

Mixed reaction gold as versatile plating solution for ENIG, ENEPIG and EPAG plating

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Abstract

The surface finish on a printed circuit board (PCB) or substrate serves as surface protection and at the same time enables a variety of assembly techniques. Depending on which final finish is selected it allows for e.g. soldering connections or wire bonding by Al, Au or even Cu-wires. Surface finishes are typically characterized by different metal layers, including tin, nickel, palladium or gold. In this context the electroless or immersion plating of gold has a long history in the electronics industry. The gold plating represents a key step in different finish systems such as electroless nickel/immersion gold (ENIG), electroless nickel/electroless palladium/immersion gold (ENEPIG) and electroless palladium/autocatalytic gold (EPAG). ENIG, ENEPIG and EPAG finishes are characterized by their capabilities to be used as solderable and wire-bondable finish with specific benefits for ENEPIG and EPAG such as enhanced solder joint reliability and gold-wire bondability.

In this paper an overview is given on the different types of electroless gold plating electrolytes from fully immersion type and autocatalytic type to mixed reaction type gold electrolytes. The details of the various plating mechanisms are presented, and the different properties and capabilities of these electrolytes are compared and explained based on the respective mechanisms.

The presented study investigates the performance of a gold electrolyte of a mixed reaction type looking into the layer properties as well as the soldering and bonding capabilities. The results show that a mixed reaction gold electrolyte can be capable for versatile application- ENIG, ENEPIG and EPAG. The capability of the process was tested with respect to the solder wetting performance, solder joint reliability, wire bonding performance, corrosive attack to the nickel and thickness distribution. It can be shown that this gold process passes or exceeds all related industry standards and target requirements for ENIG, ENEPIG and EPAG final finishes.

Key words

Plating Mechanism, Electroless gold, final finish, Solder joint reliability, ENIG, ENEPIG, EPAG

I. Introduction

The plating of gold is part of various surface finishes in the PCB industry. Depending on the plating mechanism, the deposition can be characterized as either immersion type, autocatalytic or mixed reaction type. The final finish can either consist of a combination of gold on top of an electroless nickel layer (ENIG/ENAG), an electroless palladium layer (EPAG/EPAG) or electroless nickel and palladium (ENEPIG/ENEPAG). The type of the finish is typically defined by the target requirements such as the assembly requirements, corrosion resistance, fine line capability, high frequency capability and shelf life. Related to the target requirements, all three finishes exhibit specific

benefits and limitations. The nickel/gold finish is one used for the longest time in the market. It provides a surface finish which is multiple solderable, bondable with Al-wire and provides a good corrosion resistance, in particular when high-P nickel layers are used. With that, it is also applicable for contact applications. Nevertheless, it exhibits a certain risk for ENIG corrosion in case the process is not well controlled. When it comes to Au-wire capability, the nickel/palladium/gold is the finish of choice, as the additional palladium layer enables the bondability with Au-wires and additionally leads to a reduced brittleness of the solder joint. Compared to the nickel/gold finish, it however is characterized by higher cost as a result of the use of two

precious metals. The nickel free palladium/gold finish on the other hand provides benefits when it comes to fine line plating and high frequency applications as the overall layer thickness can be kept low and the use of nickel is avoided. The gold plating is part of all three finishes and the type of the plating mechanism finally defines the layer properties such as layer thickness, ENIG corrosion risk and capability to plate on palladium.

II. Electroless gold plating

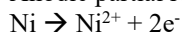
A. Plating mechanisms and deposit properties

What is common for all gold electrolytes applied in final finishing in the PCB industry is that the deposition is electroless. The electrons which are required for the gold deposition are either provided by dissolution of nickel (immersion type) or by a reducing agent (autocatalytic). Beside these two, there are also electrolytes which work with a combination of immersion reaction and autocatalytic reaction in varying ratios. These electrolytes are commonly known as mixed reaction type or reduction assisted gold. These different types of gold electrolytes are characterized by different properties of the electrolyte but also of the plated Ni/Au deposit. Majority of the gold electrolytes which are being used today belong to the group of immersion type or mixed reaction type gold with a low or high autocatalytic portion of the reaction.

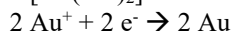
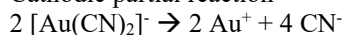
a) Immersion type gold

In immersion type gold electrolytes, the electrons required for the gold deposition are provided by the nickel dissolution only.

