Comparative performance study of different conventional silver and hard silver-plating processes for connector applications

Antoine Fares Karam, Anthony Franchini, Damien Comte, Ana Torrealba, Sophie Noël, Aurore Brézard-Oudot, Charles Copper, Jeffrey Toran

Comparative performance study of different conventional silver and hard silver-plating processes for connector applications

Antoine Fares Karam[1], Anthony Franchini[1], Damien Comte[1], Ana Torrealba[1,2], Sophie Noel[2], Aurore Brézard-Oudot[2], Charles Copper[3], Jeffrey Toran[3]

[1]Amphenol Communication Solutions, Besancon, France.
[2]Université Paris-Saclay, CentranleSupélec, Sorbonne Université, CNRS, Laboratoire de Génie Electrique et Electronique de Paris, Gif-sur-Yvette, France
[3]Amphenol Communication Solutions, Etters, PA, USA.

Abstract

Silver plating processes have become key technologies for connector applications in the past 10 years. The significant utilization increase of various pure silver plating types and various silver alloys, for electrical contact surface finishing, can be attributed to several factors such as the development of electrical vehicles, the continuous rise of many connector operating temperatures up to 150°C and 180°C, where Tin plating cannot be used anymore, the increase of smaller-size power connectors requiring higher electrical conductivity than what can be provided by hard gold plating, and finally the severe increase of Gold and Palladium metal prices. Connector users sometimes have difficulties to understand the performance differences between all the existing silver-based plating offering. This work presents a summary between several widely used commercial silver-based deposits such as soft or hard pure silver, Antimony or Bismuth based silver alloys as well low friction silver coatings. Some key tribological, electrical and mechanical characteristics are compared. Some structural surface analysis is carried out to understand certain behaviour differences. The objective is to better define the optimal performance domain of each type of silver-plating technologies.

1 Introduction

Silver plating processes are nowadays very important plating processes in the field of the electronic connectors and overall electrical and electronic interconnection applications. Historically, connectors were and are still using gold plating **(Au/Ni)** as the main plating for male/female contact interfaces. Gold Flash over Palladium-Nickel **(GF-PdNi)** was developed in the late 1970's and commercialized starting 1986 [1] as an alternative. This GF-PdNi plating was globally a very successful approach as it was adopted, (still used today), by almost all connector manufacturers [2]. Several other alternative plating processes to Au/Ni were developed and introduced in the early 2000's such as Gold over Nickel-Phosphorus [3]and Gold over other various barrier layers like Nickel-Tungsten, Cobalt-Tungsten or even Cobalt-Nickel [4]. All these alternative processes are, technically speaking, very successful, but did not become, not yet at least, the "industry standard", in a similar way to Au/Ni and GF-PdNi, for the main reason that Gold metal prices were constantly increasing, from an average of 300$/TO, in early 2000's to nearly 1900 $/TO nowadays. This steady increase of Gold prices had pushed a lot of researchers and companies to start developing Silver based plating processes as a more cost-effective alternative. Then, almost simultaneously, we have assisted to the advent, in 2010, of the first mass-produced 100% electrical vehicles (EVs), which have boosted, within the electrical interconnection systems field, the innovations related to Silver based plated connectors. We have entered the new world of electrification, which is not only limited to the automotive industry, but also to the electronic and electrical devices segments, where we need more and more autonomy, more electrical conductivity, and more resistance to higher temperatures. Electronics are progressively switching from classes 70°C and 85°C to classes 105°C, 125°C, 150°C, 180°C and more recently to class 200°C [5]. It is important to note that above 125°C, we cannot use Tin plating due rapid oxidation and formation of Tin Oxide on the surface of electrical connector contacts. This progressive change of technical specifications and the significant price increase of gold metal have favoured the development of many kinds of new silver-plating processes instead of the usual historically known gold plating processes. It is useful to make a brief comparison between Gold- and Silver-plated layers [6]. Gold presents the ad- vantages of being a very good conductive material (electrical resistivity of 2.44 μΩ.cm), of being a noble metal with excellent resistance to corrosion and of pre- senting naturally a very low coefficient of friction mak- ing it an excellent solid lubricant, which is favourable for connector higher durability (resistance to mating and unmating cycles). Gold is also known to have excellent resistance to fretting-corrosion, and thus to improve connectors resistance to vibration. Conventional silver plating has the lowest electrical resistivity among precious metals (electrical resistivity of 1.59 µΩ.cm). That is what explains its wide usage, since the mid 1990's, in the automotive industry and mainly for power applications. Conventional silver is known also to have a low hardness (practically lower than 100 Vickers), low young modulus (practically around 80~90 GPa) and a very poor coefficient of friction, between 0.8 and 1.4 according to applications. That's why Silver-plated connectors are historically rated for 50 mating/unmating cycles only, although the typical silver plating thicknesses on electrical connectors is relatively high (between 4µm and 10µm in most of cases) [7]. That's much higher than the usual thickness range that is used for Gold or GF-PdNi platings (between 0.4µm and 1.27µm). Finally, Silver is very sensitive to sulfidation and it requires the use of organic or inorganic anti-tarnishing solutions for surface protection, given that silver sulfide (Ag2S) tarnishing compounds have an electrical resistivity of 17.3 mΩ.cm, that is 11000 times higher than pure Silver. Even if this will not degrade signal or low-power connectors performance till failure, it is still critical for mid- and high-power connectors. Although this makes a certain number of disadvantages for silver plating, its moderate cost added to its good resistance to fretting-corrosion overall, does really offset these disadvantages in many applications. The huge increase of silver-plated components, connectors and interconnects modules is a good proof of evidence. In the remainder of this manuscript, we will refer to this conventional silver plating as "soft-silver" or (sAg).

