Solving the ENIG Black Pad Problem: An ITRI Report on Round 2

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Abstract
A problem exists with electroless nickel / immersion gold (ENIG) surface finish on some pads, on some boards, that causes the solder joint to separate from the nickel surface, causing an open. The solder has wet and dissolved the gold. A weak tin to nickel intermetallic bond initially occurs, but the intermetallic bond cracks and separates when put under stress. Since the electroless nickel / immersion gold finish performs satisfactory in most applications, there had to be some area within the current chemistry process window that was satisfactory. The problem has been described as a 'BGA Black Pad Problem' or by HP as an 'Interfacial Fracture of BGA Packages…'[1]. A 24 variable experiment using three different chemistries was conducted during the ITRI (Interconnect Technology Research Institute) ENIG Project, Round 1, to investigate what process parameters of the chemical matrix were potentially satisfactory to use and which process parameters of the chemical matrix need to be avoided. The ITRI ENIG Project has completed Round 1 of testing and is now in the process of Round 2 TV (Test Vehicle) build.

Round 1 of the testing helped to identify the cause of the problem and some of the process parameters which are not key contributors to the problem. Round 2 of the project involves a 19 variable experiment, using the same three chemistries as Round 1. Based on the results from Round 1 [2], plus others tests, different ENIG chemistry process parameters were selected as the most likely cause of the problem. These parameters are currently on TV's in assembly. This paper is an update to the activities that have occurred in the ITRI consortium, and some other failure analysis activities that have occurred since last fall.

Introduction
The problem was first identified on BGA (Ball Grid Array) components. An open or fractured solder joint sometimes appears after board assembly on the occasional BGA pad. The solder had wet and dissolved the gold and formed a weak intermetallic bond to the nickel. This weak bond to the nickel readily fractures under stress or shock, leaving an open circuit. The incidence of this problem appears to be very sporadic and a low ppm level problem, and it's occurrence has been very unpredictable. The problem has occurred on solder joints of other types of components, such as QFP's (Quad Flat Pack). However, leads on the QFP are very compliant and the solder joint does not experience the same stress as on BGA joints. The solder joints can be touched-up without removing the component and the defect may not be reported. A BGA solder joint cannot be touched-up without the component being removed. After the BGA component is removed, a 'black pad' is observed at the affected pad site. This black pad is not readily solderable, but it can be repaired. It appears to occur on boards more frequently on finer pitched components with smaller pads, than on larger pads. This same black pad problem has occurred on component laminate substrates as well as circuit boards, as reported by Amkor [3] and HP [4] and [5]. This ITRI project was approved in August 1997 to investigate this problem and find a solution. Since then, there have been many side projects with multiple tests and failure analysis to attempt to understand the cause and resolve the problem.

The following images, Figures 1 – 4, illustrate the problem.

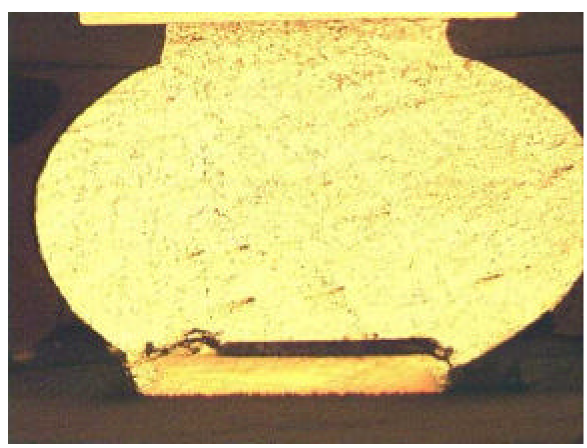

Figure 1- BGA Ball with Cracked Ball Joint

Figure 1 shows a cross section of a BGA solder joint with a crack along most of the nickel interface.

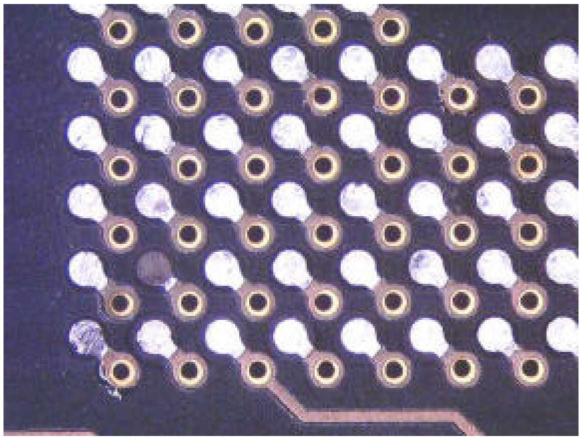

Figure 2 – BGA Site with One Black Pad

Figure 2 shows a BGA site after a component has been removed and the excess solder wicked off the pads. One pad is very dark to black in appearance.

