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Studies of tin coated brass contacts in fretting conditions under different normal loads and frequencies

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Abstract

The fretting corrosion behavior of tin-plated brass contacts is studied at various normal loads (0.25, 0.5, 1.0 and 1.5 N) and fretting frequencies (1, 3 and 8 Hz). The typical characteristics of the change in contact resistance with fretting cycles and time are explained. Irrespective of the frequencies under study, 1 N normal load suppressed the fretting corrosion of tin contacts by maintaining the mechanical stability and good electrical contact between the contacting members which makes less accumulation of wear debris at the fretted zone. For a given normal load, the fretting corrosion of tin-plated contacts occur much faster at higher frequencies as it provides more fresh metal for oxidation and generates more accumulation of oxide wear debris at the contact zone. The failure time, i.e. the time for contact resistance at the fretted surface to reach 0.1 Ω is delayed with increasing normal loads at the studied frequencies. For a given normal load, the failure time reaches early at 8 Hz, i.e. at higher fretting frequencies. The fretted surface is examined using laser scanning microscope, scanning electron microscope and energy dispersive X-ray analysis to assess the surface profile, extent of fretting damage, extent of oxidation and elemental distribution across the contact zone. From the surface profile data, the fretted area and the wear rate is calculated and correlated with the observed extent of oxidation and earlier failure of electrical contacts. The surface morphology and EDX analysis results of the fretted surface clearly revealed the severe fretting damage at 0.25 N and 8 Hz.

Keywords: Fretting corrosion; Normal load; Fretting frequency; Surface characterization

1. Introduction

Fretting corrosion is a form of accelerated atmospheric oxidation occurring at the interface of contacting materials subjected to small cyclic relative motions. The deleterious effect of fretting in electrical connections is considered to be of significant practical importance as it influences the reliability and system performance. The main causes of fretting are mechanical vibration, shock, differential thermal expansion and contraction of the contacting metals, and junction heating as the power is turned on and off, all of which may be present in the automotive environment. Such situations are classically observed not only in airplanes, satellites, and trains, but also in cars, particularly next to the engine. It is most commonly found in all kinds of press fits, spline connections, and also in electrical connections [1].

Interest in fretting corrosion studies in automotive electrical contact applications has been growing in recent years. A survey of the relevant literature is given by Antler [2,3] and other researchers [4]. It has been estimated that more than 60% of the contact failures in automobile connectors are related to fretting corrosion problems [5]. Since, fretting is one of the major deterioration mechanisms of non-arcing electrical contacts, studies on this phenomenon has gained most importance.

The deterioration of tin coated connectors is mainly caused by macro-wear during insertion/withdrawal and fretting during operation. Although tin-plated connectors have been accepted

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in many consumer applications, its susceptibility to fretting corrosion limits its use in automobile connectors. However, the quest for a suitable finish which is cost effective as well as capable of combating fretting corrosion continues. Fretting corrosion of tin-plated connectors had been discussed in many publications [6–14]. However, much of the published works had focused on the understanding of the cause of the fretting corrosion, the method of measurement, and the means of preventing it. Few papers had discussed on the characterization of contact resistance and the influence of various parameters on the fretting corrosion process. Lee [15] and Ambier and Perdigon [16] have studied the effect of normal load on the fretting corrosion behavior of tin-plated copper contacts at various amplitudes and concluded that the increase in normal load delays the failure time and higher amplitudes are detrimental to tin contacts. They also studied on the effect of fretting frequency and 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. Neijzen and Glashorster [17] have investigated on the influences of amplitude and contact load on the number of cycles to failure in a contact situation and concluded that increasing the contact load retarded the increase in contact resistance during fretting corrosion experiments. Unfortunately, no physical explanation or detailed corrosion characteristics for their observations was presented. Rudolphi and Jacobsen [18] have studied on the use of ceramic coatings to replace metallic coatings in electrical contacts and discussed the effect of normal forces and amplitudes on contact resistance. In recent years, Park et al. have investigated on the fretting behavior of tin-plated copper contacts at various fretting amplitude, frequency and temperature and characterized the fretted surface [19–22].

Fretting frequency and normal load are the two major factors that determine the contact area and time the tin coating could encounter wear and oxidation. As they have a synergic 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 behavior of tin-plated contacts with various normal loads and frequencies. In this context, the present study is an attempt to explore the fretting characteristics of tin-plated brass contacts that are subjected to fretting corrosion under the influence of different normal loads and fretting frequency. The failure time, i.e. the time for contact resistance of the fretted surface to reach 0.1 Ω is determined at various experimental conditions. The fretted surface is examined using laser scanning microscope, scanning electron microscope and energy dispersive X-ray analysis to assess the surface profile, extent of fretting damage, extent of oxidation and elemental distribution

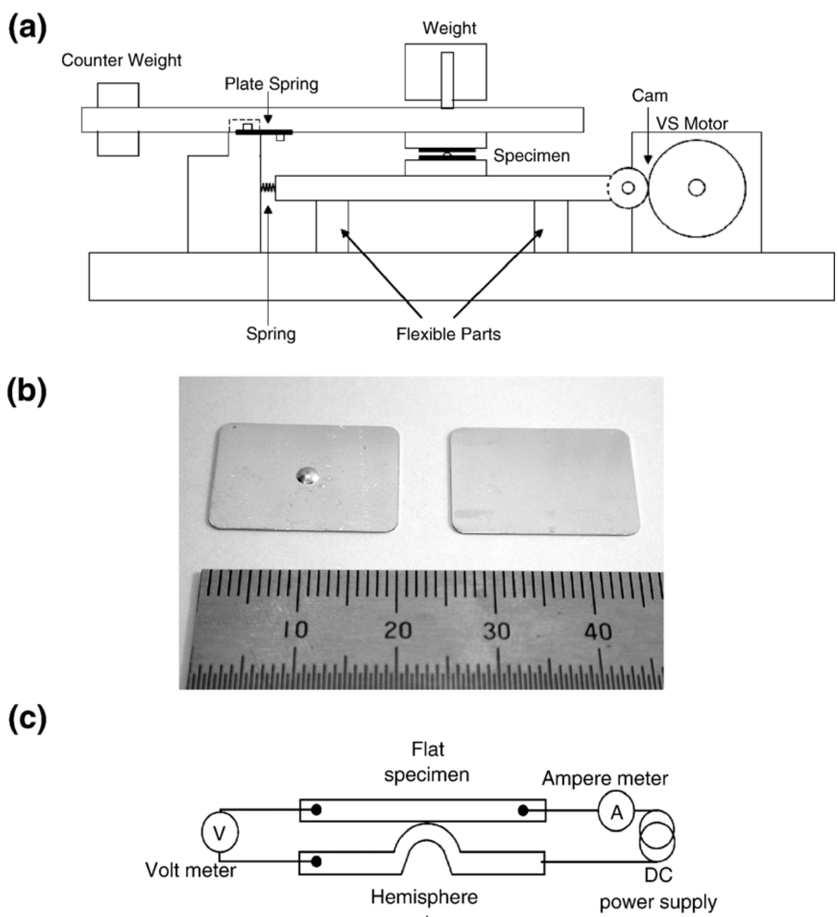

Fig. 1. (a) Schematic sketch of the fretting apparatus; (b) the rider and flat samples; (c)the geometry of the rider and flat samples and the circuit used to measure the contact resistance.

across the contact zone. The results are correlated to explain the effect of normal load and frequency on the fretting behavior of tin-plated contacts.

2. Experimental details

The fretting corrosion characteristics of tin-plated brass contacts were 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 sketch of the fretting apparatus used in this study is shown in Fig. 1(a). The normal load was applied on the balance arm. One of the contacts was flat and the other was 1.5 mm radius hemispherical rider (Fig. 1b), supplied by Korea Electric Terminal Company Ltd., Korea. Both of them were made of brass (C2600-H grade: Cu, 70%; Fe, 0.05%; Pb, 0.05%; and balance zinc) and coated with 3 μm thickness of tin.

