EVALUATION OF THE USE OF ENEPIG IN SMALL SOLDER JOINTS

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ABSTRACT
The surface finish of a printed circuit board provides a number of functions, with impacts starting at the point of design and continuing through the life of the assembled product. Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) is a surface finish that has been demonstrated to have a variety of benefits, and to be suitable for both SnPb and Pb-free circuit card assembly. Extensive testing of ENEPIG has demonstrated the reliability of this surface finish and resulted in the creation of an industry standard for its application: IPC-4556 *Specification for Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG) Plating for Printed Circuit Boards*. When soldering to ENEPIG, all of the palladium is dissolved into the solder joint, and creates a palladium-rich region at the base (Pd source) of the solder joint. This palladium-rich microstructure can spall off, exhibiting a columnar shape. With ever decreasing size of parts used in electronics assembly, the size of the solder joints correspondingly continue to shrink, which causes the relative size of this palladium-rich microstructure to grow relative to the overall joint thickness. In this study, the impact of industry standard Pd thicknesses on thin solder joints is evaluated through shear testing.

Key words: ENEPIG, SnPb, shear test

INTRODUCTION

ENEPIG is a multi-layer surface finish for circuit boards. For the purpose of soldering, the gold and Pd are applied to protect the solderability of the underlying Ni, and they are ultimately dissolved into the solder joint. Excessive amounts of these metals in the solder joint can potentially cause weakness of the solder joint, impacting reliability.

There is an industry specification (IPC-4556) which describes the requirements for ENEPIG, and the finish has some use in the industry, but is limited due to availability and the increased cost of the Printed Board (PB) relative to other surface finishes. The plated layers of ENEPIG are very flat, as all plated surface finishes are relative to Hot Air Solder Leveling (HASL), which makes it advantageous for smaller PB design features. As electronic component packaging technology advances and parts get smaller, the PB must have finer features to attach these parts. This decrease in feature size typically drives a decrease in solder paste stencil thickness for effective solder release, resulting in smaller solder joint volume. As the solder joint size get smaller, the thickness of the surface finish on the PCB remains constant, so that the relative volume of gold and palladium in the solder joint increases. ENEPIG has been demonstrated to have acceptable performance and reliability for many current packages and solder joint configurations, but some studies raise concerns for use of ENEPIG at high concentrations or in very small solder joints [1].

Round robin testing for the development of the IPC-4556 specification included palladium thicknesses of up to 17.95 microinches (μin). A 0.005 inch thick stencil was used with a 0.025 inch diameter SnPb solder sphere, resulting a solder joint containing approximately 0.17% Pd. Shear testing of the solder ball on pad resulted in both lifted pads and cohesive failure in the bulk solder.

IPC-7095C *Design and Assembly Process Implementation for BGAs* warns of reliability impacts from excessive and non-uniform intermetallic compound (IMC) layer growth. IPC-4556 mentions a 3% limit for gold and palladium, and other sources have identified 2% as a limit [2], but these limits based on a percentage are misleading when applied to Pd. Gold can (and is desired to) disperse throughout a solder joint to minimize impact, but Pd tends to form a distinct and concentrated IMC layer above the Ni.

