Surface Review and Letters, Vol. 15, No. 4 (2008) 1–10

EVALUATION OF THE PERFORMANCE OF ELECTROLESS Ni–B COATED BRASS CONTACTS UNDER FRETTING CONDITIONS

T. S. N. SANKARA NARAYANAN[a], YOUNG WOO PARK and KANG YONG LEE*

Stress Analysis and Failure Design Laboratory,
School of Mechanical Engineering, Yonsei University,
134, Sinchon-dong, Seodaemum-gu, Seoul 120-749, Korea
**KYL2813@yonsei.ac.kr*

Received 29 November 2007

The performance of electroless (EL) Ni–B coated brass contacts under fretting conditions was evaluated. The contact resistance of EL Ni–B coated brass contact was measured as a function of fretting cycles. The surface profile and wear depth of the fretted zone were measured using laser scanning microscope. The study reveals that EL Ni–B coated contacts exhibit better performance under fretting conditions. However, at conditions which are prone for severe oxidation such as, low frequency (3 Hz) or high temperature (155°C), EL Ni–B coated contacts fail to exhibit a better stability. The quick removal of the oxide film by fretting motion, rapid oxidation of the fresh metallic particles and trapping of the oxidation products in the remaining coating, cause the contact resistance to increase to unacceptable levels at such conditions. The study concludes that EL Ni–B coating is not a suitable choice for connector contacts that could experience fretting under highly oxidizing conditions.

Keywords:

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.[1,2] Gold and other precious metal plated contacts are the preferred choices where high reliability is warranted. Tin plated contacts have gained acceptance as a low-cost alternative to gold. However, the susceptibility of tin plated contacts for fretting corrosion is a major limitation for its use in connectors.[3–5] The other low-cost alternative is plating the contacts with nickel. Nickel is primarily used as an undercoating for thin noble metal coatings in connector contacts and its main function is to prevent the diffusion of base metal. The nickel underlayer also helps to slow down the creep corrosion from bare edges and it passivates the pores in the overlying layers thus minimizing pore corrosion.[1,2] Nickel coating possesses high hardness, good wear resistance, superior creep resistance, and high thermal and oxidation resistance. However, the major limitation with the use of nickel coating for connector contacts is its tendency to form a hard and insulating

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

oxide film.[6] Since the prime requirement of a coating for use in connector contacts is to maintain a low contact resistance, nickel is not considered as a suitable choice in many instances. However, nickel plating has long been used as a popular and cost-effective choice for battery contact material in applications such as flashlights, toys, etc., where the current load is sufficient enough to break the oxide film on the nickel coating.

Numerous attempts were made on the possible use of nickel and, electrodeposited (ED) Ni–P alloy and composite coatings, for electrical contact applications, which include, building self-assembled monolayers (SAM) of thiols on nickel to prevent oxidation of nickel as well as to achieve a good current flow, formation of Ni–oil containing micro-capsule and Ni-PTFE composite coatings, etc.[7–10] However, the problems associated with each of these coatings make them unacceptable for electrical connectors. Chudnovsky[11] has reported that electroless (EL) Ni–P coating is an effective alternative to silver and tin plating for protecting circuit breaking equipment from corrosion up to one year without significant discoloration. Dervos *et al.*[12] have recommended that EL Ni–P coating could be used as a low-cost stationary contact material and it can perform well even under adverse working conditions.

EL Ni–B coating possesses high hardness, superior wear resistance, moderate corrosion resistance, good solderability, and low thermal expansion coefficient.[13–15] It is more wear resistant than tool steel and hard chromium coatings. The columnar structure of the EL Ni–B coating makes it naturally lubrious and it offers improved performance under conditions of adhesive wear. EL Ni–B coating is considered as a useful alternative for gold and silver in microelectronic devices.[13,16] EL Ni–B coating possess good solderability compared to EL Ni–P coating because its oxide layer is thin and can easily be penetrated by the solder.[17] EL Ni–B coating has received considerable importance in the copper interconnect technology as a capping layer due to its ability to prevent the diffusion of copper.[18,19] Dervos *et al.*[20] have evaluated the suitability of EL Ni–B coating for electrical contact applications under low amplitude displacement with simultaneous application of electrical and mechanical loads. Based on the ability of EL Ni–B coating to exhibit a low contact resistance under such conditions, they have recommended it as a possible solution for low-cost stationary contact material. The fretting corrosion behavior of EL Ni–B coatings under such conditions is not yet studied. In this context, the present paper aims to evaluate the performance of EL Ni–B coated brass contacts under fretting conditions so as to assess its suitability for electrical connector contact applications.

2. Experimental Details

The EL Ni–B coating was deposited on brass substrates (composition, in wt.%): Zn: 28.44; Fe: 0.19; Cr: 0.04; Ni: 0.03; Pb: 0.03; Mn: 0.02; Si: 0.01; Sn: <0.05; P: 0.001 and Cu–Bal.) using an alkaline bath having nickel chloride as the source of nickel, ethylenediamine and disodium tartarate as complexing agents, sodium borohydride as the reducing agent and thallium acetate as the stabilizer. The chemical composition of the plating bath and its operating conditions are given in Table 1.

