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Review of Capabilities of the ENEPIG Surface Finish

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Surface finishes are used to protect exposed copper metallization in printed circuit boards from oxidation and to provide a solderable surface on which to mount electronic components. While it is true that some people have called electroless nickel electroless palladium immersion gold (ENEPIG) a “universal finish” for a wide range of applications from wire bonding to solder interconnects, this paper provides a review of the current literature on ENEPIG and assesses its overall capabilities compared to other surface finishes. Gaps in understanding the performance of ENEPIG as a printed wiring board surface finish are identified and further testing is recommended.

Key words: ENEPIG, surface finishes, reliability, solder interconnects

INTRODUCTION

Exposed copper regions on printed circuit boards (PCBs), which are made of copper-plated glass epoxy laminates, need a surface finish to protect them from oxidation. The surface finish needs to have good solderability and bondability in order to mount components and bond wires. The surface finish also needs to be smooth to allow for good contact in connectors. Because of the high temperatures applied to the board during soldering, the materials used for the finish will diffuse into the solder, altering the mechanical, physical, and electrical properties of the solder interconnects. Therefore, the effect of surface finishes on the reliability of solder joints needs to be investigated.

Common surface finishes in use today include: organic solderability preservative (OSP); immersion silver, gold, or tin (ImAg, ImAu, ImSn); electrolytic nickel gold (Ni/Au); and electroless nickel immersion gold (ENIG). ENIG in particular is used in a wide variety of applications due to its good solderability, bondability with Au and Al wires, and electrical conductivity. Reports of early failures of ENIG-finished PCBs due to a “black-pad” forming during immersion gold deposition[1,2] resulted in a search for an alternative to ENIG. The selected alternative was to insert an electroless palladium layer in between the nickel and gold layers, thus forming the electroless nickel electroless palladium immersion gold (ENEPIG) finish.

The adoption of ENEPIG was slow due to concerns over intermetallic formations between Pd and eutectic Sn37Pb solder[1,2] and the high cost of Pd.[3,4] With a decrease in the price of Pd and the institution of the Restriction of Hazardous Substances (RoHS) Directive in 2006, which banned Pb in electronic products, the industry has reconsidered the use of ENEPIG. Investigations into the reliability of Pb-free solder joints formed with ENEPIG have revealed that ENIG and ENEPIG offer similar reliability. In many cases, the solder joint reliability with ENEPIG was higher than with ENIG. Studies also began comparing ENEPIG to other popular surface finishes with similar findings. As a result, some researchers began to hail ENEPIG as the “universal” finish.[1,5–8]

This paper presents a review of reliability studies on ENEPIG finish. A brief introduction describing the application of ENEPIG is presented, followed by an investigation into the material properties of solder interconnects formed on the finish, including the formation of intermetallic compounds (IMCs). Reliability tests that have been conducted on ENEPIG are then introduced and analyzed, offering an individual assessment of each test. The paper

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concludes with an overall assessment of ENEPIG finish with regards to the test results, cost, and potential application of ENEPIG as a universal surface finish for electronics which can be used across all applications.

PCB PLATING PROCESSES

One of the final steps taken during the fabrication of PCBs is the application of a surface finish to oxidation-prone exposed copper regions by plating or coating. The copper on the surface of a printed wiring board may be coated with a solder mask material or directly exposed to the ambient surroundings. Surface finishes are applied to protect the exposed copper from oxidation, maintain bondability, and/or allow for electrical contact. Surface finishes can be either metallic or nonmetallic. The most commonly used nonmetallic finish is organic solderability preservative (OSP or CuOSP). Applying this finish involves immersing the board in an organic material that adheres to the bare copper surface and protects it from oxidation. The organic finish, unlike other finishes, can be applied at lower temperatures to reduce cost and environmental hazards, but it cannot withstand multiple heat cycles or be used for wire bonding applications.

Metallic finishes coat the bare copper metallization on a PCB with a more noble oxidation resistant metal, such as gold or silver, by immersion, electrolytic, or electroless plating processes. The metallic finishes also provide a flat surface that allows for mounting of electronic components. Surface finishes in use today include hot air solder leveling (HASL), immersion tin (ImSn), immersion silver (ImAg), direct immersion gold (DIG), ENIG, electroless nickel electroless palladium immersion gold (ENEPIG), and electrolytic nickel electrolytic gold (Ni/Au). There are also variations of these finishes, such as solder on pad (SoP), electroless nickel immersion gold electroless gold (ENIGEG), and electroless nickel electroless palladium immersion gold electroless gold (ENEPIGEG). With ENIGEG and ENEPIGEG, an electroless gold layer is plated on top of a flash layer of immersion gold in order to achieve the desired thickness.

Immersion plating is a process in which less-noble atoms on the surface are replaced by more-noble metal atoms, thus plating the surface with a thin layer of the more-noble metal. The immersion process stops when the less-noble surface is completely covered with the more-noble metal, which can result in plating layers only a few atoms thick. Compared to other plating processes, the immersion-plated layer does not adhere to the substrate surface as well as layers produced by other plating processes, such as electroless and electrolytic.

The electroless plating process utilizes a reducing agent that reacts with the catalytic substrate, which releases electrons from the reducing agent. This immediately reduces the positively charged metal ions in the solution and promotes their deposition onto the substrate. The process stops either when the PCB is removed from the plating bath or when the reducing agent has no additional electrons to donate. This process results in thicker metal coatings compared to the plating layers produced by the immersion process.

Electrolytic plating is deposited by the same process as the electroless plating process. Unlike the electroless process, however, the electrons are donated from an external power supply, rather than from the reducing agents in the plating bath.

ENEPIG FINISH VERSUS OTHER BOARD FINISHES

The capabilities of ENEPIG as a board surface finish have been tested and compared to other board finishes. As ENEPIG was developed from ENIG, most papers have compared ENEPIG to ENIG and Ni/Au. ENEPIG has also been compared to all the other previously mentioned finishes, most often to OSP. Figure 1 details the percentage of studies comparing ENEPIG to the previously mentioned surface finishes.

ENEPIG is composed of three layers plated on the board's copper layer: electroless nickel (EN), electroless palladium (EP), and immersion gold (IG). The Institute for Printed Circuits (IPC) standard IPC-4556[9] details the requirements for ENEPIG finish. Table I shows the range of plating layer thicknesses used in past studies, and Fig. 2 shows schematics of ENEPIG, ENIG, and Ni/Au with thicknesses as required by their respective standards. Varying the thicknesses of each of these layers will affect the interfacial reaction and potentially have an effect on solder joint reliability.[10] The preferred layer arrangement, based on results of studies conducted on ENEPIG is: EN = 5 μm, EP = 0.1–0.2 μm, and IG (or IGEG) = 0.07–0.2 μm.