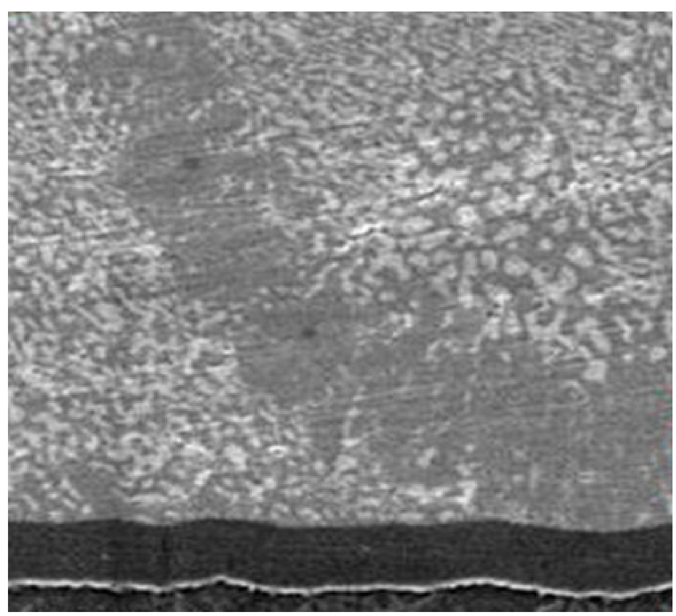


Figure 1. PdSn intermetallic structure spalling off substrate surface

Palladium has a slower solubility rate in molten solder than other metals. During soldering, the tin-palladium intermetallic compounds (either $PdSn_3$ or $PdSn_4$) will rapidly grow in the form of a thick lamellar structure perpendicular to the original palladium surface. Solder, consisting of a lead-rich phase, will be present between the lamellae. Further aging of solder joint can result in the movement (spalling) of the tin-palladium layer into the bulk solder and likely leave tin-palladium crystals within the bulk solder.

ENEPIG has been found to be prone to brittle fractures. The tin-palladium layers that form directly above the nickel plating has been found to be brittle, although some studies indicate that this may be based on weakness of a phosphorus rich nickel layer, not necessarily the Pd intermetallics [3]. The presence of tin-palladium crystals within the bulk solder has not been well-documented in terms of the effect on solder joint integrity, however as a comparison, tin-gold intermetallic crystals in bulk solder have been shown to embrittle a solder joint, enabling fracture of the solder joint along the gold intermetallics. It has not been shown that Pd intermetallics can have a similar effect within the bulk solder, the typical failure is associated with brittle fracture at the PB pad.

Based on the initial formation of a thick lamellar Pd intermetallic structure above the Ni layer, a limit on Pd thickness may be more appropriate to prevent excessive intermetallic layer thickness. A higher Pd thickness leads to an increased interfacial IMC thickness, specifically when SnPb solder is used. A thin palladium layer should dissolve rapidly into molten solder and result in no detrimental effect on solder joint mechanical properties. A variety of Pd thickness percentages or thickness limits have been proposed, some of which are lower than the 12 µin limit in IPC-4556. One paper suggests a limit of 7.8 µin [4], although one study found that Pd thickness as high as 20 µin had no impact on solder joint shear strength [5].

In this study, PBs plated with a typical ENEPIG surface finish (per IPC-4556) will be assembled with a minimum amount of solder to create a very small solder joint where the Pd concentration becomes larger relative to the overall solder joint. Solder shear strength and solder joint analysis will be used to investigate the acceptability of using ENEPIG with SnPb solder in these very small solder joints.

EXPERIMENTAL PROCEDURE

For assembly and testing, an existing test vehicle was selected for use with a small LGA package. Using an LGA package limits the solder volume in the solder joint since there is no contribution from a solder ball as there is in a BGA package, resulting in a higher Pd concentration in the solder joint. A small LGA package of 6 x 6 pad array was selected and will be installed at the four corners of a larger BGA footprint in a manner so that only the middle 4 x 4 array of pads on the part are soldered. This will be done to

