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Effects of temperature on fretting corrosion behaviors of gold-plated copper alloy electrical contacts

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ABSTRACT

A series of tests on the fretting corrosion behaviors of gold-plated copper alloy electrical contacts in the temperature range of 25∼125 °C have been carried out. The typical characteristics of the change in contact resistance average value and intermittent failure rate with fretting cycles are investigated. The results indicate that the vital role of gold coating is softening and lubricating contact surface. The contacts at higher temperature delay the time before reaching a threshold value (100 mΩ) of contact resistance. However, higher temperature aggravates oxidative wear of substrate copper alloy material after coating has worn out. Based on the change in contact resistance, surface analytical techniques and thermal equilibrium principle, the degradation mechanisms of contacts under different temperatures are proposed.

1. Introduction

The electrical connector is an essential accessory component for sensor signals and power transmission within aircraft engine and automotive engine. Metal contact pairs are a typical application for electromechanical devices as they are characterized by infinite open-circuit resistance and negligible closed-circuit resistance. The increasing electrical complexity of modern intelligence system results in increment of numbers of electrical connectors. A typical modern aircraft can have more than 4500 electrical connectors [1]. The connectivity performance of electrical connectors is vulnerable to disturbance caused by external vibration or changing temperature. Field data have shown that connector degradations and failures contribute to 30∼60% of the electrical contact problems [2].

Fretting refers to small oscillatory motion between two solid surfaces in contact. The amplitude of the motion often falls in the range 1–100 μm. Different phenomena are related to fretting, such as fretting wear, fretting fatigue, fretting corrosion [3,4]. Fretting corrosion occurs as a result of the formation of corrosion products at the friction surfaces that exert significant effect on the electrical contact behavior. In some high temperature situations, the role of the fretting corrosion mechanism to fretting wear is so important that this term is almost a separate fretting mode.

Generally, the platings of nonprecious metals are prone to fretting corrosion. The oxidative film may be generated by reaction of a metallic surface with oxygen in air or lubricant. It can significantly affect friction, wear, electrical potentials and current paths between contacting surfaces. On the other hand, the high contact temperature in the contact zone substantially affects the rate of oxidation.

Fretting corrosion depends on many factors, such as chemical compositions and microstructures of the contact surface, rigidity, porosity of the contact surface and degree to which the contact surface has been work-hardened and so on [3]. Several investigations are performed to study the fretting corrosion behavior of electrical contact materials in different amplitudes [5,6], frequencies [7,8], electric currents [9,10] and normal forces [11,12].

With the increasing demand of electrical contact materials to withstand high temperature and fretting environment, relative contact degradation modes and failure mechanism such as fretting oxidation, gas corrosion and alloy diffusion are urgent to investigate comprehensively.

Research on fretting corrosion failure problem of tin-plated copper alloy connectors at different temperatures has been growing in recent years. Lee [13] reported that tin-plated copper alloy contacts corroded faster as temperature increased to 60–80 °C, but then the corrosion rate reversed as the temperature increased further. Swingler [2] confirmed that high temperature accelerated

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chemical and physical processes leading to more severe degradation of the contact interface between the two terminals and the crimp interface of the connectors. For general tin-plated copper alloy material, diffusion rate of copper atoms into the tin lattice will promote the intermetallic compound (IMC) formation, together with the copper oxidation causing the contact resistance to change rapidly [14]. The distinct chemical characteristic of gold is that it does not oxidize when exposed to the air. Therefore, connectors with gold coatings could significantly reduce the fretting corrosion [15–17]. Gold-plated contacts may also fail by fretting if the finish is worn through. A study of contacts with different thickness of gold coating revealed that material transfer dominates fretting and an equilibrium distribution of a contact metal with a substrate is attained [18]. Ding et al [19] also concluded that the temperature rise and arc discharge affect the friction behaviors of electric sliding contact couples.

Fretting failure problems of gold-plated copper contacts that result from the high frequency vibration environment, especially the frequency range of 100 to1000 Hz, frequently appear in modern electrical connectors used in aerospace and aviation engineering. In a previous paper by the present authors, the fretting frequency of 200 Hz is selected as the typical deteriorate experimental condition with the representative fretting features, and the effect of current load on wear and fretting corrosion of gold-plated contact material is investigated explicitly [10].

