Durability of some asymmetrical contact pairs for connector application

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Abstract

Reliability of connectors is still a major concern for end users in many applications. One way to improve it is to optimize the surface coatings deposited on base substrates. Although gold remains the most widely used contact plating material, many alternative coatings have been developed in the past or recent years. Among these alternatives are silver final coatings and gold flash over palladium-nickel plated alloy. The properties of these two platings have been mainly investigated in symmetrical configurations where male and female contacts have similar deposits. In this work, asymmetrical configurations - where platings on male and female contacts are dissimilar - are studied. Wear behaviour was investigated with friction and fretting tests. The aim was to characterize the role of the various layers on the wear performances of contacts. Contact resistance behaviours were measured and correlated to the wear tracks investigated with various techniques such as SEM, EDS and 3D-Profilometry. It is shown that in some cases dissimilar final coatings on male and female contacts can significantly improve durability.

1. Introduction

The development of electrification and of connected consumer devices is causing an exponential rise of the number of connectors used and produced worldwide. Historically gold has been the best metal to meet all connector needs. However in view of its cost other alternatives have been developed, such as various palladium alloys [1] [2] in the 80s and hard silver [3]. The concerns were mainly frictional polymer and tarnish film formation for these two types of coatings respectively.

Numerous studies have been done to determine the performance in terms of fretting and wear resistance of all the coatings used in the connector industry, such as the study of the fretting and wear resistance of nickel [4], tin coatings [5] or a new alternative, gold capped silver (GCS) [6]. Gold flash over palladium nickel and the hard silver with (or without surface post-treatment and lubrication) have been used successfully for particular applications. Literature shows that in general palladium nickel alloy has good wear resistance [7] but low fretting resistance [8], while silver coatings have good fretting resistance [9] but low wear resistance. Antler's seminal work on connectors has shown in [10] that dissimilar contact pairs could be very detrimental to wear and fretting behaviour. More recently in [11] Lin et al. have shown that the fretting resistance of PdNi is improved when in an asymmetric Au (1.2 µm) versus PdNi contact.

In this paper the wear and fretting resistance of two multilayer plating systems are studied: hard pure silver plating on nickel and a gold flashed palladium-nickel on a nickel layer. The four possible configurations were tested for friction and fretting properties since the degradation modes are known to be different. The aim of the study is to bring some insight on the wear mechanisms and to determine if it is possible to improve the performance of each coating by using asymmetrical contacts.

2. Samples and experimental set-ups

2.1 Samples

A hemisphere (cap) of 1.4 mm radius was stamped on $CuSn_6$ substrates before the electrodeposition of the coating. All the samples (caps and flats) were plated on industrial reel-to-reel plating lines in order to obtain a better reproducibility and all had a 1.3-1.6 µm nanocrystalline Ni first coating. The multilayers studied are described in Table 1. The PdNi alloy coating is called GXT^{TM}; it consists of 80% w/w Pd and 20% w/w Ni deposited from a low ammonia plating bath. A cobalt hardened gold flash of about 50 to 80 nm was deposited on the top. The hardness was measured with a nanoindentation tester at 0.1 gf and found to be between 400 HV and 420 HV. The GXT™ coatings will be referred to as GXT for simplicity. Care was taken in the measurement with the X Ray fluorescence spectroscopy (XRF Fisher XDVµ model) of the Pd and Ni concentrations in the PdNi coatings. A low free cyanide silver plating bath with no alloying was used for the silver coatings. Plating parameters were adapted to obtain hard silver deposit with average hardness between 120 and 130 HV. These AGT® coatings will be referred to as nAGT because they are not lubricated. All the hardness measurements were carried out under 0.1 g load with a NHT^3 Anton Paar nanoindenter. The $CuSn_6$ substrates hardness was 230 HV with a Young modulus of 120 GPa.

GXT	
Thickness (µm)	
Au	0.05 - 0.08
PdNi	0.70 - 0.80
Ni	1.30 - 1.50
$CuSn_6$	350

nAGT	
Thickness (µm)	
Ag	Cap 4.5 - 5.0
	Flat 2.5 - 3.0
Ni	1.3 - 1.5
$CuSn_6$	350

Table 1 : Thickness and composition of the GXT and nAGT plating systems.

2.2 Experimental set-ups

Contacts were submitted to durability tests. The evaluation of a coating pair was based on the electrical properties (contact resistance Rc), the friction properties (friction coefficient µ not shown here) and wear properties after several numbers of cycles.

2.2.1 Durability and fretting tests

The durability testing was done with a Bruker UMT3 universal tester fitted with a mechanical reciprocating module. The stroke was set at 2 mm (peak to peak) under a 1 N normal load and a speed of 125 mm/min (0.53 Hz). The contact resistance and the tangential force were measured continuously every 0.1 s. The mean values of 10 measurements were calculated.

