Investigations on Electrical Contacts Subjected to Fretting Motion

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Abstract

This paper discusses the results and the consequences of the results obtained in a finished project on fretting testing at very small amplitudes. In this project a crossed cylinders model contact (radius 2.5 mm) was tested mainly in tangential oscillatory modes with strokes 2-100 µm, with forces between 0.5 and 5 N and frequencies of 1 and 10 Hz, financed by the European Commission.
For non-noble contact platings it has been shown that very small amplitudes (< 10 µm) result in surface damage and contact failure. For noble platings it results in surface damage, only followed by contact failure after wear causes exposure of the non-noble underlayer.
The most important conclusion from the project work was that the contact resistance remains low and stable in partial slip, while gross slip causes electrical failure(>0.5 Ω).
In this paper the following items are discussed: i) The application of the Mindlin theory to predict the transition from partial to gross slip ii) Aspects of tribo simulation testing of electrical contacts iii) The methods of extending the allowable external displacement amplitude by additional springs that absorb part of the motion, and iv) The options if large vibrations at the contact interface can not be avoided.

1 Introduction

Fretting is an important degradation mechanism for electrical contacts. Fretting is defined as small-amplitude oscillatory motion.. Fretting causes surface damage by surface fatigue, wear and, depending on ambient conditions, tribo-chemically accelerated corrosion. The most important causes of movement are vibration (many cycles per second) and differences in thermal expansion (one or few cycles per day). Both sources of motion are known causes of electrical failure from connector contacts. The economic impact of such failures can be enormous, roughly estimated there is an annual production amounting to a trillion connections, of which about 200 billion for the automotive market place (derived from figures by Bishop & Ass. Inc.). It makes clear that electrical failures will be a source of damages, irritations and frustrations when connection systems are not well designed and properly applied.
This paper presents the major outcome from an EC financed BriteEuram project, initiated to address these problems, specifically for the European automotive marketplace. Among the participants were a number of universities, automotive OEM's and connector manufacturers, as listed in the acknowledgements.
The main objectives were:

- To generate basic knowledge on material behaviour and surface degradation in not lubricated connector contacts
- To establish a connection between electrical functionality and slip conditions
- To explore a number of material combinations for connector contact surfaces.

A major part of the project results have already been presented at previous ICEC-Conference in Stockholm. Hannel et.al. from EC-Lyon (F), describe the finite element modelling [1], and measurements that confirm the relationship between fretting amplitude and electrical stability [2]. The fretting test rig properties and the methodology of testing is described by Kassman et. al. [3].

2 Transition from partial to gross slip

The contact situation of a curved surface in facing a plane (ball-on-disk) is schematically shown **in Figure 1**, where the contact area is divided into a central stick and a surrounding slip area.

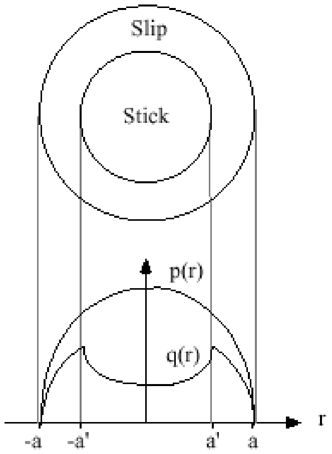

Fig 1: Pressure p(r) and tangential force q(r) distributions of an elastic fretting contact for a sphere on flat under partial slip conditions

A scanning electron microscope (SEM) micrograph of a fretting wear scar on a tin coated specimen is shown in **Figure 2.** It exhibits the division of the scar into a central stick area and a surrounding slip area.

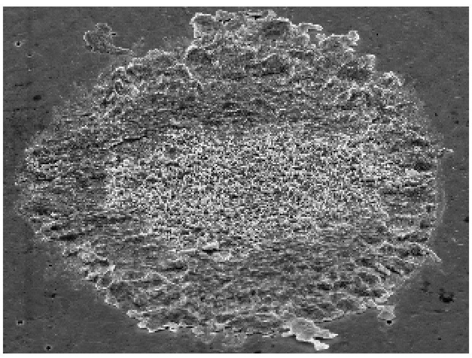

Fig 2: Surface appearance of a tin coated contact tested in the partial slip regime

When cyclic forces act on a tribocontact a relative motion can occur. If the forces are small and the friction is high there is only elastic deformation in the contact, causing very small relative motion between the mating elements. When the forces increase slip motion begins, in a ball on flat contact at the rim of the contact zone (slip circle) while the central area owing to the higher Hertzian stresses still sticks (stick zone). This situation is named "partial slip". The size of this stick zone shrinks when the external forces exceed a critical value, above which the entire contact suffers sliding ("gross slip") [4].

