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Fretting corrosion of tin-plated contacts: Evaluation of surface characteristics

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Abstract

The surface characteristics of the contact zone of tin-plated copper alloy contacts subjected to fretting motion for 8000, 16,800 and 48,000 cycles under unlubricated conditions are presented. The nature of the contact zone, at the verge of wearing out of the tin coating as well as upon the coating is completely worn out, is assessed using scanning electron microscopy (SEM), energy-dispersive X-ray (EDX) analysis and X-ray dot mapping, and the influence of these changes on the contact resistance is correlated. The study reveals that under unlubricated conditions, fretting caused significant damage at the contact zone. Occurrence of adhesive wear failure is observed at early stages whereas at latter stages, delamination wear is the predominant mode of failure. As the fretting cycle increases, the concentration of copper increases whereas the concentration of tin decreases; oxygen concentration though not appreciable at the early stages, starts to build with increase in fretting cycles, attributing to the increase in contact resistance due to the formation of oxides of copper and tin at the contact zone.

Keywords: Fretting corrosion; Tin plating; Surface characteristics

1. Introduction

Fretting, defined as the accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movement, is a common problem encountered in many engineering applications and is considered to be of significant practical importance. The main causes of fretting are vibrations and temperature variations inducing differential expansion. Such situations are classically observed not only in air planes, satellites and trains, but also in cars, particularly next to the engine. It is most commonly found in all kinds of pres fits, spline connections, leaf springs, rivets and bolted joints, nuclear fuel elements, wipe ropes, and also in electrical connections.

Bock and Whitley [1] demonstrated the importance of fretting in the degradation of electrical connections. A comprehensive review of fretting in electrical connections has been given by Antler [2,3]. Though 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 oxides in the contact zone in the form of a thick highly localized insulating layer that in turn results in a rapid increase in contact resistance and eventually leads to a virtually open circuit. Though such a phenomenon evolves with time, the main difficulty is it is not easy to detect.

In recent years, the number of electrical systems in a typical passenger vehicle continues to grow, powering everything from headlight and DVD player to body impact sensors and global-positioning systems. With the inclusion of every new system, additional connectors are provided. Today's luxury cars have about 400 connectors with 3000 individual terminals that translate into 3000 potential trouble spots. It has been estimated that more than 60% of the electric problems in cars are related to fretting contact

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problems [4]. 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 contact manufacturer 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, tin-lead) to minimize the potential for corrosion and to improve the durability. Though gold and other precious metal-plated contacts have been the preferred choice in electrical connectors, non-noble metal-plated contacts 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 [5]. Besides gold-plated contacts with low coating weight has been shown to involve failures due to pore corrosion [6]. In order to meet the requirements of EU directive 2002/95/EC, also known as RoHS, which restrict the use of lead, the connector manufacturer have to adopt lead-free plating for electronic components. The alternate choices and their commercial viability were also reported elsewhere [7]. However, the major limitation in lead-free electroplated connector finishes is the whisker formation [8–10]. Based on the performance and cost criteria, tin plating is considered as the best candidate in lead-free applications and has been recommended as the finish of choice for connectors.

Tin-plated contacts have gained acceptance in many consumer applications as a low-cost alternative to gold [11]. However, the susceptibility of tin-plated contacts for fretting corrosion is considered to be a major limitation for its use in automobile connectors. The requirements of the

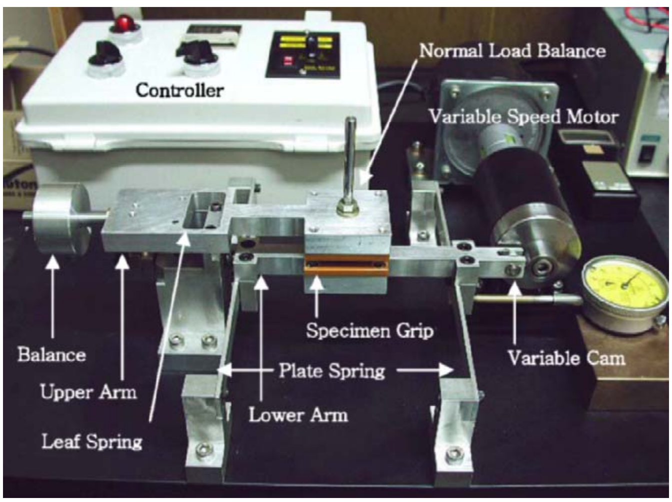

Fig. 1. The fretting apparatus used in the present study.

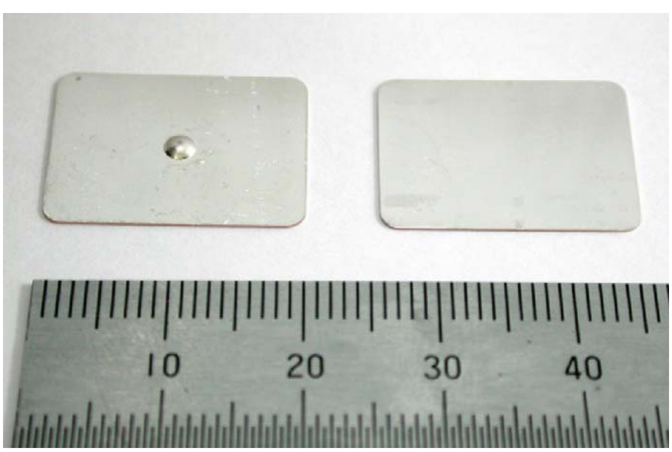

Fig. 2. The rider and flat samples used in the present study.

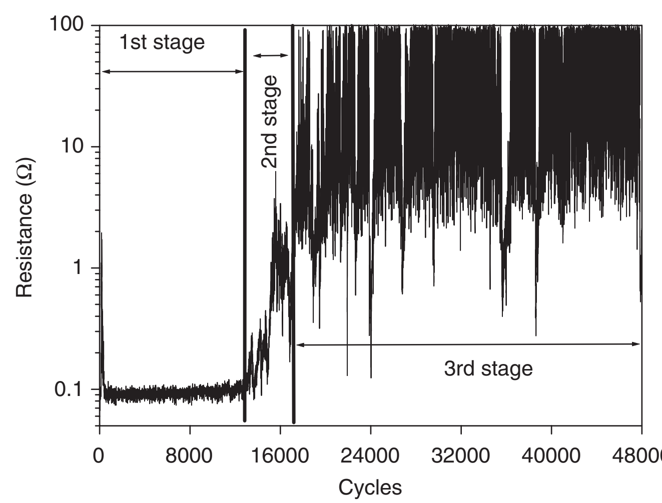

Fig. 4. Change in contact resistance of the tin-plated copper alloy contact across the contact zone as a function of fretting cycles.

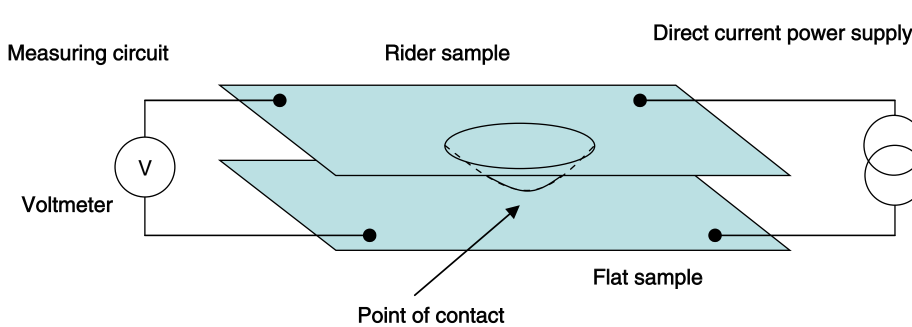

Fig. 3. The geometry of the rider and flat samples and the circuit used to measure the contact resistance.

connectors used in automobiles have to protect against wear, changing temperature, road grit and vibrations, all of which increases the rate of oxidation and fretting corrosion on tin-plated connectors. As the car companies continue to extend their warranties, the challenge for the connector manufacturers to extend the operating life of their products also increases. At one end cost factors encourage them to adopt tin plating, whereas at the other end fretting corrosion of tin-plated contacts is affecting their reliability. The quest for a suitable finish which is cost-effective as well as capable of combating corrosion and fretting continues.