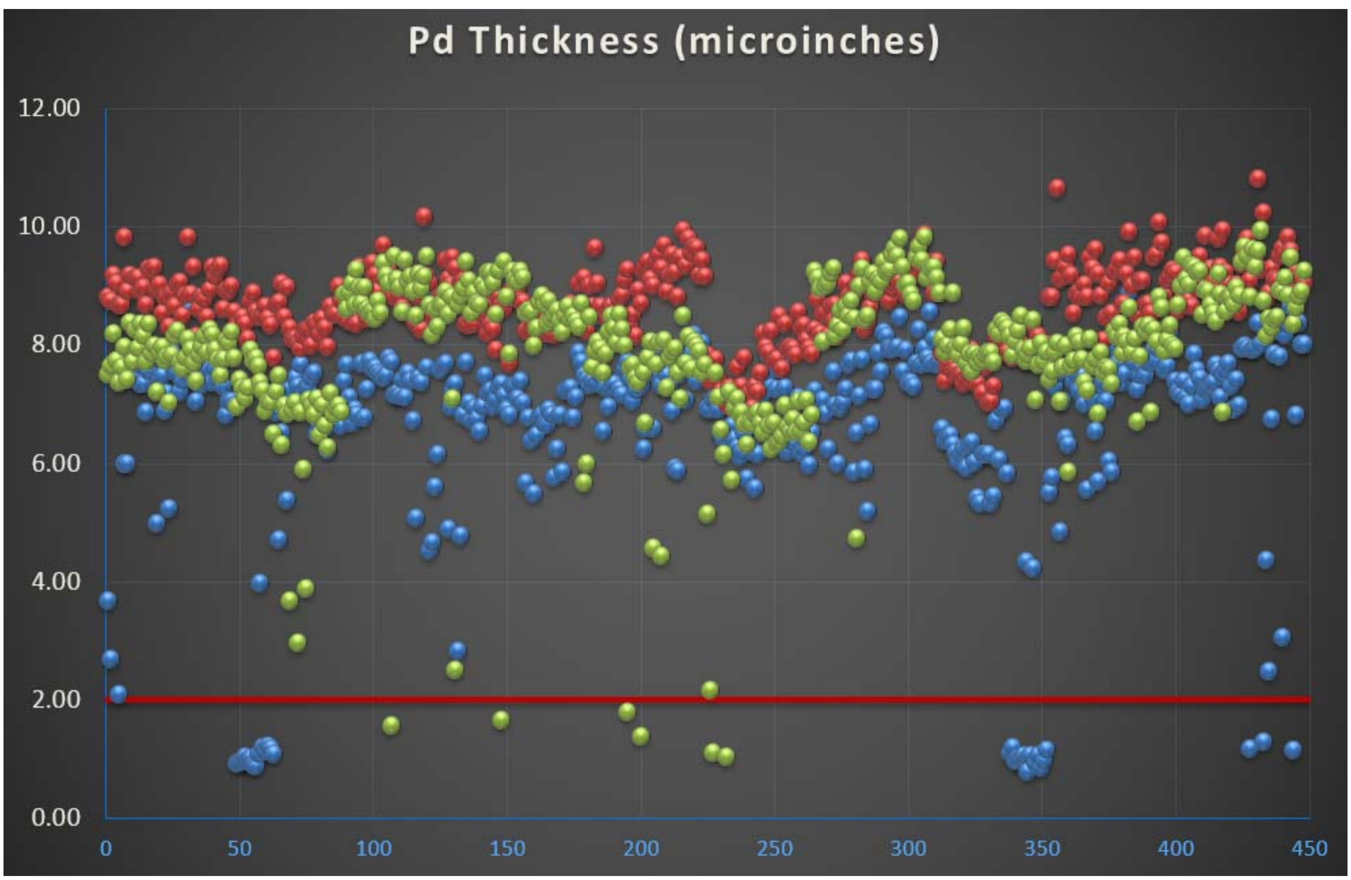


Figure 2. Palladium thickness measurements (color indicates each vendor)

increase the quantity of data points for the shear test, and to limit the number of solder joints which will limit the shear force required to remove the part.

The test vehicles (24 total) were separated into 4 sets, with three of these sets going to three separate vendors (each of which used a different plating chemistry) for application of the ENEPIG finish, and the remaining set coated with HASL (control set). Once returned, the PBs were subjected to XRF for measurement of the tri-metal layer thicknesses. The data from these measurements is shown in Figure 2 (each vendor represented by a different color.)

A stencil of 3 mil thickness was used for solder paste application. The apertures of the stencil were matched to the PB pads (as designed) at 14.8 mil diameter. Half of the assemblies were soldered using Sn63Pb37 solder of type 3 with RMA flux. The remainder of the assemblies were soldered using Sn62Pb36Ag2 solder of similar type and flux content.

RESULTS

Fabrication of the test vehicles was completed and it was determined that the solder mask thickness was greater than desired (approximately 3.5-4.5 mil compared to 1.0 mil pad thickness). This was discovered during PB fabrication, as the thickness of the solder mask interfered with board electrical testing and the HASL process. Additional boards were fabricated with thinner solder mask to enable the HASL process on the control units. PBs with ENEPIG surface finish were not replaced.