Figure 3 – QFP with Cracked and Shifted Lead

Figure 3 shows a group of QFP leads with one lead pushed to one side. The solder has lifted off the pad along the nickel interface and remains adhered to the QFP lead.

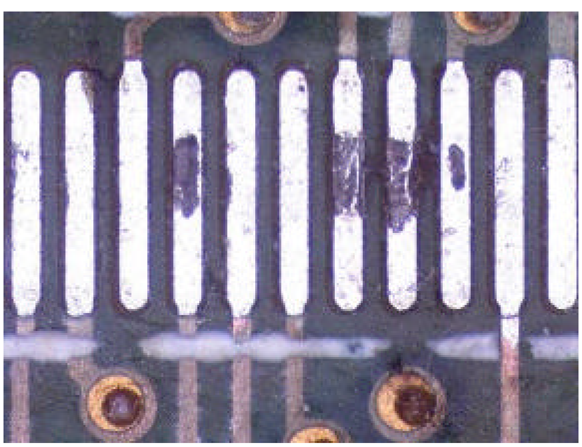

Figure 4 – QFP Black Pads after Solder Wick

Figure 4 shows a QFP site after the component has been removed and the excess solder wicked off the pads. Three pads have varying degrees of a black pad appearance.

With a problem such as this, why not give up on the use of ENIG and pick another finish? The fact is that every board finish has its own strengths, weaknesses and applications. There is no universal board finish that will meet every need. The ENIG board finish provides:

- A flat board finish
- A very solderable finish
- Relatively good shelf life
- A finish which doesn't readily tarnish or discolor
- A precious metal electrical contact surface
- A mini nickel rivet which strengthens the plated holes
- A nickel barrier which protects the barrels from copper dissolution during wave soldering and rework.

This problem of joint fractures with ENIG surface finish has not changed in the past few years but the awareness of it has increased, which has increased the level of anxiety. From my perspective, some OEMs are continuing to use the ENIG, carefully watching the progress of this consortium and other similar activities. Some OEMs are temporarily reducing the use of ENIG finish where practical, waiting for a process fix. Some are increasing the use of ENIG due to such things as the increased complexity of their boards, which need more than a HASL finish, for things such as the need for a precious metal board edge contacts for EMI shielding or the increased barrel rigidity with a nickel layer.

ITRI Problem Statement (Round 2)

Fractured solder joints have been reported on solder joints at the solder/ nickel interface on circuit boards using electroless nickel/immersion gold surface finish. The gold has been dissolved into the solder and a non-wet nickel surface remains. The defect usually occurs on fine features such as on BGA and QFP components.

ITRI Objectives of Goals (Round 2)

- To be able to turn the 'black pad' phenomena on and off by varying plating parameters in the nickel and gold baths, using a revised TV which has characteristics that are conductive to inducing the defect and is easy to perform failure analysis of it.
- Establish process parameters to prevent the defect from occurring.
- Assess alternative finishes to see if they manifest similar detrimental galvanic cell actions or that may be comparable replacement finish with the attributes of a nickel/gold finish.

Current Participants:
At the start of the project, there were 33 companies and organizations involved in its activities. Due to mergers or a lack of involvement, the following are the 20 companies and organizations that are still involved in the project: Ambitech, Atotech, Amkor, Auburn University, Cabletron, Celestica, Delphi Delco, Hadco, Hinton PWB Eng., HP, IBM, Johnson Matthey Advanced Circuits (JMACI), MacDermid, NSWC Crane (US Navy), Praegitzer, Sanmina (Altron), Shipley Ronal, Solectron, Trace Labs and Xetel, plus ITRI as overseer.

Understanding of the Problem
Chemical suppliers have been conducting tests in their labs trying to understand the black pad phenomena. Hadco, Santa Clara was doing extensive testing into the formation of the black pad. They found that the nickel was being severely corroded under the gold [6]. Celestica started to map the defects on products and found what previously appeared to be random occurrences of black pad actually exhibited a pattern.

