

## ABSTRACT

Title of Document: EFFECT OF PALLADIUM THICKNESS AND  
EXTENDED ISOTHERMAL AGING ON THE  
RELIABILITY OF SOLDER  
INTERCONNECTS FORMED ON ENEPIG  
SURFACE FINISH

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Surface finishes for copper on printed wiring boards play an important role in the reliability of electrical interconnects. Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG), developed in the mid-1990s to alleviate the “black-pad” problem created by Electroless Nickel/Immersion Gold (ENIG) surface finish, has gained interest for critical system applications. This thesis investigates the effect of palladium layer thickness and extended isothermal aging on the reliability of both tin-lead and tin silver copper solder interconnects under temperature cycling, vibration cycling, and drop loading conditions. Chip array ball grid array (CABGA) packages soldered onto ENEPIG-finished PCBs are subjected to the three previously listed conditions. Reliability and failure analyses are conducted to determine the overall effect of palladium layer thickness and isothermal aging on the reliability of these solder interconnects.

EFFECT OF PALLADIUM THICKNESS AND EXTENDED ISOTHERMAL  
AGING ON THE RELIABILITY OF SOLDER INTERCONNECTS FORMED ON  
ENEPIG SURFACE FINISH

By

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## **Dedication**

To my grandfather, Theodore H. Goldsmith, who passed on his love for science and engineering to me at a very young age.

Also to my mother, Caren Sue Pearl, who laid the foundation for my upbringing and growth to the man I am today. I will always miss you.

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## **Chapter 1: Introduction**

Printed circuit boards are typically made of copper-plated glass epoxy laminates. Some of this copper is exposed to allow for mounting of components. Because copper oxidizes quickly when exposed to the environment, a surface finish is needed to protect the copper from oxidation. The surface finish covers the exposed metallization so that it is not exposed to oxygen in the environment. The surface finish must be smooth and have good thermo-mechanical properties to allow for soldering of components. During soldering, temperatures can exceed 200°C, resulting in diffusion of the finish material into the solder and altering the mechanical, physical, and electrical properties of the solder interconnect. Because finishes can be made from different materials, each surface finish has its own advantages and disadvantages, in addition to its ideal use condition(s).

### **1.1: Common Surface Finishes**

Listed below are four common surface finishes in use today. A description of each finish, along with some of its advantages and disadvantages is provided. The four finishes discussed are Organic Solderability Preservative (OSP), Immersion Tin (ImSn), Immersion Silver (ImAg), and Electroless Nickel Immersion Gold (ENIG).

#### **1.1.1: Organic Solderability Preservative (OSP)**

Organic Solderability Preservative (OSP) is the only non-metallic finish discussed in this thesis. It is simply an organic coating over copper, protecting it from oxidation. Because it is a non-metallic coating, the cost of applying OSP is the lowest of all of the surface finishes. During soldering, the finish simply melts and allows for metallic bonding between the bulk solder material and copper, forming Cu-Sn intermetallic

compounds (IMCs) at the copper/solder interface [1]. Two common Cu-Sn intermetallics are  $\text{Cu}_6\text{Sn}_5$  and  $\text{Cu}_3\text{Sn}$ .

Because OSP is a non-metallic surface finish, it presents problems that are not often seen with metallic finishes. Firstly, the finish cannot withstand multiple solder and wave reflows, which are often used to ensure formation of strong IMCs in solder interconnects [1]. OSP also has a short shelf life, on the order of 3-6 months [2]. In addition, the finish does not allow for wire bonding applications or contact applications such as connectors. As such, OSP is not a viable surface finish for many applications.

### **1.1.2: Immersion Tin (ImSn)**

Immersion Tin (ImSn) makes use of the immersion plating process to plate a thin layer of tin directly onto copper. The immersion plating process is described in Appendix A. Because ImSn is a slick finish with uniform thickness, it is ideal for pin and press-fit connector applications. Unfortunately the thickness requirement stated in IPC-4554 [3] is  $1\ \mu\text{m}$ , which is rather thick for an immersion plating process. Furthermore, the low melting temperature of tin ( $232^\circ\text{C}$ ) does not make it an ideal surface finish for soldering, as soldering temperatures can easily exceed that temperature, rendering the finish useless.

### **1.1.3: Immersion Silver (ImAg)**

Unlike ImSn, Immersion Silver (ImAg) is a very thin layer of silver plated onto copper using the immersion plating process. Silver has a much higher melting temperature than tin ( $962^\circ\text{C}$ ), making it ideal for soldering applications. During soldering, the silver dissolves into the bulk to form  $\text{Ag}_3\text{Sn}$  IMCs within the bulk and Cu-Sn IMCs at the interface. Unlike OSP, the high melting temperature allows ImAg to

withstand multiple reflow profiles, making it an ideal surface finish for PCBs. In addition, because an immersion plating process is used to plate only 0.1-0.2  $\mu\text{m}$  of silver, the processing cost is relatively low, making ImAg a very viable surface finish, especially when considering RoHS regulations banning lead.

#### **1.1.4: Electroless Nickel Immersion Gold (ENIG)**

Unlike the previous finishes, Electroless Nickel Immersion Gold (ENIG) consists of two materials plated onto the copper. The nickel layer should have a thickness of 3-6  $\mu\text{m}$  while the gold layer thickness should be between 0.05 and 0.10  $\mu\text{m}$ . Because the nickel layer is at least 3  $\mu\text{m}$  thick, it will not fully dissolve into the bulk solder. Rather, the bond is formed between the solder and the nickel covering the pad, creating Ni-Sn IMCs. If the solder alloy contains an addition of copper, as in SnAgCu (SAC) alloys, a ternary Cu-Ni-Sn IMC can form. Copper from the terminals of the package can also migrate through the bulk solder to form these ternary IMCs.

Of all of these finishes, ENIG is the most versatile in that it is both gold and aluminum wire bondable and solder very readily wets to the exposed gold. In addition, there is virtually no corrosion risk and the finish can easily be inspected for damage. The drawback for ENIG is the potential for “black-pad”, which is a nickel-oxide that forms during the immersion gold plating step. The black-pad forms under the nickel, potentially causing the finish to lift off from the pad, greatly reducing solder interconnect reliability [1] [4].

## 1.2: ENEPIG Surface Finish

A solution to the “black-pad” problem was to apply an electroless deposition of palladium to prevent the nickel from oxidizing during the immersion gold plating process. This layer of Pd created Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) surface finish. ENEPIG was originally introduced in the mid-1990s, but adoption of the surface finish was slow due to concerns regarding the reaction between Pd and lead in eutectic tin-lead solder [4]. The institution of RoHS, which banned Pb from electronics, brought ENEPIG back into consideration as a potential surface finish. A schematic of ENEPIG, along with the required thicknesses of each of the layers as per IPC-4556, is shown in Figure (1).

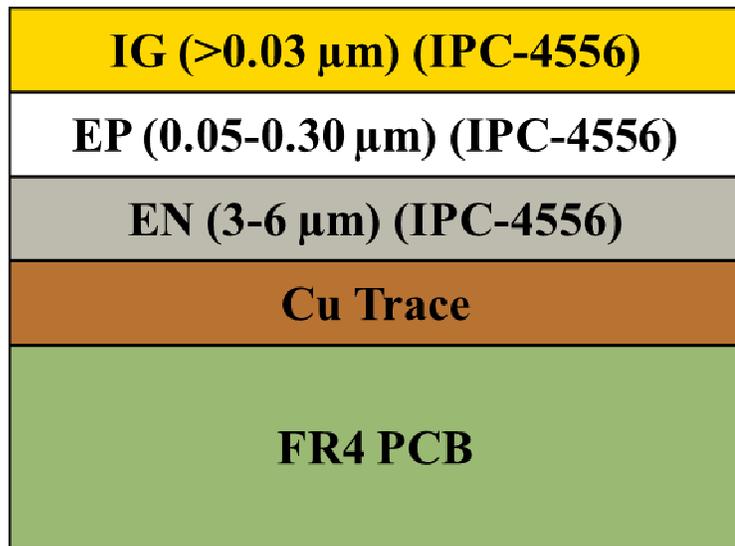


Figure 1 – Schematic of ENEPIG finish with required thicknesses as per IPC-4556

### **1.2.1: Intermetallic Formation on ENEPIG**

Similar to its predecessor, ENIG, Ni-Sn IMCs form on ENEPIG when tin-based solders are applied to the finish [5]. The exact composition and appearance of the IMCs depend on many factors including the thickness of the surface finish materials and the solder reflow profile chosen. Figures (2) and (3) show cross-sections of typical solder

interconnects formed on ENEPIG and the IMCs that create the bond between the solder and the ENEPIG-finished pad.

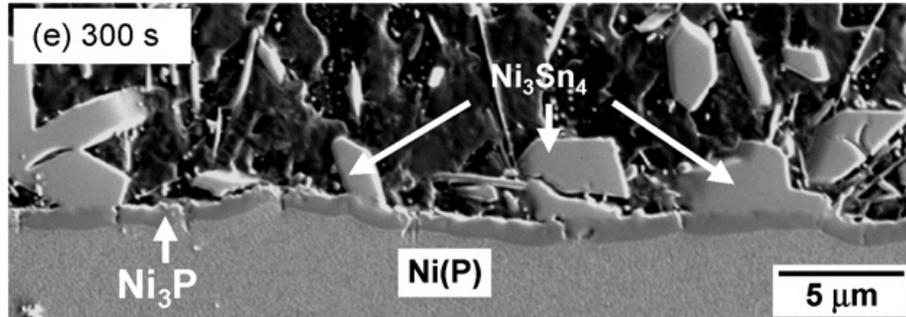


Figure 2 - IMCs formed during 300 s of soldering onto ENEPIG with eutectic SnPb [5]

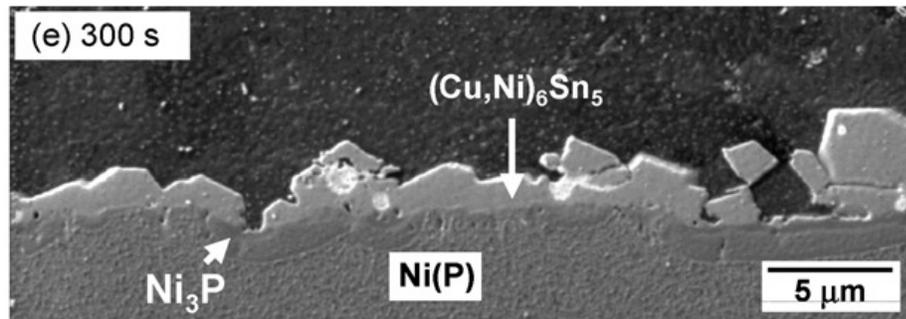


Figure 3 - IMCs formed during 300 s of soldering onto ENEPIG with SAC305 [5]

The solder interconnects shown in Figures (2) and (3) were formed using a solder reflow profile where the temperature was held at the peak temperature for 300 seconds (220°C for SnPb, 240°C for SAC305). In both images, the Au and Pd are completely dissolved; they were dissolved within 5 seconds of reaching peak temperature. For SnPb in Figure (2), the Ni<sub>3</sub>Sn<sub>4</sub> IMCs are not uniformly distributed across the pad. Rather, the crystals are dispersed randomly across, allowing the bulk to be bonded with the pad. This is not the case for SAC305, shown in Figure (3). Due to the presence of Cu in the solder alloy, the IMC is (Cu,Ni)<sub>6</sub>Sn<sub>5</sub> and these crystals remain attached to the pad, covering the surface.

### **1.2.2: Solder Ball Strength of ENEPIG**

Two very common solder interconnect tests are ball pull and ball shear, in which solder balls are pulled or pushed off of their pads. The force required to remove the ball is recorded, along with the fracture site. A fracture in the bulk solder material is indicative of a stronger solder joint, as the bonding interface (the IMC) is still intact.

Milad et. al. [6-8] conducted solder ball pull tests on solder interconnects formed on both ENIG and ENEPIG surface finishes. The ENIG finish had thicknesses of 5  $\mu\text{m}$  Ni and 0.05  $\mu\text{m}$  Au, while the ENEPIG finish had thicknesses of 5  $\mu\text{m}$  Ni, 0.06  $\mu\text{m}$  Pd, and 0.03  $\mu\text{m}$  Au. Eutectic SnPb and SAC305 solder balls were mounted onto PCBs containing these finishes, and then the balls were pulled at a rate of 170  $\mu\text{m}/\text{sec}$ . What they discovered was that between ENIG and ENEPIG, there was no significant difference in the force required to pull the solder ball off of the test coupon used. SnPb solder balls required approximately 2900 g's of force to be pulled off of both finishes, while SAC305 solder balls came off after approximately 2700 g's of force. The effect of surface finish was only seen when the failure site was investigated: bulk solder failures occurred in SnPb solder balls on ENIG and SAC305 solder balls on ENEPIG, while IMC fractures were in SnPb solder balls of ENEPIG and SAC305 solder balls on ENIG. What this means is that even though 7.4% more force is required to pull a SnPb solder ball off of an ENEPIG or ENIG finished pad than a SAC305 solder ball, the stronger IMC is found in the ENEPIG/SAC305 solder interconnect.

Johal et. al. [9] found similar results in his ball shear tests. ENEPIG was compared with ENIG and OSP, and SAC356 was used instead of SAC305 for this study. Eutectic SnPb was also used. Ni thickness was set at 5  $\mu\text{m}$  and Au thickness was 0.05

$\mu\text{m}$ , but three different Pd thicknesses were used: 0.1, 0.2, and 0.3  $\mu\text{m}$ . The effect of the varying thicknesses will be discussed in section 1.3.1, but it was found that the shear forces required to remove the SAC356 solder balls mounted on ENEPIG was 6-25% higher than those on both ENIG and OSP. In addition, the location of the failure was distinctly different across the finishes. All ENEPIG and OSP failures were within the bulk solder material, indicating a strong bond between the solder and the finish. Failures in ENIG, however, were all within the IMC, indicating a weak bond between the solder and the finish. Considering the shear force to failure and the location of the failures, the best-performing surface finish was ENEPIG, as the force required for failure was highest amongst all of the finishes, and all of its failures were within the bulk solder material.

### **1.3: Motivation and Problem Statement**

The studies discussed in the previous section showed that robust, strong solder interconnects can be formed on the ENEPIG surface finish. One fact to note is that Milad and Johal, in their work, did not use the same layer thicknesses for ENEPIG. Most notably, the thickness of the Pd layer had the most variation; Johal in fact used three different thicknesses of Pd. While Peng [5] showed that the Au and Pd layers dissolved within 5 seconds of soldering at the peak temperature of the reflow profile, varying the thicknesses of either of these layers could potentially change the size and morphology of the IMC that creates the bond between the solder and the finish. Altering the IMC in this manner could have a significant effect on the overall reliability of the solder interconnect.

These changes in size and morphology also occur naturally over time. Many researchers (and even manufacturers) subject their samples to an extended isothermal aging in a temperature-controlled oven to accelerate this process. Similar to changing the

thickness of the Pd, isothermal aging could also have a significant effect on solder interconnect reliability.

### **1.3.1: Effect of Palladium Layer Thickness**

The IPC standard for ENEPIG, IPC-4556, lists the required thicknesses of each of the layers of ENEPIG. These requirements are also shown in Figure (1). As IPC specifies a range of thicknesses, researchers have conducted many experiments to attempt to find the optimal thicknesses that would provide the most robust solder interconnects.

Referring back to Johal's shear tests [9], three different thicknesses of Pd were tested: 0.1, 0.2, and 0.3  $\mu\text{m}$ . Regardless of the thickness of the Pd layer, there was no significant change in force required to shear the solder balls off of the finish; all solder balls required approximately 12 N of force to be removed. The effect of Pd layer thickness could be seen in the failure site: increasing the thickness of Pd to 0.3  $\mu\text{m}$  shifted all but one of the failures to the IMC.