The rider and flat contacts were degreased with acetone using an ultrasonic cleaner, dried and carefully mated in the fretting test assembly in such a way so as to create a point contact in "sphere plane" geometry. The contact geometry and the circuit used to measure the contact resistance were shown in Fig. 1(c). A periodic relative displacement with an amplitude of ±25 μm and an electric current of 100 mA (direct current) were applied between the rider and flat contacts. The effect of normal load for 0.25, 0.5, 1.0 and 1.5 N at 3 Hz and the fretting frequency of 1, 3 and 8 Hz at 1.0 N were studied on the contact resistance of the tin coated brass contacts. Since the present study intends to explore the fretting characteristics of tin coated brass contacts and to characterize the nature of oxide films formed at the contact zone, the fretting tests were conducted under gross slip conditions [23]. The contact resistance was continuously measured as a function of fretting cycles with various normal loads and as a function of fretting time with various frequencies. The time to failure of contact resistance, according to Mroczkowski [1] was based on a particular application rather than the product specification of contact resistance. For a signal contact the recommended value is 100 mΩ or more and for a power contact it is 0.5 mΩ or less. For all practical purposes and in this study, the time to reach 0.1 Ω is used as the failure time for electrical contacts. All the tests were performed in un-lubricated conditions at 25±1 °C

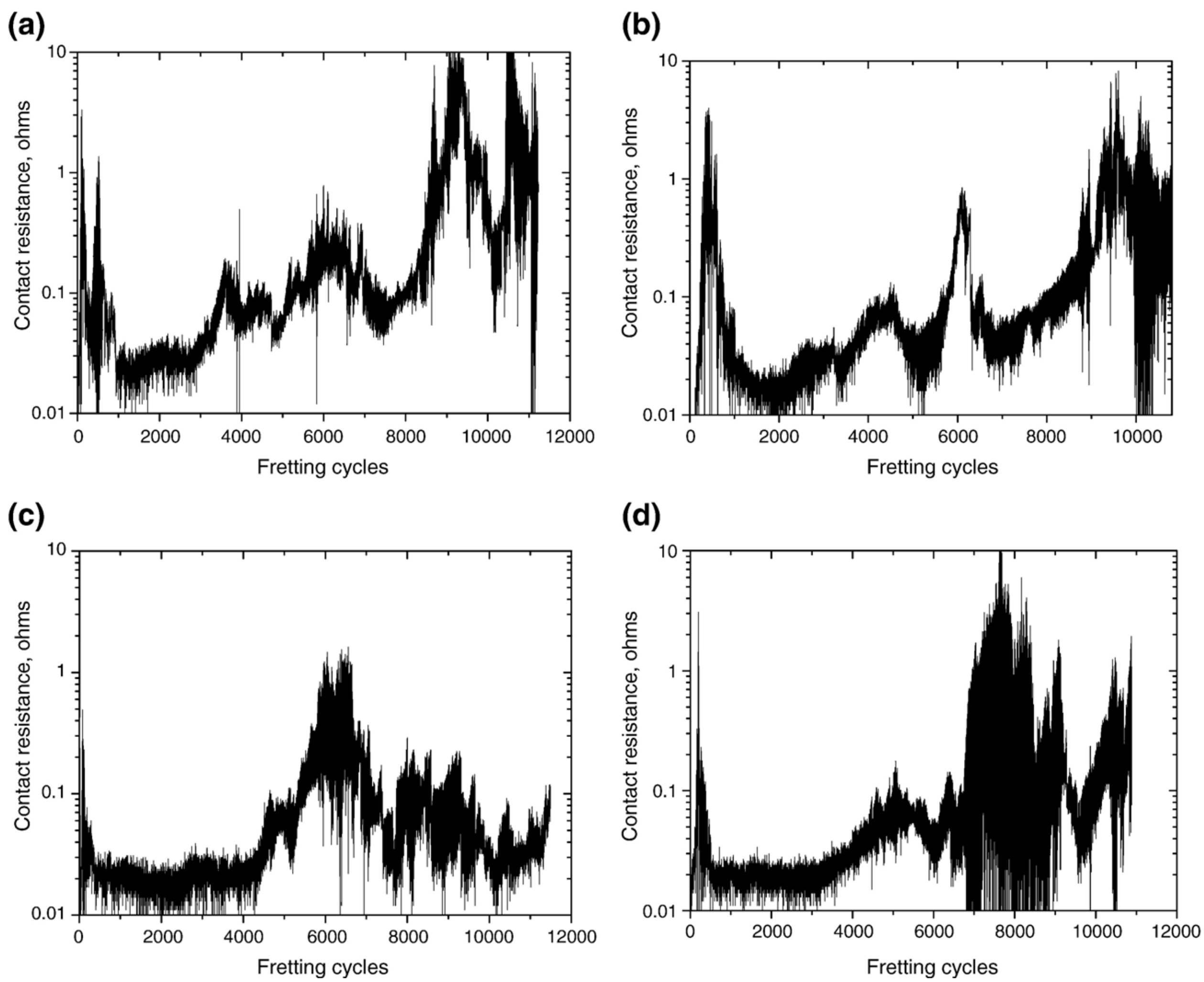

Fig. 2. Variation in contact resistance of the tin-plated brass contacts as a function of fretting cycles for a fretting frequency of 3 Hz at different normal loads (a) 0.25 N (b) 0.50 N (c) 1.0 N and (d) 1.5 N.

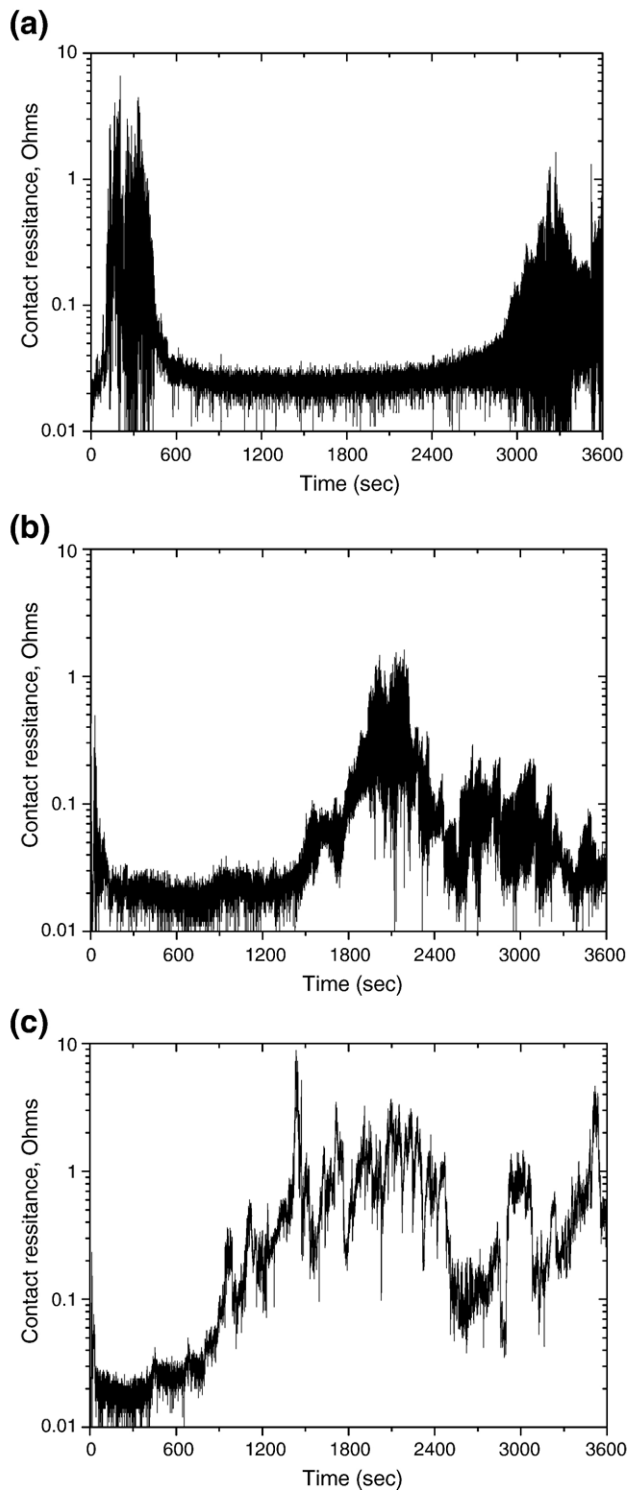

Fig. 3. Variation in contact resistance of the tin-plated brass contacts as a function of fretting time for a normal load of 1.0 N at different fretting frequencies (a) 1 Hz, (b) 3 Hz and (c) 8 Hz.

and at 45±1% RH. The fretting tests were repeated at least thrice to ascertain the reproducibility of the test results and the best one of them was represented.

