FRETTING CORROSION IN ELECTRIC CONTACTS

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ABSTRACT

Fretting corrosion is a form of accelerated atmospheric oxidation which occurs at the interface of contacting materials undergoing slight, cyclic relative motion. In electric contacts involving non-noble metals, fretting action can cause rapid increases in contact resistance, proceeding to virtual open circuits in a matter of minutes in the worst cases. Experimental results of resistance increase due to fretting action are given for 36 different contact plating combinations, including hard and soft materials and noble as well as non-noble metals. Effects of contact load, both mechanical and electrical, were studied. The results show that all non-noble metals are susceptible to some degree to fretting corrosion and will suffer contact resistance increases. The beneficial effects of boundary lubricants are demonstrated.

Fretting corrosion phenomena were studied on a laboratory test rig designed to produce a particularly damaging fretting motion. Actual and simulated connector configurations were also tested and found to exhibit similar trends in resistance increase, but at a slower rate. Differential thermal expansion is identified as one source of fretting motion in connectors.

INTRODUCTION

There is a strong economic motivation today to reduce or eliminate the usage of gold on connector contacts. Of the alternate 'materials available, those which offer significant economic advantage are non-noble materials. This paper reports our investigations of a phenomenon known as fretting corrosion, which if not recognized and controlled, represents a serious failure mechanism operative in nominally "static" contact systems employing non-noble contact surfaces.

Fretting corrosion is a form of accelerated atmospheric oxidation which occurs at the interface of contacting materials which undergo slight cyclic relative motions. In normally static contacts, we visualize the contact interface as consisting of one or more contact asperities at which metal-to-metal contact has been established. With non-noble materials. we believe these a-spot contacts to be clean-metal junctions formed by the mechanical break-through of thin oxide films on the surface. If a slight relative motion occurs between the contacting surfaces, the original a-spot contacts are broken and new ones established. The old a-spots quickly oxidize. If the motion is then reversed, additional a-spots are exposed to oxidation. With cyclic relative motions of limited. amplitude, so that the motion is ineffective in cleaning away the wear debris and accumulating oxides, a highly localized, thick, insulating layer is formed in the contact interface. We will describe experiments wherein this sequence of events leads to rapid and dramatic increases in contact resistance. proceeding to virtual open circuits. We suggest that this is a mechanism which accounts for many instances of unsatisfactory performance of non-noble metal contacts in actual field service. Finally, we present data to demonstrate that control of fretting motion and/or appropriate lubrication of contacts can effectively eliminate this failure mode in nominally static electric contacts.

Fretting corrosion is not a newly-discovered phenomenon. It was described in 1911 by Eden, Rose and Cunningham in reference to a type of corrosion occurring on a steel part in a fatigue testing machine.[1] The term "fretting corrosion" was coined in 1939 by Tomlinson, Thorpe, and Gough.[2] The process of fretting corrosion has been observed on metals as soft as aluminum and also on relatively hard steels[3]

Bethune and Waterhouse[4] further defined the phenomena in studies reported in 1968. A recent book by Waterhouse[5] treats the subject in considerable detail, and makes some mention of potentially disastrous effects in electric contacts suffering from fretting corrosion. The effects of oxygen-containing environments, inert atmospheres, the oxidation of wear debris, and the beneficial effects of lubrication are discussed there.

The work reported in thus paper started in 1969, but confirmation of its broader significance occurred within the last year.

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EXPERIMENTAL

Fretting Tests on a Variety of Contact Materials

A test apparatus was built in which electric contact consisting of a 1/4 Inch diameter sphere against a flat disc surface could be cyclically rotated against one another (Figures 1 & 2). Alignment was such that the ball made contact on the center of rotation of the paddle so that self-cleaning action at the contact spot would be minimal. During the test, the angle of rotation was fixed at 11°, while the period of motion was 5.5 seconds (11 cycles per minute). The contact force was generally held at 50 grams, although this could be varied by adjusting the dead weights on the assembly.
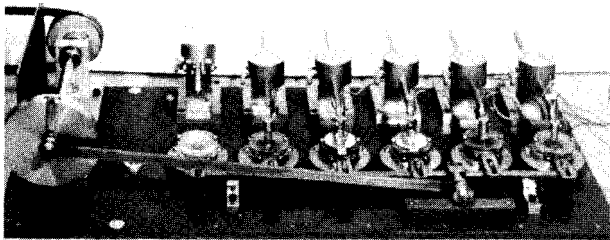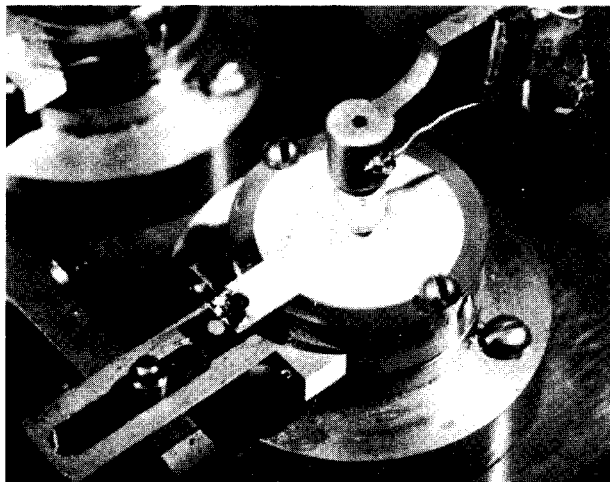
Figure 1.   Six Station Fretting Device

