Tribology International 111 (2017) 39–45

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Effect of grain size on the electrical failure of copper contacts in fretting motion

H.J. Noh, J.W. Kim, S.M. Lee, H. Jang*

Department of Materials Science and Engineering, Korea University, Seoul 02841, South Korea

ARTICLE INFO

Keywords:
Grain size
Fretting wear
Fretting corrosion
Electrical contacts

ABSTRACT

The influence of grain size on degradation of electrical contacts during fretting wear was investigated. Copper polycrystals with grain sizes of 2–162 μm were used to examine friction, wear, and electrical contact resistance. The results showed that the electrical contact failure was caused by the compact oxide layer produced at the contact junction. Copper specimens with smaller grains had a longer lifecycle because of grain-size strengthening. However, this strengthening effect was limited to a critical grain size and, with further increase in grain size, plastic deformation underneath the contact surface played a major role in delaying the contact failure caused by oxide formation on the fretting surface.

1. Introduction

The premature failure of sliding contacts because of the friction-induced wear of materials has been a crucial problem in switches and connectors used as electrical components [1,2]. In particular, electrical devices in automobiles often fail earlier than other devices because of malfunctioning electrical contacts as they are exposed to vibration and a wide range of environmental conditions [3]. These contact conditions induce fretting wear, and fretting corrosion at the contact junction is considered an important trigger for electrical contact failure [4,5], because fretting corrosion disrupts the transmission of electrical signals by producing insulating layers at the contact [6–9].

Unlike in the case of electrical contacts in static devices, the wear in electrical contacts in automobiles is often accelerated by the small-amplitude reciprocal forces generated by vibrations from the power trains and road surfaces during driving, which is followed by the corrosion of metallic wear debris. Swingler et al. [10] examined the effects of temperature on connector performance by reproducing the temperature profile of a real automobile. Park et al. [11] focused on changes in the material properties at high temperatures, such as softening of the Sn coating layer and the formation of a Cu–Sn intermetallic compound. They demonstrated that a high temperature accelerates the fretting corrosion and that humidity strongly affects the degradation of electrical connectors. Sung et al. [12] reported high durability of electrical contacts under high-humidity conditions, suggesting that water molecules prevent the agglomeration of wear debris.

Studies have attempted to improve the robustness of electrical contacts in automotive components by minimizing electrical contact resistance through the coating of the contact surface of the sliding component [13]. Gold, silver, and silver alloys have been used as coating materials for electrical connectors given their high electrical conductivity and oxidation resistance, which help maintain a low and durable electrical resistance [2,14–16]. However, the application of these noble metals is limited by their high cost and wear. If the coating layer wears and thins, the substrate becomes exposed and electrical failure occurs soon after. Fouvry et al. [17] showed that noble metal concentrations of < 5 wt% at the center of a fretted area drastically increases the electrical resistance. Sn has been used as a cheaper alternative to noble metals for coating electrical contacts, especially in electrical connectors, because the soft Sn layer reduces constriction at the contact junctions [18]. However, the Sn layer produces hard Sn oxides under fretting, which results in early contact failure [9,19].

Another alternative for reducing contact wear is to increase the hardness of the contact material, because the amount of wear is inversely proportional to the hardness of the material [20], as described by Archard's wear equation [21]. Although the electrical contacts in automobile components are normally coated with protective materials, the strength of the copper substrate affect the deformation of coating layers and the failure mode after the coating layer is stripped off. A convenient method for increasing the hardness of a metal contact is to reduce its grain size, as described by the Hall–Petch relationship [22]. This mechanism is based on experimental results and is known as grain-size strengthening. The Hall–Petch equation describes the increase in yield strength as a function of the average grain diameter [23,24] and is based on the restriction of dislocation motion by grain boundaries [25]. In particular, metallic components with small

* Corresponding author.
E-mail address: hojang@korea.ac.kr (H. Jang).

http://dx.doi.org/10.1016/j.triboint.2017.02.043
Received 17 December 2016; Received in revised form 3 February 2017; Accepted 26 February 2017
Available online 27 February 2017

grains appear to exhibit low wear coefficients because the limited dislocation activity prevents plastic deformation and produces less wear debris. Several studies have investigated the effects of grain size on fretting wear [26–29]; however, these studies have focused on the enhancement of wear resistance without considering the electrical contact resistance associated with friction and wear at the contact. Champion et al. [30] studied the effects of the grain size of copper on electrical performance, but they mainly examined the grain-size effect under normal sliding conditions and not under fretting conditions.

In this study, the relationship between the grain size of copper and the durability of electrical contacts in fretting motion is examined in order to improve the lifetime of electrical switches and connectors. Copper specimens with grain size of 2–162 µm were investigated with a focus on the deformation of contacts during fretting and the formation of a third layer, which increases contact resistance. The results indicated that grain-size strengthening effect may not be proportional to the lifetime of electrical contacts in fretting motion.

