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Impact of Corrosion on Fretting Damage of Electrical Contacts

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***Abstract*—Electrical contacts are used in a large number of industrial applications, this includes all sorts of modern transportation: airplanes, trains and automobiles. Mechanical assemblies are subjected to vibrations and micro-displacements between mating surfaces are observed leading to fretting wear. Mechanical degradation can additionally be accelerated by a corrosive factor caused by variable humidity, temperature and corrosive gas attack. Fretting-corrosion leads to an increase of contact resistance or intermittent contact resistance faults as corrosion products change the nature of the interface primary through a range of film formation processes. In this work the impact of a corrosion product film formed on copper and gold surfaces on the electrical contact fretting behavior is shown. It has been observed that modification of the interface by the formation of the surface layer can surprisingly lead to increase of the electrical contact durability.**

Keywords-connectors, fretting corrosion, sliding regimes, passive layer

I. INTRODUCTION

Safety, but often also life, of vehicles' users depends on electrical contacts reliability. They are extensively used in all sorts of modern transportation: airplanes, trains and automobiles. The global tendency to equip all units with new electronic and computer control, steadily increases the number of electrical contacts in a single vehicle. Some high specification vehicles have hundreds of meters of wires and more than 400 connectors with 3000 individual terminals on board [1]. Safety and comfort issues strictly rely on electronics with systems like antilock braking, traction control, airbags or navigation, so the integrity of electrical contacts is often crucial. The design of a typical electrical contact defines one characteristic contradiction: connections must be detachable for an installation and service, however during normal usage the separation of two parts is undesirable. Vibrations as well as thermal cycling in all transportation applications are common and cannot be excluded, which causes small relative displacements, typically tens or hundreds of micrometers between mated components of a connector. Two damage mechanisms take place: (i) the top layer of a connector wears away and (ii) a passive film is formed at the interface. In the case of (i), pure mechanical damage is observed, while in the case of (ii) also intensive corrosion processes are involved. The overall degradation process is called fretting-corrosion and leads to an increase of contact resistivity or intermittent contact resistance faults. The process can be accelerated by corrosive gas attack (typical for under-hood conditions) and increased relative humidity. It has been estimated that up to 60% of all car electric problems relate to degradation of electrical contacts by fretting [2].

Current research in the field of electrical contacts durability is mainly focused on the following issues: three body tribo-contact modeling with two rubbing members and insulating wear debris layer [3]; physical characteristics of vibration conditions [4]; monitoring of fretting sliding regime as contact damage is mainly related to gross slip condition [5]; impact of variable environmental conditions: relative humidity and temperature [6]; fretting-corrosion resistance of connectors in a DC 42 V electrical system [7]. A major scientific contribution expected from fretting corrosion research is to assure equal durability of the electrical contacts with other mechanical parts of a system. For the automotive industry, it means that all connections must maintain low contact loop resistance as long as the life of the vehicle to avoid power losses.

In this work, the effect of corrosion on mechanical degradation of electrical contacts is shown. Copper and gold samples have been pre-treated in a corrosive media to build a corrosion product layer on the surface. On gold, this is very thin layer and does not comprise what would normally be referred to as corrosion product. Unique behavior of the treated surfaces has been revealed and analyzed.

II. METHODS

A. Materials

Two types of materials have been selected for this study. Hard Drawn High Conductivity copper (HDHC, 99.9 wt.% Cu) is widely used in general electrical contact applications as it combines excellent contact performance with good mechanical properties. A series of 10mm long samples has been cut off from the 5mm diameter rod. As a second material, male components of the Lemo Company Series F electrical connectors have been used (Ø 1.5mm). Series F connectors are originally designed for demanding motorsport market, single terminals are made of brass (UNS C 34500) and coated with copper (0,5μm), nickel (3μm) and top layer of gold coating (1μm). Copper and gold surfaces have been tested in two states: (i) in the as-delivered clean state and (ii) after pre-exposure to modify the near surface. The pre-exposure was

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conducted by immersion of samples in sea water (3.5% wt. NaCl) three times for 24 hours with 24 hour intervals in air.