Oda et. al. [10-11] used the solder ball pull test to attempt to optimize the thicknesses of the Pd and Au layers in ENEPIG. Eleven different thicknesses of Pd between 0 and 0.3  $\mu\text{m}$ , and 9 different thicknesses of Au between 0.05 and 0.4  $\mu\text{m}$ , were evaluated. SAC305 solder balls soldered onto these ENEPIG finished boards were pulled at 1000  $\mu\text{m}/\text{sec}$ , and the failure site was recorded. The results showed that if the Pd layer thickness was kept between 0.02 and 0.10  $\mu\text{m}$ , all failures were within the bulk solder. Increasing the thickness shifted the failure site to the IMC, although some samples still did fail in the bulk. For Au, the optimal thickness range was between 0.05 and 0.40  $\mu\text{m}$ .

Li et. al. [12] used a more conventional reliability test to assess the effect of Pd layer thickness in ENEPIG: bend test. The problem with Li's study, however, is that no

actual thicknesses are specified; they are only classified as high, medium, and low thickness. ENEPIG-finished boards with BGA packages soldered with SAC solder were bent in such a manner that they experienced 1000, 1500, 2000, and 3000  $\mu\epsilon$  at a rate of 16000  $\mu\epsilon$ /sec. Boards with the thinner layers of Pd withstood up to 57% more cycles to failure than the boards with thicker layers of Pd. As a baseline for comparison, boards with an electrolytic nickel / gold finish were also tested. It was found that the Ni/Au finish halved the life of the components compared to thin Pd ENEPIG.

Wu et. al. [13] investigated the effect that varying the thickness of Pd had on the soldering reactions between SAC305 and ENEPIG. The Ni and Au layers were fixed at 7 and 0.1  $\mu\text{m}$ , respectively, and Pd thickness was either 0.1 or 0.2  $\mu\text{m}$ . An ENIG finish (no Pd) was also used. An investigation into the IMCs that formed revealed that the total IMC thickness decreased by over 50% when the Pd layer thickness was increased from 1 to 2  $\mu\text{m}$ . This was due to the P within the Ni and Pd layers that had been left behind from the electroless plating process. When the Pd layer dissolved into the solder, the P crystallized with the Ni and Sn at the interface to form a  $\text{Ni}_2\text{SnP}$  IMC. With a thicker layer of Pd, more  $\text{Ni}_2\text{SnP}$  is left behind, reducing the amount of Sn available to form  $(\text{Cu,Ni})_6\text{Sn}_5$  IMC, thus reducing the thickness of these IMCs. Shear tests conducted at 0.007 and 2  $\mu\text{m}/\text{sec}$  also revealed that Pd thickness had no effect on shear strength required to cause failure in the solder interconnects, but using no Pd (ENIG) reduced shear strength by 6%.

Yee [14] conducted pull tests on five different surface finishes using SAC305 solder balls. The finishes chosen were the four finishes discussed in section 1.1 and ENEPIG with four different thicknesses of Pd: 0.05, 0.1, 0.2, and 0.3  $\mu\text{m}$ . Ni and Au

thickness were fixed at 5 and 0.03  $\mu\text{m}$ , respectively. Balls were pulled off of each of these finishes at a rate of 300  $\mu\text{m}/\text{sec}$ . All of the surface finishes except for ImAg had ball strength between 1800 and 1900 g. For ENEPIG, there was no difference between 0.05 and 0.1  $\mu\text{m}$  Pd, but 0.2  $\mu\text{m}$  Pd reduced the strength to 1700 g, and a thickness of 0.3  $\mu\text{m}$  Pd further reduced this strength to 1600 g, a 12% decrease from the initial thickness of 0.05  $\mu\text{m}$ .

All of the research listed in this section proved that a thinner layer of Pd, less than 0.2  $\mu\text{m}$ , is preferred for optimal bond strength. None of the previous researchers except for Li used actual reliability tests in their research, however; all conclusions were drawn from solder ball pull and shear tests. In the field, solder interconnects will not be directly pulled or sheared off of the boards or components. Rather, they will be exposed to a variety of thermal and mechanical loading conditions. None of the previous work assesses the effect of Pd thickness on reliability under such loading conditions.

### **1.3.2: Effect of Extended Isothermal Aging**

As mentioned previously, IMCs formed from soldering reactions will change in size and morphology naturally over time. Isothermal aging can accelerate this process, allowing researchers to understand the effect of changing IMCs on reliability of solder interconnects.

Fu [15-16] studied the effect of isothermal aging on solder interconnects formed on ENEPIG (5  $\mu\text{m}$  Ni, 0.2  $\mu\text{m}$  Pd, 0.1  $\mu\text{m}$  Au) and electrolytic Ni/Au surface finishes. SAC305 solder balls soldered to these finishes were isothermally aged at 150°C for 250, 500, and 1000 hours. Following the isothermal aging steps, ball pull and shear tests were conducted. Force required to remove the solder balls was not recorded, but it was noted

that increasing the isothermal aging duration increased the number of IMC failures in ball pull on ENEPIG by 22%, Ni/Au by 14%. In shear, increasing the aging duration increased IMC failures in ENEPIG by 30%, 65% in Ni/Au. Comparing ENEPIG to Ni/Au, the choice is clear as to which surface finish is superior, but the major conclusion to be drawn is that IMCs in solder interconnects on ENEPIG are weakened by isothermal aging.

Milad [6, 17-18] in his ball pull tests discussed in section 1.2.2, conducted isothermal ages at 150°C for 0, 100, 300, 500, and 1000 hours. Without aging, the pull strength of SnPb solder balls on ENEPIG was approximately 2900 g, and the pull strength of SAC305 solder balls on ENEPIG was approximately 2700 g. With isothermal aging, SnPb strength decreased to approximately 2300 g (21%), while SAC305 strength decreased to approximately 2200 g (19%). Furthermore, without aging, 50% of SnPb failures were within the solder. After 300 hours of aging, only 10% of the failures were within the solder. Increasing the aging any further shifted all failures to the IMC. In SAC305, all failures were within the solder, regardless of how much isothermal aging was conducted. Considering RoHS, this is a very promising result for ENEPIG, since aging did not reduce the strength of the IMC bonding the SAC305 solder to the ENEPIG finished pad.

Similar to the research on Pd layer thickness, none of the previous research investigated the effect of isothermal aging on reliability of ENEPIG solder interconnects under thermal and mechanical loading conditions. While isothermal aging has clearly been shown to decrease the overall strength of solder interconnects and the IMCs that

bond the solder to the pad, Milad's results for SAC305 failures raise the issue that there may be more to this phenomenon.

### **1.3.3: Problem Statement**

The previous research has shown that changing the thickness of Pd has an effect on the strength of the solder interconnect and the IMC that forms. The primary solders in this research are widely accepted as the two most popular solder alloys in the field: eutectic SnPb and SAC305. What is unknown is the effect of Pd thickness on the reliability of these interconnects under thermal and mechanical loading conditions.

In addition to Pd thickness, isothermal aging has been shown to decrease the strength of these interconnects. For reliability tests such as temperature cycling, vibration cycling, and drop loading, isothermal aging has been suggested as a pre-conditioning step for reliability assessment.

### **1.4: Summary**

ENEPIG is a surface finish consisting of three layers: Ni, Pd, and Au. Typically Ni-Sn IMCs form upon soldering, but Cu in the solder alloy (or PCB or terminals of the part to be soldered) can migrate to the interface and form Cu-Ni-Sn IMCs. Typically SAC305 solder forms a stronger bond to ENEPIG than traditional eutectic SnPb solder, which is promising for ENEPIG considering RoHS. Varying the thickness of the Pd layer has been shown to alter the strength of the solder interconnect, with thicker layers of Pd reducing the strength by up to 25%. In addition, isothermal aging has also been shown to reduce the strength of these interconnects by up to 30%. What is unknown is

the effect of Pd thickness and isothermal aging on thermal and mechanical reliability of these solder interconnects.

This paper discusses tests conducted on SnPb and SAC305 interconnects formed on ENIG surface finish. Solder balls attaching BGA components to ENIG-finished PCBs were subjected to temperature cycling, vibration cycling, and drop loading conditions. Two thicknesses of Pd were used to quantify the effect of Pd thickness on reliability under these conditions. Isothermal aging was also conducted to quantify its effect on reliability under these conditions. Reliability and failure analyses were conducted to quantify these effects and determine a cause.

## **Chapter 2: Experimental Set-Up**

To understand the effect of Pd thickness and isothermal aging on thermal and mechanical reliability of solder interconnects, three reliability tests were conducted. This chapter discusses these three tests, including the PCBs, components, solders, and procedures used. All tests used the same PCB construction, components, and solders.

### **2.1: Test Boards**

The PCB used was a basic multi-layered PCB, measuring 9" x 4.5" x 0.062". Exposed Cu metallization was covered by either an ENEPIG or ImAg surface finish. ImAg surface finish was used as a baseline comparison to the ENEPIG finish. For ENEPIG, two different thicknesses of Pd were used to understand the effect of varying Pd thickness on solder interconnect reliability. The previous research indicated that keeping the Pd layer thinner than 0.2  $\mu\text{m}$  provided the strongest solder interconnects. Considering this fact, the two thicknesses of Pd used were 0.05  $\mu\text{m}$  and 0.15  $\mu\text{m}$ . To better distinguish the two versions of ENEPIG, the ENEPIG finish with the 0.05  $\mu\text{m}$  Pd layer will be referred to as "thin-Pd ENEPIG", and the ENEPIG finish with the 0.15 micron Pd layer will be referred to as "thick-Pd ENEPIG." Table (1) provides information regarding the thicknesses of the different layers of the ENEPIG and ImAg surface finishes used.

Ten components were soldered onto each board: four 192 I/O daisy-chain chip array ball grid arrays (CABGA), and six 2512 resistors. For this study, only the four BGAs were considered. Exposed solder pads on the left and right edges of the board were used to solder wires to an Agilent 34980A datalogger which monitored the

resistance of the BGAs. Components were soldered using either eutectic SnPb or SAC305 solders. In all cases, the solder paste and solder balls were the same, i.e. SnPb solder balls to SnPb solder paste and SAC305 solder balls to SAC305 solder paste. The test board used is shown in Figure (4).

Table 1 - Surface finish details

Board Finish	Ni Layer ( $\mu\text{m}$ )	Pd Layer ( $\mu\text{m}$ )	Au Layer ( $\mu\text{m}$ )	Ag Layer ( $\mu\text{m}$ )
Immersion Silver	-	-	-	$0.2 \pm 0.06$
Thin-Pd ENEPIG	$5 \pm 0.2$	$0.05 \pm 0.004$	$0.3 \pm 0.003$	-
Thick-Pd ENEPIG	$5 \pm 0.2$	$0.15 \pm 0.006$	$0.3 \pm 0.003$	-

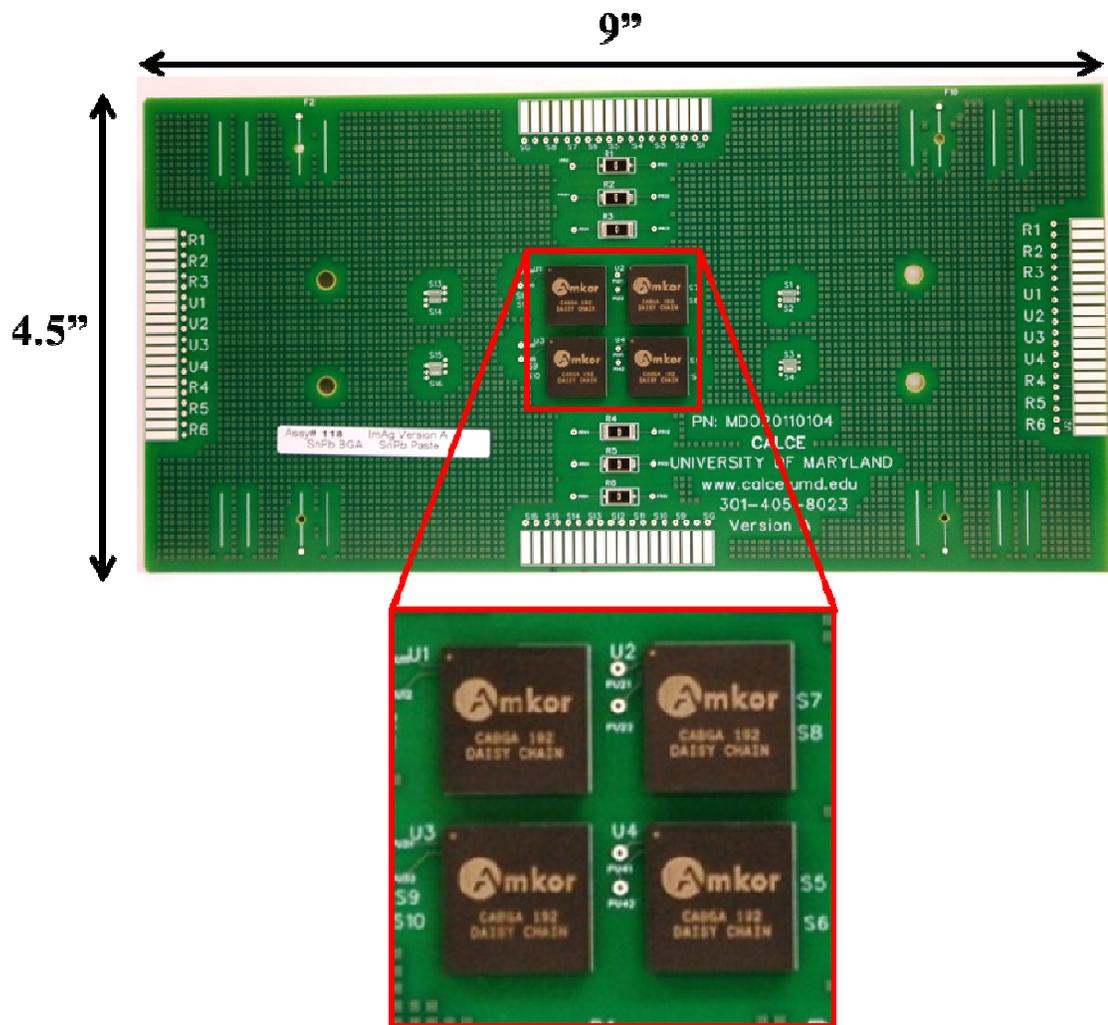


Figure 4 - Test board and close-up of BGA components

## **2.2: Reliability Tests and Parameters**

The three reliability tests conducted on the PCBs to assess thermal and mechanical reliability were temperature cycling, vibration cycling, and drop loading. The following sections describe each of these tests, including their test parameters. Following each of the tests, components were removed from the test boards, potted in an epoxy mold, and cross-sectioned to reveal the failure.

For all three tests, resistance was monitored using an Agilent 34970A datalogger. The failure criteria for each of the BGAs was a 20% increase in nominal resistance, followed by 5 consecutive resistance readings above this 20% threshold.

### **2.2.1: Temperature Cycling**

Temperature cycling was conducted to assess the effect of Pd thickness and isothermal aging on thermal reliability. Prior to testing, half of the boards were isothermally aged for 24 hours at 100°C. The other half were not exposed to this pre-conditioning step and tested as-received. Thirty-six boards were subjected to thermal cycling between -55°C and 125°C, with 15 minute dwells at the extreme temperatures and a constant 8.6°C/min ramp rate, resulting in a 72 minute temperature cycle [19]. The test matrix is shown in Table (2), and a plot of the temperature profile is shown in Figure (5).