Table 1. Shear Test results

			Shear Load (lb)			
S/N	Finish	Solder	1	2	3	4
1001	ENEPIG 1	SnPb	12.6	9.8	11.2	13.5
1004	ENEPIG 1	SnPbAg	10.7	7.9	12.7	13.8
1007	ENEPIG 1	SnPb	13.5	13.3	12.0	13.9
1010	ENEPIG 1	SnPbAg	7.5	17.6	13.2	7.1
1013	ENEPIG 2	SnPb	11.1	15.3	13.3	12.6
1016	ENEPIG 2	SnPbAg	11.7	16.0	15.5	8.9
1019	ENEPIG 2	SnPb	13.6	13.4	13.1	6.8
1022	ENEPIG 2	SnPbAg	11.9	14.0	8.8	7.5
1025	ENEPIG 3	SnPb	14.2	10.2	10.7	6.4
1028	ENEPIG 3	SnPbAg	15.5	8.9	9.5	7.3
1031	ENEPIG 3	SnPb	15.9	7.1	10.9	13.2
1034	ENEPIG 3	SnPbAg	15.9	6.0	7.6	7.0
1061	HASL	SnPb	18.8	19.2	15.8	16.1
1064	HASL	SnPbAg	18.6	21.3	14.9	12.3
1069	HASL	SnPb	19.1	19.2	14.5	17.6
1071	HASL	SnPbAg	15.7	12.2	11.3	8.5

XRF measurements were taken on the PBs at 26 locations on each board and at 20 locations on additional test coupons. These measurement locations were located on both sides of the PB, and it was found that some of the Pd layer

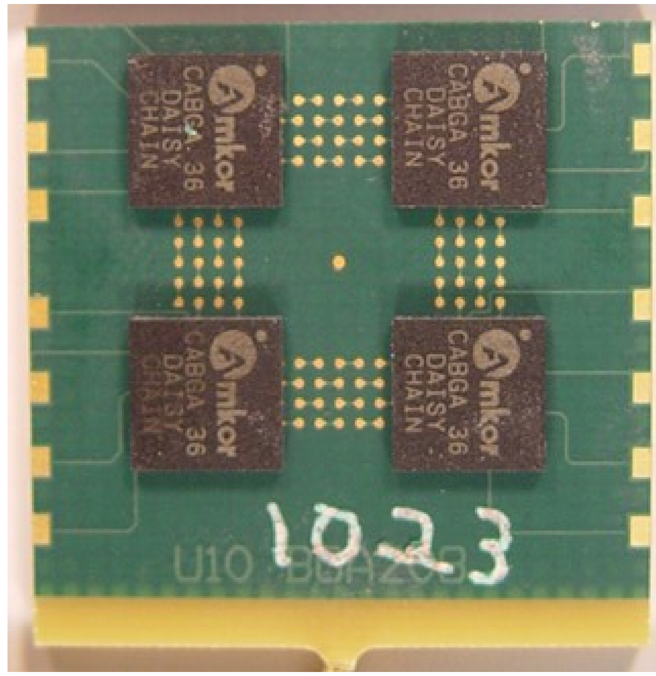


Figure 3. Test sample containing LGA36 (4 components per test sample) prior to shear test

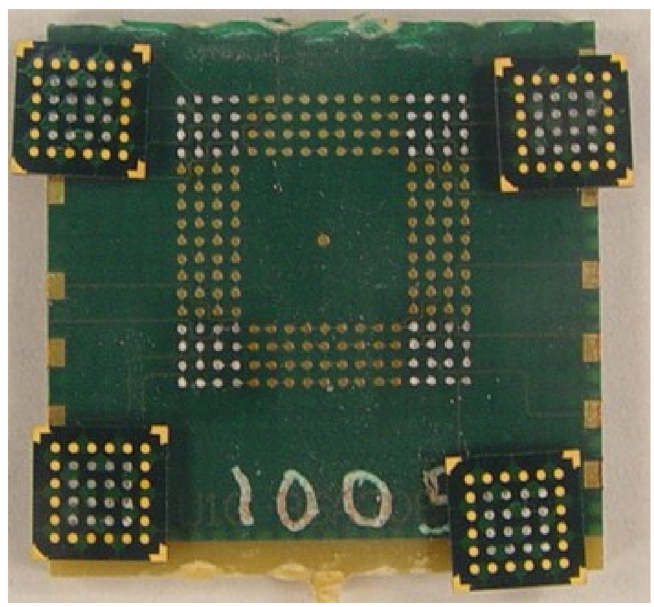


Figure 4. Sample after components have been removed through shear test

thicknesses did not meet the IPC-4556 specification requirements. In a typical production run, each board may not be measured, but a sample would be taken. Samples are collected over time and a standard deviation is calculated; this standard deviation is used to determine if the process is in control per the standard, along with the individual measurements. In our testing, multiple locations on every board were measured, so the data itself is compared to the specification limits without consideration of standard deviations.

