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Maximizing Lead Free Wetting

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Abstract
As lead free assembly is ramping up, wetting of lead free solder pastes is surfacing as the major paste performance tradeoff. Global efforts to significantly increase lead free wetting chemically have proven unproductive to date. The “drop in” lead free paste with respect to wetting looks to be improbable. This paper reports the findings of numerous studies using quantitative wetting gauges to measure solder paste wetting to the PCB surfaces. Wetting results with various lead free profiles, reflow atmosphere oxygen concentrations and lead free PCB surface metallizations are compared and contrasted for their contribution to maximizing lead free wetting. Although numerous lead free alloys are on the market today, this paper concentrates on the popular SAC (Sn/Ag/Cu) alloy specifically 95.5/4/0.5 in a no clean paste. In addition to wetting, solder defects and voiding are included in the comparisons to reveal the best overall lead free reflow process.

Introduction
The initial driver for the move away from lead-bearing materials in electronics assembly was the concern of lead contamination in ground water near land fills due to the leaching of lead from discarded electronic assemblies. Current drivers vary as reported in the 12/2003 Prismark Partners report[1]. A study conducted by Soldertec of Tin Technology Ltd reported in their 2003 European solder survey (Figure 1) that only 14% of their survey is moving towards lead free assemblies for the original environmental reason and that the majority of customers are reacting to legislation as a prime cause. Marketing pressures to either have lead free manufacturing or be fully prepared by 2006 are worldwide, Japanese manufacturers are leading the way followed by global and European suppliers. The industry-wide move towards lead free assembly is being done in the absence of a “drop in” replacement for Sn/Pb solders. Lead free alloys require higher reflow temperatures due to the higher alloy liquidus temperatures (217°C - 219°C for SAC alloys) than that of eutectic Sn/Pb (183°C). Numerous studies have reported lower wetting performance; higher solder void content and a duller fillet finish. Wetting performance of lead free solder pastes is a direct result of the wetting angle of bulk alloy. As can be seen in Figure 2 the wetting angle of the SAC alloy is considerably steeper over copper than Sn/Pb. Wetting angle differences over gold are considerably less. To counteract this alloy physical property, chemists have been increasing the activator level in the flux with minimal impact to date. From a process standpoint there is much room for improvement although experts are tending to agree that matching Sn/Pb wetting may not be obtainable.

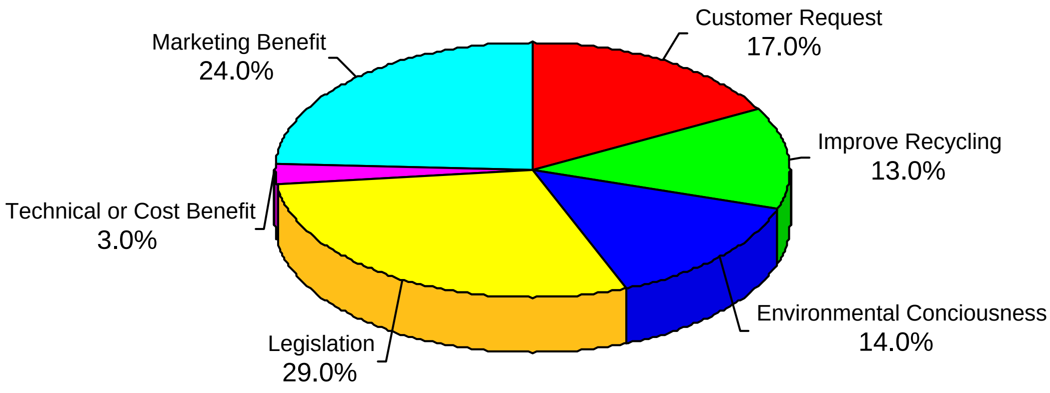

Figure 1 - 2003 Soldertec Survey

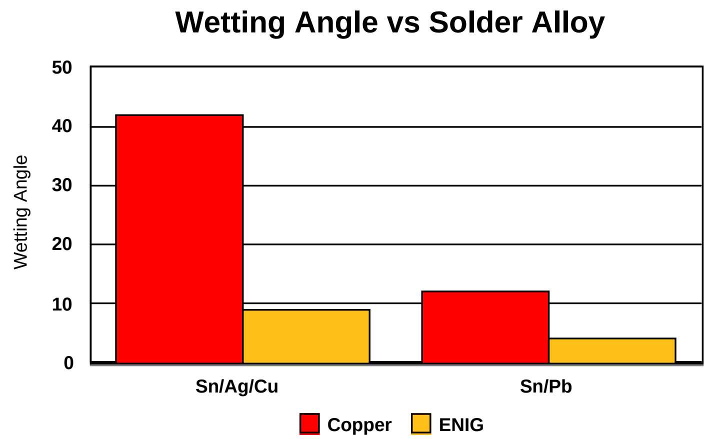

Figure 2 - Wetting Angles

Redefining the Process

Finding the best process and material set is relatively simple when working with Sn/Pb. There are numerous options of solder pastes in both no clean and water clean chemistries. Board finishes that yield excellent results are plentiful and paste sensitivity to reflow profiles are rare. With lead free we need to re-evaluate all main elements of the process and carefully select the solder paste formulation. To accomplish this we need sensitive and quantitative tools. Failure to accomplish this can result in excess rework due to wetting related defects such as miss-aligned components, tombstones, solder beads and balls.

Phase 1 - Finding the Best Profile

To begin the process of specifying the optimal profile, material suppliers must carefully study the cause and effect relationship of reflow profile and key performance attributes with the lead free formulations they are offering to the market. This process begins with quantitative tools to test key reflow attributes such as wetting, solder voiding, solder defect generation and even solder spitting or splattering that can contaminate connector fingers and wire bonding pads that are in close proximity to solder joints. Finding a profile that yields the best performance in all of the categories of attributes may not be possible but selecting the profile that yields the best *overall* performance is mandatory.

Table 1 details the main profile attributes of the 4 profile variants used in this study to identify the best overall profile for F620Cu0.5 89M3 which is a Class L rated no clean with the SAC alloy (95.5Sn/4Ag/0.5Cu). As can be seen in the table and Figure 3 of the actual profiles the key attributes varied were liquidus time and preheat style.

Table 1 – Main Profile Attributes of

Profile	Peak	Liquidus	Preheat
1	247	48s	Ramp
2	247	87s	Ramp
3	247	48s	Soak
4	247	87s	Soak

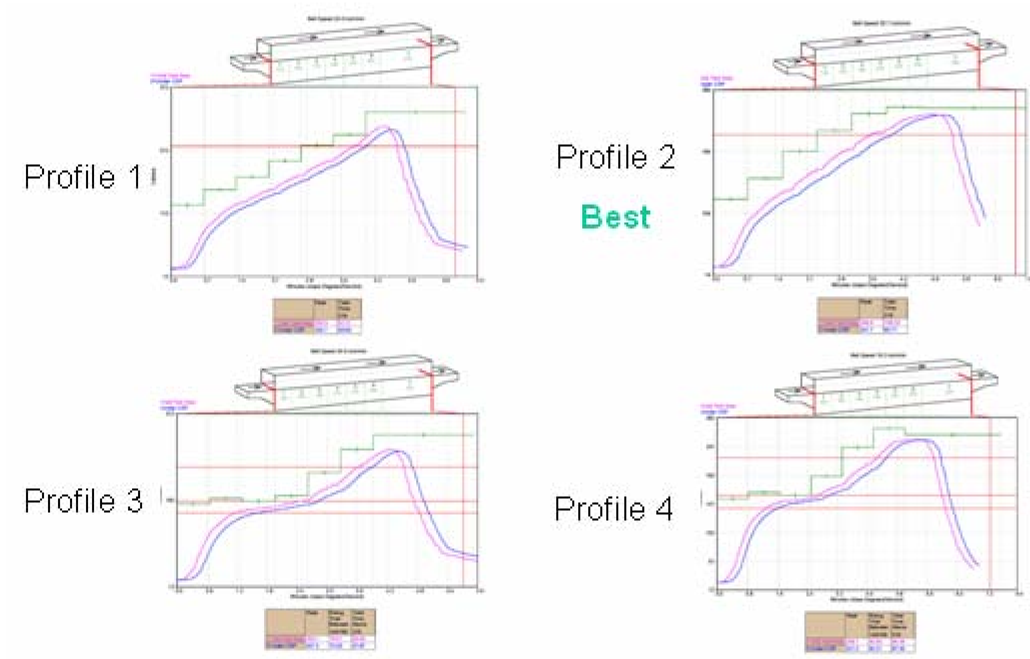

Figure 3 - Profile Matrix

Wetting Tests

Quantitative solder paste performance tests have been developed and utilized for paste benchmarking, process improvements and material selection using the *Benchmarker II* test board[2]. There are 4 wetting areas in the design as can be seen in Figure 4. In Area A the gap between each adjacent pad is increased by 1 mil rendering the difficulty of creating a bridge between printed pads of solder paste progressively more difficult as the gap increases, essentially creating a horizontal wetting thermometer. Gaps range from 10 to 85 mils. Areas B, C & D gauge pad wettability by printing varying coverages of solder paste onto round BGA, wide rectangular SOIC and narrow rectangular fine pitch pads respectively. These areas are inspected for which pads the reflowed solder was able to extend to the pad ends (Figure 5). The smaller the coverage, the more distance the solder has to wet to reach the pad ends thus increasing the difficulty of complete pad wetting. These tests provide 3 different pad geometry wetting thermometers. Results are reported in wetting points based on the paste coverage, with more points being better. As can be seen from the wetting results in Figure 6, Profile 2 yielded the strongest wetting. The profile screening tests were done in an air reflow atmosphere over an ENIG (Electroless Nickel Immersion Gold) board finish.

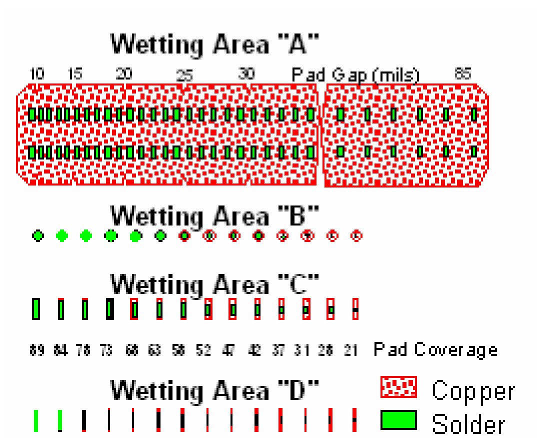

Figure 4 Wetting Gauges

Figure 5 - Wetting "C" Gauge

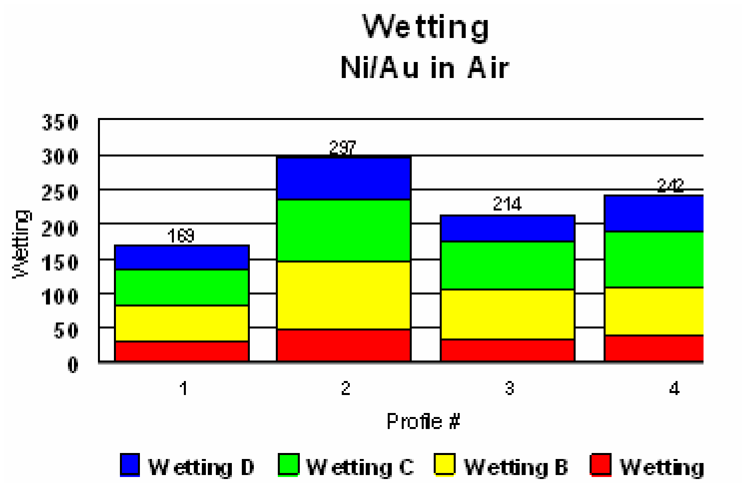

Figure 6 - Wetting Results

Passive Component Defect Tests

There are four passive chip "Stress Test" areas designed on the test board. Figure 7 is a section of the test board for 1206 chips with 0805, 0603 and 0402 test areas employing similar design logic. The first column is a series of chip pads varying the gap between the pads to the full range recommended by the IPC[3]. The next column has various stencil aperture designs that can be found on customer designs. The third column has intentional aperture misalignment. These different pad and aperture design elements are intended to push formulations to generate solder beads, balls and tombstones as well as provide a test media to evaluate stencil and pad design solutions to correct these common problems.

A solder bead is a large solder ball that forms on the side of chip components as in Figure 8. The origin of these beads can vary somewhat, but is mainly due to simply having too much solder under the center of the chip prior to reflow. Profile, inerted reflow, pad and aperture design can all contribute to solder beading. The number of chips with as little as one bead is recorded.