Figure 2.   Close-up of One Station

Several contact materials were tested on the apparatus to determine their relative susceptibility to fretting corrosion. Among the materials tested were:

(a) Dull Tin
(b) Bright Tin
(c) Tin-Lead
(d) Tin-Nickel
(e) Nickel
(f) Silver
(g) Txhd-Tempere H.D. (Sel-Rex Gold)
(h) PTB (An AMP Gold)

The materials were plated in two forms; 300 microinches over brass, and 150 microinches over 50 microinches Ni over brass. During this portion of the test the contact force was fixed at 50 grams and a constant current of 100 ma. applied. The materials were tested against themselves as well as each other. It was decided to test samples for a period of two hours running time-or until the contact resistance had risen to 5 ohms, whichever came first. Preliminary work had shown that this time was sufficient to cause large scale degradation in contact resistance on materials prone to suffer fretting corrosion.

The results of this test are to be found in Tables I and II. These data show that relatively soft oxidizable materials (dull tin, bright tin, and tin-lead) behave similarly; the initial contact resistances were in the low

150 μ" OVER 50 μ" NICKEL OVER BRASS

Each cell shows initial/final values; each material has DRY and LUB sub-columns.

STYLUS \ FLAT	DULL TIN DRY	DULL TIN LUB	BRIGHT TIN DRY	BRIGHT TIN LUB	TIN-LEAD DRY	TIN-LEAD LUB	TIN-NI DRY	TIN-NI LUB	NICKEL DRY	NICKEL LUB	SILVER DRY	SILVER LUB	TXHD-GOLD DRY	TXHD-GOLD LUB	PTB-GOLD DRY	PTB-GOLD LUB
DULL-TIN	2./5K	2./2.														
BRIGHT TIN	2./5K	2./2	2./5K	2.4/1.5												
TIN-LEAD	2./5K	1.7/1.7	2./5K	2./1.5	2./5K	1.5/1.5										
TIN-NI	150./5K	3.5/1.5	70./5K	10./1.6	5./5K	10./1.6	100./5K	400./70								
NICKEL	4.5/5K	1.5/1.5	3./5K	4./2.	5./5K	2./1.5	20./5K	30./12.	8./5K	12./5.						
SILVER	2.5/200	2.5/1.5	3./15.	3.5/1.8	1.3/25.	1.7/1.7	120./35	3.5/3.5	400./1K	150/5.	2./2.	2./2.				
TXHD GOLD	2./100	1.5/1.5	2./100	2./1.5	1.5/20	1.8/1.4	80./6.	90./2.	30./5.	6./2.	2./1.8	1.8/1.8	2.0/1.6	1.6/1.6		
PTB GOLD	3./30.	2./1.3	3.5/30.	2./1.5	2./1K	2./1.5	200./25.	300./5.	50./300	10./2.5	1.8/1.8	2.0/2.0	2.3/2.3	1.7/1.7	2./2.5	2./1.6

TABLE I
INITIAL AND FINAL RESISTANCE (MILLIOHMS) AFTER FRETTING ACTION
(1320 CYCLES) OF VARIOUS PLATED SURFACES

300 μ" OVER BRASS

Each cell shows initial/final values; each material has DRY and LUB sub-columns.

