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The Effect of EPIG Plating Thicknesses on Solder Joint and Wire Bond Reliability

Carrillo, C., Garcia, J., Labonte, A., Larson, S., Gudeczauskas, D., and Valentine, P. PhD
Uyemura
CT, USA
jgarcia@uyemura.com

ABSTRACT

There is a lack of industry consensus on the recommended plating thicknesses of Electroless Palladium / Immersion Gold (EPIG) final finish. This article aims to identify the effect on the reliability of palladium and gold thicknesses in EPIG deposits. Determining the optimal EPIG palladium and gold thicknesses will allow the electronics industry to achieve stronger solder joints and robust wire bonds. Increased ruggedness of solder joints and wire bonds provides the benefits of reduced scrap costs and increased printed circuit board (PCB) reliability over time. This study focuses on determining the effects of palladium and gold thicknesses to ensure dependable solder joints and wire bonds. The overall research consists of an in-depth literature review, design of experiments (DoE), solder joint and wire bonding testing, and statistical analysis. The results suggest that plating thicker palladium will yield higher solder joint shear results, while plating thicker gold yields a higher wire bond pull strength. Targeting these plating thicknesses will positively impact the electronics industry by eliminating scrap and the cost of poor quality.

Key words: solder joint reliability, wire bonding, plating thicknesses, EPIG.

INTRODUCTION

Electroless Palladium / Immersion Gold (EPIG) is a final finish used in the printed circuit board (PCB) industry to fulfill fine line and space and high-speed frequency requirements (see Figure 1). Due to the complete elimination of the electroless nickel layer from the traditional Electroless Nickel / Electroless Palladium / Immersion Gold (ENEPIG) surface finish, the EPIG finish is also advantageous for medical applications. With a lack of an industry-standard, EPIG thicknesses have ranged from 0.05 – 1.0 µm for the palladium layer and 0.05 – 0.20 µm for the gold layer. EPIG thickness optimization will provide preliminary industry recommendations to ensure both solder joint and wire bond reliability.

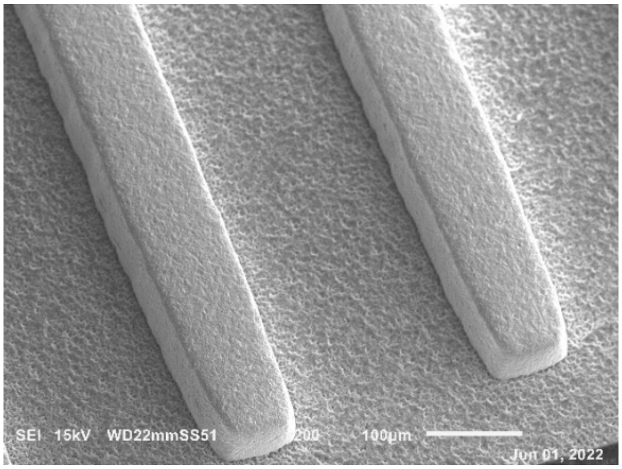

Figure 1. Top-Down Image of EPIG Finish

Solder balls electrically connect semiconductor packages to PCBs by forming a solder joint. During reflow, solder balls are generally self-centering, thus reducing placement problems during surface mount. This self-centering results in an overall increase in board assembly yields. Thermal cycling, with its inherent intermetallic (IMC) growth, then presents potential reliability concerns for EPIG finishes.

Wire bonding is a method used to attach a fine wire from one connection pad to another, completing an electrical connection in an electronic device. Palladium final finishes, including EPIG, are considered universal finishes because a wide variety of wires (gold, aluminum, copper, etc.) can be bonded. Patent wire bond defects include Non-Stick-on-Pads (NSOP), which are bonds that never or only partially form. Latent wire bond defects include Pad Metal Lift-off (PML) [1]. Both NSOP and PML present potential reliability concerns for the EPIG finish.

The Institute for Interconnecting and Packaging Electronic Circuits (IPC) has assembled committees of industry experts to develop standards for the various stages of PCB manufacturing, including standards for final finishes. Unlike other final finishes, EPIG is not governed by a universal standard. The Institute for Interconnecting and Packaging Electronic Circuits provides standards that define plating thickness specifications, reliability testing procedures, and defect tolerances. Having a universal standard helps ensure better quality, reliability, and consistency within the PCB industry.