The fretting tests were performed with a dedicated device (electro-dynamic shaker [4]) working at constant displacement. The conditions were: d=50 µm peak to peak displacement, 10 Hz and normal load 1 N. The contact radius calculated with the Hertz formulation is 25µm for the studied substrate. The tests were carried out at ±25µm, in order to be in fretting gross slip mode and not in reciprocating sliding mode. During the test, the voltage drop in the contact was measured with an acquisition card (333 10^3 samples/s), the DC current value set at 20 mA and voltage limit at 250 mV. The mean values of 500 measurements per cycle were calculated. All experiments were done at room temperature (23°C) and 55% relative humidity.

Contacts will be referred to as coating1/coating2, the first being the cap and the second the flat through all the paper.

2.2.2 Characterizations

3D images, profiles and wear volumes were measured by a Bruker Contour GT-X 3D Optical Profiler. The wear volumes calculations took into account positives volumes due to transfer and negative ones due to deformation and particles ejection; the following formula was used:

$$VV_{cccccc} = |VV^{-}_{cccccc} - VV^{+}_{cccccc}| \; aaaaaa \; VV_{ffffccff} = |VV^{-}_{ffffccff} - VV^{+}_{ffffccff}|$$

$$VV_{wwwwccww} = |VV^{-}_{cccccc} - VV^{+}_{cccccc}| + |VV^{-}_{ffffccff} - VV^{+}_{ffffccff}|$$

Scanning electron microscope (SEM) images were obtained with a ZEISS EVO MA10 microscope fitted with an Oxford Instruments Xmax probe for Energy Dispersive X-ray Scanning (EDS) analysis for the identification of the chemical elemental composition of selected surfaces. The analyses were done at 15 KeV, the depth of analysis was therefore less than 1 µm.

3. Results and discussion

3.1 Durability experiments

3.1.1 Symmetrical contacts

The evolution of Rc and of the wear were studied as a function of number of friction cycles n. Figure 1 shows Rc(n) curves for the symmetrical contacts nAGT/ nAGT and GXT/GXT up to 1200 cycles. All the experiments were performed several times and were repeatable; a representative curve is giving in the following text for all the runs.

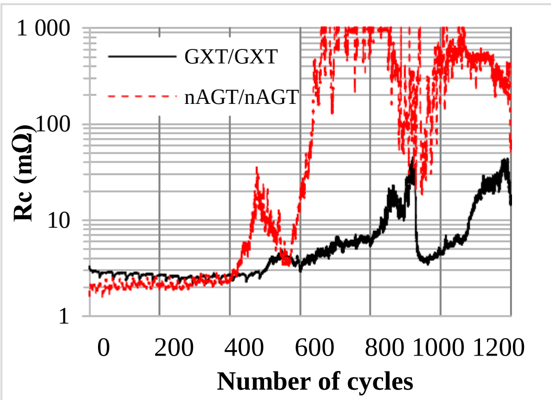

Fig. 1: Durability of nAGT/nAGT and GXT/GXT contacts

The behaviour of the nAGT/nAGT contacts is described first. An initial contact resistance (Rc_1) of 2.4 mΩ is measured, the values then remain low and stable during the first 400 cycles (~ 2 mΩ). After these 400 cycles there is a rapid increase of Rc to a value of about 30 mΩ at 480 cycles. This indicates the beginning of a degradation of the silver layer; after a decrease Rc drastically increases over a value of 1 Ω.

The composition of the wear tracks were analysed for different numbers of cycles 150, 250, 430 and 1200 cycles. Figure 2 shows the EDS chemical maps of the wear tracks pasted over the SEM images of the contact. The compositions calculated for the depicted wear tracks are plotted in figure 3. At 150 friction cycles the wear track is still fully covered with silver ([Ag]=96 and 88 at% for the cap and flat). At 250 cycles Ni starts to be exposed ([Ni]=21 and 46 at% for the cap and flat) and becomes more predominant at 430 cycles ([Ni]=25 and 55 at% for the cap and the flat). The atomic percentage of O is also more important (32 and 14 at% for the cap and flat), which correlated to the beginning of the electrical disturbances. Finally, at 1200 cycles the cap and flat are worn and oxidized through to the copper substrate ([Cu]=14 and 7 at%; and [O]=38 and 19 at% for the cap and flat respectively) while Rc values are very high (~ 100 mΩ).

