ITRI Project on Electroless Nickel / Immersion Gold Joint Cracking

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Abstract
A problem exists with electroless nickel / immersion gold (E.Ni/I.Au) board 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. An initial weak tin to nickel intermetallic bond has occurred, but the solder joint cracks and separates when put under stress or when it experiences a shock. The problem has been described as a 'BGA Black Pad Problem' or by HP as an 'Interfacial Fracture of BGA Packages…'[1]. An ITRI (Interconnect Technology Research Institute) project to investigate this E.Ni/I.Au problem was initiated about year and a half ago.

Since the electroless nickel / immersion gold board finish performs satisfactory most of the time, in most applications, there has to be some areas within the current chemistry process window that is satisfactory. A 24 variable experiment was developed to investigate what parts of the chemical matrix are satisfactory to use and which parts of the chemical matrix need to be avoided. This paper describes some of the activities that have occurred on the ITRI consortium, from the design of the test vehicle to building hundreds of BGA assemblies, then pulling those BGA assemblies apart and inspecting the results.

Introduction
The use of electroless nickel / immersion gold (E.Ni/I.Au) as a circuit board finish has grown significantly in the last few years. It provides a flat board finish, is very solderable, provides a precious metal contact surface and the nickel strengthens the plated holes. However, as the usage of E.Ni/I.Au increased, a problem was found 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, but it is very unpredictable. 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.

This interfacial fracture problem also occurs on other component pads, such as on QFP pads. It appears to occur more frequently on finer pitched parts with smaller pads, than on larger pads. However, since these peripheral leader parts can usually have the joints touched up, without removing the component, the defect is often not reported.

This ITRI project was approved in August 1998 to investigate this problem and find a solution. The project was presented at the IPC Summit on PWB Surface Finishes and Solderability, September 22-23, Bloomington, Minnesota. and received tremendous interest.

ITRI Problem Statement
Fracture solder joints have been reported on BGA solder joints at the nickel/gold interface on circuit boards using electroless nickel / immersion gold finish. The gold has been dissolved into the solder (ball) and a non-wet nickel surface remains.

ITRI Objectives of Goals
- Be able to reproduce the open solder joints in order to investigate their cause, using a test vehicle which is both conductive to inducing the defect and failure analysis of it.
- Analyze the defect to determine the cause.
- Find a solution for this finish or a comparable replacement finish with all 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), LeaRonal, MacDermid, Merix, NSWC Crane (US Navy), Praegitzer, Sanmina (Altron), Solectron and Trace Labs.

Background

Most boards produced with E.Ni/I.Au surface finish work satisfactory most of the time, for most applications. Based on that, the project focused on testing the existing chemistries within their current operating windows, but to test to the extremes of those operating windows. Brainstorming sessions were held to identify those parameters that were thought to be potential causes of the problem. A test matrix was developed from those sessions. Round 1 of the program would hopefully identify the part of the chemistry operating window that is causing the problem and that part that does not. Round 2 would verify the revised operating parameters and that the defect could be turned on and off. A Test Vehicle (TV) had to be designed and built, that would be able to demonstrate the bad joint and be manufacturable in pseudo manufacturing environment. In spite of the defect occurring on more than BGA parts, emphasis would be placed on BGA designs.

It was desirable to provide an industry benchmark board finish in the project. OSP was chosen as the benchmark finish. There was also a desire to test some alternate finishes, just in case a satisfactory solution could not be found for the current E.Ni/I.Au finish, or in a suitable timeframe.

Chemical Test Matrix

A number of sessions were spend brainstorming, in order to attempt to determine the potential causes of the brittle joints. Most boards built with E.Ni/I.Au perform satisfactory for most applications. Therefore, 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:

- 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.

Based on the work that was already in process by HP [1] and some others, phosphorous level was a suspect that would be tested at its low, mid and high values. Age of the nickel and gold baths were suspect and would be tested at new or 0 MTO (Metal Turn Over) and old or 5 MTO bath. Thickness of the nickel and gold were also suspect. The nickel would be tested at approximately 75 micro inches and 200 micro inches. The gold would be tested at the normal immersion thickness and at approximately 60% of that normal thickness. A question raised was whether the increased porosity of thinner gold would cause a solderability problem.

