A Comprehensive Study of Surface Finishes for High Frequency/High Speed Applications

Frank Xu, Ph.D., Martin Bunce, Jim Watkowski, Anna Lifton, Raghu Raj Rangaraju, and Rommel Bumagat

MacDermid Alpha Electronics Solutions
227 Freight St.
Waterbury, CT 06702 USA
Ph: 203-575-5782
Email: frank.xu@macdermidalpha.com

Abstract

The introduction of 5G/6G created growing demand for faster rates of data transfer and operation at higher frequencies, pushing signals to travel towards the outer edges of conductors. Therefore, the surface finish applied over the copper circuitry is now gaining more attention.

It has been previously shown that the low conductivity and magnetic properties of the Electroless Nickel (EN) layer negatively affect electrical signals as they travel along the conductor outer surfaces, leading to insertion losses. Subsequent studies show that reducing the EN thickness can offset some of the insertion losses observed, leading to a reduction in insertion losses. In more recent times "Nickel Free' finishes, such as EPIG (Electroless Palladium - Immersion Gold, no EN) have been promoted as solutions to improving signal losses at higher frequency.

Exactly how much *high frequency performance* these new "nickel-free" finishes by the user has not yet been fully quantified, and what are the considerations or trade-off's for solderjoint reliability with smaller diameter solder spheres when assembled using these newer surface finishes?

Comprehensive studies of signal loss, solderjoint reliability testing (ball shear, drop shock, electromigration) and other critical to quality performance data were undertaken for standard ENEPIG, Thinner EN ENEPIG's, EPIG (no EN) as well Immersion Silver, OSP and a new Ag/Au surface finish.

All surface finishes were compared across the performance requirement matrix and a Quality Function Deployment was constructed to produce a data driven tool to align surface finish performance against design needs, allowing for optimal surface finish selection for each application.

Key words

High frequency, Ni-free finishes, Signal loss, Solderjoint reliability.

I. Introduction

Throughout the lead-free movement, several surface finishes have been successfully developed, each with its advantages and drawbacks. These finishes include Organic solderability preservative (OSP), Immersion Silver (ImAg), Immersion Tin (ImSn), Electroless Nickel Immersion Gold (ENIG), and Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG). Among them, OSP, ImAg, and ImSn create a preferred Cu-Sn solder joint after assembly. In contrast, ENIG and ENEPIG lead to the formation of a Ni-Sn solder joint. On the other hand, ENIG and ENEPIG finishes offer excellent reliability, an extended shelf life, and remarkable wire bonding capabilities. These features contribute to their popularity despite the presence of Cu-Sn solder joints in other finishes.

ENIG and ENEPIG surface finishes have successfully utilized Electroless Nickel (EN) deposits as a barrier layer to prevent copper migration, ensuring robust solderability performance on the outer gold or palladium-gold surfaces. However, as mentioned earlier, with the advent of the 5G mobile network, it has become imperative to reduce signal loss at higher frequency bandwidths.

EN, with its low conductivity and magnetic properties, can adversely affect electrical signals traveling along the conductor's outer surfaces at higher frequencies, leading to insertion losses [1]. In contrast, ImAg boasts excellent signal loss properties due to its high conductivity, making it a preferred choice in Advanced Driver-Assistance Systems (ADAS) operating at 77 GHz [2]. Nevertheless, ImAg is susceptible to discoloration/corrosion [3] and has limitations regarding wirebonding capability.

Given the ongoing trend of electronics miniaturization and the increasing demand for 5G technology, the next generation of surface finishes must exhibit both excellent signal loss properties and reliable wirebonding capability. In response to this challenge, various "Ni-free" finishes have been developed to address these specific requirements.

One "Ni-free" option for surface finish involves modifying the ENEPIG finish. Since Nickel is responsible for signal loss in both ENIG and ENEPIG finishes, research has been conducted to either reduce the thickness of nickel or eliminate it entirely from the ENEPIG finish to enhance signal loss properties. Studies have demonstrated that decreasing the Nickel thickness from the standard 4 µm to 1.5 µm significantly improves signal loss [4]. It becomes intriguing to explore how signal loss data would look if Nickel thickness is further reduced to a range between 0.1 to 0.2 µm.

Another emerging approach is the complete removal of nickel to introduce a new surface finish known as electroless palladium immersion gold (EPIG). This finish has gained popularity not only for its signal loss properties but also for its potential impact on solder joint reliability. Unlike ENEPIG, EPIG forms a Cu-Sn solder joint instead of a Cu-Ni solder joint, which warrants further investigation in terms of solder joint reliability.