Defect Mapping:
Assemblies from lots that had exhibited some weak joints on QFP components had the QFP leads physically probed. Any failed joints were recorded along with their location. A number of components, that had any leads 'pop off' the SMT pad during probing, had the QFP component removed and the solder wicked off the SMT pads. Additional data was recorded on the locations of any pads that showed any signs of non-wetting, even if the solder joint had passed the physical probing. The data collected was analyzed and it was found that for any particular board design, there was a repetitive pattern to the locations that exhibited the black pads. A black pad can be located immediately beside a pad or between two pads that are perfectly OK.

The circuitry of the affected pads were then traced. It was found that the affected pads were electrically connected to some other feature on the board that tended to have a larger ENIG surface area that was not affected. Some QFP pads were electrically connected to larger plated-through-hole sites used for connectors or other PTH components. Other affected pads were electrically connected to other larger SMT pads or a series of other small pads. Some unassembled panels from the same suspect lot code had the gold removed by cyanide strip. The same pattern that had been mapped out above was seen on these boards. The mapped locations showed dark to black nickel on the suspect pads while shiny nickel existed on other sites.

This analysis along with the analysis by Nick Biunno from Hadco [6] indicated that there appeared to be some form of excessive corrosion of the nickel on the affected pads. The nickel on the affected pads was severely attacked. Instead of just a nickel / gold atom exchange, there appeared to be excessive depletion of the nickel surface before the gold finally covered the nickel. Since the larger electrically connected pads were not affected, there appeared to be some form of galvanic cell action that permitted the attack of the smaller pad in preference to the larger pad.

Chemical Test Matrix
At the start of Round 1, a number of sessions were spent brainstorming, in order to attempt to determine the potential causes of the brittle joints. There had to be some parts of the current operating windows, as defined by the chemical suppliers, that are satisfactory and some areas of the operating windows that are much worse. The following are some of the parameters that were considered in developing the test matrix in Round 1:

- Phosphorous level
- Age of nickel bath
- Age of gold bath
- Time in nickel bath (nickel thickness)
- Time in gold bath (gold thickness vs. porosity)
- Solder mask type
- Solder mask applied before or after Ni/Au
- Chemistry type
- PWB fabricator
- Board design
- pH of nickel bath
- pH of gold bath
- Temperature of nickel bath
- Temperature of gold bath
- Hang times

It was impossible to vary all of the above parameters, but it was agreed that parameters not varied should be monitored during the build. These parameters would provide a possible reference for further analysis, based on the actual results, and a guide for further testing in Round 2.

Based on the knowledge learned during Round 1 and subsequent tests, such as investigations by Nick Biunno, from Hadco [6] a new set of variables were defined for Round 2. The following are the variables being exercised in Round 2:

- Deposition rate of nickel
- Nickel thickness
- Deposition rate of gold
- Gold thickness

A full 16 factor experiment of lows and highs was defined. Then three mid points were added to the matrix, then the matrix was optimized. For the planned set of values, see: Table 1: ITRI Round 2 ENIG Chemical Test Matrix.

In addition to the above test matrix, some panels fabricated during Round 1, had ENIG applied by each finisher at nominal chemistry mid point as a comparison between Round 1 and 2. A panel was also finished with OSP and with HASL as industry benchmarks. We are also planning to test some boards with ENIG applied before soldermask to assess any possible impact by the soldermask. We will also be testing a number of alternative finishes using the same TV with silvers, tins and palladium finishes.

Test Vehicle

Based on the knowledge gained by the additional testing subsequent to Round 1 as described above in 'Understanding of the Problem', it was determined that the TV (Test Vehicle) used for Round 1 was not adequate to induce the black pad problem. The objective of the TV remained the same, that it needed to be able to demonstrate the joint fracture problem. It was desired to have enough I/O pads to be able to find the defect, but not so large that a small defect level could not be detected. Too large a BGA could also require too great a pull force for most lab Instron testers and the BGA package would crack in pieces during the tensile pull.

It also remained essential that the TV be readily built by the board fabricators and have the ENIG chemistry applied in their production environment and then be assembled in a production assembly environment. The TV needed to be easily separated into individual coupons without affecting the integrity of the joints and tested in an economical and timely manner.