ENEPIG TESTING

A summary of different tests and studies that were conducted on ENEPIG finished boards is shown in Table II. The most common test conducted on ENEPIG was the high temperature storage

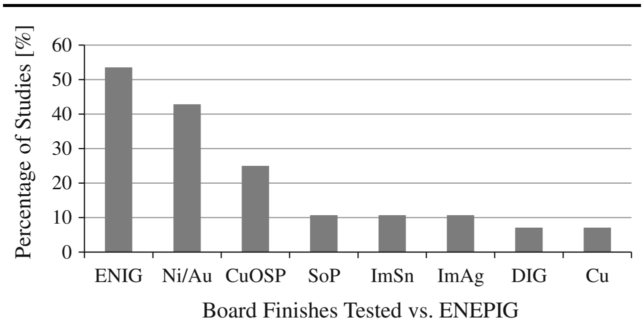

Fig. 1. Fraction of each board finish tested versus ENEPIG.

Table I. Thicknesses of ENEPIG finish layers (μm)

Layer	Thickness (μm)	References
Electroless nickel (EN)	0.1	14
	3–7	38
	5	5,7,8,14,16–18,22, 24,26–28,32,45–48
	5–7	36
	5–8	49
	5–9	2
	6	25,37
	7	11,40
	10.5	30
Electroless palladium (EP)	0–0.3	23,26
	0–0.2	40
	0.01–0.3	26
	0.05–0.3	22
	0.05–3.0	38
	0.05–0.4	27
	0.06–0.15	2
	0.04	32
	0.05	5,36,45
	0.06	7,8,28,30,48
	0.1	25,46
	0.1–0.3	18
	0.2	11,16,17,37,46
	0.3–0.6	49
	0.4	14
	0.5	24,46,47
	0.8	14
Immersion gold (IG)	0.01–0.02	38
Immersion gold electroless gold (IGEG)	0.02	48
	0.03	7,8,22,28
	0.03–0.15	27
	0.03–0.18	49
	0.03–0.4	26
	0.04	25
	0.05	5,18,24,30,36
	0.05–0.5	23
	0.06	37
	0.065	45
	0.08	47
	0.1	11,15–17,40
	0.1–0.16	2
	0.12	14,32
	0.5	46

(HTS), which investigates shelf life. The most common study on ENEPIG investigated the formation of intermetallics (IMCs). Solder ball shear (SBS), temperature cycling (TC), and board level drop test (DT), are some of the studies conducted to assess solder joint reliability (SJR).

Solder joints have been identified as a common failure site for electronics; therefore, investigating different alloys is crucial for determining the most robust alloy for each potential application. A variety of different solder alloys have been tested with ENEPIG, including SnAgCu (SAC) and SnAg alloys. As a baseline, many studies have also conducted the same tests on SnPb solder on ENEPIG for comparison. Figure 3 provides a breakdown of solders investigated with the ENEPIG finish.

When solder is applied to a board, elements of the solder react with the surface finish and form IMCs within the bulk and at the interface. Even at slightly elevated temperatures, such as those developed during soldering, reflowing, or thermal aging, the diffusion rate and thus the speed of IMC formation is increased. When a tin-rich solder is applied to a top layer of gold, the gold diffuses rapidly into the tin and forms gold-tin IMCs, including $AuSn_4$ and Au-Sn solid solution, which forms when there is not enough gold to form IMCs. The amount of $AuSn_4$ formed is dependent of the gold layer thickness.

Peng et al.[11] found that, when Sn37Pb solder was applied at 220°C to ENEPIG (7.0/0.2/0.1), the gold layer disappeared within 5 s. Subsequently, the palladium diffused into tin and formed $(Pd, Ni)Sn_4$ IMCs within those 5 s. Starting at 20 s (5 for SAC305), Ni_3P IMC is formed at the EN layer. Other IMCs, such as Ni_3Sn_4, Ni_2SnP, or $(Cu, Ni)_6Sn_5$, begin to form after 90 s with SnPb, or 10 s with SAC305.

The type, shape, thickness, and morphology of the IMCs determine the mechanical properties of the interface and influence solder joint reliability. On ENEPIG, tin-based solders form Ni-Sn IMCs. The thicknesses of these Ni-Sn IMCs are uniform across the entire interface between the bulk solder and the ENEPIG-finished pad. If the tin-based solder contains an addition of copper, most notably with

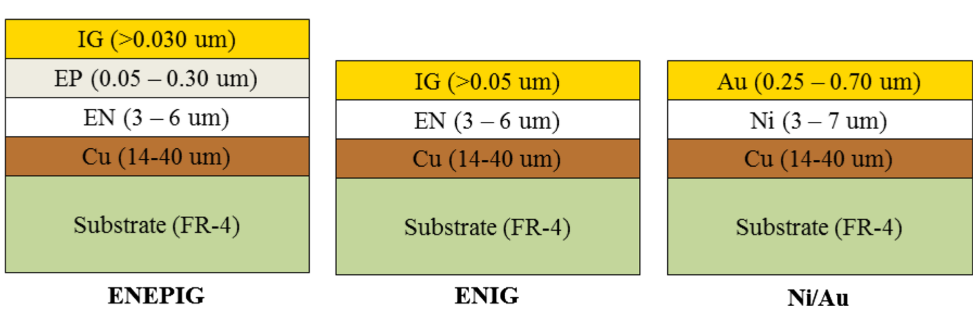

Fig. 2. Schematic of layer configurations of ENEPIG, ENIG, and Ni/Au board finishes.

Table II. Tests and studies conducted on ENEPIG finished boards

Test or study	References
High temperature storage (shelf) life test (HTS)	2,5,7,8,16–18,20–24,26,37,39,41,45,50
Intermetallic (IMCs) formation	11,12,14–17,19,21,26,28,30,32,36,38,40,45,46,49
Solder ball shear test (low/high speed) (SBS)	15–17,21,22,25,38–40,46,50
Wire bond shear test (WB)	2,17,24–28,37,47,48
Solder ball pull/cold ball pull tests (CBP)	5,7,8,16,17,22,25,26,28,38
Temperature (thermal) cycling test (TC)	2,18,20,21,37,45
Board level drop test (DT)	2,19,20,39
Solder bump electromigration stress test (EM)	29–31
Moisture sensitivity level (MSL)	2,20,22
Nanoindentation hardness	14,32
Board level cyclic bend test (BT)	20
Highly accelerated temperature and humidity Stress (HATS)	2
90° peel test	33

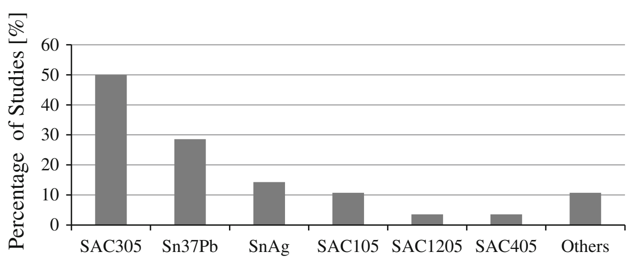

Fig. 3. Fraction of each solder studied in the papers reviewed.