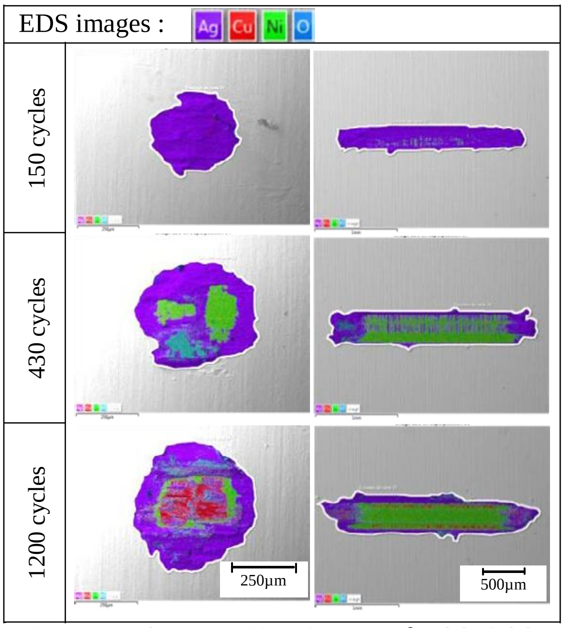

Fig. 2: EDS composition images of nAGT/nAGT contacts for different numbers of friction cycles. Left nAGT caps, right nAGT flats. The white line shows the region used for the composition calculation.

Profilometric measurements and wear volume calculations showed there was a small transfer of silver from the flat to the cap at 150 friction cycles. Beyond that, the cap and the flat are more and more worn out and at 1200 friction cycles, the wear depth reach 4 µm for the flat and 10 µm for the cap.

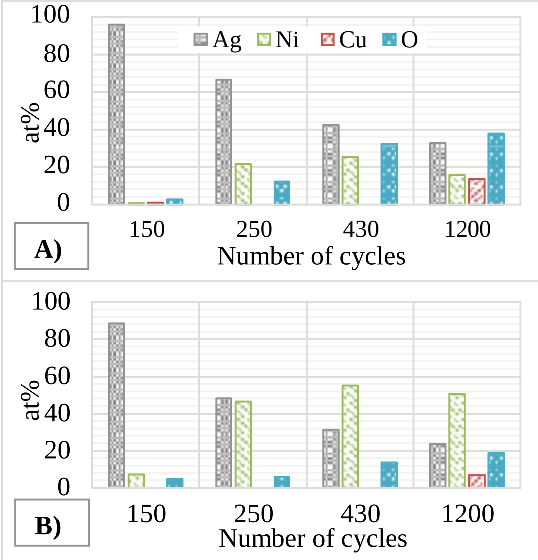

Fig. 3: Chemical composition (%at) of the wear tracks showed in figure 2 : caps A) and flats B)

The beginning of the increase of Rc at 430 cycles corresponds to the thinning of Ag and exposure of Ni. The experiments show that as long as the surface of contact involves an average composition of 57 at% of Ag, the contact resistance remains stable.

The second multilayer studied is a symmetrical GXT/GXT contact. Figure 1 shows the variation of Rc as a function of durability friction cycles. Rc values are low and stable (~ 2.5 mΩ) till 500 cycles, they start to increase slowly up to 850 cycles (10 mΩ). After 850 cycles the values vary between 5 mΩ and 40 mΩ. The durability properties of GXT/GXT is thus observed to be better than that of nAGT/nAGT

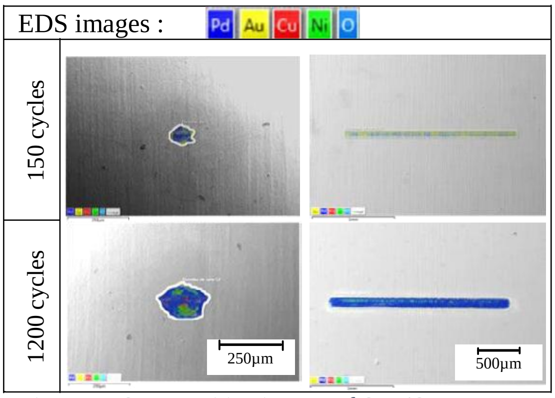

Fig. 4: EDS composition images of GXT/GXT contacts for different numbers of friction cycles. Left GXT caps, right GXT flats

The SEM images in figure 4 show the composition of the wear tracks for the friction tests of GXT/GXT contacts stopped at different numbers of cycles.

During the first 150 cycles Au is not removed. As the number of cycles increases, the percentage of gold decreases ([Au]=7 and 10 at% at 600 cycles for the cap and the flat respectively) and PdNi is more exposed ([Pd]=26 and 41 at% for the cap and the flat respectively (figure 5).