The details of surface preparation, activation before plating, deposition methodology, chemical composition, plating rate, surface morphology, structural characteristics, etc. were given in our earlier paper.[21]

The performance of EL Ni–B coated brass contact under fretting conditions was evaluated 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, contact geometry, and the circuit used to measure the contact

Table 1. Chemical composition and operating conditions of the borohydride-reduced electroless nickel plating bath.

Bath composition	
Nickel chloride	30 g/l
Ethylenediamine (98%)	15 g/l
Disodium tartarate	40 g/l
Sodium hydroxide	40 g/l
Sodium borohydride	1.0 g/l
Thallium acetate	16 mg/l
Operating conditions	
pH	13
Temperature	$45 \pm 1^\circ C$
Agitation	Mechanical: 600 rpm (using a magnetic stirrer)

Table 2. Details of the experimental conditions used in the study.

Amplitude	$\pm 90\,\mu$m
Frequency	10 Hz and 3 Hz
Normal load	0.5 N
Current load	0.1 A
Temperature	$27 \pm 1^{\circ}$C and $155 \pm 1^{\circ}$C
Humidity	55–60% RH

resistance, were given in our earlier papers.[22–25] The contacts were flat verses 1.5 mm radius hemispherical rider, both of them were made of brass (supplied by the Korea Electric Terminal Company Ltd., Korea) and EL Ni–B coated to a thickness of $5 \pm 1\,\mu$m. The rider and flat specimens were degreased using acetone in an ultrasonic cleaner, dried and carefully mounted in the fretting test assembly. The contact area is defined to be a point contact by "sphere plane" geometry. The fretting tests were conducted on unlubricated EL Ni–B coated brass contacts under gross slip conditions. The experimental conditions used for the fretting tests are given in Table 2.

Displacement amplitude of $\pm 90\,\mu$m was chosen so as to have a higher degree of oxidation in the contact zone. Since an adequate contact force was necessary to break the oxide film present on tin or nickel plated, a normal load of 0.5 N was chosen.[1,2] It has been established that conditions such as low frequency or high temperature could promote the rate and extent of oxidation of the contact zone.[1,2,22–25] Hence, some fretting tests were performed on EL Ni–B coated brass contacts, by changing the frequency and temperature to 3 Hz and 155°C, respectively. During fretting tests, the contact resistance was continuously measured as a function of fretting cycles. After testing, the surface profile and surface roughness across the fretted zone were assessed using a Carl Zeiss laser scanning microscope (LSM) (Model: LSM-5 PASCAL). Some fretting corrosion experiments were conducted on tin plated copper alloy contacts under similar experimental conditions to compare the performance of EL Ni–B coated contacts with those of the tin plated contacts. The tin plated rider and flat contacts were electroplated with pure tin to a thickness of 3 μm (supplied by the Korea Electric Terminal Company Ltd., Korea).

3. Results and Discussion

3.1. *Characteristics of the EL Ni–B coatings*

The characteristics of the EL Ni–B coating used in this study were already reported in an earlier paper.[21] Only the relevant details are provided here for the sake of brevity. The EL Ni–B coatings are matte in appearance and dark gray/black in color with a chemical composition of 96.6 wt.% nickel, 3.2 wt.% boron, and 0.2 wt.% thallium. The surface morphology of EL Ni–B coating resembles a typical cauliflower type feature with a granular structure, which makes the EL Ni–B coating naturally lubricious and enables it to achieve a higher wear resistance.[14,15,21] XRD pattern of EL Ni–B coating confirms that the coating consists of a mixture of amorphous and crystalline phases in its as-plated condition, whereas heat-treatment at 450°C for 1 h results in the formation Ni and Ni_3B phases.[21]

3.2. *Contact resistance of the EL Ni–B coatings*

One of the important criteria of any coating or lubricant applied to electrical contacts is to ensure that they should not act as an insulator or interferes with the formation of electrically active spots (known as 'a'-spots).[1] In case of tin and nickel plated contacts, which are highly prone for oxidation, the contact force used should be sufficient enough to break the oxide film so as to establish a good electrical contact.[1,2,26] To ascertain these aspects, the contact resistance of the EL Ni–B coated brass contact is measured at a normal load of 0.5 N. The average contact resistance measured at this normal load is around 25 ± 2 mΩ. Gaevskaya *et al.*[27] have reported that the contact resistance of ED Ni–B coating (30 at.% B) at a normal load of 0.4 N is of the order of 22 mΩ, which is in agreement with the values obtained in the present study. However, the contact resistance of EL Ni–B coated contact is relatively higher than that of the tin coated contacts, which is of the order of 10 mΩ under similar conditions.[22–25] The difference in contact resistance between EL Ni–B and tin coated contacts could be explained based on the hardness, chemical nature, thickness and tenacity of the coating. The hardness of EL Ni–B coating is very high compared to the soft tin plating.[1,13,15,20]