Without a standard to govern it, the EPIG process is susceptible to performance differences from one manufacturer to another. Currently, the original equipment manufacturers (OEMs) are determining EPIG plating thickness requirements from past experiences, supplier recommendations, or based on referencing other final finish standards. This has led to a wide range of EPIG plating thicknesses being used in the PCB industry without data supporting the reliability of those thicknesses. An optimal plating thickness specification for EPIG is required for PCB manufacturers, OEMs, and final users to ensure better quality.

Without a governing standard, worldwide ambiguity emerges when running the EPIG process. For instance, PCB manufacturers in North America using the EPIG process can differ in plating thicknesses from one another. In addition, North American plating thicknesses could vary from other manufacturers globally. Historical experiments capped the palladium thicknesses at 0.4 µm [2, 3]. Ultimately, having a PCB industry standard helps users collaborate, conduct characterization studies, and determine process specifications for an optimal EPIG process.

If a proactive approach is not taken with EPIG plating thickness recommendations, then incorrect assumptions can lead to solder joint and wire bond reliability issues. Historically, some product designers did not understand the result of plating thicker immersion gold and its influence on increasing nickel hyper corrosion or black pad in the Electroless Nickel / Immersion Gold (ENIG) finish. Preventing assumptions with the EPIG final finish will allow the electronics industry to progress at an accelerated rate.

METHODS AND MATERIALS

Design of Experiments (DoE) are valuable tools that allow an experimenter to investigate the effects of factors statistically. A Central Composite Design (CCD) DoE was used in this research to study EPIG plating thicknesses. Central Composite Designs allows identification and modeling of all significant terms. Design of Experiments are an efficient and statistically sound method to study process variables, with the experimenter choosing the factors and their corresponding levels.

The two factors used in the DoE were palladium-phosphorous and gold thicknesses. Due to an absence of industry standards on EPIG plating, thicknesses were varied for palladium (0.05 – 1.0 µm) and gold (0.05 – 0.2 µm). These palladium and gold thickness ranges are commonly seen in the PCB industry. Plating thickness quartiles were established to facilitate testing and analysis (see Table 1). After completing EPIG plating on the test boards, solder joint and wire bond testing were completed.

Table 1. Central Composite Design – Experimental Runs

Run ID	Palladium Quartiles	Gold Quartiles
1	Q2	Q4
2	Q2	Q3
3	Q3	Q1
4	Q3	Q2
5	Q4	Q3
6	Q3	Q2
7	Q1	Q1
8	Q1	Q4
9	Q2	Q2
10	Q4	Q3

The test boards used in this study consisted of a copper-clad laminated FR-4 substrate plated to a thickness of 20 µm using an acid copper electroplating process. The copper-plated substrate was coated with a solder mask and imaged to form 0.25 mm diameter ball grid array pads used for ball shear testing. A center ground plane on the test boards was used for the wire bonding testing. An example of the test board is shown (see Figure 2).

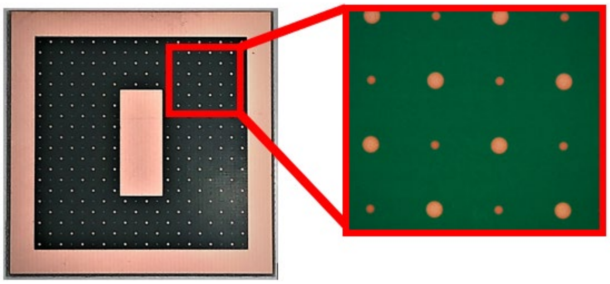

Figure 2. Solderability and Wire Bonding Test Board

An ANTOM model UNI-6116a reflow oven was used to bond 0.3 mm Senju SAC305 solder balls to the test boards. The 0.3 mm Senju SAC305 solder balls met the requirements of IPC J-STD-001H Requirements for Soldered Electrical and Electronic Assemblies. Twenty solder balls were bonded on each test board for the 10 DoE runs. Two hundred solder balls were bonded and stressed for 5x reflows at 250ºC (see Figure 3). High-speed ball shear (HSS) strength was tested per JESD22-B117B by a Dage series 4000HS tester. Both gram-shear break forces and shear locations were recorded.

