Available online at www.sciencedirect.com

ScienceDirect

Surface & Coatings Technology 201 (2006) 2181 – 2192

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

# Effect of fretting amplitude and frequency on the fretting corrosion behaviour of tin plated contacts

Young Woo Park, T.S.N. Sankara Narayanan [1], Kang Yong Lee *

*Stress Analysis and Failure Design Laboratory, School of Mechanical Engineering, Yonsei University, 134, Sinchon-dong, Seodaemum-gu, Seoul 120-749, Republic of Korea*

Received 21 February 2006; accepted in revised form 21 March 2006
Available online 2 May 2006

**Abstract**

The fretting corrosion behaviour of tin plated copper alloy contacts at 3, 10 and 20 Hz and at two different track lengths (fretting amplitude) of ±5 and ±25 μm is studied. The change in contact resistance as a function of fretting cycles, surface profile of the contact zone, extent of fretting damage, extent of oxidation and elemental distribution across the contact zone were used to assess the fretting corrosion behaviour. The time to reach a threshold value of contact resistance of 0.1 Ω is found to be early for the track length of ±5 μm compared to that of ±25 μm, at all the three frequencies. For a given track length, this threshold value reaches early at 20 Hz. The roughness and the nature of surface profile suggest considerable amount of oxidation have occurred at the track length of ±25 μm compared to that of ±5 μm. The surface morphology of the fretted zone reveals severe damage of the contact zone for samples with a track length of ±25 μm at all the three frequencies. A pictorial model is proposed to describe the evolution of change in area of the contact zone. Based on the length and width of the contact zone, the fretted area is calculated. The change is fretted area as a function fretting frequency and track length is analyzed. Delamination wear is found to be operative at both track lengths and at all three frequencies. EDX line scanning also indicates higher levels of oxidation at the track length of ±25 μm compared to that of ±5 μm. The variation in the atomic ratios of tin, copper and oxygen of the oxide debris present at the centre and edges of the fretted zone is plotted as an area plot as a function of experimental conditions. The debris is predominantly oxides of copper for the track length of ±25 μm whereas they are mostly oxides of tin for the track length of ±5 μm at all the three frequencies. The narrow and deep surface profile, lower $R_a$ values, overlapping of the tin and copper lines in the EDX line scan and the predominance of oxides of tin support the view that the chances of accumulation of wear debris at the contact zone is very high at the track length of ±5 μm. The study concludes that tin plated contacts could encounter an early failure even at shorter track lengths of ±5 μm, if there is sufficient accumulation of the wear debris at the contact zone.


*Keywords:* Fretting corrosion; Tin plated contact; Contact resistance; Oxidation; Surface characteristics

## 1. Introduction

Fretting, an accelerated surface damage that occurs at the interface of contacting materials subjected to small oscillatory movement is a common problem in many engineering applications. The deleterious effect of fretting in electrical connections assumes significance as it influences the reliability and system performance. Gold and other precious metal plated contacts are the preferred choice where high reliability is warranted. However, non-noble metal plated contacts have also gained popularity due to the market pressure to reduce the cost factors. Based on the 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. However, the susceptibility of tin plated contacts for fretting corrosion is a major limitation for its use in electrical connectors. Fretting corrosion of tin plated contacts has been the subject of many papers [1–4].

A variety of factors, such as fretting amplitude (track length), frequency, temperature, humidity, normal load, current load, corrosive gas environment, etc., influence the fretting corrosion

* Corresponding author. Tel./fax: +82 2 2123 2813.
*E-mail address:* KYL2813@yonsei.ac.kr (K. Yong Lee).
[1] On leave from National Metallurgical Laboratory, Madras Centre, CSIR Complex, Taramani, Chennai-600 113, India.

0257-8972/$ - see front matter 
doi:10.1016/j.surfcoat.2006.03.031

behaviour of tin plated contacts. Due to the increased rate of oxidation of tin and the formation of Cu–Sn based intermetallic compounds at elevated temperatures, tin coated contacts are not recommended for continuous service at high temperatures [5–7]. The effect of power (current load) on tin plated contacts is reported by Stennett and Swingler [8], Hammam [9] and Swingler [10]. The effect of normal load on the fretting corrosion behaviour of tin plated contacts is studied by Lee [11] and Ambier and Perdigon [12]. It is evident from these studies that an increase in normal load and current load delays the failure time due to fretting corrosion.

Ambier and Perdigon [12] have suggested that at fretting amplitudes below 5 μm, tin plated contacts exhibit very good electrical contact as the displacements are absorbed by plastic deformation whereas at amplitudes higher than 150 μm, the wear mechanism is based on attrition. According to them, a typical fretting phenomenon involves a mixture of adhesive, abrasive and corrosive wear and it occurs in the range of fretting amplitude between 5 and 150 μm. Lee [11] has reported that the fretting corrosion failure of tin plated contacts occurs much slower at 12 μm whereas the failure time is increased when the amplitude is increased from 12 to 80 μm. According to Wu and Pecht [13] fretting amplitude seems to have more complicated effects on the fretting corrosion of lead-free and tin–lead alloy coatings. They have reported that the fretting corrosion behaviour of these coatings is quite similar at fretting amplitudes of 10 and 20 μm whereas the lead-free (Sn–Ag–Cu) alloy coating indicates better performance at 25 and 40 μm. Ambier and Perdigon [12] have reported that the extent of damage of tin plated contacts is independent of frequency at 25 and 150 Hz and such influence becomes very important only at low frequencies. However, Lee [11] and many others have studied the fretting corrosion of tin plated contacts only at a fixed frequency. Fretting amplitude (track length) and fretting frequency are the two major factors that determine the total area and amount of time the tin coating could encounter wear and oxidation. As fretting amplitude and frequency has a combined effect on the rate of wear, extent of oxidation and, accumulation of wear debris and oxidation products, it is essential to study the fretting corrosion behaviour of tin plated contacts with various combinations of frequencies and amplitudes. In this context, the present paper aims to study the fretting corrosion behaviour of tin plated copper alloy contacts at 3, 10 and 20 Hz and at two different track lengths (fretting amplitude) of ±5 and ±25 μm.

## 2. Experimental details

The fretting corrosion behaviour 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 weight placed on the balance arm. The contacts were flat verses 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 ultrasonic cleaner, dried and carefully mounted in the fretting test assembly. The rider and flat contacts are mated in such a way to create a point contact in "sphere plane" geometry (Fig. 1b). The details of the experimental conditions used are given in Table 1. The tests were conducted at gross slip conditions. The contact resistance was continuously measured as a function of fretting cycles. The circuit used to measure the contact resistance is given in Fig. 1(b). The surface profile and surface roughness across the fretted zone was assessed using a Carl Zeiss laser

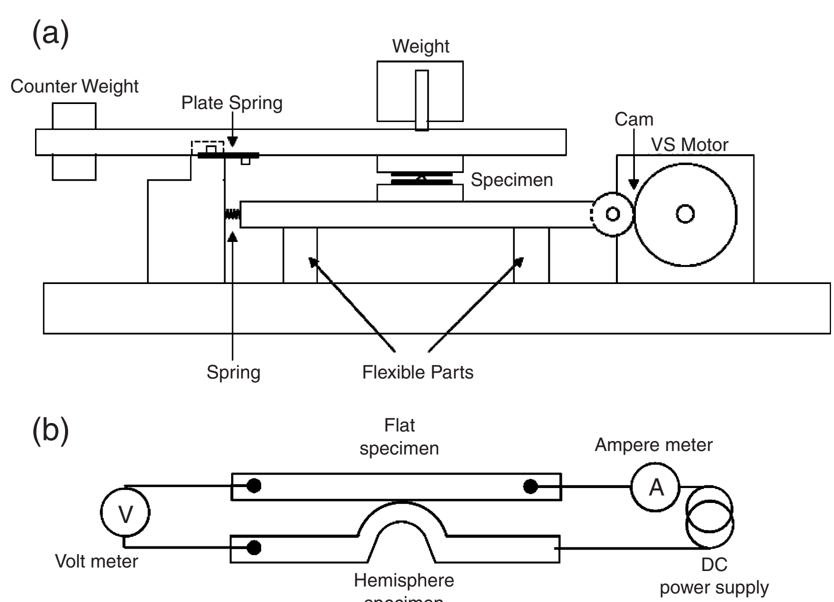


Fig. 1. (a) Schematic of the fretting apparatus used in the present study; and (b) the geometry of the rider and flat samples and the circuit used to measure the contact resistance.