1.1 Development of various silver-plating systems

Starting in the mid 2000's, we have seen an impressive number of patents and many introductions of new industrial processes describing improved or advanced silver or silver-alloy surface finishes. Many new silver-plating deposits were developed with pure silver but showing much higher hardness and Young moduli. These commercially available silver-plating baths usually use different types of additives to modify the crystallographic structure of the plated silver and favour certain crystallographic textures according to needed mechanical properties [8]. Such 'hard' silver deposits present hardness values ranging between 110 and 140 Vickers usually. We will refer to this silver plating family as hard pure silver or (hAg). Plating chemicals suppliers also introduced many silver-alloy deposition processes. These silver alloys show relatively high hardness such as silver-antimony (AgSb), silver-palladium (AgPd) and silver-bismuth (AgBi) [9]. We have seen also the introduction of other varieties of silver deposits, but these other types of plating will not be part of our current study as we are only focusing on silver-alloys electrodeposits that are mainly used for connector separable interfaces coatings. The objective of all these special hard pure silver or hard silver alloy coatings, was to extend silver usage to more and more electronic connectors, where the usual 50 mating/unmating (durability) cycles are not enough, and where typical 200 and up to 500 durability cycles are needed. In practice, these special plating processes started to compete with historical Gold and GF-PdNi plating. Moreover, under the pressure and the insistent inquiries of hybrid and electrical vehicles manufacturers, as well as the demand of electrical portable device manufacturers (handheld professional and retail tooling, autonomous household appliances…), we have been assisting to the development of many connectors where several thousands of mating/unmating cycles are required. Battery connectors are the perfect application example. In practice, such higher durability silver plating is now used by most of connectors and interconnect systems manufacturers. In the other hand, we are assisting since almost five years now, to the development and the introduction of low friction silver plating processes. These processes are quite different of the historically well-known composite silver plating, where we have graphite or carbon-black or PTFE particles dispersed in a silver metallic matrix. We are talking about commercialized soft silver (sAg) or hard pure silver (hAg) plating electrolytes, where we have special copolymer soluble additives, conferring to the silver-plated deposits much lower coefficient of friction, usually between 0.2 and 0.4 without the use of an external lubrication layer. In the remainder of this manuscript, we will call these deposits Silver-Carbon (AgC) for simplification purposes. These special silver deposits are intended to reduce drastically insertion forces for silver plated connector with high count of electrical contacts (terminals), or they are supposed to allow extremely high durability for silver plate connector, much higher than what can achieve with hAg or with hard silver alloys.

1.2 Objective of this investigation work

In short, connector users have now a very wide offering of silver-based surface finishings on connectors and interconnection modules, making it sometimes very complex to understand which type should be selected for their applications. The objective of this paper is proceed to a comparative benchmark and characterization between sAg, hAg, AgBi,AgSb and AgC in order to better identify the differences between these deposits and better guide connector users during the selection or choice of the connector plating. Another interest of this work is to offer an objective performance comparison of these different coatings on the same test vehicle using standard test procedures. Our aim is not to decide which is the best surface finishing technology, but to give product engineers and designers enough elements to determine what could be the best choice for their specific application or finished product. Any experienced scientist or engineer knows perfectly that the absolute ultimate surface finishing technology does not exist. What we are looking for is simply the most adequate plating for a specific application or end-product.

