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Research on fretting Regimes of gold-plated copper alloy electrical contact material under different vibration amplitude and frequency combinations

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ABSTRACTS

Gold-plated copper alloy electrical contact materials are widely used in electrical interconnection to meet the requirements of high quality and high reliability for aviation and aerospace engineering. Not much is known about the fretting failure mechanism of such materials when placed in an environment with a high-frequency vibration. This paper investigates the fretting wear and corrosion behavior of gold-plated copper alloy contacts experimentally under different vibration amplitude and frequency combinations. Three typical degradation features are summarized. Relative surface morphology, element distribution, and wear track of worn surfaces are also analyzed. The fretting map, which can discriminate the fretting regimes with vibration amplitude and frequency combinations, is presented. The map can be clearly divided into the infinite electrical contact life zone, the oxidation-dominated failure zone, and the transient unstable conductivity failure zone. The appropriate sliding velocity is the critical condition for the sharply degradation of contact resistance after the gold coating has worn out. The results show that the dynamic contact resistance is significantly influenced by the coarser and irregular profile features of wear track induced by higher sliding speed, as well as the high resistive oxides debris or oxide metal mixture.

1. Introduction

Electrical connectors, which are used for electrical signals and power transmission of the whole electrical and electronic system, are important interface components among the aircraft engines. The increasing complexity of modern automatic systems results in the need for more connectors. A typical modern aircraft can have more than 4500 electrical connectors [1]. The connectivity performance of electrical connectors are susceptible and vulnerable to mechanical disturbance, especially if the adjacent engine vibrates, starts up, or shuts down with high frequency. Field data have shown that connector degradations and failures contribute to 30–60% of electrical contact problems [2].

Fretting, which results from mechanical vibration, is one of the major deterioration factors of non-arcing electrical contacts that existed in a harsh environment. Different phenomena are related to fretting, such as fretting wear, fretting fatigue, fretting corrosion [3,4]. In addition, damage that occurs between two metallic surfaces can result in the increment and fluctuations of electrical resistance of the numerous electrical contacts.

There has been a growing interest in fretting failure problems in automotive electrical contact applications [5–9]. Copper alloys plated with non-noble metals (tin, tin–lead) can be used as a low-cost alternative. However, the susceptibility of tin plated contacts to fretting corrosion is a major limitation of its use [9].

Gold has almost all the desirable properties for electrical contacts, namely high electrical and thermal conductivity. Because gold does not oxidize when exposed to air, connectors with gold coatings would be guarded against fretting corrosion [10–14], unless the gold coating is worn out and followed by the corrosion of the substrate material. Therefore, the connectors with gold-coatings appear to be a preference for aircraft applications.

Nowadays, the demand for reliable electrical connectors has increased due to system requirements. Sine sweeping-frequency mechanical vibration tests are mandatory for electronic and electrical component parts used in aviation and aerospace engineering [15–16].

It is becoming increasingly important to understand and determine the failure mechanism of gold plated contacts under fretting induced by high acceleration and frequency vibration.

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Eqs. (1)–(3) show that the acceleration peak is synthetically decided by both frequency and amplitude, based on the sine vibration mathematic expression. Additionally, several authors have studied the fretting phenomenon by changing the frequency and amplitude. Braunovic et al. [3] reviewed the effects of fretting amplitude at different frequencies and for different contact material combinations. All contact material combinations show that the longer the slip amplitude is, the less time it takes to attain a given increase in the contact resistance. A shorter slip amplitude means a lower number of contact spots exposed to oxidation. This in turn delays the onset of contact resistance degradation. Hannel et al. [14] confirmed that above the threshold of fretting amplitude corresponds to the stabilized gross slip condition, resulting in the surface coating wearing out, or the substrate material fretting corrosion phenomena. However, Park et al. [5] also investigated the effect of amplitude on the fretting corrosion behavior of tin-plated copper contacts and concluded that the time to reach a threshold value of contact resistance of 0.1 Ω is found to be early for the track length of 5 μm compared to that of 25 μm. This paper argued that within a confined oxidation area the percolation limit for electrical conduction reach earlier at low amplitudes of 5 μm.

The effect of frequency on fretting is an important consideration for contact failure. For a given fretting amplitude, the fretting corrosion of contacts occur much faster at higher frequencies. This provides more fresh metal for oxidation and generates more accumulation of oxide wear debris at the contact zone [3]. However, the fretting frequency is mainly focused on 1 Hz [11,17–19], 1–10 Hz [20], 10 Hz [21], 15 Hz [21], 20 Hz [21], 30 Hz [12–13], 50 Hz [22] and 100 Hz [9], [23]. Vingsbo and Soderberg [24] first presented fretting maps and according to the slip amplitude, categorized contact surface damage into these regimes: stick, mixed stick-slip and gross slip. Lim [25] summarized the development of fretting and erosion maps for different materials. Kassman and Jacobson [26] found the four deformation patterns of silver-plated copper contacts under high contact force (40–100 N) and vibration amplitude combinations. The fretting regime map is useful in material design and failure analysis.

