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Plating systems of electrical contacts are key technologies for connectors in terms of electrical and mechanical reliability performance. Au/Ni is historically the reference plating system and Au/PdNi/Ni is widely used since 1986. More recently, plating systems like Au/Ag/Ni, Au/NiW, AgPd/Ni and AgSb/Ni were also introduced. Nevertheless, published scientific literature, concerning tribological compatibility of these various plating systems, is limited. This research work is a simplified approach to study compatibility, in terms of durability & wear, between Au/Ni, AuPdNi/Ni, Au/Ag/Ni and AgSb/Ni under different contact pressures or normal forces. Durability and frictional wear testing were performed. Various surface analysis techniques were used to analyze wear tracks and investigate wear mechanisms as well as their impact on contact resistance. Results show that terminal contact pressure range is a key parameter to take into account when mating two different platings.

1 Introduction

Electronic connectors and overall interconnect applications have historically used gold plating **(Au/Ni)** as the main plating for male/female interfaces. Gold presents the advantages of being an excellent conductive material, of being a noble metal with excellent corrosion resistance and of presenting naturally a very low coefficient of friction making it an excellent solid lubricant. Nevertheless, the economical constraints and sometimes, some technical limitations have lead, widely, to the development and use of alternative platings. Gold Flash over Palladium-Nickel **(GF-PdNi)** was developed in the late 1970's [1] and commercialized starting 1986 [2] in order to obtain a much lower cost plating as well as a higher durability (resistance to mating and unmating cycles) metallic layer. GF-PdNi presented also the advantage of being a lower porosity deposit showing better resistance to corrosion and showed better compatibility for high temperature applications. All these advantages offset its lower resistance to fretting corrosion compared to gold and final connector users had the choice of these two platings according to their technical requirements. These two platings are considered fully compatible: This means that when a connector is plated with Au/Ni, it can be mated to its counterpart which is plated with GF-PdNi, without excessive wear-through precious metal layer. In the mid 1990's the Automotive industry started developing conventional silver plating especially for some power applications. Although conventional silver is known to have a low hardness, low young modulus and a poor coefficient of friction, its excellent conductivity (it has practically the lowest resistivity among precious metals) and its moderate cost offset all its disadvantages. Silver plated connectors were historically rated for 50 mating/unmating cycles only. A lot of development work followed in the mid 2000's and new silver plating stacks and deposits were developed with pure silver showing much higher hardness and Young moduli. Several alloyed silver processes were also developed with deposits showing relatively very high hardness such as silver-antimony (AgSb) and silver-palladium (AgPd) [3,4]. Researchers developed improved organic or inorganic anti-tarnishing solutions as silver is naturally subject to sulfidation. Improved post-treatments were also developed such as new contact lubricants or low coefficient of friction grafted molecules. The objective was to extend silver usage to electronic connectors where more than 50 mating/unmating cycles are required, as gold and palladium prices have shown to be extremely volatile and unpredictable. We have seen, for example, AgSb plated connectors developed and commercialized, by several connector manufacturers, for Hybrid and Electrical vehicles where several thousands of mating/unmating cycles are required. This was unimaginable initially when considering silver plating. We have also seen gold over hard silver **(GCS)** plated electronic and power connectors [5,6] commercialized, when gold plated over silver engineering usage was limited, for decades, to special electrical switches [7] applications and special aerospace connectors.

1.1 Compatibility of various plating systems

Now that all these different plating systems are on the market, we are facing many cases where these plating systems are mated to each other on the same type of connectors. As already mentioned, conventional gold plating (Au/Ni) is known to be compatible with GF-PdNi and it has been produced and used since nearly 35 years for billions of connectors. Thus, it was important to study further the compatibility of these different platings especially when Au/Ni and GF-PdNi are mated with **GCS** (Au/Hard Pure Silver/Nickel) and **GCSb** (Gold over Hard Silver-Antimony Alloy/Nickel). In the remainder of this article, **GCS** and **GCSb** acronyms will be used to designate these alternative plated stacks. From one side, silver based platings were historically used in Automotive connectors, where we have usually relatively large connector contacts with relatively high normal forces. From another side, Au/Ni and GF-PdNi are historically mainly used for relatively mid-size and low size connectors contacts with relatively moderate or much lower normal forces. We have examined the contact pressure (Hertz Stress) for 88 connector families commercialized by the top twenty connector manufacturers. These 88 connectors families mean in practice thousands of connector models as usually every connector family could cover up to twenty+ versions of connectors which all use the same contact system and the same contact constriction model between male and females. The output of this preliminary statistical examination, shown in Table 1, should not be considered exhaustive, but simply to identify trends. The result was very interesting as most (> 75%) of automotive connectors are using electrical contacts with a Hertz stress ranging between 200 MPa and 700 MPa while the absolute majority of electronic connectors (> 90%) are using contacts with Hertz stress ranging between 600 MPa and 1400 MPa.