Solder balls are also inspected for as in Figure 9. Since the test board has no ground plane or internal traces it is possible to backlight the board and very easily inspect for solder balls. The solder balls are usually found in the "gutter" of exposed laminate between the solder mask and solder pad. Occasionally a solder ball is found some distance from the solder joint possibly from solder spitting during reflow due to paste or chip outgassing. The number of chips with as little as one solder ball is recorded.

Tombstones are also occasionally generated as in Figure 10. This usually in the third column of each chip array where the solder paste has been deliberately misregistered horizontally or diagonally.

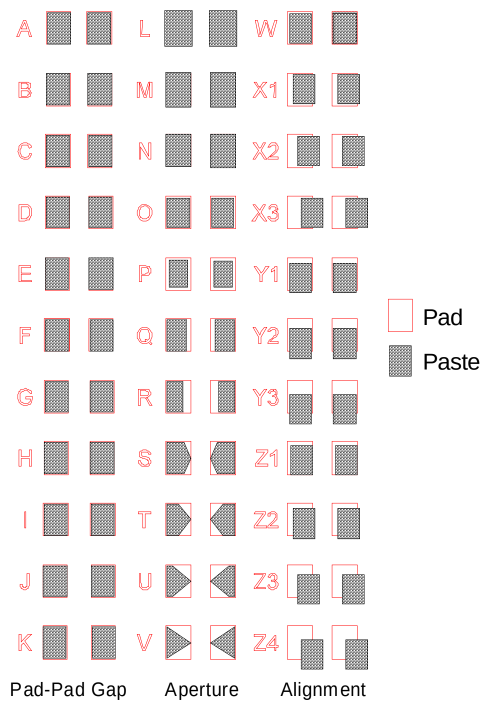

Figure 7 - Chip Defect "Stress Test"

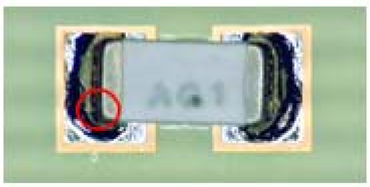

Figure 8 - Beads

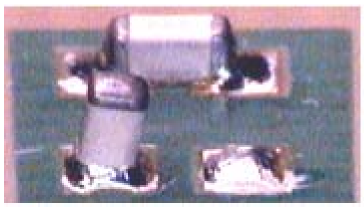

Figure 9 - Solder Balls

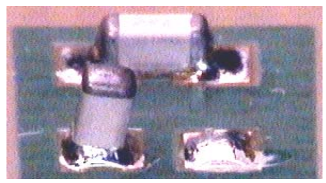

Figure 10 - Tombstone

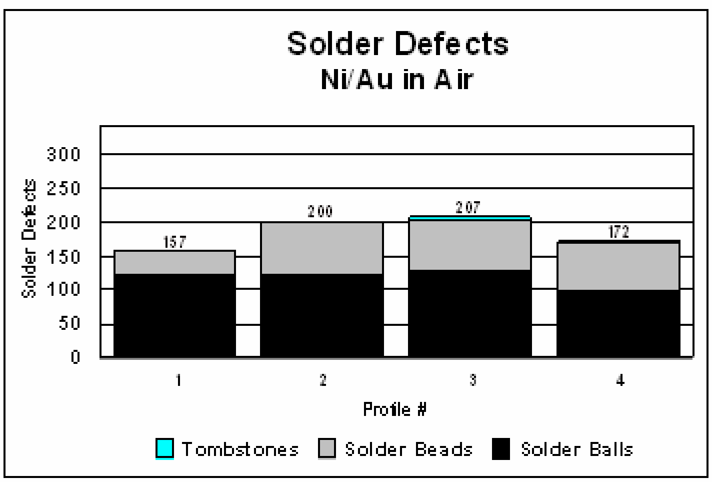

Figure 11 - Solder Defect Results

Profile testing results, as can be seen in Figure 11; indicate fairly similar defect levels when plotted against a scale of all potential defects.

X-ray Voiding

Based on the assumption that the ideal quantitative void measurement method will utilize BGA analysis software and a symmetrical Z-axis reflow structure, the "sandwich" concept was developed. This novel approach simulates the worst conditions of a solder joint for voiding, under the component where flux evacuation is the most difficult. This idea was borne out of a quest for a quantitative method of determining the percent voiding on a CCGA (Ceramic Column Grid Array) [4]. For solder paste void benchmarking a dedicated pad test area was included in the *Benchmarker II* test board. This allows the testing of solder pastes on standard PCB surfaces such as Entek OSP (Organic Solder Protectant) and ENIG (Electroless Nickel Immersion Gold). Quite simply, we are making copper sandwiches (Figure 12) that result in cylindrical structures which permit highly quantitative void analysis with standard BGA analysis software. For each paste, profile and board finish, 108 preforms are placed over solder paste, reflowed and X-rayed. The X-ray data is compressed into a single "point scale" to facilitate comparisons. These points (100 is best) are calculated as follows:

Points = (≤4% - ≥6%)

"% of structures with 4% total voiding or less minus the % of structures with 6% total voiding or more."

For the board finish and reflow atmosphere second phase of testing, 1mm pitch BGA's were included using a similar point assessment. Figure 13 shows that Profile 2 yielded the most points (lowest voiding) of all four profiles tested.

Figure 12 - Copper Preforms

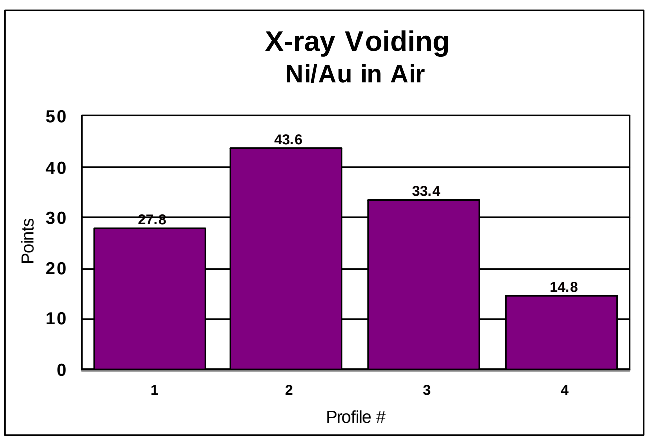

Figure 13 - Voiding Results

Spattering

Solder spitting or splattering is not unique to lead free solders, but critical to memory module and SiP (System in Package) assembly. In a large central portion of the test board used for printability testing, post reflow boards were inspected for evidence of splattering and plotted. As can be seen in Figure 14, the two profiles with a classic 140C-160C preheat soak yielded much higher splattering levels than the two ramp style preheat profiles that transition through these temperatures much more rapidly. Splattering tests were not performed in the board finish and reflow atmosphere second phase of testing because previous studies of splattering have indicated that it is caused by three mechanisms:

1. Profile.
2. Lead free passive component termination outgassing during reflow.
3. Incomplete stencil underside cleaning that transfers solder particles to the board surface.

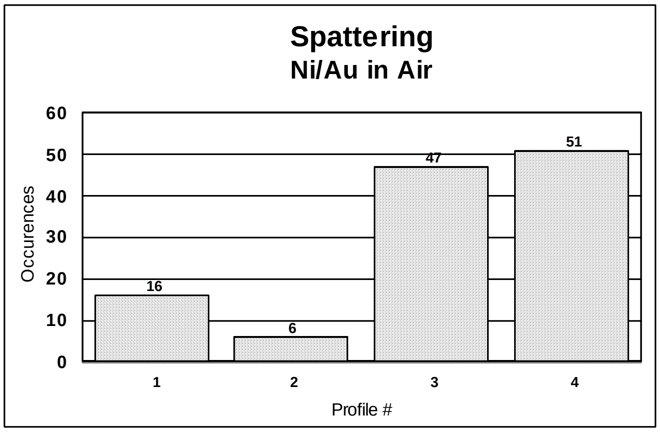

Figure 14 - Splattering Results

Phase 2 - Board Finish and Reflow Atmosphere

Now that it has been established that Profile 2 with the ramp style preheat and the longer liquidus time has maximized the wetting and minimized the solder voiding and splattering, it is time to explore the effects of board finish and reflow atmosphere. The wetting tests, solder defect tests and solder voiding tests were repeated with the addition of gauging BGA voiding on the following *Benchmarker II* finishes:

- ENIG (Gold)
- Entek (Copper)
- Immersion Tin
- Immersion Silver

Reflow atmosphere was also varied. The BTU FCB 7 zone oven was purchased with an O2 doping feature. This feature bleeds into the central portion of the oven metered amounts of air during nitrogen reflow. Oxygen content was measured in Zone 7 (Reflow) and adjusted from the pure nitrogen O2 level of 25ppm to the following levels, in addition to testing in straight compressed air (≈ 200,000ppm):

- 50ppm
- 100ppm
- 200ppm
- 400ppm
- 800ppm

In total, Phase 2 of testing had 4 board finishes in 7 reflow atmospheres.

Wetting

Wetting results (Figure 15) were somewhat expected. It was expected that the ENIG finish would have the strongest wetting from numerous internal studies. The low wetting response of the immersion silver as well as the relative lack of contrast in the O2 doping experiments however, was a discovery. The wetting of the ENIG was nearly 100X of the immersion silver. The tin finish came in third and the OSP (Entek) finished last, as expected. Photographs (Figure 16) of the far left side of wetting gauge “A”, which is the most sensitive area, illustrate these differences. On the silver immersion boards dewetting was observed. The photographs in Figure 17 of QFP leads show good fillet formation but incomplete pad wetting (red arrows) except for the ENIG finished boards.

