Performance and Reliability Evaluation of Alternative Surface Finishes For Wire Bond and Flip Chip BGA Applications

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Abstract

Due to the increased functionality of electronic devices and competitive nature of the electronics industry, there is a continuing trend toward miniaturization of circuit geometries and an ongoing need for more cost-effective processes. This is especially true for hand-held devices, where the increase in wiring density is leading to a higher use of state-of-the-art semiconductor components. All of these issues, combined with the recent Pb-free initiatives, are challenging the traditional manufacture processes for IC substrates. As a result, alternative surface finishes are receiving increased attention from fabricators of IC substrates, as well as from many OEMs in the various electronics sectors. Because of these driving forces, a comprehensive evaluation of alternative surface finishes for both wire-bond and flip chip BGA applications was undertaken.

Phase 1 of the investigations involved evaluation of several alternative surface finishes in comparison to the “process of record” for both wire-bond and flip chip applications. Both eutectic and Pb-free solder were used for this evaluation. Reliability testing was performed in accordance were applicable to JEDEC standards and involved two basic types of package: gold wire-bonded 35-mm PBGA and 40-mm FPBGA. For the wire-bonded PBGA package, two surface finishes were examined: (1) electrolytic nickel / electrolytic gold (process of record) and (2) electroless nickel / electroless palladium / immersion gold, which is the so-called ‘universal’ finish. Results of wire-bond pull tests are presented. Surface finishes investigated for FPBGA substrates were (1) electroless nickel (with medium-P content) / immersion gold, which is the process of record, (2) electroless nickel (with high-P content) / immersion gold, (3) electroless nickel / electroless palladium / immersion gold, (4) electroless palladium, (5) immersion silver, (6) immersion tin, (7) direct gold and (8) Solder on Pad (OSP-finish). The reliability investigations for FPBGA packages include ball shear testing, cold ball pull testing and SEM analysis. Based on these results, further investigations are planned in Phase II and Phase III, including four-point bend testing, followed by package-level reliability and finally by board-level reliability examinations. This paper will present the findings and conclusions resulting from Phase I of these investigations.

Background

The semiconductor die connection to the IC substrate utilizes a metal-to-metal connection. There are two basic methods to achieve this connection, wire bonding (Aluminum or Gold) or solder bumps deposited on metalized C4 pads. On the reverse side of the package, the connection utilizes a solder ball that joins metalized pads on both the IC substrate and the PWB.

In the case of wire bonding, the industry-standard pad finish has been electrolytic gold over electrolytic nickel. Although proven to be a reliable substrate bonding surface, there are technical issues such as variations in plating thickness and fabrication difficulties regarding electrical bussing, especially as wiring density is increasing. An alternative surface finish that has been used is electroless gold over electroless nickel / immersion gold. The driving force for this finish is its suitability for finer bond pad pitch applications and elimination of electrical bussing issues. Furthermore, the electroless gold bath can be aggressive to solder masks and there are related concerns regarding gold-to-gold adhesion. Of course, the cost-effectiveness of either process is an issue because of the associated precious metal consumption. As such, the packaging industry is seeking an alternative that meets both the performance and cost requirements.

For flip chip applications, the conventional ENIG process has been a commonly accepted methodology. However, excessive nickel corrosion caused by uncontrolled attack from the immersion gold step has been a source of reliability concerns. In this case, the solution is either the use of a more resistant nickel deposit or less aggressive gold bath to minimize gold corrosion or the use of an alternative surface finish.

This report summarizes the findings and conclusions from the first phase of a joint project between Atotech, Amkor and LSI Logic. The overall objective of the project is to evaluate reliability of several different surface finishes for both wire bond and flip chip BGA applications with the intention of maintaining or improving performance while achieving manufacturing cost reductions. Because of functional requirements, reliability testing included wire pull testing, ball bond shear testing, solder ball shear testing and cold ball pull testing.

Experimental Procedure

The test protocol included examinations of both wire-bonded and flipchip BGA packages. Wire-bond BGA testing was performed on a 35-mm 492 PBGA. Flip chip BGA testing was performed on a 40-mm 1413 FPBGA. Figure 1 shows examples of these two package types.

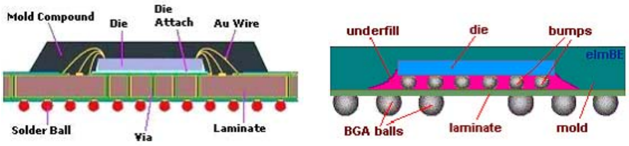


Fig. 1 Example cross-sections of PBGA (left) and FPBGA (right) package types

Alternative surface finishes were selected for investigation dependent upon the construction and assembly requirements for the two package types.

Wire Bond BGA Experimental Procedure

Two alternative surface finishes were examined with respect to wire bond BGA performance. The surface finish currently used as the "process of record" (POR) is electrolytic nickel / electrolytic gold. The second surface finish is comprised of electroless nickel / electroless palladium / immersion gold. Table 1 presents a summary of the surface finish specifications for the two deposits.

Table 1 – Deposit Specifications for Wire Bond BGA Investigations

Test Leg and Finish		Deposit	Thickness
1	El Ni/El Au (POR)	Electrolytic Ni Electrolytic Au	6.0 µm 0.7 µm
2	Ni/Pd/Au	Electroless Ni Electroless Pd Immersion Au	6.0 µm 0.1 µm 0.04 µm

+ Target thickness, actual deposit thickness may vary slightly

A summary of the testing performed on the wire bond packages is presented in Table 2.

Table 2 – Wire Bond BGA Test Matrix

Test Description	Sample Size per Finish	
Wire pull	10 packages	20 per package
Ball bond shear	10 packages	20 per package
Solder ball shear	2 packages	25 per package

Flip Chip BGA Experimental Procedure

Eight different surface finishes were examined with respect to performance of flip chip BGAs. The currently used process or record (POR) is an electroless nickel / immersion gold deposit, where the target thickness of the electroless nickel layer is 5.0 µm and includes a co-deposited phosphorus content of 6-7 percent by weight. The target thickness of the immersion gold layer in the current process is 0.05 µm. In addition to the process-of-record finish, the seven alternative finishes that were examined are as follows:

- Solder on Pad with Organic Solderability Preservative (SOP-OSP)
- Electroless nickel / immersion gold (High-P ENIG)
- Electroless Palladium
- Direct Gold
- Electroless nickel / electroless palladium / immersion gold (Ni/Pd/Au)
- Immersion Tin
- Immersion Silver

Table 3 presents a summary of the deposit specifications for the eight alternative surface finishes examined during ball shear and cold ball pull testing.

.Table 3 – Deposit Specifications for Flip Chip BGA Investigations

Test Leg and Finish		Deposit	Thickness^{+}
1	ENIG (POR)	Electroless Ni Immersion Au	5.0 µm 0.05 µm
2	SOP-OSP	Organic coating	0.2-0.5 µm
3	ENIG (high-P) (9% P by wt.)	Electroless Ni Immersion Au	6.0 µm 0.05 µm
4	Palladium	Electroless Pd	0.1 µm
5	Direct Gold	Immersion Au	0.05 µm
6	Ni/Pd/Au	Electroless Ni Electroless Pd Immersion Au	6.0 µm 0.1 µm 0.04 µm
7	Immersion Tin	Immersion Sn	1.2 µm
8	Immersion Silver	Immersion Ag	0.2 µm

+ Target thickness, actual deposit thickness may vary slightly

For each surface finish, testing consisted of five packages assembled with eutectic solder balls and five packages with Pb-free solder balls. For these investigations, the alloy of the Pb-free solder ball was Sn3.0Ag 0.5Cu (SAC305). A summary of the test matrix for the flip chip packages is presented in Table 4.