B. *Test configuration*

Fretting experiments have been carried out using the MUST tester manufactured by Falex [8]. A reciprocating sliding between samples arranged in crossed cylinders geometry has been applied (Fig. 1). The test program has been carried out under 0.5N and 1N normal load (N), 10μm to 25μm displacement amplitude (δ), and at the 1.2Hz to 2.5Hz frequency (f). The normal load has been kept constant, while the friction force (Q) and displacement amplitude have been recorded. Tests have been conducted in a room environment at the 20-22°C temperature and 45-50% relative humidity. The *four-wire* measurement technique has been applied as a particularly accurate way to measure small resistances. The value of 500mΩ has been assumed as a representative limit of electrical resistance for electrical contacts used in the automotive industry [9].

C. *Sliding conditions under fretting*

Different damage mechanisms involved in fretting are related to the sliding conditions at the interface and the following fretting regimes were distinguished [10]:

- stick regime: the interfacial sliding between two bodies does not occur as displacement is accommodated by elastic deformations. The stick domain is maintained by locked asperities that can be plastically shared in the direction of micro-movement. Low fretting fatigue damage can originate mainly by crack nucleation and propagation. For this regime, the evolution Q=f(δ), called fretting log, takes form of closed linear relation (Fig. 2a);
- stick-slip regime: even though sliding does occur, the stick zone is a dominating area in the contact. Surface degradation is characterized by cracking as a result of contact fatigue particularly close to the stick-slip boundary. If rough surfaces are subjected to contact, the stick zone can be spread for a number of single contacts. The Q - δ curve takes a characteristic elliptical shape hysteresis (Fig. 2b);

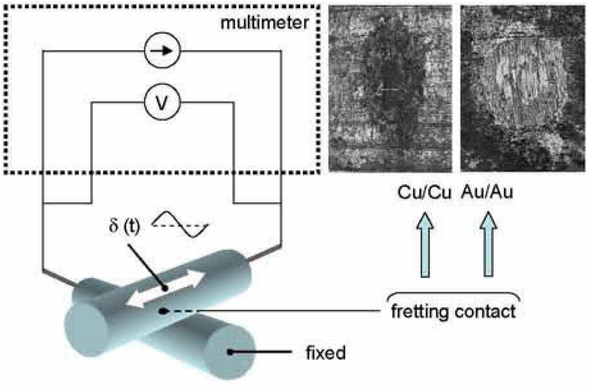

Figure 1. Schematic of experimental fretting assembly.

- gross slip regime: with still higher displacement amplitude, the stick zone no longer occurs and the entire contact area is subjected to sliding. In this regime, the wear mechanism takes place by debris formation (by creating and breaking the adhesive junctions). The debris can also remain within the contact area as abrasive particles. The maximal tangential force does not depend upon the sliding amplitude and can be described by the classic Amonton's friction law: Q=μP. The evolution of the fretting log in this regime takes more quadratic shape (Fig. 2c).

The above approach was then developed [11] by defining three fretting regimes for the running conditions recorded during the fretting test and the Running Condition Fretting Map was proposed (Fig. 3):

- partial slip regime (PSR) corresponding to the condition when stick-slip sliding regime is maintained during the running test, observed for the smallest amplitudes;
- gross slip regime (GSR) corresponding to the condition when gross slip sliding regime is maintained during running test, observed for the largest amplitudes;
- mixed fretting regime (MFR) corresponding to the condition when the gross slip and partial slip regimes are present in one fretting test, observed for intermediate amplitudes.

III. RESULTS

Evolution of the contact resistance as a function of fretting time for different loading conditions, materials, with and without the pre-exposure surface layer is depicted in Fig. 4. Because of space limitations, only selected sets of data are presented here. For each experiment, representative shapes of the fretting loops from the beginning and end of the test are included to indicate the fretting regime of the tribo-couple.