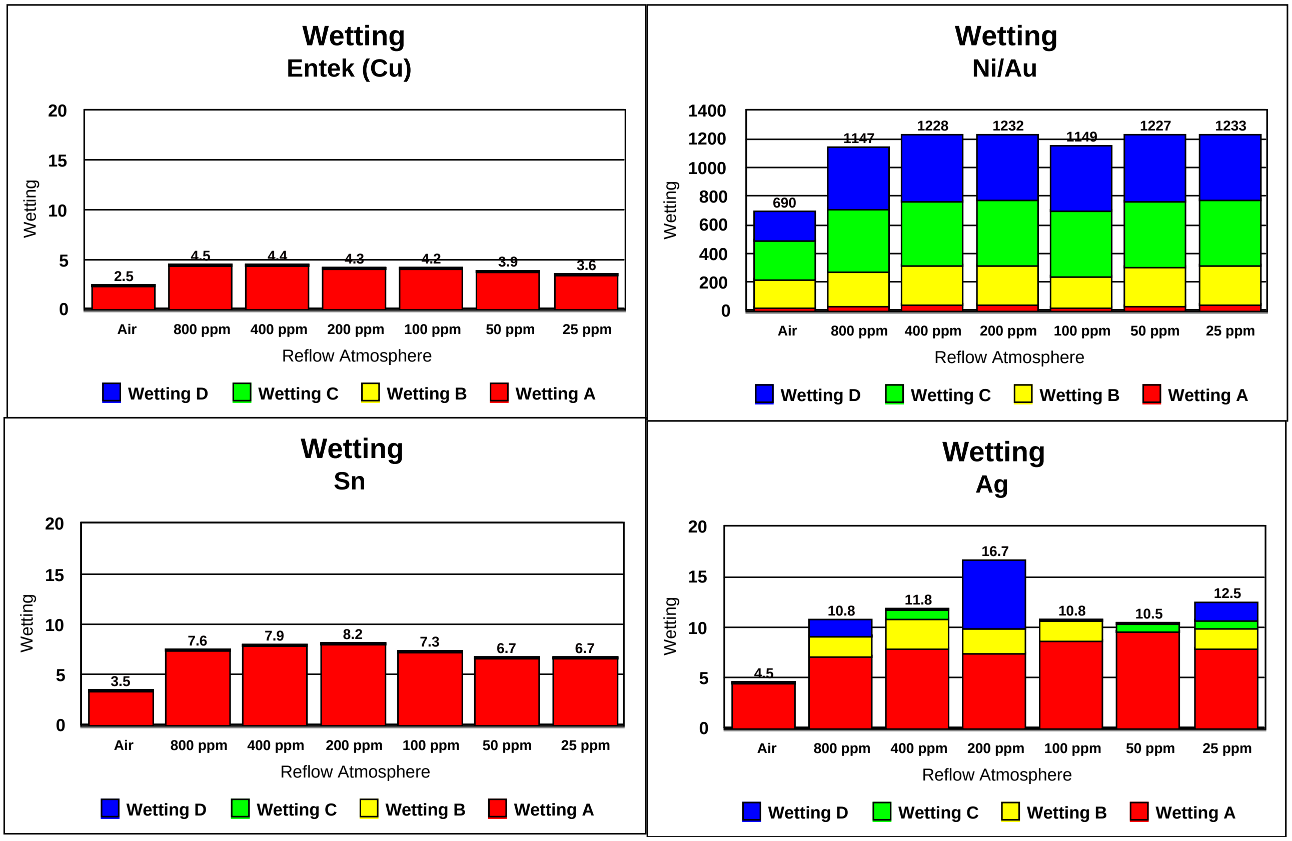

Figure 15 - Wetting Results

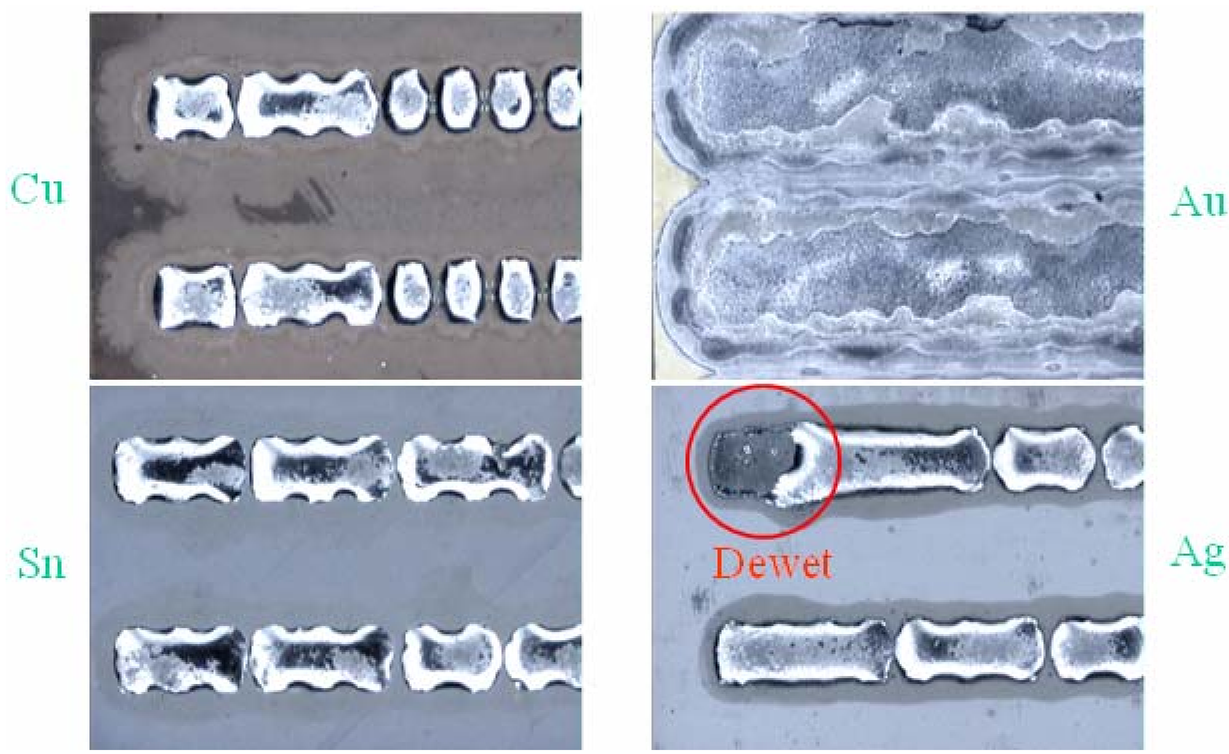

Figure 16 - Wetting Area "A"

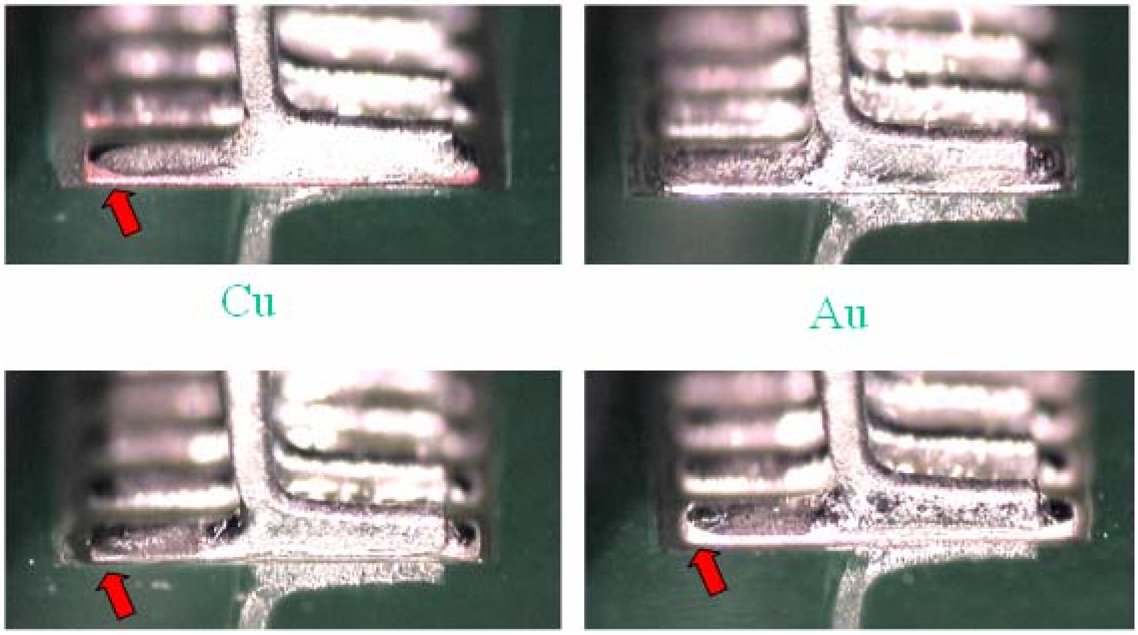

Figure 17 - QFP Wetting

Solder Defects

The solder defect results in Figure 18 show that the two precious metal based board finishes yielded the least overall defect levels. Once again the levels of O2 in the reflow section had little effect on defect levels except when comparing very low O_2 (25ppm) to pure air. The most contrast came from comparing the solder ball results of tin, the worst performing finish, to Entek (copper) which was the best for solder balling (red circles) as can be seen in Figure 19. These are 1206 chip capacitors on aperture design "L" which is overprinted by 20% (see Figure 7).

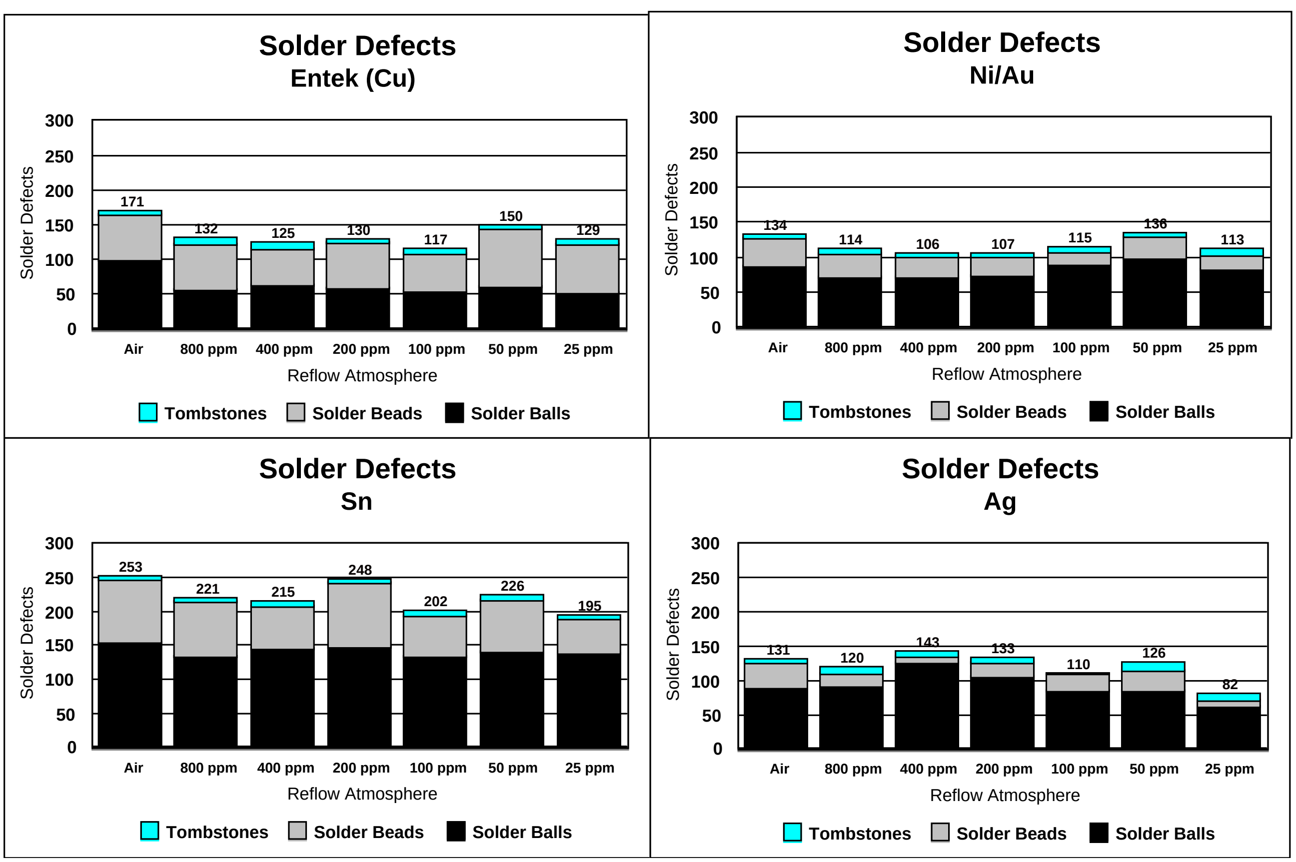

Figure 18 - Solder Defect Test Results

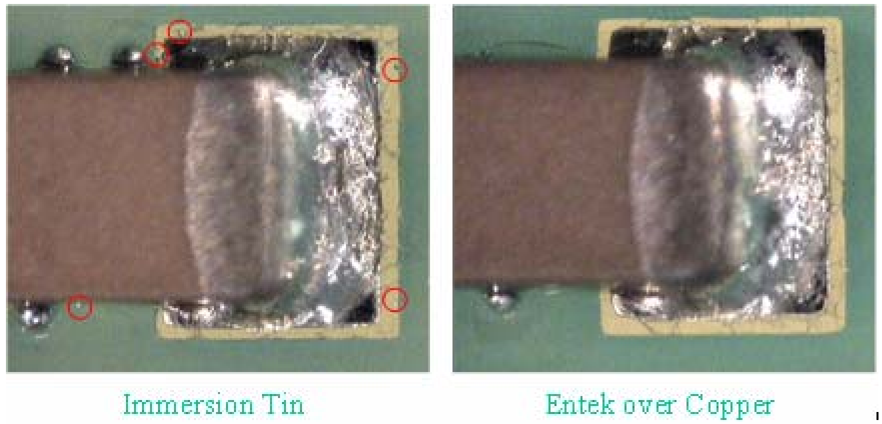

Figure 19 - Solder Balling on Tin

Solder Voiding

As with the wetting results, the solder void results (Figure 20) were somewhat expected. It was expected that the ENIG finish would have the lowest voiding from numerous internal studies. The high voiding (negative points) of the immersion silver, however, was a discovery. When the data was compiled, plotted and initially looked at it was theorized that the copper preforms and the silver pad finish combined with the acids in the flux system to form some sort of battery during the preheat that resulted in a byproduct that expanded into visible voids during reflow. Visual examination of the x-rays, however, revealed that the solder pads that had no copper preforms also had significant voiding and that the presence of the preforms simply amplified the voiding (Figure 21). Additionally, the relatively abundant large BGA void formations over the tin finish can be seen in Figure 22. The BGA's used for this study were Sn/Pb.