*Table 2 - Test matrix for temperature cycling test*

<b><i>Aging Condition</i></b>	<b>As-Received</b>		<b>100°C / 24 Hrs</b>	
<i>Solder</i>	SnPb	SAC305	SnPb	SAC305
<i>Immersion Silver</i>	3	3	3	3
<i>Thin-Pd ENEPIG</i>	3	3	3	3
<i>Thick-Pd ENEPIG</i>	3	3	3	3

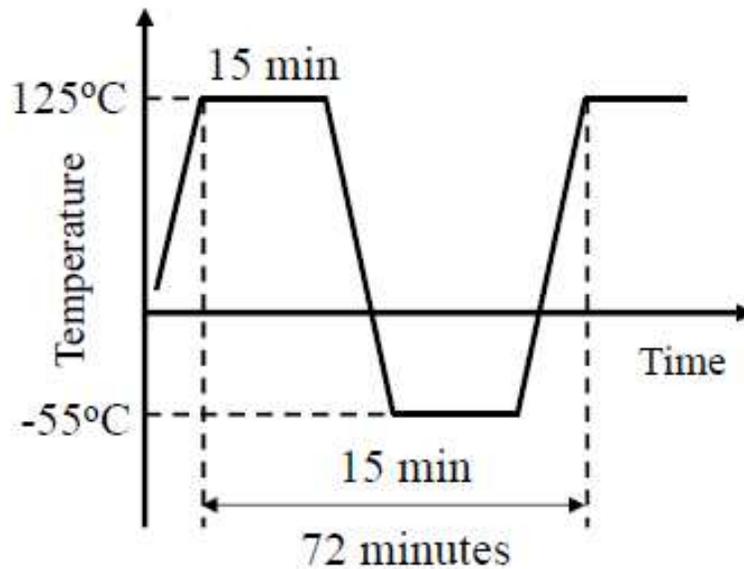


Figure 5 - Temperature cycling test profile (IPC-9701)

### 2.2.2: Vibration Cycling

One of the two tests to assess the effect of Pd thickness and isothermal aging on mechanical reliability of solder interconnects on ENEPIG was vibration cycling. Forty-eight boards were subjected to vibration cycling. All of the boards were subjected to isothermal aging at 100°C, but half were aged for 24 hours while the other half were aged for 500 hours.

For the test, boards were clamped in an aluminum fixture and subjected to a harmonic uni-axial vibration at an acceleration level of 3 g. The fixture was designed such that the components were centered in a 6" unsupported span, which vibrated at a resonant frequency between 192 and 201 Hz. At this frequency, a 90 g output acceleration was seen on the board for a transmissibility ratio of 30. A schematic of the fixture is shown in Figure (6). Strain levels were monitored by affixing 3 strain gages to

the underside of the board as shown in Figure (7). The test matrix for the vibration test is shown in Table (3).

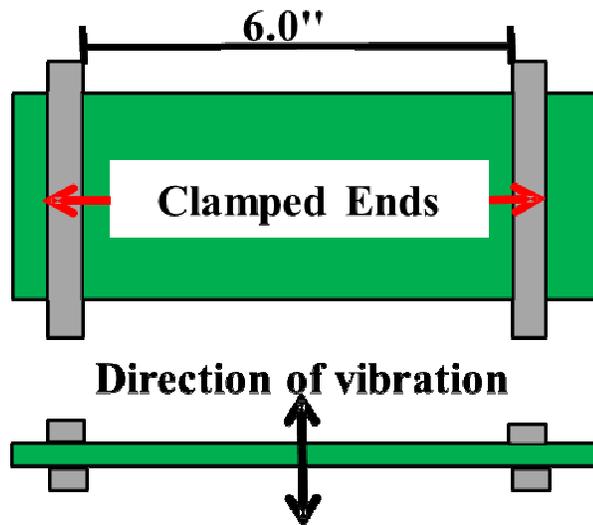


Figure 6 - Schematic of vibration cycling test set-up

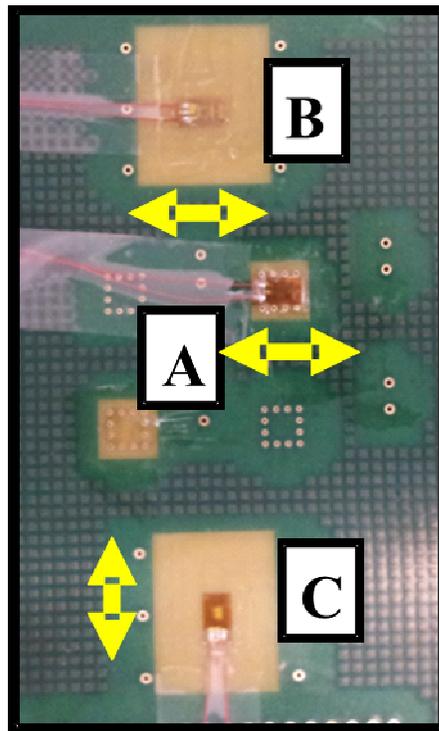


Figure 7 - Locations of strain gages for vibration test. Locations A and B are under the BGAs, while location C is under the resistors (not monitored)

Table 3 - Test matrix for vibration cycling and drop loading tests

<i>Aging Condition</i>	<b>100°C / 24 Hrs</b>		<b>100°C / 500 Hrs</b>	
	SnPb	SAC305	SnPb	SAC305
<i>Solder</i>				
<i>Immersion Silver</i>	4	4	4	4
<i>Thin-Pd ENEPIG</i>	4	4	4	4
<i>Thick-Pd ENEPIG</i>	4	4	4	4

### 2.2.3: Drop Loading

The other test to assess mechanical reliability was drop loading. The forty-eight boards for drop loading were subjected to the same aging conditions as the vibration cycling boards. Since the number of boards subjected to drop loading was the same as the number of boards subjected to vibration cycling, the test matrix for the drop loading test is the same as the vibration cycling test and is shown in Table (3).

Each drop applied a 1500 g, 0.5 ms half-sine shock pulse to the board, which was clamped in an aluminum fixture to the drop tower. The unsupported span for the drop loading was 3". A plot showing the input acceleration pulse is shown in Figure (8) and a schematic of the board in the drop fixture is shown in Figure (9). Similar to the vibration cycling, strain levels were monitored during the drop loading by three strain gages affixed to the underside of the board. The exact location of the strain gages is shown in Figure (10).

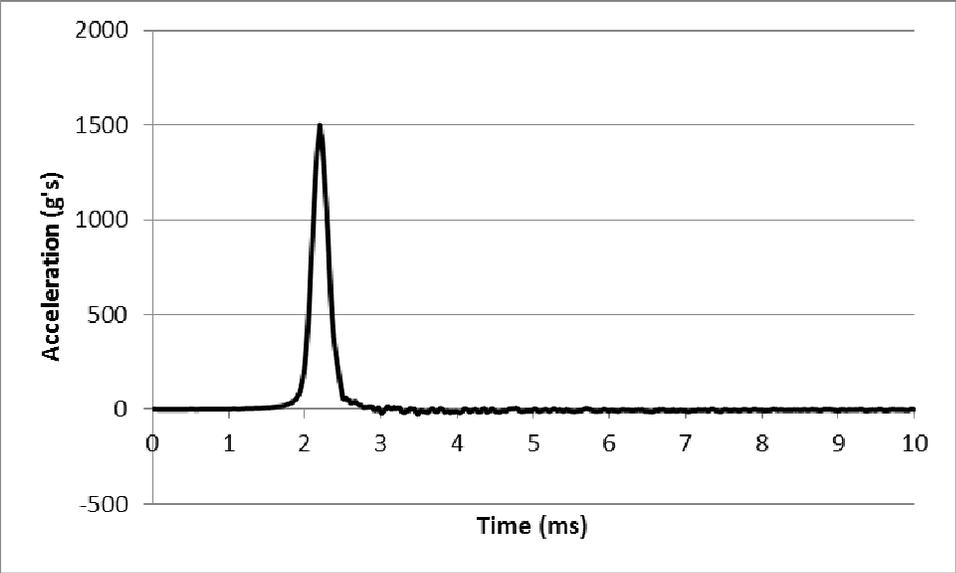


Figure 8 - Input shock pulse during each drop

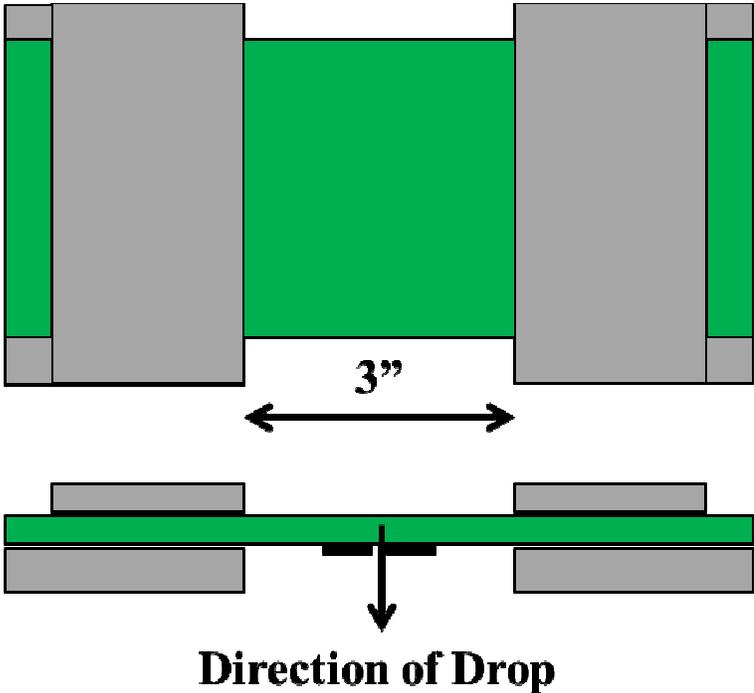


Figure 9 - Schematic of drop loading test setup

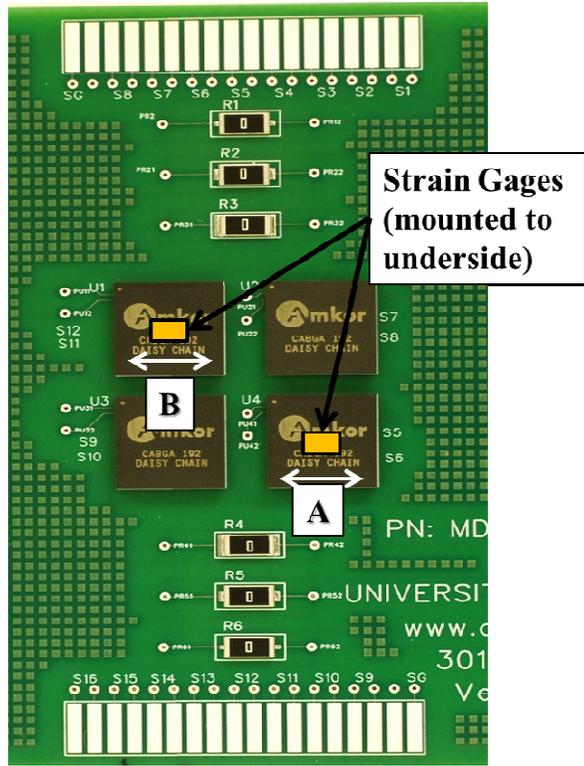


Figure 10 - Strain gage locations for drop loading. All strain gages are mounted to the opposite side of the board in the locations shown

**2.3: Statistical Significance – Kruskal-Wallis**

To quantify the effect of Pd thickness and isothermal aging, a statistical test is needed. For this study, the Kruskal-Wallis ANOVA test was used. Kruskal-Wallis compares medians of groups of data to determine if the groups come from two distinct distributions. The major benefit to Kruskal-Wallis is that the type of distribution is not assumed, whereas a typical one-way ANOVA assumes the data fits a normal distribution.

The test compares the medians of the groups of data and returns a p-value, representing the probability that the groups come from the same distribution. Generally the threshold for the p-value is 0.05, or 5%. If the p-value is less than 0.05, there is less than a 5% chance that the groups of data tested come from the same distribution, and it can be concluded that the groups are statistically different. Kruskal-Wallis was

conducted on all of the failure data for all three reliability tests to determine the effect of Pd thickness and isothermal aging. Results will be shown in table format, with a green box indicating statistical significance ( $p < 0.05$ ) and a red box showing statistical insignificance ( $p > 0.05$ ).

#### **2.4: Summary**

Three reliability tests were used to determine the effect of Pd thickness in ENEPIG and isothermal aging on solder interconnect reliability: temperature cycling, vibration cycling, and drop loading. Pd thicknesses of 0.05  $\mu\text{m}$  and 0.15  $\mu\text{m}$  were tested, and isothermal aging was conducted at 100°C for either 24 or 500 hours. Half of the boards subjected to temperature cycling were not exposed to any isothermal aging. The failure criteria for the BGA components across all three tests was a 20% increase in nominal resistance, followed by five consecutive resistance measurements above the 20% threshold. Kruskal-Wallis ANOVA test was used to determine if varying Pd thickness or isothermal aging resulted in statistically significant changes in solder interconnect reliability.

## Chapter 3: Temperature Cycling Test Results

This chapter discusses the results from the temperature cycling test of ENEPIG and Immersion Silver finished PCBs. Boards subjected to the temperature cycling test were run through 4400 temperature cycles. Nine of the 108 BGA components were still surviving after these cycles.

### 3.1: Reliability Results

All data were fitted to two-parameter Weibull distributions to determine an accurate estimation of the reliability of each of the components. Considering that there were twelve distinct surface finish / isothermal aging / solder combinations, twelve distributions were created. Probability plots showing each of these distributions, arranged by solder, are shown in Figures (11) and (12). The distributions are grouped by solder because the solders each required different reflow profiles, introducing several new factors for determining the reliability of the components.