SnAgCu (SAC) alloys, the IMC will be a Cu-Ni-Sn IMC.[11] The copper addition to the IMC could also come from copper in the part terminal. When viewed from above following chemical etching of the solder, IMCs formed on ENEPIG with SAC solder alloys appear in a ring pattern.[12] The grains themselves are needle-shaped. In addition, the overall grain size of each IMC is varied, although all grains are smaller than those formed on ENIG finish.[13] It is unknown how the varying morphologies and grain sizes of these IMCs will affect solder joint reliability. If the eutectic SnPb solder is used on ENEPIG, studies have shown this intermetallic to be an uneven, non-uniform Ni-Sn IMC.

A summary of studies that have investigated IMC formation on ENEPIG is shown in Table III, with the ENEPIG layer thicknesses, solder, IMCs formed, and location of IMCs. Test data showed that, in eutectic SnPb joints on ENEPIG, failure occurs in the non-uniform Ni-Sn IMC during solder ball pull (SPB), while the failure occurs in the bulk for SAC solders.[7,8]

Preconditioning of ENEPIG Samples

Before reliability tests, samples are often "preconditioned," by being exposed to loading conditions less extreme than the intended test conditions. Preconditioning is done to simulate loads experienced by samples during manufacturing, storage, and shipping. It can also be done to provide a common starting point for tests. The preconditioning of non-hermetic surface mount devices (SMD) prior to reliability testing is governed by Joint Electron Device Engineering Council (JEDEC) Standard JESD22-A113. Currently, preconditioning is only required in solder ball shear/pull and solder bump electromigration test methods (JESD22-B115 for solder ball shear/pull, JEP154 for electromigration), but most reliability studies include preconditioning as part of their test procedure. Preconditioning methods include temperature cycling (TC), baking (dry or wet), moisture soaking, and solder reflow(s). Preconditioning cycles used in ENEPIG tests are summarized below in Table IV.

One reliability test that could be considered as a preconditioning step is the high temperature storage (HTS) test. The HTS test is used to determine the shelf life of boards and components under prolonged storage by placing samples in a chamber held at high temperature for an extended period of time. JEDEC standard JESD22-A103 specifies seven test temperatures, ranging from 85°C to 300°C. The most common test is "B": 1000 h at 150°C. A summary of HTS parameters used in ENEPIG tests is shown in Table V and Figs. 4 and 5. Testing duration varied between 4 h and 1000 h.[14] Boards were tested at a temperature range between 120°C and 175°C.

Reliability Tests on ENEPIG

There are many existing tests that can be conducted to assess the effect of ENEPIG surface finish on the reliability of electronic products. Tests to be discussed in this section include: solder ball shear and pull, wire bonding, temperature cycling, drop, moisture sensitivity, electromigration, nanoindentation, peel, and high-altitude storage testing.

Solder Ball Shear

Solder ball shear is a destructive test method detailed in JEDEC Standard JESD22-B117. The

Table III. IMCs formed on ENEPIG, ENIG, and Ni/Au with leaded or non-leaded solders (all dimensions in μm)

References	Finish (layer thickness)	Solder type	IMCs on interface	IMCs in solder
16,17	ENEPIG (5/0.2/0.1)	SAC305	$(Cu_x,Ni_{1-x})_6Sn_5$	No Au or Pd IMCs
	Ni/Au (5/0.5)	SAC305	$(Cu_x,Ni_{1-x})_6Sn_5$	No Au or Pd IMCs
36	ENEPIG (5-7/0.05/0.05)	SAC305	$(Cu,Ni)_6Sn_5$ + Pd	$PdSn_4$
	ENIG (5-7/0.08)	SAC305	Ni_2PSn/Ni_3PSn + $(Cu,Ni)_6Sn_5$	Ag_3Sn
29	ENEPIG ()	Sn37Pb	Ni_3Sn_4	Pb
14	ENEPIG (0.1/0.8/0.12)	SAC305	Cu_6Sn_5	
	ENEPIG (5/0.4/0.12)	SAC305	$(Cu,Ni)_6Sn_5$	
32	ENEPIG (5/0.04/0.12)	SAC1205 + Ni	Cu_6Sn_5 + Cu_3Sn	
15	ENEPIG (//0.1)	SAC105	Ni-Cu-Sn + Sn	Ag_3Sn
	ENEPIG (//0.1)	Sn3.5Ag	Ni_3Sn_4 + Sn	
	Ni/Au (/0.5-1)	SAC105	Ni-Cu-Sn + Sn	
	Ni/Au (/0.5-1)	Sn3.5Ag	Ni_3Sn_4 + $AuSn_4$ (Au_3Sn_4)	
19	ENEPIG ()	SAC105 + (Ni,Co,Ce)	$(Cu,Ni)_6Sn_5$	
	ENEPIG ()	SAC0505 + (Ni,Co,Ce)	$(Cu,Ni)_6Sn_5$	
30	ENEPIG (10.5/0.06/0.05)	Sn	$(Ni,Pd)_3Sn_4$	Sn
	ENIG (10.5/0.05)	Sn	Ni_3Sn_4	Sn
5	ENEPIG (5/0.05/0.05)	SAC305	NiSnP, $(Cu,Ni)_6Sn_5$	Pd evenly
7	ENIG (5/0.5)	SAC305	n/a	Pd unevenly
8	ENEPIG (5/0.06/0.05)	Sn37Pb	NiSnP, Ni_3Sn_4	
28	ENIG (5/0.5)	Sn37Pb	n/a	
42	ENEPIG ()	Sn37Pb	Non uniform Ni-Sn	
26	ENEPIG (5/0.05/0.05)	SAC305	NiSnP, $(Cu,Ni)_6Sn_5$	Pd evenly
	ENEPIG (5/0.05/0.05)	Sn3.5Ag	NiSnP, Ni_3Sn_4, $(Ni,Pd)_3Sn_4$	Pd unevenly
12	ENEPIG ()	SAC405	$(Cu,Ni)_6Sn_5$	
	ENIG ()	SAC405	$(Cu,Ni)_6Sn_5$	
21	ENEPIG ()	SAC105 + Ni	Cu-Ni-Sn	
	Ni/Au ()	SAC105 + Ni	$(Cu,Ni)_3Sn_4$, $(Cu,Ni)_6Sn_5$	

() No data were presented.

