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Short communication

Introduction of an exponential formulation to quantify the electrical endurance of micro-contacts enduring fretting wear: Application to Sn, Ag and Au coatings

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ABSTRACT

The massive use of electronic control in automotive, plane and energy systems requires the extensive application of in board low current electrical connectors. Subjected to vibrations, the electrical contacts endure severe fretting wear damage (i.e. wear of contacts induced by oscillating small amplitude displacements). One consequence of this fretting wear damage is that oxide debris are formed and maintained within the interface, decaying the electrical transmission of information. To prevent this critical damage, various soft and thin electrolytic coatings like Sn, Ag and Au layers are usually applied. In order to better understand the damage processes and provide a quantitative strategy to select the coating palliatives, an original approach coupling representative experiments and analytical models is introduced. Using a representative micro-fretting system, the electrical resistance evolution is shown to be mainly controlled by the applied displacement and sliding condition. It is confirmed that below a threshold displacement amplitude, related to a stabilised partial slip condition, the electrical endurance is infinite. Above this threshold, when full gross slip conditions are running, a finite endurance behaviour is observed. The electrical endurance is then controlled by the interfacial oxide debris layer formation and the nature of the coating. For non-noble coatings, like Sn, the electrical failure comes about as soon as an oxide debris layer, the so-called "third body" is trapped within the interface, while the endurance of noble and semi-noble materials (i.e. Au, Ag), which is significantly greater, is controlled by the progressive decrease of noble element concentrations in the third body layer and the related increase of its current resistivity. Finally, simple and basic exponential formulations are introduced to rationalise the global electrical endurance of "connector like" micro-contacts subjected to fretting wear. Using this formulation, an endurance ratio is developed to compare the endurance performance of the different coating palliatives.

1. Introduction

Whether it be in the transportation or energy industries, there is now widespread use of electronic control systems. One consequence of this computerization process is the extensive use of sensors and electrical connectors, which indirectly promotes a critical problem regarding the sustainability of electrical contacts and their ability to transmit information [1]. In fact, subjected to heavy vibration, electrical contacts can be degraded by the so-called fretting wear process (alternating micro-displacements) which induce contact wear and the formation of an oxide debris layer (third body) promoting decay of the electrical conductance [2,3]. To overcome this problem, the connector industry is currently working on surface treatment optimizations (electroplating coating, etc.) in order to minimize tribo-oxidation damage. Depending on the loading intensity, non-noble (Sn), semi-noble (Ag) and noble (Au) coatings can be applied. However, the problem is how to draw up, a quantitative strategy to optimize the choice of the palliatives and their required thicknesses, taking into account their endurance and cost restrictions. This research work addresses this aspect, introducing a quantitative approach to formalize the electrical endurance of coating materials as a function of the fretting sliding conditions. Hannel et al. underline the influence of the displacement amplitude on the electrical contact performance [4] (Fig. 1). They conclude that the transition from infinite life-time to finite endurance response is related to the stabilised contact sliding condition. When very small displacement amplitudes are applied, there is a partial slip contact response (PS). This sliding condition is characterized by a narrow, so-called "closed" fretting loop (i.e. evolution of the tangential force versus the applied displacement) and a composite interface structure including an inner sticking zone surrounded by an external sliding annulus. Maintaining an inner sticking zone, without any sliding, promotes good metal–metal interactions, favouring low, stable electrical resistance no matter

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Nomenclature

a, b	constants related to the exponential formulation
A	energy sliding criterion
$A_t = 0.2$	threshold value of the A ratio defining the transition from partial to gross slip for a given fretting cycle
$\bar{A}$	averaged value of the energy sliding criterion over the whole test duration
$\bar{A}_t \approx 0.1$	threshold value of the $\bar{A}$ variable related to the infinite endurance (δ^*_{ilt})
δ	displacement
δ^*	displacement amplitude
δ^*_t	displacement amplitude at the sliding transition
δ^*_{ilt}	displacement amplitude related to the infinite lifetime of the electrical contact endurance
I	stabilised current
Ed	dissipated energy during a fretting cycle
GS	gross slip fretting sliding condition
K_{X_Y}	electrical endurance ratio between coating X and coating Y
μ	coefficient of friction
N_c	number of fretting cycles related to the electrical failure
P	normal force
PS	partial slip fretting sliding condition
Q	tangential force
Q^*	tangential force amplitude
R	electrical contact resistance
r	cylinder radius
ΔR	variation of the electrical contact resistance defined from the minimum electrical resistance $R_{\min}$
ΔR_c	threshold variation of the electrical contact resistance related to the electrical failure
$[X]_{cz}$	relative at.% concentration of element X measured in the central zone of the fretting scar

what the material interface is. The electrical life-time is then infinite.