For characterization, the flat contact plate was carefully removed from the holder after 3600 cycles and stored in desiccators to prevent from further oxidation and analyzed within 12 h. The surface profile and surface roughness across the fretted area was assessed using a Carl Zeiss laser 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 (mm^3), S the total sliding distance (m) and F is the normal load (N) [24]. The wear volume was determined by multiplying the average wear depth 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 line mapping were used to characterize the extent of fretting damage, extent of oxidation and elemental distribution across the fretted zone.

3. Results and discussion

3.1. Variation of contact resistance with normal loads and fretting frequencies

The variations of the contact resistance of tin coated brass contacts as a function of fretting cycles for an amplitude of ± 25 μm and a frequency of 3 Hz at the four values (0.25, 0.5, 1.0 and 1.5 N) of normal loads for 10,800 cycles are shown in Fig. 2 (a–d) respectively. Fig. 2(a) shows the variation in contact resistance at 0.25 N normal load. At the first instance, the contact resistance is 0.02 Ω and a sharp increase in contact resistance (>1 Ω) is observed up to 900 cycles. However, it decreases sharply and reaches a stable and low value (0.02 Ω) between 900 and 3250 cycles. With further increase in fretting cycles, there is a gradual increase in contact resistance for some time (4000 cycles) beyond which the increase is steep and very rapid and attains a resistance of greater than 10 Ω. The observed trend in change of contact resistance as a function of fretting cycles agreed well with other researchers [15–22]. The results are sufficiently consistent to explain the complex physicochemical processes which occur during fretting corrosion in the contact zones.

The contact resistance trends can be correlated to metal transfer and wear which occur between mating surfaces. As tin is a soft and active metal, its surface gets easily oxidized in

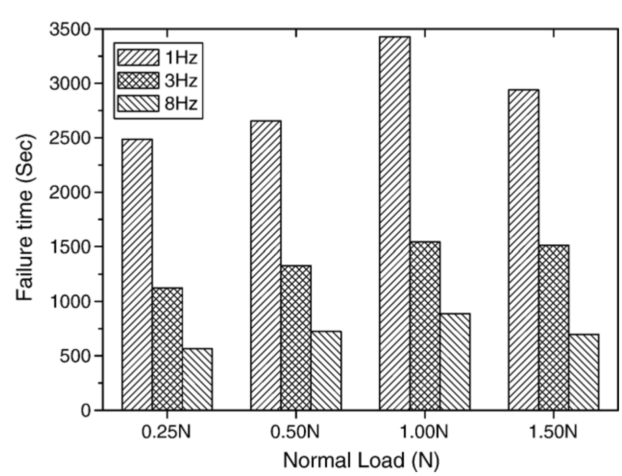

Fig. 4. Plot of failure time as a function of normal load and fretting frequency.

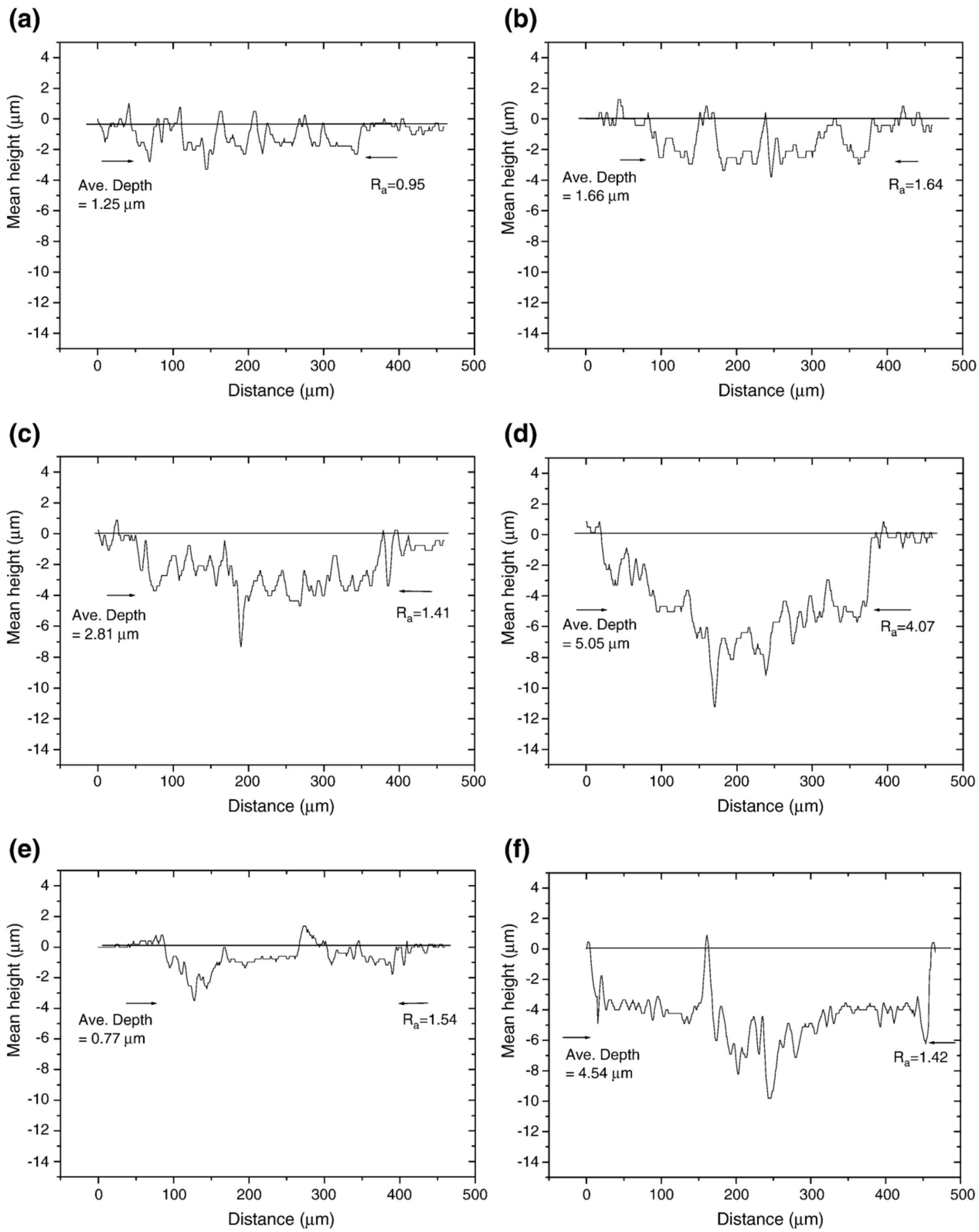

Fig. 5. Surface profile across the fretted zone of the tin-plated brass contacts after 3600 fretting cycles obtained at various normal loads and fretting frequencies. (a) 0.25 N, 3 Hz (b) 0.5 N, 3 Hz (c) 1.0 N, 3 Hz (d) 1.5 N, 3 Hz (e) 1 Hz, 1.0 N and (f) 8 Hz, 1.0 N.

atmospheric air and a thin oxide film is formed. With fretting, the first time observed sharp increase in resistance to 100 mΩ in each experiment represents the fretting corrosion of the tin plating and also due to the presence of a thin film of tin oxide on the surface of both the rider and flat contacts, which is removed in a very short span of time (900 cycles). If the oxide film is present on the tin coating, then the resistance should be relatively high when the contacts are mated together. However, the observed resistance is low and it increased only after the fretting motion is started. The authors have studied a similar

