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Effect of displacement and humidity on contact resistance of copper electrical contacts

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ABSTRACT

The effect of displacement and humidity on fretting-induced instability of electrical contact resistance (R_c) was studied. A fretting tester was used to examine R_c in partial and gross slip modes. Under the partial slip regime the contact failure was susceptible to the displacement and moisture effectively increased contact stability, which was pronounced at smaller displacements. In the gross slip mode, however, humidity effect was relatively small. The early contact failure at low humidity was attributed to the wear debris agglomeration within the sliding interface, suggesting a high propensity of electrical contact failure at dry conditions.

1. Introduction

The metallic contacts in relays, switches, and power connectors play a crucial role in transmitting power and signals for electrical devices. The robust design of electrical junctions with proper material selection, thus, has attracted much attention [1–3]. In particular, the durability of the electrical connectors in vehicles has become a greater concern during the last two decades since modern vehicles have many electrical connectors because the number of electronic devices has increased significantly for entertainment, comfort, and safety [4]. When electrical connectors present in the vehicle increase, the reliability of the electrical devices decreases. This is attributed to the unavoidable vibration during vehicle operation and the variation in temperature and humidity that the components are exposed to. Therefore, in order to design a sustainable electrical connector in a vehicle, the friction and wear of the electrical contacts in the fretting mode have to be understood in various environmental conditions.

Various metals and alloys have been used as a contact material and they have to fulfill various requirements to be reliable in the electrical connector [5,6]. These requirements include high electrical and thermal conductivity, high melting and evaporation points, and stable contact resistance (R_c) against abrasion, welding, deformation, arcing, oxidation, and corrosion [7]. Although precious metals, such as gold and silver, are known to be excellent candidates for electrical contact materials, the use of these materials has been limited because of their cost. Instead, copper, copper alloys, and copper with thin noble metal coatings have been widely used as alternative electrical contact materials, although their performance is inferior to that of the precious metals [7,8].

Fretting occurs at the contact area when subject to an oscillatory sliding motion with a small amplitude due to vibration. It is normally comprised of the transition from partial slip mode to gross slip mode when failure occurs. Partial slip indicates the situation when a section of the sliding interface is adhered without sliding while gross slip indicates the slip of the entire contact area [1,9]. Therefore, electrical contacts subjected to external vibrations are susceptible to fretting and fretting-induced wear and corrosion are considered the cause of electrical signal errors and power transfer failures [1,2,10]. Various studies have been performed using different contact materials to understand the wear and corrosion-induced wear during fretting [11]. Lee et al. [12] and Braunovic [13] studied the effect of fretting phenomena on electrical R_c and corrosion of electrical contact systems, based on tin-plated copper alloy, tin-plated aluminum, and copper as contact materials. They found that fretting corrosion and corrosion-induced wear were the main causes of electrical contact system failure, indicating the importance of humidity.

The effects of displacement on R_c and humidity effects on contact failure were also studied. It was shown that the size of the displacement during fretting determined the transition from partial slip to gross slip and that R_c was strongly affected by the slip mode (partial/gross slip) during fretting [3,8]. Under the partial slip condition, R_c remained low and stable, while a high and

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unstable R_c was found under the gross slip condition [9]. Goto and Buckley found that the humidity effect on fretting wear was critical at a specific humidity level and that the critical humidity was dependent on the type of contact materials [14], while minimal environmental effect was reported by Kassman and Jacobson [15]. The effect of humidity on the agglomeration of wear debris of ceramics was also studied. It was found that the water molecules in the air reduce the size of debris compacts, which decreases the coefficient of friction (μ) [16]. Humidity effects on the fretting wear of an aluminum alloy was studied by Cai et al. [17]. They found that humidity influence on wear behavior was determined by fretting regimes. However, the effect of humidity on electrical R_c was seldom found in the literature and, in spite of the research efforts, contact failure due to vibration, oxidation, and corrosion at various vehicle operating conditions continues to be an issue.

This study investigated the effect of humidity on fretting-induced contact failure. Using a copper-on-copper contact, the critical number of fretting cycles in a reciprocating mode that lead to high R_c at different humidity levels was examined during fretting testing. The results showed that contact failure by fretting is severe in dry conditions and the durability of the electrical contact is greatly degraded by agglomeration and pile up of the wear debris at the vibrating contact.