So, we need to validate that the plating systems which are proven systems in automotive, are compatible, in terms of resistance to wear, with electronic applications where contact pressures are quite different. Although some scientists believe that contact pressure complexity is a barrier to its usage as a parameter in

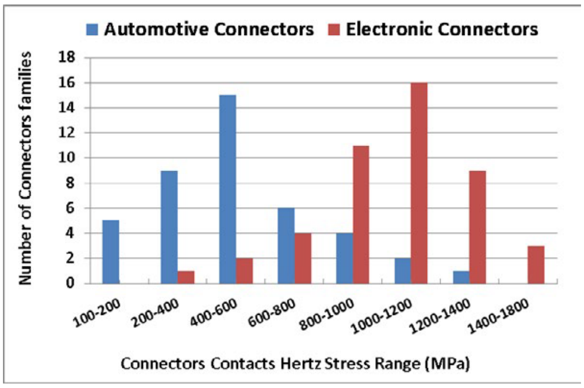


Fig.1 : Distribution of electrical contacts Hertz stress for 88 connectors families (2011-2019)

contact design [8,9], today the digital computing and numerical simulation capabilities are enormous and allow us to bypass these limitations. We also need to determine the conditions where these different plating systems perform the best (compatibility) when cross-mated, avoiding excessive precious metals wear of plated headers or receptacles.

1.1.1 Connector contact pressure calculation background

In practice, the huge development of digital electronic applications coupled to miniaturization requirements, have lead connector designers to reduce regularly the geometrical dimensions of electrical contacts while keeping constant the normal forces which are recommended by international standards. Most of these normal forces were specified in 1980's when there was much less miniaturization. The electronic connectors application went through highly accelerated miniaturization in the past 15 years while for automotive industry, this miniaturization was much slower. The current development of autonomous vehicles will probably change this quite quickly. In all cases, we can say that we are using today electronic connectors with much higher contact pressures compared to the 1970's and 1980's, while the trend in plating is to reduce the plating thicknesses for precious metals. Gold thickness of 1.27µm (50µin) and 2.0µm (80µin) were a standard in the early 1990's while today we use gold thicknesses ranging between 0.25µm (10µin) and 0.76µm (30µin) most of the time. So, this is another reason to validate compatibility between different plating systems under different contact pressures. This work shows the compatibility between Au/Ni, GF-PdNi, GCS and GCSb to ensure up to 250 mating cycles of intermateability, without excessive wear, under Hertz Stress ranging between 400 and 1300 MPa.

1.1.2 Contact pressure calculation

The Hertz theory is used to calculate the apparent contact area when two solids are pressed one against the other, provided the part geometries as well as the Young modulus and the Poisson coefficient are known. The Hertz theory assumes that the material deformations are elastic, and the contact area is small compared to the size of the solids. Without going deeply into Hertz theory it is important to note the fundamental equations. If we have two solid spheres having an elastic contact under a normal force (F), the spheres are characterized by their radii (R_1) and (R_2), their Young moduli (E_1) and (E_2) and Poisson coefficients (ν_1) and (ν_2). The contact area is a disc of radius "a". From a mathematical point of view, the problem is equivalent to the case of a sphere of radius R and Young modulus E pressing onto a plane of infinite rigidity, R and E being given by:

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2} \qquad \frac{1}{E}=\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2} \qquad \text{(EQ1)}$$

The calculation was published by Hertz in 1882 where "a" is : $a=\sqrt[3]{\frac{3FR}{4E}}$ (EQ2)

The local contact pressure at a distance “r” from the centre of the disc is given by:

$$p(r) = \frac{3F}{2\pi a^2}\left(1 - \frac{r^2}{a^2}\right) \quad \text{(EQ3)}$$

The average contact pressure is:

$$p_m = \frac{F}{\pi a^2} = \frac{2}{3}\sqrt[3]{\frac{6}{\pi^3}\frac{FE^2}{R^2}} \quad \text{(EQ4)}$$