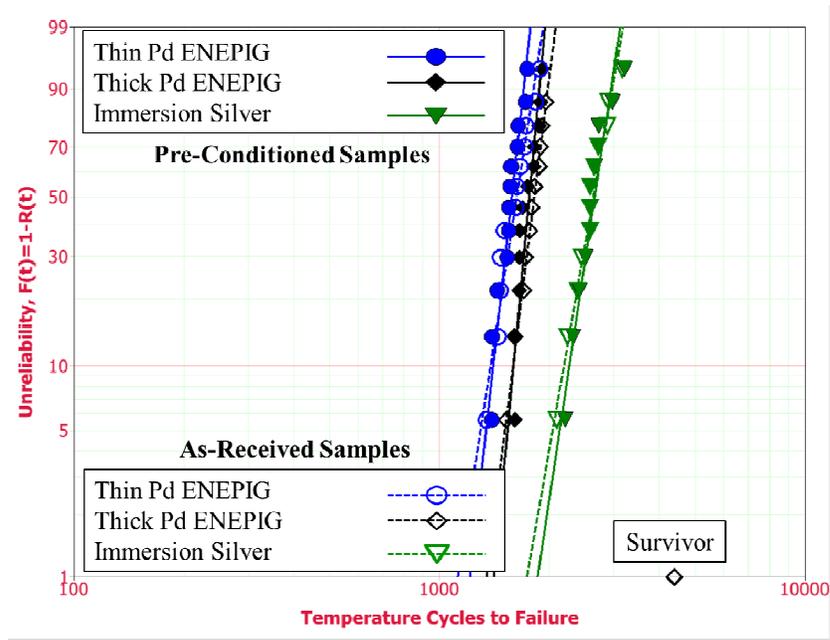


Figure 11 - Weibull probability plot for SnPb soldered BGAs subjected to temperature cycling

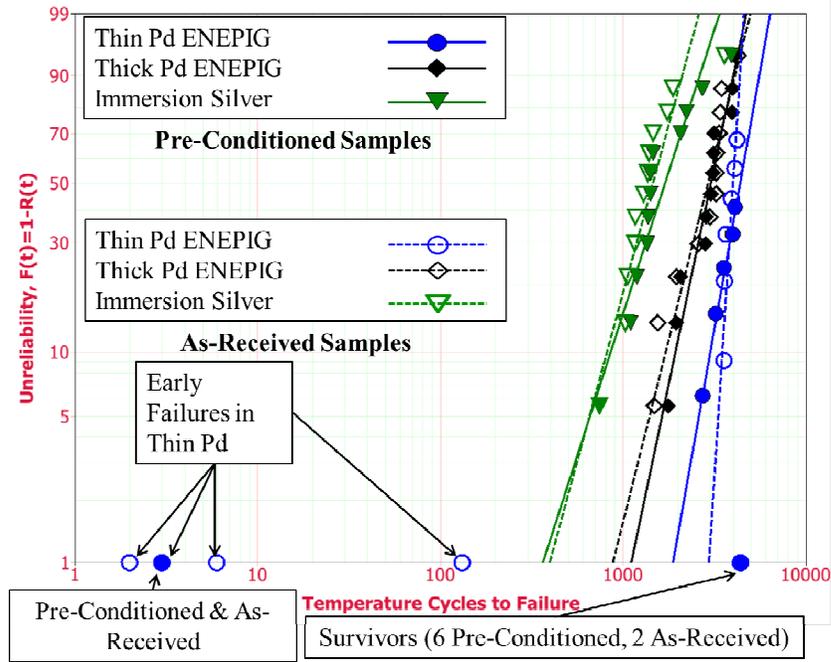


Figure 12 – Weibull probability plot for SAC305 soldered BGAs subjected to temperature cycling

The first thing to notice when examining the plots in (11) and (12) is that each of the surface finishes has its own clear distribution that does not overlap with any of the other finishes. Because of this, it was quickly concluded that the choice of surface finish does indeed have an effect on solder interconnect reliability. Therefore the Pd layer thickness in ENEPIG has an effect on thermal reliability. In both figures, it can also be seen that the data points for the pre-conditioned and as-received samples are overlapped. Thus, a 24 hour pre-conditioning has no effect on thermal reliability of BGA solder interconnects. The one exception is the thin-Pd ENEPIG / SAC305 samples, where it can be seen that there were more early failures in the as-received samples and more survivors in the pre-conditioned samples. Because there was no pre-conditioning effect, the data was combined for easier analysis. The Weibull plots containing the combined data are shown in Figures (13) and (14).

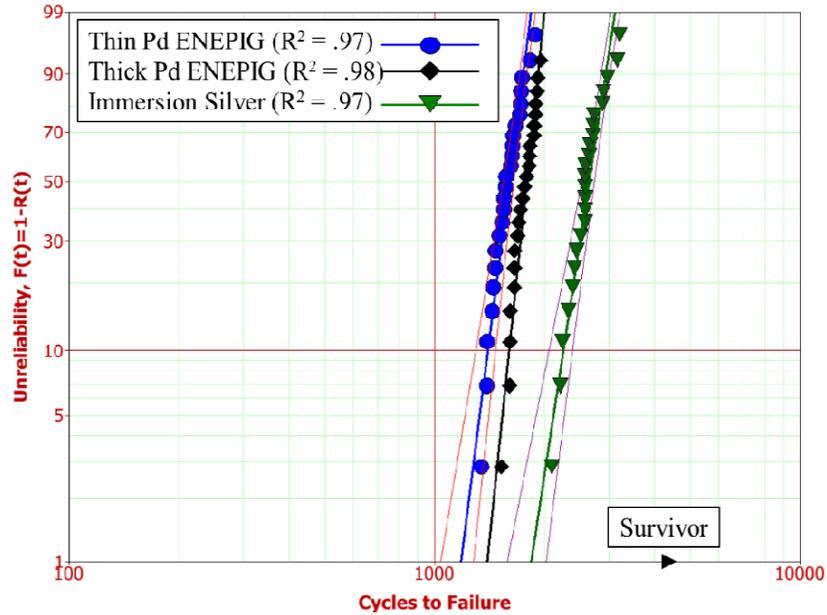


Figure 13 – Combined Weibull probability plot for SnPb solder interconnects subjected to temperature cycling.

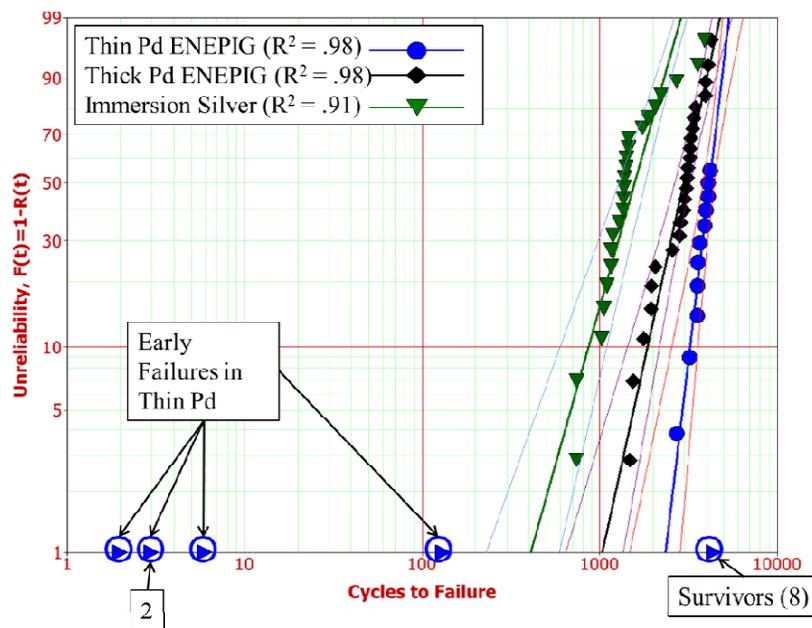


Figure 14 – Combined Weibull probability plot for SAC305 solder interconnects subjected to temperature cycling.

For SnPb solder, the Immersion Silver finish clearly outperforms both ENEPIG finishes. Restricting the focus to the Pd thickness effect, the thicker Pd layer does have later cycles to failure and one survivor while all of the BGAs soldered to thin Pd ENEPIG failed. The difference in characteristic life is approximately 10%. Due to the high slope

of the probability lines (beta), all failures were wear-out failures, which was expected for thermal cycling, which is a low strain-rate loading condition.

The results are opposite with SAC305. ENEPIG clearly performed better than Immersion Silver with this solder. In fact, characteristic life of both ENEPIG finishes with SAC305 was significantly higher than SnPb, which is consistent with the research discussed in the literature review. For Pd thickness, there are fewer total failures with thin-Pd ENEPIG, including 8 surviving BGAs. Characteristic life of thin-Pd ENEPIG is approximately 34% higher than thick-Pd ENEPIG. Despite the early failures in thin-Pd ENEPIG, which could be attributed to the lack of pre-conditioning, the thin layer of Pd, as noted in literature, improves the life of SAC305 solder interconnects. Table (4) summarizes the parameters for the Weibull plots in Figures (13) and (14).

*Table 4 - Summary of Weibull parameters for temperature cycling test.*

<b>Weibull Statistic</b>	<b>Beta</b>		<b>Eta</b>	
	SnPb	SAC305	SnPb	SAC305
<b>Immersion Silver</b>	11.58	3.14	2734	1765
<b>Thin Pd ENEPIG</b>	13.88	7.44	1646	4357
<b>Thick Pd ENEPIG</b>	17.01	4.02	1826	3249

To determine whether these differences are significant enough to conclude that Pd thickness does indeed have an effect on thermal reliability, the Kruskal Wallis ANOVA test was used, and the results are presented in Tables (5) and (6) below.

*Table 5 - Kruskal-Wallis results for effect of pre-conditioning on thermal reliability (all values are p-values)*

<b>Solder</b>	<b>Immersion Silver</b>	<b>Thin-Pd ENEPIG</b>	<b>Thick-Pd ENEPIG</b>
<b>SnPb</b>	0.817 (no effect)	0.525 (no effect)	0.413 (no effect)
<b>SAC305</b>	0.285 (no effect)	0.166 (no effect)	0.817 (no effect)

Table 6 - Kruskal-Wallis results for effect of Pd thickness on thermal reliability

<b>Solder</b>	<b>P-Value</b>
<b>SnPb</b>	1.04*10 <sup>-4</sup> (effect)
<b>SAC305</b>	0.003 (effect)

Looking at Table (5), it is clear to see why the distributions for the pre-conditioned and as-received samples could be combined. All p-values were above the 5% threshold, indicating that there was a good chance that the data all came from the same distribution. The same cannot be said for the Pd thickness; it is clear that the distributions for the thin-Pd and thick-Pd ENEPIG finishes are distinctly different. The differences in characteristic life can now be considered to be true and it can be concluded that varying the thickness of Pd in ENEPIG does have an effect on thermal reliability of both SnPb and SAC305 BGA solder interconnects.

### **3.2: Failure Analysis**

The first BGA to have failed from each solder / finish / aging combination (12 in total) was cross-sectioned to determine the exact failures that occurred during the test. Two additional thin-Pd ENEPIG / SAC305 BGAs were cross-sectioned; the two selected were from the samples that had early failures, bringing the total to 14 examined BGAs in failure analysis. Figures (15) through (17) show examples of observed failures in the cross-sectioned BGAs.

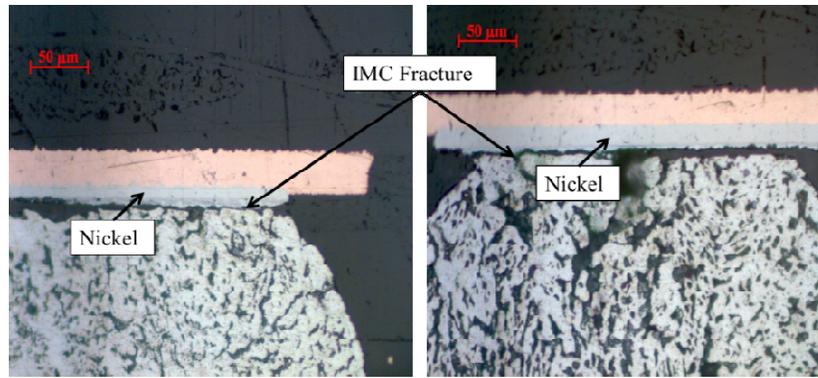


Figure 15 - Failures in SnPb solder interconnects on thin-Pd (left, failed after 1396 cycles) and thick-Pd ENEPIG (right, failed after 1705 cycles)

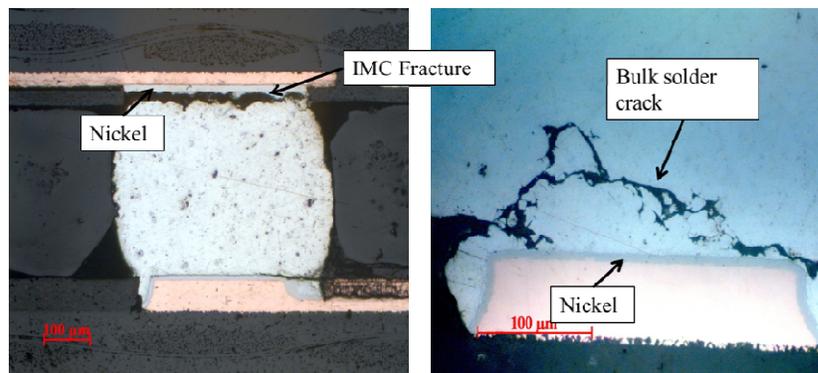


Figure 16 – Failures in SAC305 solder interconnects on thick-Pd (left, failed after 1773 cycles) and thin-Pd ENEPIG (right, failed after 2731 cycles)

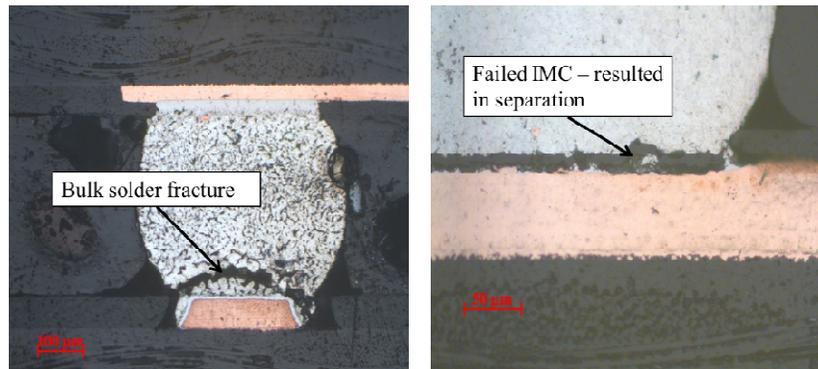


Figure 17 - Failures in SnPb (left, failed after 2216 cycles) and SAC305 (right, failed after 1004 cycles) solder interconnects on Immersion Silver.

Examining Figures (15) and (16), it can quickly be seen that failures in thick-Pd ENEPIG were component side fractures at the solder / IMC interface, indicating that the IMC bond was weaker than the strength of the bulk solder material, as shown in the literature. For thin-Pd ENEPIG, SnPb failures were similar to thick-Pd ENEPIG, but

SAC305 failures were on the board side through the bulk material. This not only explains why thin-Pd ENEPIG / SAC305 had the highest characteristic life, it also explains the high number of defects. Board side failures are uncommon in temperature cycling, and the fact that they were seen here indicates a defect in the manufacturing process. Though there was no statistical difference between the pre-conditioned and as-received samples, the pre-conditioned thin-Pd / SAC305 BGAs had 80% fewer early failures and 75% more survivors. From this, it can be concluded that while pre-conditioning has no effect on thermal reliability, it can remove potential defects and increase the component's likelihood of survival.

In Immersion Silver, all failures were board side failures through the bulk in SnPb and through the IMC in SAC305. This proved that IMCs in SnPb solder interconnects on Immersion Silver were stronger than those in SAC305 solder interconnects, which explains why SnPb solder interconnects had longer characteristic life than SAC305 solder interconnects on Immersion Silver.

### **3.3: Summary**

Comparing the characteristic life of the distributions, it was shown that changing the Pd thickness in ENEPIG does affect thermal reliability. With SAC305 solder, the thinner layer improved characteristic life of BGA interconnects by 34%. For SnPb, the thicker Pd layer was preferred as it resulted in a 10% increase in characteristic life. Table (7) summarizes the Pd thickness effect on the characteristic life of ENEPIG solder interconnects under temperature cycling.

Observed failures in ENEPIG samples were at the component side of the solder interconnect, while failures in Immersion Silver samples were at the board side of the

solder interconnect. Fractures in ENEPIG / SnPb were entirely through the IMC, while SAC305 failures went through the bulk solder as well, explaining the later failures in SAC305. In Immersion Silver, bulk solder failures were observed in SnPb while SAC305 showed IMC failures. These types of failures not only explain the high beta values seen in the SnPb distributions, but also confirm that the IMC bond between SnPb and Immersion Silver is stronger than SnPb and SAC305.

*Table 7 - Change in characteristic life of ENEPIG samples, Pd thickness effect*

<b><i>Solder</i></b>	<b>Effect of Thin-Pd over Thick-Pd ENEPIG</b>
<i>SnPb</i>	10% Decrease
<i>SAC305</i>	34% Increase

## Chapter 4: Vibration Cycling Test Results

This chapter discusses the results from the vibration tests conducted on ENEPIG and Immersion Silver finished PCBs. Boards were fixed two at a time to the vibration table and subjected to the vibration test conditions for a period of 24 hours. Following the test, all the data were fit to two-parameter Weibull distributions.

Prior to analyzing the reliability data, the strain data was collected and averaged. A box plot showing the strain ranges seen across all of the boards at each location is shown in Figure (18).