Table 4 – Flip Chip BGA Test Matrix

Test Description	Sample Size per Finish	
Solder ball shear	5 packages	20 per package
Cold ball pull	5 packages	20 per package

All FPBGA samples were subjected to artificial thermal conditioning prior to second level ball attachment. The purpose of this exercise was to simulate the standard construction sequence of the FPBGA. This thermal conditioning sequence is shown in Figure 2.

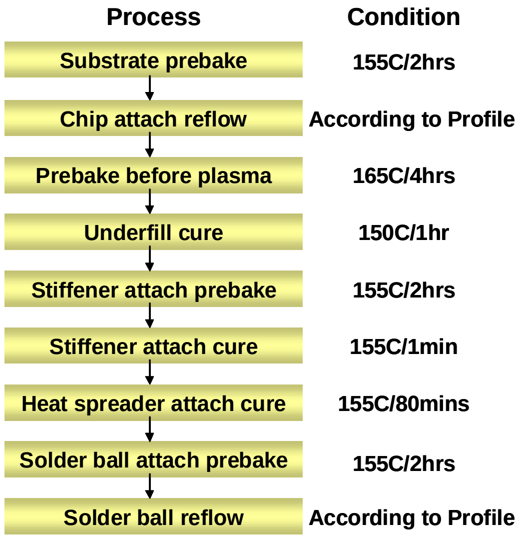


Fig. 2 FPBGA die attach process sequence for simulating surface finish thermal excursions

Wire Bomd PBGA Package Investigations

A summary of important parameters for the testing of wire bond BGA packages is presented in Table 5. The equipment used for wire pull and ball bond pull testing is shown in Figure 3.

Table 5 – Wire Bond Package Test Parameters

IC Package Type	35mm 492 PBGA
Wire Bonder Make/Model	K&S Maxµm
Wire Supplier/Type	Hereaus/Au-Beta (99.99%)
Wire Diameter	30 µm
Bonder Operating Conditions	165 °C, 120 kHz
Wire Pull Test Equipment	Dage Series 3000
Solder Ball Shear Test Equipment	Dage Series 4000

Fig. 3 Dage Series 3000 Wire Pull Tester (left) and Dage 4000 Solder Ball Shear Tester (right)

Wire Pull Test Results

A summary of the results of wire pull tests that were performed with the two surface finishes is shown in Table 6.

Table 6 – Summary of Gold Wire Pull Test Results (Wire bond PBGA)

Description	El Ni/ El Au	Ni/Pd/ Au
Average Pull (g)	8.79	8.76
Minimum Pull (g)	7.80	7.82
Maximum Pull (g)	10.27	9.98
Average Standard Deviation* (g)	0.46	0.55
Average Range, min to max* (g)	1.54	1.78
Average CPk*	2.10	1.70

* Average for ten test runs of 20 tests per run

As noted previously, ten groups of 20 test pulls were performed for both surface finishes, totaling 200 wire pulls per finish. The pass / fail criterion for wire pull strength is 6.0 grams, which all test results exceeded. Overall, the performance of the two finishes was very comparable.

The average pull strengths for the electrolytic nickel / electrolytic gold and the Ni/Pd/Au finishes were 8.79 grams and 8.76 grams, respectively. Likewise, the average minimum and average maximum pull strengths were also quite comparable. Figure 4 shows a chart for the average pull strength of each test group, where each point represents the average of 20 test pulls for a particular surface finish.

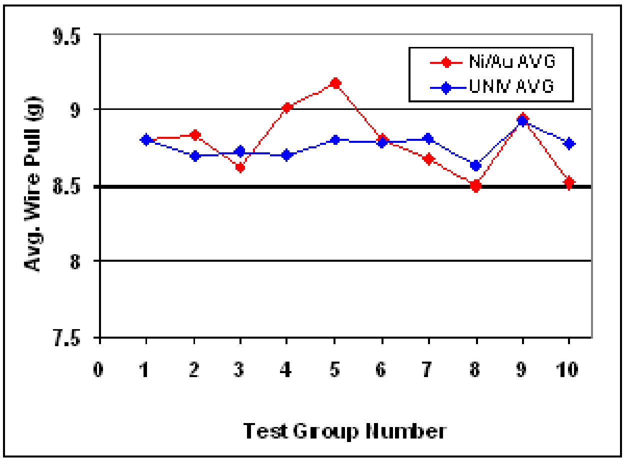


Fig. 4 Average wire pull forces for electrolytic nickel / gold vs. Ni/Pd/Au finish

The average wire pull strength for the Ni/Pd/Au finish was comparable to results for the electrolytic nickel / electrolytic gold (POR) surface. As shown, the Ni/Pd/Au finish also showed considerably less variation in average pull force throughout the test cycle. Previous investigations have been documented that support the use of the Ni/Pd/Au surface finish for wire bonding applications.[1]

Ball Bond Shear Test Results

In conjunction with the wire pull investigations, gold ball bond shear tests were also performed. Table 7 shows a summary of results of these investigations for the two different surface finishes. The pass/fail criterion for ball bond shear strength is 25.0 grams, which all test results exceeded. In this case, the Ni/Pd/Au surface provided better bonding results in terms of average, minimum and maximum ball bond shear force.

Table 7 – Summary of Ball Bond Shear Test Results

Description	El Ni/ El Au	Ni/Pd/ Au
Average Pull (g)	32.16	38.39
Minimum Pull (g)	28.14	35.21
Maximum Pull (g)	35.94	40.88
Average Standard Deviation* (g)	1.15	1.01
Average Range, min to max* (g)	3.94	3.32
Average CPk*	3.32	4.62

* Average for ten test runs of 20 tests per run

Figure 5 compares the average result for each of the ten test groups. As shown, the average ball bond shear force for the Ni/Pd/Au finish was higher and more consistent than that of the electrolytic nickel / electrolytic gold (POR) surface. However, it is important to note that all fractures were ductile in nature and sheared within the gold ball and no failures at the bond interface were noted for either finish.

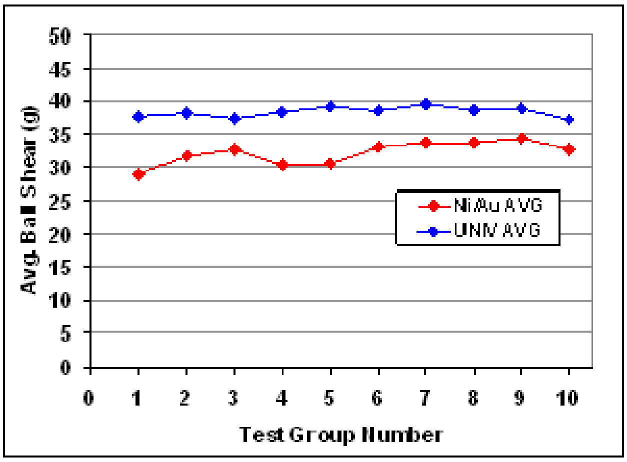


Fig. 5 Average ball bond shear forces for electrolytic nickel/gold vs. Ni/Pd/Au finish

Solder Ball Shear Test Results

In addtion to wire pull and gold ball bond shear testing, for each surface finish solder ball shear testing was also performed on two wire-bond PBGA packages, with a total of 25 solder balls sheared on each package. Table 8 presents a summary of the solder ball shear test results for the two surface finishes. The pass / fail criterion for ball bond shear strength is 1,000 grams, which all test results exceeded. Previous investigations have supported the suitability of the Ni/Pd/Au surface for both eutectic and Pb-free assembly.[2]

Table 8 – Summary of Solder Ball Shear Test Results

Description	El Ni/ El Au	Ni/Pd/Au
Average Pull (g)	2,123	1,903
Minimum Pull (g)	1,396	1,283
Maximum Pull (g)	2,379	2,235
Average Standard Deviation (g)	139	126
Average Range, min to max (g)	610	667
Average CPk	4.36	2.92

Figure 6 shows representative examples of microscopic photographs of the sheared solder ball on both surface finishes examined. All sheared solder balls exhibited ductile failure and no occurrence of bond interface failure was noted.