Table IV. Preconditioning data

References	Preconditioning parameters	Purpose
45	3× reflows at 250°C	Temperature cycling
16,17	1×, 3×, 6×, reflow at 245°C peak	Solder ball shear/pull
46	1× reflow at 205°C, 225°C, 245°C, 265°C peaks	Solder ball shear
36	1×, 5×, 10×, reflow at 245°C peak	IMCs study
25	6 h at 155°C (2 each for substrate, stiffener attach, and solder ball)	Process simulation
3	1×, 3×, 5×, reflows	Solder ball shear
20	2 h at 125°C, 6 h at 85°C/85% RH, 1×, 2×, 3× reflow at 260°C	Solder ball shear
5	5× reflows at 260°C	Solder ball pull
26	5× reflows at 260°C	Solder ball pull
22	1×, 3×, reflow at 260°C peak	Solder ball pull/shear
27	12 h at 85°C/85% RH	Wire bonding

magnitude of shear forces required to cause failure, obtained at low speed (0.0001–0.0008 m/s) and high speed (0.001–1.0 m/s), is affected by the reactions between the solder ball and the substrate, as the material properties of the interface between the ball and substrate change during these reactions. One study used a test speed of 4.0 m/s.[15] The failure mode, ductile or brittle fracture, is dependent on the intermetallics (IMCs) formed at the interface of the solder and the board finish. Ductile failure in the bulk is indicative of a higher quality solder joint than brittle failure in the IMC. The elevated soldering temperatures associated with lead-free solders such as SnAgCu (SAC) increase the thickness of the IMC layers. The test parameters of solder ball shear tests conducted on ENEPIG are summarized in Table VI.

The studies reviewed compared the shear forces and fracture modes of solder balls soldered to

Table V. High temperature storage testing data

References	Test parameters	Intended reliability test
45	Minimum 2000 h at 125°C	High temperature storage
16	250 h and 500 h at 150°C	Solder ball shear
17	250 h, 500 h, 1000 h at 150°C	Solder ball shear and pull
23	100 h, 300 h, 500 h, 1000 h at 150°C	Solder ball pull
	16 h at 175°C	Wire bonding
24	50 h at 150°C	Wire bonding
46	50 h at 150°C	Wire bonding
18	1000 h at 125°C	Solder ball shear
30	50 h and 220 h at 120°C	Electromigration
5	0 h, 100 h, 300 h, 500 h, 1000 h at 150°C	Solder ball pull
	16 h at 175°C	Wire bonding
7,8	100 h, 300 h, 500 h, 1000 h at 150°C	Solder ball pull
2	500 h at 150°C	High temperature storage
	500 h at 175°C	
31	100 h, 300 h, 500 h, 1000 h at 150°C	Solder ball pull
26	1000 h at 150°C	Solder ball pull, IMCs
21	1000 h at 125°C	Solder ball shear
22	0 h, 100 h, 200 h, 400 h, 600 h, 800 h, 1000 h at 150°C	IMC study
27	4 h at 150°C	Wire bonding

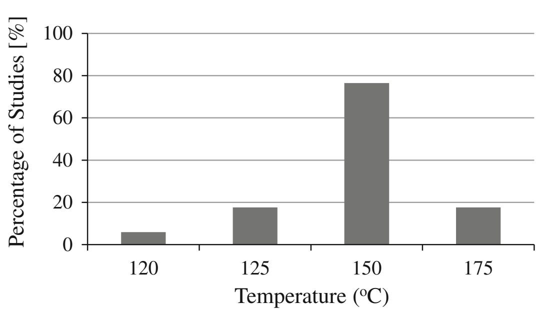

Fig. 4. Percentage of each testing temperature in HTS studies.

ENEPIG to solder balls soldered to other surface finishes. If the fracture mode is defined as ductile, then the failure occurs in the bulk solder, while a fracture mode defined as brittle only occurs in the IMC.

Fu et al.[16,17] performed low and high speed shear tests on SAC305 solder balls on ENEPIG (EN = 5 μm/EP = 0.2 μm/IG = 0.1 μm) and electrolytic Ni/Au (Ni = 5 μm/Au = 0.5 μm) finishes. The solder balls underwent 1×, 3×, and 6× reflows and were aged at 150°C for 250 h and 500 h. They found, by percentage of solder fracture (ductile fracture), that, at low speed shear (0.5 mm/s), the failure modes of both finishes were similar. At high speed shear between 100 mm/s and 2000 mm/s, there was both ductile and brittle failure, dependent on the shear speed. At the low end (100 mm/s), ductile failure occurred in all ENEPIG samples and 98% of Ni/Au samples, while at the high end (2000 mm/s) there was ductile failure in 90% of ENEPIG samples and 55% of Ni/Au samples. These results suggest that SAC305 solder joints on ENEPIG may perform better under high strain rate loading than those formed on Ni/Au.

Johal et al.[18] tested eutectic SnPb solder balls before and after thermal cycling (TC) on ENEPIG (three variations), ENIGEG, and OSP finishes. Before TC, the shear forces necessary to cause the failure of the solder balls on ENEPIG were similar to those on ENIGEG and OSP, and after TC, ENEPIG shear forces were larger than ENIGEG and OSP shear forces by 6–25%. All failures were ductile failures through the bulk solder. They also tested SAC356 ball shear force on balls soldered to ENEPIG and Ni/Au finishes before and after HTS at 150°C for 1000 h. The ball shear forces needed to induce failure on ENEPIG were 14% higher than those on Ni/Au before HTS and 17% higher after HTS. For this test, failures were all ductile in ENEPIG. In Ni/Au, failures before HTS were mostly brittle, and failures after HTS were mostly ductile. These results indicate that ENEPIG offers better solderability than Ni/Au for SAC alloys.

Lee et al.[15] used two types of lead-free solders, SAC105 and Sn3.5Ag, soldered to ENEPIG and Ni/Au surfaces with 1× reflow at 240°C. At normal shear speed (not specified), the Ni/Au finish outperformed the ENEPIG finish by 11% to 17%. At high speed shear (4000 mm/s), SAC105 balls soldered to ENEPIG outperformed those soldered to Ni/Au by 235%. When Sn3.5Ag solder balls were used, Ni/Au finish outperformed ENEPIG by 584%. Lee et al. attributed these results to the thick layer of Ni_3P formed by Sn3.5Ag on ENEPIG and to the formation of Ni_3Sn_4 spalling.