The maximum stress within the material is in the range of:

$$0.3 p_{\max} \approx 0.15 \frac{F}{a^2} \quad \text{(EQ5)}$$

Those calculations assume that the deformation of the materials are purely elastic, which is not always the case in real world applications, especially for normal forces and contact geometries generating very high contact pressures. These equations consider that the surface state is perfect while in real contacts we have always certain level of roughness although it could be extremely low. Plated layers could also go through partial plastic deformation during mating and unmating cycles [10]. Thus, it is commonly noted that a contact pressure calculation for connectors is valid for a certain specific moment and certain surface state. In other words, the contact pressure we are calculating is between male and female contacts before durability testing. We call that the nominal initial contact pressure. During durability cycles, wear occurs in the contact area resulting in Hertz stress variation, probably due to modifications in contacts spot size because of elasto-plastic or, eventually, plastic deformation [10,11]. For simplification, we always refer to the initial nominal contact pressure. Finally, Hertz stress equations consider only the 2 solids which are homogeneous material with well-defined Young Modulus. For connectors, we use plated base material and to be more representative of reality, we measure and calculate the composite Young Modulus of the total plated stack using a nanoindentation technique [11]. This methodology is commonly used as it gives more accurate Hertz stress values, which takes into account the barrier underlayer plating (nickel in our case) as well as the final precious metal(s) layers.

2 Experimental

Durability testing was simulated in the laboratory using a tribometer and validated, in most of cases, on real connector contacts. The tribometer with continuous low-level electrical contact resistance (LLCR) measurements is a Bruker UMT3 universal mechanical tester equipped with a mechanical reciprocating module. A flat real connector header contact or a flat plated specimen were fixed on this lower module. The upper module has special hemispherical coupon with different radii (between 0.8mm and 1.6mm) allowing to simulate different connector terminals receptacle geometries under different contact pressures.

A 4-wire system was used to measure ‘dry circuit’ contact resistance (Rc). A typical plated hemisphere and a schematic representation of the Rc measurement principle are shown in Figure 2. All durability tests were done according to EIA-364-09C standard. A stroke length of ±2mm and a sliding speed of 25mm/min were used. All platings were deposited using reel-to-reel plating lines including the flat and the hemispherical lab samples.

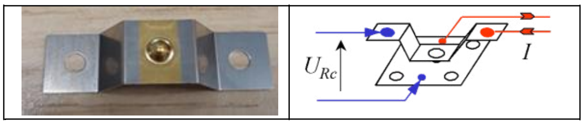


Fig.2 : Typical plated hemisphere used for durabllity simulations and wiring setup

The base material used was a commonly used C70250 (CuNiSiMg) alloy with 43% IACS conductivity. All samples and contacts went through electrochemical alkaline degreasing followed by electropolishing before plating a ductile (26%) 1.5µm ±0.25µm nanocrystalline nickel. All gold layers used an electroplated cobalt-hardened gold. Thick gold (Au/Ni) layer thicknesses were nominally 0.76µm ±0.1µm while flash gold layer thicknesses were 0.07µm ± 0.015µm. The Palladium-Nickel (PdNi) layer was plated using a low ammonia plating bath to ensure low stress PdNi layer, containing 80%Pd and 20%Ni nominal. The PdNi layer thickness was 0.69µm ± 0.16µm on contact area. The hard pure silver layers had a thickness of 3.2µm ± 0.7µm. The silver-antimony (AgSb) layers thicknesses were 2.9µm ±0.4µm and were plated at 10 A/dm² current density. They contained ~3% of Antimony (Sb). A Fischer XDV-µ polycapillary X-Ray fluorescence spectrometer (XRF) with 25µm spot diameter, was used to measure all plating thicknesses and verify base material composition. All samples were lubricated using a PerFluoroPolyEther (PFPE) lubricant. Scanning Electronic Microscopy (SEM) morphological analyses were performed using a ZEISS EVO MA-10 SEM at 15 kV operating voltage, equipped with an Oxford Instruments XMax EDS probe fitted with a 50mm² detector. Plated stack composite Young modulus and composite hardness were determined using an Anton Paar NHT3 nanoindenter.

3 Results

In this paper we have included the compatibility between Au/Ni and GF-PdNi as reference systems. We have performed 250 mating/unmating simulation cycles on hemisphere/flat setup under different contact pressures. The compatibility between these two plating systems with GCS and GCSb plating systems were studied. We provide typical observations, analysis and SEM micrographs to illustrate the methodology of investigation, but we cannot show each individual result in this short article, given the large number of plating combinations evaluated.