2 Experimental

Durability testing and fretting-corrosion tests were 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, using 4-wires method, is a Bruker UMT3 universal mechanical tester equipped with a mechanical reciprocating module interchangeable with piezoelectric 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 (1.0mm, 1.2mm and 1.4mm), allowing to simulate different connector terminals receptacle geometries under different contact pressures. A typical plated hemisphere and a schematic representation of the contact resistance (Rc) measurement principle are shown in Figure 1. All durability tests were done according to EIA-364-09C standard. A stroke length of ±2mm and a sliding speed of 127mm/min were used. All platings were deposited using reel-to-reel plating lines including the flat and the hemispherical lab samples.

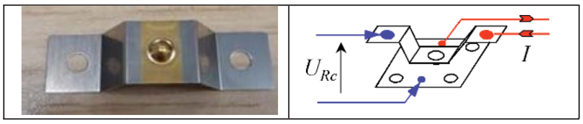


Fig.1 : Typical plated hemipshere used for durabllity simulations and wiring setup

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. Thick, soft silver (sAg/Ni) or hard pure silver (hAg/Ni) layers thicknesses were nominally 4.2µm ±0.2µm. The hard silver-antimony (AgSb) and silver-bismuth alloys layers had a thickness of 4.2µm ±0.4µm. The silver-carbon (AgC) layers thicknesses were 4.1µm ±0.3µm. All layers were plated at 10 A/dm² current density except for AgC that was plated at 6 A/dm². AgSb contained ~1.4% of Antimony (Sb), AgBi contained ~1.1% of Bismuth (Bi) and AgC contained between 2.4% and 4.3% of Carbon under non-identified chemical form (commercial bath formulation). 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. 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. All 3D profiles were achieved using a Bruker Contour GT monochromatic green light interferometer. In most of testing, both male and female contacts had similar plating types. But each time we needed to obtain specific comparative electrical or mechanical property value, we have used a counterpart which was plated with conventional hard gold with a nominal layer thickness of 0.82µm ±0.2µm.

2.1 Contact pressure calculation

In several cases, we cannot simply use normal forces to compare plating performance durability accurately. Connector designers usually adapt their design geometry and the contact normal forces to the plating to be used for the connector. Consequently, an approach using contact pressure (Hertz stress) is much more accurate and representative of reality [10]. 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. It is important to note the fundamental equations we used. 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:

$$a = \sqrt[3]{\frac{3FR}{4E}} \qquad \text{(EQ2)}$$

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

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

The average contact pressure is given by:

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

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

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

Each time we needed higher accuracy benchmark, we have used this Pm average contact pressure, which gives us much better understanding to observed phenomena. Hertz theory assumes that the material deformations are purely elastic, and the contact area is small compared to the size of the solids. Consequently, we avoided, in all our tests to use normal forces that could lead us to reach plastic deformation ranges. In real field applications it is not always the case. Sometimes we are obliged to use high normal forces with tiny contact geometries, which generates very high contact pressures at the contact interface. Nevertheless, these cases remain relatively limited. Hertz equations consider that the surface state is perfect, while in real world contacts, we have always a certain level of roughness. In these investigations, samples were electropolished during plating processing, so we may consider the impact of this roughness to be relatively negligible. Plated layers could also go through partial plastic deformation during mating and unmating cycles [11]. It is commonly admitted 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 contact 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 [12]. This methodology is commonly used as it gives more accurate Hertz stress values, given it takes into account the impact of barrier underlayer plating (Nickel in our case) as well as the final precious metal(s) layers (different silver-based layers in our case) [13].

3 Results

In this paper we have decided to compare and study the electrical characteristics of the different silver-based deposits, then to compare the durability performance under 2 different contact pressures corresponding to normal forces that are typically used on silver plated connectors families. Fretting-corrosion benchmark is following, with a clear objective of determining which type of silver-based deposits would be more adequate for the different connector's application. We insist on the fact, that the main objective of this investigation work, is to give objective guide rules for connector designers.

3.1 Benchmark of generic deposits characteristics

It is evident that electrical properties are the most important for a plated deposit to be used for connectors. In order to make a straight benchmark, we have measured the Low Level Contact Resistance (LLCR) of the different deposits vs. a hard gold plated hemisphere, with 1.0mm radius. All results are presented in figure 1. We do not present on this chart the like-to-like (both male and female contacts have the same plating) LLCR measurements curves, for the simple reason that we wanted to fix the characteristics of the first constriction half of the separable interface. We decided to evaluate only the intrinsic electrical properties of each deposit, while reducing the impact of number of "a" contact-spots at the interface. For example, using sAg vs. sAg will generate much higher number of contacts spots due to the higher known elasticity of soft silver, which would not be necessarily the case for a much harder silver-based deposit. Measuring LLCR using a gold-plated probe will allow us to highlight the electrical resistivity of each deposit and lead to a higher accuracy comparison. At the same time, it is important to measure the hardness, using nanoindentation, of these different types of silver-plating deposits. We also measured the deposits' indentation modulus to have a better identification of their elasticity behavior. Figure 2 pre-