Another "Ni-free" finish alternative revolves around ImAg. ImAg has gained prominence in high-frequency applications due to its exceptional signal loss properties. However, with recent technological advancements, current ImAg users are seeking to expand its wirebonding capability. To address this demand, a potential solution is to plate a gold layer on top of ImAg, creating what is known as the AgAu finish. By adopting this approach, not only can excellent signal loss be achieved, but it also opens up the possibility of gold and copper wirebonding thanks to the gold top-layer.
The key challenge in plating an AgAu finish lies in achieving pore-free layers. Traditional immersion gold chemistry used for ENIG or ENEPIG would not be suitable in this case since there is no nickel present as the displacement material. Direct displacement with a Cu substrate would lead to corrosion issues. To overcome this challenge, a unique hybrid gold plating process with a reduction assistance system becomes necessary. This process allows for the plating of Au on top of ImAg, resulting in a uniform and void-free AgAu surface finish that is compatible with the conventional ENEPIG process.

The “Ni-free” finishes have promising signal loss properties. However, the absence of a nickel diffusion barrier layer raises valid reliability concerns. This paper addresses these concerns by conducting comprehensive solder joint reliability tests, encompassing high-speed ball shear, drop shock, and solder joint electromigration tests.

II. Experimental Methodology

Signal Loss Test:

In this paper, the finishes of interest – AgAu, EPIG and thin / ultrathin nickel ENEPIG (nominal 0.1 µm and 0.2 µm Ni thickness respectively), as well as standard ENEPIG, OSP and ImAg are studied. The high frequency signal loss properties were tested at Roger’s Corporation using the microstrip differential phase length method (8-inch and 2-inch strips) by vector network analyzer, which is known to be capable from ~ 100 MHz to 110 GHz. The low loss Teflon® substrate is used to evaluate the signal loss performance of each finish. To ensure accuracy, each substrate will be prepared in a such a way that half will remain uncoated as a reference and the other half will be coated with the surface finish. Both will be tested by vector network analyzer to get the signal loss data on uncoated construction loss (laminate + copper traces) and total loss (construction + surface finish). The difference between the two would be the signal loss contributed by the surface finish.

High Speed Ball Shear Test:

Ball shear tests are performed to evaluate the solder joint reliability. Testing was done on ball grid array (BGA) test coupons with solder mask defined pads with solder resistor openings at 250 µm. The ball shear test at low-speed shear conditions (0.3 – 0.5 mm/sec) have been reported in the previous paper [5]. In this paper, only high-speed ball shear data is presented. Figure 1a is the schematics of a ball shear setup. It was tested at 1000 mm/sec and the spacing between the shear head and board surface is 20 µm. Three failure mechanisms are described in Figure 1b. Pad lifting, where the pad is lifted off the substrate due to the high shear force and weak pad / substrate adhesion, is rare. Die shear (DS) failure mechanism indicates a weak bond strength between the solder and pad finishes. Lastly, die break (DB) is the preferred failure mechanism where the failure happens within the solder.

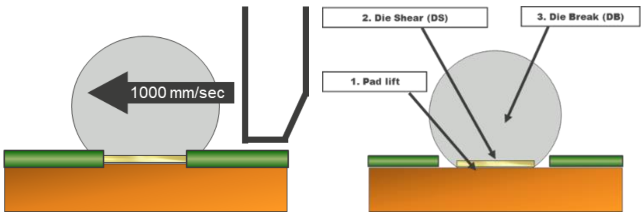


Figure 1a Figure 1b

Figure 1a: Schematic of a ball shear setup.
Figure 1b: Schematic of ball shear failure mechanism.

Drop Shock Test:

The dummy CTBGA84 components are used for the drop shock test. The drop shock table height and striking surface are adjusted to obtain a half-sine shock pulse with 1500 Gs and 0.5 msec peak, following the JESD22-B111 standard. Failures are defined as a drop of 1V or more in the applied potential for at least 0.5 msec, based on the IPC/JEDEC-9706 standard, being detected and recorded using a high-speed data acquisition system. The interval plot of the drop shock performance is presented.

