Investigation on contact surface damage of automotive connector by fretting corrosion

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Abstract

The main cause of electrical contact resistance degradation by corrosion is the vibration of contact interfaces. The purpose of this paper is to analyse the change of contact resistance under vibration test for uncoated sphere/plane contact made of new high copper alloys. The influence of electrical and mechanical properties of materials and mainly the hardness on contact resistance was studied in this work. During the fretting test, contact point was submitted to 16000 vibration cycles under fretting amplitude of 50 µm and 1 Hz frequency. The sphere part was fixed, while the plane part was submitted to a relative motion. At the end of the test, the fretted surfaces and the wear debris were analysed by scanning electron microscope and energy dispersive X-ray spectroscopy to evaluate damage, oxidation and elemental composition present in the wear surfaces. In addition, the measurement of the wear track profile using a 3D surface scanning system was introduced. Increases contact resistance and contact temperature has been examined during the fretting test. The results showed that the contact resistance for the harder alloy was higher than those obtained for the other materials. In addition, topographic measurement showed that the small wear track corresponds to the harder material. Finally, depending on the hardness and the resistivity, these uncoated materials influence fretting apparition and its level.

Keywords: contact resistance, EDX and SEM analysis, fretting corrosion, high copper alloys, wear surface, 3D scanning profiler, crack, delamination.

1 Introduction

Electrical connectors used in telecommunication, automotive and many other applications are exposed to degradation due to the vibration of mated contact surfaces. External mechanical vibration is the main cause of the fretting motion

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between contacting surfaces which is manifested by the mechanical and electrical damage of contact interfaces (Fagerstrom and Nicotera [1]). The failure process begins by wear of contact surfaces then oxidation of these surfaces or of wear debris which can cause rapid and dramatic increases in electrical contact resistance, proceeding to virtual open circuits [2–4]. Low-level relative movement between mated contacts can also be induced by differential thermal expansion of materials (Bock and Whitley [5]).

Determination of contact resistance changes during fretting of coated contact materials has been the subject of many investigations [6–10]. Unfortunately, contact materials with different coating (silver, palladium, tin…) have many inconvenient. Silver is prone to tarnish in atmospheres containing certain sulphur or chlorine compounds, which limits its application in electronic connectors while palladium will catalyse the formation of insulating frictional polymers which originate in absorbed organic air pollutants on the fretting surface. Wear was responsible for the insulating materials at the interface which caused contact resistance to rise. When the contact finish is gold, a reduction in its wear is beneficial but gold is more expensive. The improvement due to the harder nickel under-plate has also been found. It has been shown that the thicker layer leads to decrease fretting contact resistance (Antler [6]). Commonly, the main degradation of electrical connectors due to oxidation is prevented by coating. Unfortunately, after a certain number of vibration cycle, the fretting wear removes this protective metal layer leading to exposure of the base metal substrate to fretting corrosion. Regarding the disappearance of protective coating, uncoated high copper alloys were studied in this work. The subject of this paper is to analyse the effect of these new materials in apparition and increases in fretting contact resistance. Fretting corrosion behaviour has been discussed and investigated in much paper using scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) [11–13]. In this study, oxidation of the contact surfaces and the wear debris was extended and confirmed with the EDX technique. Moreover, fretting damage on the contact zone by several wear mechanisms such as abrasion, delamination wear and accumulation of wear debris were observed with the SEM technique. Analysis of the contact surface profile with the help of a profiler has been the subject of numerous recent research studies [14, 15]. In this work, surface profile of the fretted zone was examined by a profiler and then the wear volume loss and the fretted contact area have been calculated.

2 Contact geometry

The samples with a U shape fig. 1 were made with a sheet of 20 mm width, using the processing technique of stamping and bending. The two parts of the sample (plane part or lower part and a sphere part or upper part) have the same thickness i.e. 0.8 mm. The radius of the sphere segment was 3 mm fig. 1. It has been demonstrated by [16, 17] that the contact resistance for sphere/plane contact was lower than the cylindrical/plane contact. Therefore, the tested U-shaped samples have a contact shape with spherical segment.