Anodic partial reaction:



Cathodic partial reaction



The attack of the gold onto the nickel layer can be reduced by respective bath formulation and bath parameter adjustment.

b) Mixed reaction type gold (low autocatalytic portion)

In mixed reaction type gold electrolytes, the immersion reaction is supported by a certain content of autocatalytic reaction. Depending on the type of additive which is used, the autocatalytic reaction can have a low or high portion of the overall reaction. In gold electrolytes with a low autocatalytic portion, the additive is characterized by slight reductive properties. In addition to the two partial reactions as described in a, an additional reaction takes place:

Anodic partial reaction (in vicinity of the immersion reaction)

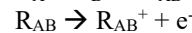
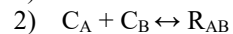
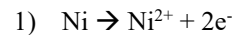


(R=Reducing agent, R⁺=oxidized form of reducing agent)

In such types of electrolytes, the major reaction is driven by the dissolution of nickel and the additives have only a supportive function.

c) Mixed reaction type gold (high autocatalytic portion)

In the third type of gold electrolytes, additives with higher reducing properties are involved. While the cathodic partial reaction remains the same, the anodic partial reaction is divided in two steps:



(C_A, C_B= bath components A and B which form reducing agent R_{AB})

The initial reaction of the gold plating is an immersion reaction. As soon as the first gold seedings are plated, those serve as catalytic surface to start the formation and activates the reducing agent (R_{AB}). Two components for a reactive intermediate which acts as reducing agent and provides the electrons. This autocatalytic reaction is infinite and contributes the major part to the deposition. [1]

As all three mentioned electrolytes contain a certain amount of immersion reaction, for the sake of simplicity, the layer will be referred to below as IG-layer.

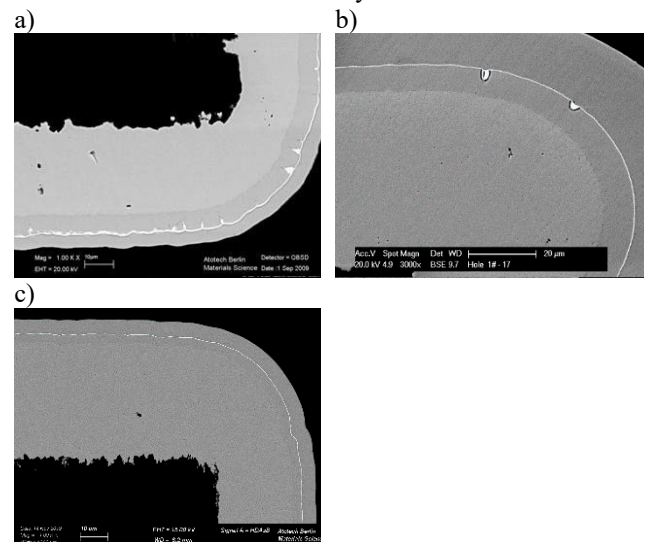


Figure 1 SEM images of an ENIG deposit plated with an a) immersion type, b) mixed reaction type (low autocatalytic) and c) mixed reaction type (high autocatalytic)

The different reaction mechanisms are also reflected in the type and number of corrosive attacks, that can be identified in the ENIG coating. In figure 1 some exemplary SEM images are presented, which show the typical shape of a corrosion event as observed with the respective gold electrolytes.

While with an immersion bath spike or spreader formed corrosive attacks can be observed – in particular at through hole entrances where high solution flow is present, the mixed reaction bathes with high autocatalytic reaction enable a formation of a defect free ENIG layer. In layers plated with a mixed reaction type with lower autocatalytic portion, the number of corrosive events is low and the penetration depth in the nickel is typically below 40% of the nickel layer depth.

B. Capabilities, benefits and limitations

Although the gold electrolytes with a high autocatalytic portion can provide the best results in terms of ENIG corrosion [2], they still have limitations compared to a fully immersion type bath which come into consideration when selecting the electrolyte for the final finish. Table 1 shows a brief overview of the key properties of the three types of electrolytes.

