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FRETTING WEAR BEHAVIOR OF TIN PLATED CONTACTS: INFLUENCE ON CONTACT RESISTANCE

Y. W. PARK, T. S. N. SANKARA NARAYANAN[†] and K. Y. LEE[*]
Stress Analysis and Failure Design Laboratory,
School of Mechanical Engineering, Yonsei University,
134, Sinchon-dong, Seodaemum-gu, Seoul 120-749, South Korea
[*]*kyl2813@yonsei.ac.kr*

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The fretting wear behavior of tin plated copper alloy contacts and its influence on the contact resistance are addressed in this paper. Based on the change in the area of contact zone as well as the wear depth as a function of fretting cycles, a model was proposed to explain the observed low and stable contact resistance. The extent of wear of tin coating and the formation of wear debris as a function of fretting cycles were assessed by scanning electron microscopy (SEM). Energy dispersive X-ray line scanning (EDX), X-ray mapping, and EDX spot analysis were employed to characterize the nature of changes that occur at the contact zone. The study reveals that the fretted area increases linearly up to 8000 cycles due to the continuous removal of the tin coating and attains saturation when the fretting path length reaches a maximum. The observed low and stable contact resistance observed up to 8000 cycles is due to the common area of contact which provides an electrically conducting area. Surface analysis by SEM, EDX, and X-ray elemental mapping elucidate the nature of changes that occurred at the contact zone. Based on the change in contact resistance as a function of fretting cycles, the fretting wear and fretting corrosion dominant regimes are proposed. The interdependence of extent of wear and oxidation increases the complexity of the fretting corrosion behavior of tin plated contacts.

Keywords: Fretting wear; tin plated contact; contact resistance; surface analysis.

1. Introduction

Fretting, an accelerated surface damage that occurs at the interface of contacting materials subjected to small oscillatory movement, is a common problem encountered in many engineering applications. The deleterious effect of fretting in electrical connections is considered to be of significant practical importance as it influences the reliability and system performance. In recent years, the number of electrical systems in a typical passenger vehicle continues to grow, powering everything from headlight, DVD player, body impact sensors, global-positioning systems, etc. With the inclusion of every new system, additional connectors are provided. A decade ago, middle class cars have about 400 connectors with 3000 individual terminals that translate into 3000

[*]Corresponding author.
[†]On leave from National Metallurgical Laboratory, Madras Centre, CSIR Complex, Chennai, India.

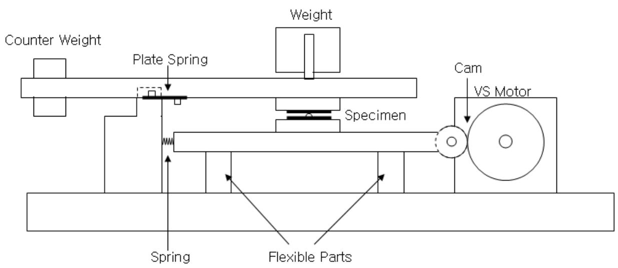
potential trouble spots. In today's luxury cars the number of connectors is significantly increased. It has been estimated that more than 60% of the electric problems in cars are related to fretting contact problems. Since fretting is one of the major deterioration mechanisms of non-arcing electrical contacts, studies on this phenomenon has assumed significance.

Copper alloys have been the preferred choice for the electrical contacts due to the unique combination of conductivity, strength, stiffness, formability, and cost. The copper alloy contacts are usually plated with either noble metals (gold, palladium, and their alloys) or non-noble metals (tin and tin-lead) to minimize the potential for corrosion and to improve their durability. Although gold and other precious metal plated contacts are recommended for high reliability electrical contacts, non-noble metal plated contacts have gained popularity due to the market pressure to reduce the cost factors. The use of gold flash as an economical practice to protect the electrical contact from corrosion has been proved to be detrimental to long-term reliability.[1] Besides, gold plated contacts with low coating weight are prone for pore corrosion.[2] Based on performance, cost criteria, and the compelling need to adopt lead-free processes, tin plating is considered as the best candidate and has been recommended as the finish of choice for connectors.