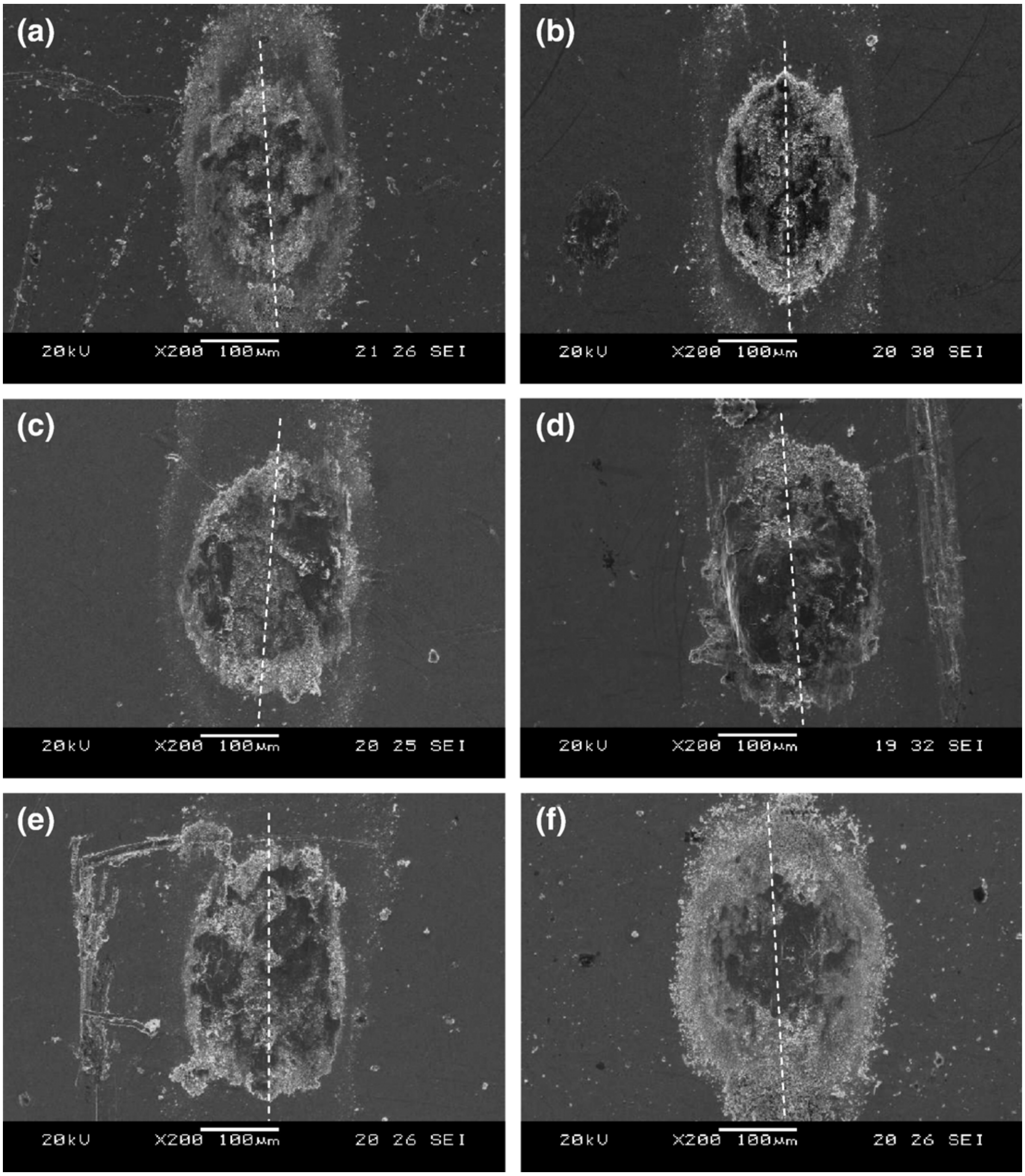

Fig. 6. Surface morphology of the fretted tin-plated brass contacts after 3600 fretting cycles obtained at various normal loads and fretting frequencies (a) 0.25 N, 3 Hz (b) 0.5 N, 3 Hz (c) 1.0 N, 3 Hz (d) 1.5 N, 3 Hz (e) 1 Hz, 1.0 N and (f) 8 Hz, 1.0 N.

fretting wear behavior of tin coated contacts and its influence on the contact resistance and reported [25] elsewhere. The low and stable contact resistance values observed following the initial sharp increase is due to the good conducting nature of the soft tin deposits. Due to the fretting motion on the contact surface, a track of fresh tin surface is exposed which immediately gets oxidized. The gradual increase in contact resistance with fretting cycles up to 4000 could be due to the formation of tin oxide film. The subsequent rapid increase in the resistance to 100 mΩ is due to the oxidation of the base material as well as accumulation of wear debris and corrosion products on the fretted surface. Beyond this fretting cycle, the oxide debris accumulation along the wear track becomes less uniform and hence shows a large fluctuation in the contact resistance reaching a higher level of resistance greater than 1 Ω. As the amount of oxide and wear debris increases with increasing fretting cycles, the electrical contact area may get reduced and the conducting path become longer. Hence, the observed rapid increase in contact resistance beyond 4000 cycles may be due to the conduction of current through an increasingly smaller area of contact.

In Fig. 2(b, c and d), the variation of contact resistance with fretting cycles for 0.5, 1.0 and 1.5 N, respectively, is shown. A similar pattern, i.e. an initial hump, a steady contact resistance, gradual increase and a rapid increase in contact resistance is observed with fretting cycles against different normal loads. However, the number of cycles at which the steady and low contact resistance value attained is significantly changed with increasing load. The failure of a connector can be taken as the number of fretting cycles or time (s) at which a gradual increase in contact resistance from a steady value (0.1 Ω) occurs. Under investigated values of normal load, the failure of contacts are found to be at 3300, 3900, 4600 and 4500 cycles respectively and a delayed failure in comparison to 0.25 N is noticed. According to Antler [3], the increasing normal loads enhance the penetration of fretting corrosion products with a consequent reduction in contact resistance. The higher normal load increases the retention force between the mating surfaces and improves the mechanical stability between the connectors. Moreover, the higher normal load suppresses the fretting corrosion effects and is better able to break the oxidation products and wipe away the accumulated wear debris. It is clearly evident from Fig. 2 that the higher normal load, 1.0 N, has significantly delayed the failure time promoting the formation of a large number of metallic contacts and conducting paths.

The variation in contact resistance as a function of fretting time is followed at 1, 3 and 8 Hz for the four values of normal loads. As a resistance pattern similar to Fig. 2 was observed, the figures for the effect of frequency on 0.25, 0.5 and 1.5 N normal loads are not shown and discussed in this text. However, to explain the effect of fretting frequency on contact resistance, in Fig. 3, the variation in contact resistance of tin-plated brass contacts as a function of fretting time for 1.0 N at 1, 3 and 8 Hz is shown. The observed variation in failure time of tin-plated contacts is due to the pronounced effect of the fretting frequency. It appears from Fig. 3 that at 1 N load, the failure time at 1, 3 and 8 Hz is found to be 3400, 1500 and 900 s respectively. For the given normal load, it is longer at 1 Hz than at 3 and 8 Hz. For a given fretting time, the total sliding distance for the fretting motion will be more at higher frequency than at lower frequency. Hence the possibility of accumulation of wear debris and oxidation products is very high at 8 Hz than that of 1 and 3 Hz. Thus the accumulation of wear debris and the unavailability of fresh metallic sites cause the contact resistance to reach early at 8 Hz. Park et al. [19] have reported that when the frequency is increased, the fretting corrosion of tin-plated contacts occur much faster as it provides more fresh metal for oxidation and generates more oxide debris. The physical process responsible for the rise in contact resistance is the enhanced oxidation of the contacting surfaces as the fresh metal is exposed in a cyclic fashion. Hence, it is obvious to expect an early failure at 8 Hz than at 1 and 3 Hz. The observed results of the present study are in good agreement with this view.

For a better understanding of the effect of normal load and frequency on fretting behavior of tin coated contacts, the failure time to reach 0.1 Ω for various frequencies is plotted as a function of normal load (Fig. 4). For a given frequency, the failure time is seen to increase with increasing normal load up to 1.0 N and then decreased. It can also be observed that under investigated experimental conditions, the failure time reaches very early at 0.25 N. As reported earlier [18], increasing the normal load increases the friction force and the mechanical stability of the contact interface. It may also increase the contact area resulting in decreased contact resistance. This explains the delayed failure time with increasing normal load. Lee [15] studied the fretting corrosion characteristics of tin-plated contacts for an amplitude of 40 μm at 0.5 to 4 N loads and found that higher loads suppressed the fretting corrosion effects. At higher loads, the contact is better able to push the oxide debris aside or break through the oxide layer. At lower loads, the oxide particles produced by abrasive wear may get entrapped, forming the insulation layer and decrease the failure time of the contacts. These observations suggest, from the point of view of failure time, an optimum normal load of 1.0 N for the tin-plated brass contacts. However, above 1.0 N, the failure time is seen to be slightly decreased. This may be due to the accumulation of higher quantities of wear debris and oxidation products between the contacting surfaces that result in increase of contact resistance and failure of the contacts [26].