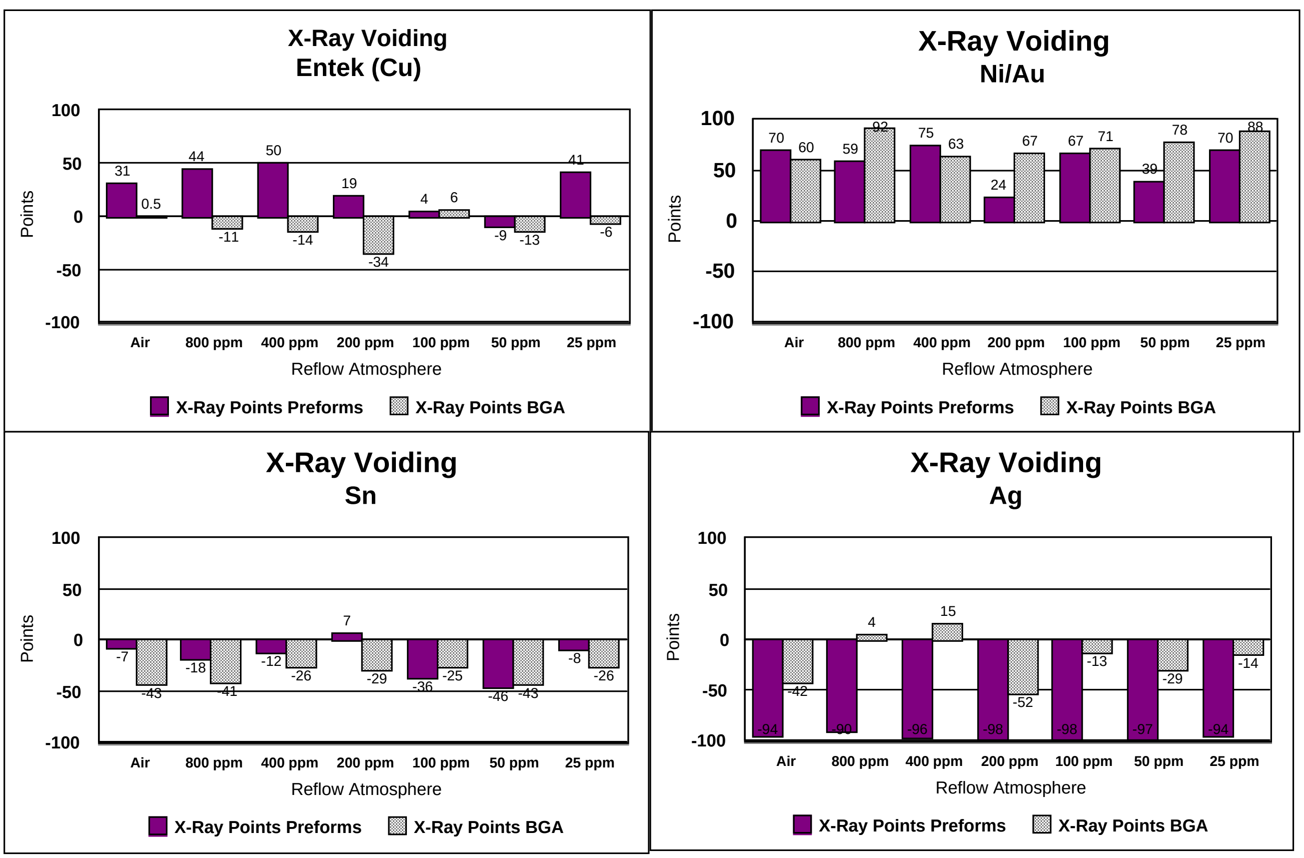

Figure 20 - Solder Voiding Results

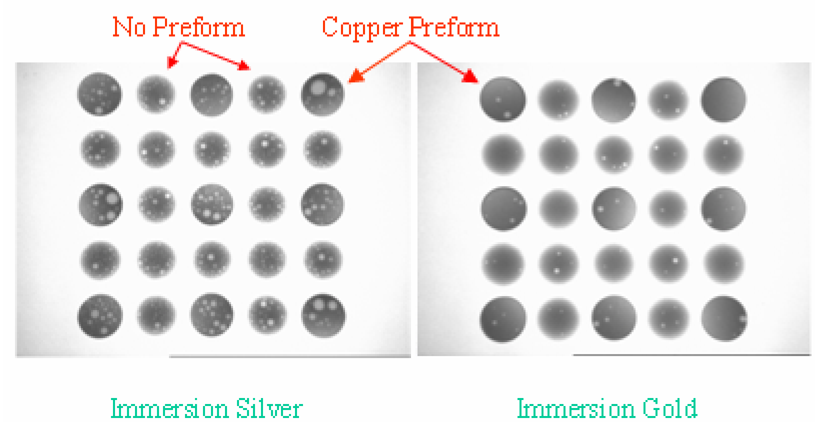

Figure 21 - Heavy Voiding over Silver in Nitrogen (25ppm O2)

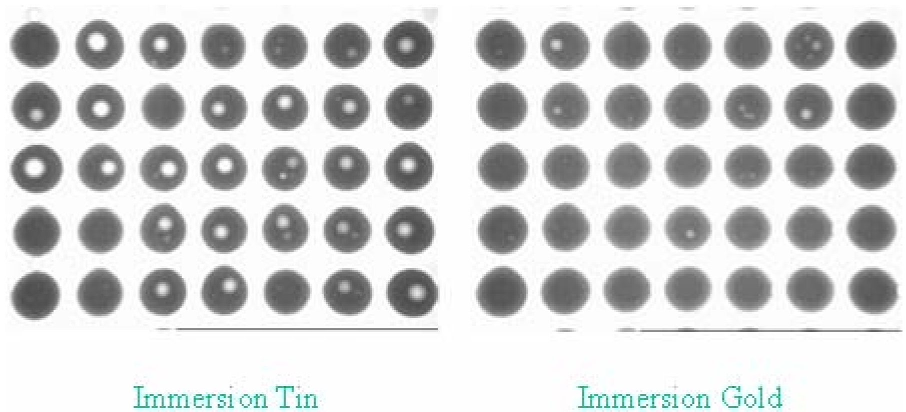

Figure 22 - BGA Voiding

Conclusions

- The best overall profile for the formulation studied is a ramp-to-spike style profile with a slightly extended liquidus time. Profiles with extended liquidus times have proven to be valuable for soldering to tin plated (lead free) components in the field even when using Sn/Pb solder pastes.
- Board surface finish had a greater effect on overall lead free performance than the reflow atmosphere O_2 content did.
- ENIG was overwhelmingly the best board finish tested with the best wetting and lowest solder voiding.
- Immersion tin, with only slightly better wetting than OSP coated copper (Entek), had high solder balling and BGA voiding behavior.
- Immersion silver did not demonstrate the strong wetting that ENIG did and produced the highest levels of solder voiding of all of the lead free finishes tested.

Acknowledgements

The author would like to thank Steve Fritzinger and Mitsuru Kondo for their tireless efforts in supporting this project.

References

1. Prismark 2003 (Soldertec of Tin Technology Ltd. European solder survey), 12/2003.
2. Richard R. Lathrop, *Defining Solder Paste Performance via Novel Quantitative Methods*, Apex 2003 Proceedings, Anaheim CA, 3/2003.
3. IPC-SM-782, *Surface Mount Design and Land Pattern Standard*, IPC, 4/1999.
4. Richard R. Lathrop, *Avoiding The Solder Void*, Apex 2003 Proceedings, Anaheim CA, 3/2003.

Maximizing Lead Free Wetting

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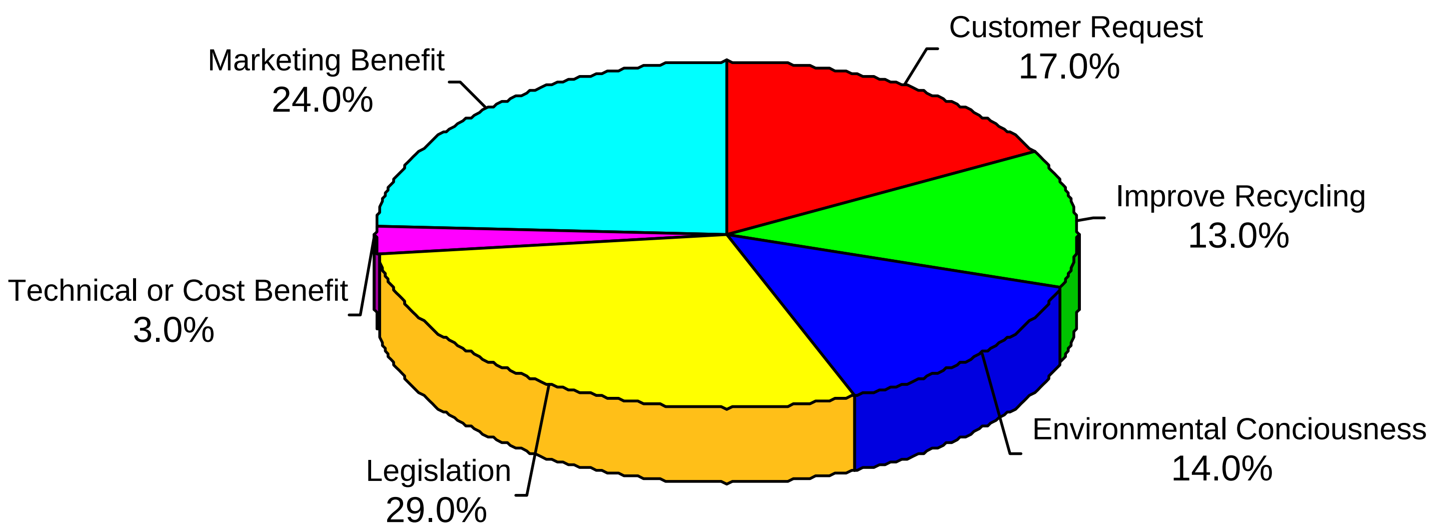
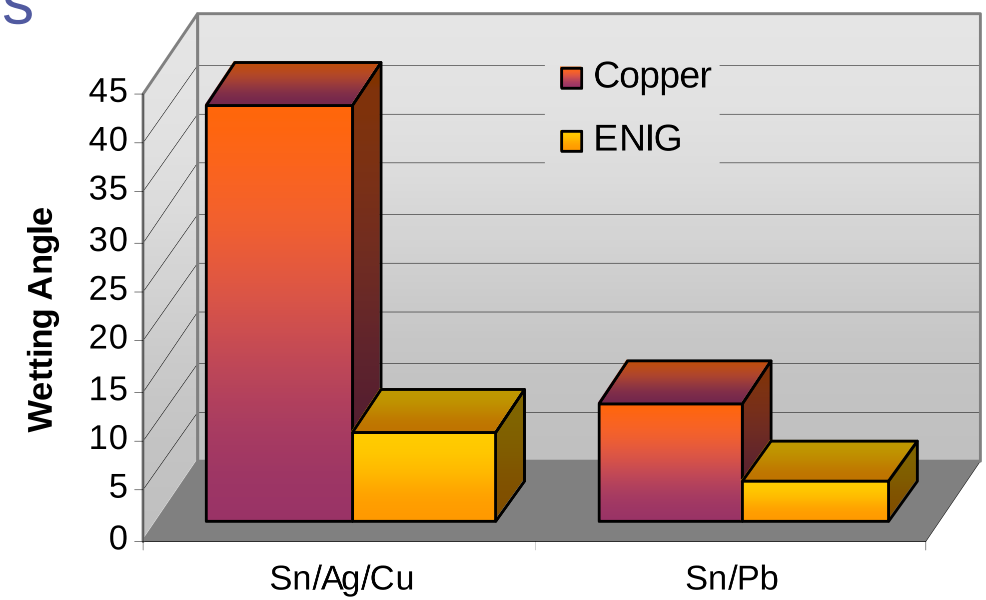
2003 Soldertec Survey (European Customers)