The first row of graphs (Fig. 4a-c) gives results for copper/copper contact with clean surfaces and all three experiments are maintained within the gross slip fretting regime. It is shown that increase of normal load from 0.5N to 1N (under equal displacement amplitude) is related to the increase of electrical contact durability. At the same time, an increase of displacement amplitude from 15μm to 25μm (under equal normal load), significantly decreased the durability of the contact.

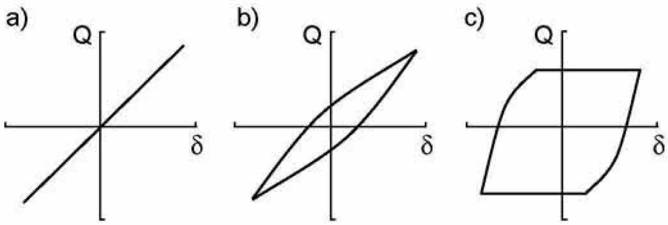

Figure 2. Fretting log characteristics for different fretting regimes: (a) stick regime; (b) stick-slip regime; (c) gross slip regime.

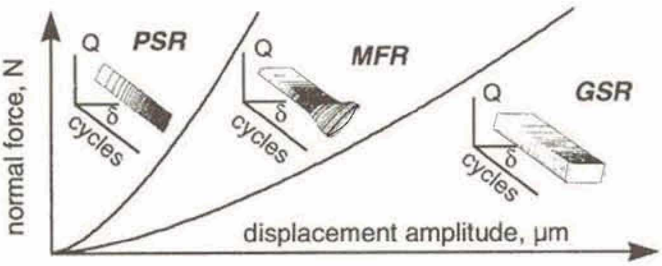

Figure 3. Running Condition Fretting Map [11].

The second row of graphs (Fig. 4d-f) presents contact resistance curves for the same loading conditions as discussed above, however with the passive layer formed on the copper samples' surface. It can be seen that modification of the interface caused both extended durability of the contacts and passage (in two cases) from the gross slip to partial slip fretting regime. It is interesting, that after initial high resistance related to the presence of the passive film followed by low resistance of the contact after passive film removal, characteristic increase of the contact resistance is not observed.