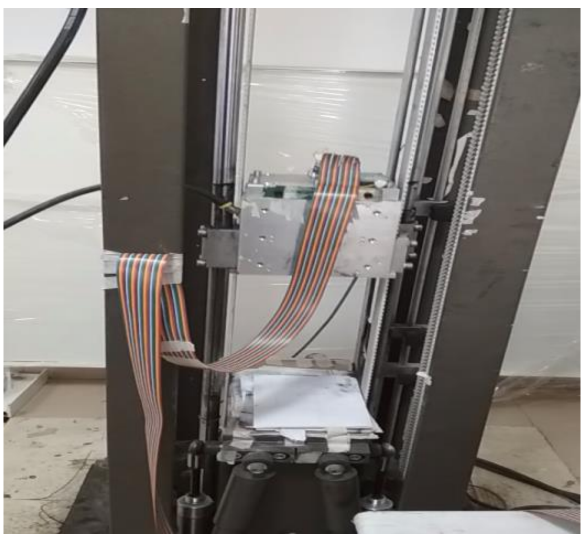


Figure 2: Drop shock test setup.

Solder Joint Electromigration Test:

Solder joint electromigration is a phenomenon that can occur in electronic devices where electrical current flowing through solder joints causes metal atoms to migrate, leading to the degradation or failure of the joint [6]. With the trend of miniaturization, the current density flowing through a solder joint gets higher, and the electrons collide with metal atoms, increasing the chance of them moving in the direction of electron flow. Over time, this movement of metal atoms can result in void formation, metal thinning, or even complete fracture of the joint [7].
Electromigration is influenced by several factors, including the magnitude and direction of the current, the temperature, the composition of the solder alloy, as well as the microstructure of the joint. Higher current densities, higher temperatures, and the presence of defects or impurities in the solder can accelerate electromigration. In order to study the effects of the various surface finishes on the electromigration, the current and temperature are fixed at 5A and 100 ºC. SAC 305 solders are used for the test.
The drawing of in-house designed PCB board is shown in Figure 3. There are ten ball grid array (BGA) patterns at the bottom of the test vehicle, plated with the finish of interest. The BGA228 components (corresponding current density: 1.0E+04 A/cm^2) are used for the test up to 400 hours. The failure is defined as 20% increase of initial resistance.

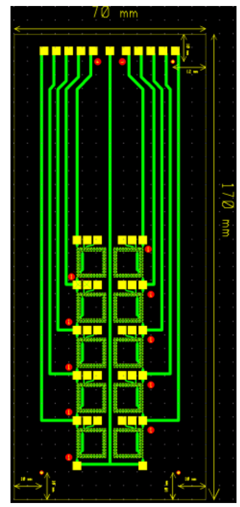


Figure 3: A drawing of the electromigration test vehicle.

III. Results

High Frequency Signal Loss

Figure 4 displays signal loss of each finish at three representative frequencies (6, 40 and 77 GHz). The signal loss value consists of two parts, the loss due to surface finish (finish loss) and the loss due to everything else – laminate, copper trace and its roughness, etc. (construction loss). As described previously, the signal loss test panel was cut in half before processing the surface finishes. Both half strips, with and without surface finishes, would be subjected to the signal loss testing. Signal loss, from both the substrate only (construction loss) and the plated panel (consisted of both construction loss and finish loss), would be obtained. The difference between the two would be the signal loss from surface finish. The purpose of this is to eliminate substrate lot-to-lot variation, although it can't eliminate the within-substrate strip variation.

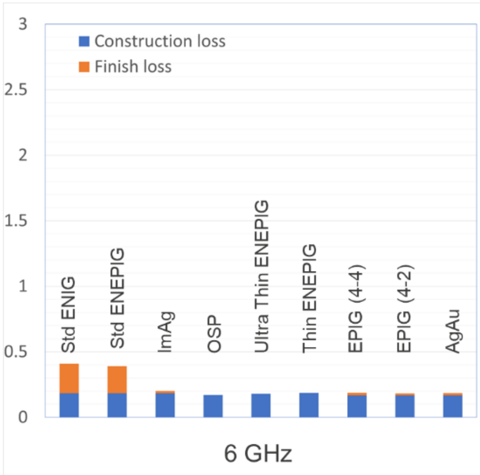


Figure 4a: Signal loss of various finishes considering the loss from both construction and surface finishes at 6 GHz.