The above parameters would be varied at the same time to check for interactions. Three different chemistries would be tested. The test matrix was finalized in a half factorial design, with a few repeats. See Table 1: Test Matrix for the full plan. The E.Ni/I.Au chemistries would be applied at three board fabricators, in their production lines. To minimize variables between board fabricators, all of the boards would be fabricated by one supplier. The solder mask would also be applied by the same fabricator, before the E.Ni/I.Au finish was applied.

Test Vehicle

The objective of the TV (test vehicle) was 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.

It was also a requirement that the TV be readily built by the board fabricators, have the E.Ni/I.Au chemistry applied in their production environment, reproduce the defect, be assembled in a production assembly environment, separated into individual coupons and tested in an economical and timely manner.

We initially considered using dummy BGA components. However, such components are very difficult to grasp and pull off a board without them cracking. We also wanted all of the joints to fracture at the same time in order to measure the total pull force. From HP's experience [1], it was determined that both the 'component' and board could be made with FR4 material. If the BGA design is symmetrical but the packages are each rectangular in size, they can be assembled at 90' to each other, forming a small cross. This cross structure, can be readily grasped with a fixture in an Instron and the assembly pulled apart.

The HP TV had 25 I/O BGA pads that are isolated from each other [1]. It was desired to have more pads than 25, to provide a greater chance of finding the random occurrences of the defect. A 100 I/O pattern was agreed on. It was also desired to have some of the pads connected, since there was a concern that interconnections of pads had some affect on the defect and real boards have pads connected to each other. It was also felt that via holes may have an affect on the deposition of the E.Ni/I.Au. The BGA pads that were connected together had robust 'dog bone' traces connecting to adjacent via land.

The 'component' side of the BGA package was designed to reflect many component type packages with solder mask defined pads. The copper pads were approximately 0.033" diameter with a 0.025" solder mask opening. The board side 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.

With a 10 x 10 I/O pattern, it was found that a symmetrical arrangement of connected and none connected pads could be made. 4 corner and 4 center pads were isolated from all others. Other pads all had traces to their adjoining via land and the via lands were connected in 2's, 4's, 8's and 12's. All via holes were to be drilled with a nominal 0.0135" drill. Figure 1 shows the symmetrical interconnection pattern that was used.

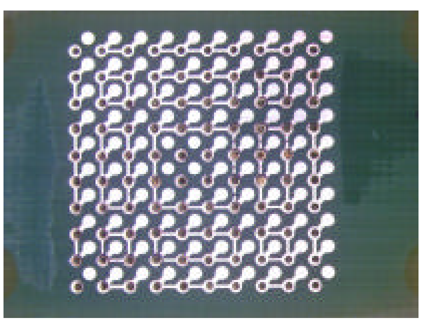

Figure 1 - 100 I/O BGA Pattern

It took a couple of iterations in the design in order to obtain a design that optimized an 18 x 24" panel and was easily assembled and separated for testing. The first design had break-off knubs between coupons. These knubs were awkward and time consuming to remove from each coupon. If the knubs were left on, they interfered with the placement of the component. The spacing of the individual coupons were also too close to each other and interfered with the adjacent component. The second design still was too difficult to build and separate for the quantity of parts that had to be made.

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 aid in automatic parts placement.

The TV has 6 mini panels per 18 x 24" panel. Each mini panel is approximately 7.25 x 7.9". Three mini panels have the 'component' side solder mask defined pad design. The other three mini panels have the board side, copper defined pad design. This layout will permit both halves of each tested coupon to have the same E.Ni/I.Au chemistry.

Each mini panel 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 would permit additional analysis of the finishes if necessary.

Board Fabrication

To minimize some variables from multiple fabricators building the boards, all of the boards were fabricated by one supplier, IBM, Endicott. Solder mask was also be applied by IBM, before the E.Ni/I.Au was applied. One third of the boards had the Ni/Au applied by IBM, with their E.Ni/I.Au chemistry. One third of the boards were sent to another board fabricator, JMACI, who applied their E.Ni/I.Au chemistry. The final third of the boards were sent to a third board fabricator, Hadco, Santa Clara, who applied their E.Ni/I.Au chemistry.

Assembly Matrix

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 no assembler on the project had that 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 paste and then reflowing the paste. This would entail using a thick stencil with a large aperture.

Some quick experiments were run to find a suitable solder paste stencil thickness and aperture size. The desire was to create a eutectic solder ball the same size as normally occurs on a 0.050" pitch BGA and result in approximately a 0.025" standoff of the component to the board. Calculations indicated that we would need approximately a 0.018" thick stencil with a 0.040" diameter aperture. The first attempt was made using a 0.018" thick stencil and various sizes of apertures. However, with the solder paste normally used for board assembly processes, there was poor and inconsistent paste release from the stencil and a lot of solder bridging occurred with the large apertures.