In another study conducted at low speed (not specified), Lee et al.[19] soldered SAC105 and modified SAC105 (+Ni/+ Co/+ Ce) balls to four different substrates—ENEPIG, CuOSP, ImSn, and Ni/Au—and tested the shear after several reflows: 1×, 3×, and 5×. After reflowing, the shear forces measured on

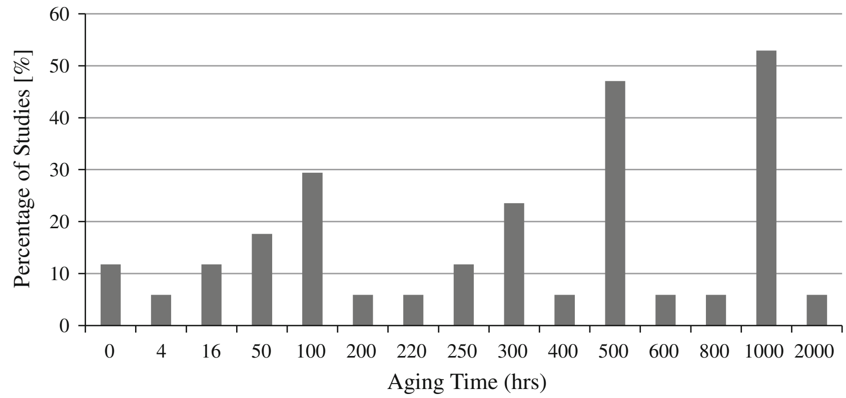

Fig. 5. Percentage of studies for each aging time.

Table VI. Solder ball shear test data

References	Parameters	Solder type
16,17	Speed: low; 0.5 mm/s, high; 100 mm/s, 500 mm/s, 1000 mm/s, 2000 mm/s	SAC305
18	Speed: 0.3 mm/s	SAC356
25	Speed: low; 0.3 mm/s, h = 50 μm	SAC305
15	Speed: low; no data, very high; 4000 mm/s	SAC105, Sn3.5Ag
19	No speed data	SAC105, SAC105 + Ni,Co,Ce
20	No speed data	SAC Alloy
21	Speed: high 500 mm/s, h = 30 μm,	SAC105 + Ni
22	Speed: low; 0.2 mm/s, h = 100 μm	SAC305

ENEPIG were 1–8% lower than those measured on Ni/Au or CuOSP. The ball shear results obtained with modified SAC105 solders were similar.

Li et al.[20] studied several combinations of Pd and Au layer thicknesses on ENEPIG and their effect on SAC solder ball shear after 1×, 2×, and 3× reflows. The measured shear forces on the Ni/Au substrates were 13–26% higher than those measured on ENEPIG finishes.

Sun et al.[21] evaluated the shear fracture mode of SAC105 + Ni solder balls soldered to ENEPIG, CuOSP, ImSn, and Ni/Au by testing them at a high speed of 500 mm/s before and after aging for 1000 h at 125°C. Unlike the other tested finishes (Ni/Au, OSP, SoP, ImSn), failures in ENEPIG were entirely in the bulk solder before and after HTS, indicating that ENEPIG provides stronger, more robust solder joints.

In another study at low speed (0.2 mm/s), Yee[22] compared the ball shear forces of SAC305 balls soldered to four combinations of ENEPIG layers—two types of ImSn, two types of OSP, one ENIG, and one ImAg. The shear forces measured on the ENIG finish without reflow and after 1× and 3× reflows were the highest of all of the finishes. For ENEPIG, thinner layers of Pd required higher shear forces to induce failure. Increasing the thickness of the Pd layer decreased the forces necessary to induce failure in shear.

Comparing all of the above results, it can be seen that ENEPIG offers a high quality solder joint under solder ball shear. Yee[22] showed that larger forces are required to induce failure in ENIG than ENEPIG. Despite this, ENEPIG is still a very good finish for electronic products that could be subjected to applications wherein solder joints could fail due to shear.

Wire Bonding

In many integrated circuit components, gold or aluminum wires are used to connect the circuitry on the die to the leadframe or substrate of the component. These wires are "bonded" to the metal pads on the die and leadframe or metal pads on the substrate. Both the leadframe and substrate metallization require the use of a surface finish, which means that wire bonding on ENEPIG needs to be investigated to ensure that it is a suitable finish for wire bonding.

Wire bonds can fail either under shear or axial (pull) loads. Wire bond shear or pull is defined in JEDEC Standard JESD22-B116. This standard describes bond ball shear and wedge bond pull. Parameters from wire bond pull tests are summarized in Table VII.

Fu et al.[17] bonded ϕ25 μm 99.99% Au wire to ENEPIG (5/0.2/0.1) and Ni/Au (5/0.5) surfaces. The measured pull forces were similar for both finishes: 6.8 g for ENEPIG and 6.6 g for Ni/Au. Gudeczauskas[23] bonded Au wire to a variety of ENEPIG and

Table VII. Wire bond pull test data

References	Parameters
17	Wire: ϕ25 μm, 99.99% Au, pull
23	No data on wire, pull
24	Wire: ϕ28 μm, Au,
25	Wire: ϕ30 μm, 99.99% Au, pull
20	Wire: no data
5	Wire: ϕ25 μm Au, pull speed = 0.17 mm/s
2	Wire: ϕ20 μm, 99% Au,
26	Wire: ϕ25 μm Au, pull speed = 0.17 mm/s
27	Wire: ϕ25 μm 99.99% Au

ENIG surfaces and reported that the pull forces on ENEPIG were higher than on ENIG by 7–33%.

Hasegawa et al.[24] studied ϕ28 μm Au wire bonded to three surface finishes: ENEPIG (5/0.5/0.5), Ni/Au (5/0.5), and ENIGEG (5/0.5). The tests were conducted before and after aging at 150°C for 3 h, 25 h, and 50 h. The results showed that the performances of wire bonding to ENEPIG and Ni/Au were similar and were not degraded by aging, while the performance of ENIGEG degraded considerably, even after 3 h of aging.

Johal et al.[25] compared the pull forces of Au wire bonding to ENEPIG (6/0.1/0.04) and Ni/Au (6/0.7), and concluded that the magnitudes of the pull forces needed to cause failure in the wire bond for both surface finishes were similar. This finding indicates that ENEPIG and Ni/Au offer similar wire bond strength. Li et al.[20] studied wire bonding to six combinations of ENEPIG layers and Ni/Au. Similar to Johal above, they found that the pull forces on both finishes were similar.

Milad[5] tried to optimize ENEPIG layer thicknesses by conducting wire bond pull tests on Au wire bonds. After 16 h of aging at 175°C, he pulled the wires at 0.17 mm/s and found that the combination of layers that yielded a pull force above 8 g consisted of 5 μm of EN, 0.02–0.15 μm of EP, and at least 0.07 μm of IG. When using ENIG finish, the IG layer should be at least 0.3 μm thick. When the IG layer of ENEPIG was thicker than 0.3 μm, the pull forces exceeded 10 g. Because this threshold is a full order of magnitude greater than the thickness requirements stated in IPC-4552, this result is indicative of ENEPIG's superiority over ENIG for wire bonding.