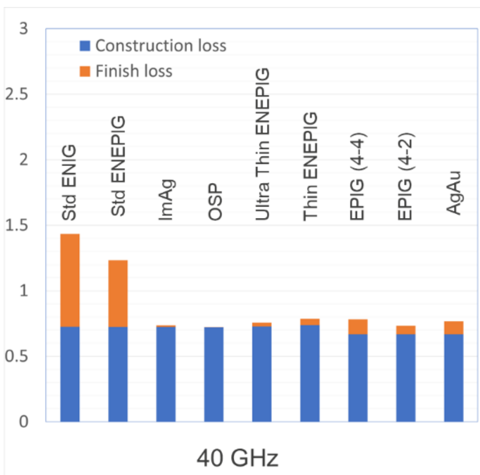


Figure 4b: Signal loss of various finishes considering the loss from both construction and surface finishes at 40 GHz.

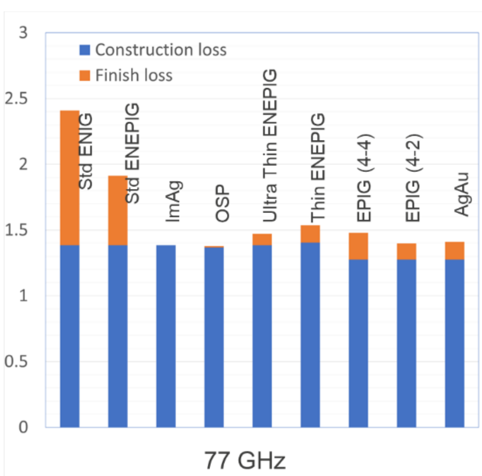


Figure 4c: Signal loss of various finishes considering the loss from both construction and surface finishes at 77 GHz.

At 6 GHz, it already shown that both standard ENIG and ENEPIG plated strip has greater signal loss (~0.4 dB/in) than other finish's plated strips (~0.2 dB/in). The signal loss from the ENIG and ENEPIG finish itself is around 0.2 dB/in, half of the total loss. When frequency goes up, so does the signal loss. The signal loss from the construction becomes more prominent than the surface finishes in higher frequencies. At both 40 GHz and 77 GHz, ENIG and ENEPIG again showed the greatest loss, while ImAg and OSP showed the least loss. Thin Nickel (0.2 µm) ENEPIG, Ultra-thin Nickel (0.1 µm) ENEPIG, EPIG and AgAu finishes showed comparable signal loss. It's interesting to note that the construction losses from both EPIG and AgAu are smaller than that of both thin and ultra-thin Nickel ENEPIG-plated strips. The difference in the construction loss is comparable to their corresponding surface finish losses.

As discussed, the three "nickel-free" finishes showed similar signal loss properties, it is important to know their solderjoint reliability respectively.

<u>High Speed Ball Shear Test</u>

As mentioned previously, the low-speed ball shear results have been reported. Here we only present the high-speed ball shear results which was done at 1000 mm/sec using DAGE 4000HS instrument. The ball grid array (BGA) with 250 µm solder resist open (SRO) is used as the testing substrate. 250 mm SAC 305 solderball and Alpha WS-608 paste flux are used to form the solder bumps. Each test condition is repeated twenty times to ensure good statistical significance. Figure 5a shows the interval plot of high-speed ball shear strength of various surface finishes. It can be clearly seen that the standard EPIG finish has the lowest ball shear strength.

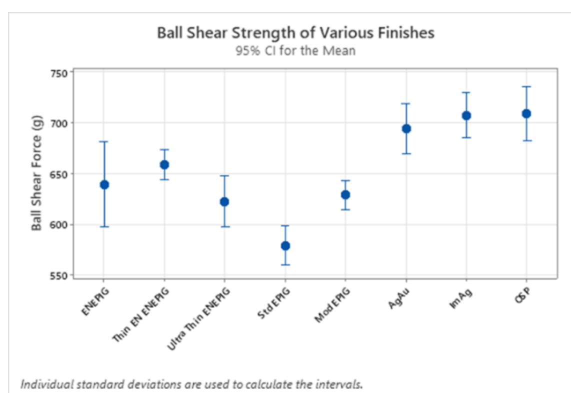


Figure 5a: Interval plot of high-speed ball shear strength of various surface finishes.

Figure 5b is the interval plot of high-speed ball shear total energy of various surface finishes. Here the total energy needed to shear the solderjoint is recorded and reported. It's clearly seen that both standard and modified EPIG finish require the least amount of energy to shear the solderjoint, while it takes similar amount of energy to shear all other finishes.