Table 1
Details of the experimental conditions used in the study

| | |
|---|---|
| Track length (amplitude) | ±5 and ±25 μm |
| Frequency | 3, 10 and 20 Hz |
| Normal load | 0.5 N |
| Current load | 0.1 A |
| Temperature | 22±1 °C |
| Humidity | 32±2% RH |

scanning microscope (LSM) (Model: LSM-5 PASCAL). The wear rate of the tin coating was calculated using the equation $K=V/SF$, where $V$ is the wear volume (in mm$^3$), $S$ the total sliding distance (in m) and $F$ is the normal load (in N) [14]. The wear volume was determined by multiplying the average depth of the wear scar with the fretted area. The total sliding distance was determined by multiplying the sliding distance by the number of fretting cycles. Scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX) and X-ray mapping were used to characterize the extent of fretting damage, extent of oxidation and the elemental distribution across the contact zone.

## 3. Results and discussion

The change in contact resistance of tin plated contacts as a function of fretting cycles for a track length of ±5 μm at 3, 10 and 20 Hz are shown in Fig. 2(a)–(c), respectively and the corresponding curves obtained for the track length of ±25 μm at 3, 10 and 20 Hz are shown in Fig. 3(a)–(c), respectively. It is evident from Figs. 2 and 3 that there is a sharp increase in the contact resistance during the initial stage (<400 cycles). However, the contact resistance decreases very quickly and reaches a stable and low value. With further increase in fretting cycle, there is a gradual increase in contact resistance for some cycles, beyond which the increase in contact resistance is very rapid. The observed trend of change in contact resistance as a function of fretting cycles at 3, 10 and 20 Hz for the track lengths of ±5 and ±25 μm correlates well with those of other researchers [1–4]. The sharp increase in contact resistance observed during the initial cycles is due to the presence of thin oxide film on the surface of both the rider and flat contacts, which is removed in a very short span of time (<400 cycles). The low contact resistance observed after the initial sharp increase is due to the good electrical conductivity of the soft tin plating. The gradual increase in contact resistance with increase in fretting cycles could be attributed to the oxidation of the tin coating and its wear debris. The subsequent rapid increase in contact resistance is due to the accumulation of wear debris and oxidation products, which reduces the electrically conducting area. These observations indicate that with increase in fretting cycles the current is conducted through an increasingly smaller area of contact.

A comparison of Figs. 2 and 3 reveals that the general trend of change in contact resistance as a function of fretting cycles is quite similar for both track lengths of ±5 and ±25 μm at 3, 10 and 20 Hz. However, there is a considerable variation in the rate of change in contact resistance as a function of track length and frequency. It appears from Figs. 2 and 3 that the rate of change in contact resistance is very high at 3 Hz for both track lengths and for the track length of ±5 μm at all the three frequencies. For a better comparison, the time to reach a threshold value of contact resistance of 0.1 Ω for both track lengths is plotted as a function of frequency (Fig. 4). It is evident from Fig. 4 that this threshold value of contact resistance (0.1 Ω) reaches very early for ±5 μm at all the three frequencies. For a given track length, this threshold value reaches early at 20 Hz. An early reach of the threshold value of contact resistance at 20 Hz for both track lengths is an expected behaviour due to the increased wear rate

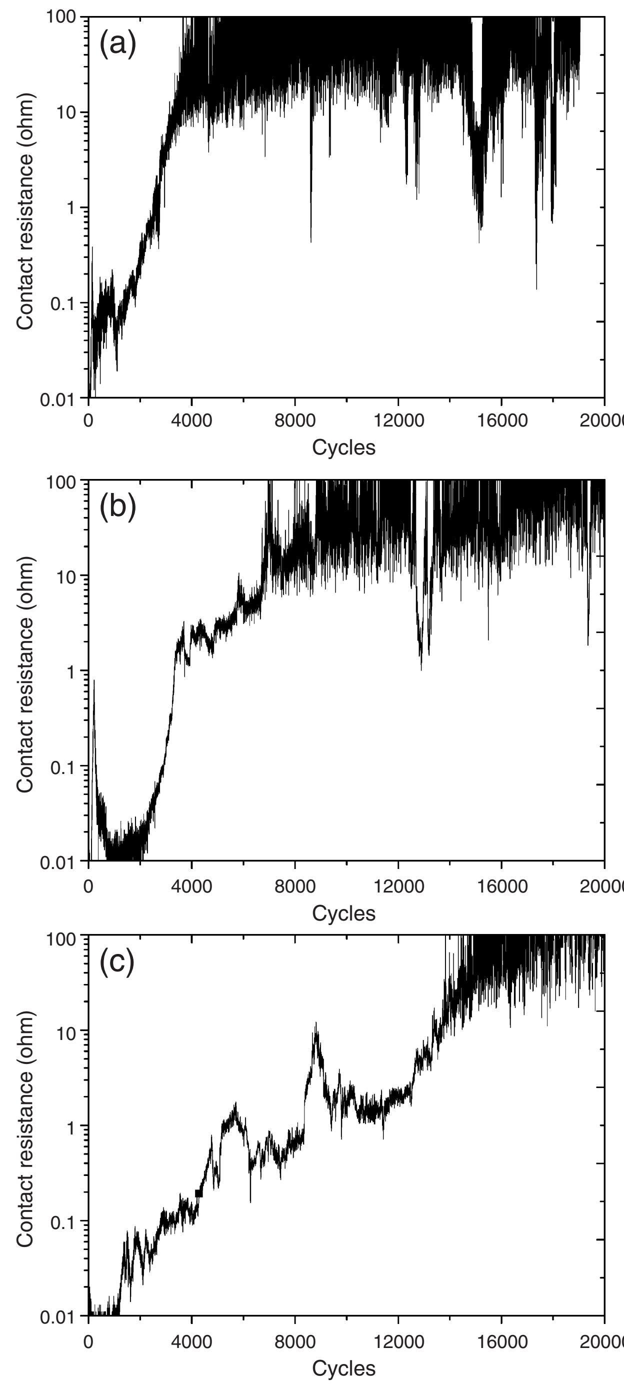


Fig. 2. Change in contact resistance of the tin plated contact measured across the contact zone as a function of fretting cycles for a track length of ±5 μm at different frequencies (a) 3 Hz; (b) 10 Hz; and (c) 20 Hz.