3.1 GF-PdNi and Au/Ni platings

Typical results under 700 MPa are shown in table 3.1 where we can see the optical images of the interface surfaces as well as the SEM/EDS elemental mapping of gold and palladium. After 250 mating cycles, when 0.76µm of Au/Ni plated on flat, we can see gold transfer to the 0.76µm GF-PdNi plated hemisphere. This local over-thickness of gold explains the dark area in the palladium elemental map at the center of hemisphere where Pd is masked by Au. We can see clearly that no excessive wear is observed and no nickel underlayer is exposed, demonstrating in this case the full compatibility and intermateability of the these two plating systems.

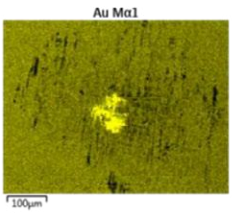
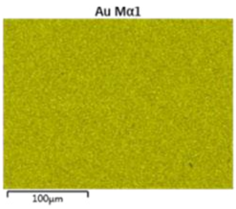
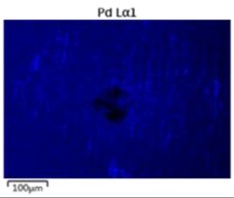
700 MPa	0.76µm GF-PdNi Hemisphere	0.76µm Au/Ni Flat
Optical		
Au EDS Mapping		
Pd EDS Mapping		N/A

Table 3.1: GF-PdNi compatibility with Au/Ni at 700 MPa of contact pressure

In practice, we always notice that, when hemispheres are plated with 0.76µm GF-PdNi and flats are plated with 0.76µm of Au/Ni, these two systems are perfectly compatible even at extremely high contact pressure such as 1300 MPa or even 1400 MPa. This is what is expected of such high durability GF-PdNi plating. To illustrate an incompatible case, table 3.2 shows the surface wear after 250 durability cycles for a hemisphere plated with Au/Ni and a flat sample plated with GF-PdNi, under 1300 MPa, which is a very high nominal initial contact pressure. Visually speaking, we could say that surfaces are acceptable as optically we still observe the golden color on the hemisphere. But we start seeing some greyish shades. That indicates that we are close to the nickel underlayer. EDS elemental mapping shows that the remaining yellow golden color is the result of an extremely thin layer of gold, probably less than 15~20nm thickness. In fact, we are starting to expose the nickel underlayer that is quite visible with EDS mapping. A quick examination of the flat samples shows that we have gold transfer from the hemisphere to the flat GF-PdNi surface which shows gold over-thickness in some areas on the wear track. The exposed nickel underlayer, calculated using an image treatment software, is less than 10% of the total contact area. This value of 10% of exposure is the maximum limit defined by Telcordia GR-CORE-1217 standard concerning the wear-through of contacts noble metallization of separable contact interfaces [12].

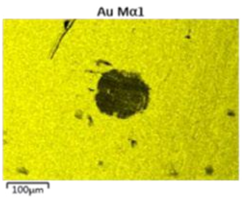
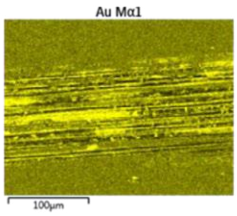
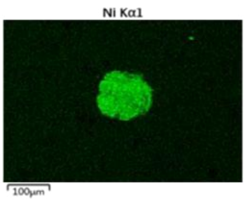
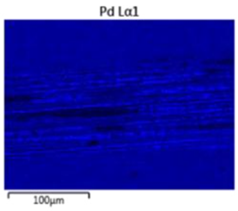
1300 MPa	0.76µm Au/Ni Hemisphere	0.76µm GF-PdNi Flat
Optical		
Au EDS Mapping		
Ni or PdNi EDS Mapping		

Table 3.2 : GF-PdNi compatibility with Au/Ni at 1300 MPa of contact pressure

Mechanically speaking, we can say that at 1300MPa of nominal Hertz stress, the 0.76µm Gold plating on female contact is incompatible with 0.76µm GF-PdNi for 250 mating/unmating cycles. Indeed, we are starting to have excessive wear. One could argue that remaining excessively thin gold layer could be acceptable, because if we examine the evolution of contact resistance (Rc) during these 250 mating cycles, shown in Figure 3, we can notice that Rc is extremely stable and quite low during the entire experiment. This is a positive element in favor of accepting a final residual gold layer of a few nm of thickness. Nevertheless we can also estimate that such final thin gold layer is not enough to protect the electrical contacts against corroding and aggressive atmospheric contaminants or pollution gases. Consequently, we can consider that under 1300MPa of Hertz stress, these two platings are incompatible, or, 1300MPa is the maximum contact pressure for compatibility. To re-establish this compatibility, we should either reduce the maximum