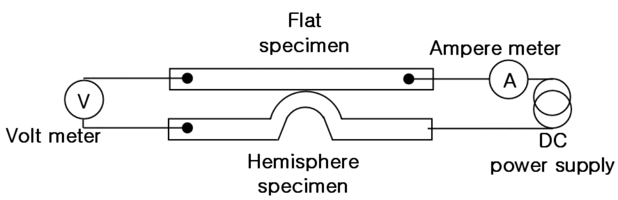
Tin plated contacts have gained acceptance as a low-cost alternative to gold. Besides cost, tin plating has two main technical advantages: the thin tin oxide film (10–30 nm) forms on the surface of the tin coating could act as a shield, inhibiting further oxidation, and being a relatively soft metal, tin provides a low constriction resistance.[3] However, the susceptibility of tin plated contacts for fretting corrosion is considered to be a major limitation for its use in electrical connectors. Fretting corrosion of tin plated connectors has been the subject of many papers.[4–7] Although fretting itself may not result in failure of an electrical connection, the deleterious effect of fretting is a great deal of concern since fretting leads to the accumulation of the wear debris and oxidation products in the contact zone in the form of a thick highly localized insulating layer. The formation of such an insulating layer results in a rapid increase in contact resistance and eventually leads to a virtually open circuit. Although such a phenomenon evolves with time, the main difficulty is that it is not easy to detect. The present paper aims to study the fretting wear behavior of tin plated copper alloy contacts and to evaluate how the wear of the tin coating, oxidation of wear debris, and accumulation of oxidation products influence the contact resistance. An evolution of the wear behavior of tin coated contacts and its influence on contact resistance, as a function of fretting cycles, are very important in the development of accelerated test methods and in reliability design.

2. Experimental Details

The fretting wear behavior of tin plated copper alloy contacts was studied using a fretting apparatus in which the relative motion between the contacts was provided by a variable speed motor/precision stage assembly. The schematic of the fretting apparatus used in this study is given in Fig. 1(a). The normal contact force was supplied by the weights placed on the balance arm. The contacts were flat versus 1.5 mm radius hemispherical rider, both of them were made of copper alloy (Ni:1.82%, Si:0.75%; Zn:0.01%; Sn:0.37% and Cu:Balance) and electroplated with tin to a thickness of 3 μm, supplied by the Korea Electric Terminal Company Ltd., Korea. The rider and flat specimens were degreased using acetone in an



(a)



(b)

Fig. 1. (a) Schematic of the fretting apparatus used in the present study and (b) the geometry of the rider and flat samples and the circuit used to measure the contact resistance.

ultrasonic cleaner, dried and carefully mounted in the fretting test assembly.

It is well established that under stabilized partial slip sliding conditions, which allows direct metal–metal interactions, the contact resistance is usually low and stable. However, under gross slip conditions, the wear process induces debris which gets oxidized and forms an insulting third body layer.[8] Such a condition prevents the metal–metal interactions and results in high and unstable contact resistance. Since the present study focuses on the fretting wear behavior of tin plated copper alloy contacts and to correlate the nature of changes with the contact resistance, the tests were conducted under gross slip conditions. A periodic relative displacement with amplitude of $\pm 90\,\mu$m and a frequency of 10 Hz were applied between the rider and flat contacts loaded by a constant normal force of 0.5 N. The use of a contact force of 0.5 N is relatively higher than that is normally used in automotive industry. However, use of lower contact loads often results in worse electrical contact behavior and under such conditions it is difficult to understand the fretting wear behavior of tin plated contacts. Hence a higher normal load of 0.5 N was chosen in this study. The contact area is defined to be a point contact by "sphere plane" geometry. An electric current of 100 mA was applied by an electrical circuit. The contact geometry and the circuit used to measure the contact resistance are given in Fig. 1(b). The contact resistance was continuously measured as a function of fretting cycles. All tests were performed in un-lubricated conditions at $27 \pm 1°$C and at $45 \pm 2\%$ RH.

After testing, the samples were characterized to assess the surface profile, surface roughness, surface morphology, and the nature of the contact zone by laser scanning microscope (LSM) and various surface analytical techniques. The samples were stored in air tight containers to prevent from further oxidation and analyzed within 2 h. The surface profile and surface roughness across the fretted zone were assessed using a Carl Zeiss laser scanning microscope (LSM) (Model: LSM-5 PASCAL). Scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX), and X-ray dot mapping were used to characterize the fretting damage at the contact zone. Studies were conducted in several modes including secondary electron imaging, EDX line scanning analysis across the contact zone, EDX analysis of selected regions on the contact zone, and X-ray elemental dot mapping to show elemental distribution across the contact zone.

3. Results and Discussion

3.1. *Contact resistance of tin plated contacts as a function of fretting cycles*

The contact resistance of tin plated copper alloy contacts as a function of fretting cycles is shown in Fig. 2. There is a hump observed (inset of Fig. 2) in the initial stage (between 100 and 400 cycles) followed by a low contact resistance up to 8000 cycles.