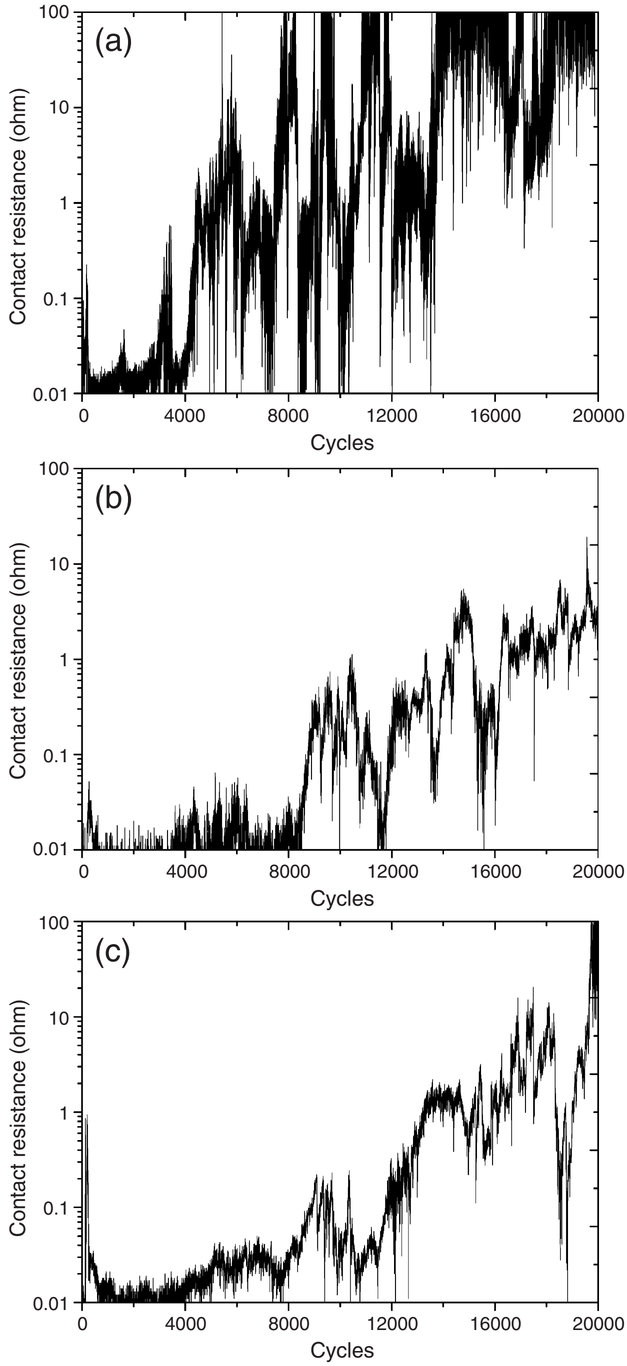


Fig. 3. Change in contact resistance of the tin plated contact measured across the contact zone as a function of fretting cycles for a track length of ±25 μm at different frequencies (a) 3 Hz; (b) 10 Hz; and (c) 20 Hz.

of tin coating and generation of higher quantities of wear debris and oxidation products at this frequency. However, the rapid increase in contact resistance observed for ±5 μm compared to that of ±25 μm at all the three frequencies is rather unusual. Lee [11] have suggested that when the track length is increased from 12 to 80 μm, the fretting corrosion of tin plated contacts occurs much faster as it provides more fresh metal for oxidation and generates more oxide debris. Antler [15] has also reported that the threshold value of 0.1 Ω for both unlubricated and lubricated palladium plated contacts reach very early at longer track lengths. Lee and Mamrick [1] have proposed that the physical process responsible for the rise in contact resistance is the enhanced oxidation of the contacting surfaces when the fresh metal is exposed in a cyclic fashion. Hence, it is obvious to expect an early failure at ±25 μm compared to ±5 μm. However, the results of the present study indicate a different trend.

The electrical characteristics of metal contacts under fretting conditions are described by asperity contact and granular interface models [16,17]. According to asperity contact model, increase in contact resistance is due to the reduction in real contact area as more of the asperities are exposed to oxidation through the relative motion of the contacting surfaces. Granular interface model considers that the formation of a granular interface consists of wear debris between the contacting surfaces and postulates that it is the accumulation of wear debris that leads to the failure of the contact. According to this model, when the contact zone is accumulated with wear debris, electrical conduction has to occur only through percolation conduction. Malucci [3] has also addressed the importance of percolation conduction of tin plated contacts under fretting conditions. As fretting progresses, electrical conduction through the tin/tin oxide film is believed to be non-metallic and is primarily dependent on the semiconductor properties of hydrated tin oxide. When the volume fraction of tin in the tin/tin oxide film is closer to the percolation limit, the tin plated contacts experience short term discontinuities and when it exceeds the percolation limit, the electrical conduction is totally affected. The rapid increase in contact resistance observed for the track length of ±5 μm could not be explained based on the asperity contact model as not enough fresh metal (tin) will be exposed for oxidation at this track length compared to that of ±25 μm. However, as the contact zone is confined to a limited region, the possibility of accumulation of wear debris and oxidation products is very high for the track length of ±5 μm compared to that of ±25 μm. The accumulation of wear debris and the unavailability of fresh metallic sites cause the

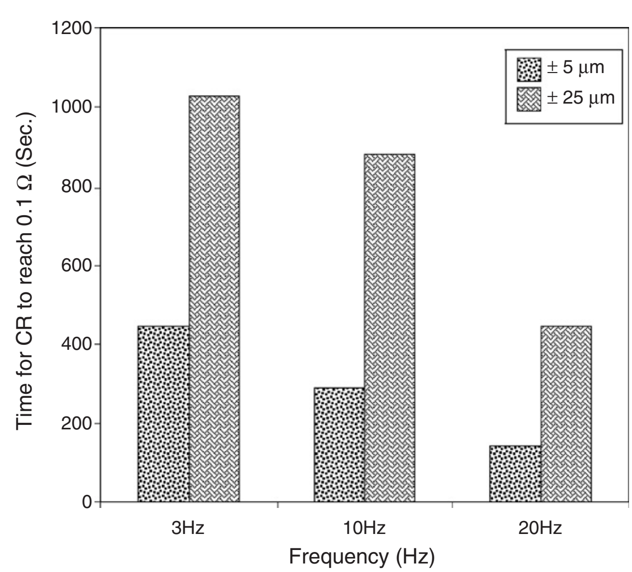


Fig. 4. Plot of time required to reach a threshold value of contact resistance of 0.1 Ω for both track lengths of ±5 and ±25 μm at fretting frequencies of 3, 10 and 20 Hz.

percolation limit for electrical conduction to reach very early at ±5 μm and this results in the rapid increase in contact resistance. This attribute seems to be valid as the increase in fretting frequency from 3 to 20 Hz at this track length decreases the extent of increase in contact resistance as increase in fretting frequency could prevent the extent of accumulation of wear debris and provide relatively more fresh metallic sites for electrical conduction.

To get a better insight about the observed changes in contact resistance at both track lengths of ±5 and ±25 μm and at 3, 10 and 20 Hz, the surface profile of the fretted zone after 20,000 fretting cycles is analyzed using LSM (Fig. 5). The surface profile reveals considerable variation in area and the depth of the fretted zone as a function of track length and frequency. The average wear depth is found to increase with increase in track length from ±5 μm to ±25 μm and increase in fretting frequency from 3 to 20 Hz. The extent of increase in the average wear depth is not appreciable at ±5 μm and at 3 Hz (about 5 μm) whereas it is more pronounced at ±25 μm and at 20 Hz (about 19 μm). A closer look at the shape of the surface profile reveals that the wear depth is narrow and deep for the track lengths of ±5 μm whereas it is broad and shallow at ±25 μm. The roughness ($R_a$) is of the order of 0.94 to 1.11 μm for the track lengths of ±5 μm whereas it varies from 1.27 to 1.59 μm when