Assembly of the test units was completed with SnPb or SnPbAg solder, then each component was removed by applying force to the component edge at a speed of 0.5 in/min. (See Figures 3 and 4) The force required to remove the test parts is given in Table 1. The shear strength values for the samples with ENEPIG finish were lower than those on HASL. For all finishes, there was a mixture of bulk solder fracture and pad lifting. For HASL, the fracture occurred in the bulk solder 18% of the time (the remaining portion resulted in pad lifting), while for ENEPIG pad lifting occurred about 35% of the time, with the remaining failures predominantly exhibiting bulk solder failure, and some instances of brittle fracture (approx. 3%) at the PB pad.

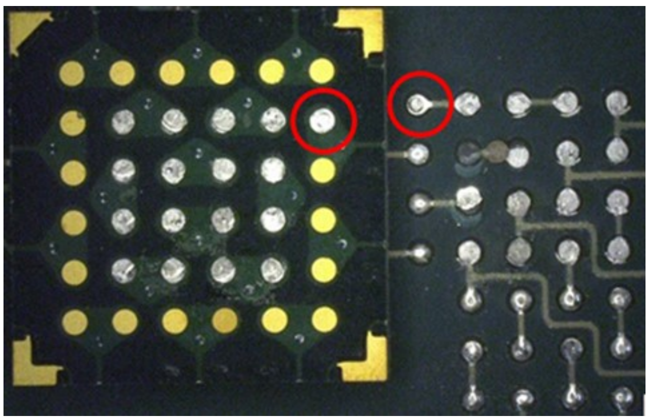


Figure 5. Example of HASL unit removed in shear test with 'extra' solder joint

The average shear strength for ENEPIG in this test was 11.5 lbs. and the average shear strength for the HASL samples was 16.0 lbs. While the difference in these results initially appear to be significant, two factors are important to comparing these values. The first is that in some cases, there was an extra solder joint that formed outside of the intended 4 x 4 array. This only occurred on the HASL boards, and is

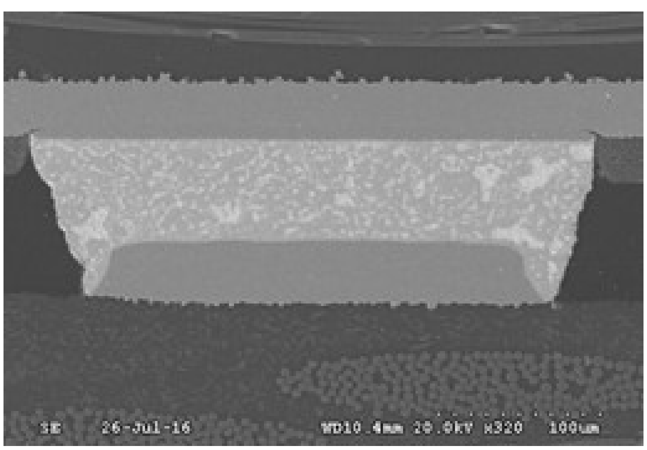


Figure 6. Cross section of solder joint on HASL

attributed to an excess amount of solder from the HASL process on the pad, which was enough to solder to the part. These connections varied from relatively little connection between the PB and component to 'full' solder joints similar to those within the 4 x 4 array. Table 1 indicates the locations where an extra solder joint occurred with values in red. Cells of this table highlighted in orange indicate that some or all of the pads lifted at that test site. The average of the shear strength values for HASL samples that did not contain any extra solder joints was 15.2 lbs., but this significantly limits the sample size.