More consistent results were obtained using a 0.010" thick stencil and an aperture size of 0.038". This would result in an approximate 0.012" standoff between the 'component' and the board. This was a lower standoff that desired, but it is about the height of a standoff on some CSP (Chip Scale Package). This 'balling' process was still a challenge to prevent solder bridging. It was found to perform best when the reflow was done in air instead of a nitrogen environment to minimize solder bridging. Next time we would most likely try a 0.012" thick stencil with a 0.035" diameter aperture or preformed solder balls.

All of the boards from the three board fabricators, were be sent to one assembler, Solectron. This was to minimize variables between different assembly processes. Solectron received two sets of mini panels for each 'component' and board type from each of the 27 chemical tests, times three chemical suppliers, plus the OPS benchmark. Total 164 mini panel sets.

The requirement was to create BGA assemblies. 'Components' from the same panel, which had the same E.Ni/I.Au chemistry were to be assembled to a board side from that same panel. The first step was to label all of the parts, so that the correct 'component' type would be placed on the correct board type. Then all of the solder balls had to be made on all of the 'components' by screen paste with the thick stencil and large aperture. The 'component' mini panel was reflowed to create the solder balls. All of the 'components' were inspected and any with bridges or missing balls were X'd out.

Each of the 25 'components' were separated from the 164 'component' mini panels. The 164 matching board side mini panels were screen pasted using a standard 0.006" thick stencil with a 1:1 aperture to pad size, or 0.025" diameter aperture. The good 'components' were placed onto the board side mini panel and reflowed. This created up to 25 BGA coupons per mini panel times 164 mini panel sets or 4100 BGA assemblies, if they were all good.

All of the BGA assemblies were X-rayed to check for opens or solder bridges. All defective parts were marked, to exclude them from the pull testing.

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. 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 to nickel interface.

Since the 'component' Cu pad is significantly larger (0.033") than the Cu pad on the board side (0.025") and the component pad has solder mask on its edge, no fails were anticipated at this location #1.

Since we have not seen a problem with nickel peeling from copper and it has not been reported as a problem in industry, no fails were anticipated at interface locations #2 and #6.

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.

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. NSWC Crane modeled this theory to verify that we should not see any fails in bulk solder at this pull rate, before the tests began. Therefore, we should not find any fails in the bulk solder, at interface #4.

Desired Failure

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 interface #7. The copper BGA pads should all be ripped off the boards. The actual results showed that this failure interface had to be split in two. The 8 pads that were isolated could be ripped totally off the board. The remaining 92 pads were connected to via lands by a wide trace. These pads could be lifted off the board, but still held by the trace. The BGA pads were left standing up in the air.

Instron Pull Testing

After assembly, the parts were be sent to a couple of test locations, NSWC Crane and Trace Labs, who would pull the BGA coupons apart. There were two sets of assemblies made from each segment of the test matrix. One set went to NWSC Crane and the other to Trace Lab. The Instron maximum pull force would be recorded, and then the parts would all be inspected to determine the mode of separation of all the 100 BGA solder joints.

Fixtures for the Instron had to be designed and both fixtures were built at the same location. Since the assembly was in a small cross, then fingers on the Instron fixture could grip the assembly from each side of the cross and rip it apart. The Instron at each location was set to pull at 0.05"/second. Both used 1000 Lb. Load cells.

The BGA assemblies were built and still attached to the board side. The individual BGA coupons were broken out of the board, along the score lines as required.

Since the BGA coupon was made from 0.060" thick FR4, it would readily bend when pulled apart on the Instron. This bending would cause the solder joints to separate from the edge of the package to the center, in a series of fractures. That would prevent obtaining a total pull force. Therefore, stiffeners had to be applied to each side of each BGA package to hold it flat, so that all of the joints would separate at the same time. Aluminum stiffeners approximately 0.125" thick, 0.50" wide and 1.5" long had to be cleaned, then epoxied to each side of each BGA coupon. One side had to be epoxied and cured at a time, with the aluminum stiffener on the bottom, to minimize epoxy running through the via holes. Then the BGA coupons could be pulled on the Instron.