Fretting corrosion of tin-plated connectors has been the subject of many papers [12–20]. However, many of them focus on the method of measurement and effect of oxide formation on change in contact resistance whereas a few address on the means of preventing it. Only a few papers have used surface analytical techniques to assess the extent of surface damage and the nature of oxide film formed [21–23]. Braunovic [21] has evaluated the fretting damage in tin-plated aluminum and copper connectors by various surface analytical techniques. Stennett and Swingler [22] have used Auger electron spectroscopy (AES) depth profile analysis to study the effect of power on the early stages of low-frequency fretting corrosion. Mottine and Reagor [23] have used scanning electron microscope (SEM) and scanning Auger microscope (SAM) X-ray dot mapping to study the effect of lubrication on fretting corrosion at dissimilar metal interfaces (Sn/Au and SnPb solder/Au). Detailed surface analytical characteristics of the nature of

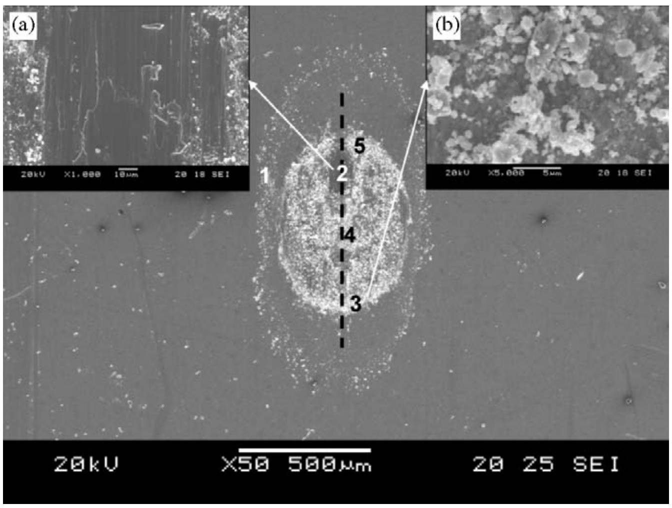

Fig. 5. Surface morphology of the tin-plated copper alloy contact after 8000 fretting cycles. (a) occurrence of adhesive wear (region marked as '2' in Fig. 5). (b) Magnified view of the bright particles observed at the outer region of the fretted zone (marked as '3' in Fig. 5).

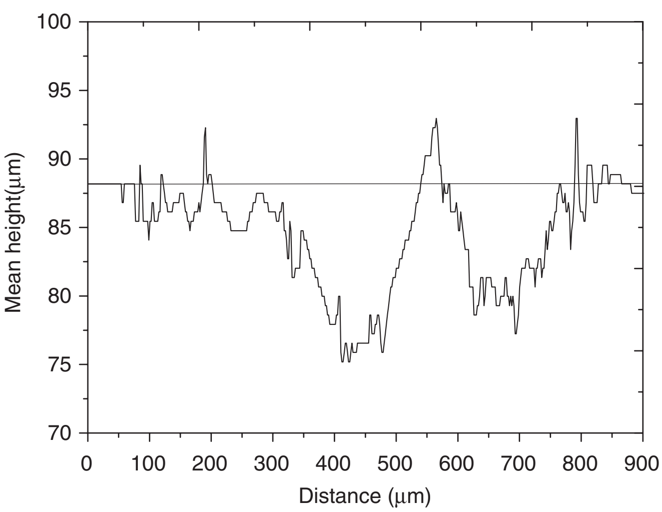

Fig. 6. Surface profile across the fretted zone after the tin-plated copper alloy sample was run for 8000 fretting cycles.

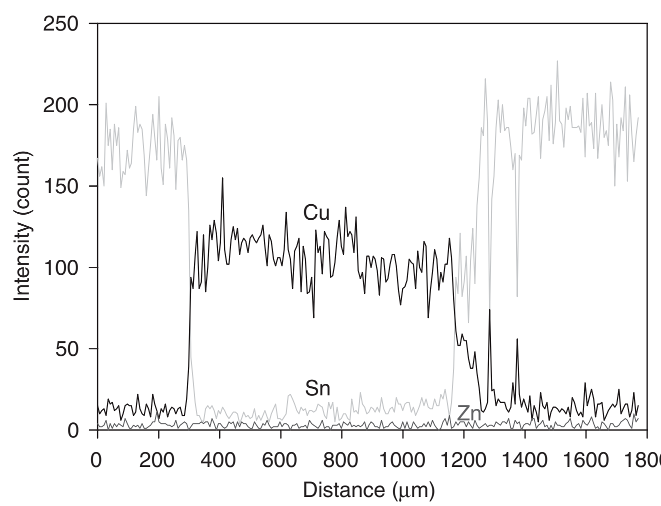

Fig. 7. EDX line scan performed across the fretted zone (indicated by the dotted line in Fig. 5) after the tin-plated copper alloy sample was run for 8000 fretting cycles.

Table 1
Roughness parameters calculated based on the surface profiles of the fretted zones subjected to fretting for different fretting cycles

Roughness parameter	After 8000 fretting cycles	After 16,800 fretting cycles	After 48,000 fretting cycles
Arithmetic mean deviation, R_a (μm)	3.63	4.33	6.74
Highest peak, R_p (μm)	12.19	11.19	15.64
Lowest valley, R_v (μm)	10.32	11.91	10.06
Absolute peak to valley, R_t (μm)	22.52	23.10	25.71
Average peak to valley, R_z (μm)	8.58	10.80	8.37
Maximum peak to valley, R_{max} (μm)	20.55	19.95	20.06

oxide film formed at the contact zone as a function of fretting cycles and how it influences the contact resistance of tin-plated copper alloy contacts are lacking. The present paper deals specifically with the surface analysis of the contact zone of tin-plated copper alloy at the verge of wearing out of the tin coating as well as upon the coating is completely worn out to assess the nature of oxide films formed and to correlate with the change in contact resistance at the respective fretting cycles.

2. Experimental details

The fretting corrosion studies of tin-plated copper alloy contacts were conducted using the fretting apparatus shown in Fig. 1. The relative motion between the contacts was provided by a variable speed motor/precision stage assembly. 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 (Fig. 2), both of them were made of copper alloy (Ni: 1.82%, Si: 0.75%; Zn: 0.01%; Sn: 0.37% and Cu: balance) and tin plated to a thickness of 3 μm, supplied by Korea Electric Terminal Company Ltd., Korea. The rider and flat specimens were degreased using acetone in an ultrasonic cleaner, dried and carefully mounted in the fretting test assembly.

It is well established that under stabilized partial slip sliding condition, which allows direct metal–metal interactions, the contact resistance is usually low and stable. However, under gross slip condition, the wear process induces debris which gets oxidized and forms an insulating third body layer [24]. Such a condition prevents the metal–metal interactions and results in high and unstable contact resistance. Since the present study intends to characterize the nature of oxide films formed at the contact zone of the tin-plated copper alloy contacts (at the verge of wearing out of the tin coating as well as upon the coating is completely worn out) and to correlate the nature of changes with the observed change in contact resistance, the tests were conducted under gross slip conditions. The fretting tests were repeated at least three times to ascertain reproducibility of the test results.