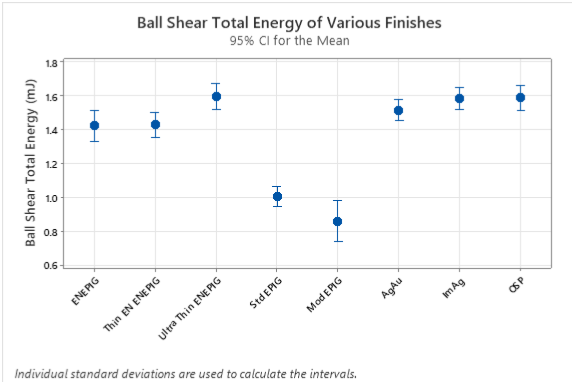


Figure 5b: Interval plot of high-speed ball shear total energy of various surface finishes.

Drop Shock Performance

As pad sizes continue to shrink, rhe significance of the drop shock test has increased, particularly in mobile phone applications. In Figure 6, the number of drop shocks for each finish is displayed. The first three finishes shown are standard ENEPIG, thin nickel ENEPIG, and ultra-thin nickel ENEPIG. Interestingly, it can be observed that as the nickel interlayer thickness decreases, the drop shock performance improves, primarily because of an increasingly higher proportion of Cu-Sn solder joint.

Initially, it was believed that the complete elimination of nickel, as seen in EPIG or modified EPIG finishes, would further enhance the drop shock performance. However, this is not the case. The reason lies in another deposition mechanism utilized during the plating process for EPIG finishes, which results in microvoids formation [5].

AgAu, ImAg and OSP finishes all provide robust drop shock performance which is linked to preferred Cu-Sn solderjoint formation in those finishes compared to more brittle Ni-Sn solderjoint.

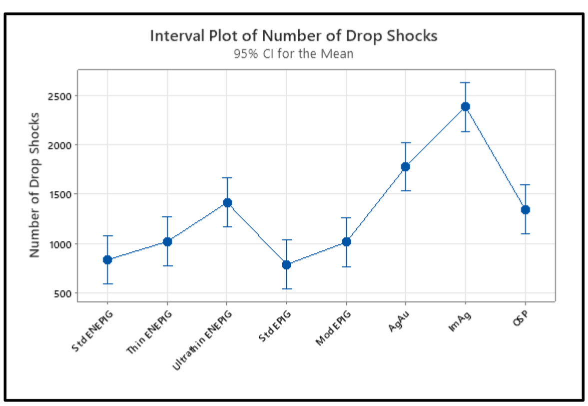


Figure 6: Interval plot of drop shock performance of various surface finishes.

Solderjoint Electromigration Test

As described in the experimental methodology section, the solderjoint electromigration tests are done at constant current (5 A) and temperature (100 ºC). The resistance is monitored throughout the testing period (400 hours). If there is a 20% increase over initial resistance, it's considered a failure.

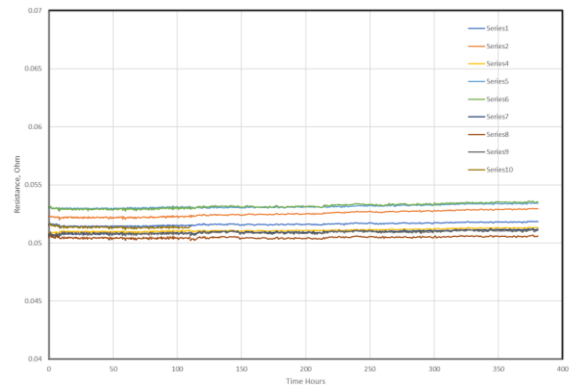


Figure 7a: Resistance vs time in electromigration test in OSP surface finish plated testing vehicle.

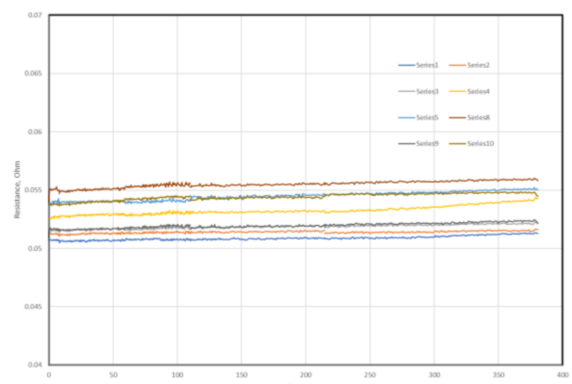


Figure 7b: Resistance vs time in electromigration test in Standard ENEPIG surface finish plated testing vehicle.