For Round 2, we were able to use the same outline of the Round 1 TV. There are still 6 mini panels per 18" x 24" panel. Each mini panel is approximately 7.25 x 7.9". Three mini panels have a 'component' side solder mask defined pad design. The other three mini panels have the board side, copper defined BGA pad design. This layout permits both the component and board coupon to have the same ENIG chemistry. The board is still 0.062" thick but it has changed from double sided board to a six layer board with two pair of internal voltage and ground planes.

Each mini panel still has 25 'components' or 'board' side coupons, each approximately 0.68 x 1.45". There are also five solder spread coupons, with 0.5" diameter copper lands and two IPC solder dip coupons on each mini panel. These extra features permit additional analysis of the finishes if necessary. The final design, combined prerouts at the long ends of each 'component' and score-to-break along each side of the component. Four fiducials were placed just outside the 100 I/O BGA pattern to aide in automatic parts placement.

For Round 1 and 2, the 'component' side of the BGA packages are designed to reflect many component type packages with solder mask defined pads. The copper pads are approximately 0.033" diameter with a 0.025" solder mask opening. With a 10 x 10 I/O pattern, it was found that a symmetrical arrangement of electrically connected and none connected pads could be made. 4 corner and 4 center pads were isolated from all others. Other pads all have traces connecting from the BGA pad to to their adjoining via land and the via lands were connected in 2's, 4's, 8's and 12's. All via holes are drilled with a nominal 0.0135" drill.

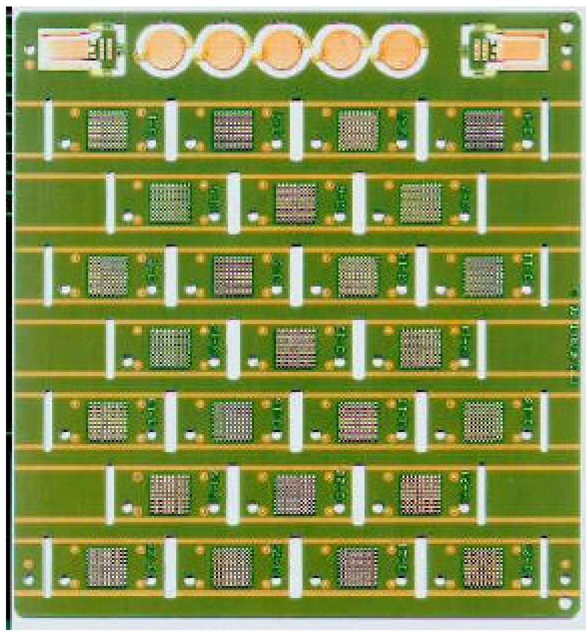

Figure 5 – TV Mini Panel Component Side

For Round 1, the 'board' side of the BGA package was designed with 0.025" diameter copper defined pads, with approximately 0.031" solder mask opening. The BGA pads are all on 0.050" centers. The same symmetrical electrically connected pad configuration was used on the board side as used on the component side for Round 1. The board side of the Round 2 TV was redesigned to add 18 larger PTH (Plated-Through-Holes) as used for connectors, 5 varying size larger surface SMT pads on the back side and 8 decoupling capacitor size SMT pads on the assembly side or each coupon. The 18 PTH are electrically connected to some of the BGA pads with varying lengths of traces created by serpentine patterns. The 13 larger SMT pads are also electrically connected to some different BGA pads with varying lengths of traces. The Round 2 board is a 0.062” thick board, but is a 6 layer construction with internal voltage and ground planes. The internal voltage and ground planes were electrically connected to some of the remaining BGA pads.