STYLUS \ FLAT	DULL TIN DRY	DULL TIN LUB	BRIGHT TIN DRY	BRIGHT TIN LUB	TIN-LEAD DRY	TIN-LEAD LUB	TIN-NI DRY	TIN-NI LUB	NICKEL DRY	NICKEL LUB	SILVER DRY	SILVER LUB	TXHD-GOLD DRY	TXHD-GOLD LUB	PTB-GOLD DRY	PTB-GOLD LUB
DULL-TIN	2/5K	2/2														
BRIGHT TIN	2/5K	2/2.5	2/5K	2/1.5												
TIN-LEAD	2./5K	1.8/1.8	2/5K	1.9/1.3	2./5K	1.5/1.5										
TIN-NI	300/5K	4./1.5	150/5K	500/2.	6./5K	2.8/1.7	40/5K	70/12								
NICKEL	4/5K	2/1.5	5./5K	4/2	5/5K	2./1.5	20/5K	15./10.	8/5K	12./5						
SILVER	2/10	2/1.5	3/15.	4./2	1.5/25	2/15	120/4	4./3	50./400	200/2	2/2	2/2				
TXHD GOLD	2/50	1.5/1.3	2/100	2./1.3	1.5/50	1.5/1.5	200/30	100./2.	12/50.	15/2	2/18	1.8/1.8	1.6/1.6	1.5/1.5		
PTB GOLD	4/15	1.6/13	2.5/100	1.8/1.6	1.5/5K	2./1.5	200/5.	300/5.	50/6.	100/2.7	2/18	1.8/1.8	2/2	1.8/1.8	2.5/17	2/1.6

TABLE II
INITIAL AND FINAL RESISTANCE (MILLIOHMS) AFTER FRETTING ACTION
(1320 CYCLES) OF VARIOUS PLATED SURFACES

milliohm range, and during the test the contact resistances climbed rapidly into the ohm range. The contact spot appears black, as shown in Figure 3. The effect of the nickel underplate seemed unimportant, with no aporeciable differences attributable to that variable. When
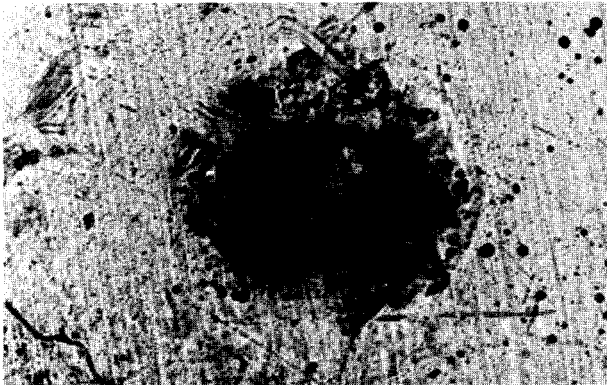

Figure 3. A "Slack Spot" Produced on a Tin Contact During Fretting

the soft-oxidizable materials were run against the noble metals, results were better but contact degradation still occurred. Hard oxidizable materials behaved only slightly differently. Initial contact resistances ran in the tens of milliohms range and during the test rapidly rose to the ohm range. The oxidation-resistant materials apparently do not suffer the fretting corrosion phenomenon-the fretting action produced contact degradation more characteristically defined as wear, in that wear debris was generated but contact resistance did not change appreciably.

The same materials were tested under conditions of fretting action in the lubricated state. Samples were dipped into a 5% solution of White Mineral Oil (remainder methylene chloride), retracted and air dried. The effects on the soft oxidizable materials was striking, in that relatively low values of contact resistance were maintained. The results with the hard materials were also very good, in fact, many of the materials decreased in contact resistance during the test. With noble materials, lubrication seemed to reduce the generation of wear debris, but generally these materials gave stable resistance values in both the dry and lubricated states.