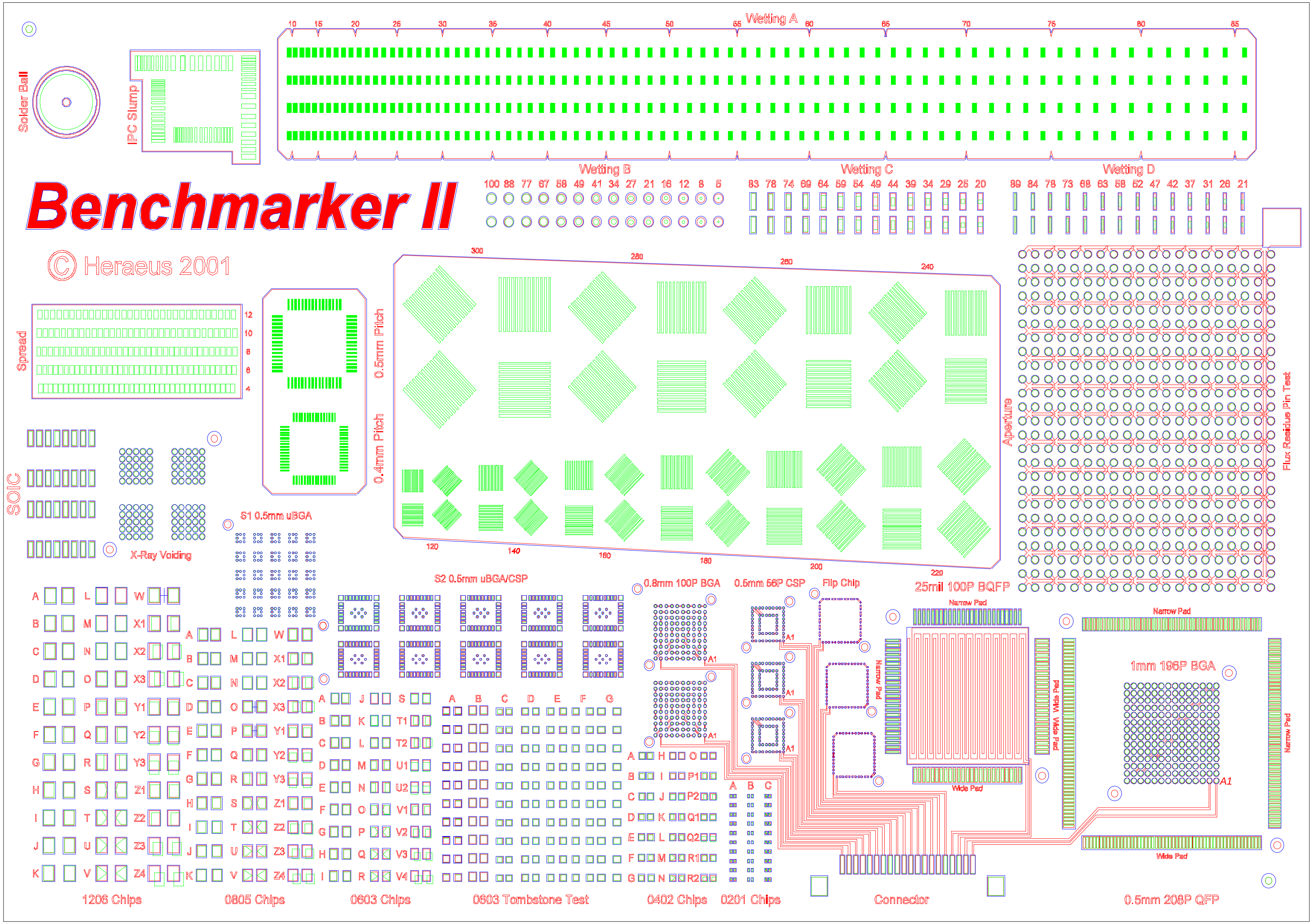
Lead Free Reflow Performance Trade-offs

- Steeper Wetting Angles
  - Copper most severe
- More Voiding
- Duller Appearance
- Higher Reflow Temperature

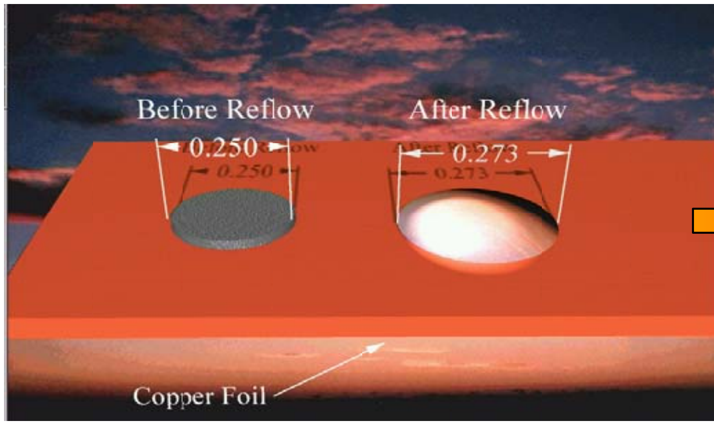


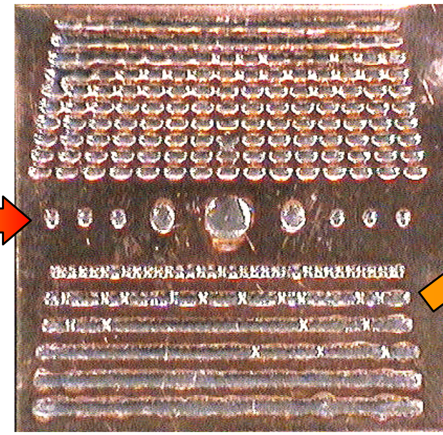
Testing Lead Free Reflow Performance

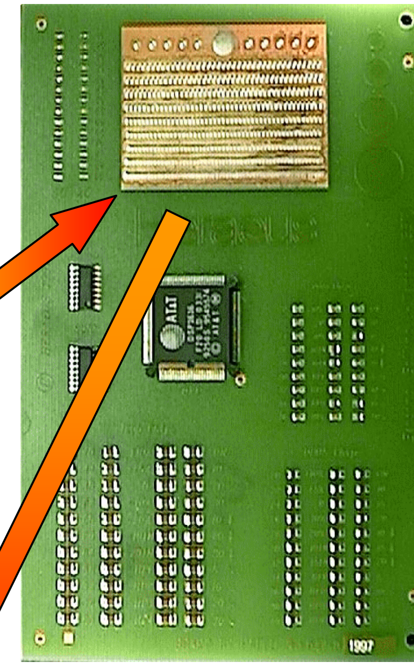
- *Benchmarker II* test board used
- Wetting main focus
- Optimal reflow performance is more than wetting
  - Solder Voiding
  - Solder Beads, Balls
  - Splattering
- Testing done with F620Cu0.5 89M3 (95.5Sn/4Ag/0.5Cu)
  - Phase 1: Finding the best overall Profile
  - Phase 2: Finding the best board finish and reflow atmosphere

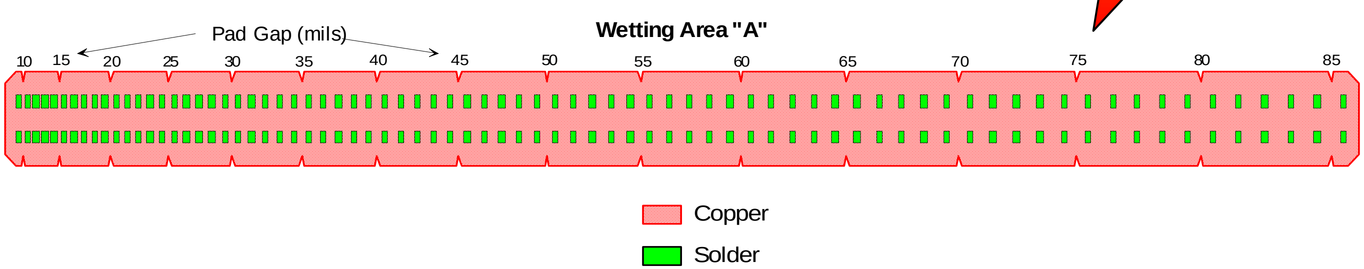

Benchmarker II
© Heraeus 2001
Solder Ball
IPC Slump
Wetting A
Wetting B
Wetting C
Wetting D
Spread
SOIC
X-Ray Voiding
S1 0.5mm uBGA
S2 0.5mm uBGA/CSP
0.5mm Pitch
0.4mm Pitch
Aperture
Flux Residue Pin Test
0.8mm 100P BGA
0.5mm 56P CSP
Flip Chip
25mil 100P BQFP
1mm 196P BGA
Narrow Pad
Wide Pad
1206 Chips
0805 Chips
0603 Chips
0603 Tombstone Test
0402 Chips
0201 Chips
Connector
0.5mm 208P QFP

Wetting Tests - Development History



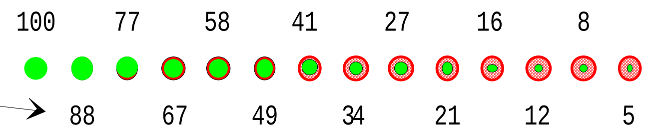




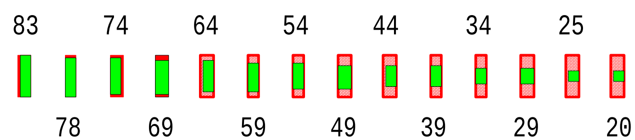


Wetting Tests - Areas B,C&D

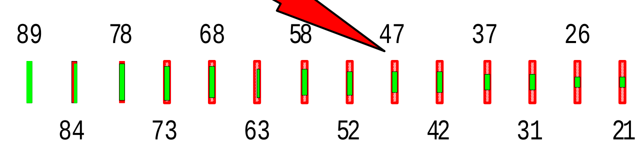
Pad Coverage



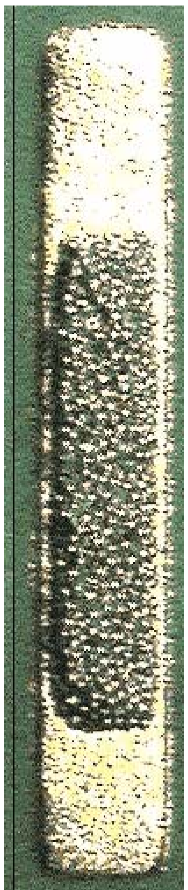
Wetting Area "B"

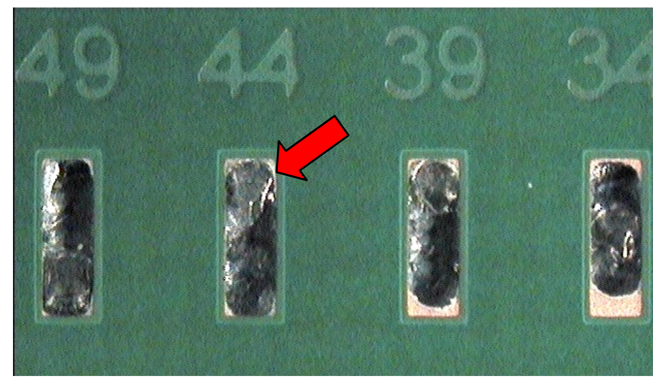


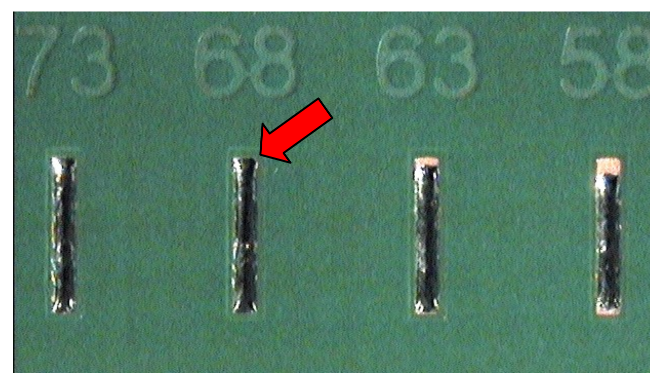
Wetting Area "C"



Wetting Area "D"