At the given normal load, the failure time changes significantly with variation in fretting frequency. According to Antler [3], the repetitive exposure of fresh metal and its subsequent oxidation and formation of wear debris at the fretted surfaces lead to the steady rise in contact resistance. This accounts the observed earlier fretting corrosion failures at higher frequencies. Therefore longer life-time of electrical contact can be acquired by operating under optimum normal load and lower frequency conditions.

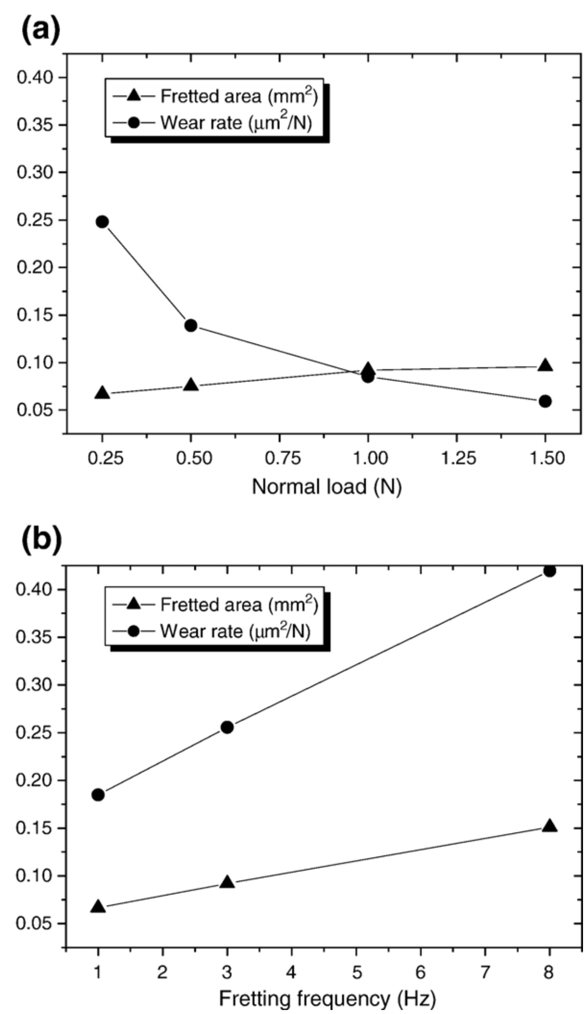

Fig. 7. Variation of fretted area and wear rate at 3600 fretting cycles as a function of (a) normal load at 3 Hz and (b) fretting frequency at 1 N load.

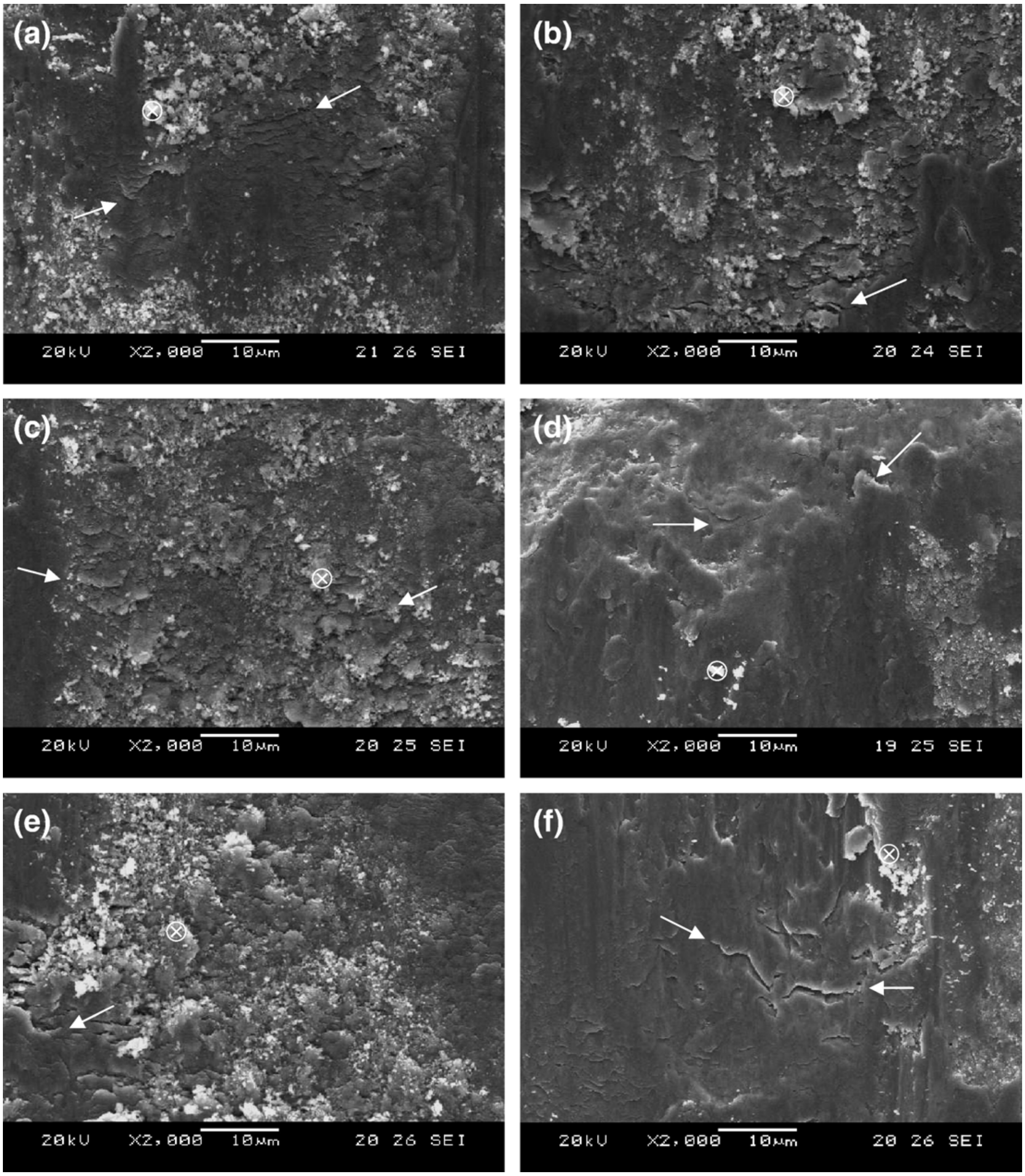

Fig. 8. Scanning electron micrograph of the worn out regions and oxide debris at the center of fretted zone of tin-plated brass contacts after 3600 fretting cycles obtained at various normal loads and fretting frequencies (a) 3 Hz, 0.25 N (b) 3 Hz, 0.50 N (c) 3 Hz, 1.0 N (d) 3 Hz, 1.5 N (e) 1 Hz, 1.0 N and (f) 8 Hz, 1.0 N.

3.2. Surface profile of the fretted zone with varying normal loads and fretting frequencies

To get a better understanding of the influence of normal loads of 0.25, 0.5, 1.0 and 1.5 N at 3 Hz and fretting frequencies of 1 and 8 Hz at 1.0 N on fretting corrosion of tin coated contacts, the surface profile of the fretted zone after 3600 fretting cycles is analyzed using LSM (Fig. 5). The surface profile reveals considerable variation in area and the depth of fretted zone as a function of normal load and frequency. It is evident from Fig. 5 that the average wear depth increases significantly with increase in normal load and frequency suggesting that the tin coating is wearing out continuously with fretting cycles. The roughness (R_a) is of the order of 0.95 to 4.07 µm with variation in normal load whereas it varied from 1.41 to 1.54 with variation in frequency. There is not much variation of R_a value with increase in frequency from 1 to 8 Hz. The higher R_a values and the higher wear depth of the fretted zone observed at 1.5 N suggest the delamination of the oxide layers from the remaining tin coating and higher oxidation. In contrast, at 0.25 N load less tin coating is exposed for oxidation and hence less oxide debris are formed and accumulated, resulting in a relatively less roughness. As the accumulated tin oxide particles are enclosed within a confined space, the surface profile is seemed to be shallow. The observed shallow surface profile and the low R_a value of fretted zone suggest that the chances of accumulation of wear debris and oxidation products at the contact zone are relatively higher at 0.25 N load than at 1.5 N. As Mallucci has pointed out [9], it is the accumulation of wear debris and the less availability of fresh metallic sites that cause the percolation limit for electrical conduction to reach early failure of contacts, resulting in the rapid increase in contact resistance at 0.25 N. The surface profile data thus confirms the observed earlier failure of contacts at low load and high frequency.