Rapid Increases of Contact Resistance

Contact resistance has been shown to increase at very rapid rates under conditions of fretting corrosion-with the test procedure as previously outlined. As shown in Figure 4, the contact resistance on a bright tin sample had increased from an initial value of 2.5 milliohms to greater than 5 ohms during just 30 minutes of fretting action. This is contrasted to the stable values obtained in the lubricated case. The results for nickel are also shown (Figure 5). Here the results are somewhat similar excepting for a short time initial reduction in contact resistance. This particular sample had increased in contact resistance from 0.1 ohm to 5 ohms in approximately 10 minutes in the unlubricated condition, and again the improvement with lubrication is noted.
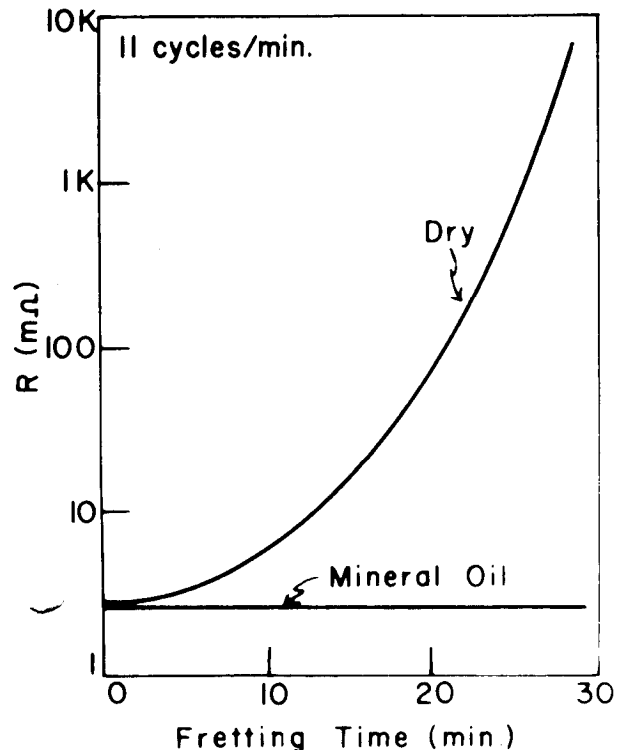

Figure 4. Variation of Contact Resistance During Fretting on Bright Tin Contacts. The Contact Force was 50 gm.
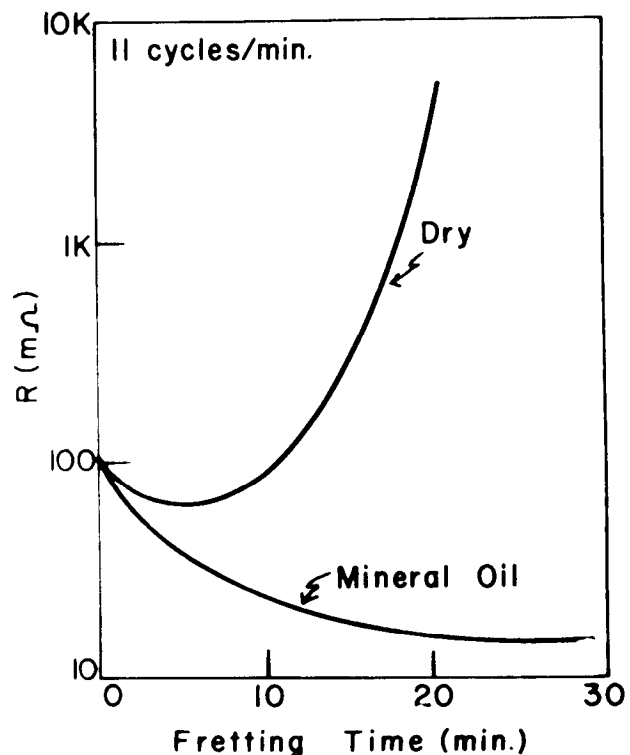

Figure 5. Variation of Contact Resistance During Fretting on a Nickel Contact. The Contact Force was 50 gm.

3

Surface Damage During Fretting

Fretting action seems to produce a surface condition that depends upon the hardness of the material. The softer materials suffer more surface damage, pitting, material loss, and generation of wear debris. The harder materials suffer very little damage and not much wear debris is generated. The effect on contact resistance cannot be determined from an examination of the contact surfaces

Examination of cross-sections given in Figure 6 thru 12 show the condition of several samples within the wear region. The set comparing tin and nickel wear regions is very interesting (Figures 6 & 7): both samples were fretted until contact resistance had risen to 5 ohms. The time to failure for each was comparable (T ∼ 30 minutes). But the different extent of surface damage is obvious. Surface damage is also noticed on lubricated samples, although not quite as severe (Figure 8). It was interesting that with the softer materials in the lubricated state, adhesion (or cold welding) was noticed throughout the test. The soft oxidizable materials in the unlubricated condition did not adhere to one another after fretting.
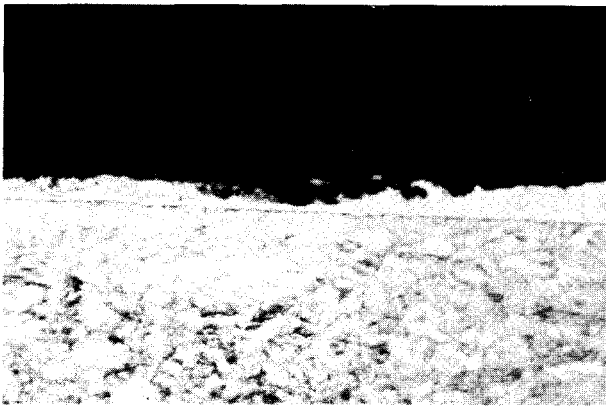

Figure 8. Lubricated Tin Plated Contact After 2 Hours of **Fretting at 50 gm. Final Resistance was 2mΩ. Original mag.** 750x.