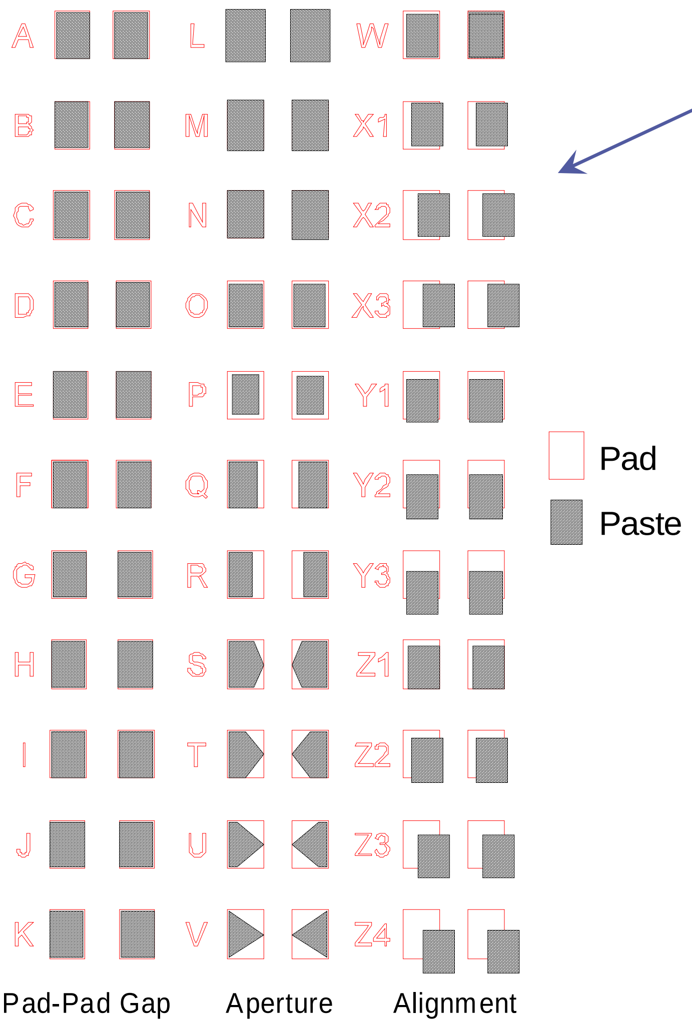




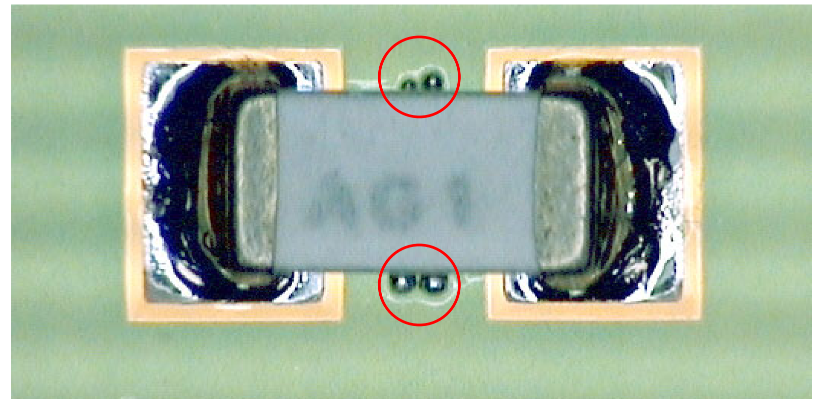


Heraeus

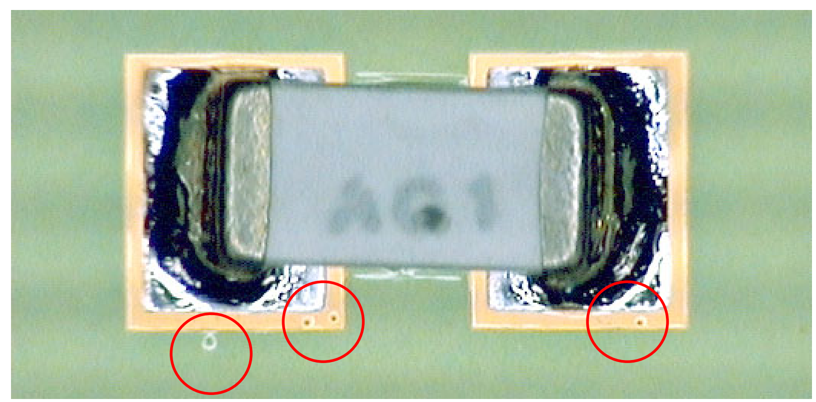
Reflow Defect Testing – Passive Components



1206, 0805, 0603, 0402



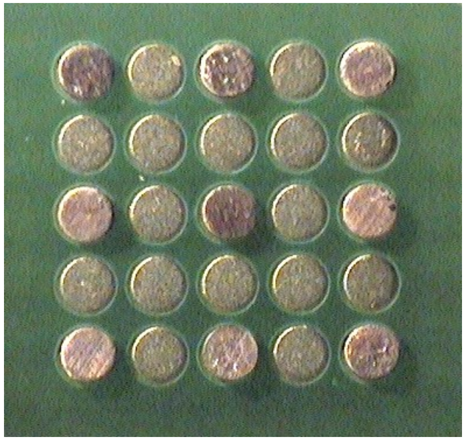
Solder Beads



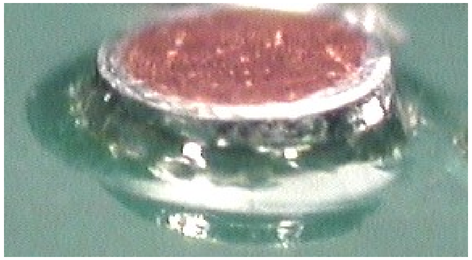
Solder Balls

X-ray Voiding – Test Method

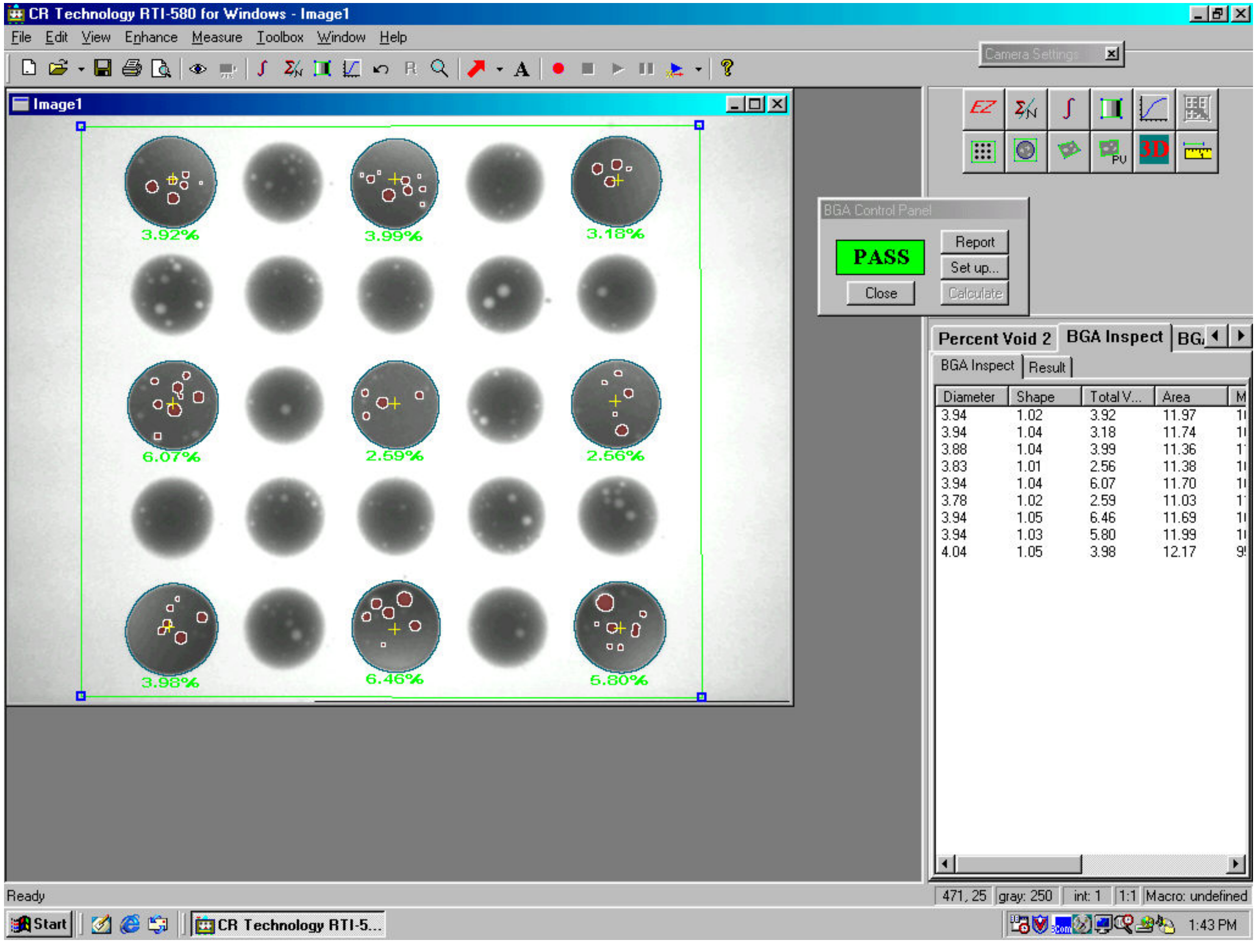
Measurement



Assembly

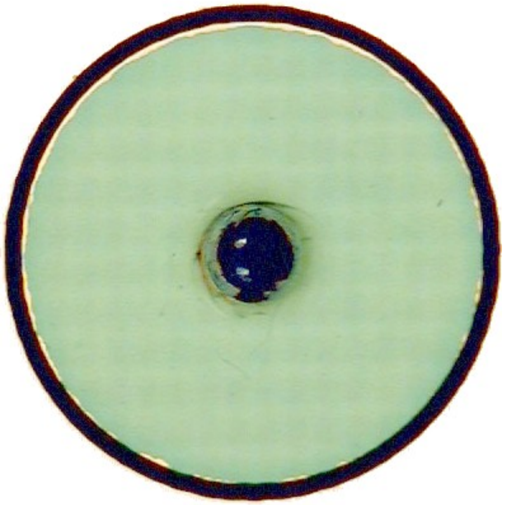


Reflow

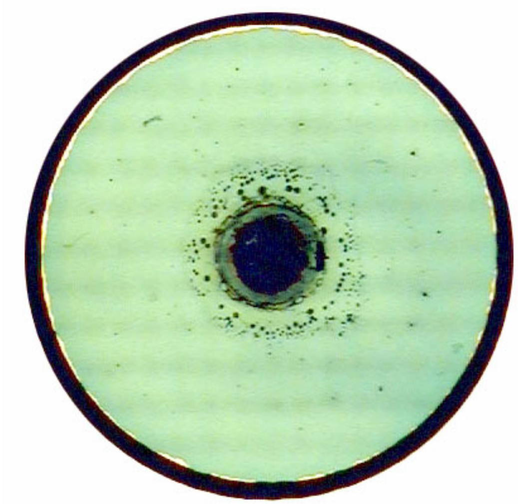


Points = (structures ≤ 4% - structures ≥ 6%)

Reflow Defect Testing – Solder Ball over Mask



None



Heavy

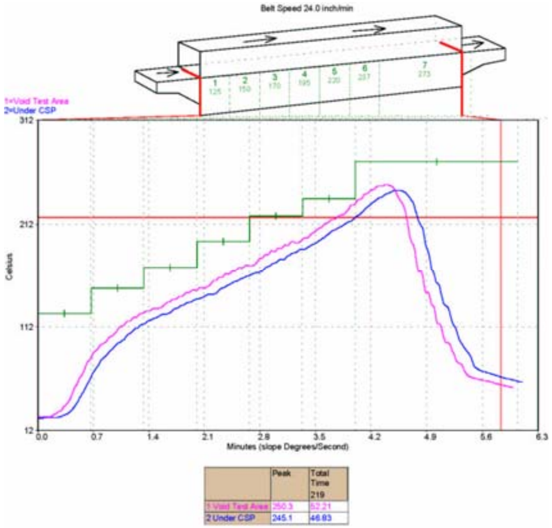
None	≤ 1
Slight	2-14
Moderate	15-40
Heavy	>40

Phase 1: Optimal Profile Determination

Profile	Peak	Liquidous	Preheat Style
1	247 °C	48 sec	Ramp
2	247 °C	87 sec	Ramp
3	247 °C	48 sec	Soak
4	247 °C	87 sec	Soak