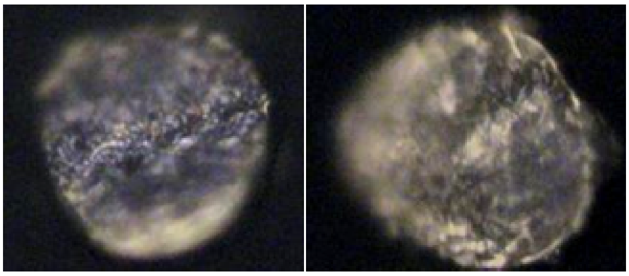


Fig. 6 Example of solder ball shear interface for El Ni/El Au (left) and Ni/Pd/Au (right)

Flip Chip PBGA Package Investigations

As noted previously, examination of flip chip BGA performance reliability consisted of solder ball shear and cold ball pull testing.

Solder Ball Shear Testing

For each of the eight surface finishes, ball shear investigations included the testing of 20 eutectic and 20 Pb-free solder balls per substrate on five different substrates (100 ball shear tests) per surface finish. All testing was performed in accordance with the OEM specifications.[3] A summary of important parameters for the testing of flip chip BGA packages is presented in Table 9.

Table 9 – Solder Ball Shear Test Parameters

IC Package Type	40 mm 1413 FPBGA-HP
Equipment	Dage 4000
Ball shear speed	300 µm/sec ±30 µm/sec
Solder mask opening	510 µm
Solder ball diameter	600 µm
Solder ball composition	Eutectic and Pb-free

A 600-µm diameter solder ball was used for both eutectic and Pb-free testing. All pads were solder-mask defined with an opening of 510 µm. Ball shear was performed at a speed of 310 µm/sec. An illustration of the ball shear test is presented in Figure 7.

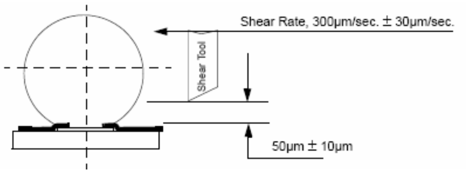


Fig. 7 Illustration of ball shear test mechanism

Figure 8 shows the location of the 20 solder balls on the test substrate. As shown, balls 1 through 4 are located at the remote corners of the grid array and the remaining 16 balls are located diagonally toward the center of the package.

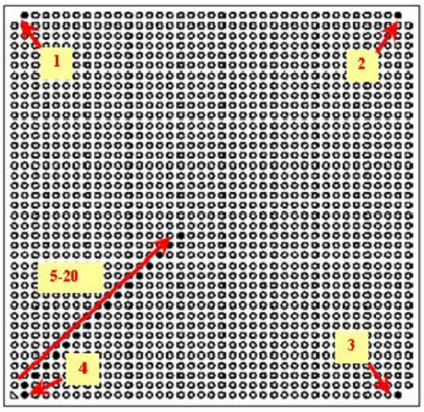
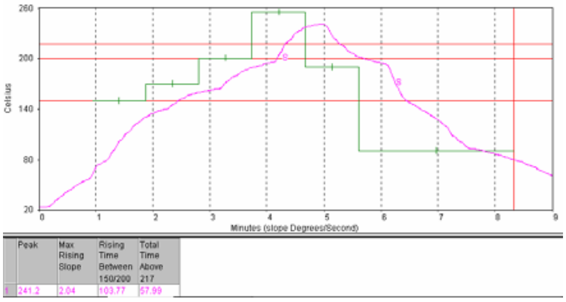


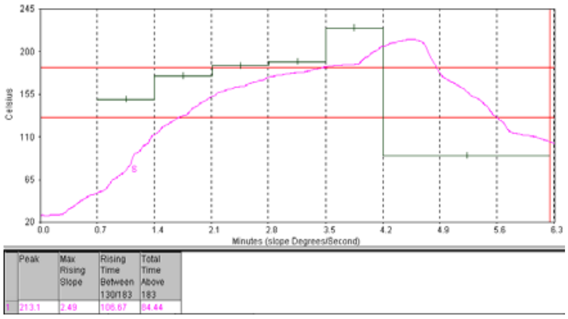
Fig. 8 Location of solder balls for ball shear test

Figure 9 presents the reflow profile used for the eutectic solder balls. As shown, the profile includes a peak temperature of 213°C and a time above liquidus of approximately 84 seconds. By comparison, Figure 10 shows the reflow profile used for the Pb-free solder balls, where the peak reflow temperature was 241°C and the time above liquidus was approximately 58 seconds.



	Peak	Max Rising Slope	Rising Time Between 150/200	Total Time Above 217
1	241.2	2.04	103.77	57.99

Fig. 10 Reflow profile for Pb-free solder ball attachment.



	Peak	Max Rising Slope	Rising Time Between 130/183	Total Time Above 183
1	213.1	2.49	106.67	84.44

Fig. 9 Reflow profile for eutectic solder ball attachment.

Ball shear failures were categorized according to the type and location of fracture. Figure 11 illustrates the location of the five different fracture modes within the solder ball joint. For ball shear, the preferred type of fracture occurs entirely within the solder ball. Brittle fracture occurs at the interface between the solder and the surface finish, often in some combination with shearing of a portion of the solder.

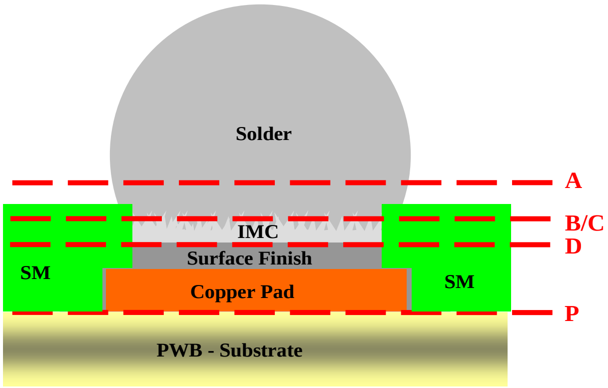


Fig. 11 Illustration of ball shear fracture modes and location within the solder ball joint

The guidelines for qualifying the five types of ball shear failures are as follows:

- Mode A: More than 95% within the solder
- Mode B: 75-95% within solder, remainder interfacial
- Mode C: 5-25% within solder, remainder interfacial
- Mode D: More than 95% within interface
- Mode P: Pad pull-out

As shown, failure types B and C occur with varying levels of interfacial fracture. Figure 12 presents microscopic photographs of sheared solder balls, showing examples of fracture Types A, B, C and D, described above.