3.3. Surface morphology of the fretted zone with varying normal loads and fretting frequencies

The surface morphology of the fretted tin coated plated brass contacts with normal loads of 0.25, 0.5, 1.0 and 1.5 N with 3 Hz and at fretting frequencies of 1 and 8 Hz with 1.0 N after 3600 fretting cycles is shown in Fig. 6. The fretting direction is vertical as indicated by the dotted line and the fretted zone is elliptical shaped in all cases under study irrespective of the load and frequency. Though the shape of the fretted zone appears to be similar, there is a distinct variation in the fretted area and the extent of damage at the contact zone. It is clearly evident from Fig. 6 that the size of the fretted spot with 0.25 N is comparatively smaller than at 1.5 N load. At 0.25 N, the wear debris ejected laterally during the fretting motion can be seen outside the fretted zone along the sliding direction (Fig. 6a). Also the amount of ejected wear debris and bright wear particles are found to decrease with increasing normal loads (Fig. 6b, c and d). For a given load of 1.0 N, increasing the frequency from 1 to 8 Hz (Fig. 6e, c and f) increased the amount of ejected wear debris remarkably. These observations suggest that abrasive wear is predominant at low normal loads and oxidation and accumulation of wear debris is predominant at low fretting frequencies. The data from the surface profile studies (Fig. 5)

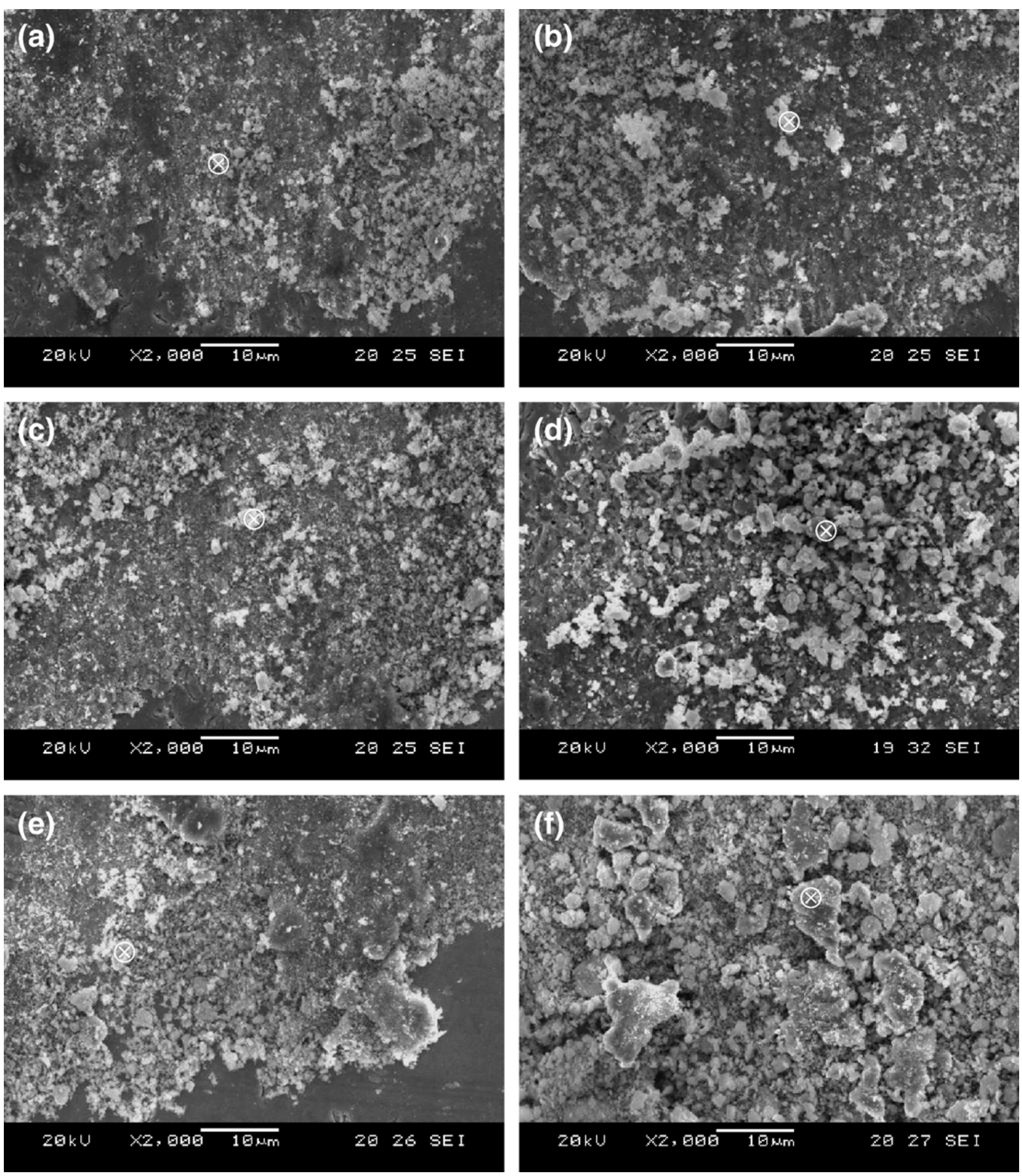

Fig. 9. Scanning electron micrograph of the wear debris and oxidation products present at the edge of fretted zone of tin-plated brass contacts after 3600 fretting cycles obtained at various normal loads and fretting frequencies (a) 3 Hz, 0.25 N (b) 3 Hz, 0.50 N (c) 3 Hz, 1.0 N (d) 3 Hz, 1.5 N (e) 1 Hz, 1.0 N and (f) 8 Hz, 1.0 N.

support the observed morphology of the fretted zone and the extent of wear of the tin coatings.

To analyze the correlation between the fretted area, contact resistance and the effect of load and frequency, the variation in length and width of the contact zone is measured using LSM. The fretted area is calculated and plotted as a function of normal load and frequency (Fig. 7). It is evident from Fig. 7 that the fretted area increased with the increase in load and frequency. However, when the load is increased beyond 1.0 N, the length of the fretting path may reach a maximum and attain saturation