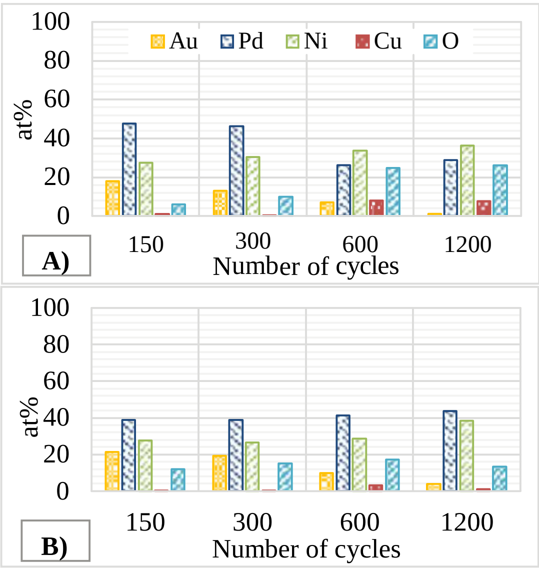

Fig. 5: Chemical composition (%at) of the wear tracks shown in figure 4: caps A) and flats B)

The composition graphs of figure 5 can be correlated to the Rc evolution: Rc values remain stable and low as long as the mean interface composition involves more than 20 at% of Au. As this percentage decreases, PdNi and Ni are exposed and Rc values start to increase.

Comparing the size of the wear tracks on the caps after 150 cycles for the two types of contacts shows that the nAGT/nAGT track is 14 times larger than the GXT/GXT one due to the difference in hardness (125HV/ 420 HV respectively) and the following wear modes.

For the two symmetrical contacts studied we have two totally different wear modes. The multilayer nAGT/nAGT shows adhesive wear with a more severe degradation. When the silver in the wear track is removed and displaced to the edges of wear area, the nickel underlayer is exposed and the contact resistance increases from 2 mΩ to 1 Ω after nearly 480 cycles. For the GXT/GXT multilayer there is abrasive wear, with a much smaller worn surface with a contact resistance that gradually increases but without ever reaching 50 mΩ.

3.1.2 Asymmetrical contacts

For an applicative point of view it was important to investigate the behaviour of contacts with dissimilar platings involving the two described above.

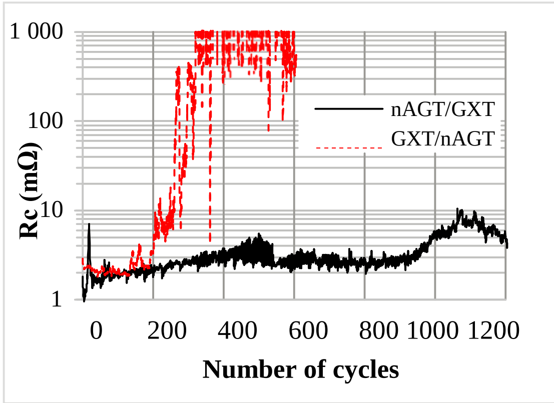

Fig. 6: Durability of nAGT/GXT and GXT/nAGT contacts

The behaviour of GXT/nAGT is described first. Figure 6 shows the initial Rc value is 2.9 mΩ, it stays stable for the first 120 cycles (~ 2 mΩ) and then increases drastically after 300 cycles (Rc=1 Ω at 320 cycles).

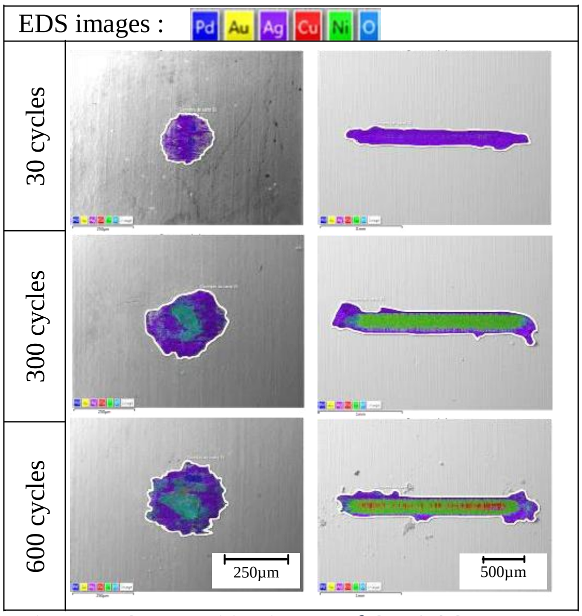

Fig. 7: EDS composition images of GXT/nAGT contacts for different numbers of friction cycles. Left GXT caps, right nAGT flats

Figure 7 shows the composition maps of nAGT flats and GXT caps. After 30 cycles Ag is transferred from the flat to the cap while the flat remains covered with 57 at% Ag. At 300 cycles the flat is mostly composed of Ni which is also detected on the cap in an oxidised form. Figure 8 confirms that there is 18 at% of Ni and 52 at% of O on the cap and 60 at% of Ni and 8 at% of O on the flat. At that stage a drastic change of Rc is observed. The percentage of gold on the cap has decreased to 1 at%: the contact is no longer Ag-Ni vs. Au-PdNi but Ni vs. PdNi.