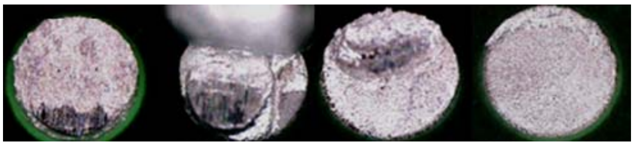


Fig. 12 Examples of ball shear fracture type showing from left to right Modes A, B, C and D

Ball Shear Test Results – Eutectic Solder Balls

Table 10 shows a summary of the ball shear test results for eutectic solder balls, representing 100 individual ball shear tests for each surface finish. Figure 13 presents a chart that summarizes results of shear testing of eutectic solder balls, showing the shear forces required for failure of each ball for the eight surface finishes examined. Figure 14 graphically depicts the distribution of fracture modes for each of the test results shown in the previous chart.

Table 10 – Summary of Ball Shear Test Results Eutectic Solder Balls

Test Leg and Finish		**Avg.** (g)	**Std. Dev.** (g)
1	ENIG (POR)	1402	41.2
2	SOP-OSP	1302	34.8
3	ENIG (high-P)	1335	68.7
4	Palladium	871	77.0
5	Direct Gold	1337	35.2
6	Ni/Pd/Au	1268	74.4
7	Immersion Tin	1202	49.3
8	Immersion Silver	1227	25.3

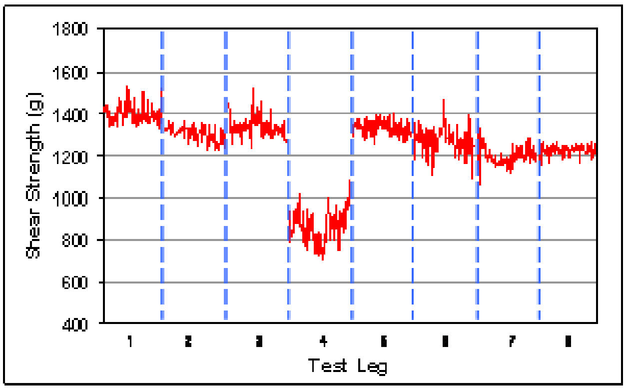


Fig. 13 Comparison of ball shear forces for the eight tested finishes with eutectic solder balls (Leg 1-8).

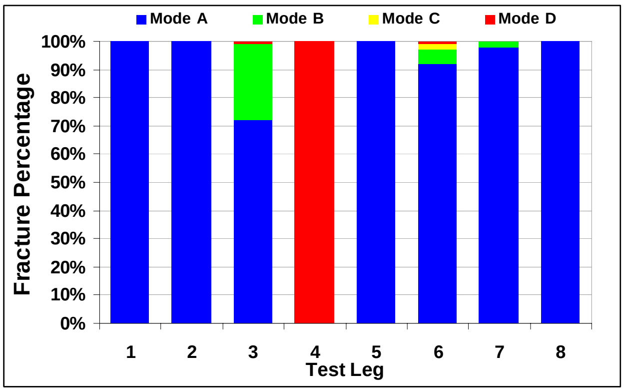


Fig. 14 Comparison of ball shear fracture mode for the eight tested finishes with eutectic solder balls (Leg 1-8).

As the indicated, with the exception of the palladium finish, all test results exceeded the pass/fail criterion for ball bond shear strength of 1,000 grams, although there seems to be more consistency of data for certain finishes. Also, with the exception of the palladium finish (Leg 4) the majority of fractures occurred more than 95-percent within the solder ball (Mode A). All fractures for the palladium finish were bond failures, meaning that more than 95-percent of the bond interface (or IMC) was visible. However, for Test Leg 3 (High-Phosphorus ENIG) nearly 30% of the failures included interfacial fractures with as much as 25% of the IMC visible. In addition, Test Leg 6 (Ni/Pd/Au) and Test Leg 7 (Immersion Sn) showed some signs of interfacial fracture, but to a lesser extent. In addition to the ENIG process of record, both the OSP and direct gold surface finishes also provided good shear strength and a relatively high level of consistency.

Ball Shear Test Results – Pb-free Solder Balls

In similar fashion, Table 11 presents the summary of the solder ball shear test results for Pb-free solder balls. Likewise, Figures 15 and 16 present charts that summarize the shear strength and fracture mode results for Pb-free solder balls.

Table 11 – Summary of Ball Shear Test Results Pb-free Solder Balls

Test Leg and Finish		**Avg.** (g)	**Std. Dev.** (g)
1	ENIG (POR)	1303	66.6
2	SOP-OSP	1328	128.3
3	ENIG (high-P)	1305	73.8
4	Palladium	889	107.2
5	Direct Gold	1270	141.7
6	Ni/Pd/Au	1280	93.3
7	Immersion Tin	1245	122.0
8	Immersion Silver	1251	140.8

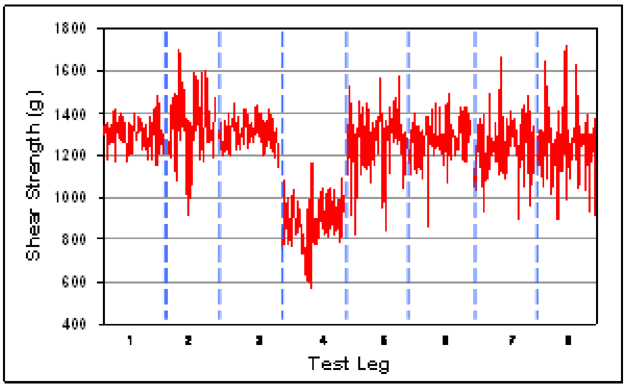


Fig. 15 Comparison of ball shear results for the eight tested finishes with Pb-free solder balls (Leg 1-8).

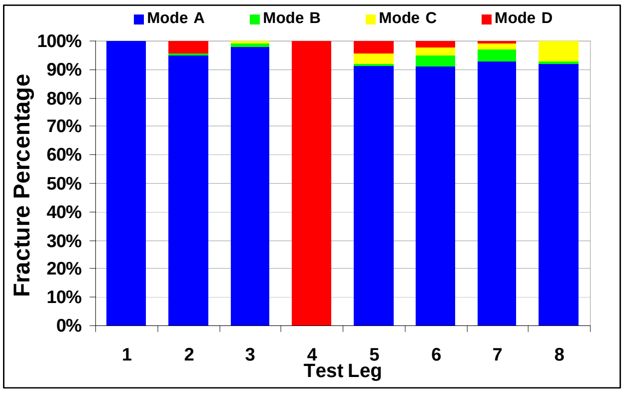


Fig. 16 Comparison of ball shear fracture mode for the eight tested finishes with Pb-free solder balls (Leg 1-8).

Compared to the results for eutectic solder balls, there is a much lower consistency of results for Pb-free solder. In addition, there are numerous cases in which the pass/fail criterion for ball bond shear strength of 1,000 grams is not achieved. As shown in figure 16, only Leg 1, the process of record (ENIG with nickel of medium-P content), resulted in failures entirely of the “A” mode. However, the majority of the failures for the other finishes still occurred more than 95-percent within the solder ball, which is the preferred fracture mode. Again, the shearing of solder balls on the palladium finish resulted in total bond (IMC) failure. Deposited directly over copper, the palladium finish appears to suffer from interfacial voiding more than other finishes. The cause may be attributed to potential reaction of the flux media with palladium generating a volatile compound that is entrapped at the interface during solidification of the solder. This reaction results in interfacial micro-voiding and during ball shear the solder may be sheared with less force across this void plane. As shown in Figure 17, the condition appears to worsen with Pb-free solders, possibly because of the higher reflow temperatures or differences in flux composition.

