 steel is dominated by a surface spallation mechanism caused by localized fatigue in the contact area.

2. The presence of moisture significantly increases the fretting wear of 9310 steel, and alters the distribution of fretting debris.

3. From the standpoint of reduced fretting wear to the uncoated surface the best coatings were silver plate, and aluminum bronze with polyester, each resulting in roughly an order of magnitude reduction in wear to the uncoated mating surface under all test conditions.

4. Chromium plate, itself the most fretting wear resistant of the coatings evaluated, markedly reduced fretting wear to the uncoated mating surface in saturated air, with no significant change in wear to the uncoated surface in dry air.

REFERENCES

1. Valtierra, M. L., Parkvis, A., and Ju, P. M., "Spline Wear in Jet Fuel Environment," Lubri. Eng. 31, 136 (1975).
2. Sibley, L. B., "Discussion of Paper: Fretting in Aircraft Turbine Engines," AGRAD CP-161, Advisory Group for Aerospace Research and Development, 5-14 (1974).
3. Goss, G. L. and Hoeppner, D. W., "Characterization of Fretting Fatigue Damage by SEM Analysis," Wear 24, 77 (1973).
4. Bill, R. C., "Fretting Wear in Titanium, Monel-400, and Cobalt-25-Percent Molybdenum Using Scanning Electron Microscopy," NASA TN D-6660 (1972).
5. Halliday, J. S., and Hirst, W., "The Fretting Corrosion of Mild Steel," Proc. Roy. Soc. (London) 236A, 411 (1956).
6. Waterhous, R. B., "Fretting Corrosion," Pergamon Press Ltd., Oxford, 113 (1972).

7. Waterhouse, R. B., "Fretting Corrosion," Pergamon Press Ltd, Oxford, 141 (1972).

8. Nishioka, K., and Hayakawa, K., "Fundamental Investigation of Fretting Fatigue (Part 5, The Effect of Relative Slip Amplitude)," Bull. JSME 12, 692 (1969).

9. Feng, I., and Uhlig, H. H., "Fretting Corrosion of Mild Steel in Air and Nitrogen," J. Appl. Mech. 21, 395 (1954).

10. Waterhouse, R. B., "Fretting Corrosion," Pergamon Press Ltd., Oxford, 126 (1972).

11. Hurricks, P. L., "The Mechanism of Fretting - A Review," Wear 15, 384 (1970).

12. Nishioka, K., and Hayakawa, K., "Fundamental Investigations of Fretting Fatigue (Part 3, Some Phenomena and Mechanisms of Surface Cracks)," Bull. JSME 12, 397 (1969).

13. Waterhouse, R. B., and Taylor, D. E., "Fretting Debris and Delamination Theory of Wear," Wear 29, 337 (1974).

14. Bill, R. C., "Selected Fretting Wear Resistant Coatings for Titanium-6-Percent Aluminum - 4-Percent Vanadium Alloy," NASA TN D-8214 (1976).

15. Fusaro, R. L., and Sliney, H. E., "Graphite Fluoride as a Solid Lubricant in a Polyimide Binder," NASA TN D-6714 (1972).

16. Jones, W. R., Jr., Hady, W. F., and Johnson, R. L., "Friction and Wear of Poly (amide-imide), Polyimide, and Pyrrhone Polymers at 260° C in Dry Air," NASA TN D-6353 (1971).