Ng et al.[2] studied wire bonding to two ENEPIG surfaces and one Ni/Au surface. In an effort to determine if the Cu substrate contributed to bond integrity, Ng chose to vary the thickness of the copper substrate below the ENEPIG finish only. The pull forces measured on both ENEPIG surfaces were higher than that measured on the Ni/Au surface by 8–11%, with the Cu thickness in ENEPIG having no effect.

Oda et al.[26] compared the wire bondability between ENEPIG and ENIG finishes. They studied different combinations of layers for both finishes and found that the wire pull forces obtained for the ENEPIG finishes were higher than those measured on the ENIG finishes by as much as 250%.

Yee et al.[27] bonded ϕ25 μm 99.99% Au wire to variations of ENEPIG layers (5 μm EN/0.05–0.4 μm EP/0.03–0.15 μm IG) and Ni/Au (3/0.25). Tests were carried out as-is after 4 h at 150°C, and when bonding was done after preconditioning by baking or humidity. Pull forces on the Ni/Au finish outperformed forces on all ENEPIG combinations by 4–20%. The ENEPIG finish layers recommended for wire bonding were 5 μm for EN, less than 0.1 μm for EP, and less than 0.07 μm for IG.

All the above results indicate strong wire bondability on ENEPIG finish. Similar bondability, if not better, can be seen on Ni/Au according to Yee,[27] but considering the thickness of Au used in that study (0.25 μm), the choice again leads to ENEPIG, which only needs 0.03 μm.

Solder Ball Pull

Another method of determining the quality of solder joints is the SPB method. In this test, solder balls are simply pulled away from the surface of the PCB. Fracture data and failure modes are documented. Balls can be pulled at low (0.1–15.0 mm/s) or high (50–1000 mm/s) speeds.

The SBP test method at both low and high speeds is defined in JEDEC Standard JESD22-B115. Test parameters for SPB tests on ENEPIG are summarized in Table VIII.

Fu et al.[16,17] performed cold SPB tests on SAC305 balls soldered to ENEPIG and Ni/Au substrates. In the first study,[16] they evaluated the fracture mode by pulling the balls after 1×, 3×, and 6× reflows at 245°C. After 1× reflow, there were 8% more IMC failures in Ni/Au than ENEPIG. After multiple reflows, however, there were 35–67% more brittle IMC failures in ENEPIG than in Ni/Au. In the second study, Fu et al.[17] aged solder balls after 1× reflow at 150°C for 250 h, 500 h, and 1000 h. The percentage of IMC fractures of Ni/Au was higher than those of ENEPIG by 11–26%.

Gudeczauskas[23] compared the percentage of different fracture modes of Sn37Pb and SAC305 balls soldered to ENEPIG finish before and after aging at 150°C for 100 h, 300 h, 500 h, and 1000 h. He found that 48% of the failures in the combination of ENEPIG with Sn37Pb solder were due to ductile fracture before aging, 8% of the failures were due to ductile fracture after 100 h of aging, and there were no ductile fractures thereafter. The combination of ENEPIG and SAC305 solder, however, yielded only ductile fracture, even after 1000 h of aging at 150°C.

Milad and Gudeczauskas[5,7,8] and Oda et al.[28] studied Sn37Pb and SAC305 solder balls soldered to ENEPIG and ENIG finishes. Ball pull tests were conducted after aging at 150°C for 100 h, 300 h, 500 h, and 1000 h. Prior to aging, the measured pull forces of Sn37Pb balls to ENEPIG and ENIG

Table VIII. Solder ball pull test data

References	Parameters	Solder type
16,17	Speed: 5 mm/s, CBP	SAC305
23	Speed: 0.3 mm/s, SBP	Sn37Pb and SAC305
5	Speed: 0.17 mm/s, SBP	Sn37Pb and SAC305
7	Speed: 0.17 mm/s, SBP	Sn37Pb and SAC305
8	Speed: 0.17 mm/s, SBP	Sn37Pb and SAC305
28	Speed: 0.17 mm/s, SBP	Sn37Pb and SAC305
26	Speed: 1 mm/s, SBP	SAC305 and Sn3.5Ag
22	Speed: 0.3 mm/s, CBP	SAC305

finishes were similar, but, on the ENEPIG finish, the percentage of the ductile fracture mode was 50% lower than that on the ENIG finish. After aging, the fracture mode for ENEPIG was mostly brittle, while that for ENIG was mostly ductile, thus indicating that with SnPb, stronger solder interconnects are formed on ENIG. When SAC305 solders were used, the pull forces on the ENEPIG finish were slightly lower than those on ENIG. The fracture mode for the ENEPIG finish was ductile, while that for ENIG showed brittle fracture after 300 h (or more) of aging. The difference in pull forces is insignificant; the more important result is that the failure in SAC305 on ENEPIG is entirely within the bulk solder, not in the IMC, unlike ENIG. This indicates stronger SAC305 interconnects on ENEPIG.

Oda et al.[26] studied plating layer thicknesses by pulling SAC305 balls soldered to various combinations of layers. Their tests were conducted after 5× reflows at 260°C at 1 mm/s. When no Pd layer was present, as in the ENIG finish, the fracture mode was primarily within the IMC. When the EP layer was 0.02–0.1 μm and the IG layer was 0.03–0.2 μm, the fracture mode was entirely within the bulk solder, indicating a high quality joint. Oda et al. also pulled Sn3.5Ag solder balls soldered to ENEPIG and ENIG finishes after 1× reflow at 240°C before and after aging at 150°C for 0–1000 h at 1 mm/s. The measured forces on the ENIG finish outperformed those on the ENEPIG finish by 7–17%, with only ductile failures in ENIG and a mix of ductile and brittle failures in ENEPIG. Increased aging times increased the frequency of the brittle failure mode, indicating that Sn3.5Ag solder offers a higher quality solder joint on ENIG than ENEPIG.

Yee[22] used SAC305 solder balls soldered to five types of surface finishes: ENEPIG (four different layer thickness combinations), ENIG, OSP, ImAg, and two ImSn processes. Tests were conducted as-is after 1× and 3× reflows at 260°C at a speed of 0.3 mm/s. The results showed that the ball pull strengths (the magnitude of pulling forces needed for failure) were similar across all the finishes. Among the fracture modes, the ENEPIG finish with thinner Pd (0.05–0.10 μm) layers offered the strongest solder ball joints.

The above findings indicate that robust solder joints are formed on the ENEPIG finish. It was shown that isothermal aging does not cause significant degradation of the joints.