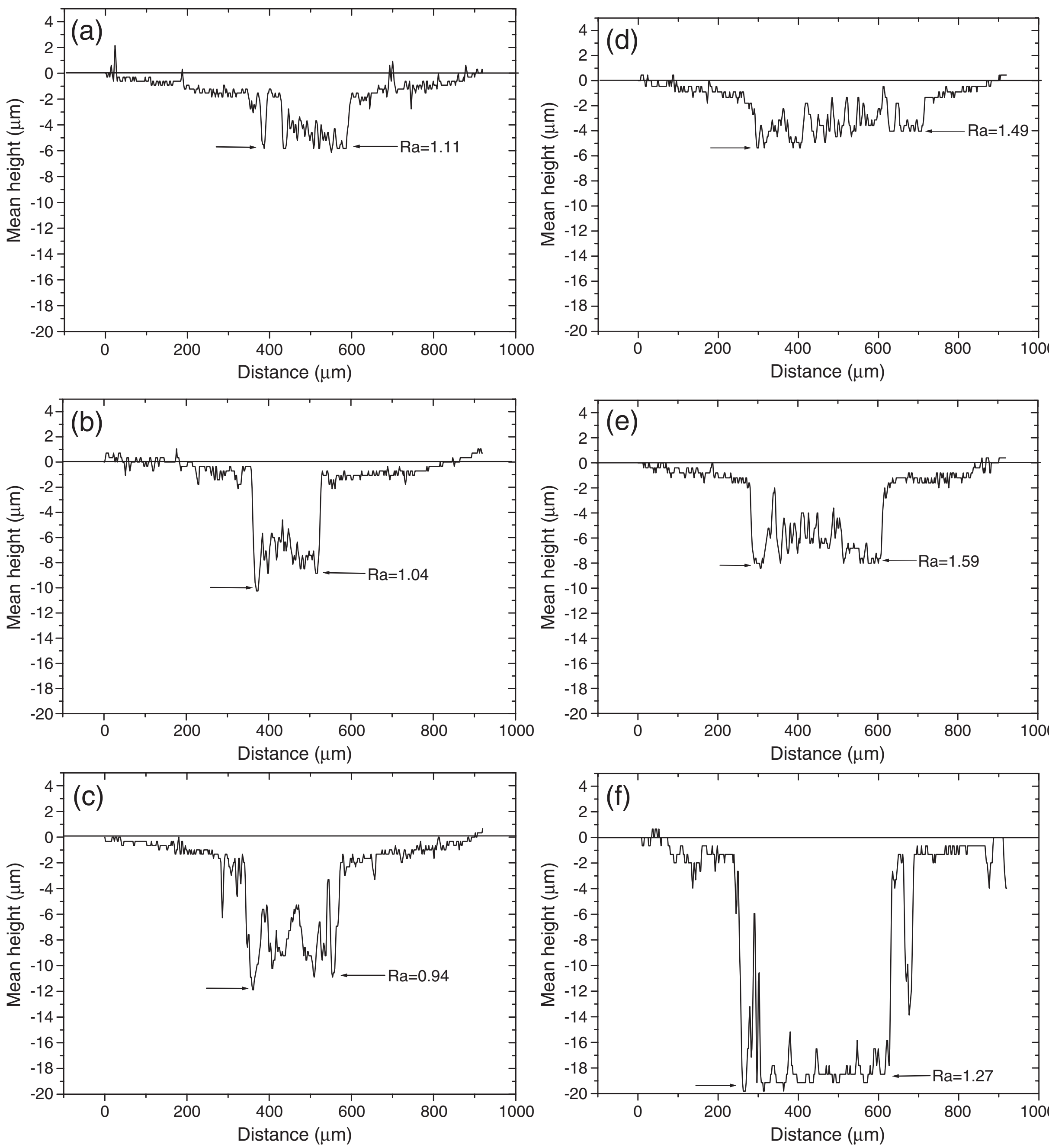


Fig. 5. Surface profile across the fretted zone of the tin plated contacts after 20,000 fretting cycles obtained at varying track lengths and fretting frequencies. (a) ±5 μm and 3 Hz; (b) ±5 μm and 10 Hz; (c) ±5 μm and 20 Hz; (d) ±25 μm and 3 Hz; (e) ±25 μm and 10 Hz; and (f) ±25 μm and 20 Hz.

the track length is increased to ±25 μm. There is not much variation in the $R_a$ value with the increase in fretting frequency from 3 to 20 Hz. The range of $R_a$ values and the nature of surface profile suggest that the extent of oxidation is higher at the track length of ±25 μm compared to that of ±5 μm. The abrasive nature of the hard oxide particles when gets pressed into the remaining tin coating causes severe damage to the coating and this has resulted in a higher roughness at the track length of ±25 μm. In contrast, at ±5 μm less fresh tin coating gets exposed for oxidation and a fewer oxide particles are formed, resulting in a relatively less roughness. At the track length of ±5 μm, the tin oxide particles are enclosed within a confined space, causing the profile to be very narrow and deep. The nature of the surface profile and the $R_a$ value of the fretted zone support the view that the chances of accumulation of debris and oxidation products at the contact zone is relatively higher at the track length of ±5 μm than at ±25 μm. As already mentioned it is the accumulation of wear debris and the unavailability of fresh metallic sites cause the percolation limit for electrical conduction to reach very early, resulting in the rapid increase in contact resistance at ±5 μm.

The surface morphology of the tin plated contacts with track lengths of ±5 and ±25 μm, at frequencies of 3, 10 and 20 Hz, after 20,000 fretting cycles, is shown in Fig. 6. The fretting direction is vertical (indicated by the dotted line). It is evident from Fig. 6 that the fretted zone is oval/elliptical shape in all the cases. The wear debris ejected laterally during the fretting motion is observed outside the fretted zone along the sliding direction. Though the shape of the fretted zone appears to be similar, there is a distinct variation in the fretted area and the

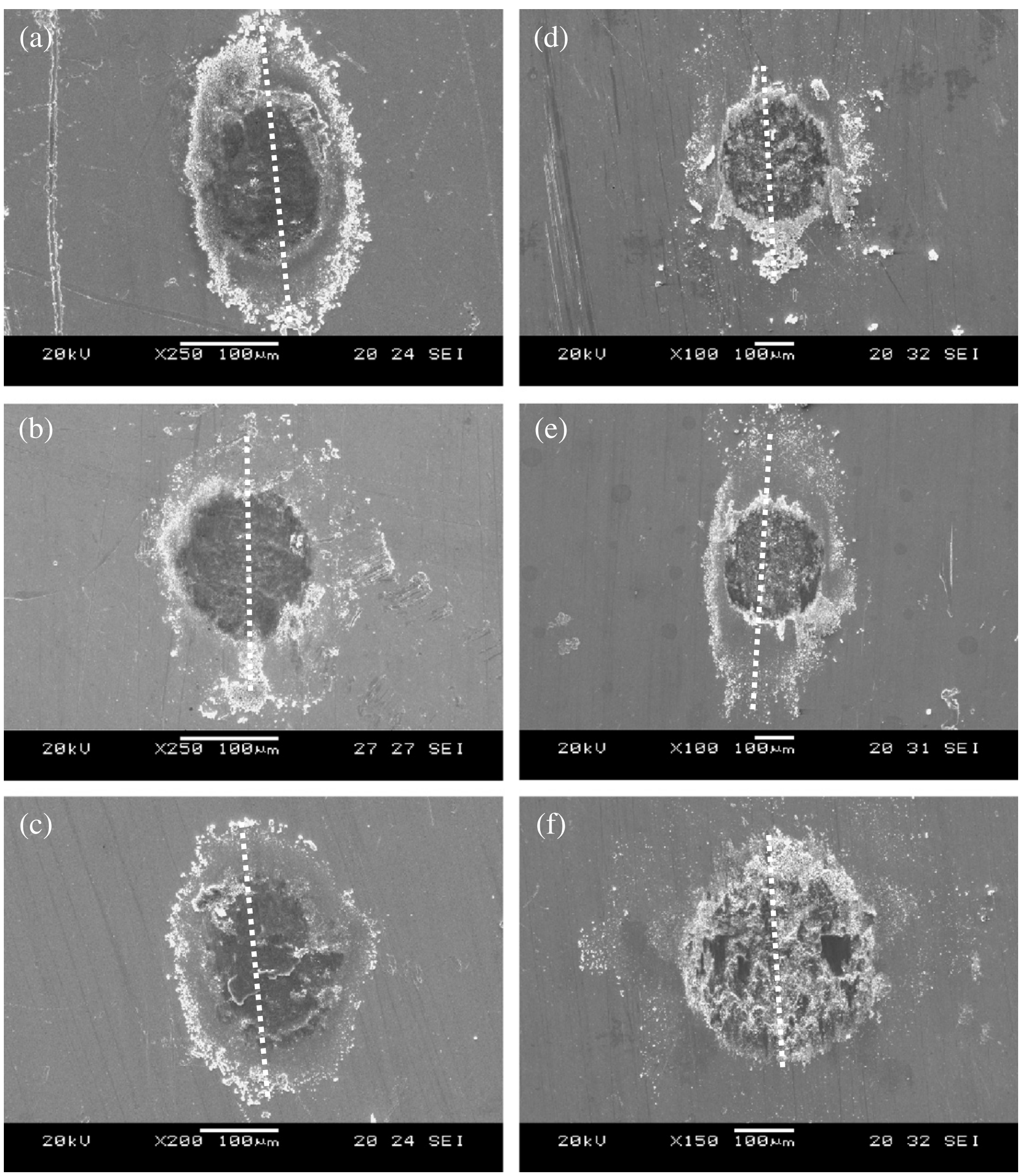


Fig. 6. Surface morphology of the tin plated contacts after 20,000 fretting cycles obtained at varying track lengths and fretting frequencies. (a) ±5 μm and 3 Hz; (b) ±5 μm and 10 Hz; (c) ±5 μm and 20 Hz; (d) ±25 μm and 3 Hz; (e) ±25 μm and 10 Hz; and (f) ±25 μm and 20 Hz.