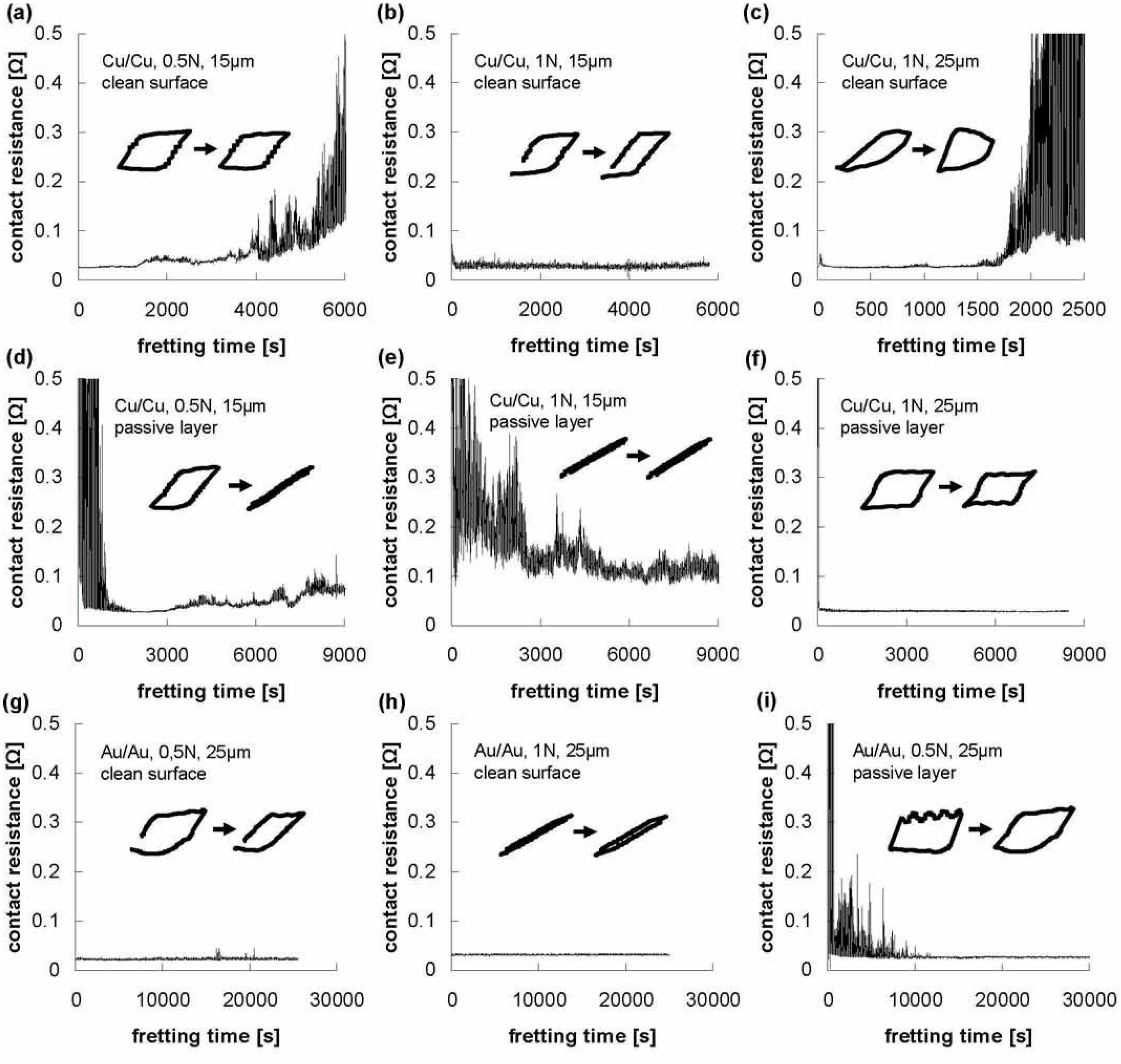

Figure 4. Evolution of the contact resistance as a function of fretting time with the fretting loops corresponding to the beginning and the end of each test.

The last row of graphs (Fig. 4g-i) depicts data for gold/gold fretting contact with clean and passivated surface. In that case, in spite of much longer test durations, building of the passive layer does not take place independently of the loading conditions and state of the sample surface. Increase of normal load from 0.5N to 1N (under equal displacement amplitude) caused a shift from gross slip to partial slip fretting regime.

It has been observed that presence of the passive layer was conducive to the higher coefficient of friction (COF) values. Comparison of mean COF for several fretting tests on clean surfaces and coated with the passive layer is shown in Fig. 5. Generally the gold/gold interface is characterized by higher friction. It can also be noticed that in the case of copper, an increase of displacement amplitude is related to higher COF values.

IV. DISCUSSION

A. Fretting contact exposure surface

Bibliographical sources quote different values of displacement amplitudes as a border between fretting and reciprocating sliding motion. This value is variously interpreted and contained within a wide range of amplitudes between 50 and 300μm [12-14]. This issue can be clarified by introducing the "*e*" coefficient [15], which is defined as a sliding ratio:

$$e = \delta / a \qquad (1)$$

where:
δ – sliding amplitude, which is different from the displacement amplitude due to the contact and testing device compliance;
a – Hertzian contact radius.

The tribo-system remains in the fretting regime (e<1) when the unexposed surface is maintained at the centre of the fretted surface. The system goes into the reciprocating sliding regime (e>1) when all the surface of mutual contact is exposed to the atmosphere. The sliding ratio can be also applied to indicate the unexposed surface of the fretting contact area (Fig. 6). The lower value of the *e* coefficient the bigger is the unexposed fretted surface. Exposure of the tribo-contact to the atmosphere has a key meaning in the oxidation process, as there is limited air access to the contact surface layer as well as wear debris within the limits of unexposed surface. Sliding ratio values for copper contact under applied normal loads are listed in Table 1.

