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Prediction of the electrical contact resistance endurance of silver-plated coatings subject to fretting wear, using a friction energy density approach

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ABSTRACT

Electrical connectors need to display low and stable electrical contact resistance (ECR). However, subjected to vibrations (engines, heat, etc.), fretting wear damages promotes the formation of insulating oxide debris and a sharp ECR increase decaying the information transmission. Noble plated coatings like silver layers are usually applied to delay the ECR failure. However, to predict such ECR endurance, it appears essential to determine the fretting wear rate. In the present study, a homogeneous crossed-cylinders Ag/Ag interface was investigated under gross slip conditions imposing various loading parameters ($\pm 2\ \mu m < \delta_g < \pm 16\ \mu m$, $1\ N < P < 6\ N$, RH=10% and f=30 Hz) for Ag layers from 1.7 μm to 4.8 μm. A global chemical investigation of the fretting scars confirms that ECR failure is reached when most of the silver is removed from the interface and an oxide debris layer is trapped in the contact. ECR endurance (Nc: $\Delta R > 4\ m\Omega$) can be formalized, using a power law function of the mean friction energy density dissipated during a fretting cycle taking into account the contact area extension. Finally, a simple ECR endurance expression is derived as a function of the fretting loading parameters and the thickness of the silver plated layer. A very good correlation between experimental and predicted ECR endurances is achieved.

1. Introduction

Fretting, i.e. micro-displacements between two surfaces, is a recurrent industrial problem. The process is usually observed in mechanical systems such as car engines, subject to vibration, and causes severe damage to electrical contacts.

Connectors have to be reliable and high quality for the security and safety of systems. Most connectors have a very low and stable electrical resistance. However, statistics show that around 15% of breakdowns are due to electrical failure in the connector [1]. Fretting induces contact wear, and the formation of oxide debris layer (third body) may increase electrical contact resistance (ECR) and decay information transmission.

Extensive studies [2–10] have been conducted to determine the mechanisms of electrical contact damage. The first researcher addressing this issue was Antler [11,12]. To resolve the fretting problem, coatings are applied to the connectors to increase ECR endurance and minimize fretting wear.

Hannel et al. [13,14], Kassman-Rudolphi and Jacobson [15] also worked on the influence of sliding regimes on ECR performance, as illustrated in Fig. 1. Small displacement amplitudes promote partial slip inducing an inner metal/metal stick zone. In this case, surface wear and oxide debris are practically non-existent, promoting stable and low ECR. The lifetime of these electrical contacts is infinite. In contrast, above a threshold displacement amplitude (δ_t), gross slip conditions operate. There is no longer a sticking area and wear, induced by the creation of oxide debris, reduces electrical performance, leading to finite electrical endurance. Moreover, under gross slip conditions, electrical endurance strongly depends on the nature of materials. For non-noble layers such as Sn, electrical failure occurs almost instantaneously, whereas for noble layer such as Ag and Au, electrical failure is observed only when most of the coating has worn out.

A gold layer is a suitable material for this application due to its properties (nobility, corrosion resistance, etc.) [16,17]. Evans, Antler and Drozdowicz [18,19] were the first to investigate gold's electrical properties. However, due to the high cost of gold, silver has been considered as an alternative coating, and many investigations focused on silver fretting response: Kassman-Rudolphi and Jacobson investigated the influence of sliding regimes on electrical contact performance [20], Chudowsky [21] assessed the impact of corrosive atmosphere, Imrell [22] focused on the influence of coating thickness in corrosive atmosphere, Sun et al. [23] investigated improvement in electrical properties by ion implantation, and Park et al.