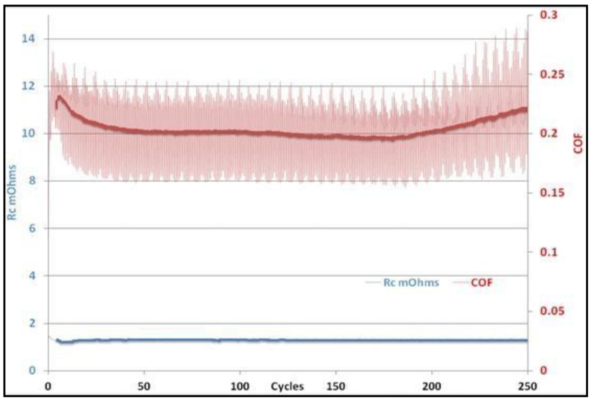


Fig.3 : Contact resistance and coefficient of friction evolution during 250 durability cycles between Au/Ni hemisphere and PFPE lubricated GF-PdNi flat under 1300 MPa of contact pressure.

number of mating/unmating cycles (durability limits), change connector contact design to reduce nominal contact pressure, reduce normal loads if this is possible or increase the precious metal layer thicknesses.

3.2 Au/Ni and GCS platings

To illustrate the wear behavior of a hard pure silver based plating system, we used the GCS plating which has a gold flash layer on top surface to protect silver. It is important to note that the Young modulus for a GCS plating is around 110~115 GPa which is much higher than the Young modulus of pure soft silver plating which is in the range of 85~90 GPa. We expect better shear resistance of GCS plating during durability cycling. But GCS still has a lower Young modulus than Au/Ni plating which is in the range of 160~170 GPa. It is also much lower than the modulus of GF-PdNi plating which is between 245 and 255 GPa. Consequently, for a constant normal force, when using a gold plated hemisphere, replacing the GF-PdNi on the flat surface by GCS plating will reduce the contact pressure by 200~300 GPa. This means, that it is extremely difficult to reach, in real GCS plated connectors, such 1300 MPa of Hertz stress. In practice, a contact pressure of 1000 MPa is considered as extremely high for a silver based plating system. This is also what explains that for automotive silver plated connectors, we use high normal forces which are practically not allowed to be used for gold plating. These high normal forces provide enough contact pressure to break the blackish silver sulfides (Ag_2S), formed on silver surface, and retrieve the excellent electrical conductivity of silver plating. Table 3.3 shows the results, after 250 durability cycles, between a hemisphere plated with 0.76µm of Au/Ni and a flat plated with GCS, at 700 MPa. Visually we see significant wear tracks and quite large contact area on the gold plated hemisphere. When performing elemental mapping on the hemisphere, we can notice silver transfer from the flat surface, which is expected knowing that silver plating is usually subjected to galling. The presence of a contact lubricant has significantly reduced such galling in this case, compared to what is historically observed with non-lubricated silver plating. This silver transfer on the hemisphere partially masks the signal of the gold layer where we can see a non-yellow (black) spot. We say partially, because EDS mapping of elemental nickel shows few nickel spots from the nickel underlayer

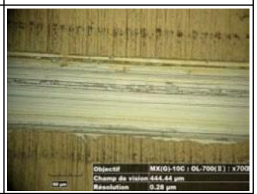
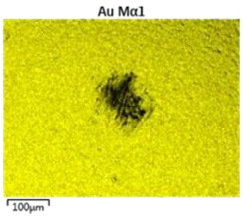
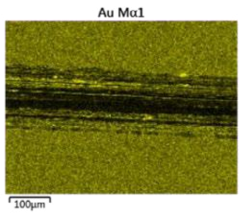
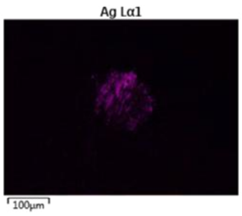
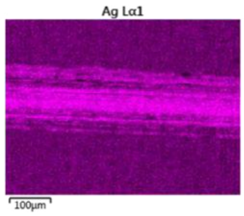
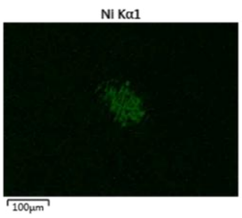
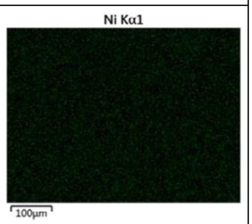
700 MPa	0.76µm Au/Ni Hemisphere	GCS Flat
Optical		
Au EDS Mapping		
Ag EDS Mapping		
Ni EDS Mapping		