Dependence of Fretting upon Contact Force

Contact forces on nickel contacts have been varied from 50 grams to as high as 600 grams. We still found little surface damage even with the higher forces. But it was possible to reach contact resistances of 5 ohms within the entire range of contact forces (50 to 600 grams). Some difference was noted in times to failure, generally 5 ohms could be reached in less than 2 hours with contact forces less than 200 grams. At 200 grams, it required between 2 and 4 hours of fretting to reach the 5 ohm value. With 600 grams it required approximately 5 hours of fretting.

With the tin samples, contact forces were varied from 50 to 200 grams. Contact resistances as high as 5 ohms were reached at contact forces up to 200 grams with fretting times of less than 4 hours. Wear was very severe on tin with the higher loads.

Cross-sections given in Figures 9 thru 12 compare tin and nickel contacts that were fretted for 2 hours, both at 50 grams and at 200 grams.

Figure 6. Cross-Section of a Tin Plated Contact After 30 min. **of Fretting at 50 gm. Final Contact Resistance was 5 Ω.** Original mag. 600X.
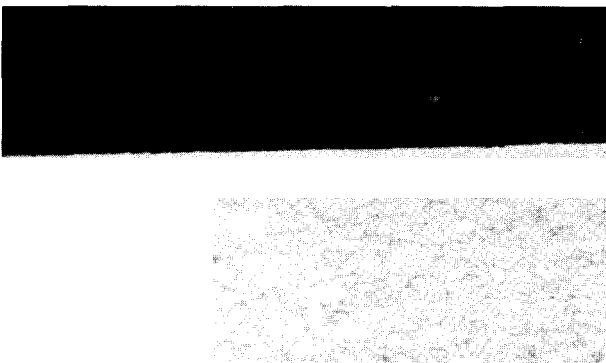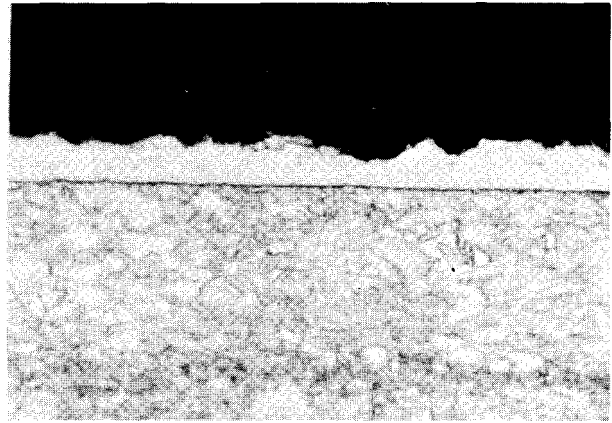

Figure 7. Nickel Plated Contact After 20 min. of Fretting at **50 gm. Final Resistance was 5 Ω. Original mag. 500X.**
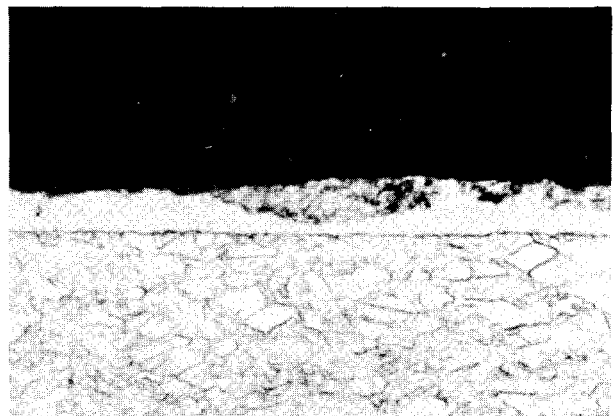