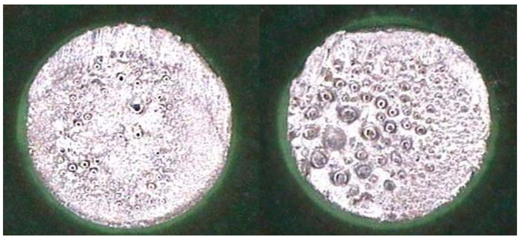


Fig. 17 Examples of ball shear fracture Type D for palladium finish with eutectic solder ball (left) and Pb-free solder ball (right)

It is also interesting to note that surface finishes that included nickel in their deposit (Legs 1, 3 and 6) seemed to exhibit somewhat more consistent results in terms of shear strength, as evidenced by the lower standard deviations shown in the table. This observation may be related to the difference between the nickel/tin IMC in comparison to a copper/tin IMC.

It is further noted that OSP, immersion tin and immersion silver each exhibited a wide inconsistency in shear strength in comparison to their eutectic results. However, since the vast majority of failures were still within the solder ball, this effect must be directly related to the make-up of the Pb-free alloy or the resulting IMC, created after reflow. The high variation in shear strength for this Pb-free solder may have a more significant impact during other types of stress investigations, including 4-point bend test or drop testing.

Cold Ball Pull Testing

Cold ball pull testing is a relatively new technique that the packaging industry is slowly adopting. This method uses a plain tensile load, as opposed to the traditional ball shear test that employs a complex mixture of tensile and compressive loading, which reportedly does not result in consistent failure at the weakest interface.[5] Thus cold ball pull testing should offer better insight to interfacial bond strength in a relatively fast, low cost manner.

However there are still many aspects that need to be investigated such as the interaction of pull speed, solder resist opening and solder ball diameter.

Cold ball pull testing was performed for the eight different surface finishes using a Dage Series 4000. Important test parameters are shown in Table 12.

Table 12 – Cold Ball Pull Test Parameters

Equipment	Dage 4000
Cartridge / Jaws:	CP5KG / 600 µm
Ball pull speed	0.3 and 5.0 mm/sec
Solder mask opening	510 µm
Solder ball diameter	600 µm
Solder ball composition	Eutectic and Pb-free

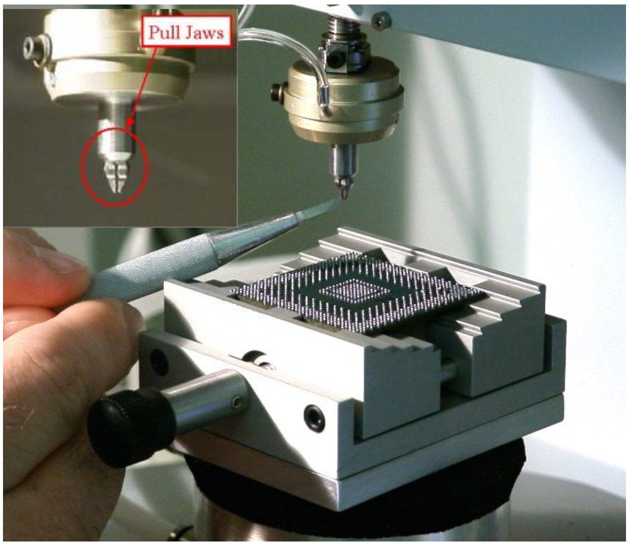


Fig. 18 Detailed views of Dage Series 4000 Cold Ball Pull instrument.

Figure 18 shows a view of the ball pull test device, detailing the mechanism that attaches to the solder balls. Testing was performed “as received” and “after one solder reflow operation”. According to the end-user specification, cold ball pull testing is typically performed within eight hours of ball attachment. However, because of logistic constraints, testing of “as received” samples actually occurred approximately four weeks after ball attachment. Other studies conducted with ball shear testing have shown statistically that room temperature aging and more dramatically accelerated dry-heat aging will decrease ball shear strength values.[4] For cold ball pull testing, the importance of this delay is yet not fully understood. In an attempt to counteract the time delay, an additional reflow was performed with the intention of returning the samples to a state similar to their “just assembled” condition. In reality, the additional thermal cycle did not apparently achieve this desired effect. New investigations would be required to obtain results that meet the end-user definition of “as received”. However, the results as obtained do provide useful information with respect to reliability following several weeks of room-temperature aging and a subsequent thermal excursion (delayed reflow), which, although not intended to serve this purpose, may actually mimic some common assembly rework situations.

Test results were classified according to the failure mechanisms shown in Figure 19.

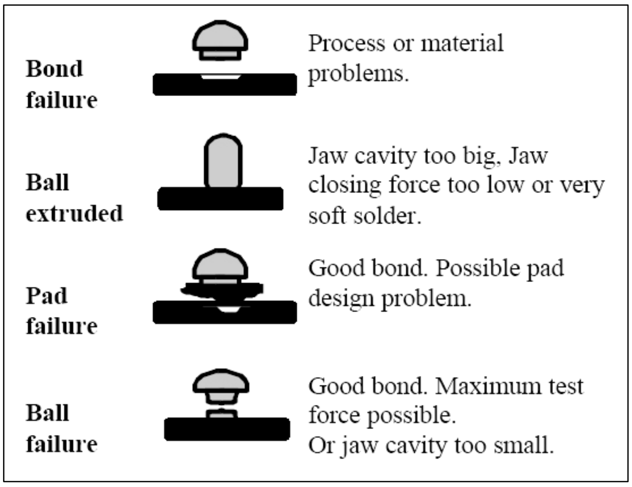


Fig. 19 Illustration of cold ball pull failure mechanisms.

▨ **Mixed Bond/ Pad Failure**
🟥 **Bond Failure**
🟨 **Ball Extrusion**
🟩 **Ball Failure**
🟦 **Pad Failure**

With this information, failure modes were identified according to the following five different categories:

Cold Ball Pull Test Results – As Received

The results of cold ball pull testing performed on samples in the “as received condition” are shown in Figures 20 through 23. For the eutectic solder balls, Figure 20 shows a comparison of the maximum pull strengths achieved for each of the eight surface finishes. Results for both slow-speed pull (0.3 mm/sec) and high-speed pull (5.0 mm/sec) are presented. Figure 21 presents a graphic distribution of the observed failure modes for those same cold ball pull investigations. Similarly, Figures 19 and 20, respectively, show the pull strength and failure mode distributions for the Pb-free solder balls. Again, both slow- and high-speed results are shown.

The following observations are noted with respect to the “as received” cold ball pull results using eutectic solder balls:

- Generally, the slower pull speed (0.3 mm/sec) yielded lower and more consistent pull strength results than the higher speed (5.0 mm/sec) for eutectic solder.
- With eutectic solder balls, several finishes provided similar results in terms of the range and average pull forces. Leg 1 (control ENIG), Leg 2 (OSP), Leg 5 (direct Au), Leg 7 (immersion Sn) and Leg 8 (immersion Ag) produced relatively high and consistent pull strengths. All fracture modes for these test segments were either ball or pad failures.
- Leg 3 (high-P ENIG) and Leg 6 (NiPdAu) exhibited a wider range of pull strength results than Legs 1, 2, 5, 7 and 8. Bond failures represented approximately 15-20% of the Leg 3 results and approximately 35-40% of the Leg 6 results, respectively.
- Again, the electroless palladium finish (Leg 4), in particular, was notable in terms of its relatively low and inconsistent pull strength. Also, all fracture modes were entirely bond failures.