There is a slight increase in the contact resistance from 8,000 to 12,000 cycles followed by a gradual increase in the contact resistance from 12,000 to 15,000 cycles, beyond which the contact resistance increases rapidly. The observed trend of change in the contact resistance as a function of fretting cycles correlates well with those of other researchers.[4–7] The initial hump is due to the presence of a thin film of tin oxide on the surface of the tin plated copper alloy contact, which is removed in a very short span of time. If the oxide film is present on the tin coating, then the contact resistance should be relatively high when the contacts are mated together. However, the contact resistance is relatively low, and the increase in the contact resistance (hump) appears only after the fretting motion is started. The observed low initial contact resistance could be explained based on

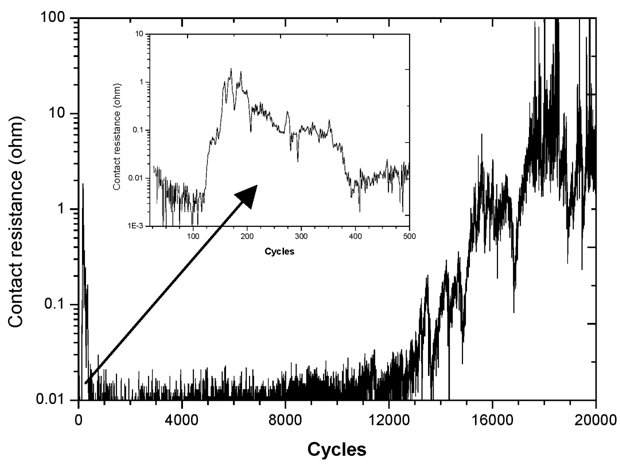


Fig. 2. Change in the contact resistance of the tin plated copper alloy contact measured across the contact zone as a function of fretting cycles.

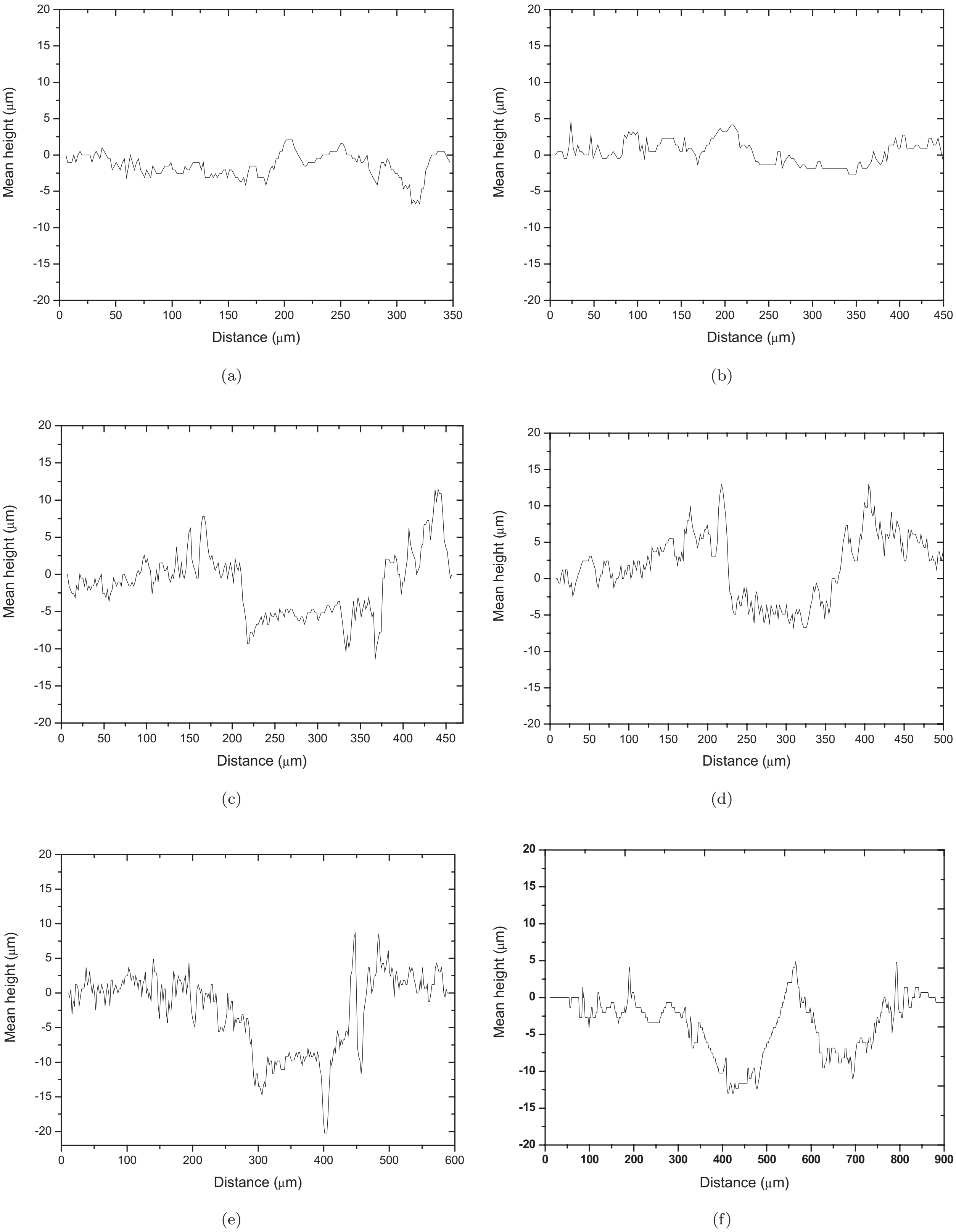


Fig. 3. Surface profile across the fretted zone of the tin plated contact measured after different fretting cycles: (a) 30; (b) 220; (c) 1000; (d) 2000; (e) 4000; and (f) 8000 cycles.