Initial testing was started at NSWC Crane with representatives from Trace Labs and Celestica in attendance. Testing was started with 7 of the 25 coupons per test matrix and six cells from the test matrix. Trace took ten of the remainder from the 25 pieces from the first six cells that NSWC Crane tested, to verify that they would obtain comparable results. When Trace had satisfactory results, to Crane, each continued testing their parts.

It was decided to initially test at least 7 coupons per cell. NSWC Crane and Trace Lab would duplicate each cell. When workload became too great, duplication of cells was discontinued, to get the testing completed.

All of the pull data and point of solder joint separation data had to be recorded for each coupon. This data then had to be analyzed back against the test matrix

Inspection after Instron Pull Testing

All of the parts had to be inspected after Instron pull testing. Counts had to be made of all 100 I/O and separated into the mode of failure. As mentioned in the Failure Modes, three locations or modes of failure were expected. However based on actual results, it was decided to add an 8th mode, splitting the last #7 category in two:

#3 Solder to Ni shear at component side
#5 Solder to Ni shear at board side
#7 Rip Cu pad off board side
#8 Lifted Cu pad from board side

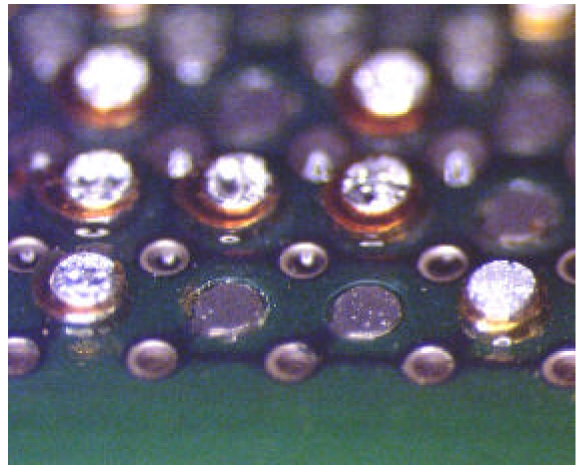

Figure 2 - Type #3 (shiny) and #5 (Gray) Fails

The 4 corner pads and 4 center pads that were isolated from all other circuits and with no trace to the adjacent via land often ripped totally off the board. The remaining 92 pads with traces to the adjacent via land usually would be ripped from the FR4 on good joints, but still held by the trace. The pad would be left standing up on end. Occasionally on a good joint, some of these pads would get ripped off the board as well.

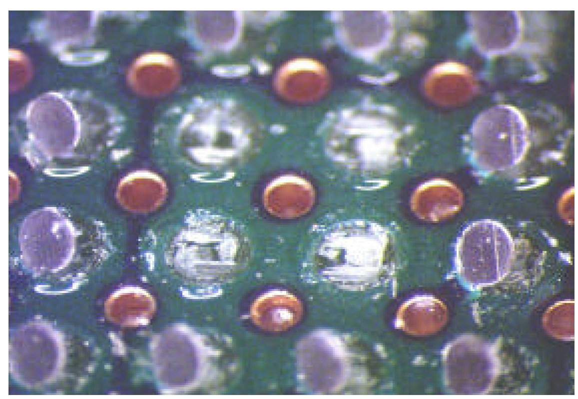

Figure 3 - Type #7 Ripped and #8 Lifted Pads

Nickel / Gold Thickness Measurement

During 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 makes of XRF units at multiple locations. The results of this round robin showed considerable variation in thickness readings on the same features. This information made the initial thickness readings of nickel and gold questionable. Comparisons of results would be difficult. Samples of the solder spread coupons from each cell of the test matrix are now being re-measured twice, on two different makes of XRF units.

Results of E.Ni/I.Au Testing

1. No 'black' pads were seen on any of the parts. There were varying degrees of gray found on the many flat pads.
2. The desired result was to have all of the pads ripped off the board side, or at least lifted off the board side and standing up in the air, held there by the thick trace connecting the BGA pad to the via land. It was expected that these ripped / lifted pads would also create the highest Instron pull strength. This alignment of high pull values to all good results did not always occur.
3. The Instron pull strengths varied from lows of 40 to 60 lbs. on bad parts to highs of 130 to 160 lbs. with mixed results. An example of parts from the test matrix with good type #7 and #8 joint separations had pull strengths of 84 to 147 lbs. An example of parts with a mix of bad type #5 plus good type #7 and #8 joint separations had pull strengths of 83 to 136 lbs. The pull strength along does not differentiate good from bad or suspect parts, based on the good verses bad criteria used in this experiment. The ideal test would be to pull every solder ball connection (410,000 of them) separately, which would be impractical.
4. The OSP finished boards, that were used as a benchmark, had pull strengths from 116 to 152 lbs. All of the BGA solder joint separations were type #7 ripped or #8 lifted pads. These pull strengths were slightly less than the best E.Ni/I.Au board.
5. Not all of the planned parameters from the test matrix were achieved. Changing more than one variable at a time resulted in deposition rates changing. All of the parts are being re-measured to verify the actual nickel and gold thickness and phosphorous percent achieved.
6. Based on the varying results from the XRF round robin testing, samples every cell of the test matrix are being re-measured on two different types of XRF unit. The actual results will be placed back into the test matrix.