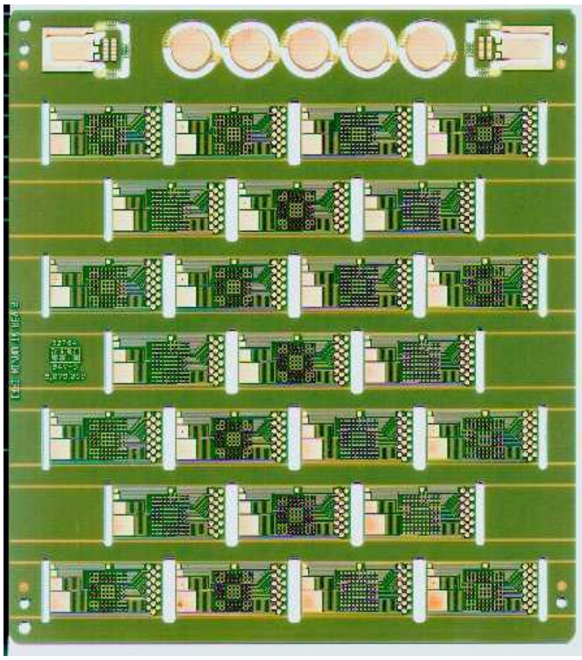

Figure 6 – TV Mini Panel Board Side Back

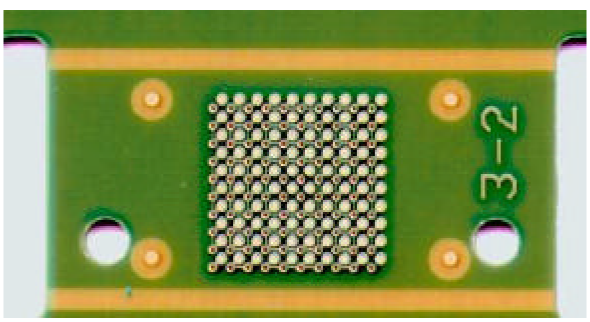

Figure 7 – TV Component Side Coupon Front

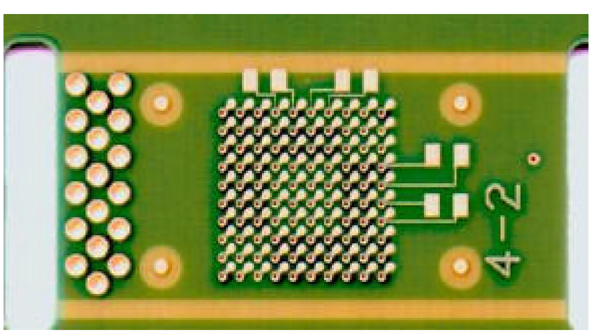

Figure 8 – TV Board Side Coupon Front

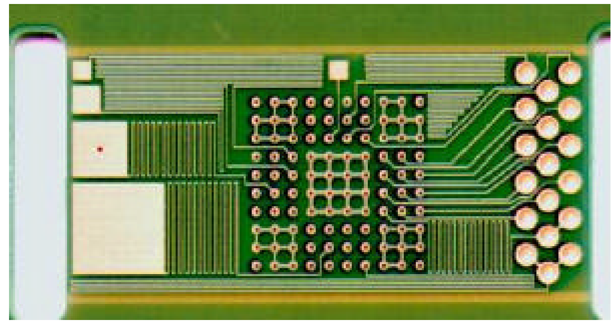

Figure 9 – TV Board Side Coupon Back

Board Fabrication

For Round 2, the boards were also made by one board fabricator to minimize variables. This time, Hadco, Santa Clara made the boards, then one third were shipped to each of the other two board finishing locations used for Round 1: IBM Endicott and JMACI and the remaining third to Solder Station One for ENIG finishing. Additional boards were also fabricated by Hadco to have alternative finishes applied.

Assembly Process

For both Round 1 and 2, in order to create a BGA component, a solder ball had to be made on the ‘component’ side of the package. The use of preformed solder balls was considered, but the assemblers for Round 1 and 2 did not have the capacity or capability at the time. It was decided that the solder balls would be made on the ‘component’ side of the mini panels by screen pasting a large volume of eutectic solder paste and then reflowing the paste. This would entail using a thick stencil with a large aperture. The same assembly process and stencil will be used for Round 2 and was used for Round 1. However, Xetel will do the assembly for Round 2. See the report on Round 1 for more details on the process [2].

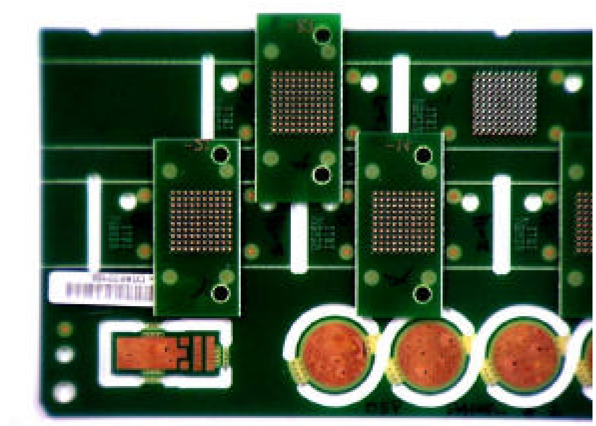

Figure 10 – TV with Partial Assembly

Failure Modes

With this BGA package, there are 8 possible failure locations where the fracture could occur when the joint is pulled apart.