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 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 resistance was continuously measured as a function of fretting cycles (Fig. 3). All tests were performed in unlubricated conditions at $25 \pm 1\,^{\circ}C$ and at $45 \pm 1\%$ RH.

Based on the change in contact resistance as a function of fretting cycles, the curve is divided into three segments, designated as stages I, II and III, representing the low contact resistance region, the region where there observed to be a gradual increase in contact resistance and the region where there is a rapid increase in contact resistance, respectively. Three independent samples were allowed to run for 8000, 16,800 and 48,000 cycles, respectively so that the fretting damage occuring at the contact zone at these three different stages could be assessed. After testing the

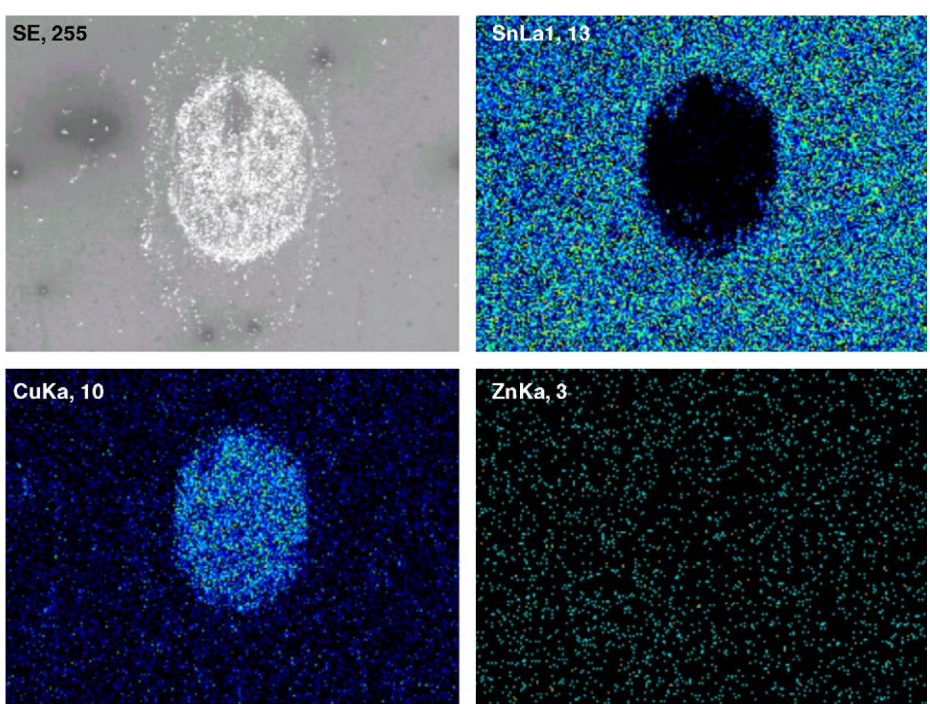

Fig. 8. X-ray dot mapping of copper, tin and zinc performed across the fretted zone after the tin-plated copper alloy sample was run for 8000 fretting cycles.

samples were stored in air-tight containers to prevent from further oxidation and analyzed within 24 h. Scanning electron microscopy (SEM), energy-dispersive X-ray (EDX) analysis and X-ray dot mapping were used as the principal analytical techniques to characterize the fretting damage at the contact zone. Studies were conducted in several modes including secondary electron imaging to assess the contact morphology, 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. The surface profile across the fretted zone was also assessed using a Carl Zeiss laser scanning microscope (Model: LSM 5 PASCAL).

3. Results and discussion

The change in contact resistance of tin-plated copper alloy contact across the contact zone as a function of fretting cycles is shown in Fig. 4. There observed to be a hump in the initial stages followed by a low contact resistance up to the first few thousand cycles. Beyond that there observed to be a rapid increase in contact resistance. The observed results correlate well with those of other researchers [12–20]. 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. The low contact resistance values observed up to the first few thousand cycles is due to the conducting

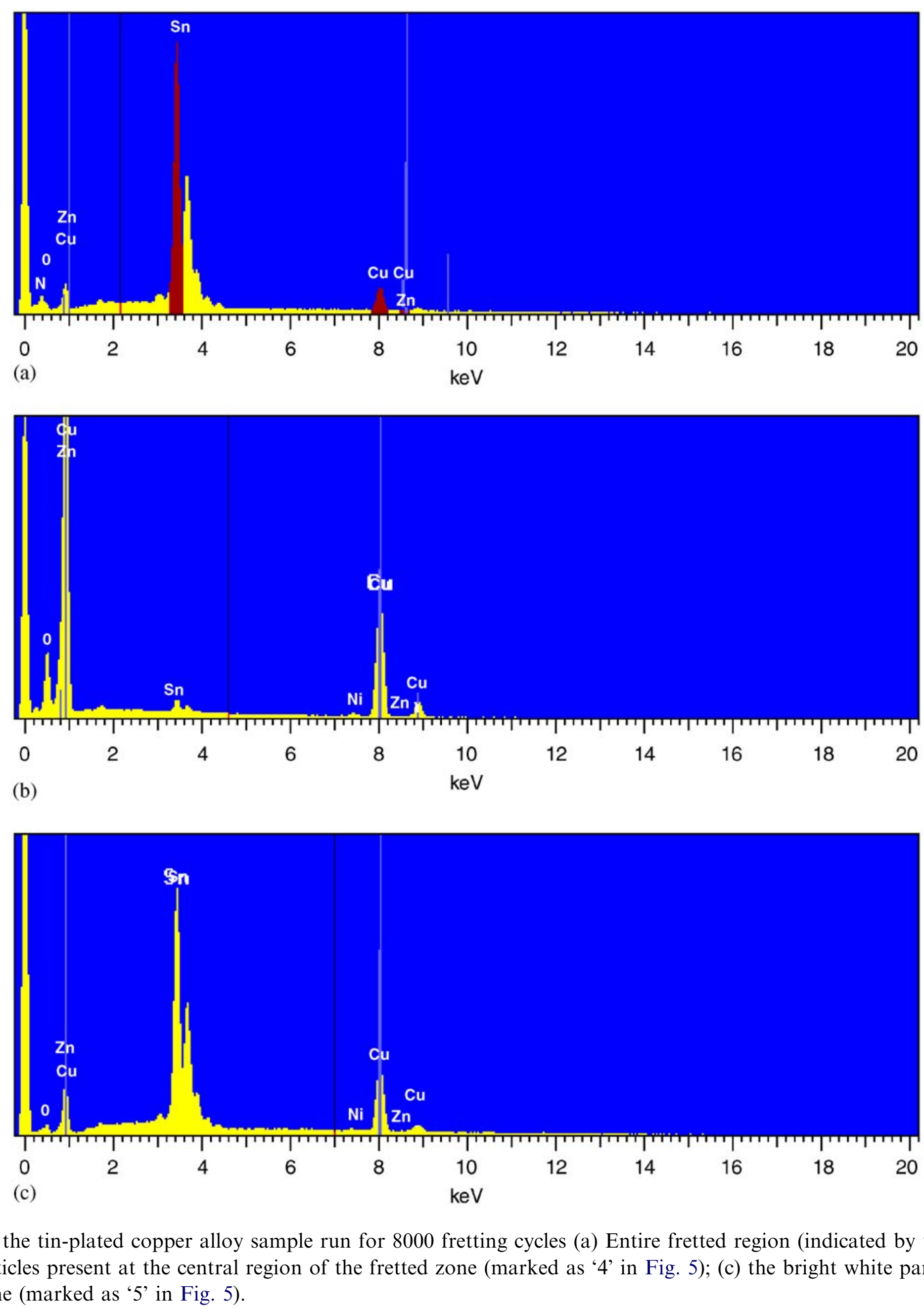

Fig. 9. EDX pattern of the tin-plated copper alloy sample run for 8000 fretting cycles (a) Entire fretted region (indicated by the dotted line in Fig. 5); (b) the bright white particles present at the central region of the fretted zone (marked as '4' in Fig. 5); (c) the bright white particles present at the edge region of the fretted zone (marked as '5' in Fig. 5).

nature of the soft tin plating. The subsequent gradual increase in contact resistance could be attributed to the formation of oxide film as well as accumulation of debris and corrosion products, further reducing the electrically conducting area. The rapid increase in contact resistance suggests that with increase in the number of fretting cycles, the current is conducted through an increasingly smaller area of contact.