Table 3.3 : Au/Ni compatibility with GCS at 700 MPa of contact pressure

This limited worn gold zone constitutes less than 5% of the total measured contact area and it was not systematically observed. We have shown, on purpose, the worst case for pedagogical illustration. A quick examination of the flat sample shows that we are still on the hard silver layer, in all cases, and there is never wear-through to the nickel underlayer. A silver layer thickness measurement using micro-XRF shows that only 60% to 70% of silver was worn after 250 mating cycles at 700 MPa. Using GCS and Au/Ni plating seems to be a robust option provided that we respect certain Hertz stress rules. In other experiments, mating GF-PdNi to GCS has shown also to give excellent results, even better than traditional Au/Ni plating, ensuring a very high durability plating couple. In practice, we notice that mating a silver plating contact to a non-silver plated contact gives better durability results than when it is mated to itself because we have less galling and more abrasion [13], which is the most frequent wear mechanism of silver.

3.3 Au/Ni and GCSb platings

GCSb in this study is a variant of GCS plating. We use a silver-antimony (AgSb) alloy instead of pure hard silver. This AgSb alloy is known to have much higher composite hardness up to 180 Vickers compared to hard pure silver limited to 120~135 Vickers. We measured its Young modulus and it is in the range of 150 GPa. The presence of an alloying element will slightly increase the silver electrical resistivity but we still observe very low electrical contact resistance between hemisphere & flat, as shown in Fig.4 under different contact pressures. Rc remains stable and very low at 900 MPa while at 400 MPa and 700 MPa, we notice a 3 mΩ average increase, as we have fewer contact spots when we reduce Hertz stress. These 3mΩ could be significant for some power connector applications. This is an additional reason to study and select the appropriate contact pressure when using different plating systems on male and female contacts.

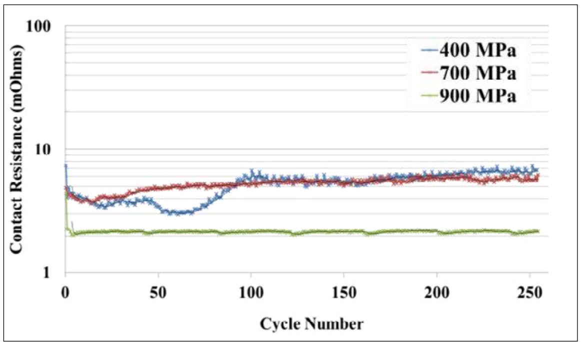


Fig.4 : Contact resistance evolution vs. durability cycles between Au/Ni hemispheres & GCSb flats

This GCSb variant indeed provides better durability in several cases given that we have better resistance to shear vs. pure silver, as well as higher hardness silver. It has been proven that the ratio between hardness and Young Modulus is much more correlated to wear extent than hardness alone [14,15] and consequently this is an important difference with GCSb. Table 3.4 presents the surface wear after 250 durability cycles, at 900 MPa of Hertz stress between a hard Au/Ni plated hemisphere and a GCSb plated flat. The optical high resolution photo of hemisphere shows that gold plating is almost not scratched and the little whitish color is the result of silver transfer from flat to hemisphere. Concerning flat GCSb plating, the elemental analysis micrograph shows that gold is removed but the AgSb layer is practically intact and no wear-through is observed to the nickel underlayer. We may think, at this stage, that with a harder Silver alloy with superior Young modulus, we may be able to use very high contact pressures, observed in many miniaturized connectors nowadays.

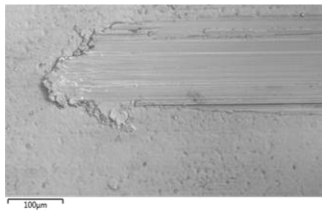
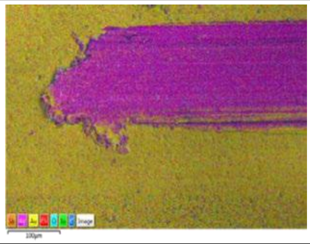
900 MPa	0.76µm Au/Ni Hemisphere vs. GCSb plated flat (Au/AgSb/Ni)
SEM Micrograph o flat	
EDS Mapping on G	
3D Photo : Gold plated hemisphere	

Table 3.4 : Au/Ni compatibility with GCSb (Au/AgSb/Ni) at 900 MPa of contact pressure

Unfortunately, even when alloying silver (Ag) with antimony (Sb), we still observe silver galling occurring, if we try to work in such high Hertz stress range. Table 3.5 shows the SEM micrograph of the GCSb surface after 250 mating cycles under nominal contact pressure of 1200 MPa.