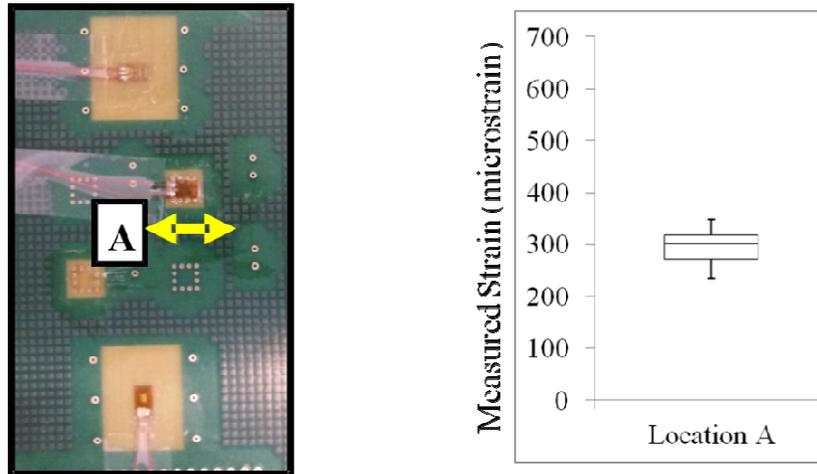


Figure 18 - Strain results for vibration cycling test

### 4.1: Reliability Results

Figures (19) and (20) show each of the probability distributions for the finish / solder / isothermal aging combinations, again grouped by solders. Unlike the temperature cycling test, there is clearly an isothermal aging effect in some of the distributions, especially the SAC305 distributions in Figure (20). For SnPb, this effect is not fully evident by inspection, but the Kruskal-Wallis test indicated that both versions of ENEPIG were affected by the extended isothermal age.

There was no aging effect in temperature cycling because of the length of the isothermal age. Prior to temperature cycling, samples were either tested as-received or only aged for 24 hours, while all samples that were used for the vibration test were aged for either 24 or 500 hours. The 500 hour age, which is almost 20x longer than the 24 hour age in temperature cycling, was expected to introduce some sort of effect.

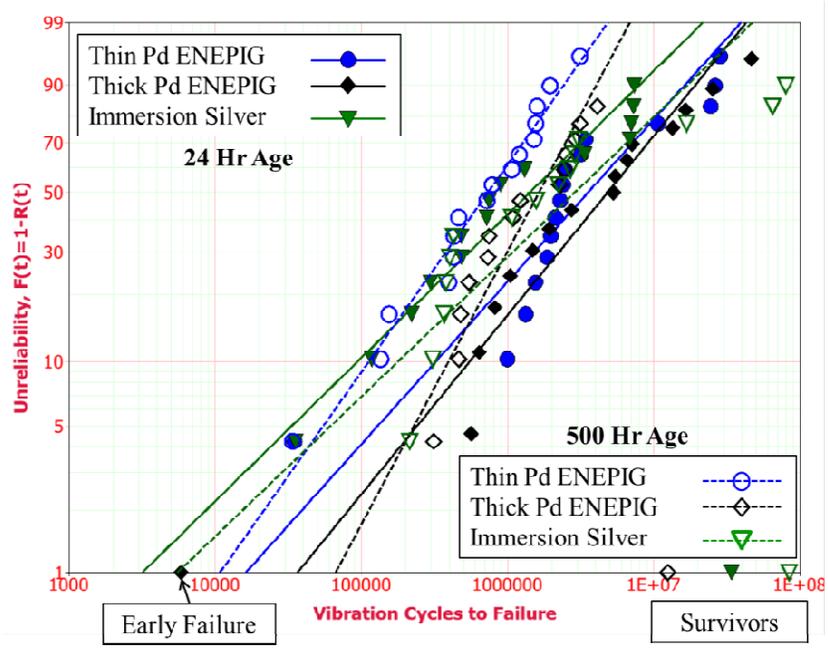


Figure 19 – Weibull probability plot for SnPb soldered BGAs subjected to vibration cycling

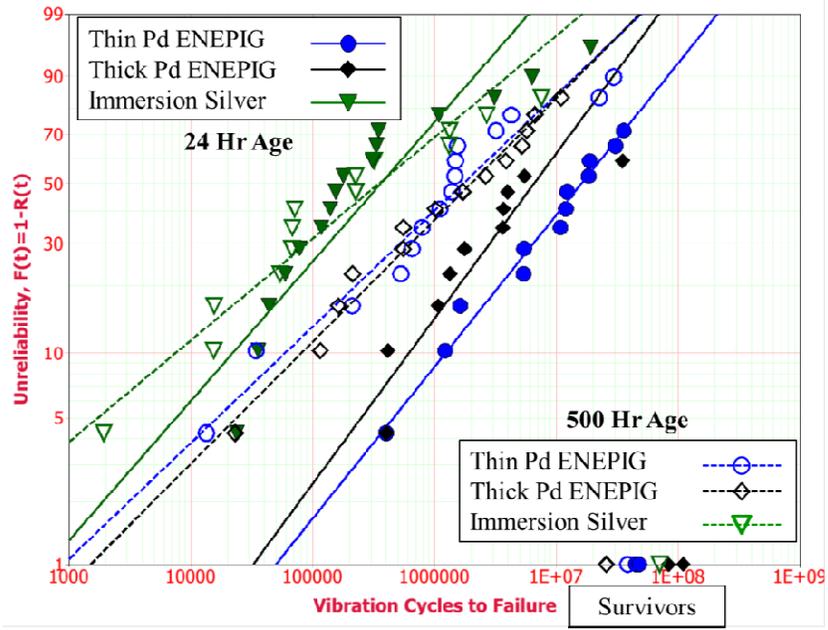


Figure 20 - Weibull probability plot for SAC305 soldered BGAs subjected to vibration cycling

To allow for easier analysis of the Pd effect, additional Weibull plots were created which grouped the distributions by both isothermal age and solder, and those plots are shown in Figures (21) through (24).

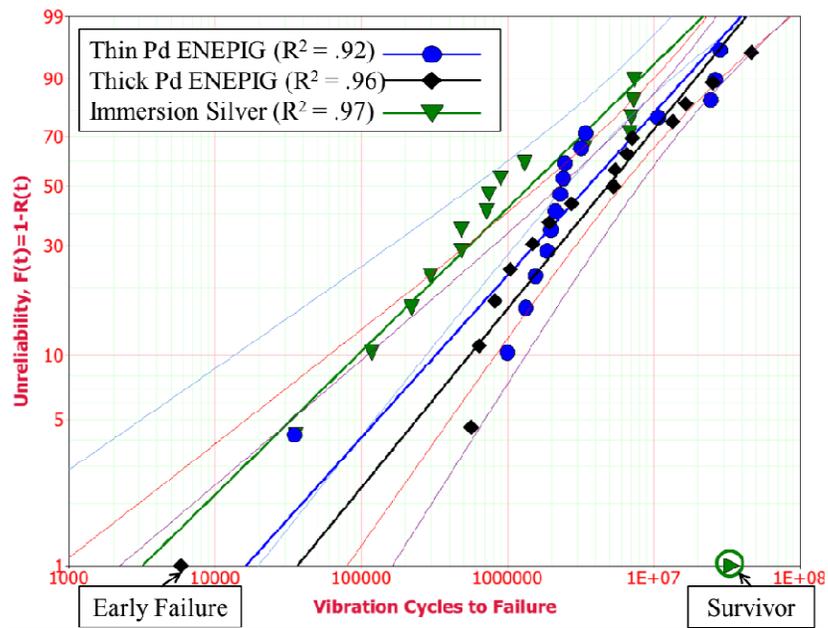


Figure 21 - Weibull probability plot for SnPb soldered BGAs subjected to vibration cycling after 24 hours of aging

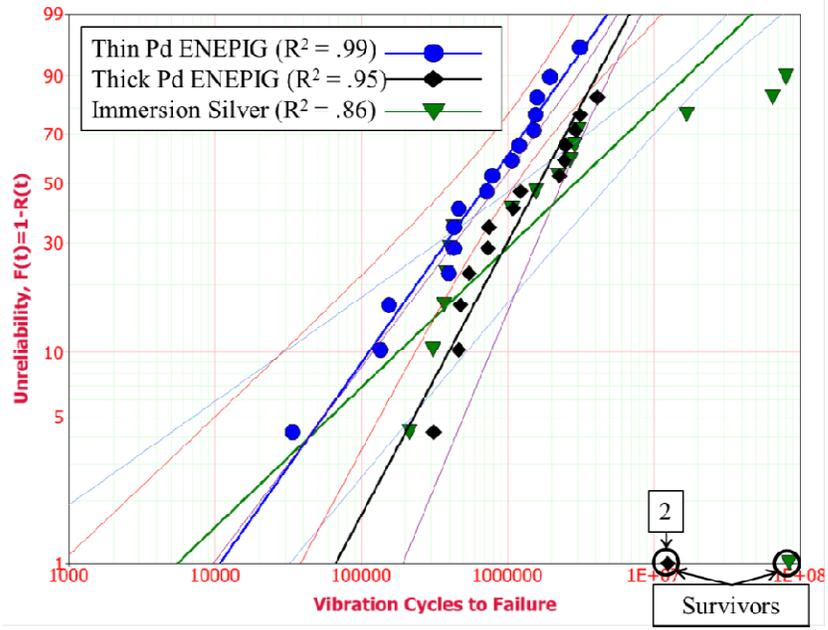


Figure 22 - Weibull probability plot for SnPb soldered BGAs subjected to vibration cycling after 500 hours of aging

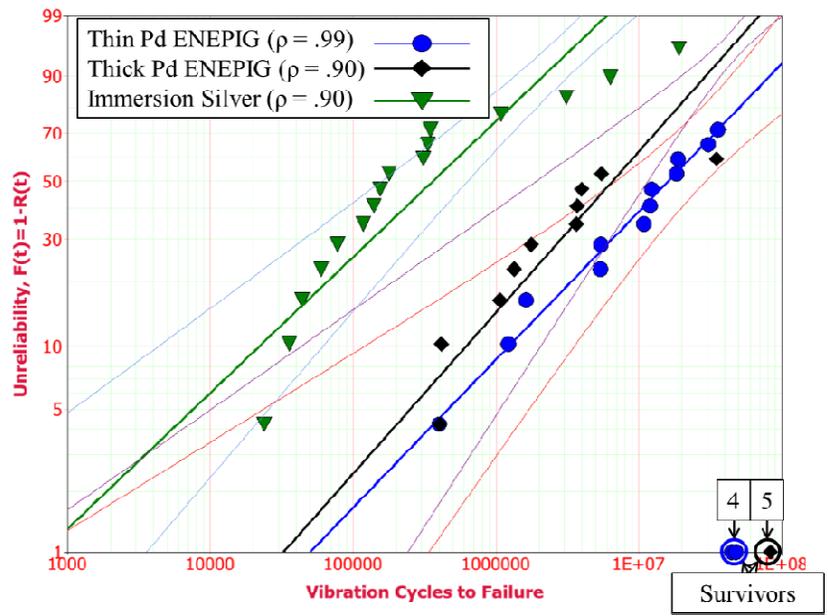


Figure 23 - Weibull probability plot for SAC305 soldered BGAs subjected to vibration cycling after 24 hours of aging

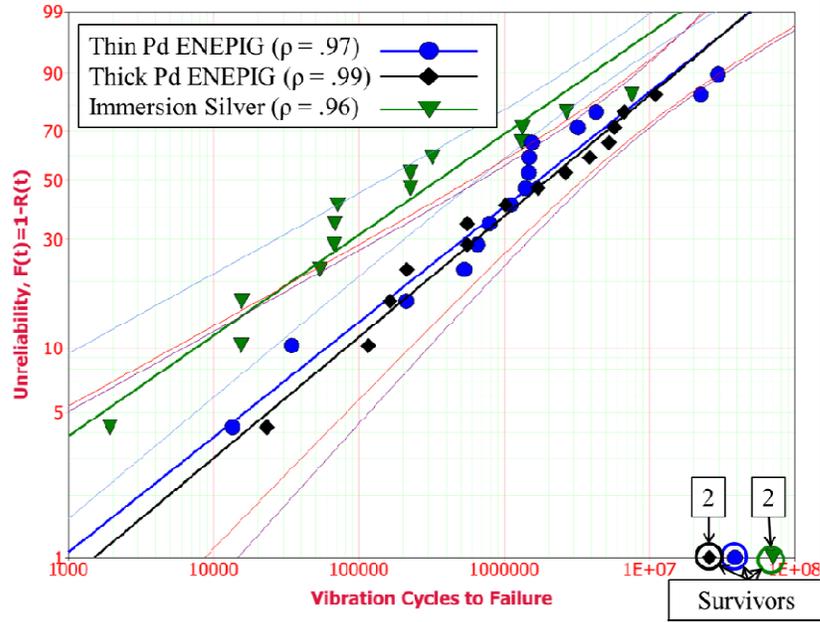


Figure 24 - Weibull probability plot for SAC305 soldered BGAs subjected to vibration cycling after 500 hours of aging

Figure (21) shows the results for SnPb interconnects after 24 hours of aging. All three distributions have similar slopes to their probability lines, indicating that all three finishes showed the same amount of variability in the failures. For the effect of Pd thickness, there is no clear difference. All of the data points overlap and the probability lines are relatively close to each other, representing no clear effect of Pd thickness. When SnPb interconnects were aged for 500 hours and then subjected to vibration cycling, as seen in Figure (22), the thicker layer of Pd doubled the life of those interconnects. In addition, two of the thick-Pd ENEPIG samples did not fail, while all of the thin-Pd samples failed during the vibration cycling test.

For SAC305 samples shown in Figures (23) and (24), the Pd effect is opposite in that it can easily be seen after 24 hours of aging, but not after 500 hours of aging. While the probability lines are relatively close in Figure (23) after 24 hours, the thin-Pd ENEPIG / SAC305 samples had a characteristic life that was 160% higher than the characteristic life of thick-Pd ENEPIG. The reason for this large increase in

characteristic life is because of the definition of characteristic life: the number of cycles at which 63.2% of the samples should have failed. This value appears much closer than the 160% that is being quoted, but that is because the probability plots are plotted on a log-log scale, and the point at which the characteristic life is defined is past the major tick mark of 1E+07 on the plot.

A summary of the Weibull parameters for each of the distributions is shown in Table (8), and the Kruskal-Wallis results are shown in Figures (9) and (10).

Table 8 - Summary of Weibull parameters for vibration cycling test.