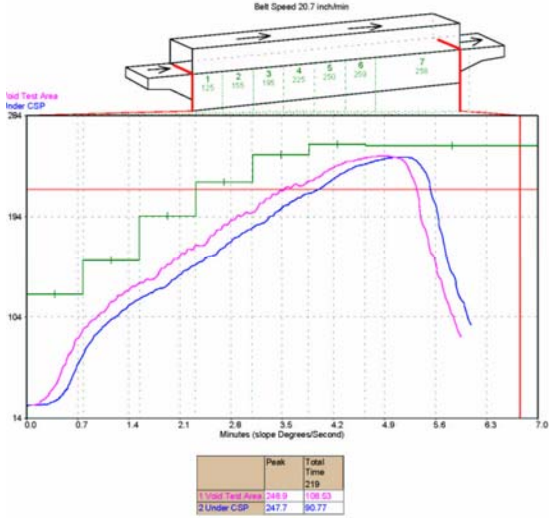
Profiles Tested

Profile 1

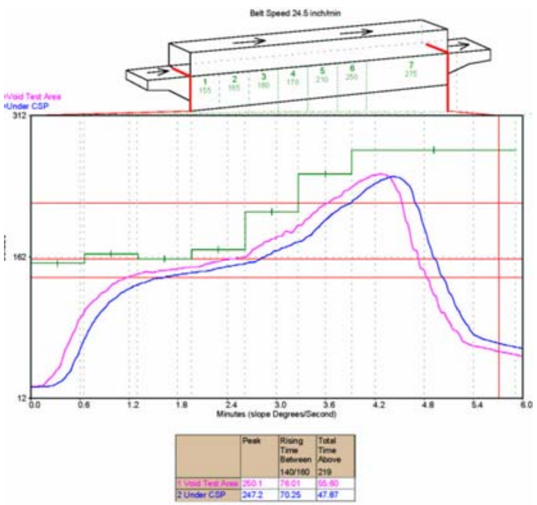


Profile 2

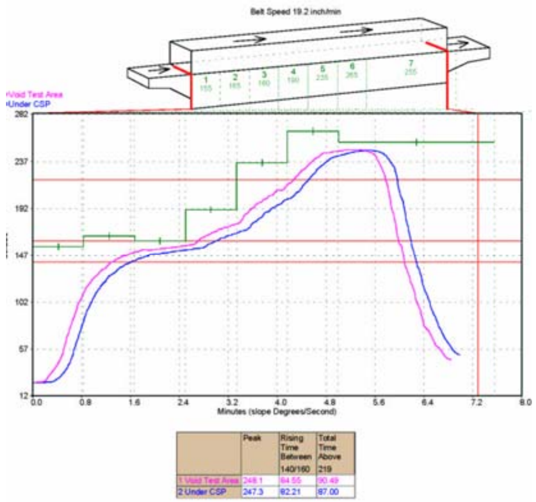
Best



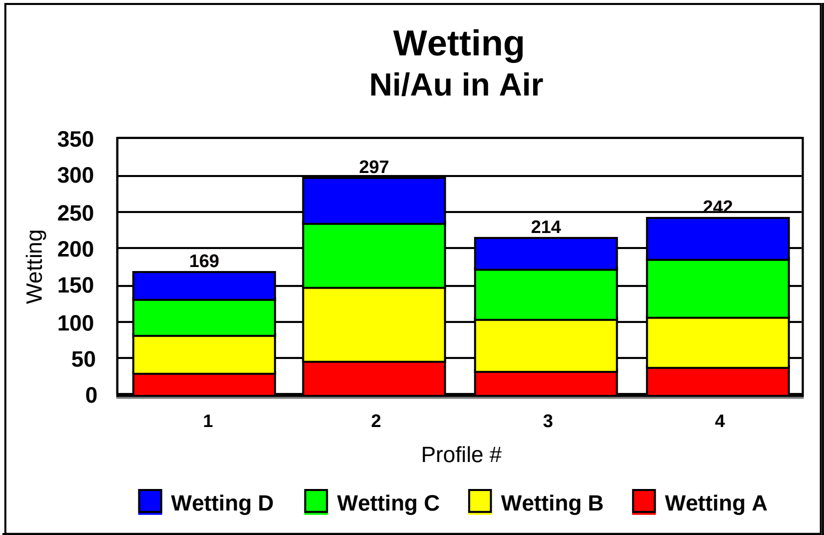
Profile 3

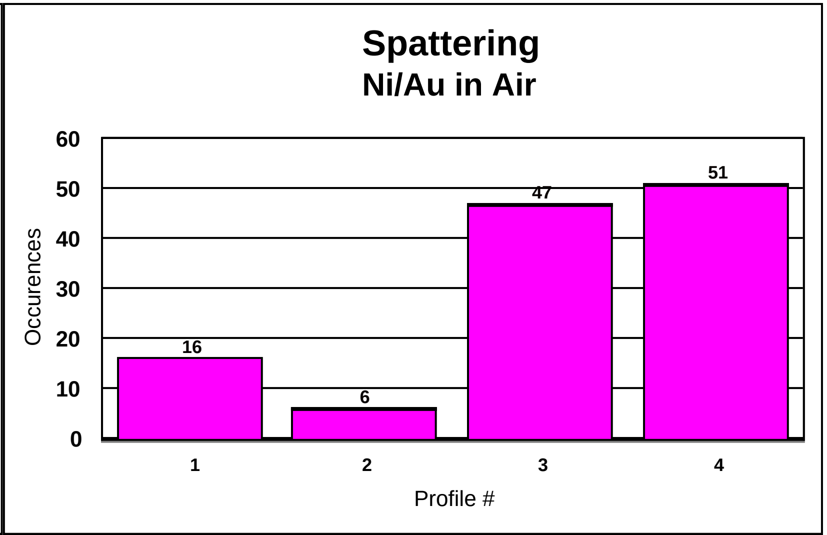


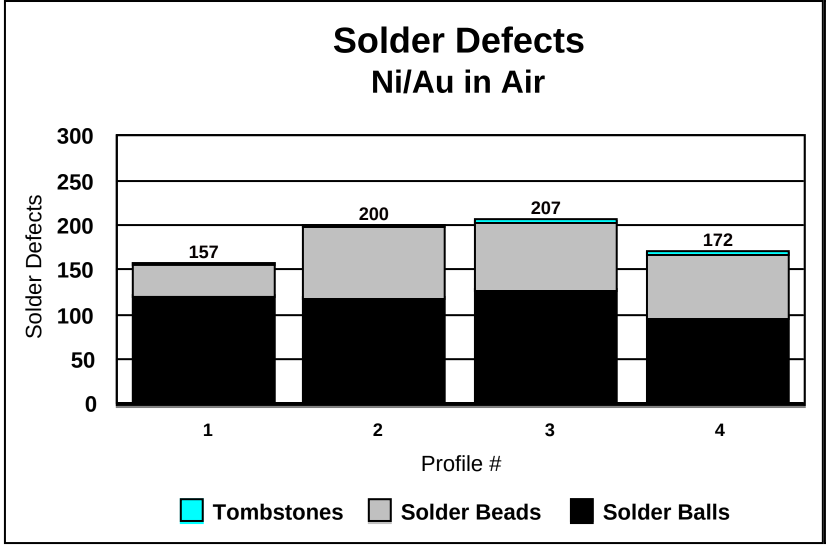
Profile 4

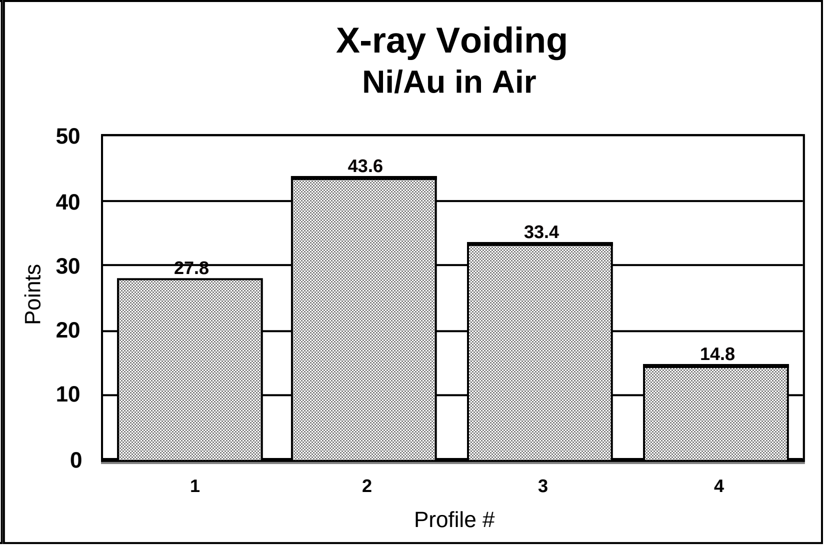


Profile Optimization : Performance Tests





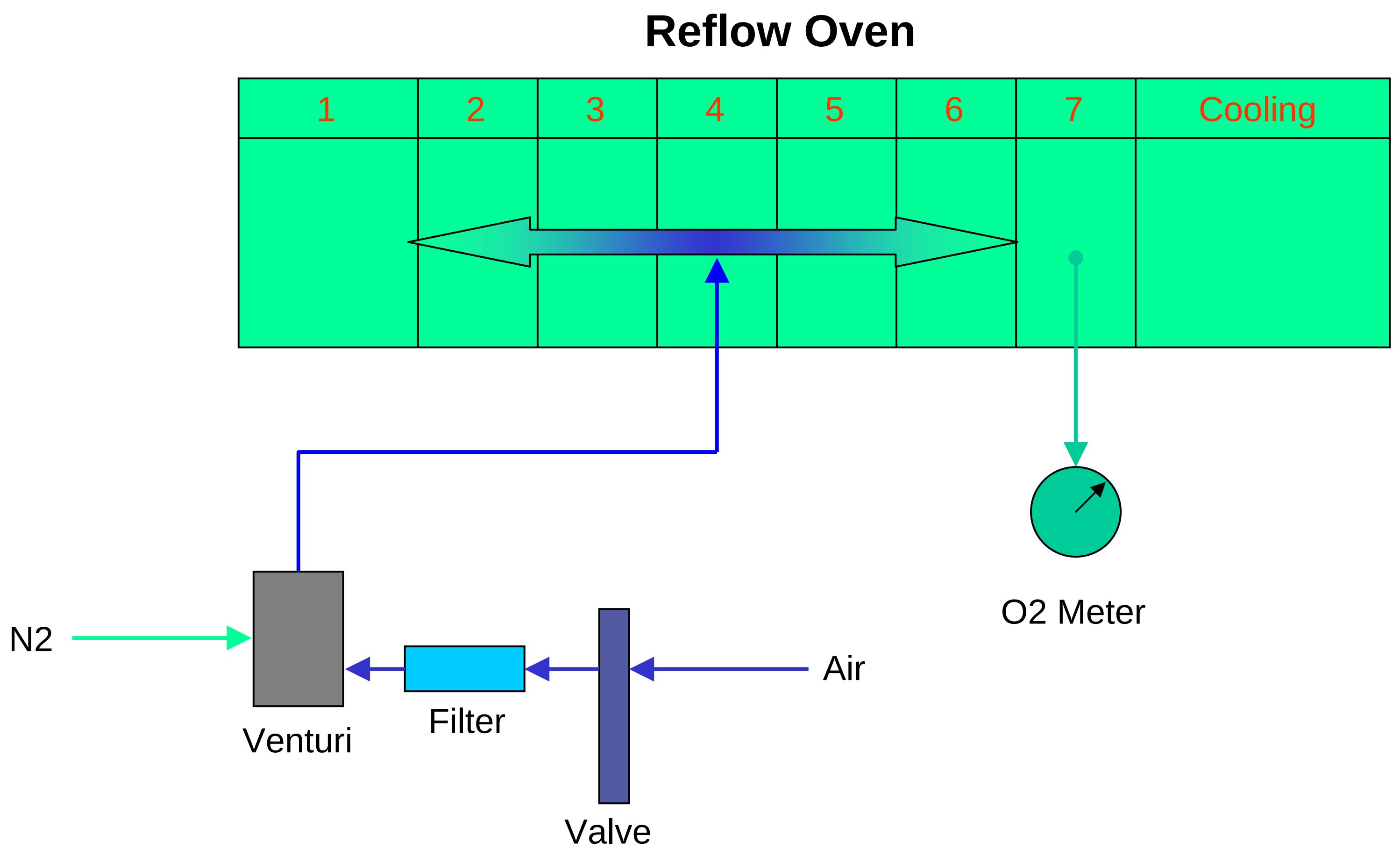




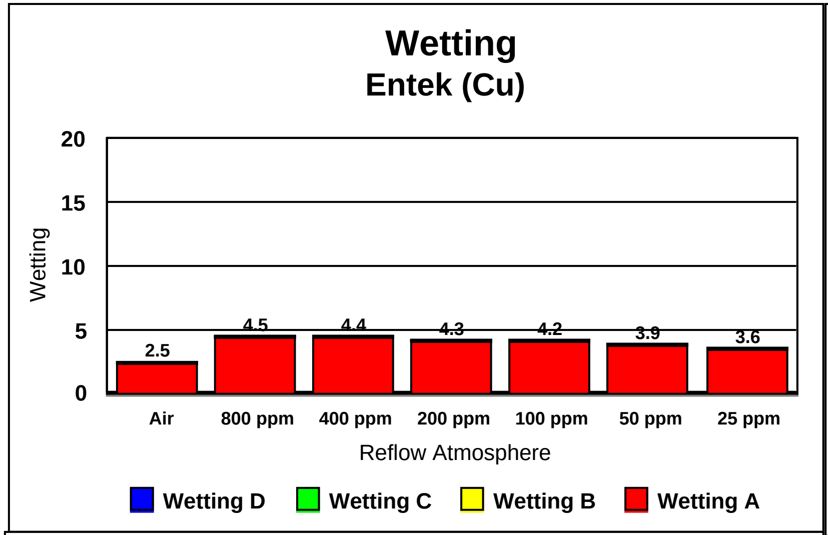
Phase 2: Vary $\boxed{\text{Surface Finish}}$ and Atmosphere