The soft tin coating could easily extrude through the cracks of the hard tin oxide film under the influence of applied load, whereas such an occurrence is rather limited in the case of hard EL Ni–B coating.[1,26] It has been established that tin oxide is the major species of the surface film on tin plated contacts, whereas the surface film on EL Ni–B coating might consists of a mixture of oxides of nickel and boron.[1–5,22–25,28] Based on X-ray photoelectron spectroscopy (XPS) studies, Ivanov *et al.*[28] have confirmed that nickel and boron are present both in the elemental and oxidized states on the surface of freshly deposited EL Ni–B coating. Diplas *et al.*[29] have confirmed the presence of boron oxide on the outermost surface of ED Ni–B coating by using XPS and secondary ion mass spectroscopy (SIMS). It has been reported that the formation of boron oxide (B_2O_3) instead of NiO is thermodynamically favorable because the former has a free energy of formation (ρG) of -801 kJ/mol O_2 whereas the later has a ρG value of -426 kJ/mol O_2.[30,31]

Kulpa and Frankenthal[32] have reported that the rate of oxide film growth on nickel is self-limiting and the film thickness increases very slowly after it reaches a thickness of 2.4 nm at 40°C and 95% RH. At temperatures below 100°C, the thickness would be less than 3 nm.[34] Zhang *et al.*[32] have reported that the thickness of the oxide layer on EL Ni–P coated aluminum is about 10 Å. Though the thickness of the oxide film formed on EL Ni–B coating under such conditions is not available in the published literature, it is presumed that it will be of the order of 1–3 nm as reported earlier for Ni and EL Ni–P coating.[32,34] The nickel oxide is exceptionally tenacious and it could remain as a barrier to the flow of current even when they get squeezed between the contact surfaces with the applied normal load. Hence, the higher value of contact resistance exhibited by EL Ni–B coated contacts compared to tin plated contacts is due to the higher hardness, presence of a mixture of oxides of nickel and boron and the tenacity of the oxide layer in spite of the limited film thickness of the order of a few nanometers (1–3 nm). If the surface film on EL Ni–B coated contact is composed of a mixture of nickel oxide and boron oxide then the electrical contact has to be established only through a limited number of contact points such as sharp asperities. The morphology of the EL Ni–B coating resembles a typical cauliflower type feature and a granular type structure.[21] This type of structural feature tends to reduce the contact surface area and decrease the number of contact points necessary to establish a good electrical contact. However, the high stress induced by the contact force at some asperity contacts could have created small breaks in the surface layer of the EL Ni–B coated contacts to establish an electrical contact through a limited number of contact points and this results in a contact resistance of 25 ± 2 mΩ.

Figure 1 shows the change in contact resistance of as-plated EL Ni–B coated brass contacts as a function of fretting cycles. Based on the nature of changes in contact resistance, the curve is divided into three segments — the region up to 5000 cycles as segment I, the region between 5000 and 15,000 cycles as segment II, and the region beyond 15,000 cycles as segment III.

During the initial fretting cycles (up to 250 cycles), the contact resistance of the EL Ni–B coated contacts remains constant around 25 mΩ, whereas a sharp increase in the contact resistance (up to 72 mΩ) is observed between 250 and 375 cycles (Inset of Fig. 1). The observed trend can be explained based on the chemical nature of the EL Ni–B coating on the surface as well as the layers underneath it. Based on the layer-by-layer composition analysis performed using XPS after etching of the EL Ni–B coating, Ivanov *et al.*[28] have confirmed a gradual decrease

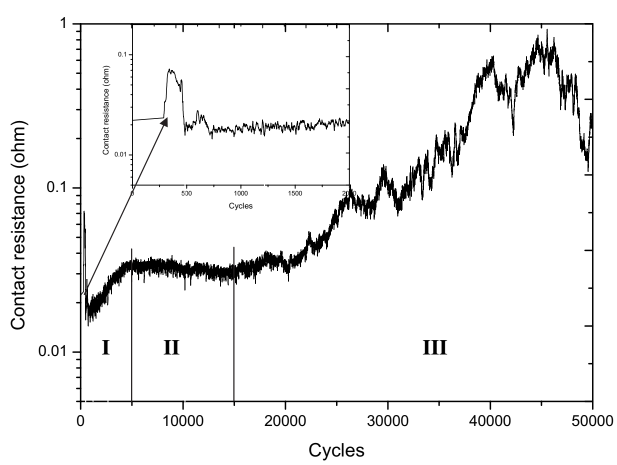
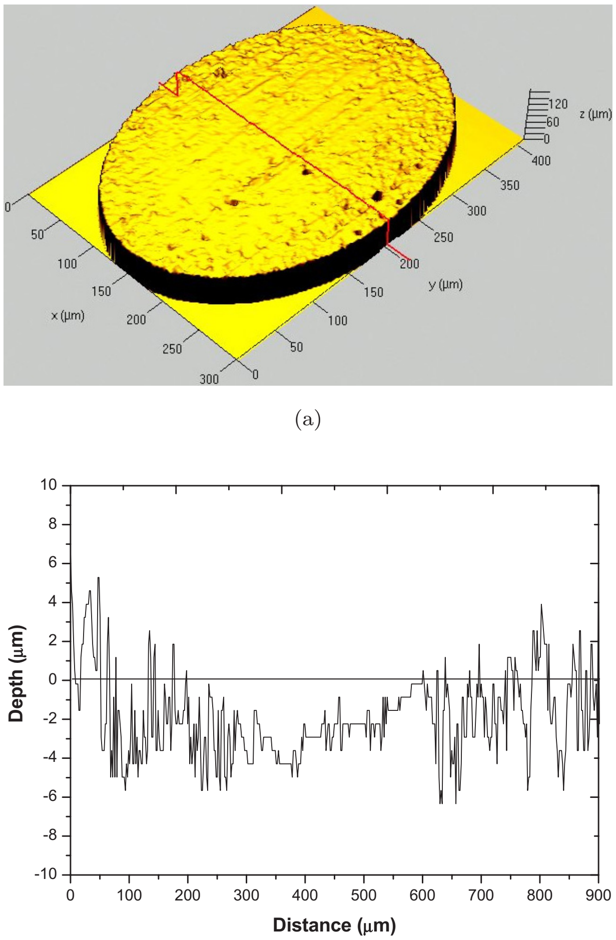