	<b>Beta</b>				<b>Eta</b>			
	24 Hours		500 Hours		24 Hours		500 Hours	
<b>Aging Solder</b>	SnPb	SAC305	SnPb	SAC305	SnPb	SAC305	SnPb	SAC305
<b>Immersion Silver</b>	0.69	0.67	0.68	0.49	2.4E6	6.2E5	4.9E6	7.3E5
<b>Thin-Pd ENEPIG</b>	0.79	0.73	1.00	0.56	5.6E6	2.6E7	1.1E6	3.3E6
<b>Thick-Pd ENEPIG</b>	0.87	0.80	1.32	0.59	7.3E6	1.0E7	2.2E6	3.7E6

Table 9 - Kruskal-Wallis results for effect of isothermal aging on vibration cycling (all values are p-values)

<b>Solder</b>	<b>Immersion Silver</b>	<b>Thin-Pd ENEPIG</b>	<b>Thick-Pd ENEPIG</b>
<b>SnPb</b>	0.341 (no effect)	0.001 (effect)	0.030 (effect)
<b>SAC305</b>	0.527 (no effect)	0.006 (effect)	0.373 (no effect)

Table 10 - Kruskal-Wallis results for effect of Pd thickness on vibration cycling (all values are p-values)

<b>Solder</b>	<b>24 Hours</b>	<b>500 Hours</b>
<b>SnPb</b>	0.782 (no effect)	0.055 (no effect)
<b>SAC305</b>	0.046 (effect)	0.763 (no effect)

Examining the Weibull results in Table (8), it is quickly seen that the vibration cycling failures were all infant-mortality type failures with a decreasing failure rate. This is owed to the variability in that unlike the temperature cycling results, there was a wider range of cycles in which each of the components failed. This was expected considering

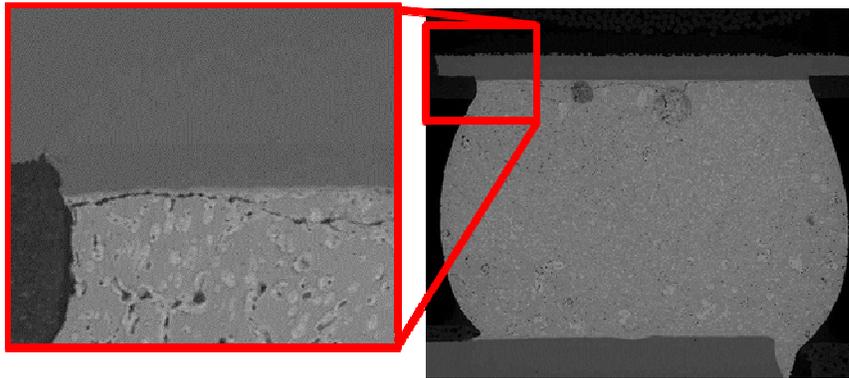
that the load of the vibration signal occurs faster and is more consistently applied than the load of the varying temperatures in temperature cycling. It can also be seen that extended isothermal aging decreased the characteristic life of all of the ENEPIG samples, but increased the characteristic life of all of the Immersion Silver samples. The reason for this increase could be due to the decreasing Beta values. Beta decreases as a result of more variance in the cycles to failure. Because of this, it is possible that some samples may fail later and indirectly increase the characteristic life of the distribution. Further research investigating this trend is recommended.

For statistical significance, Table (9) shows that extended aging only had a pronounced effect on thin-Pd ENEPIG samples and thick-Pd ENEPIG samples soldered with SnPb. Kruskal-Wallis tests to see if the groups of data came from the same distribution, so while the data for thick-Pd ENEPIG / SAC305 samples aged after 24 and 500 hours appears separated enough in the plot to be statistically significant, the K-W test indicated that there was a 37.1% chance that the data came from the same distribution, which is not low enough to conclude that the effect of aging is statistically significant.

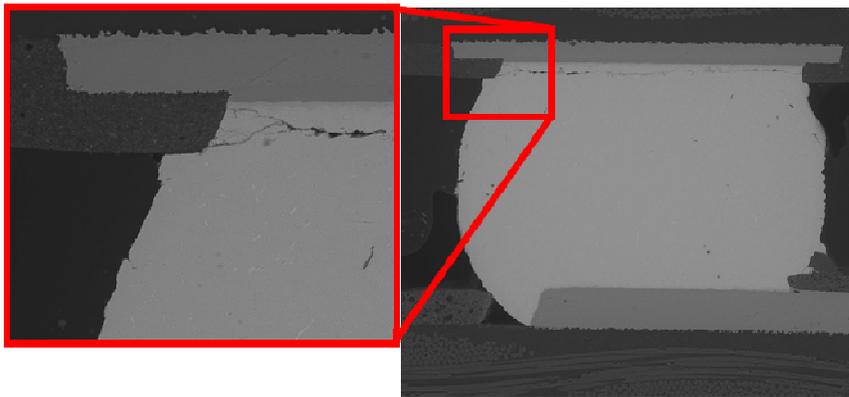
When considering Pd thickness, only SAC305 interconnects aged for 24 hours showed an effect of Pd thickness. SnPb solder interconnects after 500 hours also appeared to be statistically significant in the probability plot, but similar to the aging effect on thick-Pd SAC305, the p-value did not cross the 5% threshold. Unlike the aging effect, however, the test indicated a 5.5% chance that the data from thin-Pd ENEPIG and thick-Pd ENEPIG came from the same distribution. Despite being only 0.5% away from the threshold, it cannot be concluded that Pd thickness fully had an effect in SnPb interconnects after 500 hours of aging.

#### **4.2: Failure Analysis**

Unlike the temperature cycling samples, only one failure mode was seen in the cross-sectioned BGAs. Cracks were only seen at the component side of the solder ball going through the bulk solder, never quite reaching the IMC. Isothermal aging, surface finish, and solder did not change this failure mode. Images showing these failures are shown in Figures (25) and (26).



*Figure 25 - Bulk solder fracture at component side of SnPb solder ball to Immersion Silver finish, aged 24 hours.*



*Figure 26 - Bulk solder fracture at component side of SAC305 solder ball to thin-Pd ENEPIG, aged 500 hours*

#### **4.3: Summary**

Despite clear differences in characteristic life of all of the distributions, Pd thickness did not affect the reliability of BGA solder interconnects subjected to vibration

cycling in all cases. Only SAC305 interconnects aged for 24 hours showed an effect of Pd thickness; all other cases did not reveal any difference between interconnects soldered to thin- and thick-Pd ENEPIG. Isothermal aging was shown to only have a statistically significant effect on thin-Pd ENEPIG and SnPb interconnects on thick-Pd ENEPIG. Despite this, aging decreased the characteristic life of all interconnects soldered to ENEPIG but increased characteristic life of interconnects soldered to Immersion Silver. Tables (11) and (12) below summarize the changes in characteristic life of all of the samples subjected to vibration cycling.

*Table 11 - Change in characteristic life of ENEPIG samples subjected to vibration cycling, Pd thickness effect*

<b><i>Aging Condition</i></b>	<b>24 Hours</b>	<b>500 Hours</b>
<b><i>Effect of thin-Pd on SnPb</i></b>	18% Decrease	50% Decrease
<b><i>Effect of thin-Pd on SAC305</i></b>	160% Increase	11% Decrease

*Table 12 - Change in characteristic life of samples subjected to vibration cycling, isothermal aging effect*

<b><i>Solder</i></b>	<b>Thin-Pd ENEPIG</b>	<b>Thick-Pd ENEPIG</b>	<b>Immersion Silver</b>
<b><i>SnPb</i></b>	80% Decrease	68% Decrease	125% Increase
<b><i>SAC305</i></b>	87% Decrease	63% Decrease	88% Decrease

## Chapter 5: Drop Loading Test Results

This chapter discusses the drop loading tests conducted on ENEPIG and Immersion Silver finished PCBs. Following the isothermal aging for either 24 or 500 hours, boards were fixed to the clamp fixture described in section 2.2.3 and dropped a maximum of 1000 times until all of the components failed. Reliability and failures analyses were conducted and those results and observations are presented here.

Prior to analyzing the reliability data, the strain data were grouped and averaged. The box plot showing the strain ranges seen during the drop loading test is shown in Figure (27). A 233% higher strain was seen in the drop loading test than the vibration test; this was primarily due to the higher load levels. In the vibration test, the input acceleration was only 3 g's, while in the drop test, the input acceleration was 1500 g's.

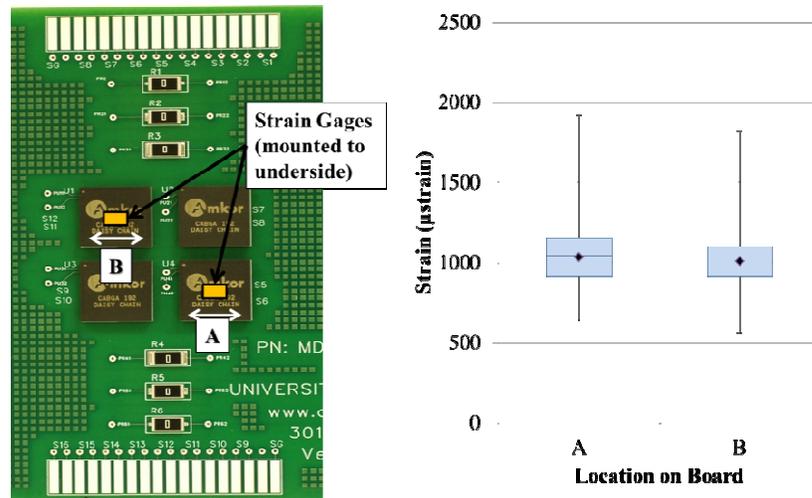


Figure 27 - Strain results for drop loading test

### 5.1: Reliability Results

Figures (28) and (29) below show the probability plots for all of the finish / solder / aging combinations, again grouped by solder. Similar to the vibration cycling results, isothermal aging reduced the characteristic life of the BGAs.

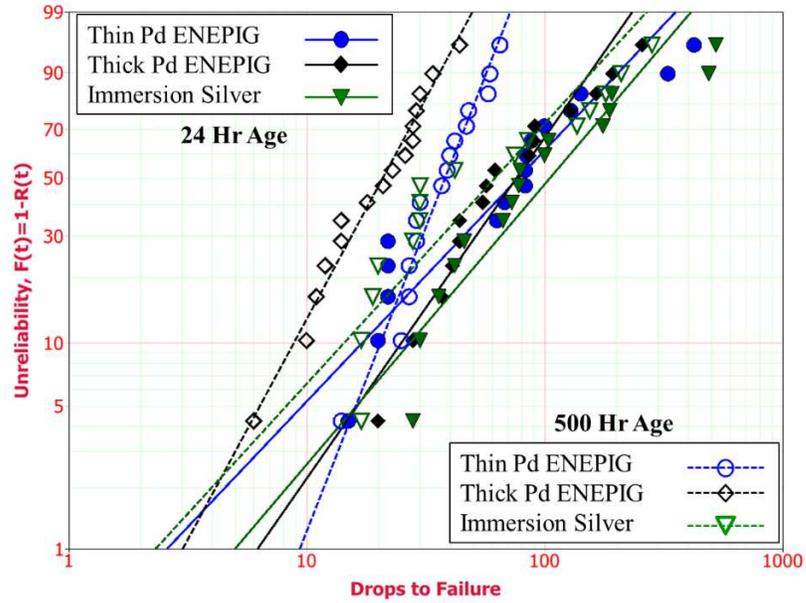


Figure 28 - Weibull probability plot for SnPb soldered BGAs subjected to drop loading

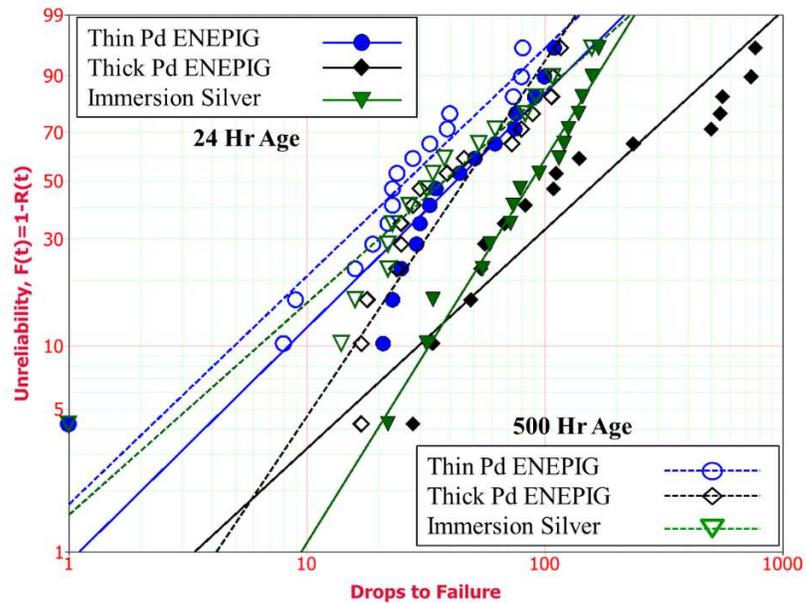


Figure 29 - Weibull probability plot for SAC305 soldered BGAs subjected to drop loading

To analyze the effect of Pd thickness, Figures (30) though (33) show the Weibull probability plots for the drop loading results grouped by solder and isothermal aging time.

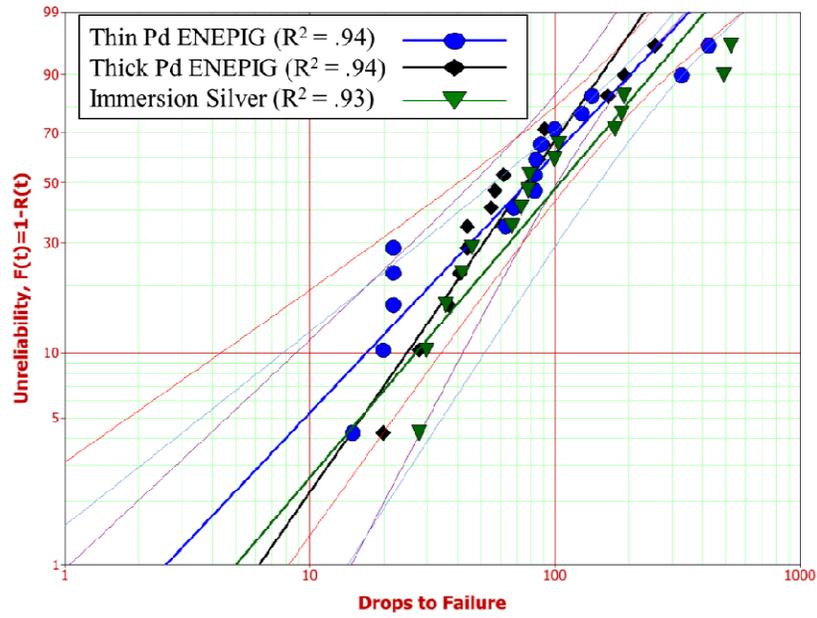


Figure 30 - Weibull probability plot for SnPb soldered BGAs subjected to drop loading test after 24 hours of aging

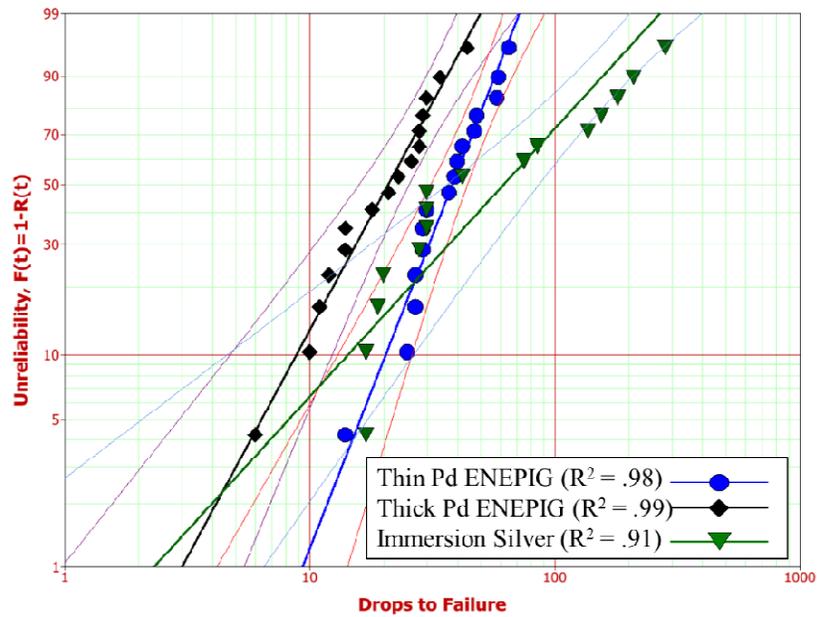


Figure 31 - Weibull probability plot for SnPb soldered BGAs subjected to drop loading test after 500 hours of aging