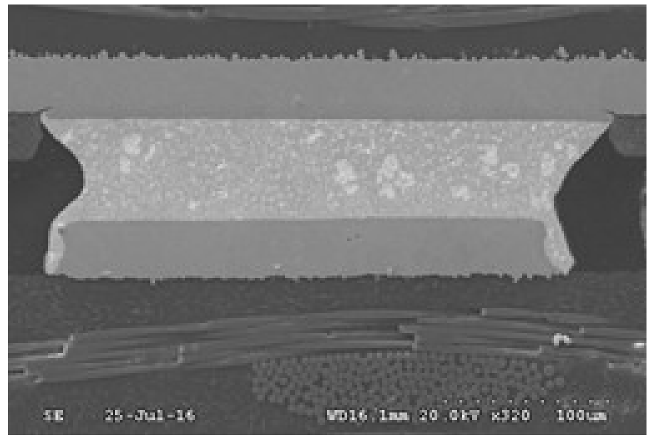


Figure 7. Cross section of solder joint on ENEPIG

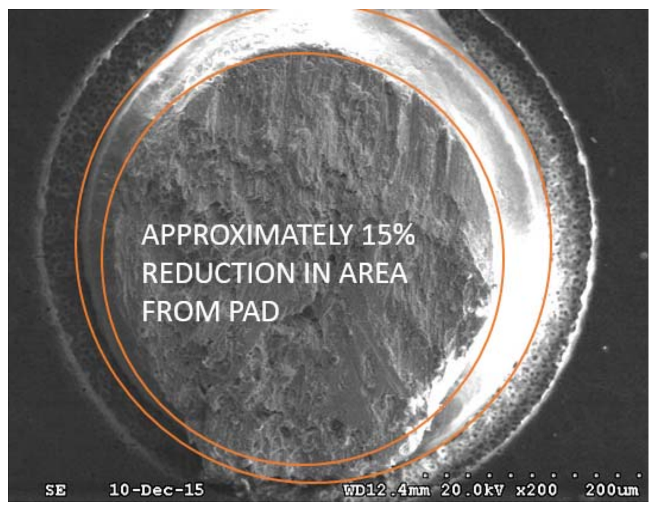


Figure 8. Shear fracture surface of ENEPIG sample with ductile fracture surface

The second factor impacting the shear test results is observed in a comparison of the cross sections from an ENEPIG sample and a HASL sample. On the ENEPIG units, the excess thickness of the solder mask previously identified prevented the parts from sitting as low as they would have otherwise. This caused the solder joints to form an hourglass shape (see Figure 7). The shape provided a smaller cross section at the middle, which reduced the overall strength of the solder joint. This reduction was in the range of 10-20%. Figure 8 shows a typical 15% reduction in solder joint cross sectional area at the fracture point. A reduction in fracture cross-sectional area due to the solder joint geometry contributed a considerable portion of the difference between HASL and ENEPIG in shear strengths. The combination of thinner solder mask and additional solder from the HASL process resulted in a different solder joint geometry on the HASL units.

Table 2. Shear Test results (lbs.) after Isothermal aging

			Shear Load (lb)			
S/N	Finish	Solder	1	2	3	4
1002	ENEPIG 1	SnPb	14.6	15.1	13.3	
1005	ENEPIG 1	SnPbAg	11.2	14.6	9.8	12.4
1008	ENEPIG 1	SnPb	15.0	14.3	16.0	16.1
1011	ENEPIG 1	SnPbAg	14.2	16.5	13.4	9.6
1014	ENEPIG 2	SnPb	16.7	15.0	15.3	
1017	ENEPIG 2	SnPbAg	14.6	15.2	15.4	14.3
1020	ENEPIG 2	SnPb	16.3	12.1	14.5	14.5
1023	ENEPIG 2	SnPbAg	15.6	15.3	15.4	11.1
1027	ENEPIG 3	SnPb	11.4	9.5	9.5	
1029	ENEPIG 3	SnPbAg	16.7	14.9	15.8	11.2
1032	ENEPIG 3	SnPb	15.9	15.3	15.8	13.2
1035	ENEPIG 3	SnPbAg	13.4	15.5	12.8	13.4
1062	HASL	SnPb	19.9	19.7	19.6	
1067	HASL	SnPbAg	15.8	19.7	20.5	14.9
1072	HASL	SnPb	19.4	22.1	21.9	17.2
1070	HASL	SnPbAg	19.6	19.4	19.6	20.5