By increasing the relative displacement above a threshold amplitude (δ_t), the interface undergoes full sliding which eliminates the undamaged inner stick zone. This sliding condition promotes wide dissipating fretting loops, the so-called “open gross slip fretting loops”, promoting wear induced by debris formation. The metallic debris quickly oxidises and agglomerates to form an insulating layer of oxidised debris, the so-called “oxide third body”, which trapped between the two metal surfaces decays the electrical conductance. This so-called gross slip condition (GS) will inevitably result in a finite lifetime of the electrical contact. Applying noble coatings can only delay electrical failure. Indeed, when the sliding interface reaches the non-noble substrate, usually consisting of CuSn bronze, again an oxidized third body layer is formed and the electrical contact resistance increases. Recently, a fast methodology has been introduced to approximate the transition amplitude value δ^*_t [5]. An extended investigation was also made into the influence of the frequency, temperature and ambient condition (i.e. relative humidity), and into the potential importance of Nickel interlayers. Most researches developed in the literature focus on very large reciprocating displacement conditions, far from the PS/GS transition. These researches investigate the dynamics of surface degradation coupling atomic force microscopy analysis and tribo-corrosion aspects [6–10]. It is surprising to note that very little has been done to better formalize electrical endurance under gross slip conditions but just above the sliding transition, thus in the “high cycle” finite endurance domain. Such an investigation could be interesting because it concerns the endurance domain usually observed in industrial applications. Combining various experiments on Sn, Au and Ag coatings, this research will address the following points:

- Clarify the correlation between the displacement amplitude marking the transition towards infinite electrical endurance (δ^*_{ilt}) and the sliding transition amplitude (δ^*_t).
- Define some morphological and surface chemical criteria to characterize the fretting interface at electrical failure.
- Quantify electrical endurance as a function of the imposed displacement amplitude using simple mathematical expressions to simplify the comparison between coating palliatives.
- Positioning the Ag coating solution versus Au and Sn materials using the given analytical formalism.

2. Experimental procedure

2.1. Experimental device

The experimental setup used in this study was specially designed and developed to simulate environmental and loading conditions representative of those observed in a car engine [5]. Fig. 2a illustrates the schematic diagram of the machine. An electromagnetic shaker was used to produce oscillatory motion of the upper holder via flexible strips. The first sample was fixed to the upper holder while the second sample was fixed to the lower table, whose slight horizontal displacement allowed the tangential force to be measured, using a piezoelectric load sensor. The displacement of the upper holder, and hence the upper specimen, was controlled using a laser displacement sensor to an accuracy of about 0.1 μm. Normal force loading was applied using a dead mass attached to the upper holder. Online measurement of the tangential force (Q) and relative displacement (δ) allow the plotting of the fretting loop from which the sliding condition can be identified and the friction response quantified (Fig. 1). Tests were carried out in a closed chamber where both temperature and relative humidity (RH) were controlled and kept constant: 10% RH at 25 °C. The contact parameters which were recorded and controlled during this investigation are frequency fixed at $f = 30$ Hz, normal force fixed at $P = 3$ N, whereas displacement amplitude was imposed between $\delta^* = \pm 2$ and ± 30 μm to quantify the contact endurance as a function of displacement amplitude.

2.2. Contact configuration and electrical resistance measurement system

To simplify the contact analysis and simulate the real contact situation, a 90° crossed-cylinders configuration was used (Fig. 2b). The radius of the cylinders is $r = 2.35$ mm. Note that 90° crossed-cylinders induce a corresponding sphere/plane contact situation which is easier to formalize using Hertz’s and Mindlin’s theories. This also prevents any discrepancy induced by contact misalignments. Assuming an elastic Hertz’s hypothesis and considering a plain CuSn4/CuSn4 bronze contact, it corresponds to a maximum peak pressure around 780 MPa and a 43 μm contact radius (i.e. young modulus E(CuSn4) = 120 GPa, Poisson’s coefficient ν(CuSn4) = 0.34 [4]). Obviously wear and plastic accommodation will extend the contact radius and reduce the peak pressure. However, the contact area is rather small, less than 500 μm diameter, justifying the “micro” contact approach which is presently developed.

Contact resistance measurements were performed using a conventional four-wire method widely used by researchers in the