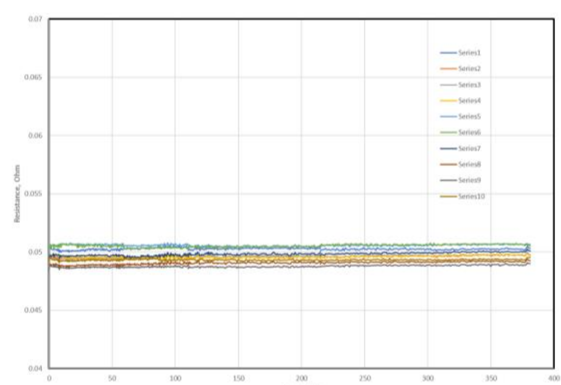


Figure 7c: Resistance vs time in electromigration test in thin nickel ENEPIG surface finish plated testing vehicle.

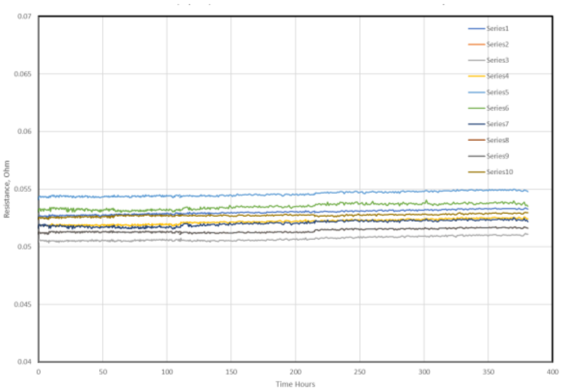


Figure 7d: Resistance vs time in electromigration test in ultra-thin Ni ENEPIG surface finish plated testing vehicle.

Figures 7a to 7h present the electromigration results for the solder joints, displaying the resistance plotted against the testing time for up to 400 hours. Among all the finishes tested, with the exception of standard EPIG and modified EPIG, consistent resistance is observed throughout the entire test duration. However, both standard EPIG and modified EPIG exhibit a sharp increase in resistance after approximately 50 to 100 hours of testing, indicating that the solder joints have been compromised during the high current/high temperature test.

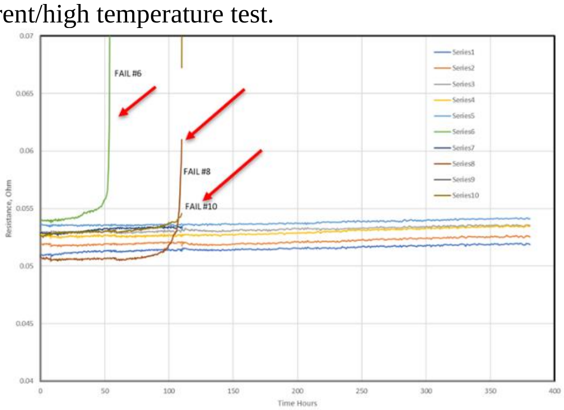


Figure 7e: Resistance vs time in electromigration test in standard EPIG surface finish plated testing vehicle.

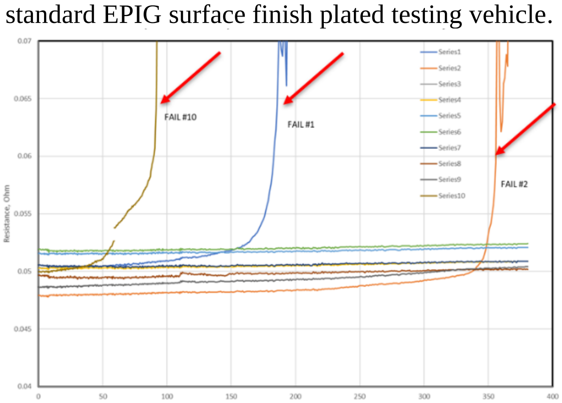


Figure 7f: Resistance vs time in electromigration test in modified EPIG surface finish plated testing vehicle.

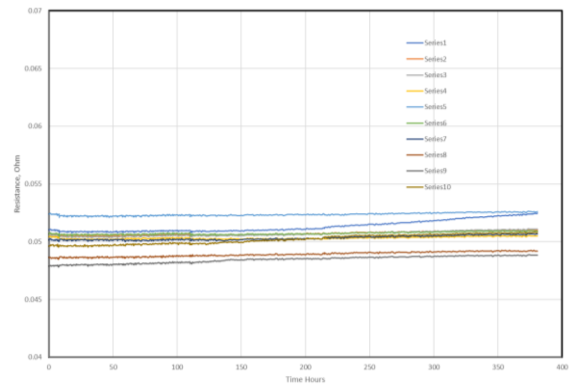


Figure 7g: Resistance vs time in electromigration test in AgAu surface finish plated testing vehicle.