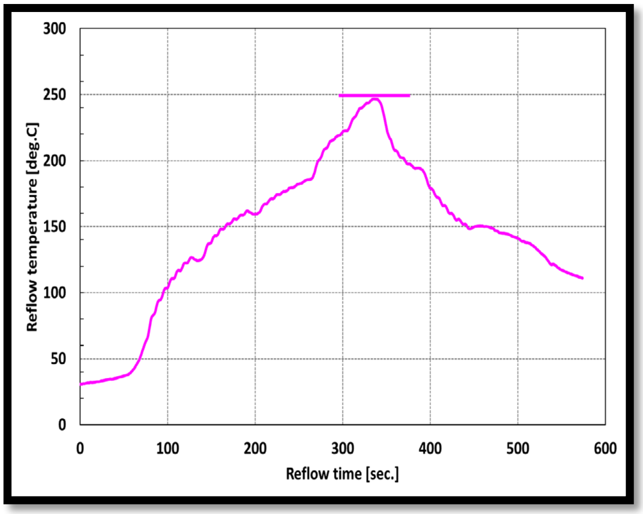

Figure 3. ANTOM model UNI-6116a - Reflow Profile

A TPT model HB16 wire bonding machine was used to bond 1.0-mil gold wire to the test boards. The 1.0-mil gold wire met the requirements of ASTM F72-21 Standard Specification for Gold Wire for Semiconductor Lead Bonding. Twenty wire bonds were made on each test board for the 10 DoE runs. A total of 200 wire bonds were made. Wire bond pull strength was tested per MIL-STD-883 Method 2011, Condition D. Both gram-pull break forces and locations were recorded. The failure modes were evaluated using scanning electron microscope/energy dispersive spectroscopy (SEM/EDS).

Scanning electron microscope images allow for high resolution and increased depth of focus compared to optical microscopes [4]. Energy dispersive spectroscopy analysis allows for the detection and distinction of different elements based on the X-ray energy generated by the sample [5]. Scanning electron microscope/energy dispersive spectroscopy was used to analyze the intermetallic (IMC) layer integrity, solder joint, and wire bond fractures. The ability to gather high-resolution images at increased magnification aids in process optimization regarding solder joint and wire bond reliability. Statistical analysis was completed on the data collected.

Minitab$^{\copyright}$ 21 was used for statistical analysis. A nonparametric Kruskal-Wallis test was used to determine differences among factor medians. Nonparametric analysis of variance (ANOVA) modeling allows for a higher degree of flexibility than parametric ANOVA [6]. All population medians were tested as being equal, with individual groups evaluated using Dunn's test. Individual group p-values were calculated for statistical significance.

RESULTS

The Kruskal-Wallis analysis showed no practical difference in gold thickness quartiles for the high-speed shear (HSS) force response. The gold thickness quartiles were excluded from further analysis. Next, the palladium thickness quartiles were analyzed.

The Kruskal-Wallis analysis showed that palladium thickness quartiles were statistically significant for the HSS force response. The palladium thickness quartiles with a family alpha p-value less than 0.05 and Z-value greater than 2.64 were determined to be significantly different in median shear force (see Table 2). Next, multiple comparisons were completed.

Table 2. Palladium Quartile HSS Comparison

Palladium Thickness Quartile Groups	Z vs Critical value	P-value
2 vs 4	$7.65 \geq 2.64$	< 0.05
2 vs 3	$4.58 \geq 2.64$	< 0.05
1 vs 2	$4.25 \geq 2.64$	< 0.05
3 vs 4	$3.56 \geq 2.64$	< 0.05
1 vs 4	$3.11 \geq 2.64$	< 0.05

A Multiple Comparisons Chart consisting of Sign Confidence Intervals and Pairwise Comparisons was used to convey the difference in shear force between palladium quartiles. The Sign Confidence Intervals depict the expected value for the shear force at each palladium thickness quartile with a 93.8% confidence interval. Palladium thickness quartile 2 yielded the lowest shear force with a median value of 391.5 g. Palladium thickness quartile 4 yielded the highest shear force with a median value of 525.5 g. The Pairwise Comparisons depicts the distance between the median forces of each palladium thickness quartile. Points that fall between the [-Z, Z] interval are not statistically different (see Figure 4). Next, the IMC integrity of the HSS testing was observed.

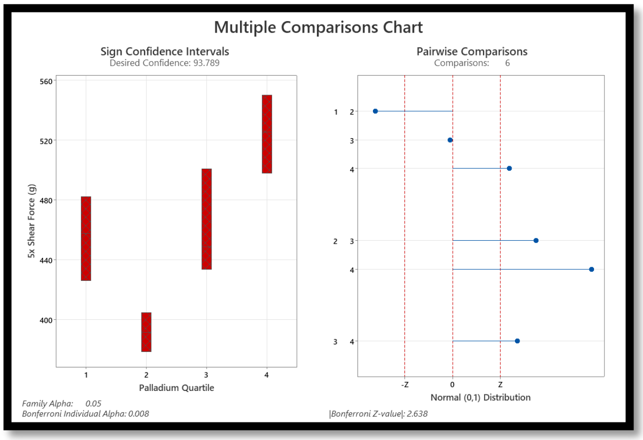

Figure 4. Palladium Quartile HSS Multiple Comparisons Chart

A scanning electron microscope was used to evaluate the integrity of the IMC after HSS testing was completed. The HSS failure modes observed show a contiguous IMC encased in bulk solder after HSS testing was completed (see Figure 5A, Figure 5B). Similar Kruskal-Wallis and SEM analyses were used to determine the main effects of the wire bonding pull strength response.