Fig. 1. Change in contact resistance of EL Ni–B coated brass contacts as a function of fretting cycles. (Amplitude: $\pm 90\,\mu$m; frequency: 10 Hz; normal load: 0.5 N; current load: 0.1 A; temperature: 27 ± 1°C; and humidity: 55–60% RH.)

in oxygen concentration from 34 at.% to 10 at.% and an increase in the nickel and boron content to 55 and 19 at.%, respectively. Based on SIMS analysis Diplas *et al.*[29] have suggested that the amount of boron oxide in the bulk of the coating is reduced compared to that present on the outermost surface of ED Ni–B coating. Thus, it appears that the surface layer of EL Ni–B coated rider and flat contacts could be composed of B_2O_3 and NiO, the former being the dominant species at the top surface, whereas in the layers underneath nickel oxide seems to be the dominant species. Hence, the stable contact resistance observed up to 250 cycles is believed to be due to the predominance of B_2O_3 on the top surface layer of the EL Ni–B coated contacts. The sharp increase in contact resistance between 250 and 375 cycles is due to the enrichment of nickel oxide following the removal of the top layers. A similar sharp increase in contact resistance is also observed in tin plated contacts due to the presence of tin oxide film on such contacts.[1,2,22–25] The decrease in contact resistance beyond 375 cycles suggests the removal of the oxide film on both the ride and flat contacts. The contact resistance reaches a stable value around 750 cycles and remains low and stable up to 2000 cycles (Inset of Fig. 1), which indicates the ability of the EL Ni–B coating to provide a good electrical contact. Beyond 2000 cycles, there is a slight increase in contact resistance from 18 and 32 mΩ up to 5000 cycles. This indicates that only a small fraction of the wear debris is oxidized, whereas a greater portion of it still remains as metallic particles. The contact resistance remains low and stable ($\sim$32 mΩ) in segment II from 5000 to 15,000 cycles. This is due to the sequence of processes, namely, wear of the coated layer, removal of wear debris and oxidation products away from the contact zone and, formation of large number of metallic contact points that occurs with the increase in fretting cycles. It has been reported earlier that the contact resistance will remain low and stable as long as the wear-through of the coated layer did not take place to a large extent.[1–5,10,22–25] Tin coated contacts also exhibit such a trend. However, the range is very limited, from 400 to 8000 cycles under similar experimental conditions.[22–25] Hence, the observed trend in contact resistance of EL Ni–B coated contacts from 5000 to 15000 cycles is due to the superior wear resistance of the EL Ni–B coating which decreases the rate of removal of the coated layer with increase in fretting cycles. In segment III, there is a gradual increase in contact resistance between 15,000 and 22,000 cycles whereas beyond 22,000 cycles the increase in contact resistance is very rapid, thus confirming the degradation of the EL Ni–B coated brass contacts. This is due to the thickening of the insulating layer containing wear debris and oxidation products and the decrease in metallic contact area. Tin coated contacts also exhibit a similar trend under similar experimental conditions. However, for tin coated contacts, the rapid increase in contact resistance is observed after 10,000 cycles itself.[22–25]

A threshold value of contact resistance has been used as the failure criterion to assess the performance of connector contacts and the time to failure (TTF) is represented by the number of fretting cycles needed for the contact resistance to reach this threshold value. Mroczkowski[1] has recommended that the choice of the failure criteria should be based on the application rather than the product specification. Though the failure criterion for electronic contacts is considered as $10\,R_c$ in many instances, where R_c is contact resistance of clean surface contact, the $10\,R_c$ rule does not apply for contacts having an oxide layer such as tin and nickel. In the present study, 100 mΩ is considered as the threshold value of contact resistance to assess the performance of the contacts. For EL Ni–B coated brass contacts the 100 mΩ threshold is reached around 29,300 cycles. Tin coated contacts, under similar experimental conditions, have reached this value in 13,400 cycles itself.[22–25] The better performance of the EL Ni–B coated contacts compared to the tin coated contacts under similar experimental conditions is due to the superior wear resistance of the EL Ni–B coating.