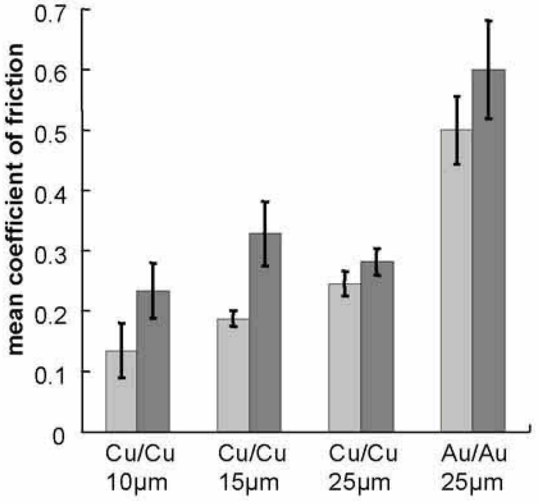

Figure 5. Mean coefficient of friction for different fretting tests (P=0.5N). Each first column – clean surface, each second column – surface with passive layer.

TABLE I. SLIDING RATIO FOR CU/CU CONTACT WITHOUT PASSIVE LAYER.

Displacement amplitude δ(μm)	*Sliding ratio e*	
	P=0.5N	*P=1N*
10	0.43	0.34
15	0.65	0.52
20	0.87	0.69
25	1.09	0.86

B. Impact of loading conditions

One of the ways to increase the durability of the electrical contact is to limit the sliding at the interface and maintain the stick-slip regime [5]. According to the Running Condition Fretting Map theory, it can be achieved by increasing the normal load. Higher normal load induces higher tangential force and changes the shape of the fretting loop by shortening the sliding part of the hysteresis (Fig. 7). In fact, the actual sliding amplitude is shorter under higher loads than the nominal one. Shorter sliding distance means that the unexposed surface is larger. In case of Cu/Cu tribo-couple under 15μm displacement amplitude (Fig. 4a, b), the durability of the electrical contact under 0.5N normal load (e=0.65) is much shorter than under 1N (e=0.52). For gold contact, increase of applied normal load caused even shift from gross slip to partial slip regime for the same displacement amplitude (Fig. 4g, h).

Increase of displacement amplitude, as expected, leads to reduction of the unexposed surface area and, as a result, shorter lifetime of the electrical contact. Change of the amplitude from 15μm to 25μm, under 1N normal load (Fig. 4b, c), leads to the increase of sliding ratio from 0.52 to 0.86.

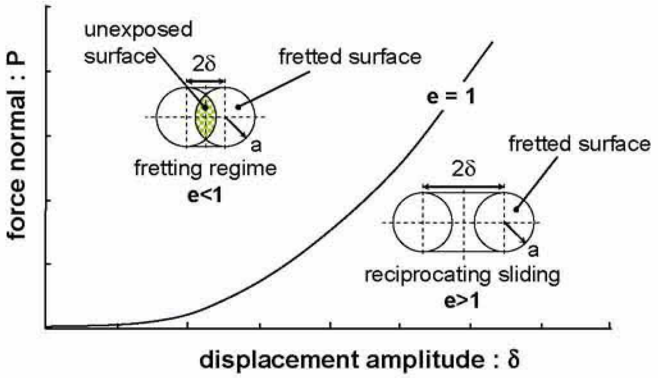

Figure 6. Definition of sliding ratio *e* and identification of transition between fretting regime and reciprocating sliding motion.

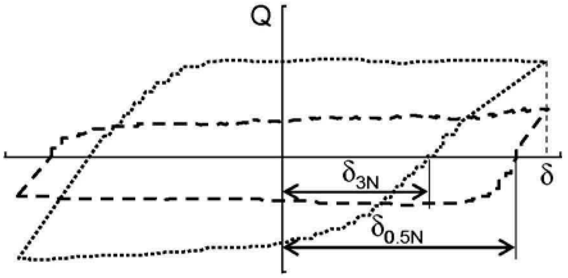

Figure 7. Identification of the actual sliding amplitude under two different normal loads for Cu/Cu contact (clean surface, δ=25µm).