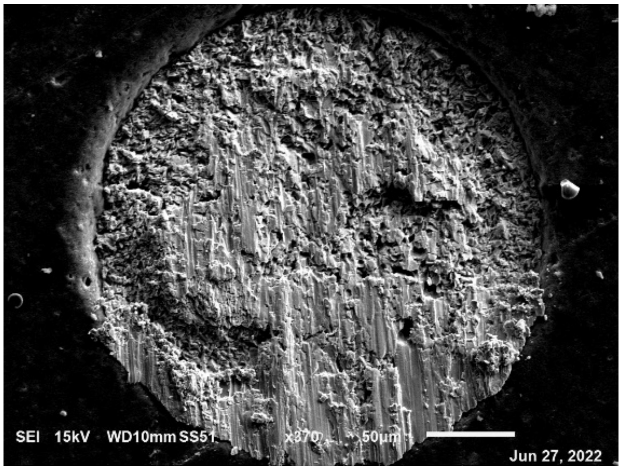

Figure 5A. SEM Image of HSS Failure Mode at 370x

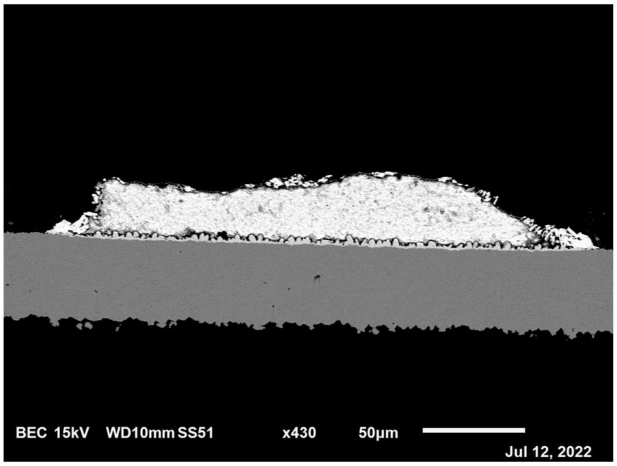

Figure 5B. Cross Section of IMC at 430x Post Etching

The Kruskal-Wallis analysis showed no practical difference in palladium thickness quartiles for the wire bond pull strength response. The palladium thickness quartiles were excluded from further analysis. Next, the gold thickness quartiles were analyzed.

The Kruskal-Wallis analysis showed that gold thickness quartiles were statistically significant for the wire bond pull strength force response. The gold thickness quartiles with a family alpha p-value less than 0.05 and Z-value greater than 2.64 were determined to be significantly different in median pull strength (see Table 3). Next, multiple comparisons were completed.

Table 3. Gold Thickness Quartile Pull Strength Comparison

Gold Thickness Quartile Groups	Z vs Critical value	P-value
1 vs 4	$3.86 \geq 2.64$	< 0.05
1 vs 3	$3.73 \geq 2.64$	< 0.05

A Multiple Comparisons Chart consisting of Sign Confidence Intervals and Pairwise Comparisons was used to convey the difference in wire bond pull strength between gold quartiles. The Sign Confidence Intervals depict the expected wire bond pull strength value at each gold thickness quartile with a 93.8% confidence interval. Gold thickness quartile 1 yielded the lowest wire bond pull strength with a median value of 5.19 g. Gold thickness quartile 3 yielded the highest wire bond pull strength with a median value of 6.88 g. The Pairwise Comparisons depict the distance between the median pull strengths of each gold thickness quartile. Points that fall between the [-Z, Z] interval are not statistically different (see Figure 6). Next, SEM images were taken to evaluate the wire bond integrity.