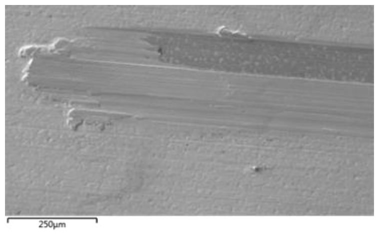
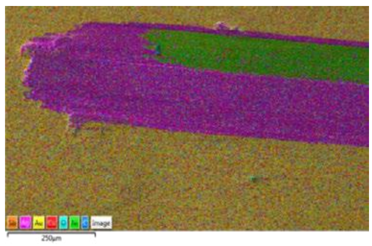
1200 MPa	0.76µm Au/Ni Hemisphere vs. GCSb plated flat (Au/AgSb/Ni)
SEM Micrograph of flat	
EDS Mapping on GC	

Table 3.5 : Au/Ni compatibility with GCSb (Au/AgSb/Ni) at 1200 MPa of contact pressure

We notice significant silver wear on the track. EDS mapping shows that nickel underlayer is exposed. Given the limited number of wear debris around the wear track, we are probably again under a galling wear mechanism coupled to limited abrasion. We have flakes of Silver detached from the surface of flat.

Unfortunately, alloying Ag with Sb and applying a lubricant does not completely offset the galling mechanism. Under such high contact pressures, the lubricant layer between male and female contacts becomes extremely thin and inefficient to reduce the intrinsically high coefficient of friction. The flash gold on top of AgSb is playing the role of a solid lubricant, same as for GF-PdNi, but it is gradually worn during the 250 durability cycles. The maximum durability cycles before wear-through, under different contact pressures, will be published separately.

3.4 Compilation of results & discussion

After showing above several examples of the investigation methodology, tables 3.6, 3.7 and 3.8 show the compilation of all obtained results from a wear compatibility point of view. When the intermateability result case is highlighted in green, this means that no wear-through of noble metal layer down to the nickel underlayer was observed on both flat and hemisphere contacts. When the case is highlighted in red, it is not advised to mate these 2 plating systems together under the specific mentioned contact pressure given we have significant wear down to non-noble barrier underlayer. When the intermateability case is highlighted in dual green-orange color or only in orange, it means that we have slight wear, less than or close to the tolerable 10% of contact area, specified by the Telcordia standard. We consider that this is the maximum contact pressure which we could adopt according to application specifications. Table 3.6 shows that 0.76µm Au/Ni plating is fully compatible with GF-PdNi up to 1200 MPa of contact pressure, and we start seeing wear-through down to the Ni layer of Au/Ni plated hemisphere starting 1300 MPa.

All Samples are lubricated	0.76µm Au/Ni Plated Hemisphere ; 250 durability cycles										
	Contact Pressure Range										
Flat Plating	400	500	600	700	800	900	1000	1100	1200	1300	1400
0.76µm GF-PdNi											
0.76µm Au/Ni											
GCS											
GCSb											

Table 3.6 : Compatibility of Au/Ni when plated on hemisphere with 3 other plating systems according to various contact pressures

In practice, this value shows also to be the limit for 250 mating cycles intermateability for Au/Ni plating with itself. It is interesting to note that when the flat is plated with GF-PdNi, this plating did not show any damage as we have gold transfer from the 0.76µm thick layer on hemisphere to the flat. When the flat is plated with similar Au/Ni plating, the gold transfer is mutual and we could observe Nickel exposed spots randomly on both hemisphere and flat. This is a known electroplated gold wear mechanism but in our case, the transfer phenomena seems to be significantly increased under high contact pressures. When mating a Au/Ni plated hemisphere to a GCS plated flat, the compatibility of these two systems is limited up to 700MPa only and 800MPa is considered as the inflection point where we should not mate these plating systems together. We have significant silver transfer from flat to hemisphere. What was not expected is the transfer of gold from hemisphere to GCS plated flat and we observed the first significant nickel underlayer exposure of Au/Ni layer at 800 MPa. Lubricant is known to reduce galling and flaking extent for metallic coatings, but it seems that gold and silver solid solution is formed under the pressure accelerating the transfer (wear) of gold on hemisphere. When plating GCSb, these two systems are compatible till 900MPa. Nevertheless, we observe in this case more conventional debris on both sides, showing that we have different wear mechanisms between GCS and GCSb. Alloying silver with 3% of Sb (Antimony) is generating quite a different plating system. When examining Table 3.7, we immediately notice that when using a GF-PdNi plated hemisphere vs. Au/Ni plated flat, we have an improvement in wear compatibility between these