Figure 9. Tin Plated Contact After 2 Hours of Fretting at 50 gm. Original mag. 750X.
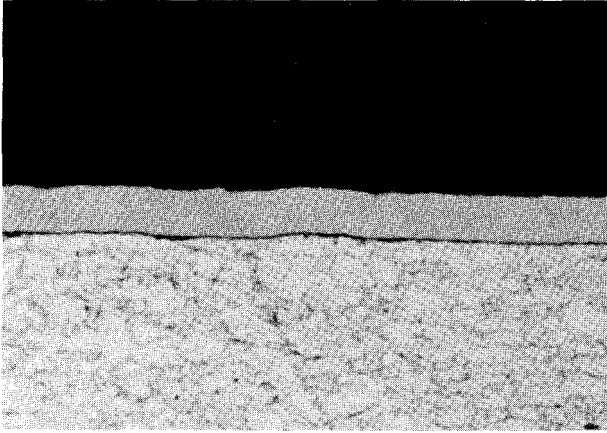
Figure 10. Nickel Plated Contact Fretted for 2 Hours at 50 gm. Original mag. 750X.
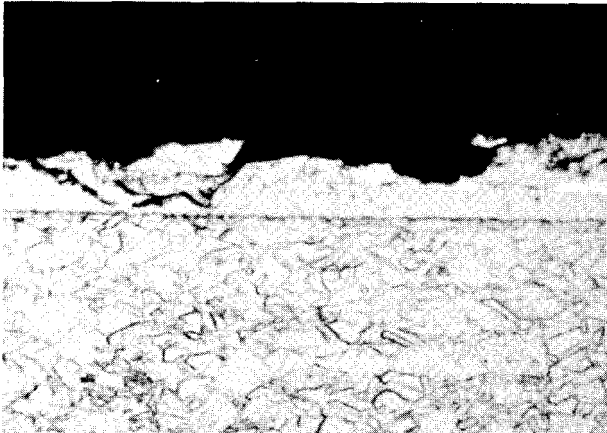

Figure 11. Tin Plated Contact Fretted for 2 Hours at 200 gm. Original mag. 750X.

Figure 12. Nickel Plated Contact Fretted for 2 Hours at 200 gm. Original mag. 750X.

Fretting Corrosion under Various Electrical Loads

Insulating films may be broken down electrically by high field effects. The process is generally referred to as *fritting*. When an electric field on the order of 10^8v/meter appears across high resistance films (oxide. etc.), what is usually noted is a sudden increase in current with a simultaneous decrease in contact resistance. This indicates that good metallic contact is established. The newly established contact resistance after fritting is related to the softening voltage of the material and to the maximum current that had passed through the contact during the fritting operation. With the idea in mind that both contact voltage and current limiting play a part in film behavior, both tin and nickel contacts were fretted for long periods of time (several days) under varying conditions of electrical loading-so that the maximum level of contact resistance could be attained.

The results of the test are to be found in Figure 13. Nickel seemed to behave worse than tin, in that higher resistances were produced at like voltages and currents It was also noted that relatively large values of resistances are generated in the volts range, and thus trouble could be anticipated on circuits operating within this range-voltages normally found in transistorized circuits. Samples with current limited to 10 ma. reached greater values of contact resistance than those limited to 100 ma. It appears that contact applications in high voltage-high current circuits will suffer less during fretting conditions; a result that is, of course, in accord with conventional ideas of film-covered contacts behavior
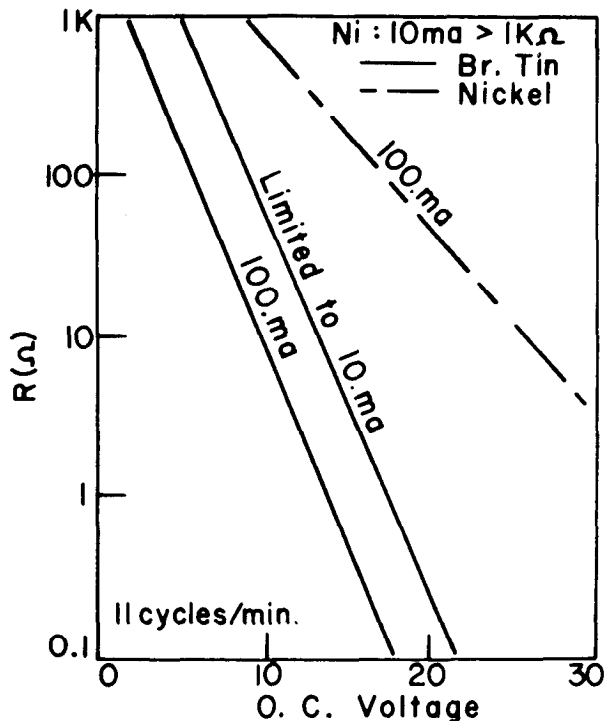

Figure 13. Maximum Contact Resistance During 2 Days of Fretting as a Function of 0. C. Voltage

Anomalous Behavior of Palladium under Fretting Conditions

Palladium plated contacts have been tested under conditions of fretting action in both the dry and the lubricated condition. It has been observed that increases in contact resistance are produced in *both* the dry and lubricated condition, and the largest resistance increases occurred in the lubricated condition.