The main mechanism of damage in the partial slip region is fatigue, while in the gross slip region additional wear and tribo-oxidation occur. The wear rates under gross slip conditions are usually much higher than in the partial slip regime. Consequently, in practical applications one has to try to avoid the gross slip regime.

This can be achieved by reducing the external forces or by increasing the friction forces. The increase of friction force can be obtained by increasing the normal forces or by increasing the coefficient of friction. The increase of normal forces, however, is limited by constructional boundary conditions, the increase of coefficient of friction (by the choice of material or coatings) is limited by requirements of electrical functionality. Some aspects of reducing acting forces are covered later (Chapter 5).

3 Aspects of tribological simulation tests for electrical contacts

The general rule for tribological tests is to choose test parameters as close as possible to that of real running conditions. Therefore, newly developed materials or designs have to be checked prior to applications in practice. Commonly used "shaker" tests are helpful to investigate electrical performance of contacts under near-practice conditions. This type of test is, however, rather time consuming. In order to steer the development of coatings simple laboratory tests can give inside in dominating mechanisms and can provide preliminary information.

3.1 Tribo test rigs

In the scope of the "Elecon" project different test rigs were used by different partners. For the generation of screening results cyclic motion in the gross slip fretting regime (stroke 10 µm - 100 µm) was applied to self-mated tribo contacts. Additional tests were performed in the regime of transition from gross slip to partial slip.

3.2 Materials and specimens

All partners used identical specimens made of a tinbronze connector base material (CuSn4) with a cylindrical bulge with a radius of 2.5 mm, **Figure 3**.

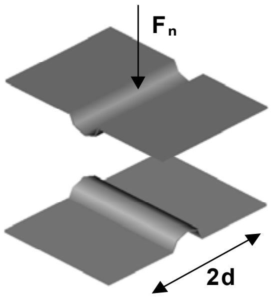

Fig 3: Specimen arrangement for "crossed cylinders" [3]

Coatings used for basic investigations were hot dipped tin (HDT), tin intermetallic (IMP, tin in a heat treatment converted to Cu-Sn intermetallic phases), and Ag and Au with a nickel underplate. All were applied on the tinbronze base material (CuSn4) in a commercial galvanic production line.

3.3 Tribotesting

In tribo tests, two specimens of the same material (coating) were brought into contact according to Figure 3, resulting in an initial point contact.

The benefit of this contact geometry is that specimens can easily be formed of original connector material and that the wear of both specimens can be calculated from the size of the wear scars which increases when wear precedes.

Optical micrographs of typical wear scars on an uncoated specimen and on a hdt coating [6] are shown in **Figure 4**.

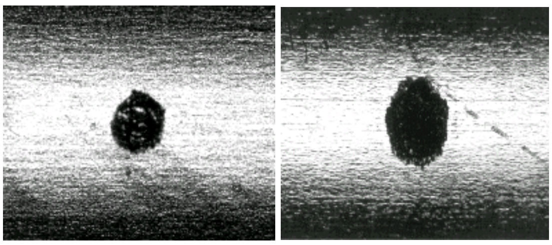

Fig. 4: Wear scars on uncoated CuSn4 and on a hdt coated specimen after gross slip fretting

The advantage of model tests is the good access to friction, wear, and electrical measurements. The coefficient of friction (friction force divided by normal force) can be recorded during a test. The wear of both specimens in a tribo contact is too small to be measured continuously, quantification of wear is possible after a test and can be calculated from the size of a wear scar (compare Figure 4).

The most important quantity in connector investigations is the electrical contact resistance (R_c) that can be measured by means of a four wire circuit with a resolution of 1 mΩ.

4 Selected results

4.1 The transition from partial slip to gross slip

The transition from partial to gross slip for different materials up to 5 N normal force was determined by EC-Lyon [2], see **Figure 5.**

The evolution of the electrical resistance has been monitored during cycling with different stroke lengths. The result in **Figure 6** (uncoated couple) and **Figure 7** (tin coated couple) confirm that the transition between partial and gross slip takes place at 2-5 µm and coincides with the transition from stable to unstable electrical behaviour.