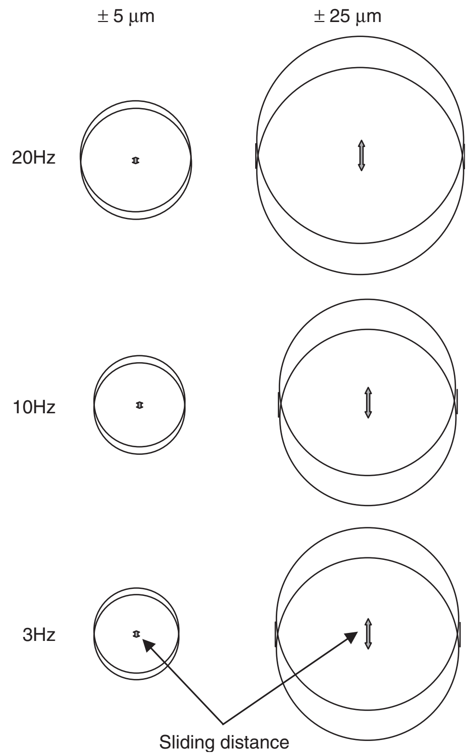


Fig. 7. Pictorial model depicting the evolution of the change in area of the contact zone as a function of fretting frequency and track length.

extent of damage at the contact zone with the change in track length and fretting frequency. For a better understanding, a pictorial model depicting the evolution of the change in area of contact zone is proposed (Fig. 7). The fretted area, calculated using the length and width of the contact zone is plotted as a function of frequency for the two track lengths (Fig. 8). It is evident from Figs. 7 and 8 that the fretted area increases with increase in frequency at both track lengths. It is obvious to expect a large increase in fretted area when the track length is increased from ±5 to ±25 µm. The extent of damage of the

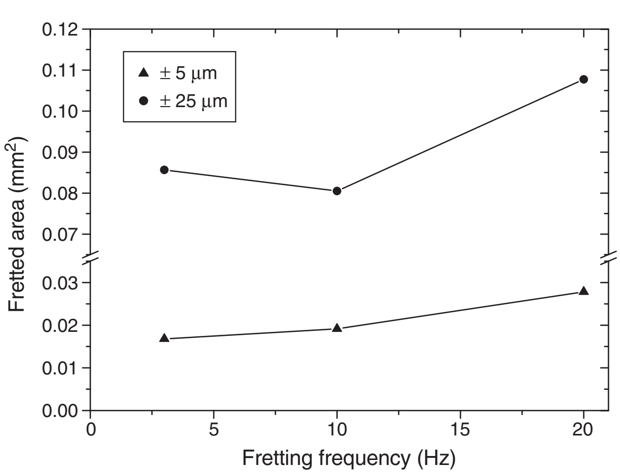


Fig. 8. Change in fretted area as a function of frequency for the track lengths of ±5 and ±25 µm.

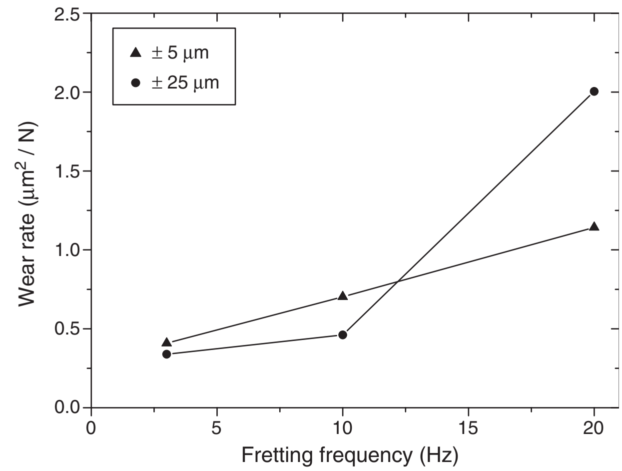


Fig. 9. Plot of wear rate as a function of frequency at both track lengths.

contact zone is high when the fretting frequency is increased from 3 to 20 Hz at both track lengths. For a given frequency the extent of damage appears to be very severe at the track length of ±25 µm. The extent of damage of the contact zone depends on the wear rate of the tin coating and extent of oxidation of wear debris. The wear rate is plotted as a function of frequency for both track lengths (Fig. 9). The increase in wear rate of the tin coating with increase in frequency at both track lengths accounts for the severe damage observed with increase in frequency. The large increase in wear rate observed for the track length of ±25 µm at 20 Hz is due to the increase in the extent of oxidation of the contact zone at this track length and the abrasive nature of the hard oxide particles which causes a severe damage of the coating. Examination of several regions of the contact zone reveals the presence of cracks on the surface of the coated layer (indicated by arrows) and loose sheet/flake like debris (Figs. 10 and 11), which suggest the occurrence of delamination wear. Antler [15] has explained that delamination wear occurs in repeat-pass sliding when cracks become nucleated below the surface and it finally result in loosening of thin sheets of metal which became the wear debris. Braunovic [5] has suggested that flake-like debris is generally associated with the delamination wear. A comparison of the morphological features at the centre of the fretted zone reveals the formation of more amount of oxide debris at the frequency of 20 Hz and at the track length of ±25 µm. One would expect the formation of higher quantities of oxide debris at 20 Hz as the rate of wear of tin coating is very high at this frequency compared to that of 3 and 10 Hz. The higher quantities of oxide debris observed at the track length of ±25 µm suggest an increase in the extent of oxidation at this track length compared to that at ±5 µm (Fig. 10). The wear debris observed at the edges of the fretted zone is expected to be predominantly tin oxide (Fig. 11). A comparison of the size of the tin oxide particles which are ejected out of the fretted zone as a function of the track length reveals that there is a reduction in size of the particles when the track length is increased from ±5 and ±25 µm (Fig. 11a and c). This is due to the entrapment and breakdown of hard abrasive oxide particles in the contact zone.