Table 1: plating properties based on gold bath electrolyte

	Immersion Rct.	Mixed Rct. (low autocat.)	Mixed Rct. (high autocat.)
Gold content	0.5 – 2 g/l	0.8 – 1 g/l	0.5 – 0.8 g/l
Bath lifetime	10 g/l Au	10 g/l Au	4 g/l Au
Bath stability	+++	+++	++
Maintenance/ Handling	Low	Medium	High
High gold thickness	Limited	Limited	Capable
ENIG corrosion	Spike and spreaders	Single bites	No detectable corrosion
ENIG	Yes	Yes	Yes
ENEPIG	Limited	Yes	Yes
EPiG	No	No	Yes

The fully immersion type bath exhibits benefit especially regarding the possible low gold content, the long bath life and the easy handling and low maintenance efforts. On the other hand, the bath with high autocatalytic portion requires more efforts in handling and maintenance, but therefore provides a corrosion free finish and is capable to plate not only ENIG but also Pd/Au and Ni/Pd/Au finishes with high gold thickness.

III. One gold electrolyte for three different finishes

Based on the reaction mechanism, the mixed reaction gold electrolytes with high autocatalytic portion in principle are capable of the plating of different finishes on nickel,

palladium or nickel/palladium. Although this type of plating bath is available in the market already for several years, still it is hardly used as one versatile plating solution for the deposition of Ni/Au, Ni/Pd/Au and Pd/Au.

As part of the study presented here, the suitability of such electrolyte for the different layer systems was examined and evaluated from various points of view. The table below summarizes the investigated parameters and target criteria for the different finish types:

Table 2: pass/fail criterial for layer performance check

	Ni/Au	Ni/Pd/Au	Pd/Au
Thickness distribution	< CV 10%	< CV 10%	< CV 10%
ENIG corrosion	IPC rating 0&1	IPC rating 0&1	
Tape test	No peeling	No peeling	No peeling
Cold ball pull test	Pull strength >1000g	Pull strength >1000g	Pull strength >1000g
Ball shear test	Shearstrength > 600g	Shearstrength > 600g	
High speed shear test		Total energy > 1 mJ	Total energy > 1 mJ
Solder spread test	Asr <20° Aged <25°	Asr <20° Aged <25°	Asr <20° Aged <25°
Wetting balance test	Asr T ₀ ≤1.5s Aged T ₀ ≤2.5s	Asr T ₀ ≤1.5s Aged T ₀ ≤2.5s	
Al-wire bonding	Pull strength > 7.5g	Pull strength > 7.5g	
Au-wire bonding		Pull strength >4.95g	Pull strength >4.95g

A. Tools and methods

Solder wetting and solder joint reliability

Solder wetting tests were performed on internal test structures using a Senju M31 solder paste. The solder joint reliability was studied focusing on Cold Ball Pull (CBP) and High-Speed Shear test (HSS), which was performed with solder balls SAC305 with 450µm diameter size. The flux used was a Tacky Flux TSF 6502 and the reflow profile was run under nitrogen atmosphere with a peak temperature of 250°C. All reflow processing was performed using a Rehm Compact Nitro B2100-400 reflow oven.

The CBP and HSS tests were performed on a BGA test board structure with openings of 380 µm. Per condition, 30 solder balls were attached and sheared.

Wire bonding

Au-wire bonding tests were performed using a Kulicke & Soffa Iconn High Performance Bonder with a 23µm Au-wire with a break load of 9.9 g. Al-wire bonding tests were performed using a F&S Bondtec 5630 automatic wedge/wedge bonder with a 25µm Al-wire with a break load

of 15 g The pull tests were done with a Dage 4000 pull tester using a WP100 cartridge and a pull speed of 500µm/s.

Plating conditions

The table below shows the plating process flow as it was used for the deposition of the ENIG, the ENEPIG and the EPAG finish. The gold electrolyte was the same for all three finishes and did not require any specific adjustment for the respective plating step.

Table 3: process flow for the final finish plating

	ENIG	ENEPIG	EPAG
Cleaner	5 min, 37°C	5 min, 37°C	5 min, 36°C
Rinse	4 min, RT	4 min, RT	4 min, RT
Microetch	30 sec, 30°C	30 sec, 30°C	2 min, 27°C
Rinse	4 min, RT	4 min, RT	4 min, RT
PreDip	3 min, 28°C	3 min, 28°C	1 min, RT
Activator	3 min, 24°C	3 min, 24°C	90 sec, 37°C
Rinse	30 sec, RT	30 sec, RT	1 min, RT
PostDip	3 min, RT	3 min, RT	-/-
Rinse	4 min, RT	4 min, RT	-/-
Nickel	26 min, 82°C	26 min, 82°C	-/-
Rinse	2 min, RT	2 min, RT	-/-
Palladium	-/-	7 min, 52°C	8 min, 48°C
Rinse	-/-	2 min, RT	1 min, RT
Gold	12/18 min, 82°C	17/35 min, 82°C	22 min, 82°C
Rinse	5 min, RT	5 min, RT	5 min, RT
Hot-rinse	2 min, 50°C	2 min, 50°C	2 min, 50°C
Drying	20 min, 60°C	20 min, 60°C	20 min, 60°C