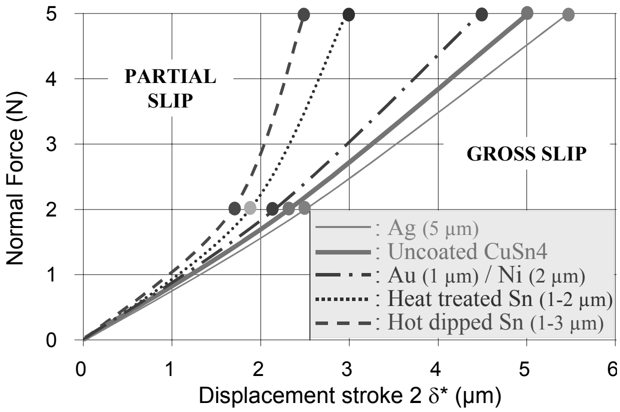

Fig 5: Running condition map for different coatings after 10 000 cycles at 10 Hz with 2 N and 5 N load at 45 - 50% R.H.

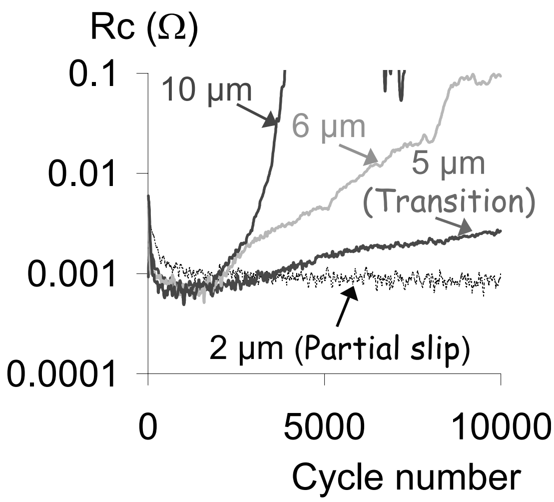

Fig. 6: Evolution of electrical resistance in tests with different strokes; uncoated couple

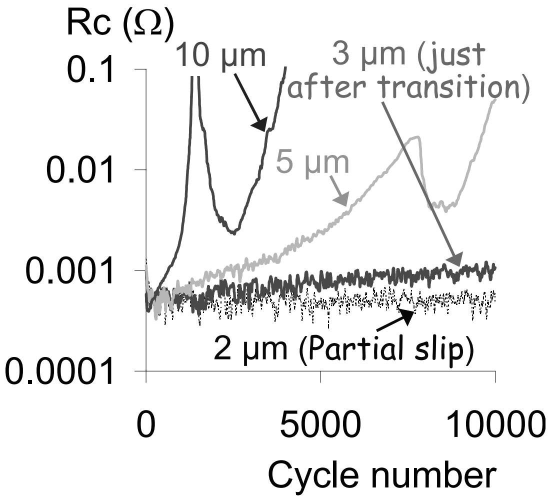

Fig. 7: Evolution of electrical resistance in tests with different strokes; hot dip tin coated couple

4.2 Influence of humidity

In order to demonstrate the possibility of model tests, all materials were investigated in dry, normal and moist air. **Figure 8** shows exemplary the influence of moisture content on the evolution of electrical resistance for a couple of CuSn4+IMP specimens.

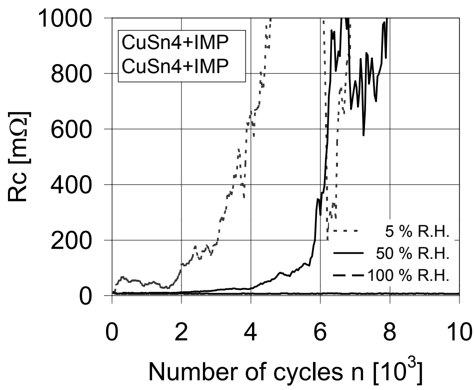

Fig. 8: Evolution of electrical resistance in gross slip fretting tests with CuSn4+IMP couple in dry, normal, and moist air

While in dry air a high resistance is measured rather shortly after the beginning of cyclic motion, the increase of resistance starts later in normal air and does not occur in moist air. **Figure 9** summarises the influence of humidity for different coatings materials. These results illustrate the importance of the control of humidity in laboratory testing. One has to keep in mind that real connectors are subjected to environmental changes in the daily duty.