Surface profile and wear depth are very useful parameters to estimate the influence of wear resistance of the coating on the extent of damage of the fretted zone. The three-dimensional surface profile and the variation in the depth as a function of the distance across the fretted zone of EL Ni–B brass contacts measured after 20,000 fretting cycles using LSM are shown in Figs. 2(a) and 2(b), respectively. The surface profile of the contact zone reveals several peaks and valleys. The peaks in the surface profile could be attributed to the accumulation of wear



(a)

(b)

Fig. 2. (a) Three-dimensional surface profile of the contact zone of EL Ni–B coated brass contact obtained using LSM; and (b) the variation in the depth as a function of the distance across the contact zone, after 20,000 fretting cycles. (Amplitude: $\pm 90\,\mu$m; Frequency: 10 Hz; Normal load: 0.5 N; Current load: 0.1 A; Temperature: 27°C; Humidity: 55–60% RH.)

debris or transfer of the coated layer between the two contacting surfaces due to adhesive wear phenomenon. The valleys could be attributed to the formation of grooves and they indicate the wear depth. The surface profile of the contact zone suggests that a single mechanism could not explain the behavior of the EL Ni–B coated contacts under fretting conditions. A combination of mechanisms such as adhesion, seizure of the contacting surfaces, delamination, etc. is responsible for the observed behavior.

The roughness parameters calculated using the surface profile is given in Table 3 along with the

Table 3. Roughness parameters calculated using the surface profile of the fretted zone of EL Ni–B and tin coated contacts after 20,000 fretting cycles at $27 \pm 1^{\circ}$C and 10 Hz (Normal load: 0.5 N; Current load: 0.1 A; Track length: $\pm 90\,\mu$m).

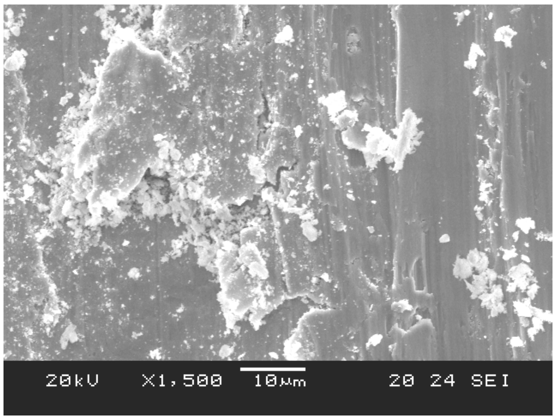
Roughness parameter	EL Ni–B coated contact	Tin plated contact
Arithmetic mean deviation, R_{a} (μm)	1.15	1.71
Highest peak, R_{p} (μm)	6.03	28.69
Lowest valley, R_{v} (μm)	7.05	23.68
Absolute peak to valley, R_{t} (μm)	13.07	52.37
Average peak to valley, R_{z} (μm)	4.59	24.56
Maximum peak to valley, $R_{\max}$ (μm)	9.66	52.37

values of tin coated contacts obtained under similar experimental conditions. It is evident that there is a significant decrease in the roughness parameters of EL Ni–B coated contact compared to tin coated contact. This observation confirms that the superior wear resistance of the EL Ni–B coating compared to the tin coating is responsible for its better performance under fretting conditions.

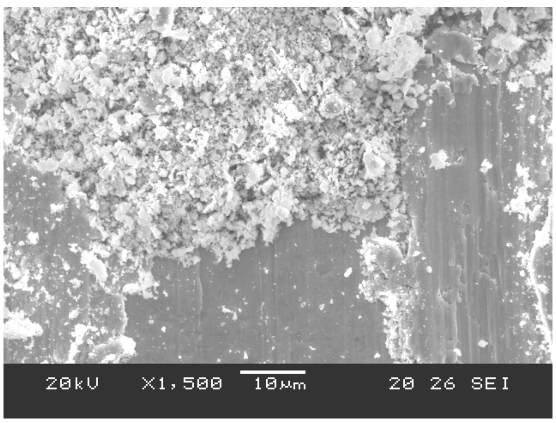
In order to get a better insight on the mechanism, the surface morphology and chemical nature of the fretted zone of EL Ni–B coated brass contact subjected to fretting for 10,000 cycles are assessed using scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX). The morphological features of the fretted zone at the center and edge regions are shown in Figs. 3(a) and 3(b), respectively.

It is evident from Fig. 3 that a combination of adhesion, seizure, and delamination mechanism is operative under the experimental conditions used in the study. EDX line scan performed across the fretted zone reveals a significant removal of the EL Ni–B coating and enrichment of copper and zinc from the base metal (Fig. 4).

The EDX spot analysis performed on the wear debris (indicated by '⊗' in Figs. 3(a) and 3(b)) suggest that they are rich in oxides of nickel in the edge region (O_2: 9.68 at.%; Ni: 52.61 at.%; Cu: 25.78 at.%; Zn: 11.93 at.%), whereas they are mostly composed of oxides of copper and zinc in the center region (O_2: 14.95 at.%; Ni: 24.18 at.%; Cu: 41.51 at.%; Zn: 19.36 at.%). The surface profile, morphological features, and chemical nature of the fretted zone of the EL Ni–B coated brass contact supports the observations



(a)



(b)

Fig. 3. Morphological features of the fretted zone of EL Ni–B coated brass contact subjected to fretting for 10,000 cycles: (a) Center region and (b) edge region.