Based on the change in contact resistance as a function of fretting cycles, Fig. 4 is classified into three segments, designated as stages I, II and III. To assess the fretting damage, nature of oxide film and the mechanism of failure at the contact zone at different stages, three individual tin-plated copper alloy samples are run for 8000, 16,800 and 48,000 cycles, respectively, corresponding to the three stages mentioned in Fig. 4. Surface characteristics of these three samples are performed by SEM, EDX and X-ray dot mapping.

3.1. Surface characteristics of sample run for 8000 fretting cycles

The surface morphology of the tin-plated copper alloy contact run for 8000 fretting cycles is shown in Fig. 5. The fretting direction is vertical (indicated by the dotted line in Fig. 5). It is evident from Fig. 5 that the area of the fretted region is small, oval/elliptical shaped and is shallow in nature. The bright debris particles that are ejected laterally during the fretting motion are observed outside the fretted zone along the sliding direction (marked as 1 in Fig. 5). A closer look at the morphology indicates the occurrence of adhesive wear (marked as '2' in Fig. 5), characteristic of transfer of material between the mated contacts (inset 'a' in Fig. 5). The bright particles observed on the outer region of the fretted zone (marked as '3' in Fig. 5) are believed to be tin oxides (inset 'b' in Fig. 5).

The surface profile of the fretted zone reveals the presence of some peaks and valleys (Fig. 6). The details of the roughness parameters are given in Table 1. The peaks in the surface profile could be attributed to the accumulation of debris, or transfer of the coated layer between the mated surfaces and the valleys could be attributed to the formation of grooves. The peaks observed in the surface profile also support the adhesive wear pattern observed in Fig. 5 (inset 'a'). The valleys in the profile indicate that the wear depth is relatively less at this stage.

The EDX line scanning performed across the fretted region (indicated by dotted line in Fig. 5) confirms the presence of tin and copper (Fig. 7). The intensity of oxygen is not appreciable to be detected in the line scan of the overall fretted zone. Within the fretted zone the intensity of tin is decreased whereas the intensity of copper is increased, suggesting that during fretting the tin coating is removed and the base metal is exposed in most of the areas. X-ray dot mapping of the fretted zone (Fig. 8) substantiate the observations of EDX line scanning.

The EDX pattern of the fretted region (indicated by dotted line in Fig. 5) indicates the presence of copper and tin as the predominant elements (Fig. 9(a)). The EDX pattern taken on the bright white spots at the central region (marked as '4' in Fig. 5) of the fretted zone indicated that it is predominantly copper (53.10 at%) and oxygen (44.13 at%) with very little amount of tin (1.82 at%) (Fig. 9(b). However, the EDX pattern taken on the bright white particles at the edge region (marked as '5' in Fig. 5) of the fretted zone indicates that it consists of a mixture of tin (43.81 at%) and copper (40.86 at%) with relatively lower concentration of oxygen (14.39 at%) compared to that observed at the central region (Fig. 9(c)). A small amount of nickel is also noticed in Fig. 9(b) and (c). This could have originated from the copper alloy beneath the tin coating. Although the intensity of oxygen is very weak to be observed in the line scanning of the overall fretted region, the EDX pattern taken at the bright white particles

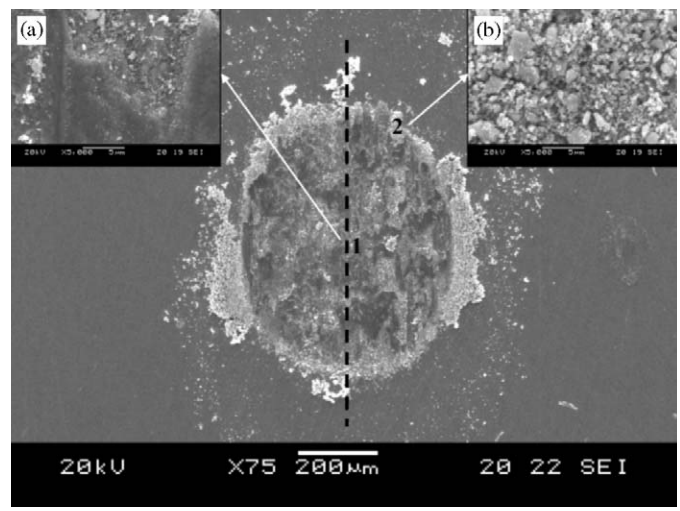

Fig. 10. Surface morphology of the tin-plated copper alloy contact after 16,800 fretting cycles. (a) Magnified view of the surface damage observed at the fretted zone. (b) Magnified view of the particles formed on the surface of the fretted zone.

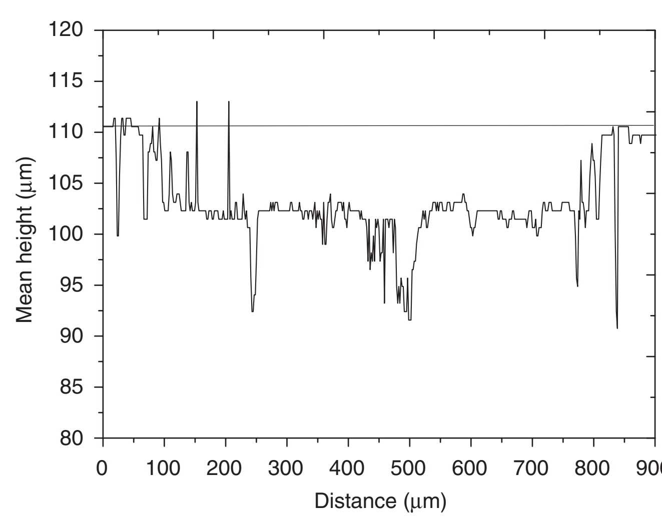

Fig. 11. Surface profile across the fretted zone after the tin-plated copper alloy sample was run for 16,800 fretting cycles.

at the central region of the fretted zone indicates the presence of appreciable amount of oxygen (44.13 at%), suggesting the early stage of formation of oxides of copper and tin.

3.2. Surface characteristics of sample run for 16,800 fretting cycles

The surface morphology of the tin-plated copper alloy contact run for 16,800 fretting cycles is shown in Fig. 10.

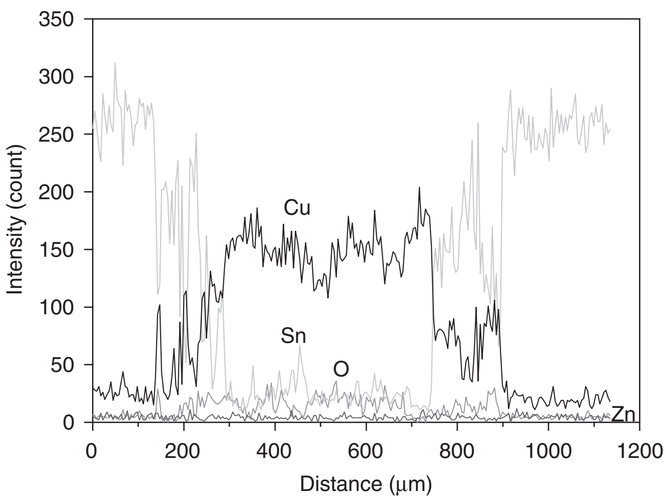

Fig. 12. EDX line scan performed across the fretted zone (indicated by the dotted line in Fig. 10) after the tin-plated copper alloy sample was run for 16,800 fretting cycles.