TABLE I. - COMPOSITION OF AISI 9310 STEEL

Element	Fe	C	Ni	Cr	Mo
% by wt.	Bal.	0.1	3.25	1.2	0.1

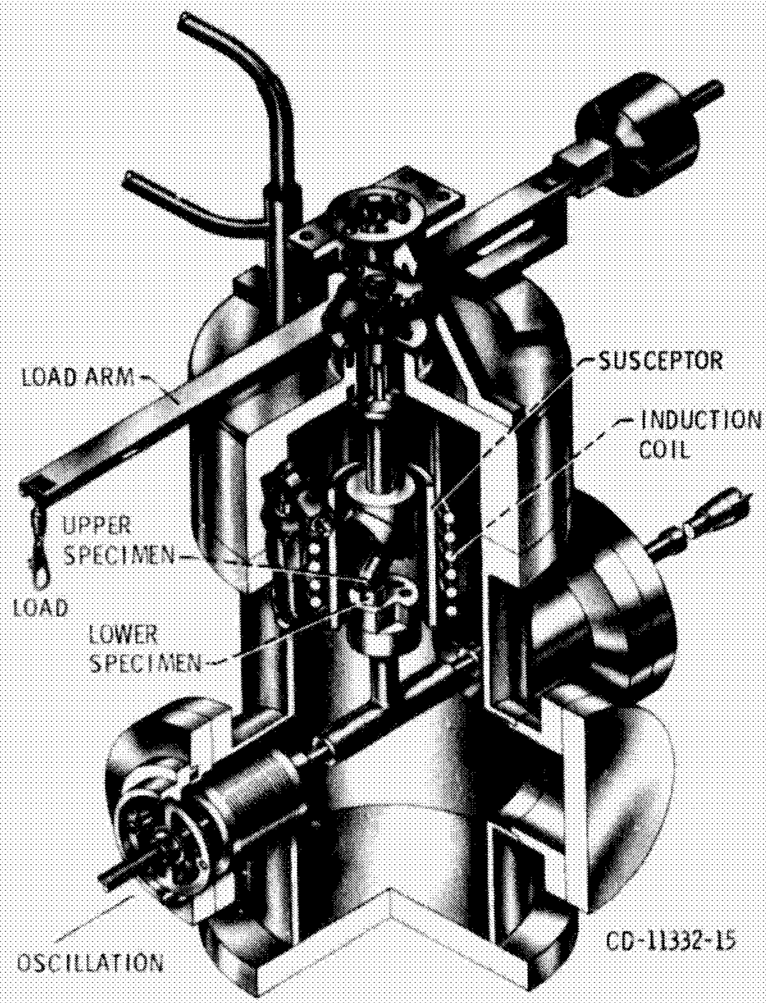


Figure 1. - Fretting apparatus.

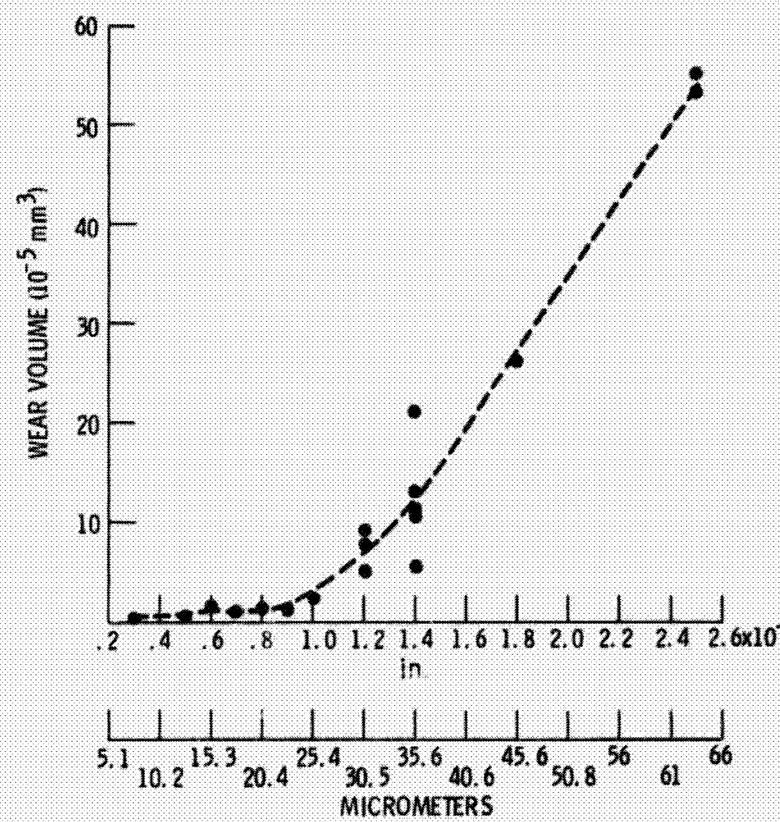
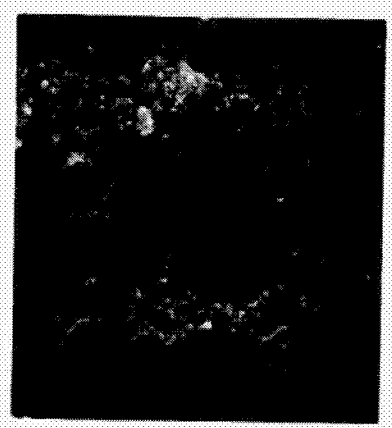


Figure 2. - Fretting wear volume versus fretting amplitude; fretting exposure, 10^6 cycles; normal load, 1.47 N; frequency, 163 Hz; dry air.

(a) 7.5 - 10 μm AMPLITUDE (0.3 - 0.4 MILS).