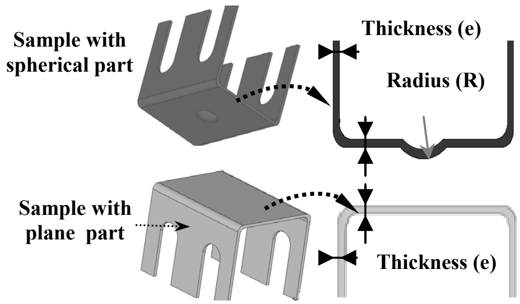


Figure 1: U-shaped samples.

3 Materials studies

The previous U-shaped samples were made by recent high copper alloys. Four types of contact materials have been selected for this study. These materials will be used in automotive power connectors and they combine excellent contact performance with good mechanical and electrical properties. Table 1 shows according to the descending order of electrical conductivity some of the electrical, thermal and mechanical properties of the selected alloys (Zauter and Kudashov[18]).

Table 1: Characteristics for different used copper alloys.

Copper alloy (UNS Designations)	C10100	C19210	C12200	C70250
Composition	Cu 99.99	CuFeP	Cu 99.9% + 0.008% P	CuNi3SiMg
Yield stress (MPa)	200	322	200	514
Vickers hardness (HV)	65-95	100-130	65-95	180-220
Young modulus (MPa)	$1.2\ 10^5$	$0.9\ 10^5$	$1.2\ 10^5$	$1.22\ 10^5$
Tensile strength (MPa)	240-300	360-440	240-300	620-760
Thermal conductivity (W/mK)	401	350	340	190
Electrical resistivity (Ω.mm)	$1.68\ 10^{-5}$	$1.88\ 10^{-5}$	$2.12\ 10^{-5}$	$4\ 10^{-5}$
Electrical conductivity (%IACS)	100	91	80	43

The primary selection criterion for these alloys was based on their variation on the electrical and mechanical properties. Table 1 shows that C70250 alloy is harder and less electrically conductive than the other copper alloys. So, the aim is to determine the relative susceptibility of these materials to fretting corrosion.

4 Test apparatus

Fig. 2 illustrates schematically a fretting test apparatus for measurement of electrical contact resistance during vibration.

The two parts of the contact specimen were fixed in the Teflon insulator supports. A DC power supply was used to apply a constant current which was equal to 2 A with an open circuit voltage of 2 V. This electrical current was transmitted from the flat sample to the spherical sample through the contact zone. When high currents are employed, there can be a profound effect on interfacial topography, film formation, contact resistance, resistance heating which accelerates oxidation, and micro-arcing.

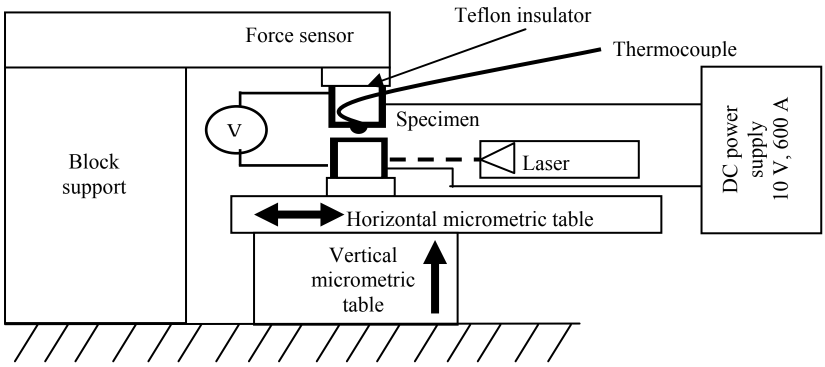


Figure 2: Schematic of the fretting apparatus and the circuit used to measure the contact.