Regarding the “as received” cold ball pull results using Pb-free solder balls, the following observations are noted:

- Again, the slower pull speed (0.3 mm/sec) typically yielded lower and more consistent pull strength results than the higher speed (5.0 mm/sec). However, the average pull strengths were generally higher with the Pb-free solder balls compared to the eutectic balls.
- Particularly for the high-speed ball pull results, Leg 3 (high-P ENIG) and Leg 6 (NiPdAu) exhibited a wider range of pull strength results than Legs 1, 2, 5, 7 and 8.

- The incidence of bond failure was significantly higher with the Pb-free solder balls, in comparison to the eutectic balls. Bond failures represented the majority fracture mode for all surface finishes. The high-speed pull test also yielded a much higher incidence of bond failure in comparison to the slow-speed test.

Cold Ball Pull Test Results–With One Additional Reflow

The results of cold ball pull testing performed on samples with “one additional reflow” are shown in Figures 24 through 27. For the eutectic solder balls, Figure 24 shows a comparison of the maximum pull strengths achieved for each of the eight surface finishes for both slow-speed pull (0.3 mm/sec) and high-speed pull (5.0 mm/sec). Figure 25 presents a graphic distribution of the failure modes for the same cold ball pull investigations performed with eutectic solder balls. Similarly, Figures 26 and 27 show the pull strength and failure mode distributions, respectively, for the Pb-free solder balls after the additional reflow. Again, both slow- and high-speed results are shown.

The following observations are noted with respect to the cold ball pull results “after one additional reflow” using eutectic solder:

- In comparison to the slow-speed pull results for eutectic solder balls, higher average pull strengths were achieved after one additional reflow (Fig. 24). However, there was much less consistency in the results.
- Surfaces that include nickel in their deposit (i.e. Legs 1, 3 and 6) displayed a wider spread of results than the other finishes. Also, with the additional reflow, an increased incidence of bond failures was noted with the eutectic solder balls in comparison to the “as received” samples.

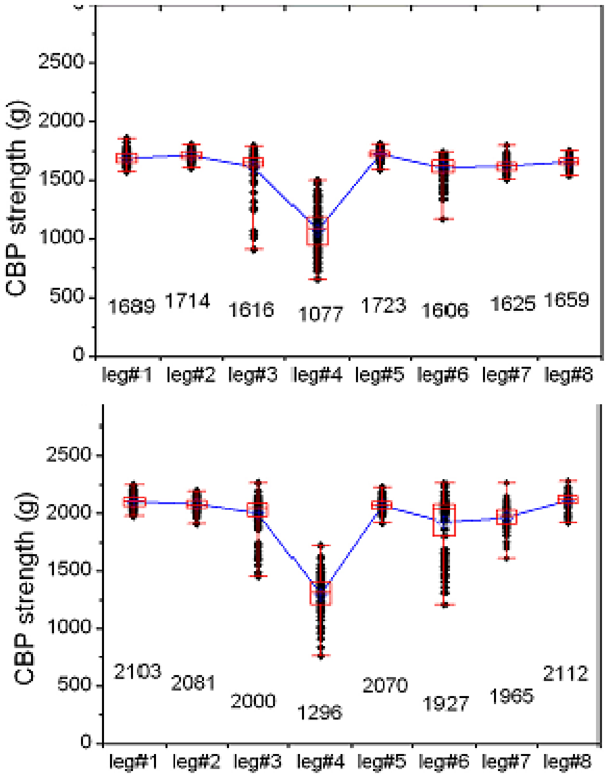


Fig. 20 Cold Ball Pull test distributions of maximum pull strength for **eutectic** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) as received

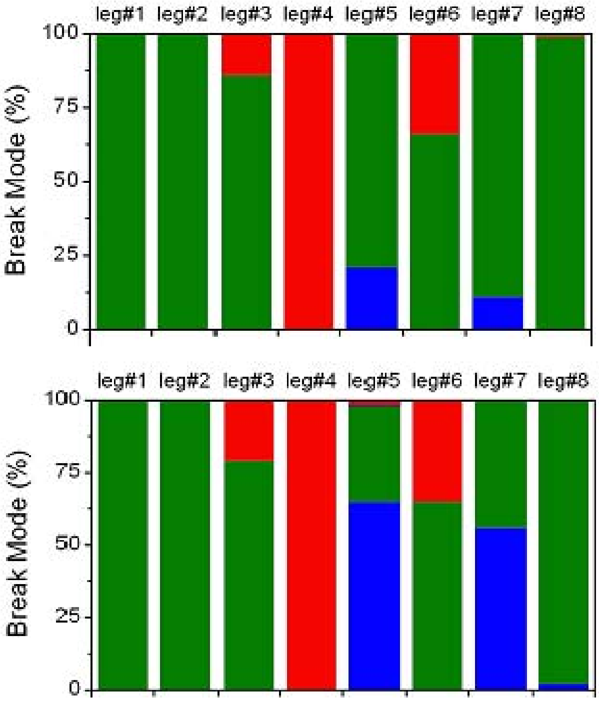


Fig. 21 Cold Ball Pull test distributions of break mode for **eutectic** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) as received

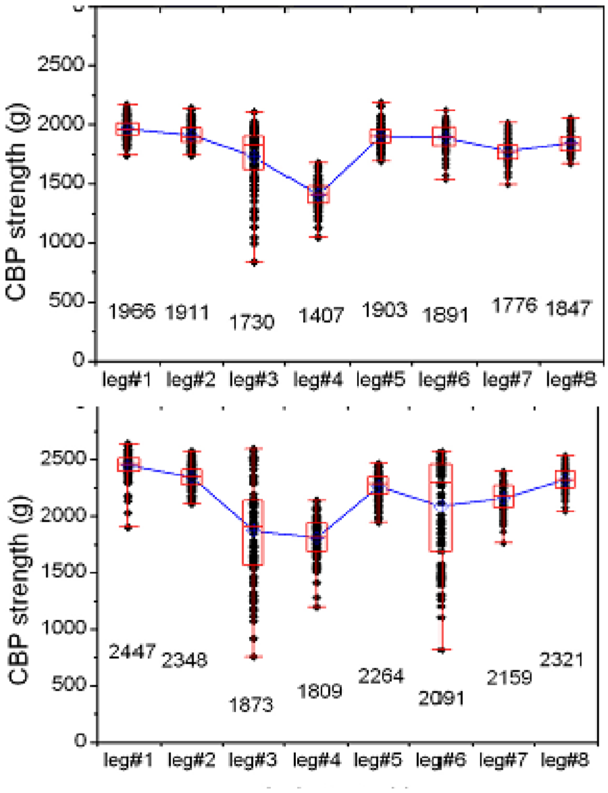


Fig. 22 Cold Ball Pull test distributions of maximum pull strength for **Pb-free** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) as received

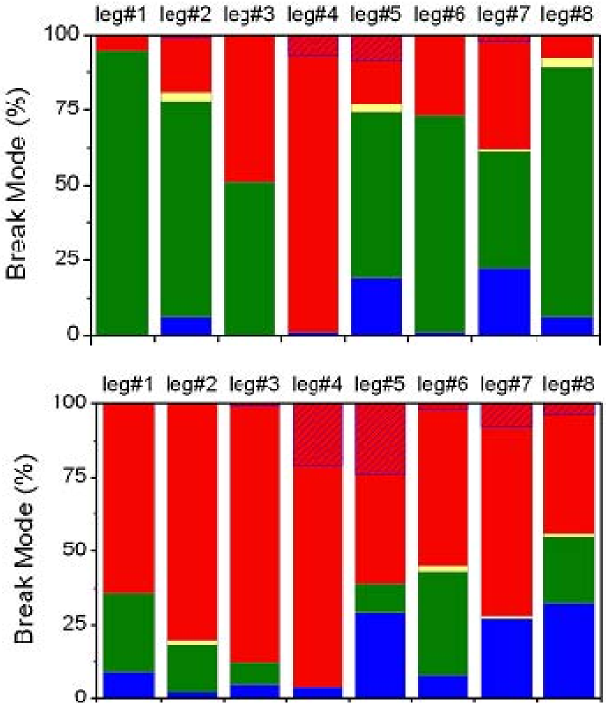


Fig. 23 Cold Ball Pull test distributions of failure mode for **Pb-free** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) as received