Alternative Finishes Testing

In case no fix could be found for the E.Ni/I.Au 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 E.Ni/I.Au. The emphasis would be 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 would be kept separate from the other E.Ni/I.Au parts to prevent impact to its schedule.

These boards were assembled and tested at Celestica. The same processes were used in the build and testing of these parts as those used on the main test matrix on the E.Ni/I.Au boards. The following board finishes were tested on the same TV:

- electroless nickel / immersion gold
- electrolytic nickel / immersion gold
- electrolytic nickel / electrolytic gold
- electroless nickel / electrolytic gold
- electroless nickel / electroless palladium / immersion gold
- electroless palladium / immersion gold (0 MTO)
- electroless palladium / immersion gold (3 MTO)
- immersion silver
- OSP (benchmark)

The E.Ni/I.Au boards were from the same build as the main test matrix. They were boards from duplicates in the matrix. The other board finishes were applied by two of the board fabricators and a chemical supplier. Two samples of each of the electroless palladium / immersion gold were requested. One sample was requested to be made from a new gold bath (0 MTO) and a second sample made with an average age gold bath (3 MTO). This test was to check for possible impact of nickel accumulating in the gold bath that might deposit on the palladium. Two palladium thicknesses were also received from one fabricator.

Results of Alternate Finishes

1. No 'black' pads were seen on any of the parts, the same as above.
2. The results of all the finishes showed a far greater range of pull strengths than those obtained from the E.Ni/I.Au test matrix.
3. Excellent results were obtained from OSP, electrolytic nickel / electrolytic gold and silver. Electroless nickel / electroless palladium / immersion gold results were also very good.
4. Some fairly good to very bad results were obtained from the electroless palladium / immersion gold boards. These poor results do no match Celestica's previous experience with this E.Pd/I.Au finish in these thicknesses. Analysis has not been done on these boards to attempt to determine any cause for the poor results.
5. There was no significant difference in results between the electroless palladium / immersion gold boards from a new gold bath verses those from an averaged gold bath.
6. There was a significant difference in results between thick (15 micro inches) palladium and thinner (8 micro inches) palladium. Thick Pd averaged 87 lbs. pull strength with a lot of type #3 and #5 failures. The thinner Pd averaged 132

lbs pull strength, with all type #7 and #8 separations.

Additional Testing and Analysis

In addition to the build and test of the TV's, there has also been a lot of additional testing and analysis of the E.Ni/I.Au chemistries and plating processes. Some of this analysis has lead to discovery of the cause of the black pad phenomenon. Analysis has also been conducted on real product that has revealed black pad, to relate it back to the cause.

Conclusions

1. The test results revealed good to very poor solder joints. Therefore there are areas of the chemistry matrix that should be used and areas that should be avoided. However, no black pads were found.
2. All of the points on the chemical matrix that were planned were not achieved due to interactions of the chemistry when more than one variable is changed at the same time.
3. At the time of writing the report, the actual nickel and gold thickness values and phosphorous percent are being re-measured. The chemical suppliers must retrofit the original test matrix with the actual results to determine their best operating range.
4. The results showed varying pull strengths. However, a high pull strength on 100 I/O BGA package did not 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 at the same time as this project, the root cause of the black pad problem has been identified, that being the gold attacking the nickel. Nick Biunno from Hadco, Santa Clara has defined the various stages in the development of the black pad. He has prepared a paper describing the details found. Amkor found the gold attacked the nickel as well [3]. HP believed that gold was the problem based on their last experiment [2].
6. Based on additional analysis that was conducted at the time of this project, it has been determined that board design has some bearing on the incidents of black pad.
7. Another round of testing will be required to focus 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.
8. It is desired to use preformed solder balls on the next round of testing to minimize variations in screen pasting of solder balls. If not, a slightly thicker stencil with slightly smaller apertures may reduce solder bridging when creating the 'component' side solder balls.
9. Electrolytic nickel and gold provided all good results, however, it is difficult to get adequate nickel plating in small via holes in thick boards. The throwing power of electrolytic nickel is not very good. Gold plating thickness varies considerable 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.
10. The electroless nickel / electroless palladium / immersion gold finish performed very well and requires more testing.