the multispot contact model, which assumes that the metal oxide is more brittle than the metal.[9] When the tin plated copper alloy contacts are mated together with a normal load of 0.5 N, the hard tin oxide layer (hardness: 1650 kg/mm^2) gets cracked and induces a stress on the softer tin coating (hardness: 5 kg/mm^2) lying beneath it. As a result, the softer tin coating extrudes through the cracks in the tin oxide layer and establishes a good metal-to-metal contact. The low contact resistance values observed up to 8000 cycles, after the initial hump, are due to the conducting nature of the soft tin plating. The gradual increase in the contact resistance could be attributed to the formation of tin oxide film. The subsequent rapid increase in the contact resistance is due to the accumulation of wear debris and oxidation products, which reduces the electrical conducting area, suggesting that with increase in number of fretting cycles the current is conducted through an increasingly smaller area of contact.

The formation of oxide film and the decrease in conducting area are responsible for the failure of the electrical contact. Hence it is important to understand how the tin coating wears out during fretting motion and how the wear debris and oxidation products influence the contact resistance. In order to get a better insight on this phenomenon, the nature of changes that occur at the contact zone is assessed after 30, 220, 1000, 2000, 4000 and 8000 cycles by LSM, SEM, EDX, and X-ray mapping. The choice of 30 and 220 cycles is to understand the nature of changes when the surface of the tin plated contact is covered with the thin tin oxide film, whereas 1000, 2000, 4000 and 8000 cycles are selected to understand the fretting wear behavior of the soft tin coating.

3.2. *Surface profile of contact zone*

The surface profile as a function of distance, measured perpendicular across the fretted zone, after 30, 220, 1000, 2000, 4000 and 8000 cycles is given in Fig. 3. It is evident from Fig. 3 that the area of the contact zone as well as the wear depth increases dramatically, suggesting that the tin coating is wearing out continuously with increase in fretting cycles. To analyze the variation in the surface profile with fretting cycles, the fretted area is plotted as a function of fretting cycles (Fig. 4). For a better understanding, the fretted area of 16,800 and 48,000 cycles is also included in Fig. 4. The linear increase in the fretted area up to 8000 cycles indicates continuous removal of the tin coating due to wear. The saturation in the fretted area beyond 8000 cycles indicates that the fretting path length has reached a maximum.

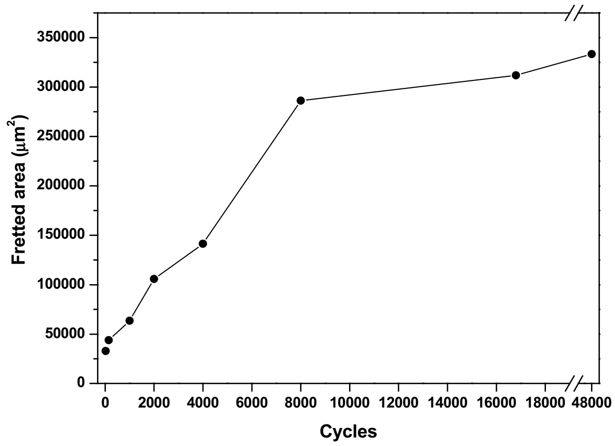


Fig. 4. Variation of the fretted area of the tin plated contact calculated from LSM measurements as a function of fretting cycles.

In spite of the linear increase in the fretted area up to 8000 cycles, the contact resistance remains low up to this stage (Fig. 2). To analyze the correlation between the fretting wear behavior and the contact resistance, the change in length and width of the contact zone at 30, 220, 1000, 2000, 4000, and 8000 cycles measured from LSM measurements is used to model the contact zone (Fig. 5). According to this model, at 30 cycles the contact zone is represented by two small circles which have no common point of contact, while at 1000 cycles the size of the two circles increases so as to create a very small common area of contact. From 1000 to 8000 fretting cycles the common area of contact between the circles increases along with the size of the two circles whereas from 8000 to 48,000 cycles the increase in the common area of contact is very less. The common area of contact between the two circles provides an electrically conducting area, and this area is responsible for the observed low and stable contact resistance up to 8000 cycles.