All of the samples (6 pair dry, 6 pair lubricated) were fretted for a period of two hours (~1 k cycles), the contact force was 50 grams and the test current 100 ma. The initial contact resistances were in the 10 mrlliohm range. The average increase in contact resistance for the dry samples was 100% while the average increase for the lubricated samples was 300%.

It is known that organic polymers-or frictional polymers-may be produced when catalytic metals are rubbed together. It is tentatively suggested that such an effect is responsible for our observations during fretting on palladium. Perhaps the abundance of organic material (lubricant) tends to enhance the amount of polymer produced/time-thus, giving the higher resistance on lubricated samples.

Fretting Corrosion induced by Differential Thermal Expansion

Most of the data presented so far in this paper have been generated on a fretting test apparatus designed to produce rotational oscillatory motion by purely mechanical means. Thermal shock tests on various types of tin plated contacts very often produce disastrous results. Sample calculations with several typical connector geometries taking into account coefficients of thermal expansion and temperature transistions, suggest that fretting action could occur because of differential thermal expansion (DTE). Special test fixtures were constructed to explore the idea that DTE could induce fretting and fretting corrosion. The basic fixture is illustrated in Figure 14. One model was constructed wholly of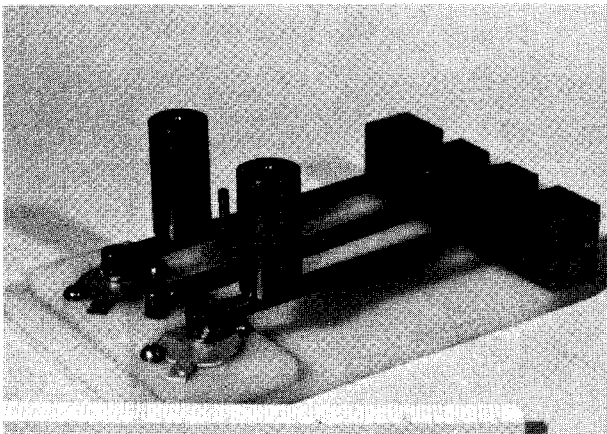 steel parts, another of nylon and steel. The first would not be susceptible to DTE, the second was designed to produce a translational motion of about 3/4 mil/° C By using other combinations of materials this thermal motion capability could be varied.

With these fixtures a series of fretting tests was conducted in a temperature chamber cycling between 55° C and 60° C ($\Delta T = 5$° C). This temperature variation would produce a wiping action of about 3 mils on the nylon-steel fixtures. Cycle times were on the order of 1 hour; 45 min. at 60° C - 15 min. at 55° C. Bright tin and nickel plated samples were tested. Normal forces were maintained at either 80, 100, 450 grams. The interesting, but not unexpected, results were that samples tested on the all-steel fixture maintained low and stable resistance values throughout the test, while the results on the steel-nylon fixture were similar to those found on the oscillatory motion apparatus. Approximately 100-200 cycles produced very high resistance values on both the tin and the nickel plated samples. In most cases, resistances went from initial values in milliohms to final values in excess of 10 ohms. Often complete open circuits were observed. Figure 15 gives the results on one of the bright tin samples. Figure 16 shows a cross-section taken in the contact region. Of special interest was the fact that open circuits were produced on both tin and nickel plated samples with contact forces as high as 450 grams (the highest force tested). Breakdown voltages were generally found to be on the order of 9-10 volts.

We are now conducting DTE tests on fixtures designed to produce smaller motions (down to 60 micro-

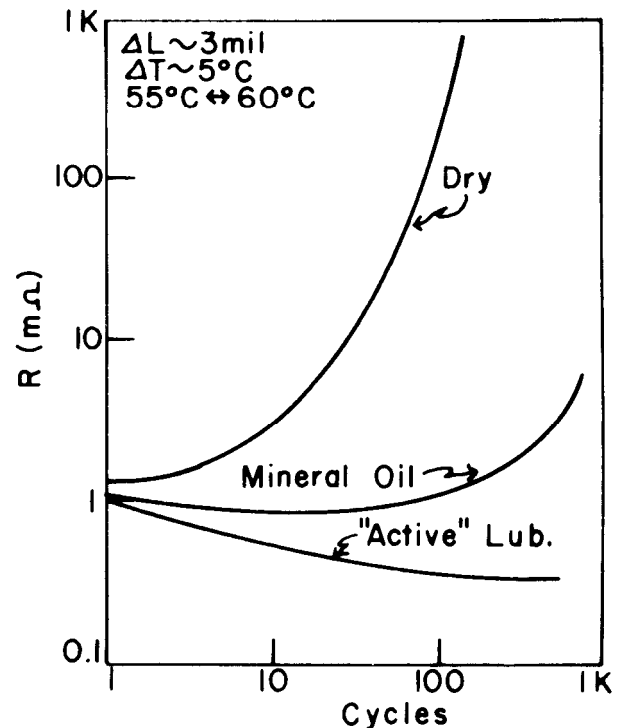Figure 14. DTE Device Producing 3 mils of Wipe With a 5°C Change in Temperature