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
Auburn U.: designed the TV
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 E.Ni/I.Au finishes and a lot of analysis
Atotech: chemistry and technical support
HP: provided technical reports on their activity
IBM: Built all the TV's plus E.Ni/Au chemistry
ITRI: Parts stocking / sorting and telecon minutes
JMACI: one of the E..Ni/I.Au finishes
Praegitzer/Integraph: quick turn of TV Rev 2
LeaRonal: chemistry and technical support
MacDrermid: chemistry and technical support
NSWC Crane: round 1 Instron pull testing
Solectron: round 1 assembly
Trace: round 1 Instron pull testing

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Table 1 - Chemical Test Matrix

Sid	Run	Block	Factor Ni MTO A: old/new	Factor Ni B: thickness Low/High	Factor Au MTO C :old/new	Factor Au D: thickness Low/High	Factor P: Rate Low/Norm /High
4	1	**Block 1**	-1.00	1.00	1.00	-1.00	-1.00
10	2	**Block 1**	1.00	-1.00	1.00	1.00	1.00
17	3	**Block 1**	1.00	1.00	1.00	1.00	0.00
24	4	**Block 1**	1.00	1.00	1.00	1.00	-1.00
14	5	**Block 1**	-1.00	-1.00	1.00	-1.00	-1.00
11	6	**Block 1**	-1.00	1.00	1.00	1.00	1.00
18	7	**Block 1**	1.00	-1.00	-1.00	-1.00	-1.00
9	8	**Block 1**	1.00	-1.00	-1.00	-1.00	1.00
22	9	**Block 1**	-1.00	-1.00	-1.00	1.00	-1.00
5	10	**Block 1**	1.00	-1.00	-1.00	1.00	-1.00
3	11	**Block 1**	1.00	-1.00	1.00	-1.00	-1.00
23	12	**Block 1**	1.00	1.00	1.00	1.00	0.00
12	13	**Block 1**	-1.00	-1.00	-1.00	1.00	1.00
6	14	**Block 1**	-1.00	1.00	-1.00	1.00	-1.00
19	15	**Block 1**	-1.00	1.00	-1.00	-1.00	-1.00
27	16	**Block 1**	-1.00	1.00	-1.00	-1.00	1.00
25	17	**Block 1**	-1.00	-1.00	1.00	-1.00	1.00
13	18	**Block 1**	1.00	1.00	-1.00	1.00	1.00
15	19	**Block 1**	-1.00	1.00	-1.00	-1.00	1.00
16	20	**Block 1**	1.00	1.00	1.00	-1.00	1.00
21	21	**Block 1**	1.00	1.00	1.00	-1.00	-1.00
26	22	**Block 1**	1.00	-1.00	-1.00	-1.00	1.00
2	23	**Block 1**	1.00	1.00	-1.00	-1.00	-1.00
20	24	**Block 1**	-1.00	-1.00	1.00	-1.00	-1.00
1	25	**Block 1**	-1.00	-1.00	-1.00	-1.00	-1.00
8	26	**Block 1**	1.00	1.00	1.00	1.00	-1.00
7	27	**Block 1**	-1.00	-1.00	1.00	1.00	-1.00

Factors		**Quantitative data**	**Response factor**
1.	**Ni new**	**0 MTO**	**-1.00**
2.	**Ni Old**	**5 MTO**	**1.00**
3.	**Ni thickness low**	**75 microinches**	**1.00**
4.	**Ni thickness high**	**200 microinches**	**1.00**
5.	**Au new**	**0 MTO**	**- 1.00**
6.	**Au Old**	**5 MTO**	**1.00**
7.	**Au thickness low**	**2 - 3 microinches**	**1.00**
8.	**Au thickness high**	**4 - 7 microinches**	**1.00**
9.	**P content**	**Low 6 - 7 %**	**1.00**
10.	**P content**	**Normal 7 - 9 %**	**0.00**
11.	**P Content**	**High 8 - 10 %**	**1.00**