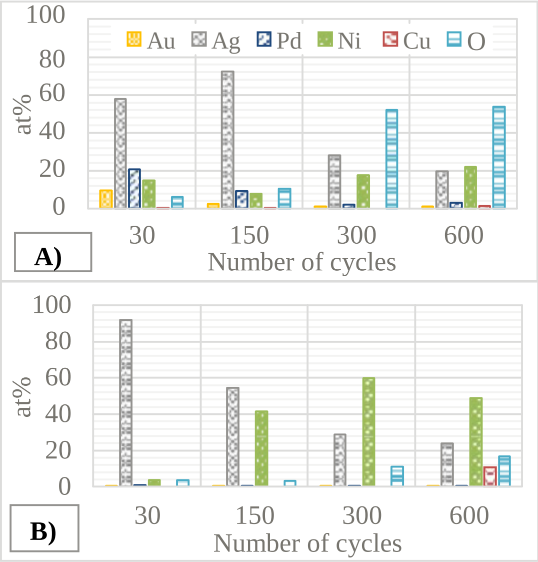

Fig. 8: Chemical composition on the wear tracks shown in figure 7: caps A) and flats B)

Figure 9 shows the 2D profiles of the flats at the corresponding wear stages and the maximum wear depths d_z. After 30 cycles d_z. = 2.8 µm which is about the thickness of the Ag layer; at 300 cycles d_z. =3 µm and for 600 cycles d_z. = 4 µm. The wear volumes calculated from the 3D measures (not shown here) showed that the wear volume on the caps were always positive.

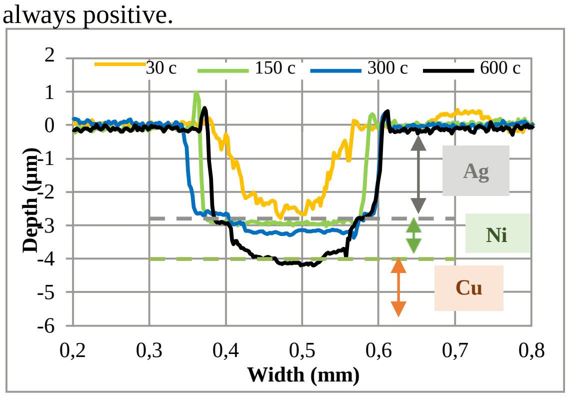

Fig. 9: 2D profiles of the nAGT flats after 30, 150, 300, 600 cycles (GXT/nAGT contacts)

The beginning of the increase of Rc at 300 cycles corresponds to the thinning of Ag and exposure of Ni on the flat. Experiments show that as long as the contact surface involves an average composition of at% Ag higher than that of Ni, the contact resistance remains stable.

The behaviour of the nAGT/GXT contact shown in figure 6 is very different. After an initial Rc value of 1.9 mΩ a small peak at around 7 mΩ is recorded followed by a stabilized value of 2.5 mΩ. After 850 friction cycles the Rc increases, but remains below 10 mΩ. For all the experiments carried out this peak was present during the first 40 cycles; it corresponds to the beginning of Ag transfer on the flat. 3D profiles of the GXT flats (not shown here) stopped during the peak showed that Ag is first transferred to the top of the delamination waviness of the flat. After 90 cycles Ag is spread homogeneously on the flat and Rc=2 mΩ.

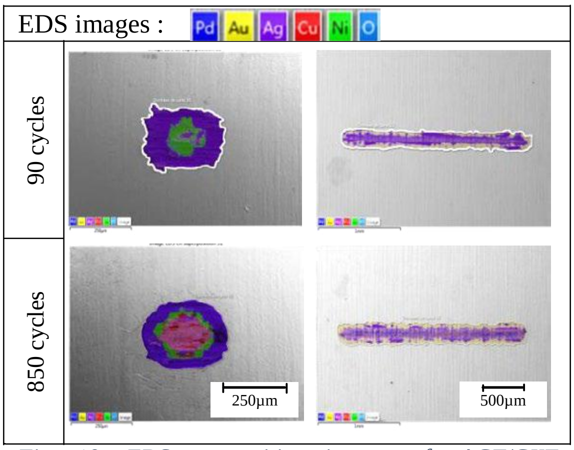

Fig. 10: EDS composition images of nAGT/GXT contacts for different numbers of friction cycles. Left nAGT caps, right GXT flats

The compositions maps of figure 10 shows that at 90 cycles Ag the cap is worn and that Ni is exposed on the cap. At 850 cycles a zone in the middle of the cap seems to be composed of Ni on the outside and a mixture of Cu, Au and Ag in the middle.