A micro-voltmeter with 1 μV resolution was used to measure the voltage drop when passing a DC current through the contacts and then deduct the dynamic contact resistance. Contact resistance determinations were made using a DC four-wire dry circuit technique [19]. Constant contact force *Fc* was applied with the help of the vertical displacement of the micrometric table. This force was equal to 10 N and was controlled and maintained constant throughout the testing. The contact force was measured by a force sensor which was connected to a voltmeter through a conditioner. A horizontal micrometric table was used for producing fretting motion. These micrometric tables were driven by a DC stepping motor through a micrometer screw and were controlled by a motion controller. The upper sample or the spherical sample was fixed while the flat sample was submitted to a relative movement with a frequency of 1 Hz and fretting amplitude of 50 μm, this amplitude was measured by a laser with 0.1 μm resolution. The minimal distance between the tested flat sample and laser head was 3 cm. Bibliographical sources quote different values of displacement amplitudes as a border between fretting and reciprocating sliding motion. This value is variously interpreted and contained within a wide range of amplitudes between 50 and 300 μm (Ohmae and Tzukizoe [20]). Three specimens were used for each test. For each series of tests the fretting motion was carried for 16000 cycles where the contact voltage attained the open circuit value. The laboratory air ranged from 20 to 25°C and 40 to 50 percent relative humidity. Contact resistance and contact temperature data were collected by personal computer through GPIB General Purpose Interface Bus IEEE-488 and then stored for subsequent statistical analysis. Before each experiment, the samples surfaces were wiped with an antioxidant paste and then the samples were cleaned in an ultrasonic alcohol bath, dried by a wiper paper and carefully mounted in the fretting test assembly. Since the geometries of the flat and upper specimen were relatively small, thermo-couples with high response time (J type) was used to measure during the test the temperature variation near to the contact zone. The collected data of temperature were carried out with the help of a voltmeter through a conditioner. For security reasons, the test will be stopped when the contact temperature exceeds 50°C. In order to avoid any accidental arcing between the contacts, the connecting members were brought into contact with the current power supply OFF. The power supply was switched to ON only once the contact force was established and then the contact resistance and contact temperature were measured at each end of cycle and plotted according to the number of fretting cycles.

5 Experimental results and discussion

5.1 Electrical contact resistance

Fig. 3 shows the results with logarithmic scale of the contact resistance as function of fretting cycles only for high copper alloy C10100. The dotted curve presents the obtained results of contact resistance for three tested specimens. For all materials, the maximum contact resistance which corresponds to the open

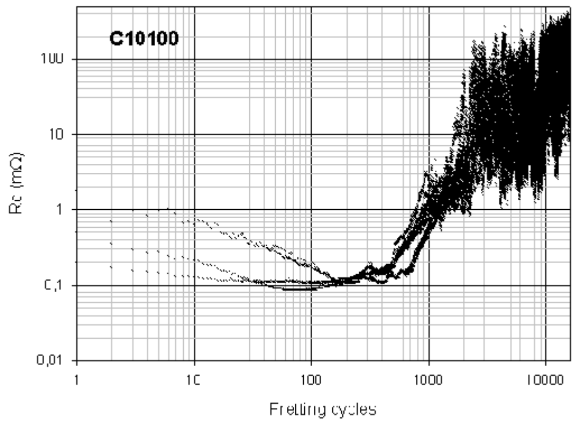


Figure 3: Change in contact resistance of copper alloy C10100 according to the fretting cycles.

circuit voltage of 2 V occurs at 16000 cycles where insulating materials tend to accumulate.

This is manifested by a rapid increasing of the contact resistance stability as the fretting progresses. For all materials, the contact resistance behaviour seems to be characterized by three distinct stages. In the first stage, which represents 500 cycles of fretting, the contact resistance decreases with very low fluctuation. Relative movement leads to a sliding/wiping action which facilitates the escape of the wear debris and cause burnishing with rupturing the asperities, ensures good metallic contact and increasing the conductive contact surfaces. Hence, the contact resistance decreases. It is well known that current passes through a micro asperities or spots present on the contact area. For metallic contact of rough surfaces [21, 22], has shown that contact resistance R_c can be approximated by the formula:

$$R_c = \frac{\rho}{2}\left(\frac{1}{na} + \frac{1}{\alpha}\right) \tag{1}$$

where ρ is the resistivity of contacting materials and α is the radius of a circle containing a cluster of n uniformly distributed contact spots, the radius of each spot is a. In the second stage, apparently between 500 cycles to 2500 cycles of fretting, the fretting was initiated and the contact resistance of all materials increases progressively until 2 orders of magnitude. However, as the fretting progresses, wear debris were generated and accumulated between the contacting surfaces and then oxidized. Removal of oxide exposes original surface which then oxidizes in a repeating process. Hard oxidized wear debris accelerates the progress of wear. As a result, contact resistance enhances continuously, this phenomenon was known as fretting corrosion. In the third stage or the saturation stage between 2500 cycles and 16000 cycles, the contact resistance increases sharply and is very unstable as characterized by large fluctuations between 1 and 3 orders of magnitude and sometimes by an open circuit. The peak and bottom values of contact resistance were speculated to be formed by accumulation of wear debris and oxidized wear debris in the fretting area, and subsequently, by extrusion of the accumulated wear debris on the contact area, respectively. Then, a hypothesis was set up that wear debris and copper-alloy have a different hardness from each other and that hard materials crush soft materials and crack the oxides which leads to a lower contact resistance. In this third stage, a thick insulating layer containing oxides and wear debris will form and any remaining metallic contact will be lost, causing a sharp increase in the contact resistance. In addition, prolonged exposure to fretting action will create the conditions for fatigue to occur and cause softening and progressive separation of contacting metals. When the current is confined to flow through the conducting spots (*a*-spots), the temperature of the point of contact (T_c) may be higher than that of the bulk (T_b). Hence, the increase in constriction résistance over the resistance that would exist (R^i_c) if the metal-metal contact were continuous across the entire contact area can be expressed as:

$$R_c = R^i_c\,[1+ 2/3(T_c-T_b)] \tag{2}$$

The term ($T_c - T_b$) is called the super-temperature and is related to the voltage drop across the contact interface (U) as:

$$T_c^2 - T_b^2 = \frac{U^2}{4L} \quad (3)$$

where L is the Wiedemann-Franz Lorenz number (2.45 x 10^{-8} V^2/K^2). Hence, a small increase in the contact voltage (U) can raise the super-temperature high enough to produce metallurgical changes such as softening or even melting of the conducting areas (Timsit [23]). Accumulation of fretting debris and oxides in the contact zone reduces the size of contact spots surrounded by oxidized debris thus increasing the current density and the super-temperature of these conducting paths (Gagnon and Braunovic [11]). The contact temperature measured after 16000 cycles for all materials was about 30°C.

5.2 Comparison of contact resistance results

Fig. 4 shows a comparison between the smoothing curves of contact resistance for the all tested materials. A running average smoother was applied with sampling proportion of 0.01 and an interval of 100 points. Contact resistance was slightly higher for the harder material C70250 then the other softer