The fretting direction is vertical (indicated by the dotted line in Fig. 10). Though the shape of the fretted zone remains the same, examination of several regions of the contact zone reveals the occurrence of severe damage. The presence of cracks on the surface of the coated layer (inset 'a' in Fig. 10) and loose sheet/flake like debris (inset 'b' in Fig. 10) suggest the occurrence of delamination wear. Antler [25] has explained that delamination wear occurs in repeat-pass sliding when cracks become nucleated below the surface and it finally results in loosening of thin sheets of metal which become the wear debris. Zhang et al. [26] have also observed the formation of flake-like debris on tin-plated contacts. Shao and Zhang [27] have observed the formation of surface cracks on heat-treated tin-plated contacts, under both unlubricated and lubricated conditions. Braunovic [28] has suggested that flake-like debris is generally associated with the delamination wear.

The bright white particles observed both at the central and edge regions are tin oxide particles (insets 'a' and 'b' in Fig. 10). However, compared to the sample run for 8000 cycles, the size of the tin oxide particles are reduced, suggesting the entrapment and breakdown of the particles with the progressive increase in fretting cycles. The surface profile indicates that the wear depth is increased when the fretting cycle is increased from 8000 to 16,800 (Fig. 11 and Table 1). The formation of grooves in the fretted zone makes evident of the fact that significant damage has occurred for the sample run for 16,800 fretting cycles compared to the sample run for 8000 fretting cycles. The entrapment of the debris and oxide particles at the contact zone enables the formation of more grooves and supports

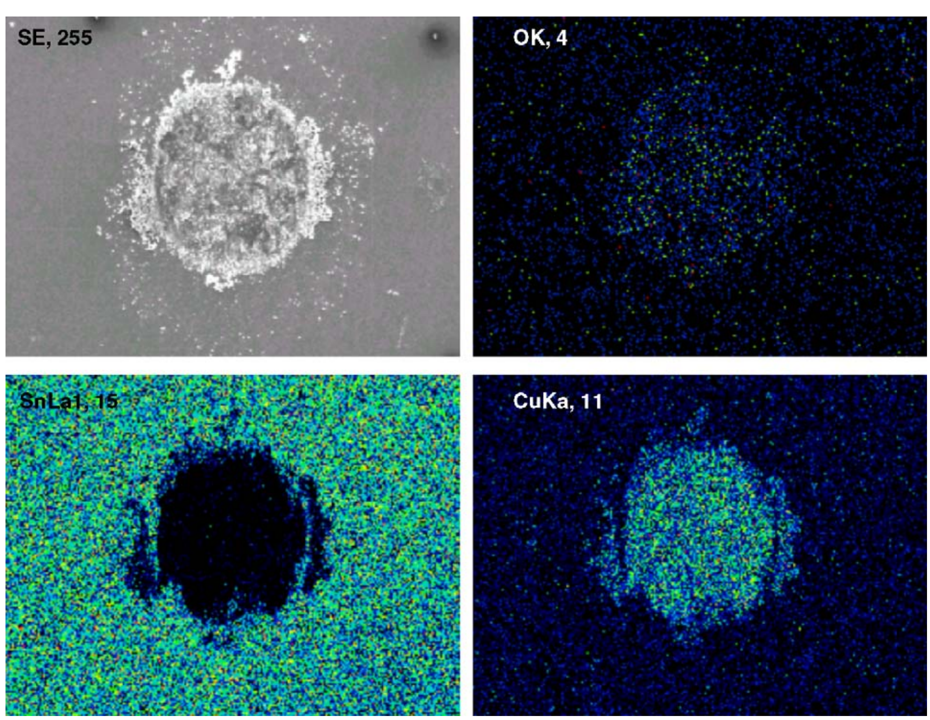

Fig. 13. X-ray dot mapping of copper, tin and oxygen performed across the fretted zone after the tin-plated copper alloy sample was run for 16,800 fretting cycles.

the increase in wear depth with the increase in fretting cycles from 8000 to 16,800.

The EDX line scanning performed across the fretted region (indicated by dotted line in Fig. 10) confirms the presence of tin, copper, oxygen and traces of zinc (from the base metal) (Fig. 12). There is no significant change in the intensity of the zinc line throughout the region analyzed. Similar to the sample run for 8000 cycles, within the fretted zone, the intensity of tin is decreased whereas the intensity of copper is increased. However, in the sample run for 16,800 cycles, the intensity of oxygen is also increased at the fretted zone, suggesting the removal of the tin coating, exposure of the base metal and oxidation of tin and copper. X-ray dot mapping of the fretted zone (Fig. 13) substantiate the observations of EDX line scanning.

The EDX pattern of the fretted region (indicated by dotted line in Fig. 10) indicates the presence of copper, tin and oxygen as the predominant elements (Fig. 14(a)). The EDX pattern taken on the bright white spots at the central region (marked as '1' in Fig. 10) of the fretted zone indicated the presence of appreciable amounts of copper (59.91 at%) and oxygen (37.61 at%) and a small amount of tin (1.49 at%) (Fig. 14(b)). Although a similar trend is noticed in the EDX patterns taken at the edge regions (marked as '2' in Fig. 10), the amount of tin is relatively higher (14.32 at%) compared to those in central region (Fig. 14(c)). A small amount of nickel is also noticed in Fig. 14(b) and (c). As already mentioned, this could have originated from the copper alloy beneath the tin coating. EDX pattern taken at both the central and edge regions