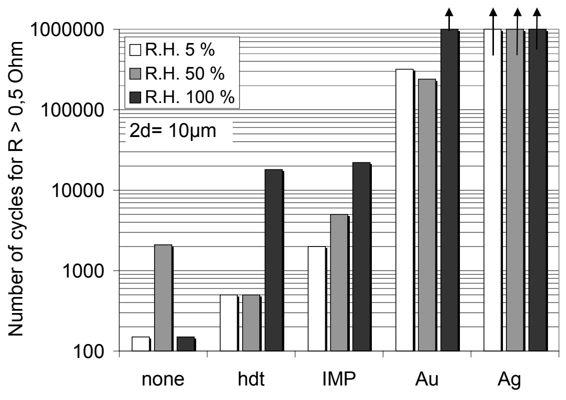

Fig 9: Influence of relative humidity (R.H.) on the "life time" of different coatings

4.3 Evolution of electrical resistance in normal air

Another example of the benefit of model testing is the direct comparability of different materials of course running under identical test conditions. **Figure 10** shows the evolution of electrical resistance in tests with the bare connector material in comparison to hdt coated samples and IMP coatings. While the hdt coating shows an earlier electrical degradation than the uncoated couple, the IMP coating has an increased life time.

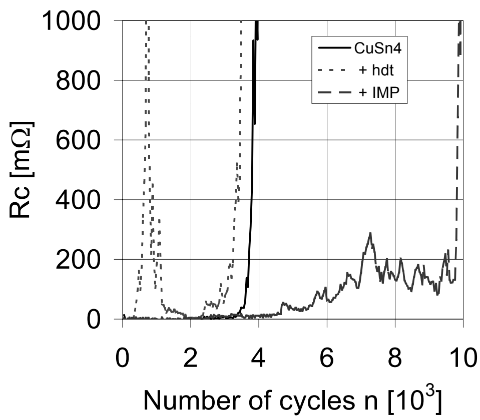

Fig. 10: Evolution of electrical contact resistance in gross slip fretting tests with couples of CuSn4, CuSn4+HDT and CuSn4+IMP in normal air, 2d = 20 µm, frequency 10 Hz

4.4 Influence of coating thickness

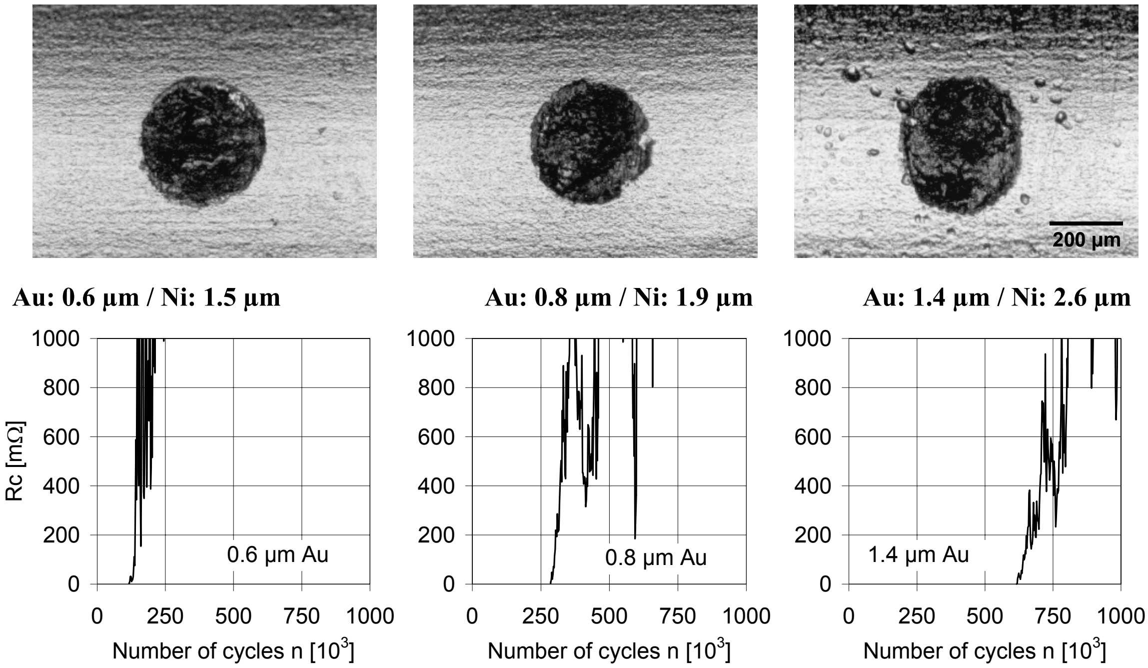

Fig 11: Optical micrographs of wear scars on Au coating (with Ni underlayer) of different thickness (top) and evolution of electrical contact resistance, gross slip tests with 20 µm stroke in normal air