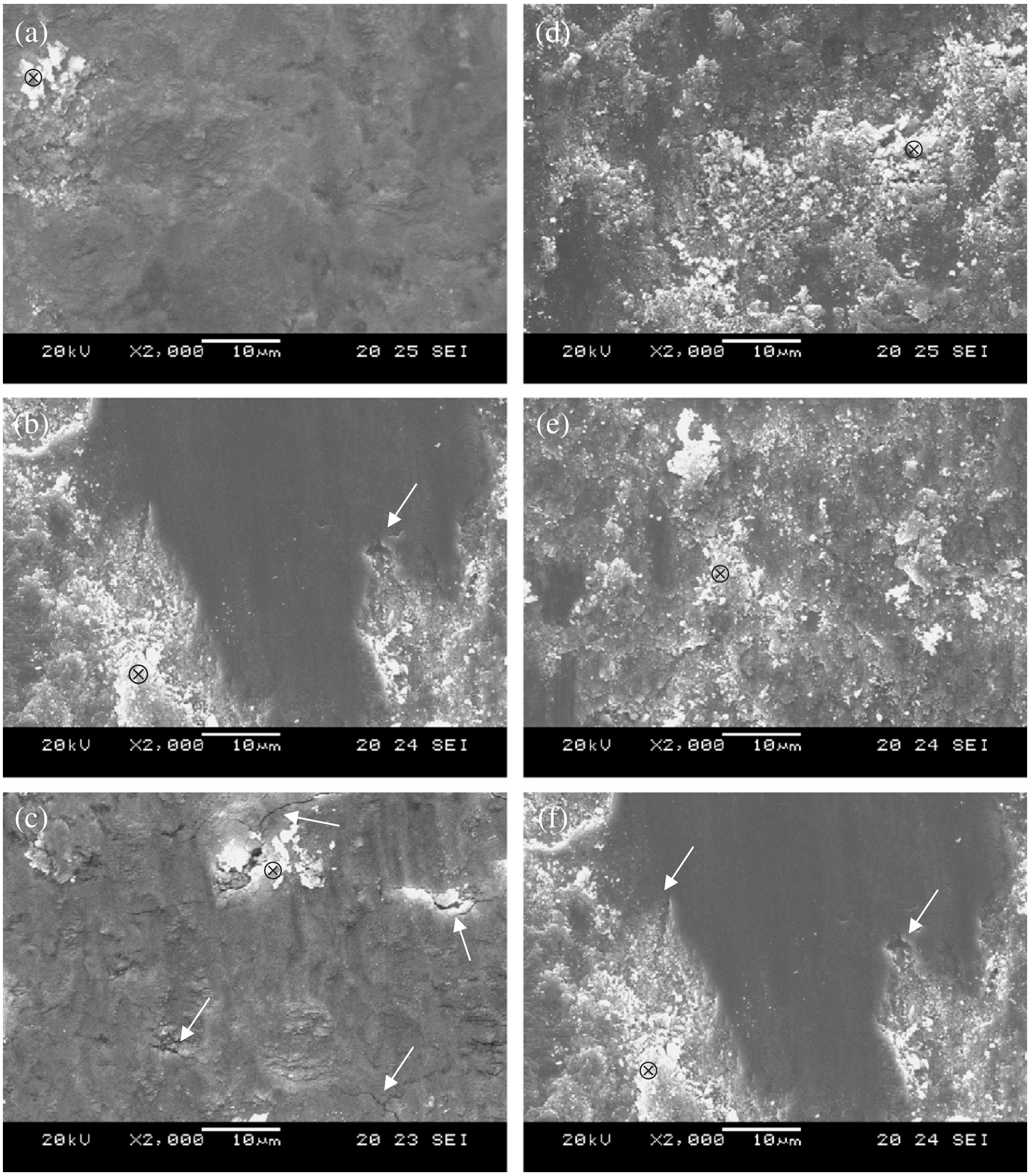


Fig. 10. Scanning electron micrograph of the worn out regions and oxide debris at the centre of the fretted zone of tin plated contacts after 20,000 fretting cycles obtained at varying track lengths and fretting frequencies. (a) ±5 μm and 3 Hz; (b) ±5 μm and 10 Hz; (c) ±5 μm and 20 Hz; (d) ±25 μm and 3 Hz; (e) ±25 μm and 10 Hz; and (f) ±25 μm and 20 Hz.

For the track length of ±5 μm, the size of the particles is in the range of 0.2–3 μm whereas their size is reduced to 0.05–1.5 μm when the track length is increased to ±25 μm.

The EDX line scanning performed across the fretted zone (indicated by dotted line in Fig. 6) confirms the presence of tin, copper and oxygen (Fig. 12). Within the fretted zone (marked between the dotted lines in Fig. 12) the intensity of tin is decreased whereas the intensity of copper and oxygen is increased, suggesting the removal of the tin coating, exposure of the base metal and oxidation of tin and copper. X-ray mapping of copper, tin and oxygen in the fretted zone substantiates the observations of EDX line scanning. A comparison of the EDX line scan results of samples with a track length of ±5 and ±25 μm reveals overlapping of tin and copper lines (within the fretted zone) when the track length is ±5 μm whereas there is a distinct separation between these lines when the track length is ±25 μm. The distinct separation between the copper and tin lines suggests that the tin coating is mostly worn out. The overlapping of tin and copper lines observed at the track length of ±5 μm cannot be attributed to the lesser wear of the tin coating as the rate of wear of tin coating is a function of fretting frequency. Hence, the overlapping of the tin and copper lines could be due to the accumulated tin/tin oxide wear debris. The intensity of oxygen is relatively higher for samples with a track length of ±25 μm, suggesting higher levels of oxidation at the track length of ±25 μm compared to that of ±5 μm. For a given track length, the intensity of oxygen is found to be higher at 20 Hz.

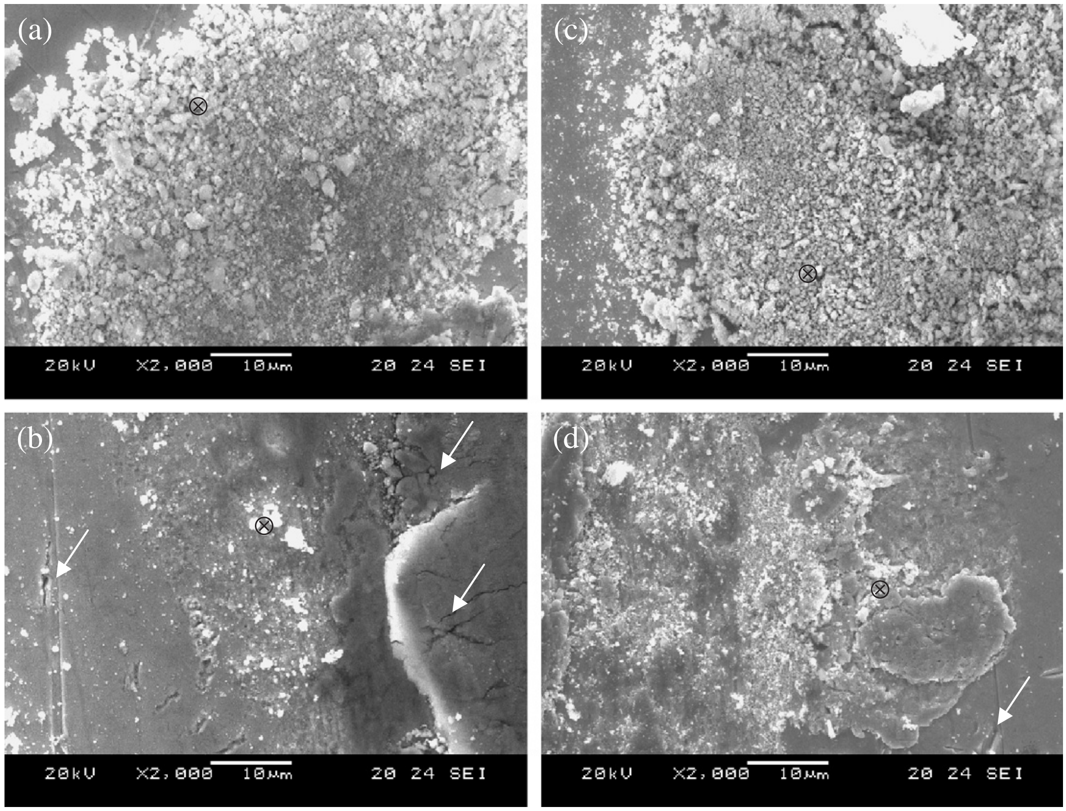


Fig. 11. Scanning electron micrograph of the wear debris and oxidation products present at the edges of the fretted zone of tin plated contacts after 20,000 fretting cycles obtained at varying track lengths and fretting frequencies (a) ±5 μm and 3 Hz; (b) ±5 μm and 20 Hz; (c) ±25 μm and 3 Hz; and (d) ±25 μm and 20 Hz.