1. Rip Copper (Cu) pad from component side
2. Cu to Nickel (Ni) shear at component side
3. Solder to Ni shear at component side
4. Fracture in bulk solder
5. Solder to Ni shear at board side
6. Cu to Ni shear at board side
7. Lift Cu pad off the board but still attached via the trace from pad to via hole.
8. Rip Cu pad off the board side

It is also possible for a fracture to occur in a combination of the above modes, such as a joint partially fracturing in solder and partially shearing along a solder / nickel interface.

Based on the results from Round 1, no failures are expected at locations #1, 2, 4, or 6 during Round 2.

If the nickel to solder bond is a problem, then the failure could occur at either interface #3 or #5. The solder would separate from either of these surfaces, leaving the pad still attached to the FR4 and a potentially 'black pad' on the nickel surface. Fractures at either of these surfaces was considered a bad failure mode in Round 1 and likewise for Round 2.

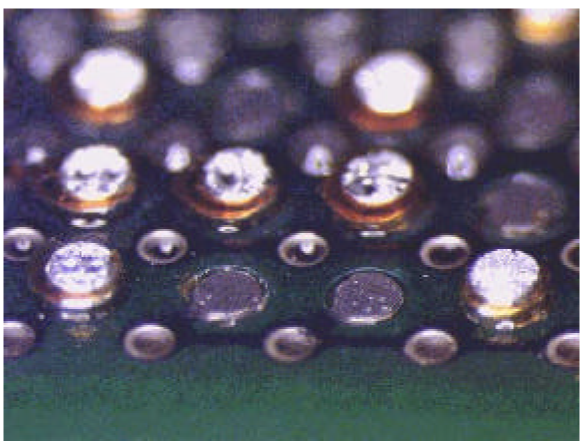

Figure 11 – Instron Bad Pull Result

Failure could occur in bulk solder, if the solder to nickel interfaces are strong and if the copper to FR4 adhesion is also very strong. However, if the Instron pull rate is fast enough, then the shear strength of the solder will be much greater than the peel strength of the copper to FR4. A fast pull rate of 0.05"/sec. was chosen for Round 1 and will also be used for Round 2. At the start of Round 1, NSWC Crane modeled this theory to verify that we should not see any fails in bulk solder at this Instron pull rate. We did not find any fails in the bulk solder, at interface #4, during Round 1 and none are expected during Round 2.

Desired Failure Mode:

If all of the solder joints between nickel and bulk solder are solid joints, then the failures should all occur at the board BGA copper pad to FR4 with either the pad lifting at interface #7, or being totally ripped off the board at interface #8.

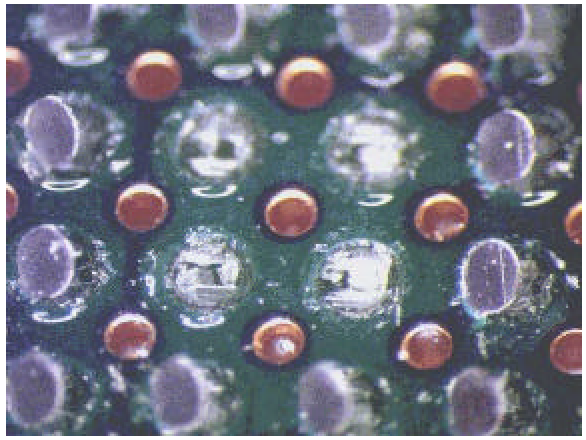

Figure 12 – Instron Good Pull Result

The board side has been totally redesigned for Round 2. The 4 corner pads are still isolated, but the interconnects on all of the other pads have changed, so the results are expected to be different. The chemical matrix has also been altered so that some of the matrix is expected to give good results on all pads, while other parts of the matrix should yield intentional poor results.

Instron Pull Testing

At the time of writing this paper, the parts are just starting to be assembled. The Instron testing is planned to be performed the same in Round 2 as was performed in Round 1. The Instron maximum pull force will be recorded, then the parts will all be inspected to determine the mode of separation of all the 100 BGA solder joints on each coupon. The same fixtures for the Instron will be used for Round 2 as were used for Round 1 using the same pull rate at 0.05"/second with a 1000 Lb. Load cells.