(b) 35 μm AMPLITUDE (1.4 MILS).



(c) 62 μm AMPLITUDE (2.5 MILS).

Figure 3. - Fretting damage features resulting from 10^6 fretting cycles in dry air, under the indicated fretting amplitude conditions. X1000.

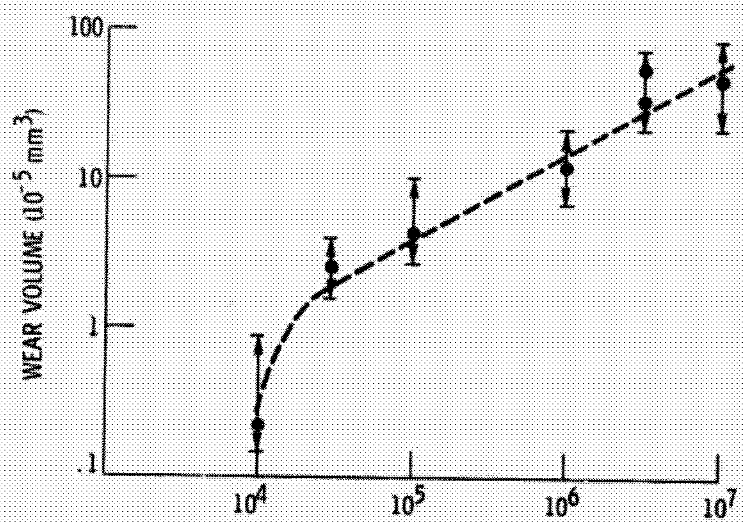
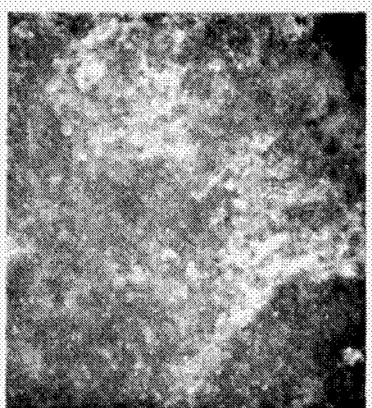


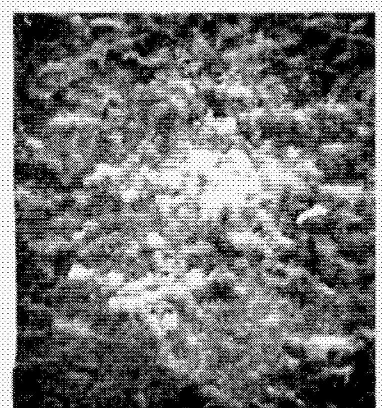
Figure 4. - Fretting wear volume versus number of fretting cycles; fretting amplitude, 35.6 micrometers; normal load, 1.47 N; frequency, 163 Hz; dry air.

(a) 10^4 CYCLES.

(b) 3×10^4 CYCLES.

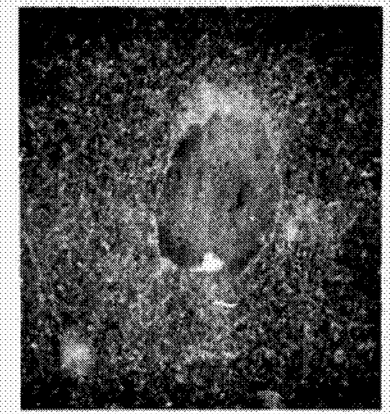


(c) 10^5 CYCLES.

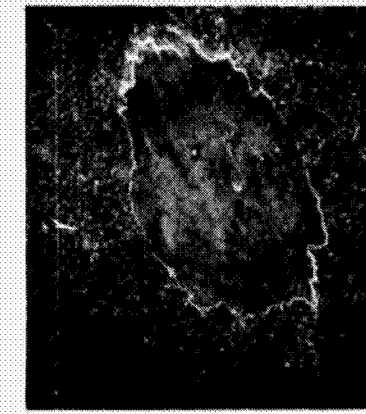


(d) 12×10^6 CYCLES.

Figure 5. - Typical fretting damage features seen after the indicated fretting exposures under the following fretting conditions: 35 μm amplitude, 163 Hz frequency, 1.47 N load, dry air. X1000.

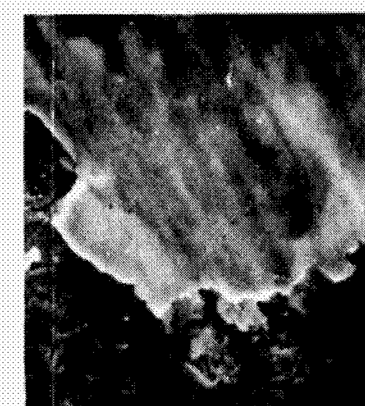


(a) 10^5 CYCLES, X100.