C. *Impact of pre-exposure and surface film modifications*

The sliding interface has been modified by the presence of the formed passive film and durability of the electrical contacts has been extended. An increase of the mean coefficient of friction has been recorded for all samples with passive film. Higher tangential force is again a factor responsible for change of sliding conditions at the interface. In some cases, a shift from *gross* to *partial* or from *gross* to *mixed slip* fretting regime has been observed, compared to clean surfaces under the same loading conditions. The passive film is worn out more quickly under bigger displacement amplitudes.

The interesting question to pose is why the high resistance state of the electrical contacts has not been reached after degradation of the formed passive layer. The crucial factor seems to be the incubation period of the sliding contact as the first few hundred fretting cycles appear to determine the overall degradation process of the mated surfaces. It has been shown that metallic materials subjected to alternating sliding, tend to generate a specific transformed layer on the top surface [16]. This layer, called tribologically transformed structure (TTS), has a particular nanocrystalline structure, corresponding to the chemical composition of the primary material. Under successive fretting cycles, TTS is fragmented and wear debris is generated (Fig. 8). Wear debris is then subjected to the progressive oxidation process and, as a result, sliding surfaces are separated by a film of fully oxidized particles.

Clean copper surfaces follow this classical degradation mechanism and, under particulate loading conditions, the resistance of the contact has reached the critical value of 500mΩ. However, in the case of surfaces with a passive layer, this process has been disturbed. Gold/gold contacts have not shown the resistance increase and the degradation mechanism is related in that case to adhesive wear promoted by higher friction.

V. CONCLUSIONS

In this work, some preliminary results of the broader research program on interaction between corrosion and fretting damage of electrical contacts have been presented. Nevertheless, even this introductory study has revealed some crucial results and indicated the importance of corrosion in overall fretting-corrosion degradation process. The following conclusions can be drawn:

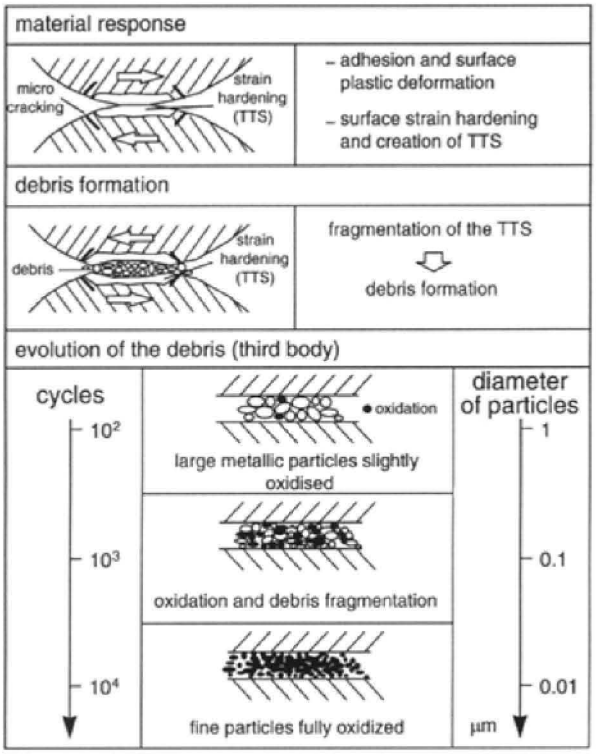

Figure 8. Generation and evolution of the third-body at the contact interface [17].

- Durability of the electrical contacts is strictly related to the sliding conditions at the interface. Sliding ratio can be applied to indicate the unexposed surface of the fretting contact area, which has an impact on intensity of the oxidation process.
- After initial high resistance related to the presence of the passive film followed by low resistance of the contact after passive film removal, characteristic passivation of the contact is not observed.
- Higher normal load induces smaller sliding amplitude and increase of contact durability.
- Larger displacement amplitude leads to reduction of the unexposed surface area and, as a result, a shorter lifetime of the electrical contact.
- Increase of mean coefficient of friction has been established for all samples with passive film.