The EDX pattern taken at the centre and edges of the fretted region indicates the presence of copper, tin and oxygen as the predominant elements. The EDX spot analysis performed on the debris particles (indicated by '⊗' in Figs. 10 and 11) indicates the presence of appreciable amounts of copper (30.57 to 64.70 at.%) and oxygen (31.76 to 55.16 at.%) with a small amount of tin (3.19 to 14.27 at.%) in the centre and, considerable amounts of tin (14.08 to 39.89 at.%) and oxygen (35.70 to 61.09 at.%) with a relatively less amount of copper (11.85 to 34.72 at.%) at the edges of the fretted region. The variation in the atomic concentration of tin, copper and oxygen of the oxide debris present at the centre and at the edges of the fretted zone is plotted as a function of the experimental conditions used (Fig. 13). A comparison the extent of change in the atomic concentration of copper, tin and oxygen at the centre (Fig. 13a) and edge (Fig. 13b) regions makes evident of the fact that the debris present at the centre is predominantly oxides of copper whereas those present at the edges are mainly oxides of tin. For a given track length, there is only a slight variation in the concentration of any element when the fretting frequency is increased from 3 to 20 Hz. However, the variation in the concentration of copper, tin and oxygen is significant when the track length is increased from ±5 to ±25 μm. There is a decrease in the tin content and an increase in the copper content, both at the centre and edge regions, when the track length is increased from ±5 to ±25 μm. The variation in the area covered by copper, tin and oxygen as a function of experimental conditions indicates that the debris is predominantly oxides of copper when the track length is ±25 μm. Though appreciable amounts of copper are present at the centre, the trend, in general, indicates that the debris is mostly oxides of tin when the track length is ±5 μm.

The predominance of oxides of copper observed for the track length of ±25 μm, both at the centre as well as at the edges, could be explained as follows: At this track length, more fresh tin coating gets exposed for oxidation, which results in the generation of higher quantities of wear debris and subsequent faster removal of the remaining tin coating due to the abrasive nature of the hard tin oxide debris. If the same analogy is applied for the track length of ±5 μm, the availability of less fresh tin could have resulted in the formation of lesser quantities of tin oxide and a slower rate of removal of the remaining tin coating. However, EDX analysis indicates the presence of appreciable amounts of copper even at this track length (Fig. 13). Hence, the predominance of oxides of tin observed at the track length of ±5 μm could be due to the accumulation of tin oxide debris at the contact zone. The narrow and deep surface profile, lower $R_a$ value and overlapping of the tin and copper lines in the EDX line scan, support the view that the chances of accumulation of wear debris at the contact zone is very high at the track length of ±5 μm. The accumulation of wear debris decreases the availability of fresh metallic sites and causes the percolation limit for electrical conduction to reach very early, resulting in the rapid increase in contact resistance at the track length of ±5 μm.

If the time to reach 0.1 Ω is considered as the point of failure, then the tin plated copper alloy contact will fail early at 20 Hz

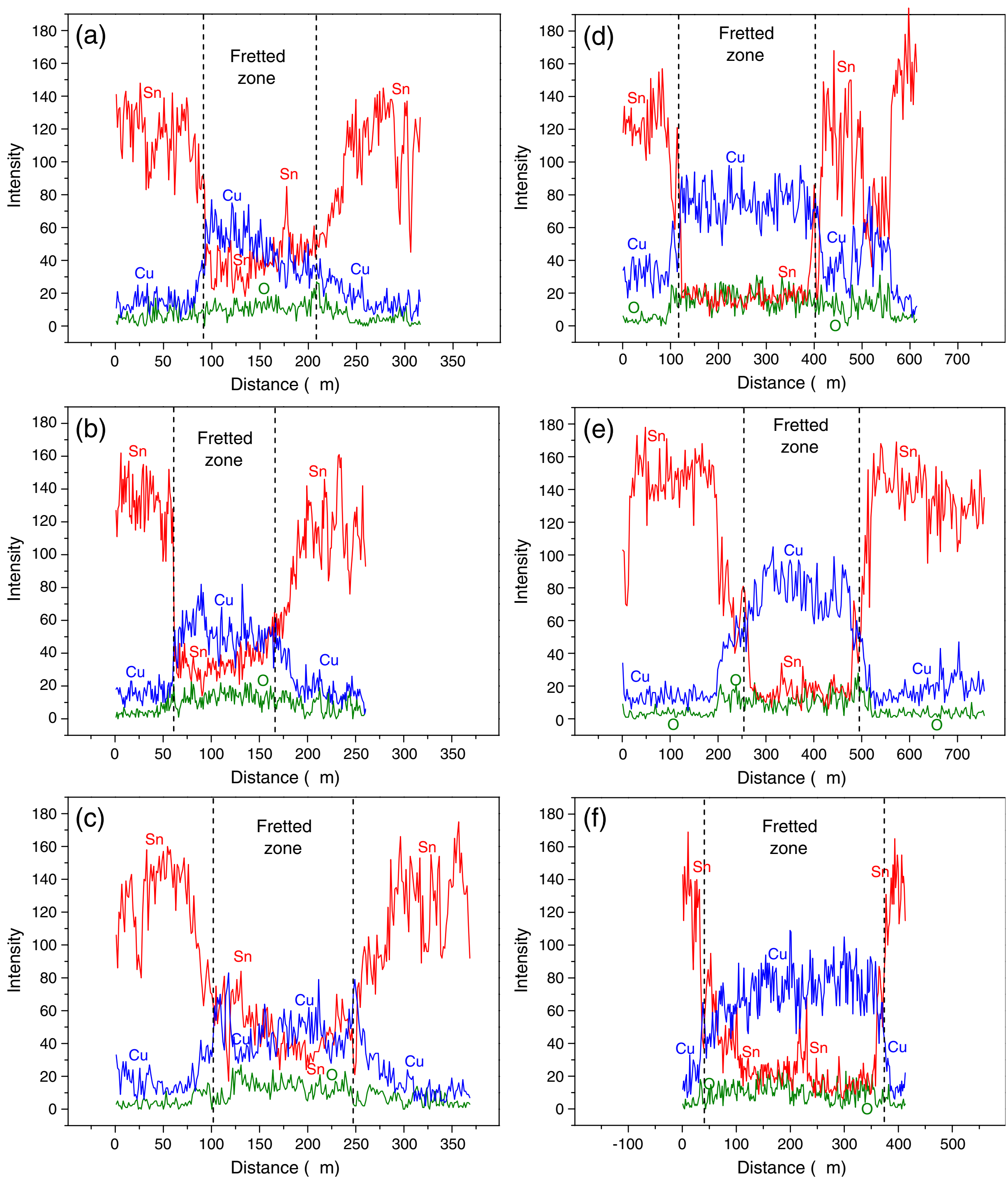


Fig. 12. EDX line scan performed across the fretted zone (indicated between dotted line) of the tin plated contact after 20,000 fretting cycles obtained at varying track lengths and fretting frequencies (a) ±5 μm and 3 Hz; (b) ±5 μm and 20 Hz; (c) ±25 μm and 3 Hz; and (d) ±25 μm and 20 Hz.

for both track lengths and at the track length of ±5 μm for all the three frequencies. The rate of wear of the tin coating, availability of fresh metal (tin), extent of oxidation and accumulation of wear debris at the contact zone influences the time to reach the percolation limit for electrical conduction. The extent of change in these factors, as a function of track length and frequency, determines the rate of change in contact resistance. The rate of wear of the tin coating will increase with increase in frequency from 3 to 20 Hz for both track lengths. The availability of more fresh metal (tin) will be higher at 20 Hz. The extent of oxidation and accumulation of wear debris at the contact zone will be high at 3 Hz. The availability of fresh metal and extent of oxidation will be low at the track length of ±5 μm whereas the extent of accumulation of debris is high at this track length. In contrast, at the track length of ±25 μm, the availability of fresh metal and the extent of