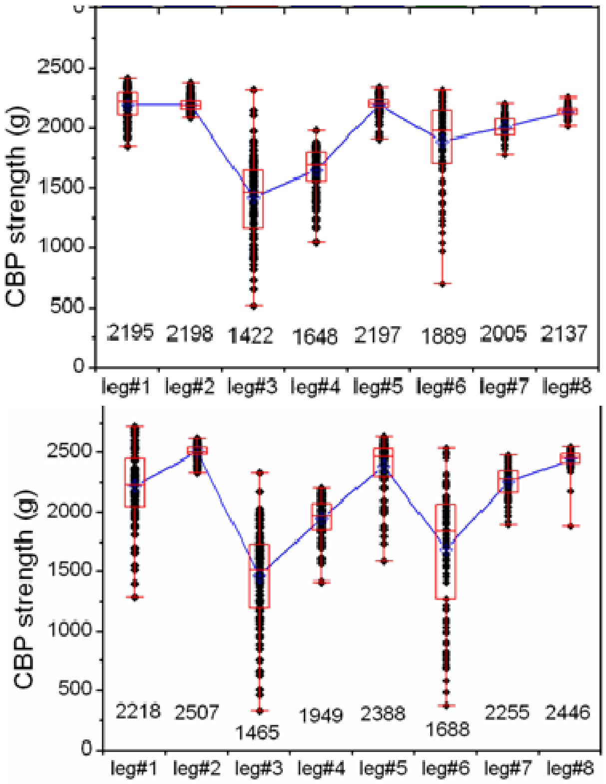


Fig. 24 Cold Ball Pull test distributions of maximum pull strength for **eutectic** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) after one additional reflow

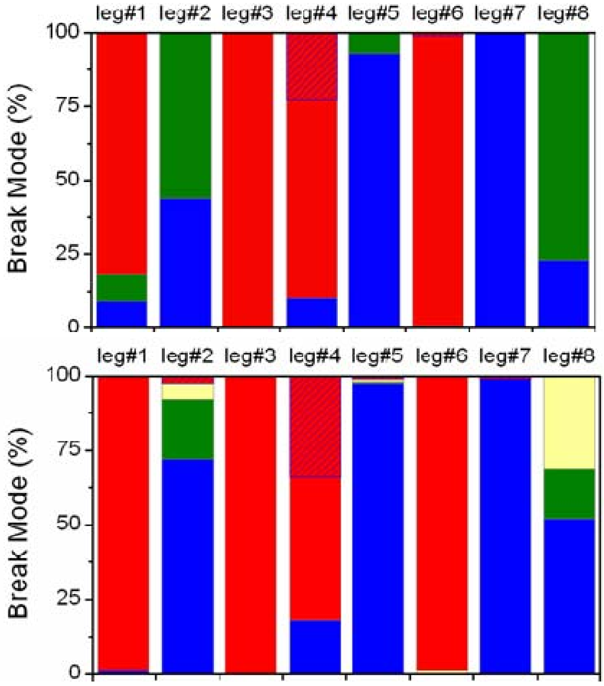


Fig. 25 Cold Ball Pull test distributions of break mode for **eutectic** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) after one additional reflow

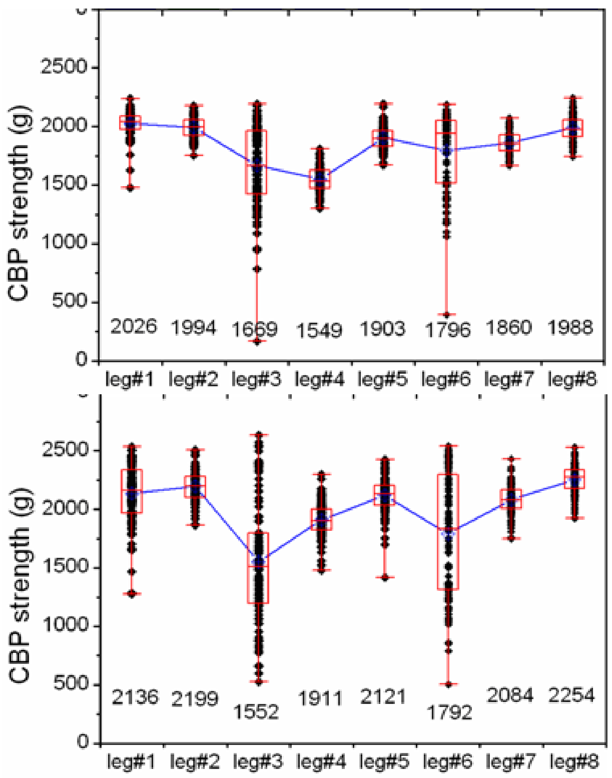


Fig. 26 Cold Ball Pull test distributions of maximum pull strength for **Pb-free** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) after one additional reflow

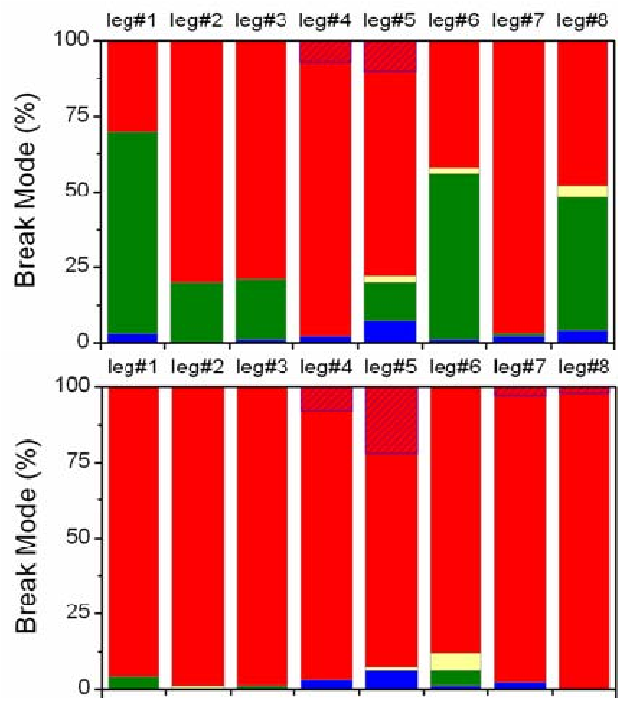


Fig. 27 Cold Ball Pull test distributions of break mode for **Pb-free** solder balls at pull speeds of 0.3 mm/sec (top) and 5.0 mm/sec (bottom) after one additional reflow

- Certain surface finishes, including OSP (Leg 2), Direct Gold (Leg 5), Immersion Tin (Leg 7) and Immersion Silver (Leg 8) may have actually increased their bond strength to the point of causing the occurrence of pad failures.