Figure 16. Variation of Contact Resistance with Fretting Cycles Produced by DTE
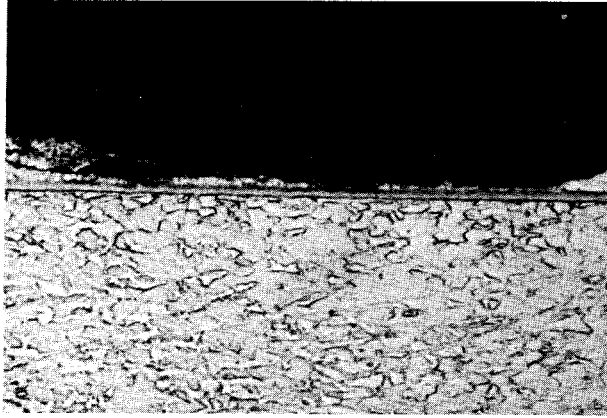
Figure 16. Tin Plated Contact After 200 Cycles Produced by DTE. Original meg. 760X.

inches) with the 5° C temperature variations. The purpose of these tests, and perhaps further testing, is to define a magnitude of fretting motion below which contact integrity is not affected.

The effect of mineral oil lubricant in this portion of the fretting study was not nearly as dramatic as had been observed in the earlier purely rotational test. We did experience some increases in contact resistance within 100-200 test cycles. As noted in Figure 15, the contact resistance on a bright tin sample increased to 10 milliohms. However, we note that the unlubricated sample went to nearly open circuit conditions. Similar tests results were observed on nickel plated samples. Long term DTE tests (thousands of cycles) on lubricated contacts has produced resistance increases into the 10's of milliohms range; however, the very large resistances as produced in the dry condition have never been observed. This test usually produced severe wear at contact interfaces, and it is felt that trapped wear debris is responsible for the observed increases in contact resistance-even in the lubricated condition.

The results of these tests, with the knowledge that many electric and electronic devices often have quite large temperature variations during operation, does raise serious question about the indiscriminate usage of alternate materials for gold.

Lubrication and Effectiveness of Lubrication

A variety of synthetic and natural oils have been found to be effective in preventing, or at least minimizing, fretting corrosion. A number of oil-wax combinations have also shown promise. Generally, it has been our experience that liquid or semi-liquid lubricants are more effective than solid lubricants. The self-healing qualities of a lubricant appear to be very important.

Fretting tests on lubricated samples have often produced some increases in contact resistance, generally we have seen this on long term tests in which wear had been very severe. The DTE fretting test can produce resistance increases (of the order of 100%) after a few hundred cycles with lubricated samples, whereas similar increases are observed on the rotational fixture only after tens of thousands of cycles. Lubricants do vary in their effectiveness against fretting corrosion, and our current effort is directed toward identifying the best formulation for the specific use on electric contacts. At the time of writing this paper several promising candidate materials are being tested, and the results on one are shown in Figure 15.

CONCLUSION

We have shown that all of the more commonly used non-noble contact materials experience large increases in resistance during fretting action (small amplitude cyclic motion). The results of our tests were such that a warning could be issued concerning the indiscriminate use of such materials in applications where fretting action could occur on electric contacts as a result of vibration, mechanical motion, or differential thermal expansion. Resistance increases noted during fretting action are felt to be due to trapped wear debris composed mainly of oxides. This process is commonly referred do as "fretting corrosion." Lubrication has been identified as a very good deterrent to fretting corrosion; the important mechanisms imparted by lubrication are postulated as: first, a reduction in wear; second, that the treatment aids in the self-cleaning and flushing of wear debris from contacts; and finally, and perhaps most important, liquid lubricants have the ability of excluding oxygen from the contact, thus preventing oxidation of wear debris and freshly exposed contact material.

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