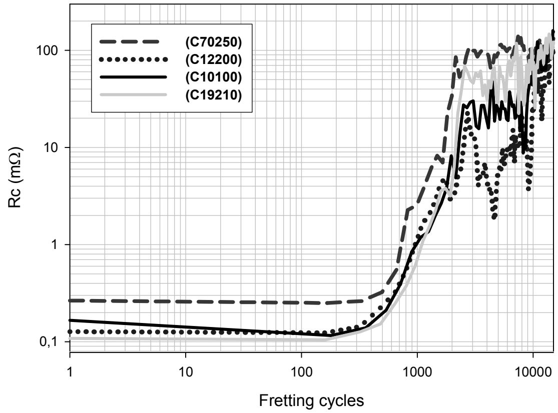


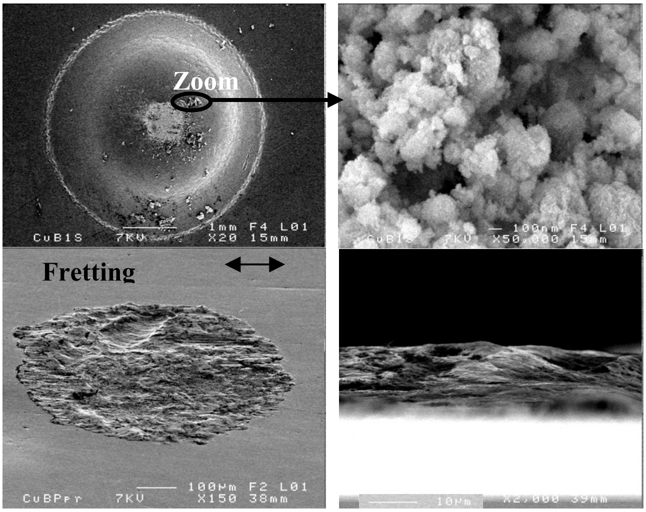
Figure 4: Comparison of smoothing contact resistance results for tested materials.

materials. It has been shown in an earlier paper (El Abdi et al. [24]) that static contact resistance measured under indentation test for C70250 alloy was higher then the other alloys. C70250 copper alloy which contains hard Nickel element has been hardened by precipitation and offer an interesting mechanical properties with high strength, high Young's modulus, high hardness and a low electrical conductivity (table 1) (Zauter and Kudashov [18]). This causes the highest contact resistance to be obtained with lower contact area.

6 Surface studies of fretted contact zone

6.1 SEM observation and EDX analysis

Fretting damage of contact surfaces was examined by Scanning Electron Microscopy (SEM). Some representative examples of the SEM examination of the fretting damage in contact zones are shown in fig. 5 and fig. 6 SEM micrographs were taken at 16000 cycles before and after cleaning of the fretted surface for the harder material C70250 and softer material C12200. Fig. 5 (a) shows the accumulated wear debris at the edges of the fretted zone for the softer alloy C12200 and the zoom of wear particles with x50000 of magnification. Wear debris seem to be more compact than the observed wear debris for the harder alloy C70250 (fig. 6(a)).

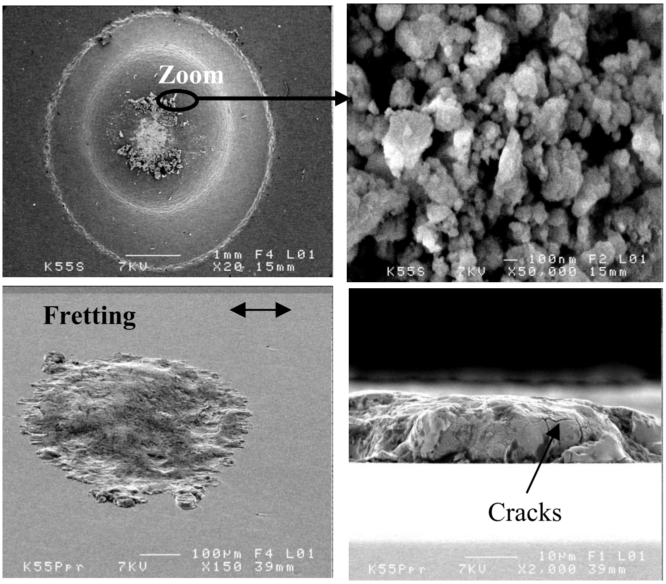


(a) Spherical sample before cleaning of the fretted surface.

(b) Flat sample after cleaning of the fretted surface.

Figure 5: SEM micrograph of the fretted contact zone for C12200 copper alloy.