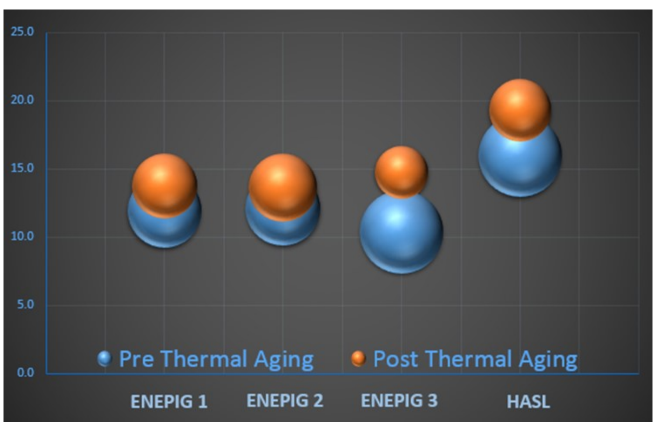


Figure 9. Shear force of failure (lbs.) for each surface finish prior to and after thermal aging. The size of each bubble indicates the standard deviation of the data for that group

A second set of test units for all surface finishes was aged at 100°C for 10 days. Results for these units in shear testing were similar, with several consistent differences from the initial shear testing. The force required to shear the parts increased slightly for each surface finish, the standard deviation of values went down slightly in each group, and there was a significant reduction in the number of lifted pads. The incidence of pad lifting dropped from 50% to 3%. These values are based on the number of individual pads lifted rather than the locations indicated in Tables 1 and 2 (identified by highlighted cells.) It is expected that this is a result of further curing of the PB to improve pad adhesion. Remaining failures on the HASL samples were exclusively ductile failures in the bulk solder again.

When the solder type is considered, SnPbAg solder had a lower force at failure relative to SnPb (11.8 vs. 13.4 lbs.) After thermal aging, the average shear values relative to solder alloy both increased, but SnPb still demonstrated a slightly higher strength (15.1 lbs. for SnPbAg vs 15.7 lbs. for SnPb.)

In both the pre-thermal aging samples and the post-thermal aging samples, there were some instances of brittle facture on the ENEPIG units. Some of the brittle fractures were associated with each of the three ENEPIG surface finishes. The proportion of this failure mode was very low at about 3% regardless of thermal exposure, although the occurrence of brittle failure on the post-thermal samples was limited to two part locations, and was associated with lifted pads at each of those locations.

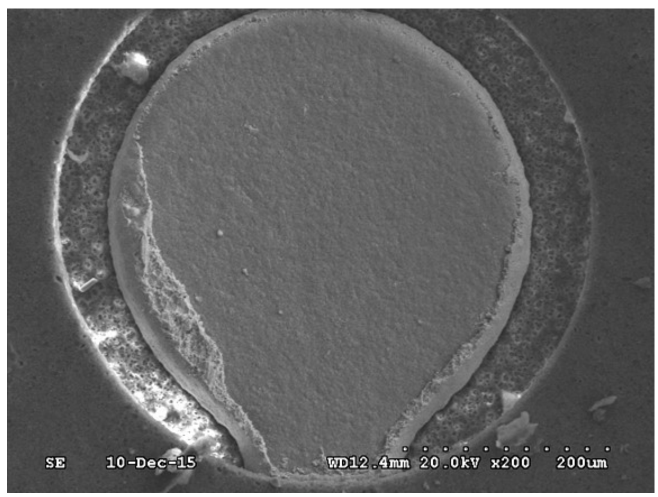
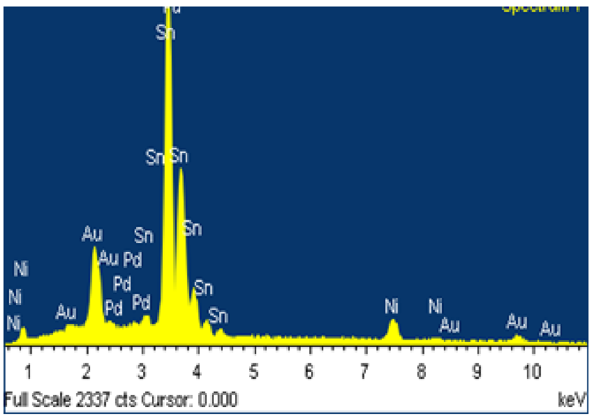


Figure 10. Brittle fracture surface on PB pad with small amount of solder remaining around perimeter

Several locations of brittle fracture on the ENEPIG samples were selected for further evaluation. Analysis of the PB pad surface using EDS indicates that the remaining surface is predominantly nickel, with a small amount of tin. The material exposed on the solder joint side of the fracture surface was measured to have a high level of tin, but also up to 0.79% by weight Pd and 17.5% by weight Au (as well as low levels of Pb and Ni.) These values varied based on the area selected (see Figure 11 for an example.). Analysis of an overall solder joint in cross section showed 0.5% by weight Pd and 3.3% by weight Au. Considering the volume of solder that was applied to the joint, this level of overall Pd is consistent with the Pd layer thicknesses measured on the PBs, but the level of Au is higher than expected.