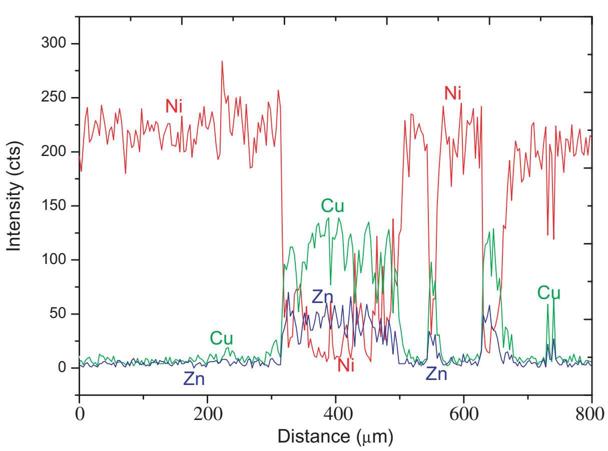


Fig. 4. EDX line scan performed across the fretted zone of EL Ni–B coated brass contact subjected to fretting for 10,000 cycles.

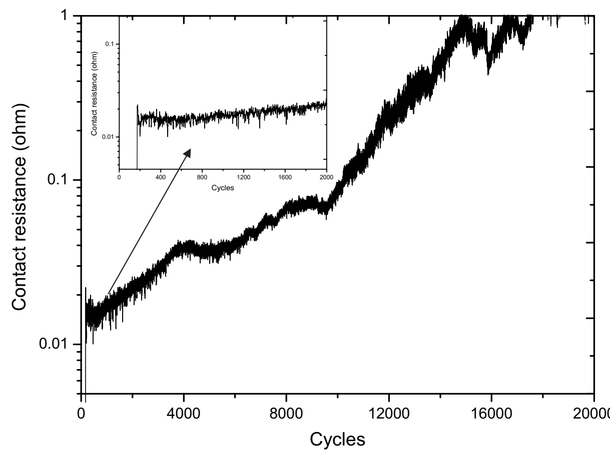


Fig. 5. Change in contact resistance of EL Ni–B coated brass contacts as a function of fretting cycles at low frequency. (Amplitude: $\pm 90\,\mu$m; frequency: 3 Hz; normal load: 0.5 N; current load: 0.1 A; temperature: $27 \pm 1^{\circ}$C; and humidity: 55–60% RH).

of the variation in the contact resistance as a function of fretting cycles.

Since the EL Ni–B coated contacts could offer better stability during fretting, it will be of interest to know whether they could perform well even under highly oxidizing conditions such as low frequency or high temperature. The change in contact resistance of EL Ni–B coated contacts as a function of fretting cycles at 3 Hz is shown in Fig. 5. It is evident that the general trend in contact resistance with increase in fretting cycles and the nature of changes during the initial cycles (Inset of Fig. 5) are quite similar to that observed at 10 Hz. However, the rate of increase in contact resistance appears to be very high at 3 Hz as the 100 mΩ threshold is reached around 10,200 cycles compared to 29,300 cycles at 10 Hz. At 3 Hz, the rate of wear of the EL Ni–B coating will be less, whereas the contact zone will have more time for oxidation compared to that at 10 Hz. Hence, for a better comparison, the time to reach 100 mΩ is calculated at these two frequencies. The 100 mΩ threshold is reached in 3433 s at 3 Hz compared to 2930 s at 10 Hz. For tin coated contacts the 100 mΩ threshold is reached in 2100 s at 3 Hz and in 1340 s at 10 Hz.[22]

Being a hard and wear resistant coating, the EL Ni–B coating should have offered a much better performance at 3 Hz compared to that at 10 Hz. The observed trend at 3 Hz is due to the increase in the

Table 4. Roughness parameters calculated using the surface profile of the fretted zone of EL Ni–B coated contacts after 20,000 fretting cycles. (Normal load: 0.5 N; Current load: 0.1 A; Track length: $\pm 90\,\mu$m).

Roughness parameter	27°C/ 10 Hz	27°C/ 3 Hz	155°C/ 10 Hz
Arithmetic mean deviation, R_a (μm)	1.15	0.93	1.81
Highest peak, R_p (μm)	6.03	7.59	22.42
Lowest valley, R_v (μm)	7.05	3.88	18.60
Absolute peak to valley, R_t (μm)	13.07	11.48	43.12
Average peak to valley, R_z (μm)	4.59	3.70	10.84
Maximum peak to valley, R_{max} (μm)	9.66	9.65	39.18