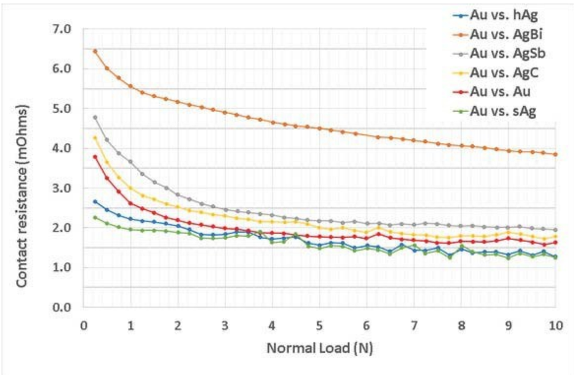


Fig.1 : Contact resistance evolution vs. normal force between between Au/Ni hemispheres & flats plated

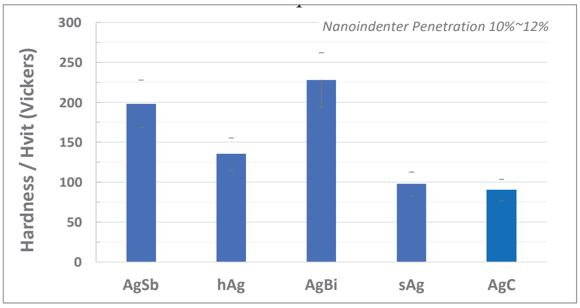


Fig.2 : Hardness (Hvit) measurements, using nanoindentation, on flats electroplated with various silver based deposits

sent the hardness measurement results and each result is the average of 50 individual measurements. The high number of measurements was required to consider potential plated layers non-homogeneity, potential partial recrystallization of silver and differential crystallographic texture distribution within the silver-based deposit that may eventually be occurring. Figure 3 is showing the indentation modulus for the different silver-based deposits. It shows clearly that AgC has much higher elasticity than conventional sAg, that have also higher elasticity then the 3 other high-hardness silver-based electroplated layers. Now we have these 2 above-studied key characteristics, we can try to understand the electrical behavior of the deposits shown in figure 1. All silver-based electrodeposits show excellent electrical contact resistance as expected, but AgBi silver alloy has clearly much higher LLCR which is 2.5~3.0 times higher than sAg. This is probably due to the intrinsic local disorders and joint defects within the silver-bismuth alloy [17] which are well documented

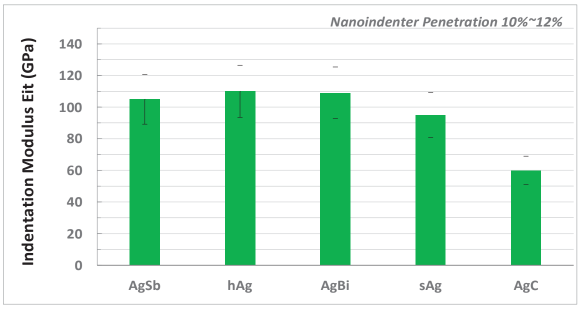


Fig.3 : Indentation modulus measurements, using nanoindentation, of flats electroplated with various silver based deposits