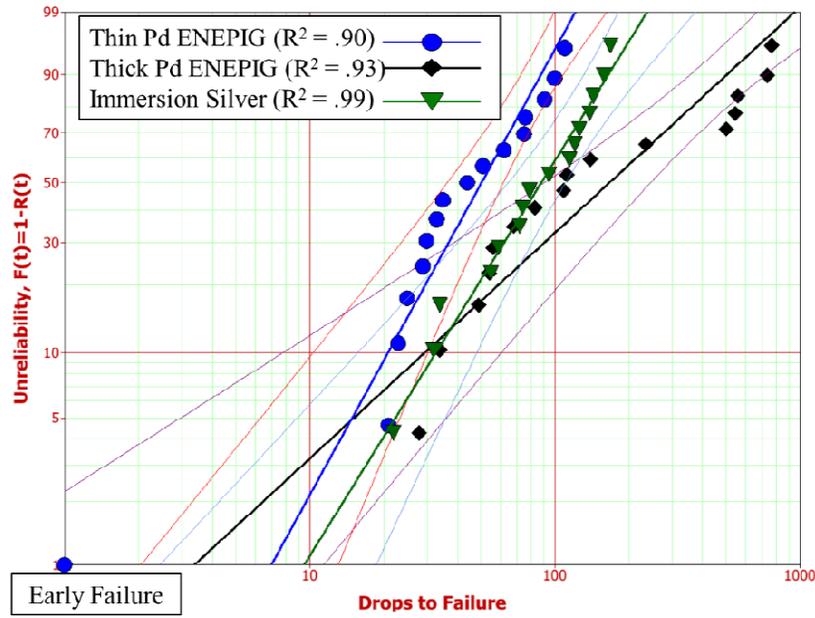


Figure 32 - Weibull probability plot for SAC305 soldered BGAs subjected to drop loading test after 24 hours of aging

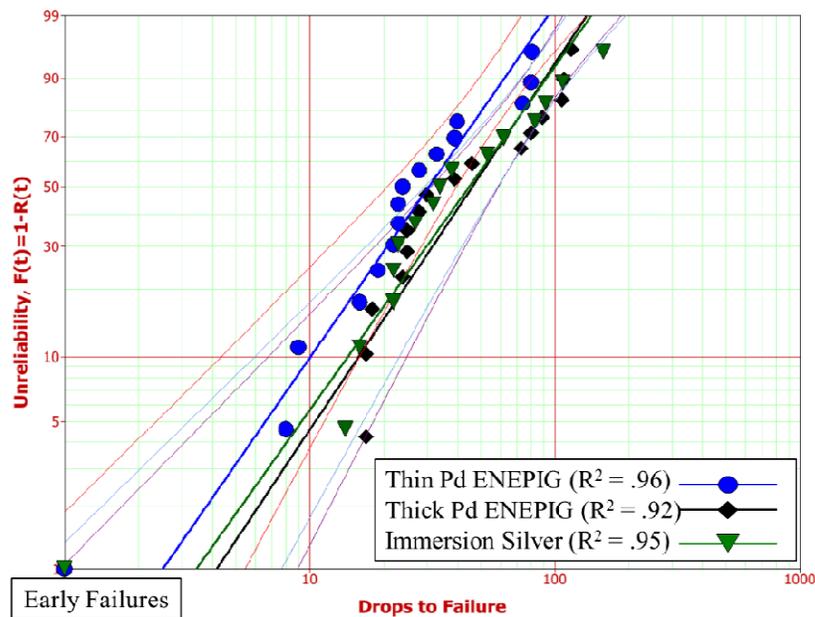


Figure 33 - Weibull probability plot for SAC305 soldered BGAs subjected to drop loading test after 500 hours of aging

A similar trend from the vibration cycling test can be seen in the drop loading test in that it is difficult to see any discernible effect of surface finish or Pd thickness for SnPb interconnects after 24 hours and SAC305 interconnects after 500 hours. For SnPb interconnects subjected to drop loading after 24 hours of aging shown in Figure (30), the

effect is non-existent. All of the distributions and their confidence bounds overlap and cross each other at different points. Because of this, it is concluded that changing the Pd thickness in ENEPIG has no effect on reliability of SnPb interconnects subjected to drop loading after 24 hours of isothermal aging.

After 500 hours, however, Pd thickness does have an effect. The characteristic life of SnPb interconnects soldered to thin-Pd ENEPIG is almost double the characteristic life of SnPb interconnects soldered to thick-Pd ENEPIG. The slopes of the probability lines for both thin- and thick-Pd ENEPIG are also similar, indicating that changing the thickness of Pd only alters the characteristic life, not the variability of the results.

In SAC305, the results are again opposite, similar to the vibration cycling results. Pd thickness was only seen to have an effect after 24 hours of aging, and it is clear that the thicker layer of Pd is now preferred over the thinner layer. The primary reason for this is the type of loading condition that drop loading is. Unlike temperature cycling and vibration cycling, which were low strain-rate applications, drop loading is a high strain-rate load that delivers maximum load for a very short amount of time; in this case only 0.5 ms. High-strain rate applications tend to induce failure in the IMC more frequently than the bulk solder. While thin-Pd ENEPIG / SAC305 was shown to have stronger IMCs in literature, those results came from low strain-rate applications such as ball pull and shear, not drop loading. As a result, the drop loading results indicate that thin-Pd ENEPIG / SAC305 decreased characteristic life by 75%.

Tables (13) through (15) show a summary of all of the Weibull parameters from the drop loading test and the results of the Kruskal-Wallis ANOVA test on each of the distributions.

Table 13 - Summary of Weibull parameters for drop loading test

<b>Aging</b>	<b>Beta</b>				<b>Eta</b>			
	24 Hours		500 Hours		24 Hours		500 Hours	
<b>Solder</b>	SnPb	SAC305	SnPb	SAC305	SnPb	SAC305	SnPb	SAC305
<b>Immersion Silver</b>	1.39	1.90	1.29	1.05	137	107	82	53
<b>Thin-Pd ENEPIG</b>	1.25	2.14	3.01	1.69	104	59	43	38
<b>Thick-Pd ENEPIG</b>	1.69	1.09	2.19	1.65	94	234	25	56

Table 14 - Kruskal-Wallis results for effect of isothermal aging on drop loading (all values are p-values)

<b>Solder</b>	<b>Immersion Silver</b>	<b>Thin-Pd ENEPIG</b>	<b>Thick-Pd ENEPIG</b>
<b>SnPb</b>	0.075 (no effect)	0.050 (effect)	$2.83 \times 10^{-5}$ (effect)
<b>SAC305</b>	0.007 (effect)	0.022 (effect)	0.003 (effect)

Table 15 - Kruskal-Wallis results for effect of Pd thickness on drop loading (all values are p-values)

<b>Solder</b>	<b>24 Hours</b>	<b>500 Hours</b>
<b>SnPb</b>	0.895 (no effect)	0.001 (effect)
<b>SAC305</b>	0.003 (effect)	0.086 (no effect)

From Table (13), it can be seen that failures were more random in drop loading than they were in temperature cycling and vibration cycling. This was again due to the high-strain rate application of drop loading. Because all of the Beta values are higher than 1, there was an increasing failure rate, which was expected. Isothermal aging decreased characteristic life in all distributions, none more so than thick-Pd ENEPIG. The effect of this decrease was not significant in Immersion Silver / SnPb, but in all other cases the Kruskal-Wallis test showed that isothermal aging did indeed have a statistically significant effect on the characteristic life.

The effect of Pd thickness was only seen to be significant in SnPb interconnects aged for 500 hours and SAC305 interconnects aged for 24 hours. It was impossible to see any effect of Pd thickness in SnPb interconnects aged for 24 hours and the Kruskal-Wallis test showed it with an 89.5% chance that the data from thin- and thick-Pd

ENEPIG came from the same distribution. In SAC305 interconnects aged for 500 hours, this percentage reduced to 8.6%, which is still above the required 5% threshold.

### 5.2: Failure Analysis

Images showing representative failures from the BGAs subjected to drop loading are shown in Figures (34) through (39). The BGAs chosen for failure analysis were the first BGAs to fail within each finish / solder / isothermal aging group, similar to the selection criteria for temperature cycling. A total of 12 BGAs were cross-sectioned.

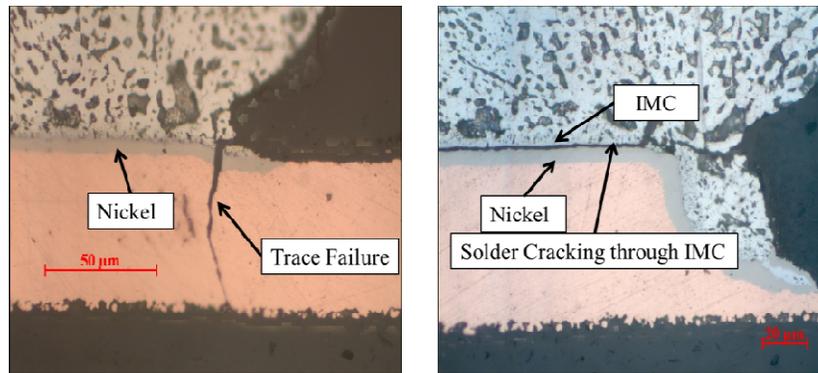


Figure 34 - Failures in SnPb solder interconnects aged for 24 hours soldered to thin-Pd (left, failed after 22 drops) and thick-Pd ENEPIG (right, failed after 90 drops)

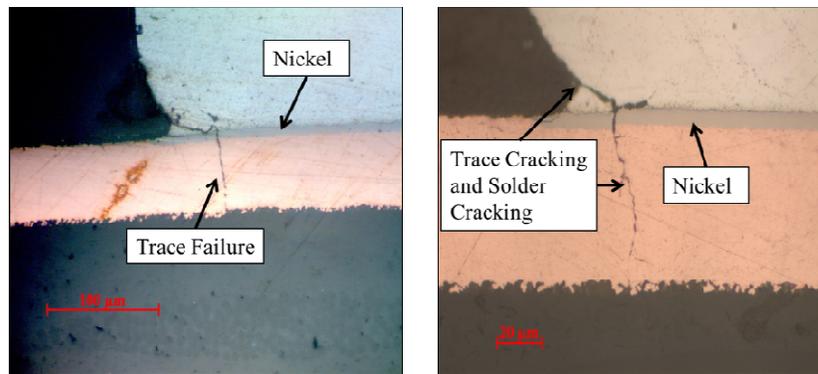


Figure 35 - Failures in SAC305 solder interconnects aged for 24 hours soldered to thin-Pd (left, failed after 62 drops) and thick-Pd ENEPIG (right, failed after 34 drops)

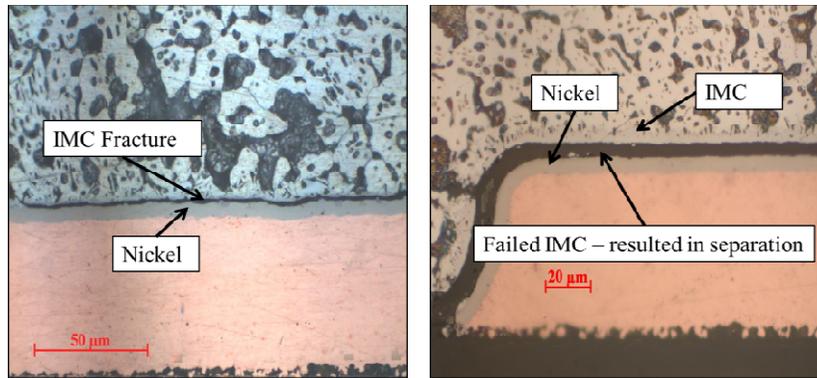


Figure 36 - Failures in SnPb solder interconnects aged for 500 hours soldered to thin-Pd (left, failed after 29 drops) and thick-Pd ENEPIG (right, failed after 11 drops)

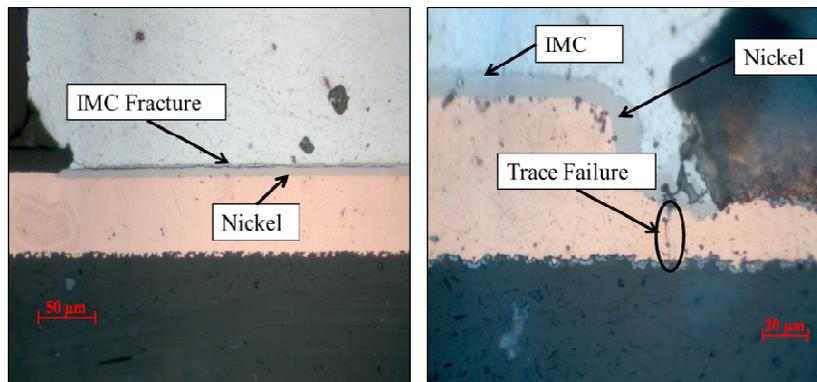


Figure 37 - Failures in SAC305 solder interconnects aged for 500 hours soldered to thin-Pd ENEPIG (left, failed after 33 drops) and thick-Pd ENEPIG (right, failed after 25 drops)

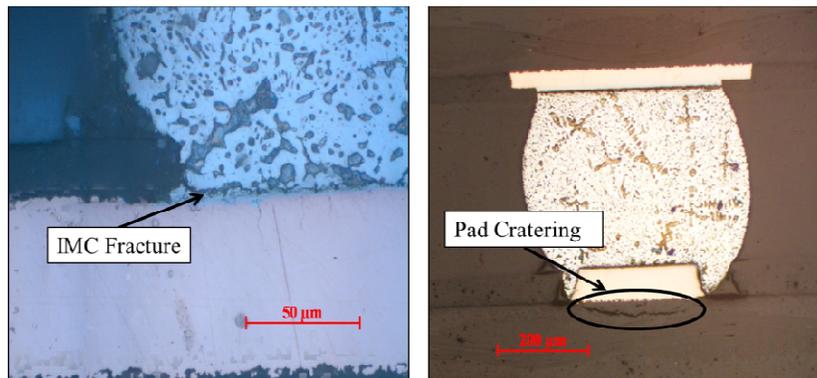


Figure 38 - Failures in SnPb solder interconnects soldered to Immersion Silver aged for 24 hours (left, failed after 104 drops) and 500 hours (right, failed after 283 drops)

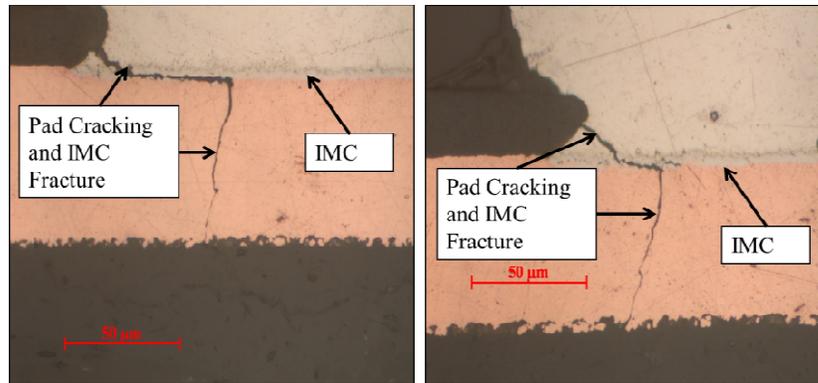


Figure 39 - Failures in SAC305 solder interconnects soldered to Immersion Silver aged for 24 hours (left, failed after 159 drops) and 500 hours (right, failed after 108 drops)

All failures were either IMC fractures or trace failures, which was expected from the drop loading test. IMC fracture was seen in all samples as the dominant failure mode. Trace failure occurred primarily in SAC305 samples. This was because SAC305 has a higher Young's Modulus and Hardness than SnPb solder. As a result, the SAC305 solder could not absorb the stress of the shock pulse that was applied to the solder interconnect during the drop. Because of this, the stress was transferred to the copper trace underneath the solder interconnect, resulting in failure. Because SnPb is a more elastic material than SAC305, it absorbed the stress of the impact and protected the copper trace, although there were instances of trace failure in SnPb interconnects as seen in Figure (35).