B. ENIG corrosion evaluation

For the ENIG corrosion evaluation a ENIG finish with a low and a high gold thickness has been plated and investigated. The ENIG corrosion evaluation was conducted following the description in the IPC 4552B on 10 plated through holes (PTH) on the panel. For each PTH, 7 locations have been checked by light microscope with a magnification of 1000x and corrosion events have been counted to identify corrosion level and product rating. Table 3 shows an overview of the results on 3 different samples: On the left a ENIG finish on a test substrate with a gold layer thickness of 2.75 µinch, in the middle the same finish on a production panel and on the right an ENIG finish on a test substrate with a gold layer thickness of 13 µinch.

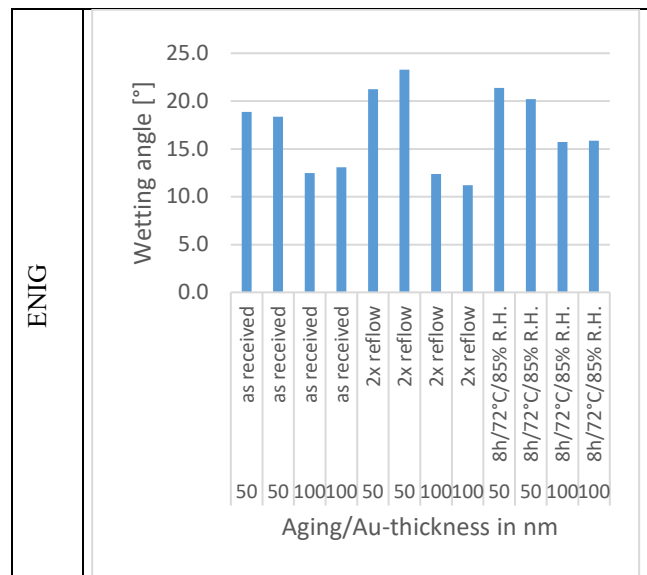
Table 4: Corrosion rating for ENIG

Unit	Au 2.75 µinch										Au 2.75 µinch										Au 13 µinch									
	ATO SFTB1										TTM STE ATB										ATO SFTB1									
PTH	level 1	level 2	level 3	level 4	level 5	level 6	level 7	level 8	level 9	level 10	level 1	level 2	level 3	level 4	level 5	level 6	level 7	level 8	level 9	level 10	level 1	level 2	level 3	level 4	level 5	level 6	level 7	level 8	level 9	level 10
Sample 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Location 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Count	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Level 0	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Level 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Level 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Level 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Product Rating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The results show that in none of the investigated areas corrosion could be detected. So, 100% of Level and product rating 0 can be achieved for the ENIG finish.

C. Solder wetting and solder joint reliability

To test the solder wetting, a solder depot was printed on the finish and the wetting angle was measured after reflowing. For the ENIG and ENEPIG finish two different gold layer thicknesses were evaluated indicated as 1 (50 nm) and 2 (100 nm).