All Samples are lubricated	0.76µm GF-PdNi Plated Hemisphere ; 250 durability cycles										
	Contact Pressure Range										
Flat Plating	400	500	600	700	800	900	1000	1100	1200	1300	1400
0.76µm GF-PdNi											
0.76µm Au/Ni											
GCS											
GCSb											

Table 3.7 : Compatibility of GF-PdNi when plated on hemisphere with 3 other plating systems according to various contact pressures

All Samples are lubricated	GCS Plated Hemisphere ; 250 durability cycles										
	Contact Pressure Range										
Flat Plating	400	500	600	700	800	900	1000	1100	1200	1300	1400
0.76µm GF-PdNi											
0.76 µm Au/Ni											
GCS											
GCSb											

Table 3.8 : Compatibility of GCS when plated on hemisphere with 3 other plating systems according to various contact pressures

platings. GF-PdNi vs. GF-PdNi shows in this case its higher durability, technically speaking, compared to other plating systems. Using GF-PdNi plating on hemispheres allows us to use GCS plating on flats up to 1000 MPa before we observe adhesive wear on these flats. When plating the flat with GCSb, compatibility with GF-PdNi is up to 1100 MPa and then we start observing abrasive wear. Above 1200MPa, we observe additional oxidation wear beyond abrasion debris which may be the result of localized frictional heat generation [13] at such high Hertz stress for these two high stiffness platings. Nevertheless, this remains a hypothesis as durability tests were conducted at moderate sliding speed of 25mm/min and frictional heat generation is theoretically minimized. Further investigations are ongoing to understand the mechanisms of such oxidation. The results in table 3.8 show that when using GCS on the hemisphere, the maximum contact pressure which can be used is 1000MPa when mating to a 0.76µm Au/Ni plating or GCSb on flat samples. This is already a very high contact pressure for a silver based plating. It is interesting to notice that when using GF-PdNi flat samples vs. GCS on hemisphere, we have much less wear, for GCS evidently, compared to the opposite configuration discussed above. When the flat is plated with GF-PdNi, the maximum contact pressure to be used is 800MPa while it was 1000MPa in the opposite case. The continuous solicitation of GCS plating, during 250 durability cycles, when plated on hemisphere (simulating female contacts), leads to continuous galling and transfer of silver from hemisphere to flat, resulting in faster nickel underlayer exposure which is not desirable for corrosion resistance issues. Another important observation is the maximum 700MPa contact pressure when GCS is mated to itself. We have in this case maximum galling, although attenuated by lubrication. Nevertheless, 700MPa with both parts plated with GCS is obtained with normal forces which could generate a contact pressure higher than 1000MPa if the plating would have been GF-PdNi or Au/Ni on both parts. In other words, using GCS as a plating system is still very interesting from an electrical and economical point of view, provided that connector contact designer would forecast this since the beginning. All the plating systems investigated above have various hardness and Young moduli and many results were unexpected. All this suggests and confirms that hardness is not the main major parameter influencing wear evolution [16]. Again, it seems that the ratio of hardness to Young's modulus correlates much more accurately to the wear behaviour on multi-layered coatings. The existing mathematical relationship between this ratio (hardness/Young Modulus) and the wear observed on our real connectors and the tribological hemisphere/flats will be presented elsewhere.

4 Conclusions

We have presented in this investigation work, the compatibility ranges for different plating systems according to the nominal initial contact pressure of sphere/flat contact configuration, up to 250 durability (mating/unmating) cycles. The objective was to offer connector designers some guidance when developing a connector with several plating options, as compatibility, in terms of wear resistance, will vary according to defined normal force and thus contact pressure. This work covered traditional gold plating, the historical GF-PdNi alternative plating, as well as 2 other silver based platings which are used now in the industry. Using asymmetrical platings (different platings on male and female contacts) allows higher performance and in some cases it can simultaneously reduce plating costs.

5 Further inquiries

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