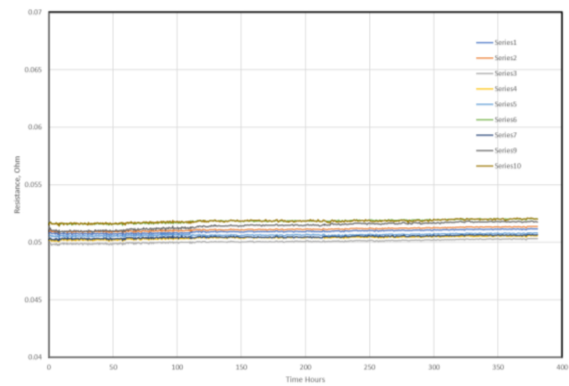


Figure 7h: Resistance vs time in electromigration test in ImAg surface finish plated testing vehicle.

X-ray imaging is employed to examine the alterations in solder joints before and after undergoing the solder joint electromigration test, indicated by the red arrow in Figure 8. As the X-ray images clearly display, it is evident that the solder joints in both standard EPIG (Figure 8a) and modified EPIG (Figure 8b) have collapsed following the test. In contrast, all the other surface finishes demonstrate intact solder joints after completing the electromigration test.

This non-destructive imaging technique provides valuable insights into the reliability and structural integrity of the solder joints, shedding light on the performance of different surface finishes under the influence of the electromigration test. It also helps with the subsequent more focused cross section investigation. The observations on the standard EPIG and modified EPIG finishes highlight the importance of selecting appropriate surface finishes to ensure the long-term stability and functionality of electronic devices subjected to high-current and high-temperature conditions.

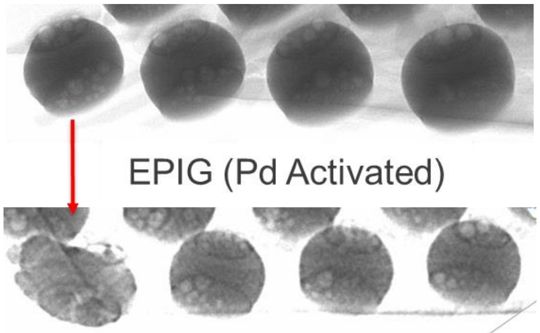


Figure 8a: X-ray imaging of standard EPIG solderjoints before and after electromigration test.

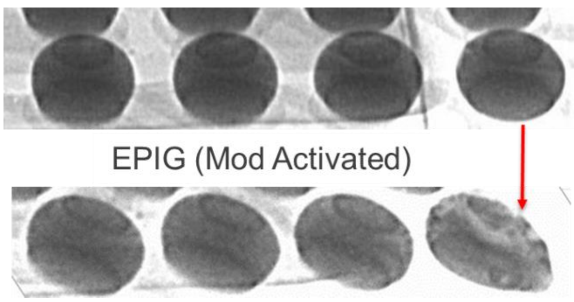


Figure 8b: X-ray imaging of modified EPIG solderjoints before and after electromigration test.

To conduct a detailed examination of the solder joints, a cross-section sample is made based on the X-ray imaging results. Figure 9 displays a scanning electron microscope (SEM) image of a standard EPIG solder joint (cathodic side) after undergoing the electromigration test. The inset provides an overview of the cross-section. The red circles indicate voids that appear in the solder joint when subjected to high current density, leading to collisions between electrons and metal atoms. These collisions cause the metal atoms to move in the direction of electron flow. Over the course of the electromigration testing, this movement of metal atoms results in the formation of voids, primarily on the cathodic side of the solder joint.

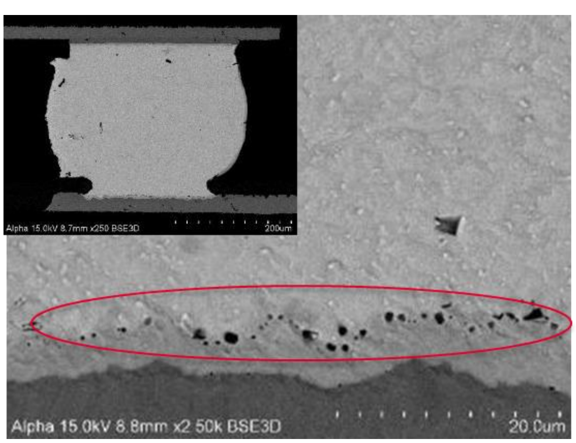


Figure 9: SEM cross section view of standard EPIG solderjoint after the electromigration test.