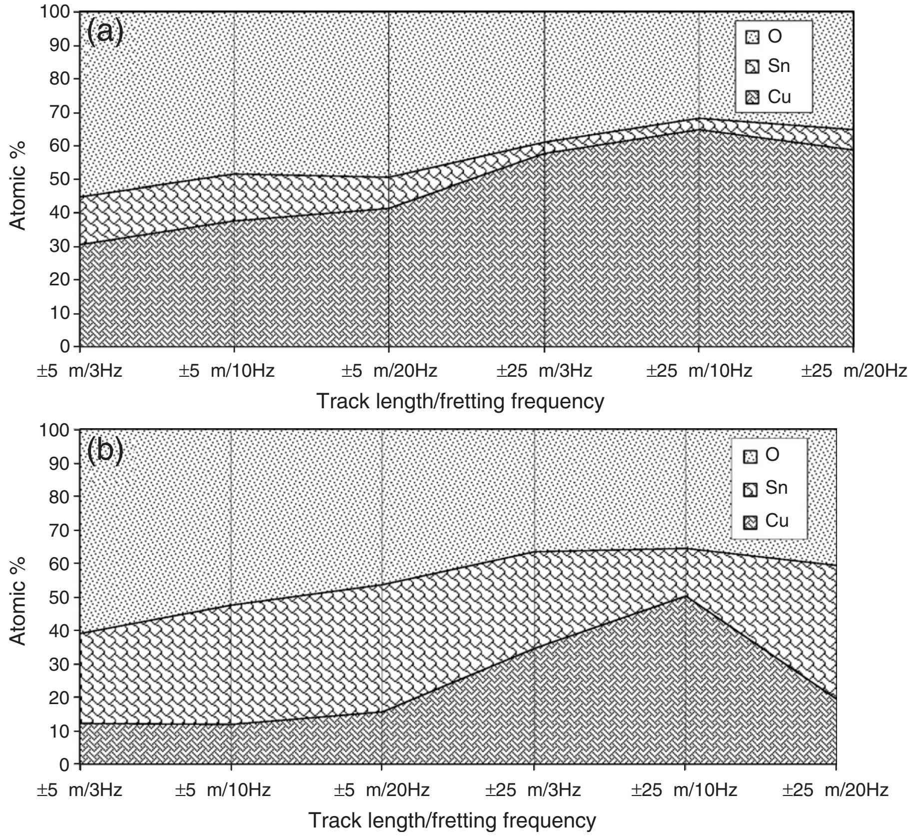


Fig. 13. Area plot depicting the variation in atomic concentration of tin, copper and oxygen of the oxide debris as a function of the experimental conditions (a) at the centre of the fretted zone; and (b) edge of the fretted zone.

oxidation will be high whereas the extent of accumulation of debris will be low.

## 4. Conclusions

The fretting corrosion behaviour of tin plated copper alloy contacts at 3, 10 and 20 Hz and at two different track lengths (fretting amplitude) of ±5 and ±25 μm is studied. The threshold value of contact resistance of 0.1 Ω reaches very early for the track length of ±5 μm at all the three frequencies. For a given track length, this threshold value reaches early at 20 Hz. The average wear depth increases with the increase in track length from ±5 to ±25 μm and with the increase in frequency from 3 to 20 Hz. The extent of increase in the average wear depth is not appreciable at ±5 μm and at 3 Hz (about 5 μm) whereas it is more pronounced at ±25 μm and at 20 Hz (about 19 μm).The surface profile is narrow and deep with an average depth of 5 to 10 μm for the track length of ±5 μm whereas it is broad and shallow with an average depth of 5 to 19 μm for the track length of ±25 μm. The roughness ($R_a$) is of the order of 0.94 to 1.11 μm for the track lengths of ±5 μm whereas it varies from 1.27 to 1.59 μm when the track length is increased to ±25 μm. The surface morphology of the fretted zone reveals severe damage for samples with a track length of ±25 μm at all the three frequencies. The presence of cracks on the surface of the coated layer and loose sheet/flake like debris confirms the occurrence of delamination wear at both track lengths and at all the three frequencies. The distinct separation between the tin and copper lines when the track length is ±25 μm and overlapping of these lines when the track length is ±5 μm confirms that tin coating is mostly worn out at ±25 μm whereas accumulation of tin/tin oxide wear debris occurs at ±5 μm. The increase in the intensity of oxygen for samples with a track length of ±25 μm compared to that of ±5 μm, confirms a higher level of oxidation at the track length of ±25 μm. The area plot of the variation in the atomic concentration of tin, copper and oxygen of the oxide debris reveals that the debris present at the centre is predominantly oxides of copper whereas those present at the edges are mainly oxides of tin. The variation in the area covered by copper, tin and oxygen as a function of experimental conditions indicates that the debris is predominantly oxides of copper when the track length is ±25 μm. Though appreciable amounts of copper are found at the centre, the trend, in general, indicates that the debris is mostly oxides of tin when the track length is ±5 μm. The narrow and deep surface profile, lower $R_a$ value, overlapping of the tin and copper lines in the EDX line scan and the predominance of oxides of tin support the view that the chances of accumulation of wear debris at the contact zone is very high at the track length of ±5 μm. The accumulation of wear debris decreases the availability of fresh metallic sites and causes the percolation limit for electrical conduction to reach very early, resulting in the rapid increase in contact resistance at the track length of ±5 μm. Hence it is evident from the study that the extent of oxidation of the contact zone is higher at a track length of ±25 μm whereas the extent of accumulation of wear debris is higher at a track length of ±5 μm. The study concludes that tin plated copper alloy contacts could experience an early failure even at shorter track lengths, if there is enough accumulation of the wear debris at the contact zone.

## Acknowledgements

This work was supported by grant No. M1-0403-00-0003 from Korean Institute of Science and Technology Evaluation and Planning. One of the authors (TSNSN) expresses his sincere thanks to the Korea Federation of Science and Technology Societies, for awarding a fellowship under the Brain Pool Program, to carry out this research work.

## References

[1] A. Lee, M. Mamrick, IEEE Trans. Components Hybrids Manuf. Technol. 10 (1987) 63.
[2] R.D. Malucci, IEEE Trans. Compon. Packag. Technol. 22 (1999) 53.
[3] R.D. Malucci, IEEE Trans. Compon. Packag. Technol. 24 (2001) 399.
[4] G.T. Flowers, X. Fei, M.J. Bozack, R.D. Malucci, IEEE Trans. Compon. Packag. Technol. 27 (2004) 65.
[5] M. Braunvoic, IEEE Trans. Compon. Packag. Technol. 24 (2001) 384.
[6] J. Swingler, J.W. McBride, C. Maul, IEEE Trans. Compon. Packag. Technol. 23 (2000) 157.
[7] AMP Technical Report, The Tin Commandments: Guidelines for the Use of Tin on Connector Contacts, AMP Inc., 1996.
[8] N.A. Stennett, J. Swingler, Proc. of the 39th IEEE Holm Conference on Electrical Contacts, IEEE, 1993, p. 205.
[9] T. Hammam, IEEE Trans. Compon. Packag. Technol. 23 (2000) 278.
[10] J. Swingler, Proc. Inst. Mech. Eng. —Part D 214 (2000) 615.
[11] A. Lee, in: P.G. Slade (Ed.), Electrical Contacts: Principles and Applications, Marcel Dekker Inc., New York, 1994, p. 300.
[12] J. Ambier, P. Perdigon, IEEE Trans. Components Hybrids Manuf. Technol. 8 (1985) 197.
[13] J. Wu, M. Pecht, Proc. of the 4th Electronics Packaging Technology, IEEE, 2002, p. 20.
[14] L. Wang, Y. Gao, T. Xu, Q. Xue, Mater. Chem. Phys. (in press) (doi:10.1016/j.matchemphys.2005.10.014).
[15] M. Antler, in: P.G. Slade (Ed.), Electrical Contacts: Principles and Applications, Marcel Dekker Inc., New York, 1994, p. 309.
[16] R. Schubert, Phys. Rev., B 43 (1991) 1433.
[17] S.R. Murrell, S.L. McCarthy, Proc. of the 43rd IEEE Holm Conference on Electrical Contacts, IEEE, 1997, p. 1.