Element	Weight %	Atomic %
Ni K	9.75	18.81
Pd L	0.79	0.84
Sn L	76.10	72.66
Au M	13.37	7.69



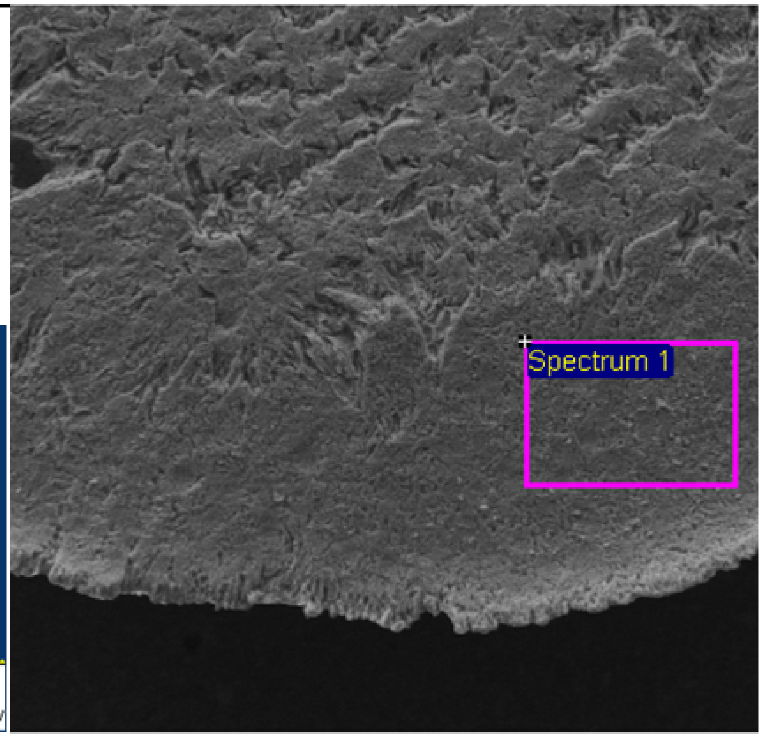


Figure 11. Cross section and EDS analysis of brittle fracture surface (solder side)

It was anticipated that the part had an ENIG finish, which would add only a small amount of gold to the solder joint and which, in combination with the Au present on the PB, would not be a major factor to integrity of the joint. Actual measurements of the part, however, indicated that it had a thicker gold finish (14.3 – 15.5 µin), which resulted in the higher level of gold in the final solder joint. The high level of gold measured at the fracture surface indicates that could have played a role in the brittle nature of the failure.

CONCLUSIONS

The thick solder mask present on the PBs in this test not only had an impact on the solder joint geometry, it also had an apparent impact on solder volume applied during the card build, which affected the resulting metal content of the solder joints. This resulted in a lower level of Pd than originally intended for this study. As expected, the Pd formed a lamellar intermetallic with the Sn in the solder, but did not create a continuous layer due to the limited amount of Pd.

Incomplete curing of the PB appears to have contributed significantly to lifted pads in the unaged test samples, and brittle fracture of the solder joints on ENEPIG was often associated with those lifted pads. Isothermal aging of the test samples decreased the occurrence of both lifted pads (on both HASL and ENEPIG samples) and brittle fracture failure (on ENEPIG samples). It should be noted, however, that bulk solder failures on the ENEPIG samples occurred at the narrow point of the solder joint (the middle of the hourglass shape), and this solder joint geometry may have an impact on the failure point.

The results confirm that the shear strength of SnPb solder joints on ENEPIG is similar to that of solder joints on HASL (when the results of this study are adjusted for solder joint geometry.) The specific cause of the brittle fracture on ENEPIG, however, was not determined in this study, and so the influence of the Pd content is not known.

The use of a Ag bearing solder had a small impact of shear strength, but there was not a significant difference of this impact when HASL and ENEPIG are compared.

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