in the literature. The sAg deposit presents by far the lowest contact resistance whatever is the applied normal force. sAg and hAg both show lower LLCR compared to plated hard Gold which can be considered as the reference in our case. AgC and AgSb show slightly higher LLCR compared to Gold without being able to reach the same low values as Gold or pure silver deposits, even with quite high normal forces. As a preliminary remark, we can say that AgBi is much less advised for mid- and high-power connectors and ideally it should be kept for signal- and low-power connector applications. For the remaining deposits, we may distinguish 2 areas delimited by the normal force range between 2.8N and 3.2N, so an average normal force of 3N approximately. Above this range, corresponding to a contact pressure between 610MPa and 640 MPa, we may notice that the LLCR difference between plated layers is always lower than 0.8 mΩ, but always respecting the following order: AgSb>AgC>Au>hAg~sAg. Below the average normal force of 3N, corresponding to low contact pressure areas, we can see significant differences in the electrical behavior of these electrodeposits. LLCR is always respecting the following order AgSb>AgC>Au>hAg>sAg, where hAg shows higher LLCR than sAg probably, due to the lower hardness of sAg and its higher elasticity (so lower measured indentation modulus) that leads unavoidably to a much larger number "a" contact spots and automatically larger contact area [14]. But it is interesting to notice the 2.5mΩ difference between sAg and AgSb for the lowest normal force, so lower contact pressure. That's a very important increase when we are dealing with mid- and high-power connectors. Knowing that sAg will not be suitable for more than average 50 mating/unmating cycles, there is still practically 2mΩ difference between hAg, the high durability pure hard silver, and AgSb, the high durability silver alloy. And even if we use the latest AgC, low friction silver technology, this difference remains 1.6Ωm and that's a significant difference for power connectors used for batteries and for Electrical Vehicles (EV). Knowing that this lower normal force area (< 3N) corresponds to a contact pressure area between 200 MPa and 600 MPa, it is important to note that these are contact pressures that can be commonly found on many high durability connectors on the market. Potentially, we must be careful when using high power connectors within this low contact pressure area, if we are using these alternative silver deposits. We are not talking about a theoretical academic approach, but about real field connectors which performance can be seriously impacted by the choice of the silver-based deposit characteristics. In summary, when working with very high durability connectors (over 2000 durability cycles), lower contact pressures are usually used, the choice of silver-plating type is crucial if such connector will carry high electrical current intensity. When dealing with medium durability connectors (500~2000 durability cycles), we usually use slightly higher contact pressures, lower than 400~450 MPa in most cases, the performance difference between hAg, AgC and AgSb is less crucial although it remains important. For connectors where the contact pressure is higher than 600 MPa (the frontier of ~3N normal force on Fig.1), we have much more choice to select the most competitive silver-based alloy plating. The studied 5 silver-based electrodeposits are all, economically speaking, much more competitive compared to typical Gold plating or GF-PdNi plating. But the choice should be really function of the contact pressure that the connector is designed for, thus the total number of durability cycles that are required for the application.

3.1 Benchmark of durability

Following the observations listed before, we decided to benchmark the durability of these five silver-based deposits (sAh, hAg, AgBi, AgSb, AgC) at two different contact pressures. The first is a 400 MPa, corresponding to pressure value selected in the low contact pressure area, and the second is 650MPa corresponding to a pressure value selected in the higher contact pressure area. Besides, we noticed that several medium and high durability power connectors on the market, from different connectors manufacturers, are operating at contact pressures very close to these selected values. For practical reasons, durability tests were performed using a hemisphere of 1.4mm radius. Table 1 gives the normal forces allowing to obtain the nominal contact pressure used for each type of plating. Using a simple approach with a fixed normal force applied on these different silver-based surface finishings, would have been less accurate, given that each of these deposits have different hardness and different elasticity modulus [15]. Let's take 2 examples to illustrate the investigation methodology. Figure 4.1 shows the evolution of electrical contact resistance for AgC deposit (Low friction silver-carbon) as well as its coefficient of friction up to 2000 durability cycles under a contact pressure of 400 MPa.

	Normal Force to obtain:	
Plating Type	***400 MPa Contact Pressure***	***650 MPa Contact Pressure***
sAg	1.25 N	5.14 N
hAg	0.72 N	3.08 N
AgBi	0.69 N	2.84 N
AgSb	0.61 N	2.64 N
AgC	1.42 N	5.98 N

Table 1 : Normal forces applied on hemispherical coupons during durability tests on flats electroplated with various silver based deposits

We can notice that in all cases, we have very stable LLCR, except during the first few cycles where we can see minor perturbations. The friction coefficient starts at very impressive low value around 0.15 and then it gets stabilized, beyond 250 durability cycles, around 0.33 during the rest of the experiment. This is perfectly repeatable and reproducible. Each experiment was repeated 3 times. If we examine for example, in Table 2, the 3D interferometric profile of flat surface, we notice that after 100 durability cycles, wear is negligible while after 2000 durability, we are able to observe a noticeable wear track. 3D interferometry allows us to calculate accurately the worn volume and the maximal wear depth. In this case, the maximal wear depth after 2000 cycles was 1.82 µm out of initially plated 4.2µm. The SEM/EDS elemental mapping can confirm that we do not have any wear through the silver AgC layer even after 2000 cycles. In few words, this AgC deposit can