Table IX. Thermal cycling (TC) test data

References	Parameters	Purpose
18	500 cycles at −55°C to 125°C	Solder ball shear
20	1000 cycles at −55°C to 125°C	Primary test
2	700 cycles at −55°C to 125°C	Primary test
21	2000 cycles at −40°C to 125°C	Primary test

Thermal Cycling

Temperature, or thermal, cycling (TC), which is detailed in JEDEC Standard JESD22-A104, is used to evaluate how products withstand alternating extreme temperatures. The intended uses of the components determine the range of test temperatures. TC was carried out in four of the reviewed papers, where the temperature was cycled between −40°C and +125°C and −55°C and +125°C. The number of cycles is usually determined by the end user or users of the boards. A summary of the reliability tests that were performed is presented in Table IX.

Johal et al.[18] studied the effect of TC on three combinations of ENEPIG, ENIGEG, and OSP soldered with Sn37Pb. Following TC, they conducted the ball shear tests discussed previously. They reported that the shear forces needed to induce failure decreased with TC. This occurred on all finishes, but the decrease for ENEPIG was less than that for ENIGEG and OSP.

Ng et al.[2] conducted temperature cycling on boards (TCoB) using IPC-9701. This standard describes testing procedures for conducting thermal cycling on surface-mounted components. Test boards had an ENEPIG finish on two different thicknesses of Cu layers, 14–18 μm and 35–39 μm. The boards underwent 700 cycles between −55°C and 125°C with no reported failures. Sun et al.[21] evaluated the life cycles of SAC305 solder interconnects on five substrates through TCoB tests: Ni/Au, OSP, SoP (SAC305), ImSn, and ENEPIG. The tests were conducted between −40°C and 125°C with a 15-min dwell. The characteristic life cycles (Weibull with 90% confidence) were: Ni/Au = 2912, OSP = 1124, SoP = 2283, ImSn = 2287, and ENEPIG = 2266. Ni/Au performed better than ENEPIG by 28%.

Comparing these results, ENEPIG is shown to offer reliable solder interconnects, although Ni/Au was shown by Sun to have 28% longer characteristic life. Despite this, Johal showed that temperature cycling does not significantly reduce shear forces required for failure of solder interconnects on ENEPIG. Considering that nearly all electronic products undergo thermal cycling of some sort, this is a good result for ENEPIG.

Drop

Drop testing is specified in the JEDEC/JESD22-B111 standard, which details procedures for drop testing of surface mounted components on PCBs. This standard is primarily used to assess the drop reliability of components for portable electronics. As the market has shifted towards these products, the need to assess the drop reliability of components, solders, and surface finishes, including ENEPIG, has also increased.

Lee et al.[19] conducted drop tests according to JEDEC/JESD22-104 (mechanical shock) condition B: drop height = 1.12 m, velocity change = 4.67 m/s, acceleration peak = 1500 g, pulse duration = 0.5 ms. They compared the drop properties of SAC105, SAC105-Ni, SAC105-Co, and SAC0505 on ENEPIG and Ni/Au finishes. Using the number of drops to obtain a resistance of 100 Ω as the failure criterion, for the components, it was shown that on the ENEPIG finish, SAC105-Ni required the most drops to failure. It was also noted that solders with lower Ag content (SAC0505 in this study) offer more robust solder joints that require the most drops to failure.

Li et al.[20] gave no specific details on the Ni/Au or ENEPIG board finishes. Their description of the tested ENEPIG finishes was medium Pd and high Au thickness, while Ni/Au was described as "traditional". The characteristic lives of the two finishes were nearly identical: therefore, no definite conclusion could be made between the two finishes.

Ng et al.[2] performed the drop test on a CuOSP (Cu thickness = 14–18 μm) finished board and two ENEPIG board finishes (5–9/0.06–0.15/0.1–0.16), which differed by the Cu underlayer thickness: 35–39 or 14–18 μm. They used Sn3.5Ag solder. The estimated number of drops to arrive at 66% failure taken from the Weibull probability plot was 1800 for CuOSP, 950 for ENEPIG with a 35–39 μm Cu layer, and 500 for ENEPIG with a 14–18 μm Cu layer.

Sun et al.[21] tested the drop properties of boards soldered with SAC305 on five pad finishes: Ni/Au (8/2), CuOSP, SoP (SAC305), ImSn, and ENEPIG (10/10/0.7). The characteristic Weibull drop life was 270 for CuOSP, 260 for ImSn, 220 for SoP, 190 for ENEPIG, and 155 for Ni/Au. Hence, ENEPIG performed better than Ni/Au, but worse than CuOSP, SoP, and ImSn.

Electromigration

The Electromigration (EM) stress test is detailed in JEDEC Standard JEP 154: "Guideline for Characterizing Solder Bump Electromigration under Constant Current and Temperature Stress." Solder bumps, leaded or lead-free, are susceptible to migration under high current densities (3×10^3–2×10^4 A/cm^2) and elevated temperatures (100°C–150°C).

Kim et al.[29] compared the EM of leaded (Sn37Pb) bumps on ENEPIG and CuOSP surface finishes. They found that the EM life of eutectic solders on CuOSP is about four times longer than that of leaded solders on ENEPIG. Lu et al.[30] used Sn bumps soldered to an ENIG surface finish to study the electromigration of Ni(P) and the subsequent formation of a Ni_3Sn_4 IMC layer, as well as the effect of adding a Pd layer (making it ENEPIG) on the electromigration. The test parameters were a current density of 10,000 A/cm^2 and a temperature of 120°C. They found that a thin layer of Pd (0.06 μm) slowed the EM of Ni(P).

Nicholls et al.[31] used SAC305 as SoP on three types of surface finishes—bare Cu, ENIG, and ENEPIG—and measured the EM of Sn2.3Ag bumps. Tests were conducted at two current densities: 7860 A/cm^2 and 11,000 A/cm^2, and two bump temperatures, 135°C and 150°C. The expected life of SAC305 on Cu was a minimum of two times longer than that of SAC305 on ENIG or ENEPIG. The life expectancy of SAC305 on ENIG in three current density/temperature combinations was longer than that of SAC305/ENEPIG.

Nanoindentation

Nanoindentation hardness is a test used to estimate the physical and mechanical properties of materials. A nanoindentation machine makes nanometer-sized indents into materials and estimates properties such as Young's Modulus and Hardness.

Kim et al.[14] used nanoindentation to estimate the drop impact reliability of SAC solder on ENEPIG finish. Two types of ENEPIG were used: one with a very thin layer of EN (0.1 μm), and a second one with a 5-μm-thick layer of EN. They soldered SAC305 balls to the two finishes and found that, on the ENEPIG with a thin layer of EN, Cu-Sn IMCs were formed with a Young's modulus of 85 GPa. These IMCs form because the thin layer of Ni (0.1 μm) gets consumed entirely within the solder, allowing the Cu to be exposed to the high temperatures of solder reflow. On ENEPIG with a thicker EN layer, stiffer Cu-Ni-Sn IMCs were formed, and the estimated Young's modulus was 120 GPa. Those moduli were used for finite element analysis (FEA) and the results showed that the Ni in the Cu-Ni-Sn system acted as a "stiff board" that could not transport flexible deformations seen in drop testing. As a result, higher stresses are introduced to solder joints with Cu-Ni-Sn IMCs, resulting in potentially earlier failure than Cu-Sn IMCs.