2. Experiments

2.1. Materials

Electrical contacts with different grain sizes were fabricated from electronic-grade pure copper (99.99 wt%). A pure copper plate of size 5×2.5 cm^2 and thickness 4.5 mm was cold-rolled to produce a plastically deformed microstructure with high dislocation density. To obtain polycrystalline copper with different grain sizes, the cold-rolled specimens were heat-treated in an argon atmosphere under a series of annealing temperatures ranging from 650 °C to 950 °C for annealing durations ranging from 10 s to 10 h. After the heat treatment and the subsequent chemical etching with 20% nitric acid solution in distilled water, the grain size of the copper plate was examined. The grain-size distribution was examined using an optical microscope (OM; Leica DM6), and the surface hardness was measured using a Vickers hardness tester (HMV-G, Shimadzu).

2.2. Fretting tests

Fretting tests were performed using a reciprocating friction instrument (RFW160, NeoPlus, Inc., Korea; Fig. 1). An S45C steel ball of diameter 9.5 mm was used as the rider. The use of this hard steel ball facilitated the investigation of the deformation mode of the copper specimens without welding at the contact junction during fretting. The surface roughness (R_a) of the copper substrate was approximately 0.2 µm. After preliminary tests at various conditions, fretting tests were performed under a gross-slip condition and with an applied normal load of 10 N at a frequency of 4 Hz; the displacement amplitude was fixed at 300 µm, which was larger than the largest grain size of the copper specimens. Preliminary tests were conducted in a range of the normal load, which plays an important role in determining the friction coefficient, wear rate, and the electrical contact resistance. During fretting, constant direct current of 1 A was supplied, and the voltage drop was measured using a four-point probe setup (Fig. 1) [31]. The fretting tests were conducted under an ambient condition. The experimental conditions are summarized in Table 1. After the fretting tests, the contact zone was examined using an X-ray photoelectron spectroscope (XPS; Phi X-Tool, ULVAC-PHI), a scanning electron microscope (SEM; S-4300, Hitachi), and a laser confocal microscope (VK-8710, Keyence).

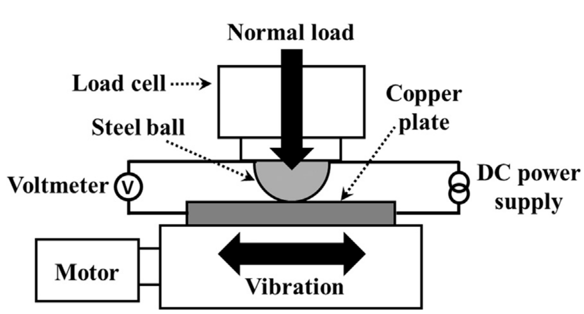

Fig. 1. Schematic of the fretting tester showing a steel-ball rider on the copper plate; the electrical resistance of the contact was measured through the four-point probe method.

3. Results and discussion

3.1. Grain-size strengthening of contact metals

The effect of surface hardness on the wear of metallic contacts was investigated by altering the grain size of polycrystalline copper through recrystallization of the cold-worked copper plate at different heat treatment schedules. This is because contact metals with high hardness tend to be more resistant to wear and produce less wear debris. Fig. 2 shows the microstructure of the copper specimens after heat treatment. The figure shows grain boundaries and thermal twins, which are the typical microstructures of annealed copper and copper alloys. The average grain size was determined through the linear intercept method [32], and the calculated average grain sizes were 2, 29, 58, 88, 135, and 162 µm. The twin boundaries were considered in the calculation of the average grain size, because they play a role similar to that of grain boundaries in grain-size strengthening [33,34].

Fig. 3 presents the surface hardness of the copper specimens as a function of the average grain size. In accordance with the well-known Hall–Petch relationship [22], which describes the effect of grain size on the yield strength of metals and alloys, surface hardness exhibited a linear relationship with $d^{-1/2}$, where d is the average grain size. This correlation between grain size and surface hardness indicates that the indentation process for hardness measurement comprises plastic deformation of the copper substrate and that the internal boundaries, such as grain boundaries and twin boundaries, act as barriers to dislocation movement.

3.2. Grain-size effect on electrical contact resistance

The change in electrical contact resistance was monitored during the fretting tests to investigate the effects of copper grain size on the critical number of fretting cycles at which an abrupt increase in contact resistance was observed. In this study, the critical number of cycles for contact failure was defined as the cycle number at which the contact resistance exceeded 0.1 Ω for 10 or more subsequent cycles. Fig. 4 shows contact resistance as a function of the fretting cycle. Contact resistance began to increase after a certain cycle, and the critical number of cycles changes with the average grain size of copper.

The coefficient of friction was measured to examine its possible correlation with electrical contact resistance (Fig. 4). The friction coefficient increased after approximately 10^2 cycles because of the increase in contact area and saturated after approximately 10^3 cycles. No direct correlation was found between the critical number of cycles and the profile of the friction coefficient, suggesting that different mechanisms govern the contact resistance and the friction coefficient. The friction coefficient appears to be governed by the interfacial shear of materials at the contact area, whereas electrical contact resistance is governed by the size of the junctions and the thickness of the electrically insulating third layer. This result is consistent with that of Sung et al. [12], who reported no direct correlation between the critical number of cycles in fretting experiments and the friction coefficient under humid conditions.

To understand the increase in the contact resistance at the critical cycle, the contact area was examined during the fretting tests. Fig. 5 shows the OM images of the contact area at 40, 2400, and 5000 fretting cycles for the copper specimen with an average grain size of 29 µm. The size and color of the contact area changed over the course of the fretting