Relatively little is known about the fretting mechanism of gold-plated contacts used in frequency over the range of 1–100 Hz.In this paper, fretting characteristics of gold plated copper alloy contacts are investigated in the frequency range from 60 Hz to 1000 Hz, and the slip amplitude range from 4 μm to 62 μm. The fretting map of gold plated copper alloy contacts is developed based on the change rate in mean electrical contact resistance and RMS tangential force up to 90,000 fretting cycles. It also combines the factors of surface morphology, element distribution and wear track study of worn surfaces at various combinations of experimental conditions. Then, the infinite electrical contact life zone, the oxidation dominated failure zone, and the transient unstable conductivity dominated failure zone are clearly divided in the whole map. Finally, the fretting mechanism of contact resistance rapidly increases and the degradation is higher than 1 Ω. This is proposed by considering the electrical resistivity of oxides debris on contact surfaces and the dynamic conductive area comprehensively.

2. Experimental details

The fretting regimes of gold-coated copper alloy material were studied by using a designed test rig, which is described in detail in [27,28]. Fig. 1 shows a schematic diagram of the test rig that was used in the fretting experiments. The relative motion between the contacts was accurately simulated by an electro dynamic shaker imposing controlled cyclic movements. The desired displacement of the shaker is realized by the power controller with acceleration feedback loop. This feedback loop is provided by the assembled acceleration transducer. The application direction of the transducer aligns with the fretting direction.

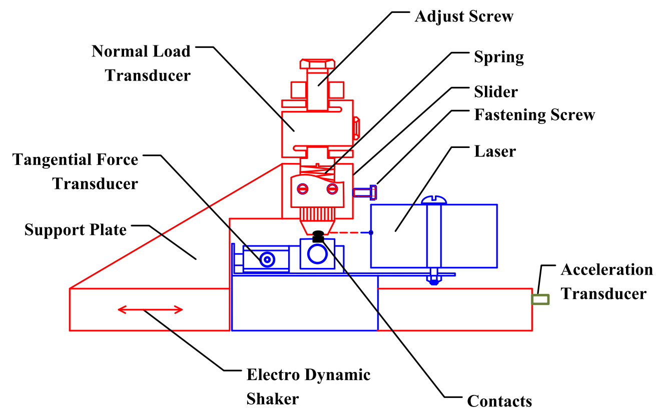

Fig. 1. Schematic diagram of the test rig.

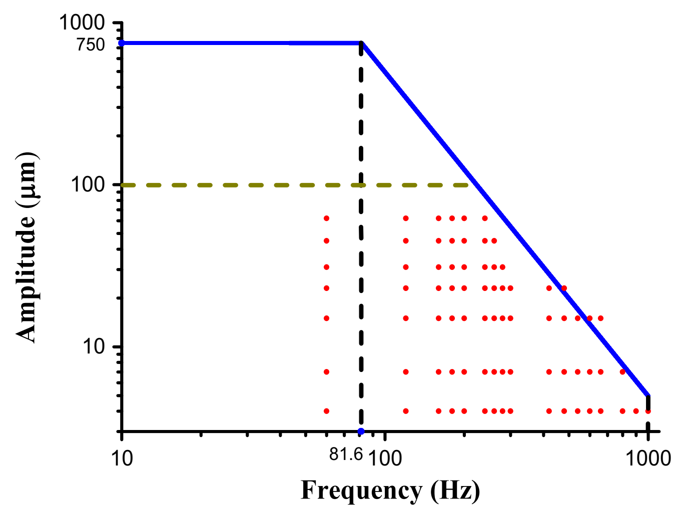

Fig. 2. High frequency vibration test curve and the selected vibration amplitude and frequency combinations in this paper.

According to the electrical shaker's working principle, the rider's micro-sinusoidal displacement can be written as $x = A \sin 2\pi f t$, where A is the vibration amplitude and f is the vibration frequency.

Then, the rider's velocity and acceleration can be written as

$$v = 2\pi f A \cos 2\pi f t \tag{1}$$

$$a_{cc} = -4\pi^2 f^2 A \sin 2\pi f t \tag{2}$$

Thus, the fretting amplitude A could be expressed as

$$A = A_{cc}/4\pi^2 f^2 \tag{3}$$

where A_{cc} is the fretting acceleration amplitude. The typical high frequency vibration test curve (shown in Fig. 2) is listed in Refs. [15,16]. The vibration frequency varies between 10 and 1000 Hz, and the constant vibration amplitude 0.75 mm is applied during 10–81.6 Hz. The varied amplitude maintains a constant peak acceleration of 196 m/s^2, adopted between the approximate 81.6–1000 Hz. Therefore, 81.6 Hz in this figure is defined as the transition frequency. The fretting amplitude refers to as much as 100 μm. In the experiments, the frequencies of the applied vibration include 18 levels that range from 60 Hz to 1000 Hz, and the amplitudes of the applied vibration include 7 levels that range from 4 μm to 62 μm. Such vibration combinations of fretting frequency and amplitude, which are distributed in Fig. 2, correlate