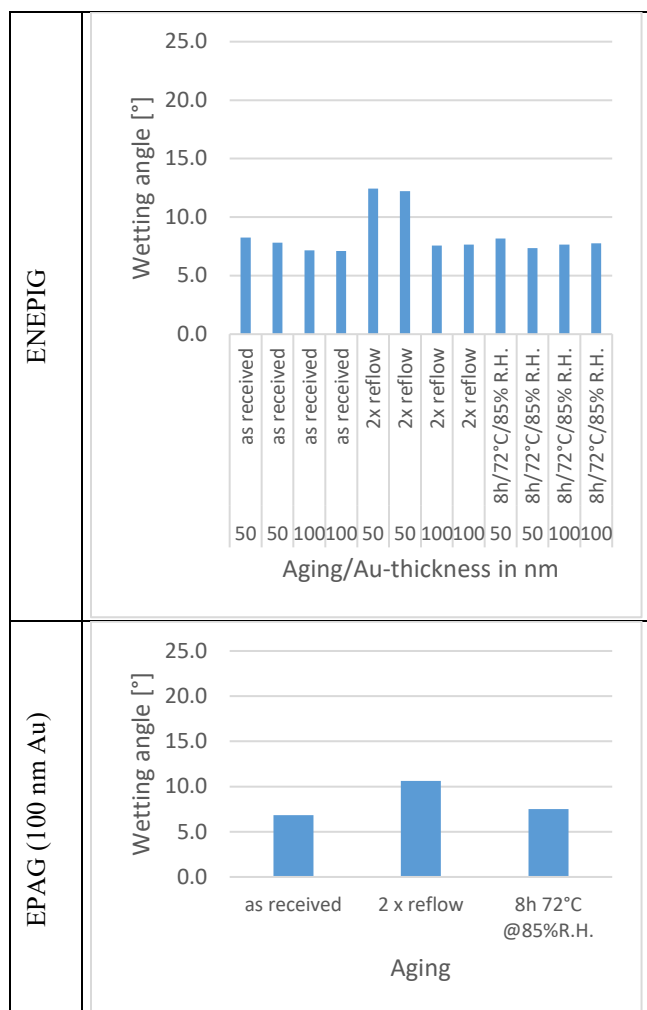


Figure 2: Solder spread test result for ENIG, ENEPIG and EPAG

All finishes can pass the required target limits. In particular, for the ENIG finish the result shows clearly, that with higher gold thickness, the solder wetting can be improved, and lower wetting angles can be achieved.

Beside solder wetting, quality of the solder joint is also of interest. For this purpose, cold ball pull tests and high speed shear tests were conducted with SAC 305 solder balls on a BGA test substrate.

Similar to the solder spread test, reflow and humid aging was performed for 2 IPC reflow cycles and 8h at 72°C and 85% RH. The cold ball pull test forces all pass the minimum value of 1000 g and are consistent for the as received condition as well as for the aged conditions.