With model tests the effect of coating thickness on "life time" can be evaluated. **Figure 11** shows the evolution of electrical resistance for three gold coated specimens with different thickness. The number of cycles, when a drastic increase of R_c starts, increases with increasing thickness.

The two above examples provide preliminary information of the possibilities of model testing. Many of the relevant parameters can be varied (temperature, humidity, external current, etc.) and their effect on coating performance can be studied separately.

5 Methods of extending the allowable displacement

It can be derived from the Mindlin theory that a certain lateral travel between two contacts is possible while maintaining a central stick zone which makes a stable electrical contact. In this theory one contact is assumed to move laterally, while the other contact is rigidly fixed. In other words the Mindlin theory takes into account the elastic deformation of the material in the contact zone, directly surrounding the contact spot. For normal-forces as usual in connectors such zone is about 50 µm in diameter and 100 µm deep. In practice there is additional elasticity, each contact zone is part of a supporting mechanical structure consisting of the contact pin or spring and the boundary conditions of their fixation. The elasticity of the supporting structures works in addition to the compliance of the contact zone and helps achieving a central stick zone and thereby electrical stability, see **Figure 12**.

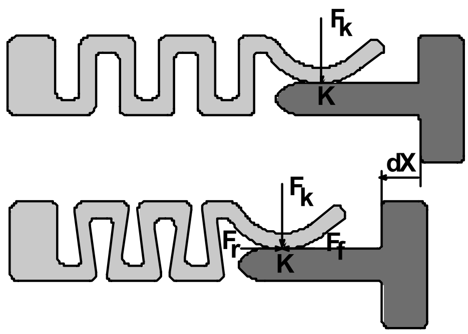

Fig 12: Scheme of anti-fretting spring design

In other words: the mechanical structure determines how much more lateral motion can be accommodated above the lateral elasticity of the contact zone. Horn et. al. [7], Kassman-Rudolphi and Jacobson [8] and v. Dijk and v. Meijl [9] have described the principle and the associated calculations in more detail.

They describe examples where 40-50 µm has been accommodated, which is an order of magnitude more than the contact zones alone can provide. Field experience shows that a compliance of this size is sufficient for virtual all applications.

This solution, however, introduces a new point of consideration: fracture of contact springs due to fatigue. Vibration will cause that stresses in the spring material alternate instead of a fretting motion taking place, which under extreme circumstances can lead to fatigue.

Another point of consideration is the effect of lubrication and of the coefficient of friction. The maximum of the lateral distance that a contact can move while maintaining a central stick zone is proportional to the static coefficient of friction: the higher the friction the better. The contrary is true in a situation where gross slip does occur: the lower the friction the lower the wear rate. This means that it is important to mechanically analyse a contact system before a decision is made about lubrication.

6 If large vibrations cannot be avoided

When gross slip cannot be prevented the contact surfaces must be sufficiently environmental stable and the wear rate should be low. For unlubricated non-noble materials under gross slip conditions, wear processes quickly induce oxidation and formation of an electrically insulating layer at the contact interface. How quickly this occurs depends for example on humidity (see Figure 8 and 9).

Two possible routes are possible. The first route is to use noble coating materials. The Elecon project showed that gold and silver are excellent candidates under sliding conditions, see Fig. 9. (It should be noted however that aggressive environments were not simulated).

Gold is expensive, however with selective application cost can be reduced to about 10% of connector cost. Silver may deserve more attention than it gets today. The cost of silver is low enough to have hardly any impact on connector cost. However, protection against sulfidation is important.

The contact lifetime of silver and gold coated contacts during gross slip depends on the wear rate of the coatings. Gold and silver are both relatively soft materials. In order to increase the wear resistance several actions have been suggested, e.g. inclusion of nano-particles in the plating layer, inclusion of lubricant droplets in the plating layer, and multi-layered platings. Also for such coatings it is important to study the effect of underplatings and plating thickness, compare Figure 11.