The undertaken research program will be continued by investigations directed towards understanding the mechanism of electrical contact surface modification. The answer for the following question needs to be provided: how to benefit from the fact that chemical treatment of the surface leads to an increase of contact durability? Future challenges include wear debris analysis, focus on the initial state of the surfaces with characterization of the surface energy and fretting experiments under wider spectrum of loading conditions.

Gold-plated electrical contacts show outstanding fretting-corrosion resistance but due to high costs, their application is limited in medium and low specification vehicles. With dramatically increasing prices of gold market rates during last years, manufacturers would appreciate reliable design of cheaper electrical contacts.

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REFERENCES

[1] G. Bolger, "The selection of automotive connectors", Senior Thesis, Coventry Univ., U.K., 1997.

[2] J. Swingler and J.W. McBride, "The synergistic relationship of stresses in the automotive connector", Proc. 19th Int. Conf. Electric Contact Phenom., Nuremberg, Germany, 1998, pp. 141-145.

[3] C.E. Heaton and S.L. McCarthy, "High cycle fretting corrosion studies on Tin-coated contact materials", Proc. 47th IEEE Holm Conf. on Electrical Contacts, Montreal, Canada, 2001, pp. 209-214.

[4] G.T. Flowers, F. Xie, M.J. Bozack and R.D. Malucci, "Vibration thresholds for fretting corrosion in electrical connectors", IEEE Transactions on Components and Packaging Technologies, 27 (2004), pp. 65-71.

[5] S. Hannel, S. Fouvry, Ph. Kapsa and L. Vincent, "The fretting sliding transition as a criterion for electrical contacts performance", Wear, 249 (2001), pp. 761-770.

[6] N. Saka, M.J. Liou and N.P. Suh, "The role of tribology in electrical contact phenomena", Wear, 100 (1984), pp. 77-105.

[7] K. Takahashi, O. Sakaguchi, T. Yamamoto and H. Inaoka, "Investigation of contact materials in 42VDC automotive relay", Joint 22nd Int. Conf. on Electrical Contacts & 50th IEEE Holm Conf. on Electrical Contacts, Seattle, USA, 2004, pp. 22-27.

[8] S. Achanta, D. Drees and J.-P. Celis, "Friction and nanowear of hard coatings in reciprocating sliding at milli-Newton loads", Wear, 259 (2005), pp. 719-729.

[9] A.K. Rudolphi, et al., "Fretting testing of electrical contacts at small displacement amplitudes – experience from a BriteEuram project", in: Proc. of 20th Int. Conf. on Electrical Contacts, Stockholm, Sweden, 2000, pp. 471-476.

[10] O. Vingsbo and S. Soderberg, "On fretting maps", Wear 126 (1988), pp. 131-147.

[11] L. Vincent, Y. Berthier, M.C. Dubourg and M. Godet, "Mechanisms and materials in fretting", Wear 153 (1992a), pp. 135-148.

[12] J.S. Halliday and W. Hirst, "The fretting corrosion of mild steel", Proc. Roy. Soc. A 236 (1956), pp. 411-425.

[13] N. Ohmae and T. Tzukizoe, "The effect of slip amplitude on fretting", Wear 27 (1974), pp. 281-293.

[14] S.C. Gordelier and T.C. Chivers, "A literature review of palliatives for fretting fatigue", Wear 56 (1979), pp. 177-190.

[15] S. Fouvry, Ph. Kapsa and L. Vincent, "Quantification of fretting damage", Wear 200 (1996), pp. 186-205.

[16] P. Blanchard, "Usure induite en petits débattements: TTS d'alliages de titane", Thèse Ecole Centrale de Lyon, No 91-32 (1991).

[17] E. Sauger, S. Fouvry, L. Ponsonnet, Ph. Kapsa, J.M. Martin and L. Vincent, "Tribologically transformed structure in fretting", Wear 245 (2000), pp. 39-52.