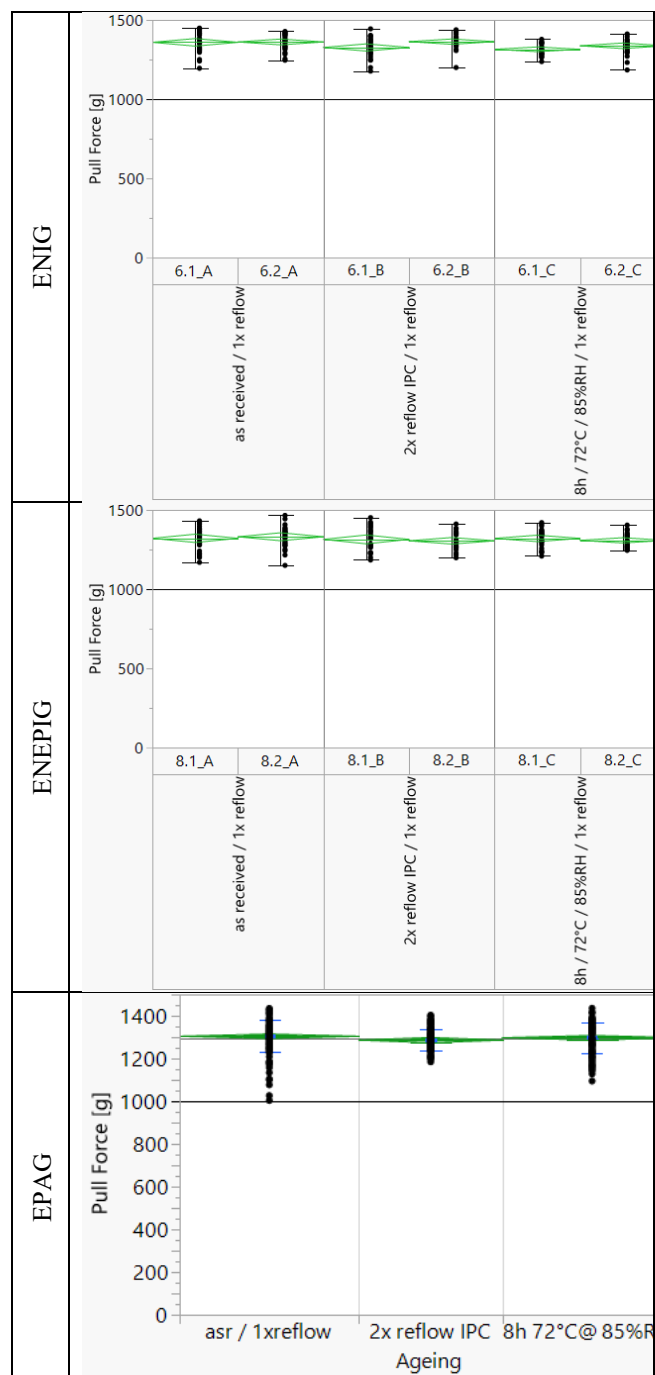


Figure 3: Pull forces for cold ball pull testing for ENIG, ENEPIG, EPAG

For the ENEPIG and EPAG finish additional high speed shear tests were conducted to identify the potential difference in the solder joint reliability of both finishes.

The high-speed shear test serves as an indicator for the solderjoint reliability, and the total energy (mJ) is a numerical description of the strength and ductility of the solder joint. A high total energy value represents a strong solder joint with a high ductility.

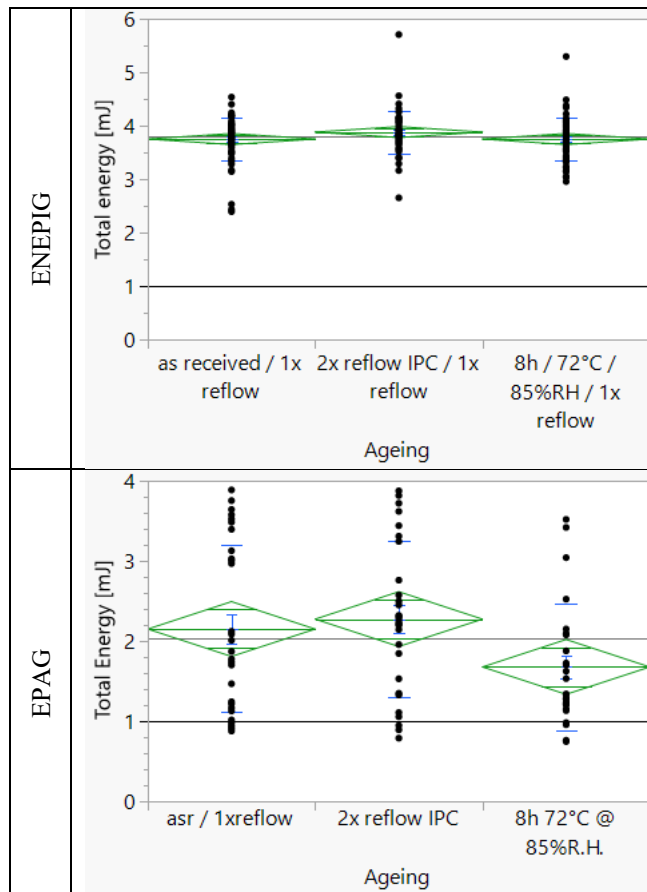


Figure 4: HSS test results for ENEPIG and EPAG finish

The results of the tests are shown in figure 4. For the ENEPIG it can be clearly stated that the finish provides consistent performance in as received as well as in aged conditions on a high level. The overall values are slightly lower for the EPAG finish, but still can fulfill the demands of a minimum value of 1 mJ. A slight decreasing trend can be observed for the humid aged finish, but the achieved values all can fulfill the target requirements.

D. Wire bonding

Beside the investigation of the solder wetting and solder joint reliability, also the wire bonding capability of the three finishes was investigated. Focus was thereby on Al-wire bonding for ENIG and ENEPIG and Au-wire bonding on ENEPIG and EPAG.

Figure 6 and 7 represent the results for Al-wire bonding for ENIG and ENEPIG. The tests were performed in as received condition and after a thermal aging of 3 hours at 120°C. It can be concluded, that both finishes show comparable pull forces and a dominating fracture mode of 2. No peeling or lift off, which would be represented in a failure mode of 1 or 5, can be detected.

This result shows that the gold layer on the surface finish is well connected to the underlying nickel and palladium respectively.