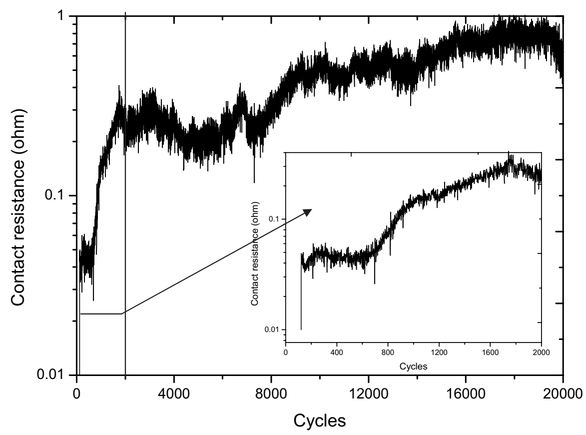


Fig. 6. Change in contact resistance of EL Ni–B coated brass contacts as a function of fretting cycles at high temperature. (Amplitude: $\pm 90\,\mu$m; frequency: 10 Hz; normal load: 0.5 N; current load: 0.1 A; temperature: 155 ± 1°C; and humidity: 55–60% RH.)

extent of oxidation of the contact zone in spite of the lower wear rate of the EL Ni–B coating at this frequency, which results in the continuous increase in contact resistance with increase in fretting cycles. The roughness parameters of EL Ni–B coated contact subjected to fretting at 3 and 10 Hz are given in Table 4.

There is a decrease in the roughness parameters of EL Ni–B coated contact subjected to fretting at 3 Hz compared to that obtained at 10 Hz. In spite of the slow wear rate supported by relatively lower values of roughness parameters, EL Ni–B coated contacts fails to exhibit a better performance due to the increased level of oxidation of the contact zone.

The change in contact resistance of EL Ni–B coated contacts at 155°C as a function of fretting cycles is shown in Fig. 6.

It is evident that the general trend in contact resistance with increase in fretting cycles and the nature of changes during the initial cycles (Inset of Fig. 6) are quite similar to that observed at 27°C. There is no appreciable increase in the contact resistance before 700 cycles. This is due to self-limiting thickness of the oxide film formed on EL Ni–B coated brass contacts. However, the increase in contact resistance is very rapid from 700 to 1600 cycles that the 100 mΩ threshold is reached within 850 cycles itself compared to 29,300 cycles at 27°C. This is due to the rapid oxidation of the fresh metallic particles generated due to fretting wear at 155°C. From 1600 to 7200 cycles the contact resistance exhibits a stable value; but it is very high of the order of 300 mΩ. This is due to the trapping of the oxidation products in the remaining coating. Beyond 7200 cycles the contact resistance increases further and reaches 600 mΩ in 10,000 cycles. This is due to the accumulation of the wear debris and oxidation products at the contact zone, which reduces the electrical conduction paths across the interface. The roughness parameters calculated using the surface profile of EL Ni–B coated contact subjected to fretting at 155°C is given in Table 4 along with the values obtained at 27°C. The EL Ni–B coated contact subjected to fretting at 155°C exhibit an increase in the roughness parameters when compared to that obtained at 27°C. The EL Ni–B coated contacts fails to exhibit a better performance when subjected to fretting at 155°C due to the increased level of oxidation of the contact zone at higher temperature.

The change in contact resistance measured as a function of fretting cycles at different experimental conditions reveals that the EL Ni–B coated brass contacts could exhibit a better stability during fretting due to its better wear resistance. However, the EL Ni–B coated contacts fail to exhibit a better performance at conditions such as low frequency and high temperature, in spite of its better wear resistance. Though the initial oxide film formed on EL Ni–B coated contacts is self-limiting, their quick removal by fretting motion, rapid oxidation of the fresh metallic particles, and trapping of the oxidation products in the remaining coating causes the contact resistance to increase to unacceptable levels.

4. Conclusions

The performance of EL Ni–B coated brass contact under fretting conditions is evaluated. The contact resistance of EL Ni–B coated brass contacts, when the rider and flat contacts are mated together at a normal load of 0.5 N, is $25 \pm 2\,\mathrm{m\Omega}$. The higher value of contact resistance indicates that the oxide film present on the surface of EL Ni–B coated rider and flat contacts is not completely broken when they are mated together at a normal load of 0.5 N and the electrical contact is established only through a limited number of contact points. During fretting, the oxide film is broken quickly and allows exposure of fresh metallic coating/particles for oxidation. The change in contact resistance as a function of fretting cycles reveals the ability of EL Ni–B coated brass contacts to offer a better stability under fretting conditions. The surface profile, wear depth, morphological features, and chemical nature of the fretted zone suggest that a combination of adhesion, seizure, and delamination mechanism is operative under the experimental conditions used in the study. The EDX analysis confirms that the wear debris is rich in oxides of nickel in the edge region, whereas they are mostly composed of oxides of copper and zinc in the center region. The better performance of EL Ni–B coated contacts compared to tin coated contacts under fretting conditions is due to the superior wear resistance of the EL Ni–B coating, which is further confirmed by the roughness parameters. However, the EL Ni–B coated contacts fail to exhibit a better performance at highly oxidizing conditions such as low frequency and high temperature. Though the initial oxide film formed on EL Ni–B coated contacts is self-limiting, their quick removal by fretting motion, rapid oxidation of the fresh metallic particles and trapping of the oxidation products in the remaining coating causes the contact resistance to increase to unacceptable levels at highly oxidizing conditions. The study concludes that EL Ni–B coating is not a suitable choice for connector contacts that could experience fretting under highly oxidizing conditions.