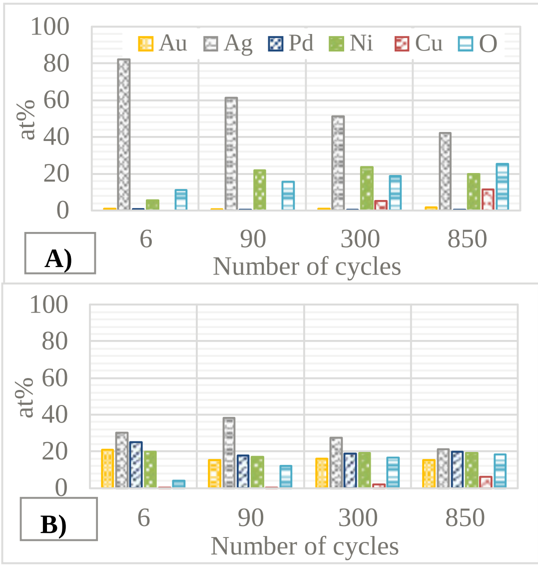

Fig. 11: Chemical composition on the wear tracks shown in figure 10: caps A) and flats B)

From the compositions of figure 11 a wear mechanism can be proposed. At the very beginning of the friction test (6 cycles) some Au of the GXT flat is transferred to the cap but mainly Ag form the cap is transferred to the flat ([Ag]=36 at% at 90 cycles). Then the concentration of Ag decreases with the number of cycles on the cap and flat. After 850 cycles [Cu] reaches 11 and 6 at% for the cap and flat respectively. An analysis focussed on the centre of the cap wear scar did not show any O. It can be observed that at all the stages the GXT flat wear tracks show some Au (probably located on the side on the wear tracks). These two observations are correlated to the stable and low values of Rc measured during the 850 cycles.

3.2 Fretting experiments

Fretting behaviour of Ag/Ag contacts has been described in several works [9] [12] as well as that of Au flashed PdNi [8] [1] [13]. The first type of contacts (soft/soft) shows minor fretting degration while the second one (hard/hard) shows a severe one; the severity of this latter one depends of the thickness of the gold flash and the contact pressure.

The same four pairs have been submitted to fretting tests (described above) in order to investigate the fretting behaviour of hard/soft and soft/hard contacts.

3.2.1 Dissymmetric contacts

Figure 12 shows the electrical behaviour during 150 000 cycles for the two asymmetrical pairs.

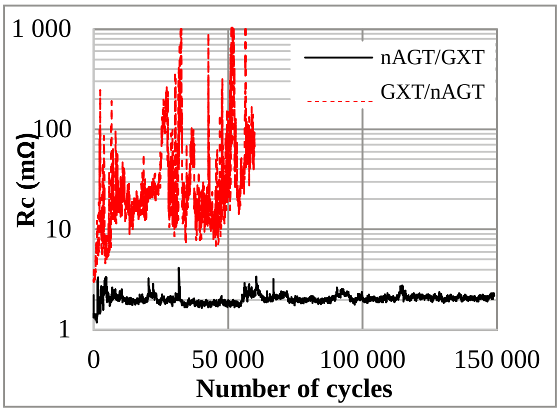

Fig. 12: Fretting behaviours of nAGT/GXT and GXT/nAGT contacts

The behaviour of the GXT/nAGT contacts is described first. For 600 cycles the Rc values stay constant and low (~ 3mΩ); they then increase and vary strongly.

Figure 13 shows the EDS images in the wear scars and figure 14 the compositions of this wear tracks. At 200 cycles (during the low Rc plateau) Ag from the flat is transferred to the cap; Ni is exposed on the flat and becomes lightly oxidized.

After 1000 cycles the compositions of the tracks are similar to those after 200 cycles. The strong increase in Rc has started but the values are still below 10 mΩ. For higher numbers of cycles less Ag is observed inside the wear tracks of the cap and flat. Rc values are high and fluctuate. After 60 000 cycles severe wear is observed and both cap and flat tracks are composed of O, Ni, Cu and small amounts of Ag.

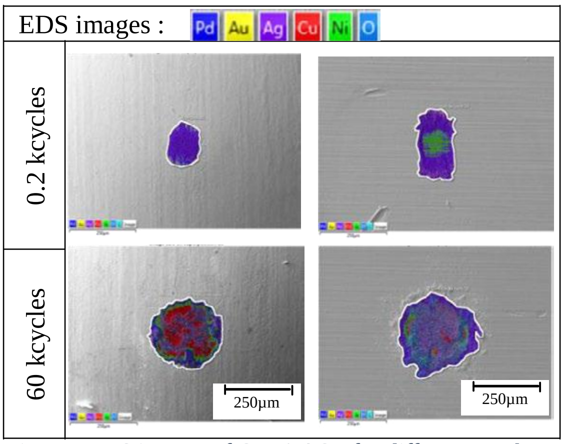

Fig. 13: EDS images of GXT/nAGT for different numbers of fretting cycles. Left GXT caps, right AGT flats

Comparing the wear scars after 10 000 fretting cycles (corresponding to a distance of 1m) to those after 300 friction cycles (distance 1.2m) it can be seen that the wear of the fretting test is more severe. Cu starts to be exposed for the fretting test, while for the friction test flat and cap are still coated with Ag at more than 25 at%.