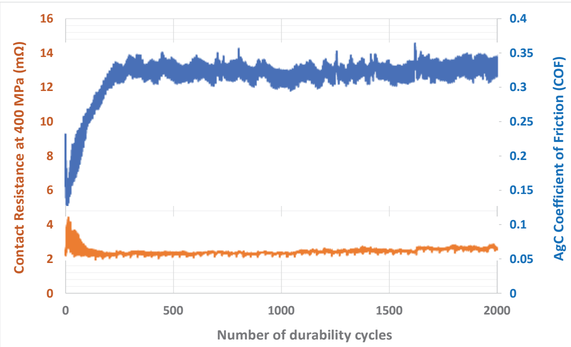


Fig.4.1 : Electrical Contact Resistance and Friction Coefficient evolution of AgC silver-carbon electrodeposit according to durability cycles

be considered for connectors, each time we need extreme tribological performance, with a limitation for certain types of very high-power connectors, given it is slightly less conductive than sAg or hAg (both are pure silver). If the application can tolerate such slightly higher electrical resistivity or if we are only looking for lower insertion forces, then this plating is the adequate one. Let's take another example of hAg under 650 MPa of contact pressure, Figure 4.2, to see how worn surface would look like under more critical operating conditions. In this example we can notice that the friction coefficient of hAg starts at 1.4, a quite common value for pure silver-plated layers, then it decreases gradually down to a minimal value of 0.45 around 450~550 cycles, corresponding to a significant contact resistance increase. We assume that we have an important wear-through occurring at this level. Then we have again a

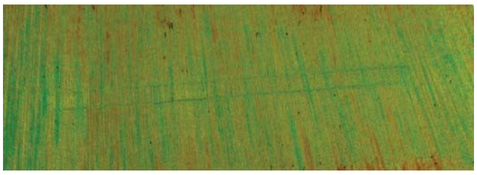
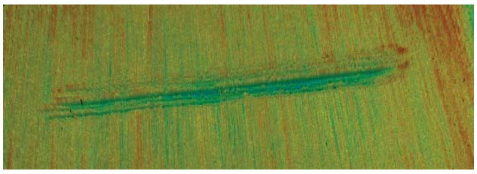
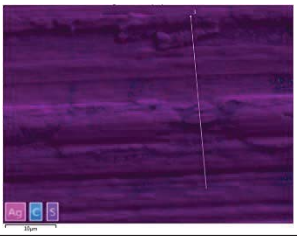
Interferometric 3D p 100 cycles	
Interferometric 3D pr 2000 cycles	
EDS Mapping 200 cycles	

Table 2: 3D interferometric profiles and SEM/EDS elemental mapping of AgC worn surfaces, under 400 MPa

low contact resistance around 1.8mΩ and a stabilized friction coefficient around 0.8, corresponding probably to contact resistance and gradual wear on copper base

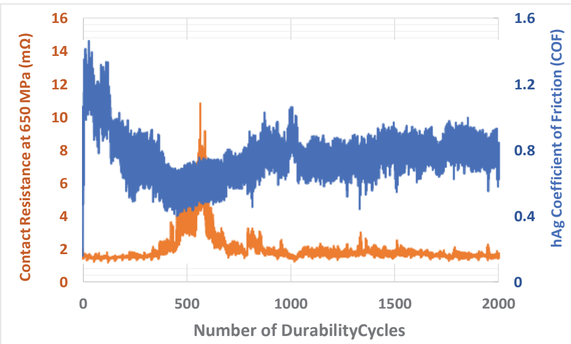


Fig.4.2 : Electrical Contact Resistance and Friction Coefficient evolution of hAg Hard Pure Silver electrodeposit according to durability cycles

material. This is confirmed by interferometric 3D profiles, given in table 3, that show example of surface state. In practice, hAg, as plated and without any subsequent lubrication, can withstand maximum 500 to 550 durability cycles. SEM/EDS elemental mapping clearly shows that at 500 cycles we still silver in the wear track, but we also started to have exposed nickel and copper base metal.

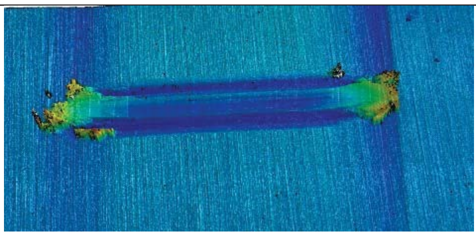
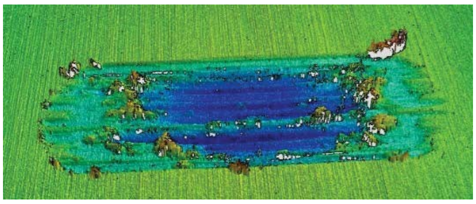
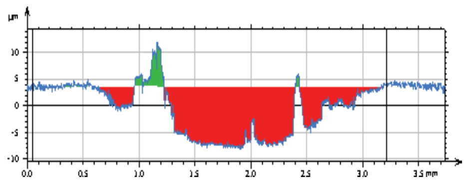
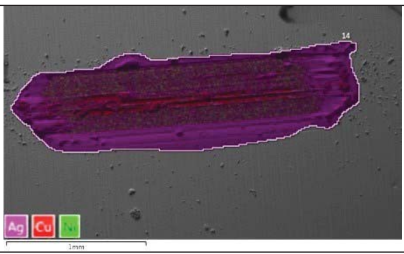
Interferometric 3D p 100 cycles	
Interferometric 3D pr 2000 cycles	
wear depth pro-file : 2000 cycles	
EDS Mapping 500 cycles	