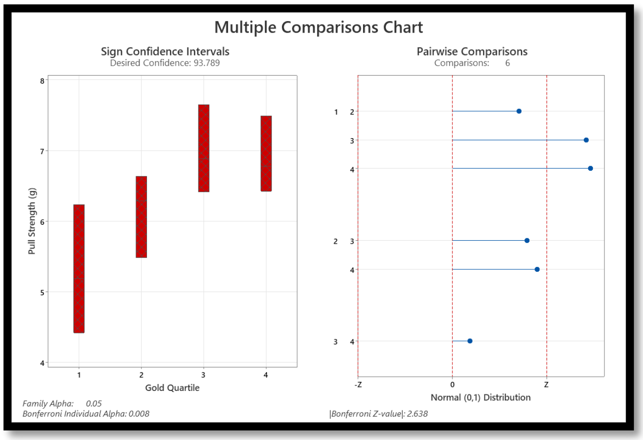

Figure 6. Gold Thickness Quartile Pull Strength Multiple Comparisons Chart

A scanning electron microscope was used to evaluate the integrity of the wire bonds after pull strength testing. The wire bond failure modes observed show no voiding or separation between the bond and the EPIG finish (see Figure 7A, Figure 7B). Wire pull testing yielded only neck, heel, and span breaks. Lastly, response optimization was performed.

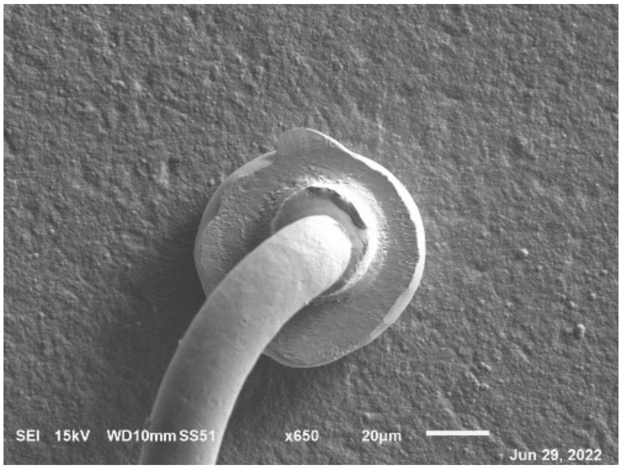

Figure 7A. SEM Image of a Ball Bond at 650x Post Pull Testing

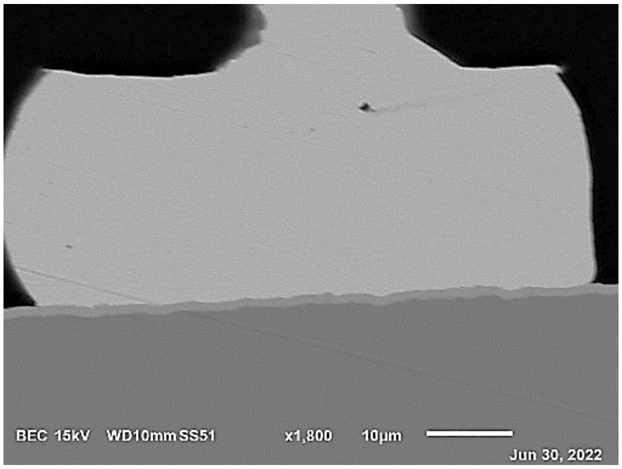

Figure 7B. Cross Section of a Ball Bond at 1800x Post Pull Testing

Response optimization was used to identify the combination of EPIG plating thicknesses to enhance solder joint and wire bonding reliability. The plating thickness combinations targeted high shear forces, and high wire bond pull strengths. Results of the response optimization are discussed in the conclusions.

CONCLUSIONS

The EPIG final finish is currently not governed by an industry standard. Without an optimized standard, the threat of solder joint and wire bond failures is present. The DoE completed provided the primary contributing factor levels for optimizing solder joint and wire bond reliability. Looking at these contributing factor levels, solder joint reliability is primarily affected by palladium thickness, while wire bond integrity is affected by gold thickness (see Figure 4, Figure 6).

The following conclusions are provided to optimize solder joint and wire bonding reliability in the EPIG process:

1) Palladium quartile 4 yielded the highest solder joint shear results
2) Gold quartile 3 yielded the highest wire bond pull strength results

Optimizing plating thickness ranges for EPIG can significantly impact the electronics industry. Establishing industry standard plating thickness ranges reduces plating thickness ambiguity amongst OEMs, PCB manufacturers, and chemical suppliers. Optimized thicknesses can reduce the possibility of solder joint and wire bond failures. Decreasing scrap and the cost of poor quality in the EPIG process will positively impact the industry.

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