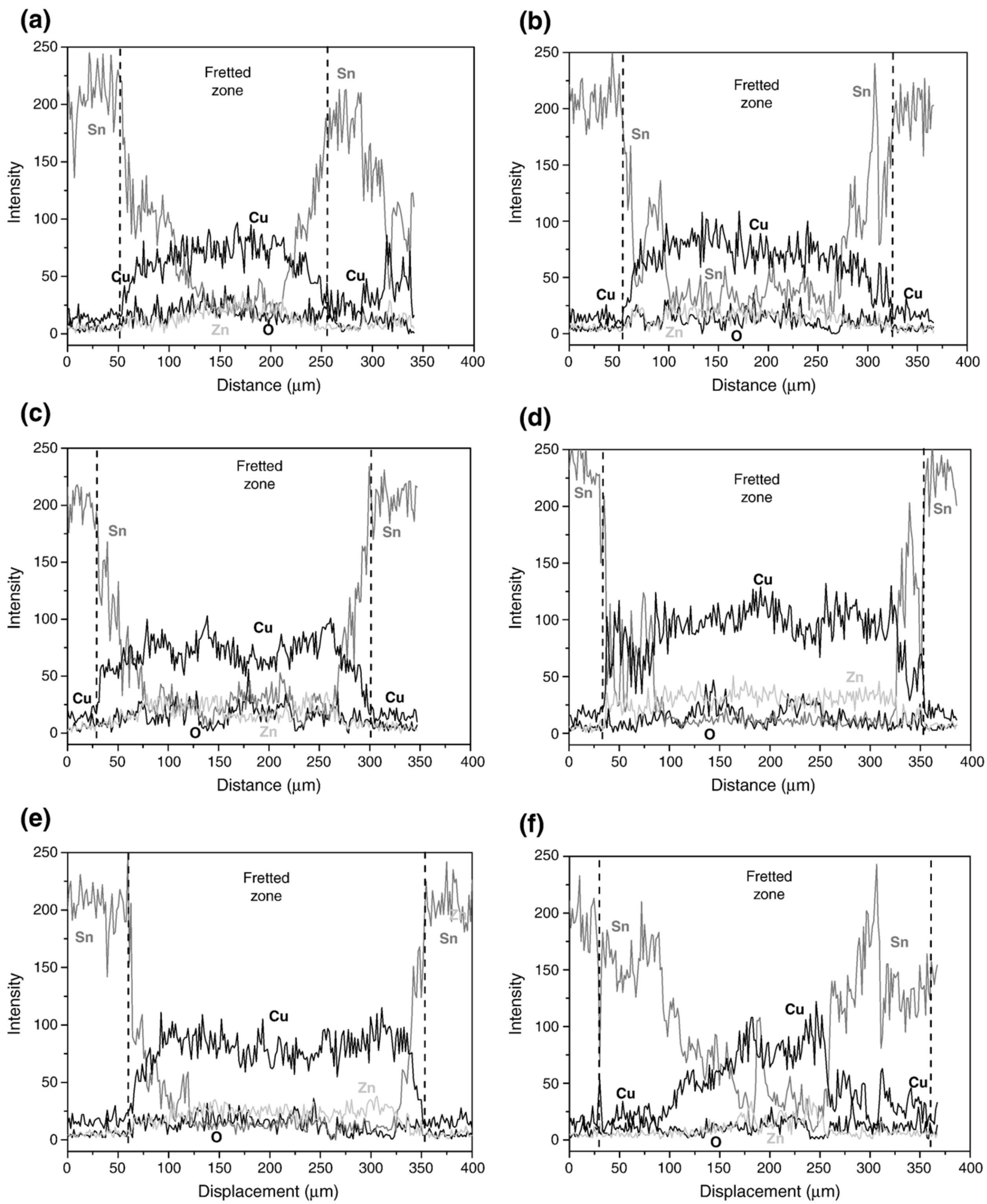

Fig. 10. EDX line scan performed across the fretted zone (indicated between dotted line) of the tin-plated brass contacts after 3600 fretting cycles obtained at various normal loads and fretting frequencies (a) 3 Hz, 0.25 N (b) 3 Hz, 0.50 N (c) 3 Hz, 1.0 N (d) 3 Hz, 1.5 N (e) 1 Hz, 1.0 N and (f) 8 Hz, 1.0 N.

in fretted area where the abrasive wear which increases the contact resistance is predominant [26]. Therefore, at 1.5 N, the fretted area attains saturation and causes the contact resistance to increase to more rapidly than that of 1.0 N. This was clearly evident from Fig. 2c and d. As seen from Fig. 7b, the fretted area also increased with the increase in frequency, which in turn causes the steep rise in contact resistance and earlier failure of the tin coated contacts observed at 8 Hz (Fig. 3c).

As the extent of damage of the contact zone and the oxidation of wear debris depend on the wear rate of the tin coating, it can also be related with normal load and frequency (Fig. 7). The rapid decrease in wear rate of tin coating with increasing normal load (Fig. 7a) accounts for the severe damage observed in the surface morphology of the fretted tin contact at a low normal load (Fig. 6a). As is seen at 0.25 N, the high wear rate produces a greater extent of oxide particle by abrasive wear and makes high accumulation of wear debris in the fretted zone whereas at high normal load, the fretted zone is compressed resulting in a hardened oxide layer. The hardened surface layer is then easily delaminated which makes relatively less accumulation of debris and wear rate. The surface morphology of tin contact (Fig. 6d) fretted at 1.5 N confirms this trend. In a similar manner, the large increase in fretted area and wear rate at a high frequency (Fig. 7b) accounts for the observed increase in extent of oxidation of the contact zone and severe damage of the coating (Fig. 6f).

SEM examination of several regions of the fretted zone (Fig. 8) reveals the presence of cracks and loose sheet/flake-like debris on the surface of the coated layer (indicated by arrows), which suggest the occurrence of the delamination wear [27–30]. Braunvoic [27] has suggested that flake-like debris is generally associated with the delamination wear. Suh [30] has explained that delamination wear occurs in repeat-pass sliding when cracks become nucleated below the fretted surface and it finally results in loosening of thin sheets of metal which became the wear debris.

A comparison of the morphological features at the center of the fretted zone reveals the formation of more amount of oxide debris at 0.25 N than at 1.5 N (Fig. 8a–d). One would expect higher quantities of oxide debris at low normal load as the wear rate of tin coating is very high at these loads compared to that of 1.5 N. For a given load of 1.0 N, increasing the frequency

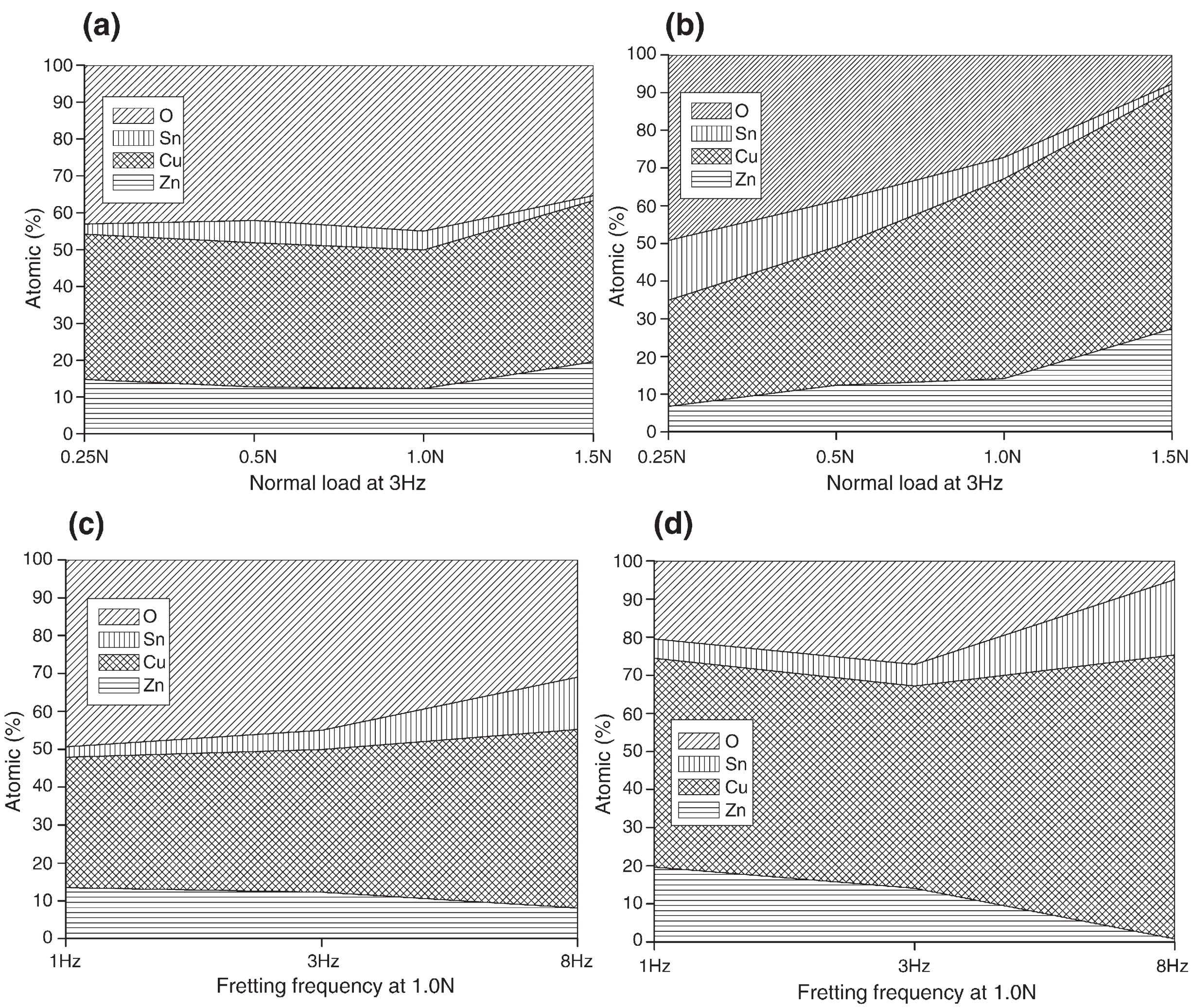

Fig. 11. Pictorial model depicting the variation in atomic concentration of zinc, copper, tin and oxygen of the oxide debris at the fretted zone with normal load variation at (a) center of fretted zone and (b) edge and with frequency variation at (c) center (d) edge.

increases the oxide wear debris and reveals the crack surface formed by the delamination wear (Fig. 8e, c and f).