(b) 10^6 CYCLES, X100.

(c) FRETTING DAMAGE AT RANDOM LOCATION IN CONTACT AREA, X1000.



(d) BUILD-UP OF TRANSFERRED MATERIAL, EDGE OF CONTACT AREA, X1000.

Figure 6. - Build-up of transferred material resulting from fretting in moisture saturated air under a 1.47 N normal load at 163 Hz, 35 μm (1.4 mil) amplitude.

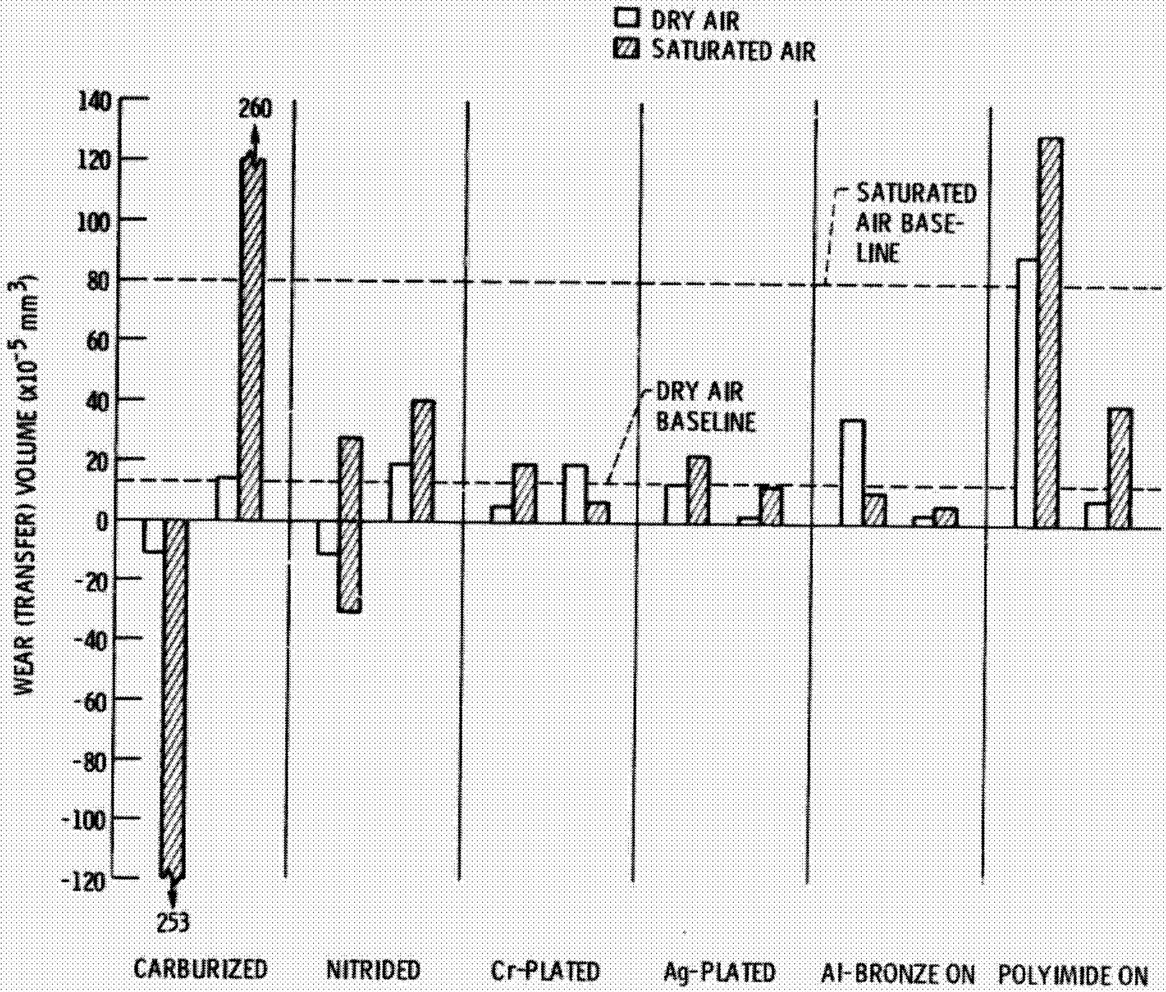
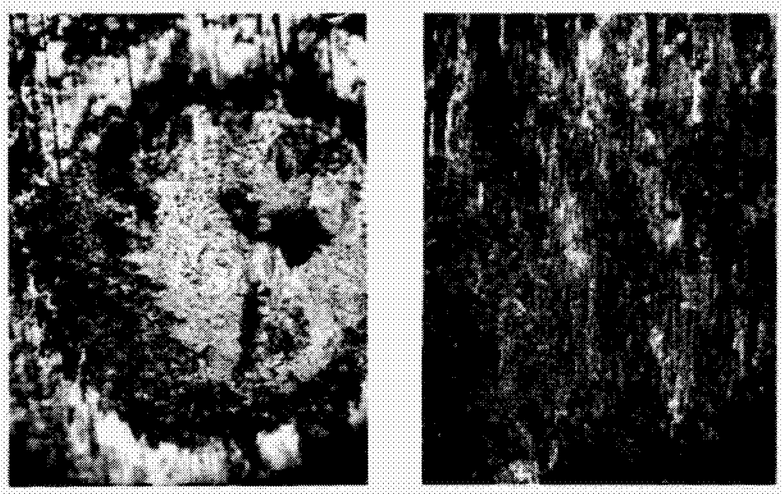
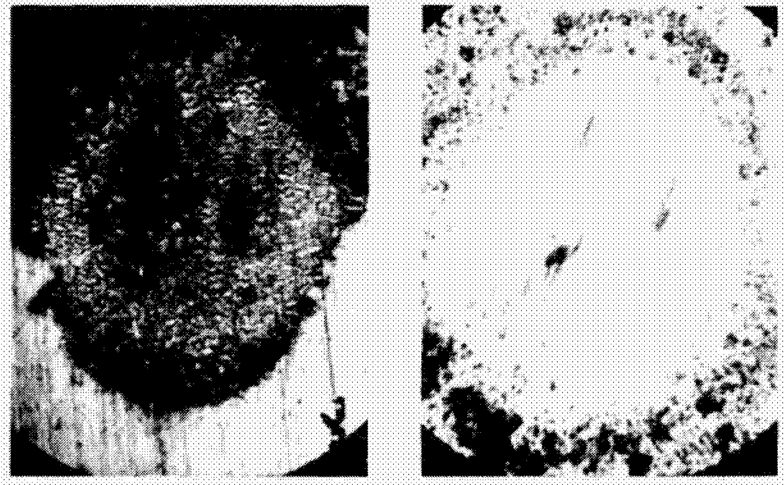