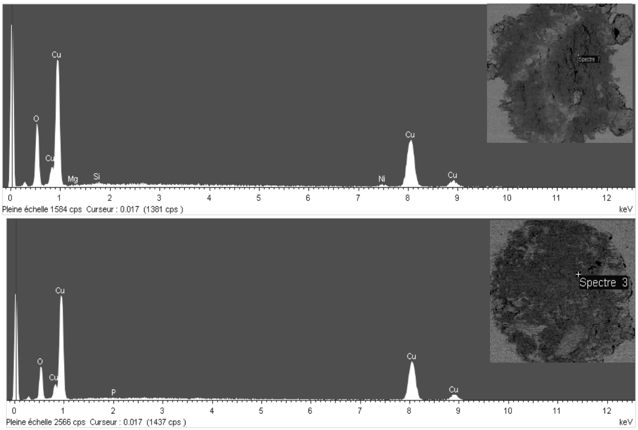
Fig. 5(b) shows delamination wear and wears marks following the direction of the fretting motion caused by the abrasive particles remaining between the two contacting areas. A pushed material in the edge of the wear track was observed on the cross sectional fig. 5(b). The characteristic features of plastic deformation, abrasion and delamination wear were observed in the contact zones (fig. 6(b)). The micrograph of the cross sectional presented in fig. 6(b) shows a surface degradation which is characterized by extensive delamination and cracking as a result of contact fatigue (Antler [25]). It is clear that fretting causes serious damage in the contact areas. Typical damage being severe as abrasion, delamination and accumulation of the wear debris in the edges of the wear track leads to an increase of contact resistance. Elemental compositions of the fretted contact zones were determined by the Energy Dispersive X-rays analysis (EDX).



(a) Spherical sample before cleaning of the fretted surface.

(b) Flat sample after cleaning of the fretted surface.

Figure 6: SEM micrograph of the fretted contact zone for C70250 copper alloy.



(a)

(b)

Figure 7: EDX spectra taken inside the fretted surfaces. (a) C70250 copper alloy; (b) C12200 copper alloy.

The main advantage of this type of X-ray fluorescence analysis is the ability to identify a wide range of elements simultaneously and to obtain a semi-quantitative measure of their concentrations in the contact regions under examination. Fretting contact areas have been examined by EDX analysis after the end of 16000 fretting cycles inside the wear track and on the wear debris for the C12200 and C70250 alloys. The elemental composition spectre measured from a spot across the wear track for the two materials was shown in fig. 7. The spectre presented in fig. 7 (a) shows the presence of strong peak of oxygen (26.5%) for the harder alloys C70250 and 20.7% of oxygen for the softer material C12200 (fig. 7 (b)). The presence of strong peaks of oxygen and copper indicates that wear tracks were composed mainly of these elements.

X-ray elemental mapping clearly reveal the nature of chemical species present at the contact zone and the extent of oxidation. The X-ray elemental mapping confirms the oxidation of the removal copper.

6.2 Profile measurement

The cleaned wear track of the tested alloys was examined by a 3D scanning profiler [26] to evaluate the dimensions of the wear tracks. Fig. 8 shows the smoothing initial profiles and the smoothing profiles of the wear tracks for the C70250 and C12200 alloys obtained after 16000 fretting cycles. The X,Y grid resolution for the collected data was 1.2 µm over a measurement area of 1.2 mm x 1.2 mm. 3D sub-micrometric profiler method can determine the parameters of wear in fretted surfaces.

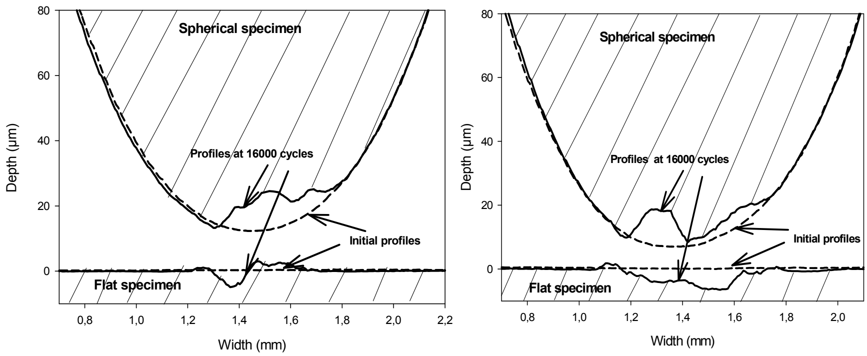


Figure 8: Scanning fretted surfaces and profiles of the wear track after 16000 fretting cycles (a) C70250 copper alloy; (b) C12200 copper alloy.

The real contact area, volumetric wear removal, width, and length of the wear track were presented in table 2 for the flat specimen and for all tested materials.