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Nomenclature

A	contact area (μm²)
A_H	Hertzian contact area (μm²)
A_f	contact area at electrical failure (μm²)
A_{av}	averaged contact area (μm²)
a_f	contact radius at electrical failure (μm)
a_H	Hertzian contact radius (μm)
d	analysis diameter (μm)
E_d	dissipated energy during a fretting cycle (J)
e	layer thickness (μm)
f	frequency (Hz)
I	stabilized current
Nc	number of fretting cycles leading to electrical failure
P	normal force (N)
Q	tangential force (N)
Q^*	tangential force amplitude (N)
Q_t	tangential force at sliding transition (N)
RH	relative humidity (%)
T	temperature (°C)
V	total wear volume (μm^3)
$V_{(-)}$	negative volume (μm^3)
$V_{(+)}$	positive volume (μm^3)
V_u	wear volume of the upper cylinder (μm^3)
V_l	wear volume of the lower cylinder (μm^3)
V_{Nc}	wear volume (μm^3) leading to electrical failure
α	energy wear coefficient (mm^3/J)
ΔR	ECR variation with respect to minimum electrical resistance $R_{\min}$ (Ω)
ΔRc	ECR variation threshold for electrical failure (Ω)
δ	displacement (μm)
δ^*	displacement amplitude (μm)
δ_0	fretting cycle aperture (μm)
δ_g	sliding amplitude (μm)
δ_t	displacement amplitude at sliding transition (μm)
$\Sigma\varphi$	accumulated dissipated energy density (J/mm²)
ΣE_d	accumulated dissipated energy (J)
$Ø_f$	fretting scar diameter (μm)
μ	coefficient of friction
μ_t	coefficient of friction at sliding transition
φ	mean friction dissipated energy density (J/mm²)
φ_f	mean friction dissipated energy density extrapolated from the final contact area at Nc (J/mm²)
φ_H	mean friction dissipated energy density extrapolated from the Hertzian contact area (J/mm²)
φ_{av}	mean friction dissipated energy density extrapolated from the averaged contact area (J/mm²)
$[X]$	relative at% concentration of element X

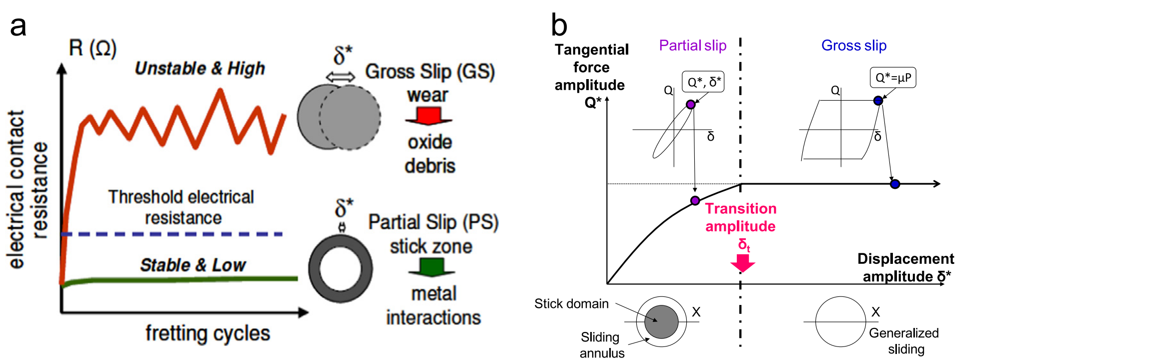

Fig. 1. Illustration of the influence of the sliding regime on the performance of electric connectors: (a) identification of finite and infinite behavior, (b) sliding condition for material of a given geometry, and normal force P.

studied the influence of temperature [24,25] and fretting corrosion [26,27] on silver contact resistance.

The present study reports a complete analysis of a homogeneous Ag/Ag interface. The first part correlates ECR evolution versus fretting wear damage and the evolution of fretting scar composition; ECR failure is related to a threshold concentration of Ag remaining in the interface. The second part of the study demonstrates that ECR endurance is related to the silver fretting wear rate; applying a friction energy density concept [28], simple formulations are provided to predict fretting ECR endurance.

2. Experimental details

2.1. Experimental setup

A dedicated set-up was designed and built for the study in order to reproduce the fretting and environmental conditions observed around a car engine. Fig. 2 shows a diagram of the set-up. The oscillatory motion of the upper holder was provided by an electromagnetic shaker. The upper specimen holder was fixed to the shaker by flexible strips to guarantee application of a normal force. The lower sample was fixed to a fixed table linked to a piezoelectric load sensor to measure the evolution of tangential force during the fretting cycle. The upper specimen movement was controlled by a laser displacement sensor to an accuracy of about 0.1 μm. A dead mass was placed on the upper holder to provide a normal load (P=1 to 6 N).

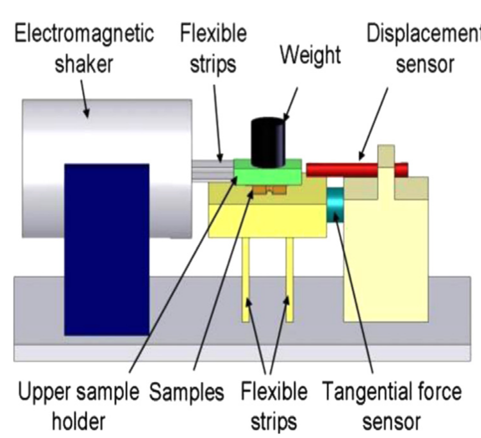

Fig. 2. Diagram of the experimental set-up used in the study.

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