Aluminum stiffeners approximately 0.125" thick, 0.50" wide and 1.5" long will be epoxied to each side of each BGA coupon to prevent the BGA coupons from bending during the Instron pulling, the same as Round 1. During Round 1, we aimed for at least 7 good Instron pulls per cell. During Round 2, we are aiming for 10 good Instron pulls per cell, for a higher degree of confidence in the results. This data will then have to be analyzed back against the test matrix.

Instron testing is expected to start by the middle of August '99.

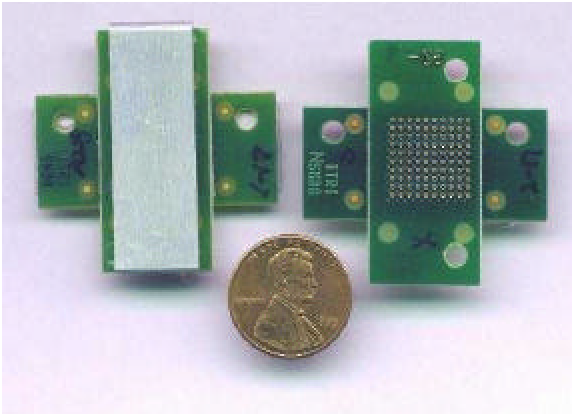

Figure 13 – TV Coupons Ready for Stress Test

Nickel / Gold Thickness Measurement

During Round 1 of the project, sample boards were sent on a round robin to check the consistency, or lack thereof, of XRF measurements. Two sets of coupons were sent through testing on three different manufacturers of XRF units at multiple locations. The results of this round robin showed considerable variation in gold thickness readings on the same features. This information made the initial thickness readings of the gold questionable on Round 1. The round robin coupons then had the gold sputtered off by two different means by two different companies and obtained similar results. These sputtered results became a reference to retrofit the results from Round 1.

For Round 2, weight gain coupons were plated with ENIG with the test panels. These weight gain coupons will be stripped and analyzed to determine the gold thickness. The nickel thickness measurements were not an issue during Round 1 and are not expected to be during Round 2.

Implication of XRF readings to the user and board fabricator:

The board assembler needs a board that is solderable. The assembler and fabricator need to agree that whatever XRF readings the board fabricator is producing, that work for the assembler, become the reference XRF readings for ongoing product, whatever that number may be. The current thought is that thick gold in the greater than 6 micro inch range is too thick. It causes excessive attack of the nickel. The gold needs to be just thick enough to ensure solderability though the normal shipping, storage and assembly processes.

Alternative Finishes Testing

In case no fix can be found for the ENIG problem, or that a fix would take too long to develop, it was decided to also do some testing of alternative board finishes that could be potential replacements for ENIG. The emphasis during Round 1 was on finishes that had a gold or other precious metal finish that would be suitable for both soldering and for electrical board surface contact to unsoldered areas. The build of these boards was kept separate from the other ENIG parts to prevent impact to its schedule. For Round 2, this matrix has been expanded to all the alternative finishes. This includes: two silver, three tin and several palladium, along with OSP and HASL as benchmarks. These boards will be assembled and tested at Celestica after the ENIG boards are complete.

Conclusions

1. Round 1 test results revealed good to very poor solder joints. Therefore there are areas of the chemistry matrix that appear much better than others and should be used and some areas that should be avoided. Round 2 should further define these operating parameters. However, no black pads were found.

2. The thickness of nickel does not appear to be a major contributor to the problem as long as a minimum of at least 100 micro inches is maintained.

3. High phosphorous is not a problem, as was thought when starting Round 1. Low phosphorous can be a problem, and it can also affect solderability. This was also confirmed by HP [5].

4. The results showed varying pull strengths. However, a high pull strength on 100 I/O BGA package did not by itself guarantee that there would not be some solder joint(s) that separated, leaving a failure mode #3 or #5 flat pad at the nickel interface. All of the parts had to be 100% inspected for the failure mode. One might argue that some of the pull strengths were more than adequate for many applications.

5. Based on additional analysis and testing that was conducted in conjunction with this project, the root cause of the black pad problem has been identified, that being the nickel being attacked or excessively corroded in the gold bath. Nick Biunno from Hadco, Santa Clara has defined the various stages in the development of the black pad [6].