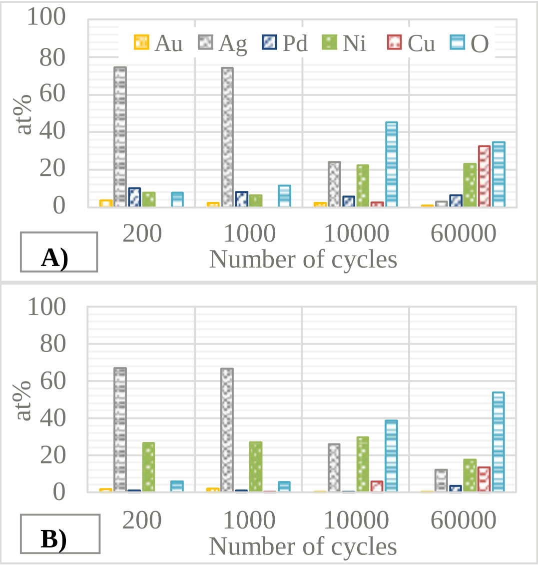

Fig. 14: Chemical composition (%at) of the wear tracks shown in figure 13: caps A) and flats B)

Although Rc values increase rapidly and vary widely, they are lower than with GXT/GXT contacts due to the presence of Ag in the interface. The beginning of the increase of Rc corresponds to an [Ag] below 25 at% on average.

Finally the most interesting case is the nAGT/GXT contact. Figure 12 shows that during the whole test the contact resistance values never reach 10 mΩ. Rc starts at 2.1mΩ, then during 1 400 cycles there is a plateau at 1.5mΩ, then an increase to about 2 mΩ and finally a plateau of stable values lasting 150 000 cycles.

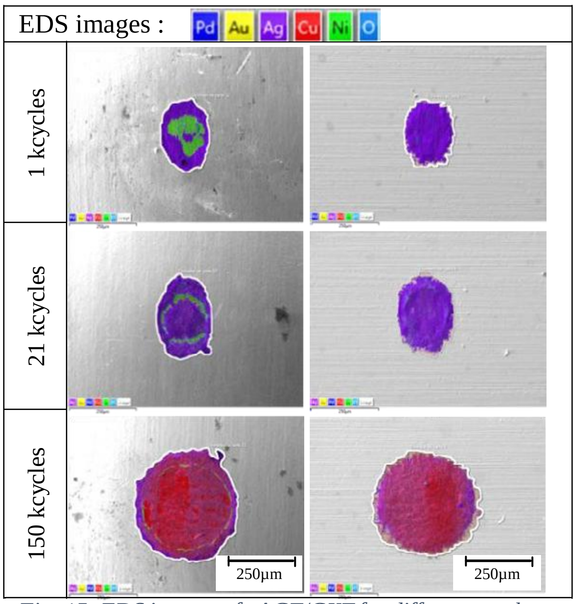

Fig. 15: EDS images of nAGT/GXT for different numbers of fretting cycles. Left nAGT caps, right GXT flats.

The EDS images in figure 15 show that Ag from the cap is transferred to the flat, exposing Ni. The compositions in figure 16 indicate that th e percentage of Ag remains between 36 and 52 at% on the cap and between 40 and 76 at% on the flat during 21 000 cycles. After 150 000 cycles the wear tracks of both the cap and the flat are composed of Cu, O and some Ag.

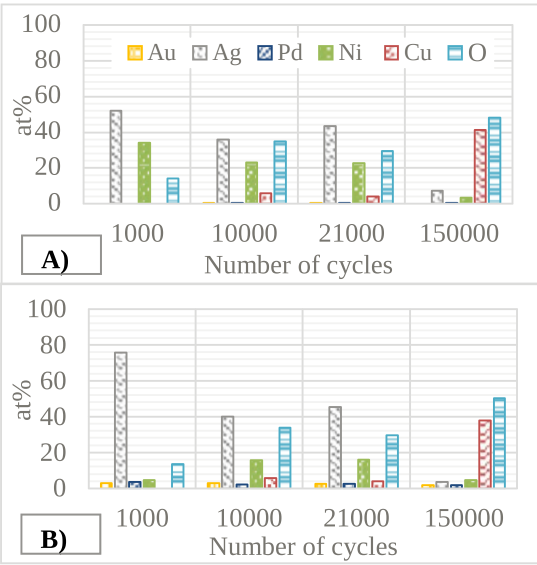

Fig. 16: Chemical composition (%at) of the wear tracks shown in figure 15: caps A) and flats B)

Figure 17 displays the 2D profiles of the nAGT cap and the GXT flat after 150 000 cycles. The cap has been worn by the hard GXT flat and the remaining scar is 5 µm deep. Transferred material 5µm high can be seen on the flat. Oxygen is detected in rather high quantities on the cap and the flat due to the presence of Cu and Ni. Nevertheless at this stage the measured contact resistance is 2.8 mΩ probably due to the presence of Ag on the periphery of the wear scars.