Table 2: Wear sizes for all tested high copper alloys.

	C10100	C12200	C19210	C70250
Depth (µm)	7.7	6.54	7.8	4.94
Width (µm)	593	600	659	450
Fretted area (mm^2)	0.37	0.34	0.35	0.28
Fretted volume loss (mm^3)	$5.9\ 10^{-4}$	$4.7\ 10^{-4}$	$6.1\ 10^{-4}$	$1.4\ 10^{-4}$

The measured wear sizes for the harder material C70250 were lower than the softer materials C10100, C12200 and C19210. The softer materials suffer more surface damage, material loss, and generation of wear debris.

The harder materials suffer very little surface damage and not much wear debris generation. It is well known that the wear volume is proportional to load F_c and fretting amplitude x and is inversely proportional to hardness H, the wear volume V can be calculated by the following equation of Archard [27]:

$$V = \frac{2\,K\,F_c\,N\,x}{3H} \tag{4}$$

where N is the total number of cycles, and K is a wear coefficient.

The radius of contact area (a) can be calculated by the following equations:

$$a = \left(\frac{3F_c R}{4E^*}\right)^{1/3} \tag{5}$$

$$\frac{1}{E^*} = \frac{2(1-\nu^2)}{E} \tag{6}$$

Where R is the radius of spherical specimen (R=3mm), E is the Young modulus and ν is the Poisson coefficient. The calculated diameter by the eqns. (5) and (6) for the C12200 alloys was equal to 140 µm. Fig. 9 gives a schematic

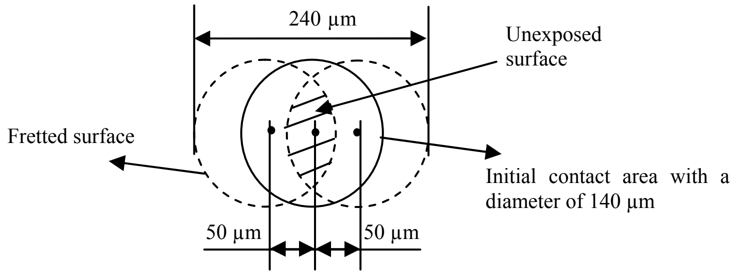


Figure 9: Fretted surface for one fretting cycle (fretting amplitude of 50 µm, C12200 alloys).

of the fretted surface for one fretting cycle. The fretted area after 16000 fretting cycles was higher than the fretted area for one cycle. The measured width of the track for the C12200 after 16000 fretting cycle was equal to 600 µm (table 2) and was higher than the initial width 240 µm. The width and depth increase during the fretting test. This is due to the progressive wear of the spherical specimen; the initial contact area was spherical and then increase and became flat.

7 Conclusion

Resistance increases noted during fretting action are felt to be due to trapped wear debris composed mainly of oxides. Based on the variation in contact resistance as a function of fretting cycles, wear debris, elemental composition of the wear track, surface profile and wear track sizes, were assessed by surface analytical techniques (SEM, EDX and profile-meter). SEM results showed that fretting causes serious damage in the contact areas as abrasion, delamination wear, fatigue cracks and accumulation of the oxidized wear debris which can leads to an increase of contact resistance. EDX analysis confirmed the presence of a strong percentage of oxygen in the wear track for the tested copper alloys. 3D scanning profiler showed that softer materials suffer more surface damage, material loss, and generation of wear debris than the harder material. The hard material was more wear resistant than soft materials and lead to high electrical contact resistance during fretting test. These studies underline the importance and necessity of using different surface characterization techniques in order to obtain an unambiguous explanation and information of the phenomena occurring at the contacting interfaces. The obtained results could help the connector manufacturers in the choice of contact materials and were a useful tool to evolve compromise between the electrical and mechanical aspects for connectors.

Some proposed solution could lead to a decreasing of the contact resistance and increasing the contact durability as the use of a lubricant between the two contacting surface and increasing of the contact load which will reduce the micro-displacement of the contact interface by increasing the friction force.

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