Table 3: 3D interferometric profiles and SEM/EDS elemental mapping of hAg worn surfaces, under 650 MPa

The interferometric wear depth profiles made every 100 durability cycles show that the hard pure silver (hAg) is fully worn at ~600 cycles, which corresponds perfectly to what is given the friction coefficient curve. Now that we have given typical example of our methodology, we can summarize the durability results in table 4, given it is impossible to show in this paper all experimentation curves, interferometric 3D profiles and SEM/EDS mapping. We can notice the low friction silver AgC can exceed all other soft silver or hard silver tribological performance by far. The most interesting data in this table is the number of durability cycles before the silver layer is worn through, and the nickel underplating is exposed. If we compare the different hard silver deposits, we can notice that the highly popular AgSb is not necessarily the best performing in terms of durability, and that hard pure silver performs better in terms of resistance to wear. AgBi, the plating that exhibits higher resistivity and shows higher contact resistance compared to the other deposits (as seen earlier), shows surprisingly higher durability performance compared to AgSb and hAg.

		Number of cycles to	
Plating Type	**Contact Pressure**	**Ni exposure**	**Cu exposure**
sAg	400 MPa	~70	~1050
	650 MPa	~50	~250
hAg	400 MPa	~550	~750
	650 MPa	~270	~500
AgC	400 MPa	>2000	>2000
	650 MPa	>2000	>2000
AgSb	400 MPa	~250	~350
	650 MPa	~200	~450
AgBi	400 MPa	800	>2000
	650 MPa	350	850

Table 4: Summary of wear performance of various silver-based deposits: Number of durability cycles that these deposits can withstand wear through.

Finally, it is important to note that, although wear through of the soft silver (sAg) occurs very quickly, it takes a lot of durability cycles, more than 1000 cycles (unexpectedly), to reach the copper base material. SEM micrographs have shown that continuous galling and continuous detachment of silver flakes or particles from one side of the interface to the other side, are responsible of such “good” performance [16]. With soft silver, we don’t see an excessive number of wear particles that are pushed out of the contact area. Larger particles have clearly the tendency to remain within the wear track. In practice, to use hAg, AgSb and AgBi in high durability connectors, requiring more than 1000 mating/unmating cycles, they should be lubricated, if the final application allows it, which is not always the case.

3.2 Benchmark of fretting-corrosion

Pure Silver plating (sAg) is known to have a good resistance to fretting corrosion. The objective for this study is simply to make a summary characterization, to determine if the various silver-based deposits also have this characteristic. In pure silver plating, we already know that the galling mechanisms are typical, and explain partially such good resistance to fretting [16, 17]. Figure 4.3 shows the fretting-corrosion curves of the various silver-based electrodeposits as function of the number of fretting cycles. The frequency used for this testing is 10Hz for a stroke length of ± 30µm, typical of fretting-corrosion regimes [18]. Overall, all silver-based electrodeposits have very good fretting-corrosion resistance. Except for AgSb deposits, that showed serious electrical contact resistance increase around 150K cycles, experiments were stopped at 200K cycles without noticing serious plated layers failures nor oxidation. The related detailed fretting-corrosion study for all these deposits will be published elsewhere. Finally, we did not present SEM/EDS photos of the related deposits on hemispheres, because the overall observations were almost similar on both sides of the separable interface. The hemispherical contact area always

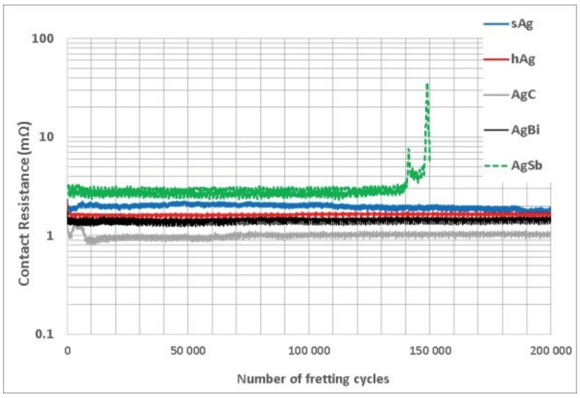


Fig.4.3 : Electrical Contact Resistance evolution of various silver-based deposits according to the number of fretting cycles under 650 MPa of contact pressure

showed higher final roughness because of silver transfer, but the wear was occurring almost simultaneously on both sides.