3.3. *Surface characteristics of the contact zone*

The surface morphology of the tin plated copper alloy contacts run for 30, 220, 1000, 2000, 4000, and

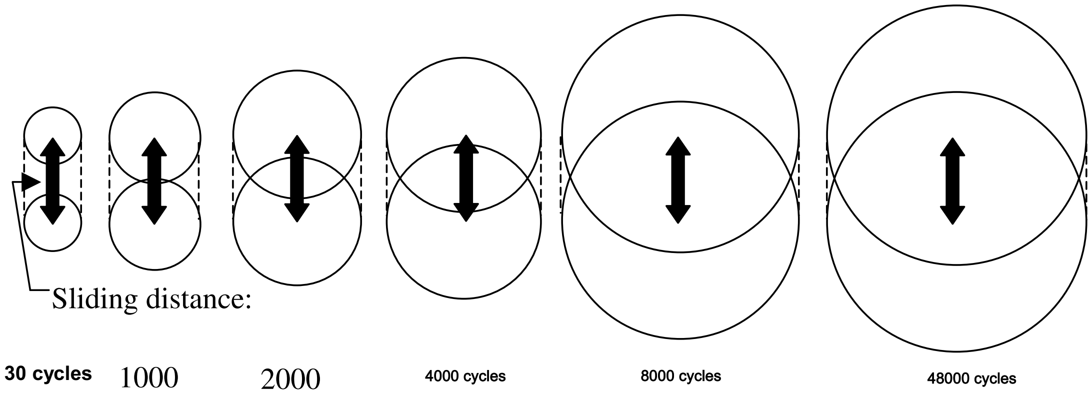


Fig. 5. Pictorial model of the area of the contact zone proposed based on the length and width of the fretted area as a function of fretting cycles.

8000 fretting cycles is shown in Fig. 6. The fretting direction is vertical (indicated by the dotted line). The fretted zone is oval/elliptical in shape. The area of the fretted zone and the extent of wear of the tin coating are increased with increase in fretting cycles, supporting the observations of the surface profile measurement. A closer look at the morphology indicates the occurrence of adhesive wear, characteristic of the transfer of material between the mated contacts, and the formation of bright debris particles that are ejected laterally during the fretting motion. The bright debris particles observed outside the fretted zone along the sliding direction are believed to be tin and its oxides. The extent of formation of these debris particles increases with increase in fretting cycles.

The EDX line scanning performed across the fretted region (indicated by the dotted line in Fig. 6) confirms the presence of tin and copper as the major elements (Fig. 7). The intensity of oxygen is not appreciable in the line scan of the overall fretted zone. A comparison of the EDX line scan results obtained at different fretting cycles reveals that at 30 cycles the intensity of tin is very high compared to that of copper, whereas at and above 220 cycles, the intensity of tin decreases with a corresponding increase in the intensity of copper at the contact zone. X-ray dot mapping of tin, copper, and oxygen performed across the fretted zone substantiates the observations of EDX line scanning (Fig. 8). A comparison of the tin, copper, and oxygen maps (Fig. 8) taken at 220 and 8000 cycles reveals that the tin coating is constantly removed with increase in fretting cycles, and the copper alloy is exposed at those areas where the coating is removed. The X-ray maps of tin and copper suggest that around 8000 cycles the tin coating is almost removed, and in a major portion of the contact zone the copper alloy is exposed. The X-ray map of the oxygen reveals that an appreciable amount of oxidation of the contact zone occurs around 8000 cycles.

The EDX pattern of the whole fretted region (indicated by dotted line in Fig. 6) indicates the presence of tin as the predominant element even up to 8000 cycles, and the intensity of copper starts to increase only around 8000 cycles. This observation suggests that the tin coating is present in a major portion of the contact zone, and it is removed only in a smaller region where the copper alloy is exposed. The EDX spot analysis performed at the damaged sites (indicated by "⊗" in Fig. 6) in the center of the fretted zone indicates that at 30 cycles it is predominantly tin (53.36 at.%) and oxygen (42.53 at.%) with a small portion of copper (4.21 at.%), whereas at and above 220 cycles it is predominantly copper (76–84 at.%) with a small proportion of tin (2–9 at.%) and oxygen (15–26 at.%). The higher oxygen content observed at 30 cycles is due to the tin oxide coating that is already present on the tin plated copper alloy, which is removed only between 100 and 400 cycles (inset of Fig. 2). The EDX spot analysis performed at the bright white debris particles at the edge of the fretted zone indicates that it is predominantly tin (45–65 at.%) and oxygen (28–47 at.%) with a small portion of copper (6–10 at.%). The EDX analysis indicates that the center of the fretted zone contains