The wear debris observed at the edges of the fretted zone (Fig. 9) is expected to be predominantly tin oxide. The effect of applied load and frequency on the ejected particle size is significant. A comparison of the size of the tin oxide particles which are ejected out of the fretted zone reveals that there is an increase in size of the particles when the normal load is increased from 0.25 to 1.5 N (Fig. 9a–d). At 1.5 N, the size of the particles is in the range of 0.5–2.5 μm whereas their size is reduced to 0.05–1 μm at 0.25 N. For a given normal load of 1.0 N, with an increasing frequency, the size of the tin oxide particles is found to be increased (Fig. 9e, c and f). At 1 Hz, the size of the particles is in the range of 0.05–1.5 μm whereas it increased to 2.5–10 μm at 8 Hz. At higher load and frequency, the accumulated particles are pushed away from the fretted zone whereas at lower load and frequency, the particles get entrapped and the subsequent abrasive process breaks the oxide particles and reduces their sizes. This explains the observed differences in the size of the ejected particles.

The EDX line scanning performed across the fretted zone under various experimental conditions are used to characterize the extent of fretting damage at the contact zone. The spectrum shows the level of tin, copper, oxygen and zinc (Fig. 10a–f). Within the fretted zone, the intensity of tin is found to be decreased and that of copper and oxygen is increased, suggesting the removal of the tin coating, exposure of the substrate metal and oxidation of tin and copper. The observed tin profile confirms that the size of fretted zone in 1.0 N is larger than that of 0.25 N (Fig. 6). For the given frequency, the tin and copper lines had closely overlapped at 0.25 N whereas there was a distinct separation between these lines at 1.0 N (Fig. 10a–d). The separation of copper and tin lines suggests that the tin coating is mostly worn out. The observed overlapping of the tin and copper lines at 0.25 N load could be due to the accumulated tin/tin oxide wear debris and the higher intensity of oxygen suggests higher levels of oxidation. For the given load of 1.0 N, increasing the frequency reduced the separation between the copper and tin lines and increased the intensity of oxygen (Fig. 10e, c and f). These account for the earlier failure of the contacts and the observed accumulation of wear debris and higher rate of oxidation at 8 Hz.

The atomic percent (at.%) of tin, copper, zinc and oxygen present at the center and edge of the fretted zone (indicated by '⊗'in Figs. 8 and 9) is also analyzed using EDX and plotted as a function normal load and frequency (Fig. 11). For a given frequency (Fig. 11a, b) when the normal load is increased from 0.25 to 1.5 N, there is only a slight variation in the atomic concentration of any element at the center whereas at the edges, the decrease in the concentration of oxygen and tin is significant. It suggests a high accumulation of oxide debris at low normal load. For the given normal load (Fig. 11c and d) when the frequency is increased from 1 to 8 Hz, in the center and edges, there is a marginal increase in the concentration of tin and a significant decrease in the oxygen content. These observations suggest a high accumulation of oxide debris at 0.25 N and at 1 Hz. The observed increase in failure time with 1 N and earlier failure at 8 Hz could thus be accounted with EDX analysis of the fretted zone.

4. Conclusions

The fretting corrosion behavior of tin coated brass contacts is studied at various normal loads (0.25, 0.5, 1.0 and 1.5 N) and frequencies (1, 3 and 8 Hz) at an amplitude of ±25 μm. Under the investigated experimental conditions, the results show that fretting causes significant deterioration of tin coated contacts as manifested by sharp rises and fluctuations in their contact resistance after 4000 cycles. Irrespective of the frequency and normal load, the failure time reached early at 0.25 N and 8 Hz respectively. The observed high wear rate and overlapping of the tin and copper lines in the EDX line scan further confirmed that the accumulation of wear debris at the contact zone is high at 0.25 N and 8 Hz. The repetitive exposure of fresh metal and its subsequent oxidation and formation of wear debris at the fretted surfaces decreased the availability of fresh metallic sites and failed early resulting in the rapid increase in contact resistance. Application of higher normal loads and lower frequencies apparently diminished somewhat the deleterious effect of fretting. The results of the study suggested an optimum load of 1 N at 100 mA current load for the tin-plated contacts. The wear rate of tin coating, availability of fresh tin metal, 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 variation in these factors determines the change in contact resistance.

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References

[1] R.S. Mroczkowski (Ed.), Electronic Connector Handbook, McGraw Hill, New York, 1998.
[2] M. Antler, Wear 106 (1985) 5.
[3] M. Antler, IEEE Trans. Components Hybrids Manuf. Technol. 8 (1) (1985) 87.
[4] Y.W. Park, J.P. Jung, K.Y. Lee, Int. J. Automot. Technol. 7 (1) (2006) 75.
[5] U. Stocker, G. Bonisch, ATZ, Automobiltech. Z. 93 (1991) 7.
[6] L. Tristani, E.M. Zindine, L. Boyer, G. Klimek, Wear 249 (2001) 12.
[7] S.L. Heaton McCarthy, Proceedings of the 47th IEEE Holm Conference on Electrical Contacts, IEEE, 2001, p. 209.
[8] R.D. Malucci, Proceedings of the 42nd IEEE Holm Conference on Electrical Contacts, IEEE, 1996, p. 395.
[9] R.D. Malucci, IEEE Trans. Compon. Packag. Technol. 24 (3) (2001) 399.
[10] G.T. Flowers, X. Fei, M.J. Bozack, R.D. Malucci, IEEE Trans. Compon. Packag. Technol. 27 (1) (2004) 65.
[11] R.B. Waterhouse (Ed.), Fretting Corrosion, Pergamon press, Oxford, 1972.
[12] P. Debaets, K. Strijckmans, A.P. Van Peteghem, Wear 208 (1997) 169.
[13] A.K. Rudolphi, S. Jacobson, Wear 201 (1996) 244.
[14] H.M. Ghasemi, M.J. Furey, C. Kajdas, Wear 162–164 (1993) 357.

[15] A. Lee, in: P.G. Slade (Ed.), Electrical Contacts: Principles and Applications, Marcel Dekker Inc., New York, 1994, p. 300.
[16] J. Ambier, P. Perdigon, IEEE Trans. Components Hybrids Manuf. Technol. 8 (1) (1985) 197.
[17] J. Neijzen, J. Glashorster, Micro. Electron. Reliab. 28 (4) (1988) 654.
[18] A.K. Rudolphi, S. Jacobsen, Surf. Coat. Technol. 96 (1997) 364.
[19] Y.W. Park, T.S.N. Sankara Narayanan, K.Y. Lee, Surf. Coat. Technol. 201 (2006) 2181.
[20] Y.W. Park, T.S.N. Sankara Narayanan, K.Y. Lee, Wear 262 (3–4) (2007) 320.
[21] Y.W. Park, T.S.N. Sankara Narayanan, K.Y. Lee, Tribol. Int. 40 (2007) 548.
[22] T.S.N. Sankara Narayanan, Y.W. Park, K.Y. Lee, Wear 262 (1–2) (2007) 228.
[23] S. Hannel, S. Fouvry, Ph. Kapsa, L. Vincent, Wear 249 (2001) 761.
[24] L. Wang, Y. Gao, T. Xu, Q. Xue, Mater. Chem. Phys. 99 (2006) 96.
[25] Y.W. Park, T.S.N. Sankara Narayanan, K.Y. Lee, Surf. Rev. Lett. 13 (5) (2006) 635.
[26] S.R. Murrel, SL. Mc Carthy, Proc. of the 43rd IEEE Holm conference on Electrical contacts, Philadelphia, 1997, p. 1.
[27] M. Braunvoic, IEEE Trans. Compon. Packag. Technol. 24 (2001) 384.
[28] C.B. Shao, J.G. Zhang, In proceeding of the 44th IEEE Holm conference on electro contacts, IEEE, 1998, p. 26.
[29] J.G. Zhang, L. Tang, C.B. Shao, In proceeding of the 40th IEEE Holm conference on electro contacts, IEEE, 1994, p. 70.
[30] N.P. Suh, Wear 25 (1973) 111.