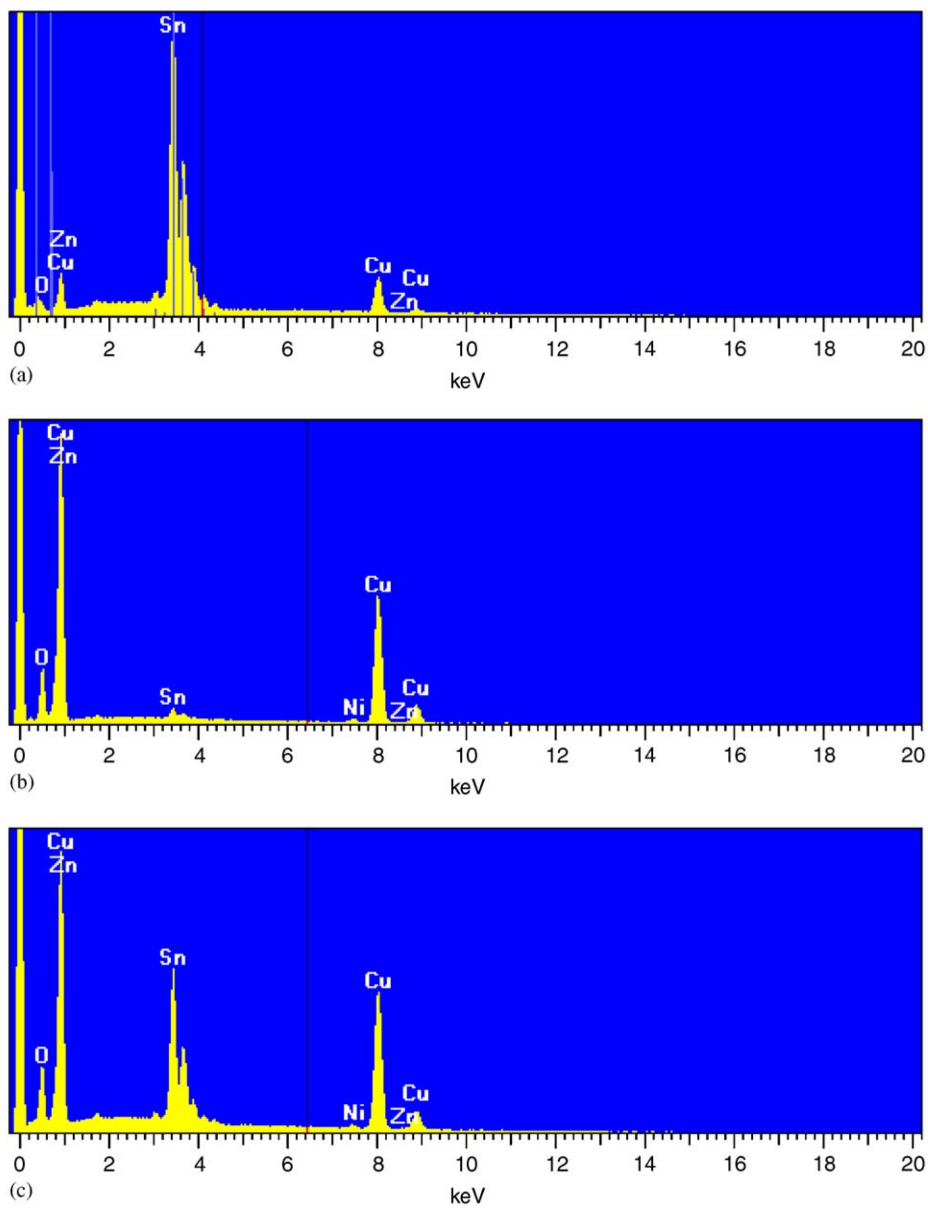

Fig. 14. EDX pattern of the tin-plated copper alloy sample run for 16,800 fretting cycles: (a) entire fretted region (indicated by the dotted line in Fig. 10); (b) the bright white particles present at the central region of the fretted zone; (c) the bright white particles present at the edge region of the fretted zone.

indicates the presence of appreciable amounts of oxygen, suggesting the formation of oxides of copper and tin. However, the volume fraction of copper oxide is higher than that of tin oxide.

3.3. Surface characteristics of sample run for 48,000 fretting cycles

The surface morphology of the tin-plated copper alloy contact run for 48,000 fretting cycles is shown in Fig. 15. The fretting direction is vertical (indicated by the dotted line in Fig. 15). The shape of the fretted zone remains the same. However, severe damage has occurred at the contact zone. The presence of cracks on the surface of the coated layer (inset 'a' in Fig. 15) and loose sheet/flake-like debris (inset 'b' in Fig. 15) suggests that the delamination wear is the main mechanism failure. Delamination wear occurs during repeat-pass sliding, which leads to the nucleation of cracks below the surface and finally results in loosening of thin sheets as wear debris [25]. The formation of surface cracks and flake-like debris on tin-plated contacts has been observed earlier by Zhang et al. [26] and Shao and Zhang [27]. Braunovic [28] has also suggested that flake-like debris is generally associated with the delamination wear. The bright white tin oxide particles are observed both at the central and edge regions (insets 'a' and 'b' in Fig. 15). However, compared to the samples run for 8000 and 16,800 fretting cycles, the size of the tin oxide particles are further reduced (inset 'a' in Fig. 15), confirming the breakdown of the particles with the progressive increase in fretting cycles. The surface profile also indicates that the wear depth is increased when the fretting cycle is increased from 16,800 to 48,000 (Fig. 16 and Table 1). The formation of grooves in the fretted zone makes evident of the fact that significant damage has occurred for the sample run for 48,000 fretting cycles compared to the sample run for 16,800 fretting cycles. The entrapment of the debris and oxide particles at the contact zone enables the formation of more grooves and supports the increase in wear depth with the increase in fretting cycles from 16,800 to 48,000.

The EDX line scanning performed across the fretted region (indicated by dotted line in Fig. 15) confirms the presence of tin, copper, oxygen and traces of zinc (Fig. 17). Similar to the samples run for 8000 and 16,800 cycles, within the fretted zone, the intensity of tin is decreased whereas the intensity of copper is increased. Similar to the sample run for 16,800 cycles the intensity of oxygen is increased at the fretted zone, suggesting the removal of the tin coating, exposure of the base metal and oxidation of tin and copper. X-ray dot mapping of the fretted zone (Fig. 18) substantiate the observations of EDX line scanning. However, the oxygen dot map is relatively more

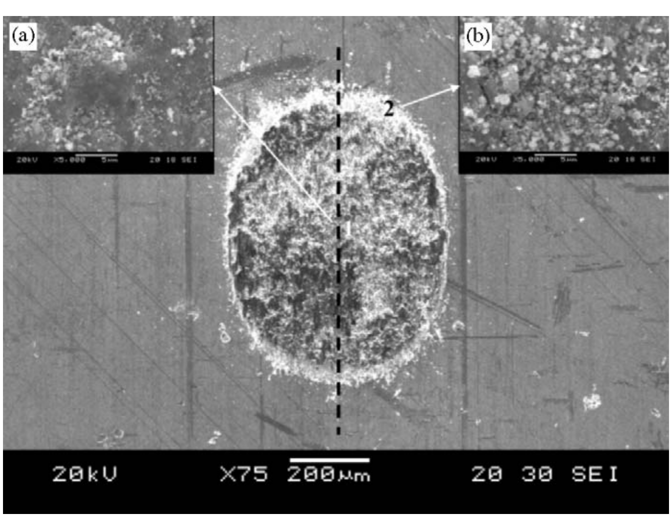

Fig. 15. Surface morphology of the tin-plated copper alloy contact after 48,000 fretting cycles. (a) Magnified view of the surface damage observed at the fretted zone. (b) Magnified view of the particles formed on the surface of the fretted zone.

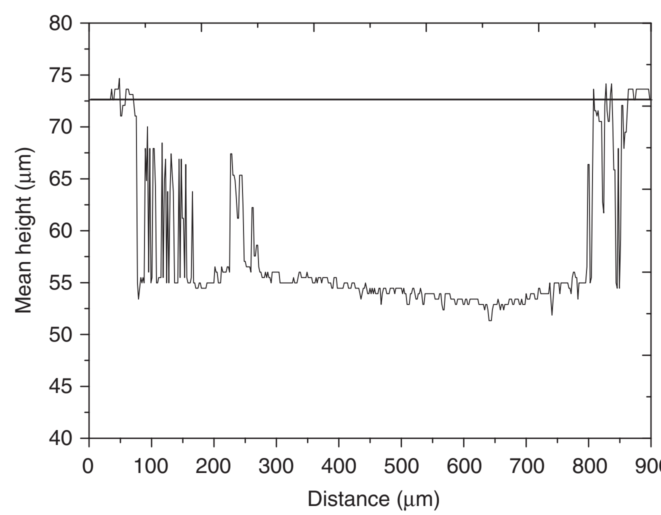

Fig. 16. Surface profile across the fretted zone after the tin-plated copper alloy sample was run for 48,000 fretting cycles.

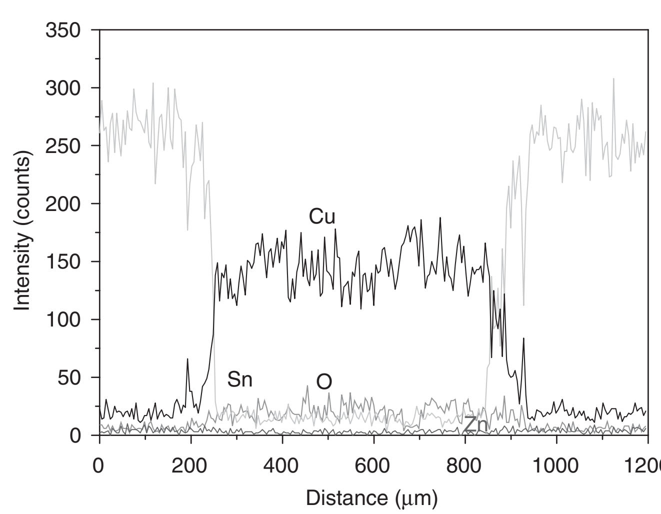

Fig. 17. EDX line scan performed across the fretted zone (indicated by the dotted line in Fig. 15) after the tin-plated copper alloy sample was run for 48,000 fretting cycles.