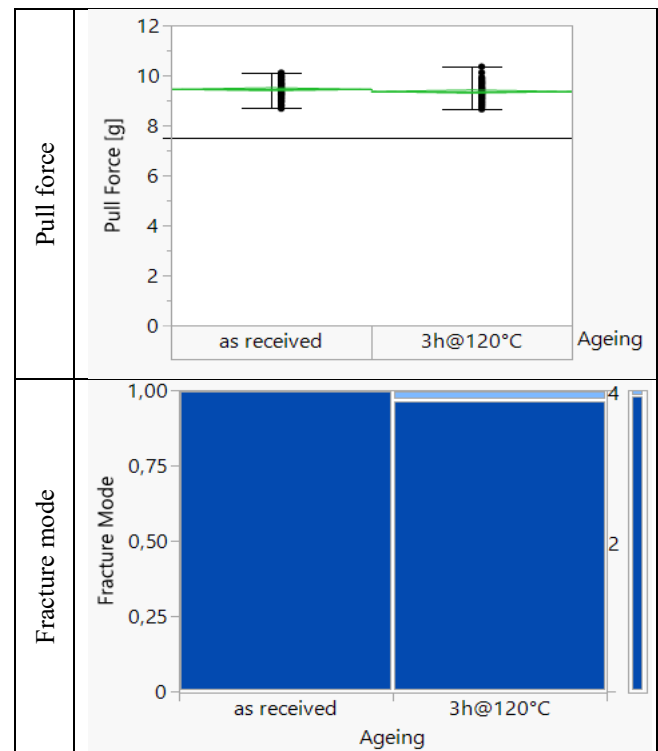


Figure 5: Al-wire bonding results for ENIG

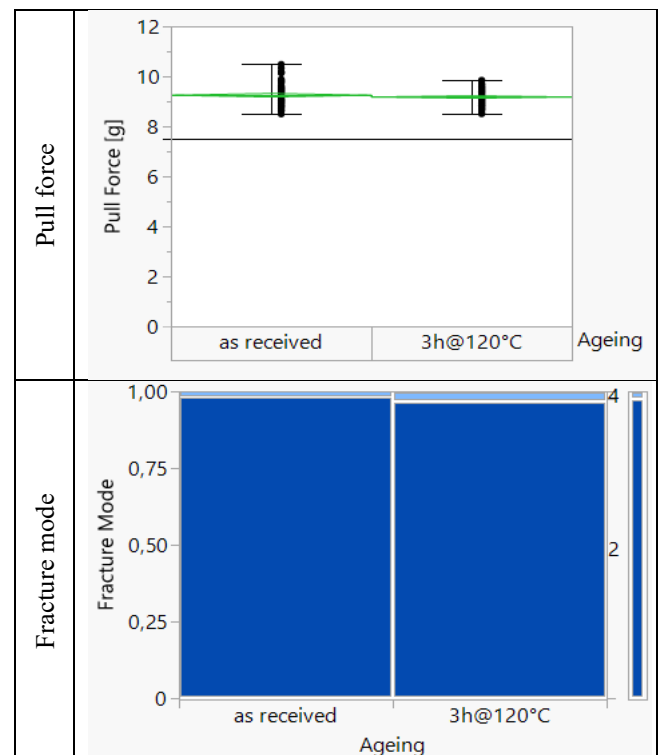


Figure 6: Al-wire bonding results for ENEPIG

For the Pd-containing finish also Au-wire bond tests were performed. Similar to Al-wire bond tests, 30 bonds per condition were set and tested. The tests were conducted in as received condition and after 4 hours aging at 150°C. The results are presented in figure 8 and 9. Also in this case the fracture modes of 2 and 4 indicate a good joint of the gold and the underlying palladium layer. Also, the gold surface appears clean and even so that no issues in the bondability can be observed. The pull force values which can be achieved for the EPAG finish are in a similar level as for ENEPIG and are consistent for the as received condition as well as after thermal aging.