Figure 7. - Fretting wear to coated and uncoated AISI 9310 after 10^6 fretting cycles. Normal load was 1.47 N, frequency 163 Hz, and amplitude 35 micrometers. For each coating, the first set of bars refers to wear of the uncoated mating surface. The baselines show the wear of uncoated 9310 fretted against uncoated 9310.



(a) 10^6 CYCLES, DRY AIR. (b) 10^6 CYCLES, SATURATED AIR.

Figure 8. - Surface damage to AISI 9310 resulting from fretting against carburized 9310. After fretting in dry air (left), the 9310 showed heavy wear in the center of the contact area, with distinct pitting damage around the edges. Close examination reveals a mosaic of interconnecting cracks over the entire contact area after fretting in saturated air (right). X327.



(a) UNCOATED AISI 9310 SURFACE. (b) Cr PLATED SURFACE.

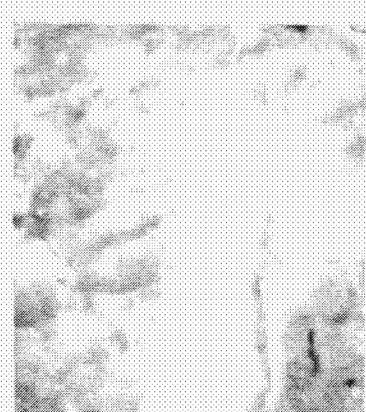
Figure 9. - Fretted surfaces on untreated AISI 9310 and Cr plated 9310 after 10^6 cycles in moisture saturated air under a 1.47 N normal load, 163 Hz fretting frequency and 35 micrometer amplitude. X127.

(a) X100.

(b) X1000.

Figure 10. - Fretting damage to the surface of uncoated AISI 9310 after 10^6 cycles against Ag coated 9310 in dry air. The material on the surface in identified as being silver.

(a) X300.



(b) X3000.

Figure 11. - Fretting damage to uncoated AISI 9310 after 10^6 cycles against aluminum bronze - polyester coated 9310.