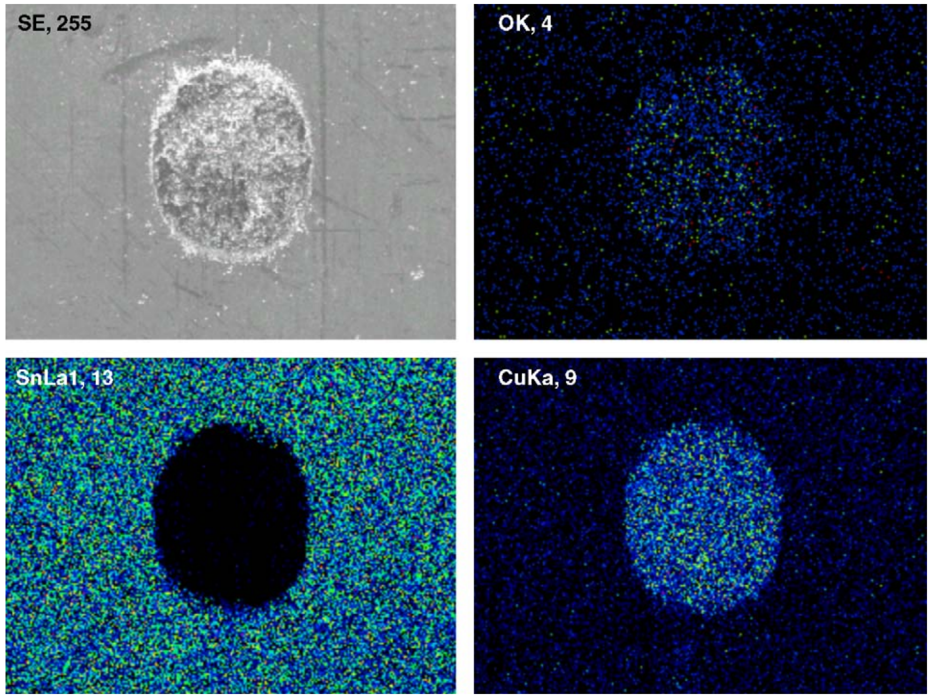

Fig. 18. X-ray dot mapping of copper, tin and oxygen performed across the fretted zone after the tin-plated copper alloy sample was run for 48,000 fretting cycles.

intense than that of the sample run for 16,800 cycles, suggesting an increased level of oxidation at this stage.

The EDX pattern of the fretted region (indicated by dotted line in Fig. 15) indicates the presence of copper, tin and oxygen as the predominant elements (Fig. 19(a)). The EDX pattern taken on the bright white spots at the central region (marked as '1' in Fig. 15) of the fretted zone indicates the presence of appreciable amounts of copper (62.51 at%) and oxygen (35.58 at%) and a small amount of tin (1.05 at%) (Fig. 19(b)). Although a similar trend is noticed in the EDX patterns taken at the edge regions, the amount of tin is relatively higher (16.06 at%) compared to those in central region (Fig. 19(c)). EDX pattern taken at both the central and edge regions indicates the presence of appreciable amount of oxygen, suggesting the formation of oxides of copper and tin. However, the volume fraction of copper oxide is higher than that of tin oxide.

The surface characteristics of the contact zone of the tin-plated copper alloy contacts, assessed after 8000, 16,800 and 48,000 fretting cycles confirm the following points:

- Adhesive wear pattern appears at the early stages whereas the latter stages suggest the occurrence of delamination wear.
- As the tin coating wears out, the debris and oxide particles gets accumulated at the contact zone, which enables the formation of more grooves and causes the wear depth to increase with increase in fretting cycles.
- The size of the tin oxide particles is also reduced due to the entrapment and breakdown of the particles with the progressive increase in fretting cycles.
- The presence of tin and copper at the contact zone as well as the formation of tin oxide suggests the early stages of oxidation at 8000 cycles.
- The presence of appreciable amounts of oxygen, decrease in tin and increase in copper suggests the accumulation of copper and tin oxides at the contact zone at 16,800 and 48,000 cycles. The volume fraction of copper oxide is higher than that of tin oxide both at 16,800 and 48,000 cycles.

Hence the observed changes in the contact resistance of tin-plated copper alloy contacts as a function of fretting cycle (Fig. 4) could be attributed to changes in the contact zone as evidenced by the surface analytical studies. Accordingly, the early stages of oxidation occur around 8000 cycles. With increase in fretting cycles from 8000 to 16,800, the oxidation of the contact zone is responsible for the gradual increase in contact resistance. However, beyond 16,800 cycles as the accumulation of the debris and oxide particles continues to build up at the interface, the contact resistance starts to increase rapidly and becomes erratic beyond a level.

4. Conclusions

The surface characteristics of tin-plated copper alloy contacts subjected to 8000, 16,800 and 48,000 fretting cycles under unlubricated conditions are assessed to evaluate the nature of oxide film formed at the contact zone and how they influence the contact resistance of tin-plated contacts as a function of fretting cycles. The study

