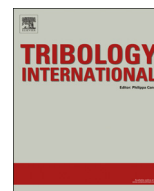




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Fretting corrosion degradation of non-noble metal coated contact surfaces: A theoretical model



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ABSTRACT

Fretting corrosion would result in unacceptable degradation or even failure of performance of electrical connectors. Predicting the contact resistance variation due to fretting corrosion is critical to assessing the reliability and lifetime of contact surfaces. In the present paper, a theoretical model is constructed to estimate the resistance rise and oxide accumulation during fretting cycles. A physically based-continuum description is formulated for the fretting corrosion process. The normalized resistance variance and oxidation volume are derived in an analytical form, and thereby the impacts of fretting frequency and normal force on lifetime are obtained. The predicted resistance buildup and metal depletion agree well with relevant experimental results.

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1. Introduction

Connectors are widely used to distribute power and signals. The development of advanced electrical and electronic technologies raise increasing demands on the reliability of connectors, which are often regarded as the weakest parts in a system and blamed for system malfunctions [1]. Connectors are required with a low and stable contact resistance through their entire service period [2]. Therefore, for the long-term performance of a connector, contact resistance is a core and widely-accepted measure of its aging contact surface [3]. More specifically, the reliability of a connector can be defined in terms of its probability to maintain a low resistance in an acceptable range during service. The degradation of metal-to-metal contacts could be caused by deleterious processes such as normal force relaxation, contamination, oxidation, and formation of intermetallic compounds. Among others, fretting corrosion is a plague, especially for non-noble coatings (e.g., tin) in an environment with vibration or varying temperature [2,4,5].

Fretting refers to the minute cyclic relative motion between a pair of contact surfaces under a normal load. The fretting motions normally have an amplitude smaller than 300 μm (often from 10 μm to 100 μm) and are caused by mechanical disturbances (e.g., vibration and shock), or temperature variation-induced thermal expansion and contraction. Fretting corrosion is a deleterious

process that especially associated with non-noble coatings suffering oxidation. During fretting corrosion, the oxidation products are continuously generated and broken. In details, under fretting movement subjected to applied normal forces, the oxidation film is ruptured and the fresh metal is exposed, thus the metal-to-metal contact is maintained with acceptable contact resistance. As the contact site shifts, the newly exposed metal is in turn oxidized and then broken. Such a repetitive oxidation-breaking process leads to the continuous buildup of oxides and depletion of coating materials. Thus, the contact resistance oscillates and rises up, causing the final degradation of connectors. Increasing the contact force can stable the contact, resulting in a reduction of the amplitude of fretting, and make the oxide layer easier to be ruptured and eliminated [6]. In addition, there are many other factors that affect the process of fretting, for instance, contact spot area, fretting motion frequency, motion amplitude, temperature, electrical load, and lubricants [2,4].

Fretting corrosion is regarded as the principle limitation for the use of non-noble finishes on connectors. As a prime example, tin, which is widely applied in different kinds of connectors for its desired solderability and low cost [7], is easily oxidized. The oxidation film is hard and brittle whereas the inner pure tin is relatively ductile, making tin finishes a typical sufferer of fretting corrosion. It has been reported that the resistance of tin-coated surfaces can become thousands times greater than the initial value after only a few hundreds of cycles [4]. In view of the practical significance of fretting corrosion, researches have done intensive works to analyze the corrosion conditions and processes, [8,9] to determine the surface characters, [10] to measure the contact

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resistances [11,12], and to create solutions [13]. Systematic parametric analyses have been carried out for different surface materials under different current loads, normal forces, vibration characters, and environmental conditions [4,14–16]. From these works, the deleterious impacts of fretting corrosion are clearly demonstrated.

In addition to experimental findings, a theoretical prediction of the effects of fretting corrosion is critical to assessing the connector reliability and estimating its lifetime. Although fretting fatigue and wear are common for various surfaces in engineering applications and have been comprehensively accounted for by many theories [17–21], the fretting corrosion is more associated with electrical connection and calls for targeted theoretical analysis. Efforts have been put on modeling the contact resistance buildup due to fretting [3,22–25]. These models are based on the multispot theory of real contact surface, which states that because of surface roughness, the mated surfaces get contacted by the deformation of a series of opposing high spots (often called A-spots) [26]. The contact resistance is treated as the series connection of the block resistance and the resistance of asperities which among themselves are parallel. Such a detailed microscopic treatment involves strong assumptions about the surface topologies, contact conditions, oxidation process, asperity deformation, and local resistance calculation.

In this paper, we provide a novel model to describe the fretting corrosion based on continuum analysis. Our treatment considers the physical mechanisms of contact and oxidation. The evolutions of contact resistance and metal volume are described by modeling the oxide generation and peeling-off. The lifetime of a contact surface is assessed by using the variation of its contact resistance. The influences of fretting frequency and normal force are taken into account. The work helps understand the fundamentals of fretting-caused connector degradation and predict the degradation process.