4 Conclusions

In this investigation work, we have presented a benchmark between widely used silver-based plating systems in the connector industry. Silver plating usage for interconnect solutions, is increasing significantly for many technical new requirements and also for economical cost reasons, so connector end-users can find in our results some clear guidance to select the right and adequate silver-based plating. Such a choice is always a compromise between durability performance, electrical performance, and fretting-corrosion resistance performance. To our knowledge, this is the first published direct benchmark under exactly similar testing conditions, and consequently this study is a perfect complementary investigation to what can be already found in technical literature, separately for each of these plating systems.

5 Further inquiries

Dr. Antoine FARES KARAM
Amphenol FCI, Global Plating Engineering Service,
2 Rue La Fayette, 25000 Besançon, France.
E-Mail: antoine.fares-karam@amphenol-fci.com

6 Literature

[1] J. Bare, A. Graham, "Wear resistance characterization for plated connectors", Proc. IEEE Holm Conf. on Electrical Contacts, 1985; pp. 147-155.

[2] J. Abys, H. Straschil, "The electrodeposition and material properties of Palladium-Nickel alloys", Metal Finishing, July 1991, pp.43-52.

[3] H. Law, E. Sproles, J. Sapjeta, "Protective treatments for gold-flashed contact finishes with a nickel substrate", IEEE Trans. Comp. Pack. Manuf. Tech, Vol.18, Issue 2, 1995, pp. 405-408.

[4] C.Schuh, A.Lund, Patent WO2007136994A3, "Methods for the implementation of nanocrystalline and amorphous metals and alloys as coatings", 2007.

[5] K. Reif, "Fundamentals of Automotive and Engine Technology", Springer, 2014, pp.154-160. ISBN 9783658039721

[6] A. Blair, "Silver Plating", Metal Finishing 76th Guidebook and Directory, Iss. 2009, pp. 227-236

[7] M. Myers, "The Performance Implications of Silver as a Contact Finish in Traditionally Gold Finished Contact Applications", Proc. 55th IEEE HOLM Conf. Electrical Contacts, Sept. 2009.

[8] A. Fares Karam, D. Anderson, "Overview of FCI new AGT Plating System for Power Connectors", Proc. 3rd Tricoat-Finishair Cong., France, 2013.

[9] Y. Zhou. C. Yuan, S.Ge, "Usability of Silver Plating and Silver Bismuth Alloy Plating on Electrical Contacts", IEEE 59th Holm Conference on Electrical Contacts, 2013.

[10] H. Fluss, "Hertzian Stresses as A Predictor of Contact Reliability", Connection Technology, Dec. 1990, pp. 12-2.

[11] P. Van Dijk, "Contacts Spots, Proc. ICEC Conference, 2000, pp. 135-140.

[12] K. Tinvisut K.; H. Branter, "Determination of mechanical properties of thin films and substrates from indentation tests", Philosophical Magazine A, 2002, Vol. 82, No.10, pp.2013-2029.

[13] A. Fares Karam, A. Franchini, S. Noel, J. Toran, "Intercompatibility of Gold, Palladium and hard Silver based plating systems for connectors applications"; Proc. 30th Int. Conf. Elec. Contacts, ICEC2020, Switzerland, p.260-267.

[14] G. Pintaude, "Introduction of the Ratio of the Hardness to the Reduced Elastic Modulus for Abrasion". Tribology: Fundamentals and Advancements; Chap. 7, pp.217-230.

[15] N. Wangyang, D. Grummon, "Effects of the ratio of hardness to Young's modulus on the friction and wear behavior of bilayer coatings", App. Phys. Lett., 2004, Vol.85, No.18, pp. 4028-4030.

[16] K. Koji, A. Koshi, "Wear Mechanisms", Modern Technology Handbook, Chap.7, CRC Press, 2001.

[17] M. Aadarsh, "Analysis of relation between friction and wear". Int. J. Mech. Eng. & Rob. Res. 2014, Vol. 3, No. 3, pp. 603-606.

[18] J. Laporte, J. Perrinet, S. Fouvry, « Prediction of the electrical contact resistance endurance of silver plated coatings subjected to fretting wear", Wear, Vol. 330-331, 2015, pp.170-181.