In another study, Kim et al.[32] used nanoindentation hardness to estimate the properties of the formed IMCs. In this study, 300 μm SAC1205 + Ni solder balls were attached to ENEPIG (5/0.04/0.12) finish and formed a 1.5-μm-thick layer of IMCs, which they identified as Cu-Sn IMCs. The nanoindentation hardnesses of Cu_xSn_y IMCs were measured, and the Young's modulus of Cu_6Sn_5 IMC was estimated to be 118.8 GPa, while that of Cu_3Sn IMC was estimated to be 123.8 GPa. The estimated yield strengths were 2385 MPa for Cu_6Sn_5 and 2490 MPa for Cu_3Sn.

Peel and HAST

The peel test is used to determine adhesive strength in flexible PCBs. While not a standard test method, the peel test can be used for flexible circuits that involve copper electrodes finished with ENEPIG.

Lee et al.[33] used this method to test bonding between a rigid printed circuit board (RPCB) and a flexible printed circuit board (FPCB). They dipped FPCBs plated with ENEPIG and ENIG in tin. The RPCBs were plated with ENIG. The boards were then bonded by ultrasonic energy and peeled at 90° at 0.1 mm/s. ENEPIG performed a little better than ENIG, where the peel strength after 1 s of bonding was 78 g/mm for ENIG finish and 80 g/mm for ENEPIG finish. When the bonding time was increased to 3 s, the peel strength dropped to 66 g/mm for ENIG and to 72 g/mm for ENEPIG finish.

COST AND UNIVERSALITY OF ENEPIG FINISH

Most of the studies presented above[2,3,18,20,23–25,27,30,34–41] mention that the overall cost of the ENEPIG finish is less than that of an electrolytic Ni/Au finish. While the solder joint reliability and wire bonding ability of ENEPIG are similar to Ni/Au, the processes needed for the ENEPIG finish are cheaper than the processes for the electrolytic Ni/Au finish. ENIG finish is cheaper than ENEPIG because it does not have the extra palladium layer, but ENIG gold wire bonding has an inferior performance when compared to ENEPIG.[3,5,23,24,26]

ENEPIG was described by several papers as being a universal finish: that is, it is suitable for a wide variety of applications, unlike most other surface finishes.[1,18,34,38,41,42] The universality of ENEPIG comes from its suitability for soldering (SAC solders only), wire bonding (gold, aluminum, copper), and contact resistance. Since several studies[5,7,8,23,28,29] have found that the reliability of eutectic SnPb solder interconnects on ENEPIG is much lower than that with SAC and other lead-free alloys, ENEPIG will not be a universal finish until leaded solders are no longer used in electronics. With regard to wire bonding, the suitability of Ni/Au and ENIG finishes for aluminum wire bonding is disputed. Three studies claim that the electrolytic Ni/Au and ENIG finishes are unsuitable for aluminum wire bonding[18,35,37], while three others[1,6,42] state that they are suitable. No studies dispute the suitability of ENEPIG for aluminum wire bonding.[18,35,38]

Further ENEPIG Studies

Not all the existing test methods or procedures have been used to assess the solder joint reliability of ENEPIG finish. Thus, studies using the unused test methods are needed to assess solder joint reliability with an ENEPIG finish. Examples of such tests include: solderability after storage, vibration, temperature shock, electrochemical migration, and combined environment tests. Most of these tests expose boards to extreme environments, which are not uncommon in aerospace and military industries. If interconnects on ENEPIG can withstand these types of loading conditions, more manufacturers will begin to use ENEPIG. Because it has also been shown through pull and shear tests that reliability of Sn37Pb solder interconnects on ENEPIG is lower than SAC interconnects, the use of ENEPIG and SAC solders can expedite the removal of Sn37Pb, which was banned in RoHS.

In addition to these unused test methods, researchers should keep an eye to the future of electronics. Products are shrinking in size, and this will require components and interconnects to also become smaller. As such, solder interconnects will become as small as micro-bumps, thereby reducing the amount of bulk solder in the interconnect. The size of the IMC, however, will not be changed, and Kao et al.[43] showed that Au and Pd embrittlement in the bulk could degrade overall solder interconnect reliability. A potential solution would be to add Au or Pd into the bulk solder prior to soldering. Specifically adding Pd has been shown by Lee et al.[44] to improve drop reliability by 65%.

CONCLUSIONS

Based on the literature, ENEPIG is a surface finish with physical, mechanical, and electrical properties that make it a reliable surface finish for PCBs. When compared to its predecessors, ENIG and electrolytic Ni/Au, ENEPIG has been shown to offer stronger solder interconnects and wire bonds. Pull and shear forces needed for failures on ENEPIG were a minimum of 5% higher than ENIG and Ni/Au when SAC3xx solders were used. Furthermore, the failure modes in the ENEPIG/SAC3xx solder interconnects were primarily ductile in the bulk, while failure modes in ENIG/SAC3xx and Ni/Au/SAC3xx were primarily brittle in the IMC, even after preconditioning steps were taken. Ductile failure in the bulk implies that the IMC is stronger than the bulk, meaning that ENEPIG has better solderability with SAC3xx solders than ENIG and Ni/Au. Other solders, including other SAC alloys, SnAg alloys, and eutectic SnPb, showed that all three finishes required similar forces for failure, yet there were brittle IMC failures in ENEPIG with these different alloys.

With regards to loading conditions such as thermal cycling, drop, and electromigration, results were mixed. SAC interconnects on ENEPIG do not have as long a life as other finishes, but it has been shown that the load itself does not degrade interconnects as much as those formed on other finishes. For drop loading, ENEPIG was shown to require a minimum of 16% fewer drops to cause failure than finishes such as OSP, ImSn, and SoP. Preconditioning steps reduced drops to failure across all the finishes, yet the reduction was lowest for ENEPIG. Unlike other loads, electromigration was shown to be a major concern for ENEPIG when compared to other finishes. EM life for all solders was shortest on ENEPIG, though it was shown that a thin layer of Pd (0.06 μm) slowed the EM of Ni(P) in ENEPIG.

Many different plating thicknesses for the ENEPIG finish were tested. From these studies, the highest solder joint reliability under all presented tests was achieved when the following plating thicknesses were used: EN = 5 μm, EP = 0.1–0.2 μm, and IG = 0.07–0.2 μm, which all fall within the required ranges as specified in IPC-4556. Plating layers thicker than these recommended thicknesses hindered solder joint reliability, although thicker gold layers are recommended for improved gold wire bonding.

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