2. Experiments

Rods made of pure copper (99.99% Cu, radius=2.5 mm) were used for fretting testing in this work. Before the tribotests, the rod specimens were ground using abrasive paper (#2000) to produce a similar level of surface roughness ($R_a = 1.2 \pm 0.3$ μm). Friction and wear of the copper specimens were examined using a fretting test instrument (RFW160, NeoPlus Inc.). By constructing a Hertzian contact during fretting R_c was measured using two rod specimens crisscrossing each other. Fig. 1 shows a schematic of the fretting test instrument with an installed electric circuit.

The fretting tests were performed at different displacements (10–110 μm) and at different humidity levels (10%, 40%, and 70% relative humidity (RH) which were equivalent to 2.3, 9.2, and 16.1 g/m^3 in absolute humidity). The normal load was set at 5 N to simulate the clamp force for electrical connectors in the automotive wiring system and the test was carried out at 4 Hz. The direct current at the contact was maintained at 1 A and the system was enclosed in an environmental chamber, which was maintained at room temperature (22–25 °C). The detailed test condition was given in Table 1. The RH was controlled by blowing humid air into an environmental chamber. A hygrometer (Fluke971, Fluke) was used to measure humidity. The 4 point probe method was used to measure R_c [18]. After the tribotests, the worn surfaces of the cylindrical specimens were examined using a laser confocal microscope (VK-8710, Keyence) and an optical microscope (MZ6, Leica).

3. Results and discussion

3.1. The COF and displacement

The change of the COF as a function of displacement (F-D curve) was examined first before investigating the humidity effects on R_c. The COF at different displacements was recorded at 10% RH and is shown in Fig. 2. At small displacements (less than 40 μm), the F-D curves showed an ellipsoidal shape with small hysteresis, whereas the ellipsis became wider and changed to a quasi-parallelogram at displacements greater than 40 μm. This indicates that the fretting mode changed from partial slip to gross slip as the displacement increased. The F-D curves suggest that the friction and wear of the contact are governed by partial slip around the contact junction adhered in the central region when the displacement is small. On the other hand, when the displacement is greater than 40 μm, the apparent interfacial sliding can determine the friction and wear of the junction.

3.2. Humidity effect in the partial slip mode

The change of the COF and R_c at the partial slip mode with the diplacement in the range of 10–40 μm was examined first to investigate the effect of humidity. Fig. 3 shows the COF and R_c as a function of the fretting cycle and the morphology of the contact area after 12,000 cycles when fretting tests were performed with the displacement of 10 μm at different humidity levels (10%, 40%, and 70% RH). The figure shows that a low, stable R_c was maintained, regardless of the humidity levels. The humidity-independent R_c shown in Fig. 3(a) is attributed to the adhered area of the contact junction. Fig. 3(a) also indicates that the microslips occurring in the outer periphery of the adhered junction do not affect R_c significantly. On the other hand, the COF increased from 0.1 to 0.2 during the fretting tests and the critical cycle for the increase of the COF was approximately 2000 cycles, at 10% RH and 9000 cycles at 40% RH. However, the COF did not increase at 70% RH up to 12,000 cycles.

The increase of the COF in the dry condition is attributed to the increased adhesion by cold welding at the contact junction [8,19,20]. The surface morphology and depth profile in Fig. 3 (b) also demonstrate the occurrence of cold welding during the test. It shows that a part of the contact area comes off when the two specimens were detached after the fretting test at low humidity. The depth profiles of the surface indicate that the size of the cavity produced by detachment was reduced at higher humidity levels. This result suggested that the water molecules on the surface can delay cold welding for an extended period of fretting time at high humidity. The results in this study agree well

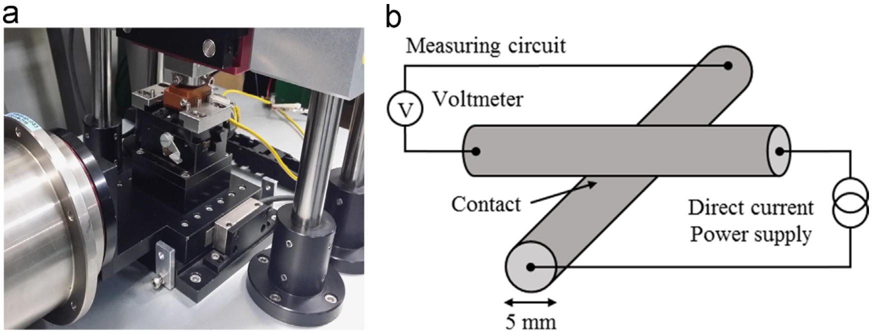

Fig. 1. Schematics of (a) the fretting test assembly and (b) the specimen configuration with the electrical circuit used to measure contact resistance (R_c).