5. Acknowledgments

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. R. S. Mroczkowski, *Electronic Connector Handbook* (McGraw-Hill, New York, 1998).
2. M. Antler, in *Electrical Contacts: Principles and Applications*, ed. P. G. Slade (Marcel Dekker, Inc. New York, 1999), Chap. 7, p. 403.
3. R. D. Malucci, *IEEE Trans. Comp. Packag. Technol.* **24** (2001) 399.
4. G. T. Flowers, X. Fei, M. J. Bozack and R. D. Malucci, *IEEE Trans. Comp. Packag. Technol.* **27** (2004) 65.
5. A. Lee, in *Electrical Contacts: Principles and Applications*, ed. P. G. Slade (Marcel Dekker, Inc. New York, 1999), Chap. 5, p. 279.
6. W. H. Abbott, *Mater. Perform.* **30**(6) (1991) 55.
7. S. Noel, F. Houze, L. Boyer, Z. Mekhalif, J. Delhalle and R. Caudano, *IEEE Trans. Comp. Packag. Manufact. Technol.* **22**(1) (1999) 79.
8. H. van Oosterhout, *AMP J. Technol.* **2** (1992) 63.
9. C. T. Dervos, C. Kollia, S. Psarrou and P. Vassiliou, *IEEE Trans. Comp. Packag. Technol.* **22**(3) (1999) 460.
10. A. de Vooys and J.-P. Celis, Technical Article on Corus Steel Strip — HYBREL$^{\mathrm{TM}}$ F, http://www.hybrel.info/eng/html/service_contact/downloads/articles.htm
11. B. H. Chudnovsky, in *Proc. 49th IEEE Holm Conf. on Electrical Contacts* (IEEE, 2003), p. 98.
12. C. T. Dervos, P. Vassiliou, J. Novacovich and C. Kollia, *IEEE Trans. Comp. Packag. Technol.* **27**(1) (2004) 131.
13. W. Riedel, *Electroless Plating* (ASM International, Ohio, 1991).
14. T. S. N. Sankara Narayanan and S. K. Seshadri, *J. Alloys Comp.* **365**(1–2) (2004) 197.
15. K. Krishnaveni, T. S. N. Sankara Narayanan and S. K. Seshadri, *Surf. Coat. Technol.* **190**(1) (2005) 115.
16. Yu. V. Prusov and V. F. Makarov, *Russ. J. Appl. Chem.* **78**(2) (2005) 193.
17. Y. M. Chow, W. M. Lau and Z. S. Karim, *Surf. Interface Anal.* **31** (2001) 321.
18. S.-M. Ho, S.-M. Lian, K.-M. Chen, J.-P. Pan, T.-H. Wang and A. Hung, *IEEE Trans. Comp. Packag. Manufact. Technol.* **19**(2) (1996) 202.
19. T. Osaka, N. Takano, T. Kurokawa, T. Kaneko and K. Ueno, *Surf. Coat. Technol.* **169–170** (2003) 124.

20. C. T. Dervos, J. Novakovic and P. Vassiliou, *Proc. 50th IEEE Holm Conf. on Electrical Contacts and the 22nd Int. Conf. on Electrical Contacts* (IEEE, 2004), p. 281.
21. I. Baskaran, R. Sakthi Kumar, T. S. N. Sankara Narayanan and A. Stephen, *Surf. Coat. Technol.* **200**(24) (2006) 6888.
22. Y. W. Park, T. S. N. Sankara Narayanan and K. Y. Lee, *Surf. Coat. Technol.* **201** (2006) 2181.
23. T. S. N. Sankara Narayanan, Y. W. Park and K. Y. Lee, *Wear* **262** (2007) 228.
24. Y. W. Park, T. S. N. Sankara Narayanan and K. Y. Lee, *Tribol. Int.* **40**(3) (2007) 548.
25. Y. W. Park, T. S. N. Sankara Narayanan and K. Y. Lee, *Wear* **262** (2007) 320.
26. W. Liu and M. Pecht, *IC component and Sockets* (Wiley-Interscience, John Wiley & Sons Publication, NJ, 2004), Chap. 3, p. 64.
27. T. V. Gaevskaya, I. G. Novotortseva and L. S. Tsybulskaya, *Met. Finish.* 94(6) (1996) 100.
28. M. V. Ivanov, E. N. Lubnin and A. B. Drovosekov, *Prot. Met.* **39**(2) (2003) 133.
29. S. Diplas, J. Lehrmann, S. Jørgensen, T. Våland, J. F. Watts and J. Taftø, *Surf. Interface Anal.* **37** (2005) 459.
30. C. J. Smithells, *Metals Reference Book*, 5th edn. (Butterworths, London, 1976).
31. R. C. Weast, *Handbook of Chemistry and Physics* (CSC Press, Boca Raton, FL, 1982).
32. S. H. Kulpa and R. P. Frankenthal, *J. Electrochem. Soc.* **121** (1974) 118.