The other possible route is to use a copper alloy (with or without a plating) and a lubricant that shields the contact interface from the surrounding atmosphere. Drawbacks and inherent difficulties with lubricants are that:

- lubricated surfaces can retain dust,
- there is a risk of removal during handling or by cleaning,
- the long term and high temperature properties are not well known/tested,
- the control of quality and of quantity in the contact area is difficult,
- the methods of application are not well developed and
- there is a possible problem with the compatibility to sealing and housing materials.

Still lubrication is a route to deal with the fretting problem in a cost effective way. Both the lubricant and the application method must be environmentally friendly. Thus, lubricants should preferably be solvent-free and be applied solvent-free. Longer life of connectors is by itself good for the environment, considering that complete products are often thrown away when just the connectors start failing.

Preferably the lubricant should be applied in the production line of the connector and only on the areas of interest. Here, ink-jet or lithographic offset techniques may be considered. Of interest could also be different ways to include lubricant droplets in the plating or ways to structure the surface in order to produce lubricant reservoirs.

7 Conclusions

The following conclusions are based on results produced in a finished EC financed BriteEuram project and from the discussion of the results in this paper.

1. Fretting testing under well defined conditions show that **for non-noble surface materials** the transition from partial slip to gross slip is also the transition from stable to unstable electrical behaviour.

2. The transition from partial slip to gross slip takes place at very small amplitude, 2-5 µm, compared to the size of a contact spot, 20-50 µm

3. Theoretical work and Mindlin theory predict the transition from partial slip to gross slip fretting conditions

4. The mechanical structure determines how much more lateral motion can be accommodated above the lateral elasticity of the contact zone. By smart design the supporting structure can accommodate motions of an order of magnitude more than the contact zone alone can provide.

5. When gross slip fretting conditions cannot be prevented the contact surfaces must be sufficient environmental stable and the wear rate should be low. Two possible routes are possible: noble coating material such as gold and silver, or lubricated contacts

6. One can do some screening tests under well defined conditions with materials under development to this. The outcome is always of "screening" character, one has to perform tests on a higher level, more close to practical conditions

7. Proper simulation of fretting conditions in the µm-range requires expert-knowledge and tribological education

8. The improvement of lifetime of electrical contact by coating the connector surfaces without using lubricants is an ecological requirement. The development of coatings for this purpose can be steered by tribological model tests that allow the study of the effect of individual operational parameters.

Acknowledgements

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References

[1] Hannel, S., Fouvry, S and Kapsa, P.: Finite Element Modelling of the fretting transition as the criterion for Electrical Performance, Proc. 20th ICEC Conference 2000, Stockholm, 445-450.

[2] Hannel, S., Abry, J. C., Fouvry, S., Kapsa, P.: Experimental relationship between the Electrical Performance and the Fretting Regime, Proc. 20th ICEC Conference 2000, Stockholm, 451-456.

[3] Kassman Rudolphi, Å. et.al.: Fretting Testing of Electrical Contacts at Small Displacement Amplitudes- Experience from a BriteEuram Project, Proc. 20th ICEC Conference 2000, Stockholm, 471-476.

[4] Vingsbo, O. and Söderberg S.: On fretting maps, Wear, 126 (1988) 131-147.

[5] Buresch, I., Rehbein, P. and Klaffke, D.: Possibilities of Fretting Corrosion Model Testing for Contact Surfaces of Automotive Connectors. Proc. 2nd World Tribology Congress, ed. F. Franek, W. J. Bartz, A Pauschitz. Sept. 2001, 413-416

[6] Klaffke, D. and M. Hartelt: Investigations on fretting performance of connector materials by model tests. Tagungsband 19. Internationale Tagung über elektrische Kontakte, 14.-17. Sept. 1998, VDE-Verlag Berlin und Offenbach, 181-185

[7] Horn, J. et. al.: Avoiding Fretting Corrosion by Design AMP Journal of Technology, Vol. 4, June 1995:

[8] Kassman-Rudolphi Å. and Jacobson S.: The Contact Resistance of Rolling Silver Coated Copper Contacts, Proc.43rd IEEE Holm Conf. on Electrical Contacts 1997, 33-40.

[9] van Dijk, P. and van Meijl, F. A.: Design Solution for Fretting Corrosion, Proc. 42nd IEEE Holm Conference on Electrical Contacts 1996, 375-382.