An interesting note about the trace failures is that they all occurred at the edge of the solder ball, where the ball began to wet upon the solder masked defined pad. The reason for this is because this location is considered to be a corner and stress from mechanical loading conditions is typically concentrated at corners. Because of these higher stress concentrations, all of the fractures began at corner locations.

Pad cratering, shown in Figure (39), is not actually a failure, but it is a pre-cursor to trace failure. This is because the crack that goes through the resin under the copper pad causes the pad to lift off from the board, introducing additional stress to the trace.

The added stress from this crater accelerates the process of the trace failure. Pad cratering was not seen in all of the trace failures, but it was seen in many of them.

### **5.3: Summary**

The reliability data indicated that isothermal aging had a significant effect on mechanical reliability of BGAs subjected to drop loading. The characteristic life of all of the solder interconnects decreased after the extended isothermal aging step. Varying the Pd thickness in ENEPIG was shown to only have an effect on SAC305 solder interconnects aged for 24 hours and SnPb interconnects aged for 500 hours. In those cases, the thicker layer of Pd was preferred for SAC305 and the thinner layer of Pd was preferred for SnPb. This was due to the higher strain-rate application of drop loading causing more failures in the IMC. While it had been shown in literature that IMCs on thin-Pd ENEPIG / SAC305 were stronger than those on thick-Pd ENEPIG / SAC305, the random nature of failures from the high-strain rate application led to later failures in thick-Pd ENEPIG. A similar flow of logic can be applied for thin-Pd ENEPIG / SnPb. Tables (16) and (17) below summarize the effects of Pd thickness and isothermal aging on mechanical reliability of solder interconnects subjected to drop loading conditions.

*Table 16 - Change in characteristic life of ENEPIG samples subjected to drop loading, Pd thickness effect*

<b><i>Aging Condition</i></b>	<b>24 Hours</b>	<b>500 Hours</b>
<b><i>Effect of thin-Pd on SnPb</i></b>	11% Increase	72% Increase
<b><i>Effect of thin-Pd on SAC305</i></b>	75% Decrease	37% Decrease

*Table 17 - Change in characteristic life of samples subjected to drop loading, isothermal aging effect*

<b><i>Solder</i></b>	<b>Thin-Pd ENEPIG</b>	<b>Thick-Pd ENEPIG</b>	<b>Immersion Silver</b>
<b><i>SnPb</i></b>	59% Decrease	73% Decrease	40% Decrease
<b><i>SAC305</i></b>	38% Decrease	76% Decrease	50% Decrease

## Chapter 6: Conclusions and Future Work

From this work, it is concluded that the thickness of Pd in ENEPIG has an effect on both thermal and mechanical reliability of solder interconnects formed on the surface finish. Literature reviewed prior to the work in this study concluded that a thinner Pd layer, less than 0.2  $\mu\text{m}$ , offered the strongest solder interconnects, with failures in SAC solders entirely within the bulk material when subjected to solder ball pull and shear. The work in this study showed that keeping the Pd layer smaller than 0.05  $\mu\text{m}$  greatly improved the thermal reliability of SAC solder interconnects on ENEPIG. For mechanical reliability, the thinner layer improved the characteristic life of SAC solder interconnects subjected to vibration cycling, which is a low strain-rate application similar to temperature cycling, but the thinner layer decreased characteristic life of SAC solder interconnects subjected to drop loading, which is a high strain-rate application. Opposite results were seen with SnPb in that the thicker layer of Pd increased the characteristic life of solder interconnects subjected to temperature cycling and vibration cycling, but decreased the characteristic life of solder interconnects subjected to drop loading.

This study also showed that extended isothermal aging had a significant effect on the mechanical reliability of SAC and SnPb solder interconnects formed on ENEPIG and Immersion Silver surface finishes. Extended aging at 100°C for 500 hours decreased the characteristic life of all solder interconnects subjected to vibration cycling and drop loading except for solder interconnects formed on Immersion Silver subjected to vibration cycling.

## **6.1: Contributions**

From this work came several contributions to the effect of Pd thickness, the effect of extended isothermal aging, and pre-conditioning for temperature cycling. These specific contributions are listed below.

### **6.1.1: Effect of Pd Thickness**

This research showed that varying the thickness of the Pd layer in the ENEPIG surface finish had an effect on the thermal and mechanical reliability of SAC305 and SnPb solder interconnects formed on the ENEPIG surface finish. The optimal thickness depends on not only the solder being used, but the expected loading conditions on the PCB. If using a SAC305 solder and subjecting to low strain rate applications, such as temperature and vibration cycling, the Pd layer should be no thicker than 0.1 microns. For high strain rate applications such as drop loading, it was shown that Pd layers thicker than 0.1 microns increased the characteristic life of those solder interconnects.

The opposite results were seen with SnPb solder. For low strain rate applications, a Pd layer thicker than 0.1 microns increased characteristic life, while high strain rate applications increased the characteristic life of solder interconnects on ENEPIG with layers of Pd that were thinner than 0.1 microns.

### **6.1.2: Pre-Conditioning for Temperature Cycling**

The effect of pre-conditioning on thermal cycling reliability was investigated. From the results, a 24-hour exposure to a 100°C environment did not significantly change the life of the solder interconnects, regardless of solder or surface finish used. As such, this research does not recommend a pre-conditioning step prior to reliability testing.

### **6.1.3: Extended Isothermal Aging**

Extended isothermal aging was shown to have a negative effect on mechanical reliability of solder interconnects on both ENEPIG and Immersion Silver surface finishes. The one exception was SnPb solder interconnects on Immersion Silver subjected to vibration cycling. Brief investigations on the IMC's formed in these solder interconnects were carried out, and those results are shown in Appendix B. IMC's did increase in thickness with a 500 hour age, but the amount of growth seen did not correlate with the drop in characteristic life of the solder interconnects.

### **6.2: Recommendations for Future Work**

All of the above reliability tests were conducted using multiple components on one PCB. In order to acquire data, boards were not removed from the test when one of the components failed. Rather, all of the components on the board needed to fail before the board was removed. The failure analysis revealed multiple failure modes, but considering that boards stayed in the test, it was impossible to determine exactly which failure mode caused each component to fail. Because of this, some of the probability distributions appeared to be multi-modal, complicating the reliability analysis. It is recommended that in future tests, only one component is on the board so that it may be removed for analysis when it fails. This way, failure modes can be quickly identified and components can be sorted out by failure mechanism to allow for better reliability analysis.

During temperature cycling, SAC305 solder interconnects on thin-Pd ENEPIG subjected to temperature cycling experienced early failures. While pre-conditioning was

shown to decrease the number of early failures (and increase the number of survivors), further investigation into why these early failures happened is recommended.

Finally, ENEPIG was originally developed as a replacement to ENIG. Some of the research discussed in Chapter 1 compared ENEPIG to ENIG, but in this study ENEPIG was not compared to ENIG. In future tests, it is recommended that reliability tests be conducted which compare ENEPIG to ENIG to truly determine if ENEPIG is a viable replacement for ENIG and its “black-pad” problem.

## **Appendix A – Plating Processes**

### **Electroless Plating**

To make ENEPIG, Ni is plated onto the exposed copper metallization through an electroless plating process. Pd is then plated onto the Ni with the same electroless plating process. Au is plated using the immersion plating process, which is described in the next section.

For electroless Ni plating, Ni ions are suspended in an aqueous solution of reducing agents, which drive the chemical reaction that plates the Ni onto the copper. A commonly used reducing agent is sodium hypophosphite ( $\text{NaPO}_2\text{H}_2$ ). The PCB with exposed copper regions is submerged into the solution, beginning the plating process. Cu reacts with the reducing agents and releases electrons into the solution. These electrons then immediately reduce the positively charged Ni ions, drawing them to the catalytic copper surface. This plating process continues until either all of the reducing agents are consumed by the reaction with Cu, or the board is removed from the solution. This process is repeated for Pd plating, with the exposed Ni now releasing the electrons, which reduce the positively charged Pd ions, drawing them to the exposed Ni (IPC-4556).

### **Immersion Plating**

Au is plated onto the Pd layer using an immersion plating process. Immersion plating is similar to electroless plating in that the PCB with exposed metallization is submerged into the solution bath. The difference here is the chemical reaction that takes place. When submerged, the base metal (Pd for ENEPIG) dissolves into the solution, releasing the electrons which reduce the positively charged ions of the material to be

plated. This material is Au for ENEPIG, Ag for Immersion Silver. The reduced ions are then drawn to the base metallization, thus creating the immersion plating layer.

This reaction, shown in Figure (40), is self-limiting because it can only proceed as long as there is exposed base metal. As a result, immersion plating layers are very thin, on the order of 0.1-0.3  $\mu\text{m}$  or less, and sometimes cannot fully cover the base material.

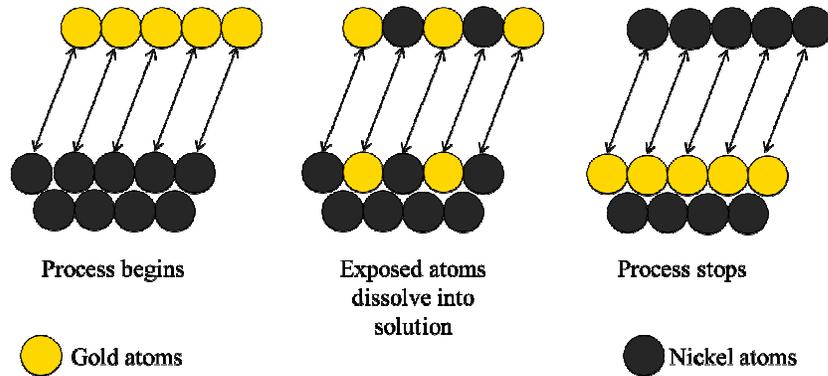


Figure 40 - Schematic of immersion plating process (not drawn to scale)

## Appendix B – Effect of Isothermal Aging on IMCs

When the solder interconnects were isothermally aged, it was expected that the morphology and size of the IMCs that bonded the solder to the surface finish would be changed. To investigate the effect of this isothermal age, additional ENEPIG finished PCBs with the same construction as the PCBs used for the reliability tests were constructed. Following the isothermal aging steps, one BGA from each board was cross-sectioned and analyzed in the ESEM to see the IMCs bonding the solder to the pad. Because there were two version of ENEPIG, two solders, and two isothermal aging times, a total of 8 BGAs were cross-sectioned for this investigation. Images showing the IMCs from each of these BGAs are shown in Figures (41) through (44) below. Table (19) summarizes the thickness of each of these IMCs.

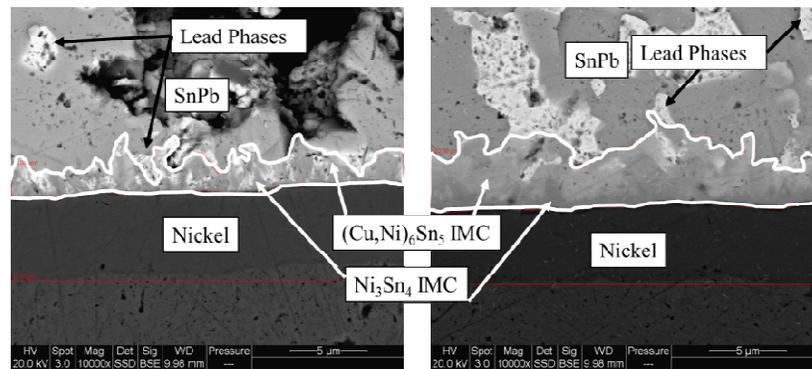


Figure 41 - IMCs formed in SnPb solder interconnects on thin-Pd ENEPIG, aged for 24 hours (left) and 500 hours (right)

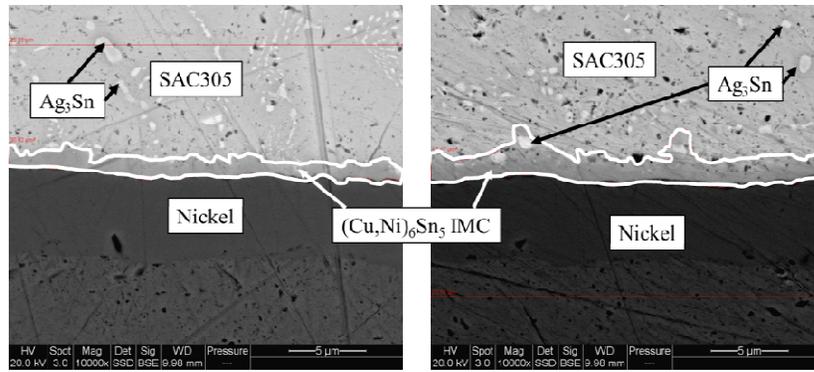


Figure 42 - IMCs formed in SAC305 solder interconnects on thin-Pd ENEPIG, aged for 24 hours (left) and 500 hours (right)

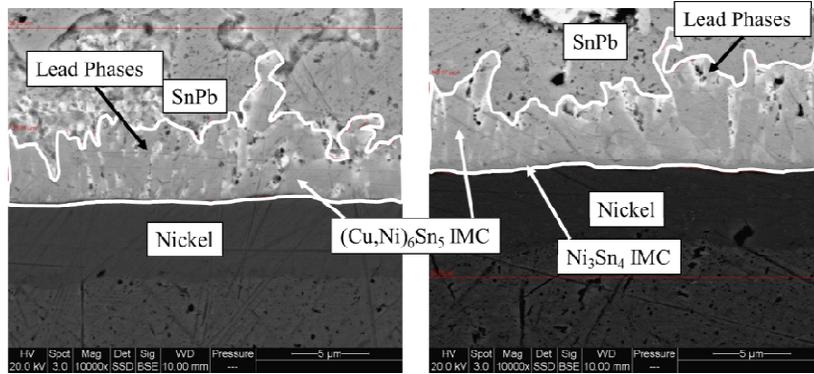


Figure 43 - IMCs formed in SnPb solder interconnects on thick-Pd ENEPIG, aged for 24 hours (left) and 500 hours (right)

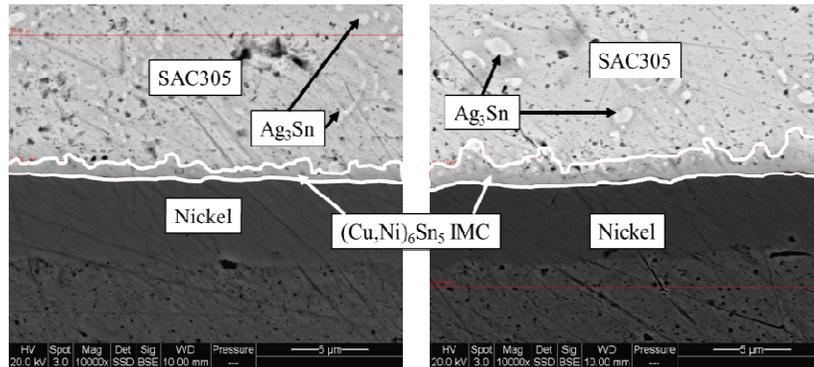


Figure 44 - IMCs formed in SAC305 solder interconnects on thick-Pd ENEPIG, aged for 24 hours (left) and 500 hours (right)

Table 18 - Summary of IMC thicknesses and size increase after 500 hours of aging

<b>Solder</b>	<b>SnPb</b>			<b>SAC305</b>		
	<b>24 Hrs</b>	<b>500 Hrs</b>	<b>Difference</b>	<b>24 Hrs</b>	<b>500 Hrs</b>	<b>Difference</b>
<b>Thin-Pd ENEPIG</b>	2.08 µm	4.03 µm	94%	1.17 µm	1.86 µm	59%
<b>Thick-Pd ENEPIG</b>	4.92 µm	5.75 µm	17%	0.96 µm	1.69 µm	76%

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