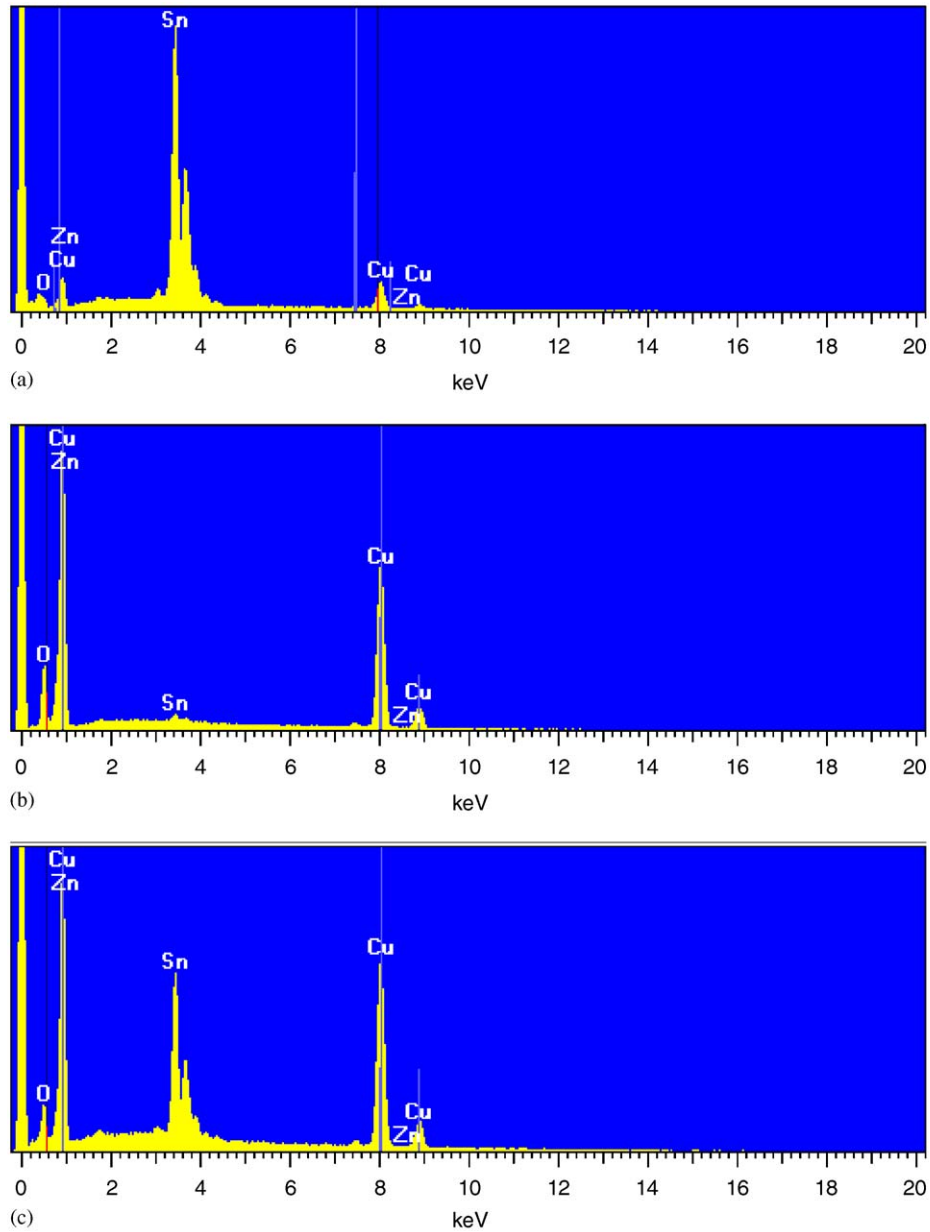

Fig. 19. EDX pattern of the tin-plated copper alloy sample run for 48,000 fretting cycles: (a) entire fretted region (indicated by the dotted line in Fig. 15); (b) the bright white particles present at the central region of the fretted zone; (c) the bright white particles present at the edge region of the fretted zone after 48,000 fretting cycles.

reveals that under unlubricated condition, fretting causes considerable amount of surface damage at the contact zone and leads to a significant increase in the contact resistance with increase in fretting cycles. The surface profile of the fretted zone reveals the presence of some peaks and valleys at early stages of fretting corresponding to the accumulation of debris/transfer of material and formation of grooves. With increase in fretting cycles, the depth of the grooves increases. The fretting corrosion of tin-plated copper alloy contacts is a complex physicochemical process and is difficult to attribute the mode of failure to a single mechanism. The occurrence of adhesive wear, characteristic of transfer of material between the mated contacts is noticed at the early stages, whereas delamination wear occurs at the latter stages. Across the fretted zone, the concentration of copper increases whereas the concentration of tin decreases with the increase in fretting cycles. The concentration of oxygen though not appreciable at early stages, increases significantly with the increase in fretting cycles due to the formation of oxides of copper and tin at the interface. However, the volume fraction of copper oxide is higher than that of tin oxide with increase in fretting cycles.

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References

[1] Bock EM, Whitley JH. Fretting corrosion in electric contacts. In: Proceedings of the 20th annual Holm seminar on electric contacts. IEEE; 1974. p. 128–38.

[2] Antler M. Electrical effects of fretting connector contact materials: a review. Wear 1985;106:5–33.

[3] Antler M. Survey of contact fretting in electrical contacts. IEEE Trans Comp, Hybrids, Manuf Technol 1985;8(1):87–104.

[4] Stocker U, Bonisch G. ATZ Automobiltech Z 1991;93:7–10.

[5] Xie J, Sun M, Pecht M, Barbe DF. Why gold flash can be detrimental to long-term reliability. J Electron Packaging 2004;126(3):37–40.

[6] Martens R, Pecht M. Effects and interactions of design parameters for gold-plated electrical contacts. J Mater Sci Mater Electron 2000;11:209–18.

[7] Tanimoto M, Tanaka H, Suzuki S, Matsuda A. Pb-free plating for electronic components. Furukawa Rev 2000;19:91–6.

[8] Galyon GT, Palmer L. An integrated theory of whisker formation: the physical metallurgy of whisker formation and the role of internal stresses. IEEE Trans Comp, Packaging Manuf Technol 2005;28(1): 17–30.

[9] Rickett B, Elmgren P, Flowers G, Gale S, Suhling J. Whisker formation potential in Pb-free electroplated connector finishes. Circ Assembly 2005;16(2):52–9.

[10] Britton SC. Spontaneous growth of whiskers on tin coatings: 20 years of observation. Trans IMF 1974;52:95–102.

[11] Evans C. Connector finishes: tin in place of gold. IEEE Trans Comp, Hybrids, Manuf Technol 1980;3(2):226–32.

[12] Ambier J, Perdigon P. Fretting corrosion of separable electrical contacts. IEEE Trans Comp, Hybrids, Manuf Technol 1985;8(1):197–201.

[13] Lee A, Mamrick MS. Fretting corrosion of tin-plated copper alloy. IEEE Trans Comp, Hybrids, Manuf Technol 1987;10:63.

[14] Neijzen J, Glashorster J. Fretting corrosion of tin-coated electrical contacts. IEEE Trans Comp, Hybrids, Manuf Technol 1987;10(1): 68–74.

[15] Yasuda K, Umemura S, Aoki T. Degradation mechanism in tin- and gold-plated connector contacts. IEEE Trans Comp, Hybrids, Manuf Technol 1987;10(3):456–62.

[16] Lee A, Mao A, Mamrick MS. Fretting corrosion of tin at elevated temperatures. In: Proceedings of the 34th IEEE Holm conference on electrical contacts. IEEE; 1988. p. 87–91.

[17] Heaton, CE McCarthy SL. High cycle fretting corrosion studies on tin-coated contact materials. In: Proceedings of the 47th IEEE Holm conference on electrical contacts. IEEE; 2001. p. 209–14.

[18] Malucci RD. Impact of fretting parameters on contact degradation. In: Proceedings of the 42nd IEEE Holm conference on electrical contacts. IEEE; 1996. p. 395–403.

[19] Malucci RD. Characteristics of films developed in fretting experiments on tinplated contacts. IEEE Trans Comp Packaging Technol 2001;24(3):399–407.

[20] Flowers GT, Fei X, Bozack MJ, Malucci RD. Vibration thresholds for fretting corrosion in electrical connectors. IEEE Trans Comp Packaging Technol 2004;27(1):65–71.

[21] Braunovic M. Fretting damage in tin-plated aluminium and copper connectors. IEEE Trans Comp, Hybrids, Manuf Technol 1989;12(2): 215–23.

[22] Stennett NA, Swingler J. The effect of power on low frequency fretting corrosion. In: Proceedings of the 39th IEEE Holm conference on electrical contacts. IEEE; 1993. p. 205–10.

[23] Mottine JJ, Reagor BT. The effect of lubrication on fretting corrosion at dissimilar metal interfaces in socketed IC device applications. IEEE Trans Comp, Hybrids, Manuf Technol 1985;8(1): 173–81.

[24] Hannel S, Fouvry S, Kapsa Ph, Vincent L. The fretting sliding transition as a criterion for electrical contact performance. Wear 2001;249:761–70.

[25] Antler M. In: Slade PG, editor. Electrical contacts: principles and applications. New York: Marcel Dekker Inc.; 1994. p. 309.

[26] Zhang JG, Tang L, Shao CB. Floating and moving abilities of particulate in lubricated sliding contact surfaces. In: Proceedings of the 17th international conference on electrical contacts. IEEE; 1994. p. 70–6.

[27] Shao CB, Zhang JG. Electric contact behaviour of Cu-Sn intermetallic compound formed in tin platings. In: Proceedings of the 44th IEEE Holm conference on electrical contacts. IEEE; 1998. p. 26–33.

[28] Braunvoic M. Overheating of flexible tinned copper connectors. IEEE Trans Comp Packaging Technol 2001;24(3):384–8.