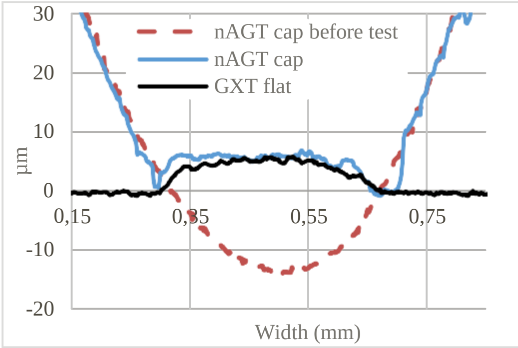

Fig. 17: 2D profiles of the nAGT/ GXT contact after 150000 fretting cycles

Figure 18 shows the wear volumes of the cap and flat. Negative volumes represent displaced matter and ejected matter and positive ones represent displaced matter and transfer. These wear volumes are almost constant during the first 100 000 cycles. After that a very large increase of the cap wear volume (900 10^3 µm^3) is observed. It is due to the filing of the Ag top of the cap by the hard flat. Simultaneously some transfer of silver on the flat occurs as seen in figure 17.

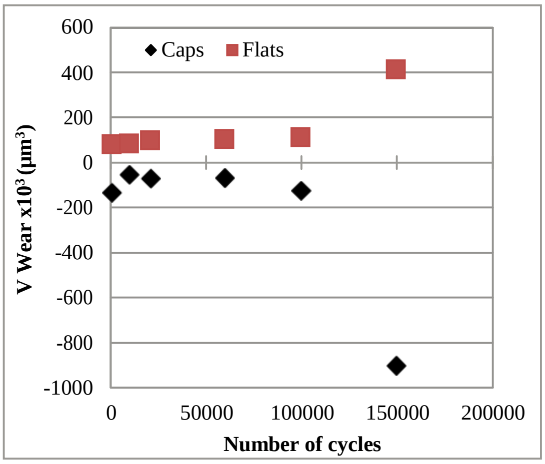

Fig. 18: Wear volumes of the caps and flats for nAGT/GXT contacts

The fretting results have shown that dissimilar contacts involving one Ag and one GXT contact behave differently whether the Ag or the GXT is on the cap. In the conditions of this study, an Ag coating on the cap allows very low and stable Rc values because of the beneficial transfer of the silver from the cap to the flat.

4. Conclusion

Durability tests of four configurations of contacs were investigated. Soft (AGT) cap on soft (AGT) flat, hard (GXT) cap on hard (GXT) flat and mixing the two for disymetric contacts. It was shown that:

- With the soft/soft configuration strong wear of the soft Ag coating occurred, leading to an Ag/Ni contact interface, the beginning of Rc increase and finally to a Cu/Ni interface giving high Rc.
- With the hard/hard configuration the 50 nm flashed Au remained long enough in the interface for the Rc to increase slowly with Rc < 10mΩ after more than 800 cycles.
- For the hard cap on soft flat strong wear is recorded, Ag transferred to the cap and finally the contact interface becomes Ni/Cu leading to a very fast Rc increase. This is the worse case of the study.
- Finally the soft/hard configuration gave very long lasting low Rc because of low wear with some transfer of the flashed Au on the cap and some tranfer of the Ag to the flat. An unexpected "alloy-type" Ag-Au-Cu acted as a third body during friction.

These results were compared to fretting experiments and summarized in table 2.

	N friction cycles for Rc > 10mΩ	N fretting cycles for Rc > 10mΩ
nAGT/nAGT	450	1800
GXT/GXT	850	1000
GXT/nAGT	220	1200
nAGT/GXT	-	-

Table 2: Number of friction and fretting cycles for Rc>10 mΩ.

Friction of GXT/GXT contacts lasts twice longer than nAGT/nAGT. Using a GXT cap on nAGT (asymmetrical GXT/AGT) degrades the behaviour as compared to the symmetrical contacts. Using a nAGT cap on GXT flats ensures low Rc values. Fretting duration of GXT/GXT is 1.8 smaller than that of nAGT/nAGT. Using a GXT cap on AGT multiplies by 1.3 the fretting duration as compared to GXT/GXT contacts. Finally using a nAGT cap on GXT (asymmetrical nAGT/GXT) no Rc increase due to fretting was recorded for 150 000 cycles. This study has shown that the transfer of a soft relatively "noble" metal such as silver on a hard surface acted as a solid lubricant diminishing fretting degradation.

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