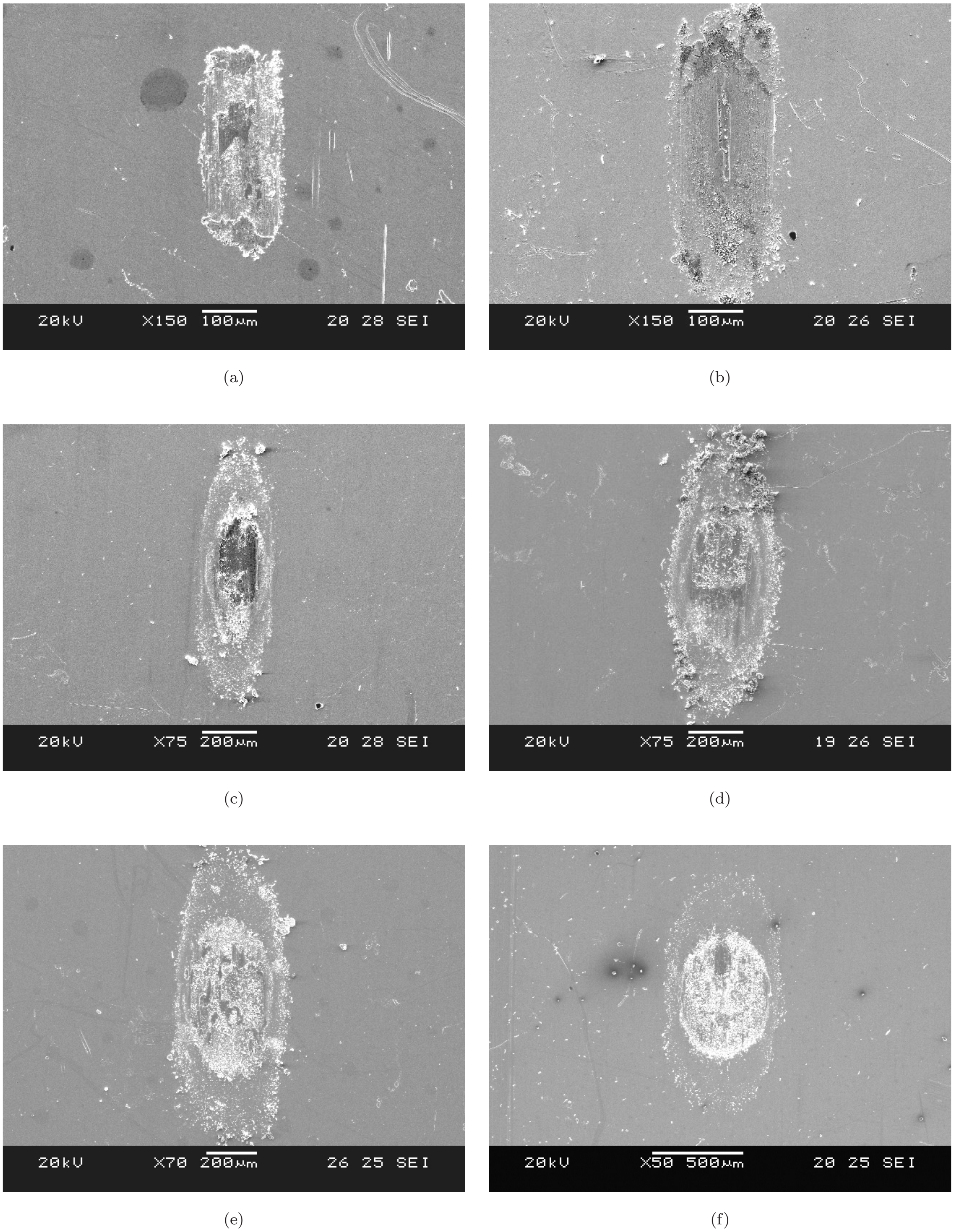


Fig. 6. Surface morphology of the contact zone of the tin plated contact after different fretting cycles: (a) 30; (b) 220; (c) 1000; (d) 2000; (e) 4000; and (f) 8000 cycles.