No systematic studies of fretting corrosion behaviors of gold-plated copper contacts used at different temperatures have been reported. In this article, an attempt is made to explore the effect of various temperatures on the change of electrical contact resistance of electroplated gold contacts. In addition, the fretted surface morphology, roughness and element distribution are analyzed. The formation mechanisms of scratches, wearing craters and delamination wear in the process of contacts fretting induced by corrosion wear at different temperatures are discussed.

2. Experimental details

2.1. Description of the test rig

In general, the test rig allows researching the fretting behaviors of contact materials under normal and tangential loading at different temperatures and different atmospheres. It was designed to fulfill the following goals, i.e.:

- Variable temperatures and atmospheres (or vacuum rates) to achieve comprehensive environment condition simulation of electrical contact materials.
- Different electrical current levels to discriminate the roles of electrical loads and mechanical wear in fretting failure mechanisms accurately.
- Synchronization of data with electro dynamic shaker actuation to allow real measurement of normal and tangential force, contact resistance and relative displacement between two contacts.

The test rig consisted of the mechanical structures, the electrical resistance measuring module and PC. A schematic diagram of the mechanical structure is shown in Fig. 1. An electro dynamic shaker was used to produce oscillatory motion of the upper holder through the "S" type normal load transducer. The first flat contact sample was fixed into the lower holder, which is connected with the heating trough. The second sphere contact sample was fixed into the upper holder. The flat and sphere contacts were mated in such a way to create a point contact in 'sphere plane' geometry (shown in Fig. 2). A piezoelectric load sensor was introduced to connect with the heating trough for measuring the tangential force during the fretting process. The normal contact force was supplied by the spring and adjusted by the screw placed on the spring. A laser displacement transducer was installed to further ensure the amplitude of relative motion between the flat and sphere contacts. The support frame, in the form of 'L' type, held the upper vertical loading shaft and connected the holder, and thus excludes any undesired vertical micro-vibrations that can exist in experimental setups.

The environment temperature can be set from ambient temperature to 125 °C by using the heating trough. The real-time temperature of environment is measured by the K-thermocouple, and monitored by the heating controller with a resolution of ±1 °C. The bell jar is designed and placed outside of the mechanical structure to form the controllable vacuum rate environment.

The electrical resistance measuring module is configured for the four-wire technique, which eliminates the lead resistance including the resistance of soldered joints. It has a built-in current source capable of providing a constant current, which could be set from 1 mA to 1000 mA in steps of 1 mA. The optional open circuit voltage can be varied from 5 mV to 200 mV in 1 mV steps. The accuracy of the measured resistance between contacts is within 1% after calibration. During the test, the contact resistance, tangential force and relative motion between two contacts are measured simultaneously. The module is interfaced to a personal computer using a USB cable. The data acquisition and logging process are controlled through a PC with the help of LabVIEW software specifically programmed for this purpose.

2.2. Experiment methods

The contacts were a ball-shaped rider, with a diameter of 2 mm, on a flat sample, both made of copper alloy and electroplated with Au with a thickness of 1 μm. The samples were measured immediately by X-RAY fluorescence measuring systems (XAN220, Helmut Fischer, Germany) after electroplating and the thickness of gold coatings was 1 μm. The surface roughness of all test samples was rigorously controlled, and measured by a con-focal optical microscope (LEXT3000, Olympus, Japan) and the surface roughness of the rider (SR_a) and the coupon (R_a) is below 0.4 μm, calculated from a scan size of 50 μm × 50 μm. The surface hardness of rider and flat copper alloy substrates is uniformly about 140 HV (98 mN). After electroplating, the hardness of surface with gold coating is about 92 HV (98 mN). The sphere and flat specimens were degreased using alcohol and distilled water in an ultrasonic cleaner, dried and carefully installed in the fixtures. Table 1 shows the details of the experimental conditions. The contact resistance was continuously measured as a function of fretting cycles at different temperatures from 25 °C to 125 °C. In this article, the typical experimental results at 25 °C, 60 °C, 80 °C, 100 °C and 110 °C are present individually in detail. Scanning electron microscopy (SEM), energy dispersive analysis of X-rays (EDX), X-ray line mapping and con-focal scanning laser microscope (CSLM) were used to characterize the extent of fretting damage, extent of oxidation, elemental distribution and roughness across the fretted zone.

3. Results and analysis

3.1. Effect of environment temperature on contact resistance

Fig. 3(a), (b), (c), (d) and (e) show the variations in contact resistance of gold-coated copper alloy contacts as a function of fretting cycles for amplitude of 25 μm and frequency of 200 Hz at 25 °C, 60 °C, 80 °C, 100 °C and 110 °C respectively. It is found that