IV. Conclusion

As the "nickel-free" finishes exhibit similar high-frequency signal loss properties, it becomes important to evaluate other characteristics of these finishes. In this paper, high speed ball shear, drop shock performance and solderjoint electromigration test have been thoroughly undertaken for standard ENEPIG, thinner EN ENEPIG's, standard and modified EPIG (no EN) as well Immersion Silver, OSP and a new Ag/Au surface finish.

All surface finishes were compared across the performance requirement matrix and a quality function deployment (Figure 10) [8] was constructed to produce a data driven tool to align surface finish performance against design needs. As it shows, there is no one perfect surface finish that fits every application. Fabricators would pick the performance criteria with corresponding importance rating and evaluate the surface finishes according to their specific needs.

Acknowledgment

The authors would like to thank MacDermid Alpha AMD and SAMPL lab for the analytical support, as well as John Coonrod from Roger's Corporation for the high frequency signal loss measurement.

References

[1] Coonrod, J., "The Impact of Final Plated Finishes on Insertion Loss for High Frequency PCB". *SMTA International*, September 2017

[2] Clark, L., Salerno, P., Kanagavel, S, "Materials Considerations for Automotive Radar Designs: Increasing Reliability in Automotive Safety Systems." *IPC Apex Expo*, Jan 2020

[3] Xu, C., Smetana, J., Franey, J., Guerra, G., "Creep Corrosion of PWB Final Finishes: Its Cause and Prevention," *IPC Apex Expo*, Jan 2009.

[4] Coonrod, J., "Insertion Loss Performance Differences Due to Plated Finish & Circuit Structure." *IPC Apex Expo*, Jan 2019

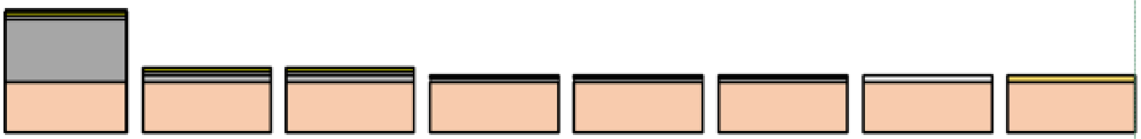
[5] Xu, F., Bunce, M., Long, E., and Watkowski, J., "Reassessing Surface Finish Performance for Next Generation Technology". *IPC APEX Expo*, Jan 2023

[6] Chan, Y.C., Yang, D., "Failure mechanisms of solder interconnects under current stressing in advanced electronic packages", *Progress in Materials Science*, 55 (2010) 428-475.

[7] Chen, C., Tong, H.M., Tu, K.N., "Electromigration and Thermomigration in Pb-Free Flip-Chip Solder Joints", *Annual Review of Materials Research*, 40 (2010) 531-555.

[8] https://asq.org/quality-resources/qfd-quality-function-deployment

Correlation Key	
Strong Corelation	9
Medium Correlation	3
Weak Correlation	1
No Correlation	0



Performance Criteria	Importance Rating	Standard ENEPIG	Thin Ni ENEPIG	Ultra-Thin Ni ENEPIG	Std EPIG	Mod EPIG	ImmAg-Hybrid Au	Immersion Silver	OSP
Micro-strip Insertion Loss	9	1	3	3	3	3	3	9	9
Drop Shock	9	1	3	3	1	3	9	9	9
Low Speed Ball Shear (0.25 mm)	9	9	9	9	9	9	9	9	9
High Speed Ball Shear (0.25 mm)	9	9	9	9	1	1	9	9	9
Wirebond Capability	9	9	9	9	9	9	9	1	0
Solderspread	9	9	9	9	9	9	3	9	3
Electromigration-SI Reliability	9	9	9	9	1	3	9	9	9
Mixed Flowing Gas	9	3	3	9	9	9	3	1	3
Final Finish Score		50	54	60	42	46	54	56	51
Final Finish Relative Score		450	486	540	315	414	486	504	459
Final Finish Ranking				1					

Figure 10 Quality function deployment matrix of various surface finishes