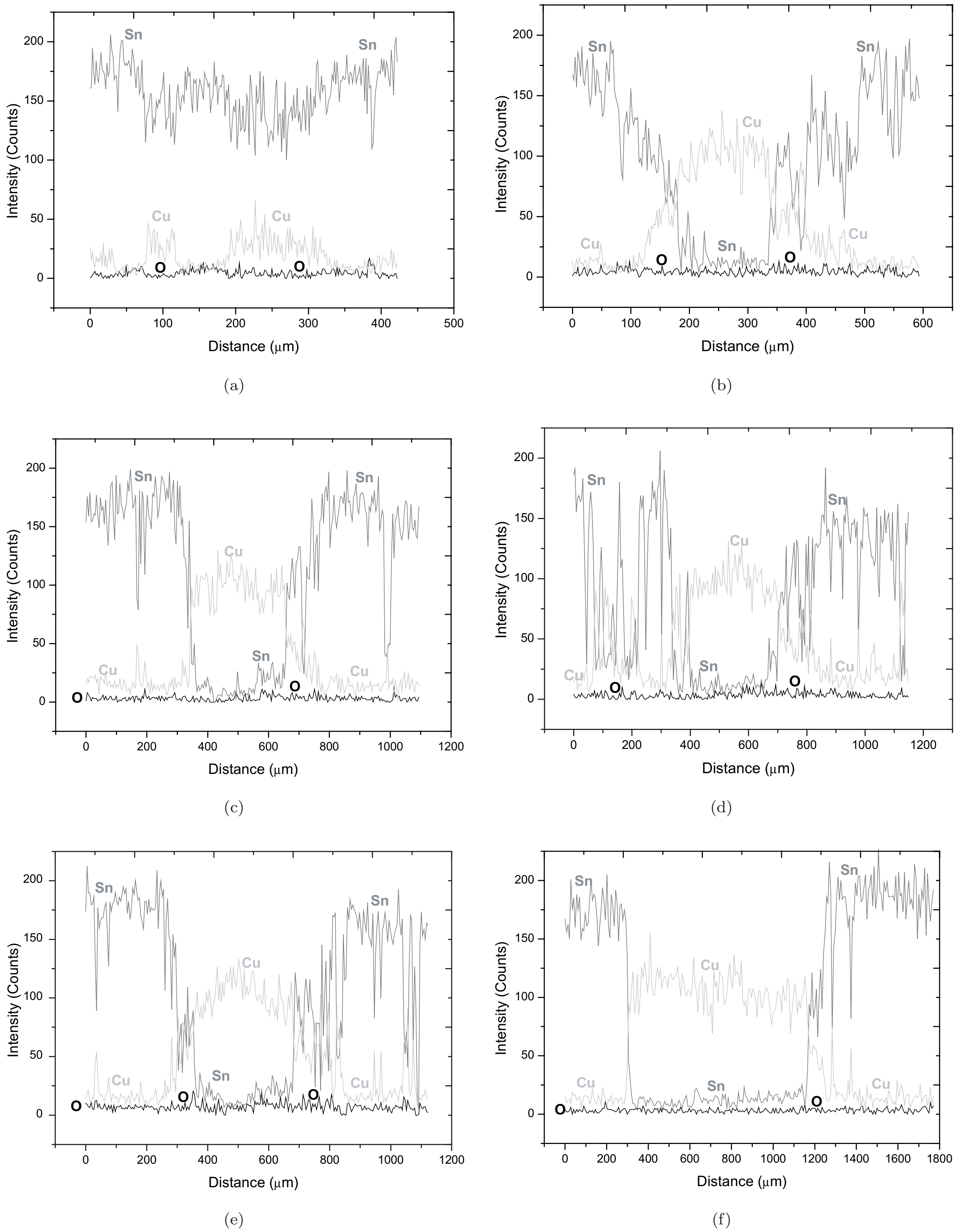


Fig. 7. EDX line scan performed across the fretted zone (indicated by the dotted line in Fig. 6) after different fretting cycles: (a) 30; (b) 220; (c) 1000; (d) 2000; (e) 4000; and (f) 8000 cycles.