2. Model

2.1. Formula of contact resistance

The contact resistance of an intact coating of surface area S and thickness H is expressed as $R = \rho H/S$, where ρ is the electrical conductivity. For the practical contact surface of a connector suffering fretting corrosion, the coating is partly oxidized and the oxide distribution varies along the thickness direction. Let $c(h)$ denote the area fraction of uncorroded metal at depth h , which will be derived in the next subsection. Then, $S_c(h)$ is the actual area that is conductive, and the contact resistance is written as

$$R = \frac{\rho}{S} \int_0^H \frac{1}{c(h)} dh \quad (1)$$

The above treatment has neglected the variation of oxide distribution in the planar directions by using an averaging method. Due to the asperities (roughness) of the contact surface, here S is regarded as the effective contact area (net contact area), instead of the designed area (nominal contact area) S_0 . S is always smaller than S_0 , and with the increase in the normal stress applied to the mating surfaces, the asperities undergo increasing deformation, leading to a rise of the net contact area S . Each asperity can be considered as an indenter pressing the opposing surface. Therefore, the net contact area is approximately formulated as

$$S/S_0 = 1 - \exp\left[-\alpha\left(\frac{\sigma}{G}\right)^n\right], \quad (2)$$

where α , n , and G are model parameters that are mainly related with material properties. σ is the apparent normal

stress (the average stress per unit area) and G is the shear modulus. Here, we use the Weibull empirical cumulative distribution function to correlate the net contact surface area S with the nominal surface area S_0 [26,27]. Since the value of the stress σ is usually far less than the modulus G , Eq. (2) can be approximately written as $S/S_0 \approx \alpha(\sigma/G)^n$. The parameter n is mainly determined by the geometrical characters of the surface [28], and a typical value $n=1/2$ can be found from the literature [26,29].

Substituting Eq. (2) into (1) gives

$$R = \frac{\rho}{S_0 \alpha} \left(\frac{G}{\sigma}\right)^n \int_0^H \frac{1}{c(h)} dh. \quad (3)$$

Both the enlargement of oxidation area (the decrease of $c(h)$ at a certain depth) and the buildup of oxide debris (the increase of depth with oxide debris), the two mechanisms that fretting corrosion is attributed to [2,3], result in the increase of the integral part in Eq. (3), and therefore the increase of resistance.

2.2. Model of coating oxidation

In this subsection, the expression $c(h)$ in Eq. (3) will be derived by considering both the enlargement of oxidation area and the buildup of oxide debris in the fretting-caused oxidation process. The oxidation is deemed as an outside-in process. Only when an upper oxide cover is broken and removed, the metal beneath the oxides tends to be oxidized. The inner metal covered by an oxide layer will not be oxidized. Therefore, at depth h , the area of metal exposed to oxidation is

$$S_{\text{oxi}} = [1 - c(h - \Delta h)]S_0 - [1 - c(h)]S_0 = [c(h) - c(h - \Delta h)]S_0. \quad (4)$$

Here, on the right of the first equal sign, the first and the second terms mean the oxidized areas at depth $h - \Delta h$ and h , respectively.

The oxidation rate is described by Arrhenius equation [30], and then the rate of metal loss is given as

$$\dot{m} = -AS_{\text{oxi}} \exp\left(-\frac{Q}{kT}\right), \quad (5)$$

where m is the mass of the remaining non-oxidized metal, Q is the activation energy of the oxidizing reaction, k is the Boltzmann constant, T is the temperature, and A is a scaling coefficient. \dot{x} represents the derivative versus time of a variable x . The corresponding change of the metal area ratio $c(h)$ is expressed by

$$\dot{c} = \frac{\dot{m}}{S_0 \rho_c \Delta h}, \quad (6)$$

where ρ_c is the density of the coating metal.

Substituting Eqs. (4) and (5) into Eq. (6) gives

$$\frac{\partial c}{\partial t} = -B \exp\left(-\frac{Q}{kT}\right) \frac{\partial c}{\partial h}, \quad (7)$$

where $B = A/\rho_c$. Eq. (7) is the governing differential equation of the spatial and temporal evolutions of oxidation. Its general solution has the form of

$$c(h, t) = F\left[h - Bt \exp\left(-\frac{Q}{kT}\right)\right], \quad (8)$$

where $F(x)$ is a function, which will be derived in the following. The term $h - Bt \exp(-Q/kT)$, considered as a whole, is the independent variable of the function.

Now we analyze the oxidation process at the top surface of a contact area, i.e., $h = 0$, which can give the boundary condition of Eq. (8). At $h = 0$, the area exposed to oxidation, $S_{\text{oxi}}|_{h=0}$, equals the

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