Regarding the cold ball pull results “after one additional reflow” using Pb-free solder balls, the following observations are noted:

- The pull strength distribution for Pb-free solder balls was quite similar to the results shown for eutectic solder balls. A higher level of inconsistency of results was noted for finishes that included a nickel deposit.
- Again, surfaces that include nickel in their deposit (i.e. Legs 1, 3 and 6) displayed a higher standard deviation of results than the other finishes. The percentages of bond failures for Pb-free solder balls increased dramatically with the additional reflow, in comparison to the eutectic solder ball results. Pad failures previously observed with eutectic solder balls for Legs 2, 5, 7 and 8 no longer occurred.

Discussion

The investigations presented in this paper are part of a comprehensive project focused on examining alternative surface finishes for both wire bond and flip chip BGA packages. The objectives of this project are to identify alternative surface finishes that (1) meet or exceed reliability and performance standards achieved by the current process of record and (2) reduce manufacturing costs.

Cost Considerations

As presented herein, for wire bond PBGAs, one such alternative that may offer cost savings is the Ni/Pd/Au process. Based on the comparison shown in Figure 28, there is a measurable difference (i.e. more than three times) between the precious metal costs of the two surface finishes. Additional cost savings would be realized with a simplified manufacturing process. As an added benefit, Ni/Pd/Au is an electroless type of process, meaning that no electrical buss is required, thus simplifying the process and reducing costs. More importantly, as an electroless process, it allows a wire bond product of finer pitch of to be produced.

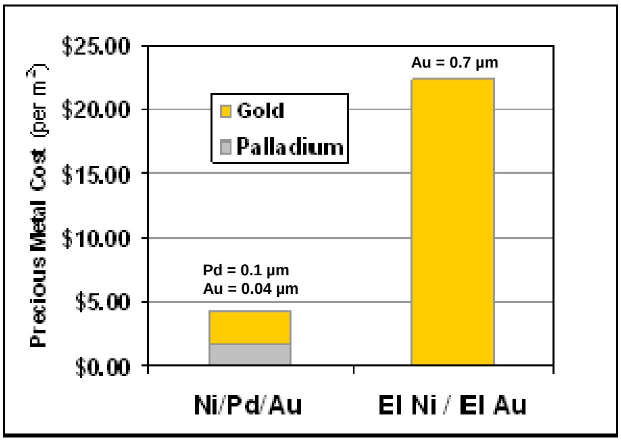


Fig. 28 Comparison of total precious metal costs for electroless nickel / electroless palladium / immersion gold and electrolytic nickel / electrolytic gold surface finishes (basis: palladium price ~ $6 per gram; gold price ~ $14 per gram)

Cold Ball Pull Test Methodology

The results of several different reliability tests have been summarized in this paper. Several of these, including wire pull testing, gold ball bond shear testing and solder ball shear testing have considerable historical data and well documented industry standards. In particular, cold ball pull testing is receiving increased attention within the electronics packaging industry, but is a relatively new technique and the standards are not well recognized. It has been theorized that cold ball pull testing is a more accurate methodology for testing solder joint integrity in comparison to ball shear testing. In this analysis, we have included complete results of both slow- and high-speed cold ball pull testing. It has been shown that different results occur for the two pull speeds, both in terms of recorded pull strength and fracture mode. One “school of thought” offered within the industry contends that the different pull speeds should be used dependent upon the test objective. Specifically, the slow-speed results are better suited for determining the actual pull forces, while the high-speed results are better suited for analyzing the mode of fracture. It has recently been reported that pull strength increases with test speed and that the rate of interfacial solder joint fracture increased with test speed.[6] The same investigation noted that at high test speeds, a greater force is transferred from the solder ball to the bond between the ball and pad interconnect, resulting in a test that examines bond reliability. The results contained herein certainly support these findings; particularly with respect to testing of Pb-free solder balls. However, because definitive standard test are not well known to this point, the results of both test methods are included herein for consideration.

Conclusion

Based on the investigations performed in Phase I of this evaluation, the following conclusions are offered:

1. With respect to wire bond package surface finishes, the electroless nickel / electroless palladium / immersion gold (Ni/Pd/Au) finish has been shown to be of equivalent or better reliability in comparison to the more traditional electrolytic nickel / electrolytic gold finish. This statement is made on the basis of gold wire bond, ball bond shear and solder ball shear results. The Ni/Pd/Au finish also offers an opportunity for measurable cost savings in comparison to the more traditional approach. A more comprehensive engineering reliability examination will be initiated before formal qualification of the Ni/Pd/Au finish can be issued.

2. For flip chip package surface finishes, relatively different results were obtained from the ball shear and cold ball pull investigations:

   a. With the exception of the palladium finish, traditional ball shear testing showed that performance criterion were met consistently for eutectic soldering and also in most cases for Pb-free soldering, although the Pb-free investigations yielded a much wider variation in the measured shear strength. From the standpoint of failure mode, with the exception of the palladium finish, the predominant fracture type was the preferred ball failure for both eutectic and Pb-free applications. It is important to note that the presence of palladium in the Ni/Pd/Au finish did not exhibit such voiding or low shear strength, likely due to the immersion gold capping layer.

b. In reference to cold ball pull testing, the exercise must be repeated to determine the effect of the delay encountered between solder reflow and testing. Additionally, because the repeatability and reproducibility of the cold ball pull test equipment must be determined, a GR&R will be completed. However, based on this investigation, there seems to be significantly different results between eutectic and Pb-free cold ball pull testing, regardless of pull speed. Furthermore, variations in pull strength and fracture mode were also documented within each test group depending on the pull speed that was used. In comparison to the ball shear test results, a significantly higher incidence of interfacial (i.e. brittle) fracture was found with cold ball pull testing, particularly with the Pb-free alloy and using the higher test speed. With the variation in cold ball pull test results that have been observed, other factors such as solder resist opening (SRO) diameter and solder ball diameter further complicate interpretation of the data. Until the items described above are repeated and other factors are more fully understood, this initial data should be regarded as preliminary.

As a result of the findings from Phase I of this evaluation, additional investigations will be required. Further investigations will be conducted with respect to the possible influence of the IMC thickness and consistency on Pb-free failures. The next phase of this study to isolate key suitable surface finishes for Pb-free application is currently under way and cold ball pull testing is being repeated (without delay after reflow), according to the end user specification. Such investigations may also provide information for quantifying the impact of delayed testing. Following completion of that stage, traditional functional testing of the devices will be initiated, including thermal cycle testing, four-point bend testing and drop testing with the goal of identifying any correlation with the results of the earlier phase.

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References

1. K. Johal, S. Lamprecht and H. Roberts; “Electroless Nickel / Electroless Palladium / Immersion Gold Plating Process for Gold- and Aluminum-Wire Bonding Designed for High-Temperature Applications”; SMTA 9th Annual Pan Pacific Microelectronics Symposium; January 2004.
2. K. Johal, H. Roberts and S. Lamprecht; “Electroless Nickel / Electroless Palladium / Immersion Gold Process for Multi-Purpose Assembly Technology”; SMTA International Conference; September 2004.
3. LSI Logic “Material Specification Laminate Substrates for Flip Chip Plastic Ball Grid Array Packages; Oct. 20, 2004.
4. S. Bukhari, D.L. Santos, L.P. Lehman, and E. Cotts; “Continued Evaluation of the Effects of Processing Conditions and Aging Treatments on Shear Strength and Microstructure in Pb-Free Surface Mount Assembly”; Binghamton University
5. L. Garner, et al; “Finding Solutions to the Challenges in Package Interconnect Reliability”; Intel Technology Journal; November 2005.
6. L. Peters; “Lead-Free Brings Out Problem of Brittle Fracture”; Semiconductor International; September 2005.