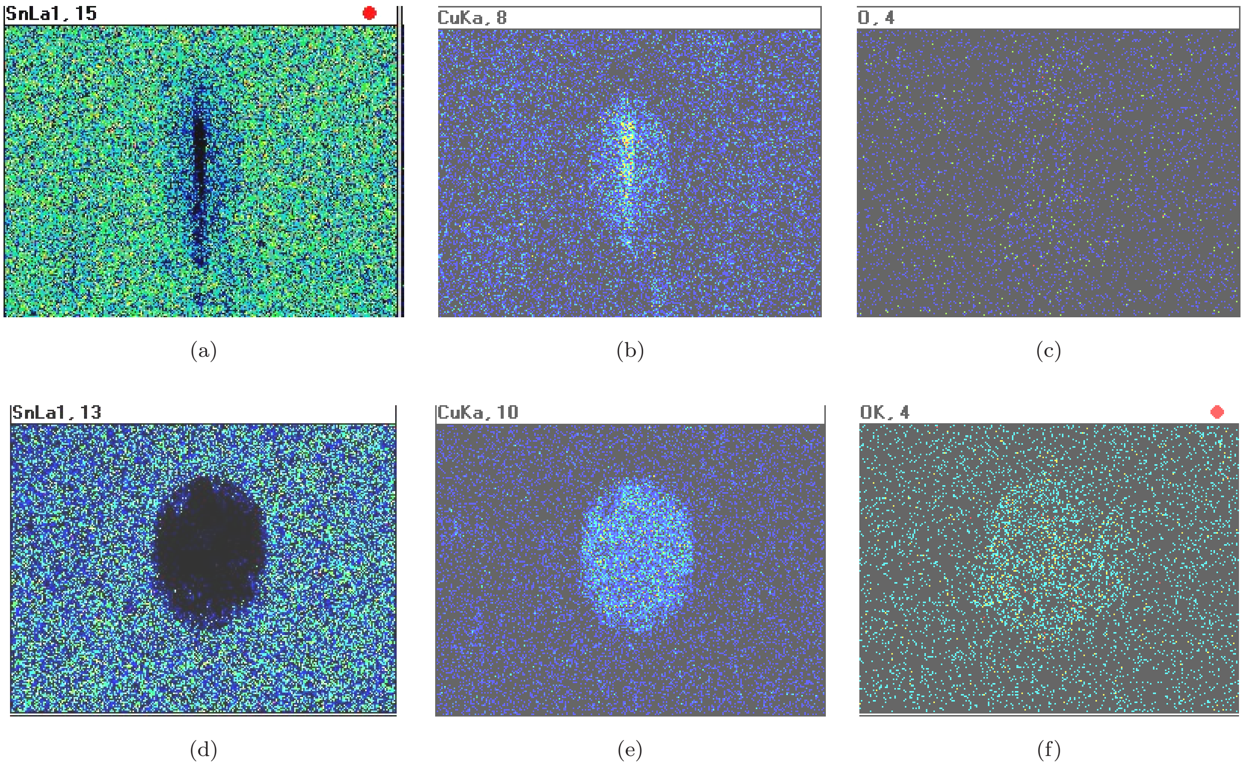


Fig. 8. X-ray dot mapping of tin, copper, and oxygen performed across the fretted zone after 220 (a–c) and 8000 (d–f) fretting cycles: (a and d): Sn map; (b and e) Cu map; (c and f): O map.

predominantly oxides of copper, whereas the edges are rich in oxides of tin. Both at the center and edge regions, an appreciable amount of oxygen is observed only around 8000 cycles.

Based on the results of surface profile measurements and surface characteristics of the contact zone, the change in the contact resistance of the tin plated copper alloy contact measured as a function of fretting cycles (Fig. 2) can be classified into two segments. The first segment up to 8000 cycles represents the fretting wear dominant regime, whereas the second segment, beyond 8000 cycles, represents the fretting corrosion dominant regime. It could be visualized that the fretting wear dominant regime involves the following sequence of changes at the contact zone:

(i) removal of the tin oxide layer (between 100 and 400 cycles);
(ii) partial removal of the tin coating due to adhesive wear phenomenon;
(iii) removal of the tin coating due to fretting wear in many areas and displacement of wear debris outside the fretted zone;
(iv) exposure of base metals, where the coating is removed;
(v) continuous formation and rupture of oxide films;
(vi) initial stages of oxidation of the contact zone;
(vii) attainment of a critical level, where the number of contact points starts to decrease,

while the fretting corrosion dominant regime involves the following sequence of changes:

(i) formation and removal of the oxide film due to fretting motion;
(ii) accumulation of wear debris and oxidation products at the contact zone;
(iii) thickening of the oxide film;
(iv) reduction in number of electrical contact points;
(v) virtual open circuit.

As the rate of wear of tin coating and the rate of oxidation of the contact zone are dependent on many factors, such as frequency, normal load, temperature, humidity, current load, etc., the transition point from the fretting wear dominant regime to the fretting corrosion dominant regime also varies with the operating conditions. The interdependence of the extent of wear and oxidation further increases the complexity of the fretting corrosion behavior of tin plated copper alloy contacts.

4. Conclusions

The fretting wear behavior of tin plated copper alloy contacts and its influence on the contact resistance are studied. The fretted area increases linearly up to 8000 cycles due to the continuous removal of the tin coating due to wear. Beyond 8000 cycles, the fretted area attains saturation when the fretting path length reaches a maximum. The nature of the contact zone as a function of fretting cycles is modeled based on the change in length and width of the contact zone. The observed low and stable contact resistance observed up to 8000 cycles is due to the common area of contact which provides an electrically conducting area. The increase in the area of fretted zone, increase in the extent of wear of tin coating, occurrence of adhesive wear, and the formation of bright debris particles are confirmed by SEM. EDX line scanning confirms that tin and copper are the major elements in the fretted zone, and the presence of oxygen is not appreciable. The results of EDX line scanning are also substantiated by X-ray dot mapping of tin, copper, and oxygen. Based on the results of surface profile measurements and surface characteristics of the contact zone, the change in the contact resistance of the tin plated contact measured as a function of fretting cycles is classified into two segments. The first segment up to 8000 cycles represents the fretting wear dominant regime, whereas the second segment, beyond 8000 cycles, represents the fretting corrosion dominant regime. Since the extent of wear of tin coating and oxidation of wear debris is highly interdependent, the fretting corrosion behavior of tin plated contacts becomes a complex phenomenon.

Acknowledgments

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