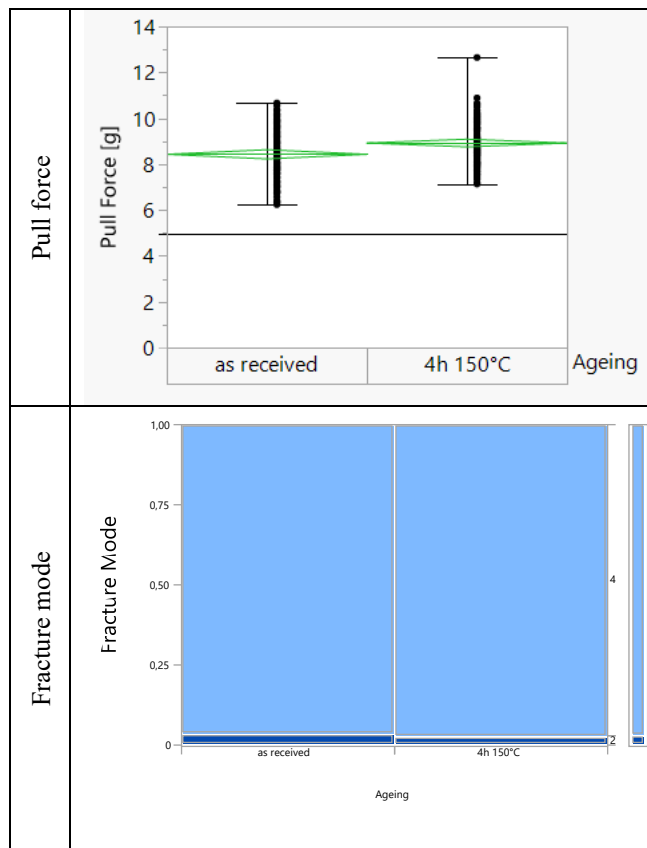


Figure 7: Au-wire bonding results for ENEPIG

The data confirm, that the EPAG finish can achieve similar reliability performance like the ENEPIG finish in the tested conditions. For the gold plating step, no adjustment of the plating electrolyte was required and all three finishes were plated using the same gold electrolyte.

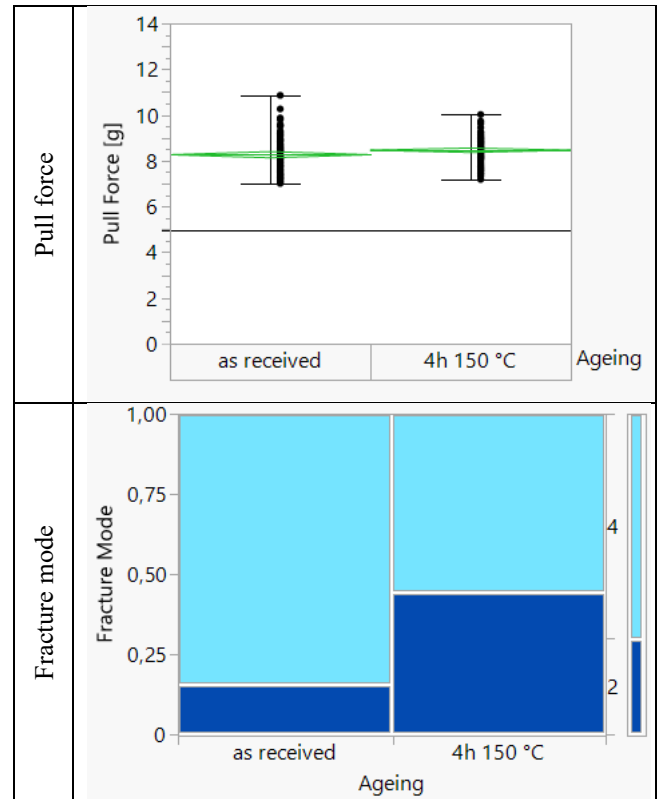


Figure 8: Au-wire bonding results for EPAG

IV. Conclusion

The electroless gold plating can be conducted by either fully immersion reaction or by support of a reducing agent. Typically, gold electrolytes which contain a reducing agent exhibit a mixed type reaction – a portion of immersion reaction and a portion of autocatalytic reaction. The strength of the reducing agent thereby defines the portion of the autocatalytic properties of the bath. Therefore, the naming for IG/AG for mixed reaction electrolytes in the abbreviation of the process name does not necessarily state precisely the actual properties of the plating bath.

The mixed reaction type electrolytes can be characterized by a wide applicability, as their reaction mechanism allows the plating on nickel as well as on palladium layer. In the presented study, it could be shown, that with one electrolyte it is possible to plate ENIG, ENEPIG and EPAG layers, which can fulfill all target requirements as defined by the industry demands and standards. No additional process steps or bath adjustment are required, and the reliability of the finishes could be proven in terms of solder wetting, solder joint reliability, wire-bonding and ENIG corrosion.

References

- [1] Unpublished work, Atotech Deutschland GmbH 2013
- [2] B. Schafstetter, G. Ramos, M. Rosin, T. Schlosser, SMTAi conference Rosemont USA 2020