6. Based on additional analysis and mapping of defects that was conducted in conjunction with this project, it has been determined that board design has some bearing on the incidents of black pad. A particular design that is subject to black pads will have a repetitive pattern to the location of the black pads.

7. Round 2 of testing is aimed at focusing on the good areas of the chemical test matrix to verify that it does not produce bad product and that the process can be continuously run in the redefined operating window of each chemical supplier to produce good product.

8. Electrolytic nickel and gold provided all good results, however, it is difficult to get adequate nickel plating in high aspect, small via holes in thick boards. The throwing power of electrolytic nickel is not very good. Gold plating thickness varies considerably across a board. Plating densities cause isolated copper features to plate much thicker gold than dense copper areas. Excess gold thickness can cause embrittled solder joints. The Ni/Au plating must be done after copper plating and is then susceptible to contaminants such as solder mask residues being left on the gold. The Ni/Au plating becomes the etch resist and is subject to undercut and slivering. Coating all external traces with Ni/Au can affect any high speed signals that go through those traces.

9. The electroless nickel / electroless palladium / immersion gold finish performed very well and requires more testing, along with other surface finishes.

Acknowledgments

I would like to thank all of the participating companies and organizations and the many people in each for their support through all of the activities from the concept, test matrix, TV design, initial qualification builds, actual parts build, assembly and test. In addition to the hours spent on conference calls and providing guidance through the project, the following provided some of the physical processes and or parts for the project:

Ambitech: quick turn of TV Rev 1
Atotech: chemistry and technical support, Round 1 & 2
Auburn U.: designed the TV for Round 1
Cabletron: provided TV design and prototype testing
Celestica Tor.: chairman, built of TV prototype
and alternative finishes
Celestica CO.: Instron fixture design.
Hadco: provided one of the ENIG finishes, a lot of analysis in defining the cause of the nickel corrosion, redesign of the TV for Round 2 and board fabrication for Round 2
HP: provided technical reports on their activity
IBM: Built all the TV's for Round 1, plus ENIG chemistry for Round 1 & 2
ITRI: Parts stock / sort, and weekly telecon. minutes
JMACI: one of the ENIG finishes for Round 1 & 2
LeaRonal: chemistry and technical support for Round 1 & 2
MacDrermid: chemistry and technical support for Round 1 & 2
NSWC Crane: Round 1 & 2 Instron pull testing
Praegitzer/Integraph: quick turn of TV Rev 2
Solectron: Round 1 assembly
Trace: Round 1 Instron pull testing
Xetel: Round 2 assembly

At Celestica, I wish to acknowledge the assistance of Neil Maskery and our Core Lab for the build of the initial TV's and the alternative finishes boards, our TPA people for their Lab assistance, especially Ryan Petersen for Instron support, George Riccitelli for Instron fixture and cross sections, Dr. Polina Snugovsky and Dr. John Kong for SEM and Auger analysis of fractured joints, Linda Klober, Marti Ellis and Dr. Bob Lussow for the mapping of the defective boards.

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Table 1: ITRI - ENIG Round 2 Chemical Test Matrix

STD	RUN	Block 1	Ni Thickness	Ni Rate %	Au Thickness	Au Rate %
4	1	Block 1	225	80	2	100
8	2	Block 1	225	80	6	80
15	3	Block 1	75	120	6	80
2	4	Block 1	225	120	6	100
9	5	Block 1	225	120	2	120
3	6	Block 1	225	120	2	80
13	7	Block 1	75	80	4	80
6	8	Block 1	75	80	2	120
10	9	Block 1	75	120	2	100
16	10	Block 1	75	100	4	120
17	11	Block 1	225	100	4	80
19	12	Block 1	225	80	6	120
1	13	Block 1	150	100	4	100
12	14	Block 1	75	80	6	100
14	15	Block 1	225	80	6	120
18	16	Block 1	225	120	2	120
5	17	Block 1	75	120	6	120
11	18	Block 1	150	80	2	80
7	19	Block 1	75	100	2	80

Notes:
1) Nickel Thickness in microinches
2) Nickel Rate % = % of normal deposition rate
3) Gold Thickness in microinches
4) Gold Rate % = % of normal deposition rate
5) Run = board number - the tracking number
6) STD = a randomizing of the parts build