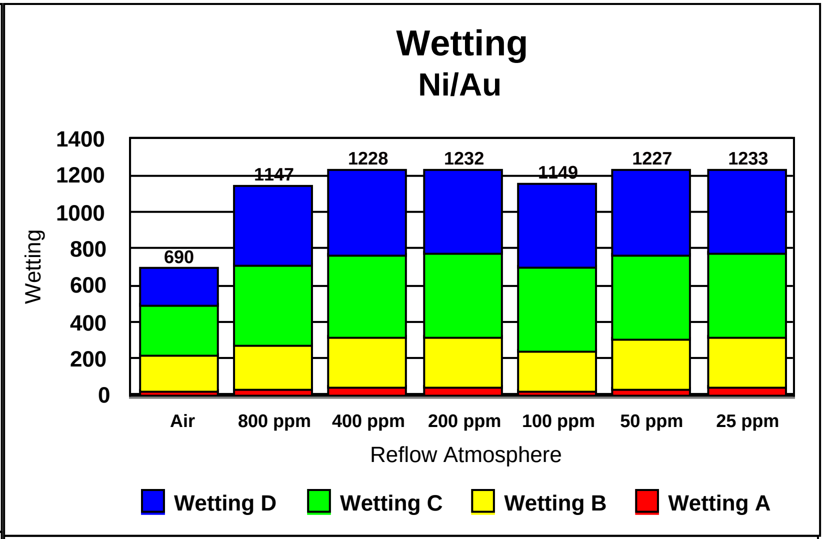
- Profile 2 used (Ramp-to-Spike, 90s liquidus)
- Board Finishes
  - ENIG (Gold)
  - Entek (Copper)
  - Immersion Tin
  - Immersion Silver
- Atmospheres
  - Air
  - Nitrogen
    - 25, 50, 100, 200, 400 & 800 ppm O_2

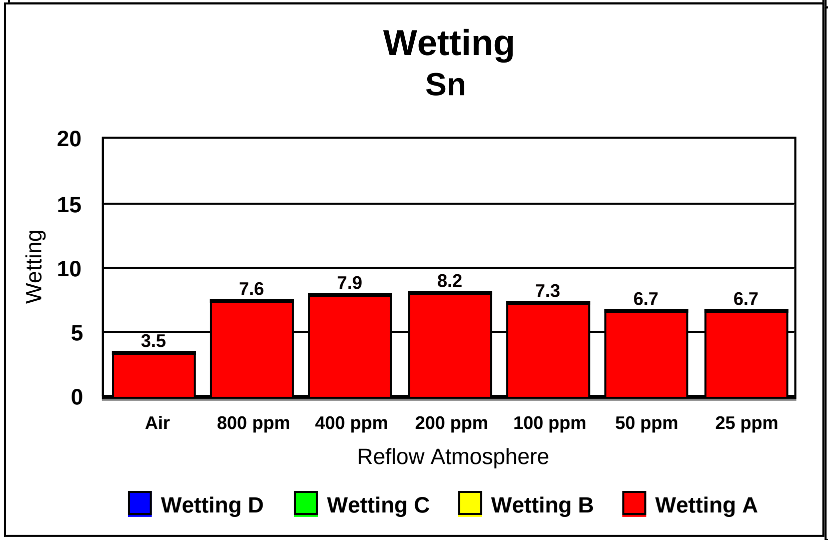
Oven O2 Doping

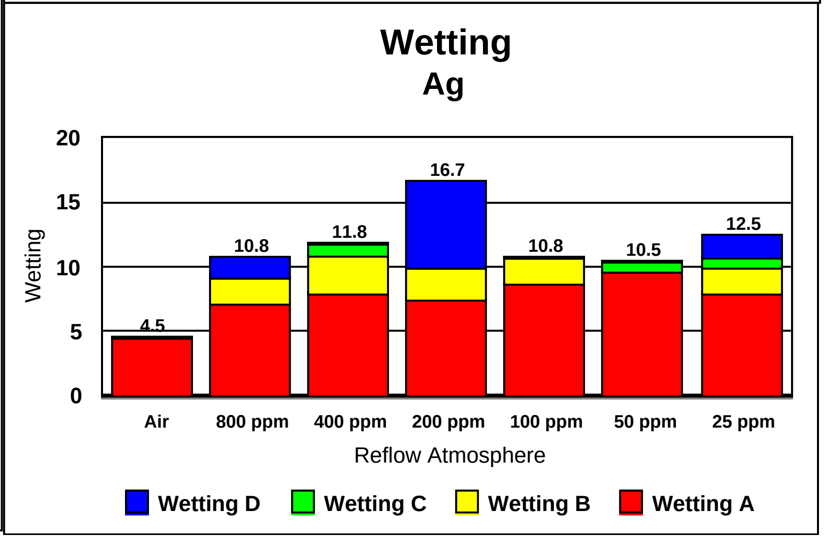


Wetting Performance in Optimal Profile



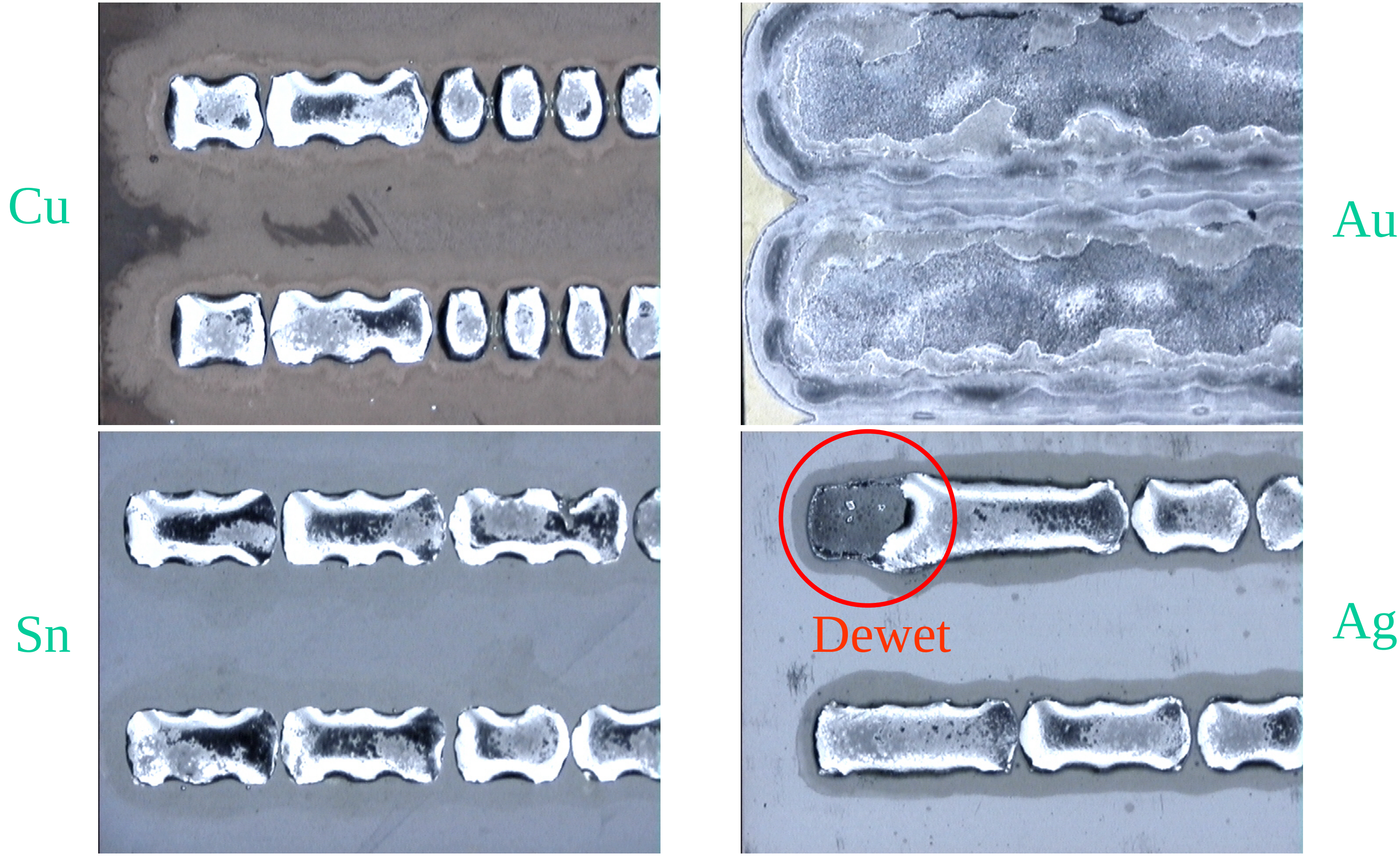




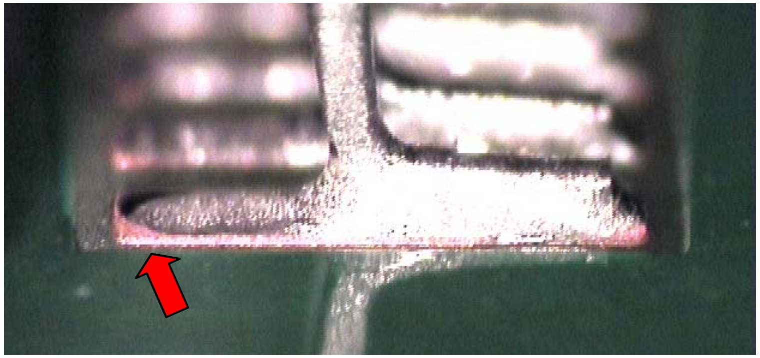


Heraeus

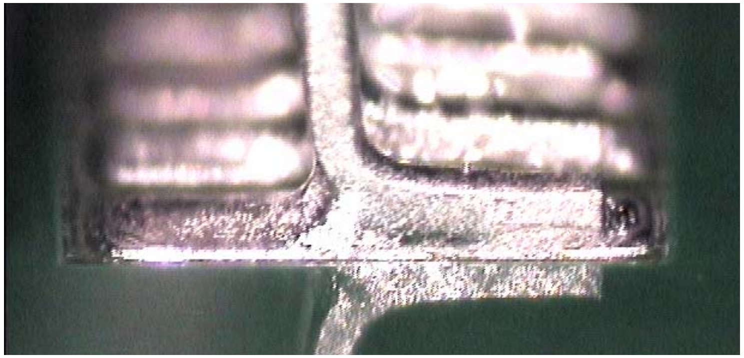
Wetting Test “A” in Nitrogen (25ppm O_2)



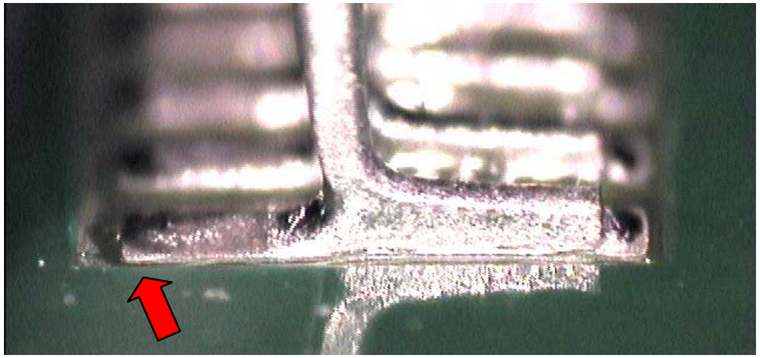
QFP Wetting



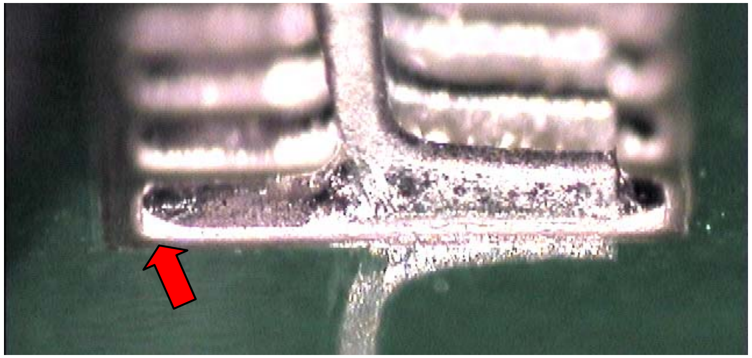
Cu



Au

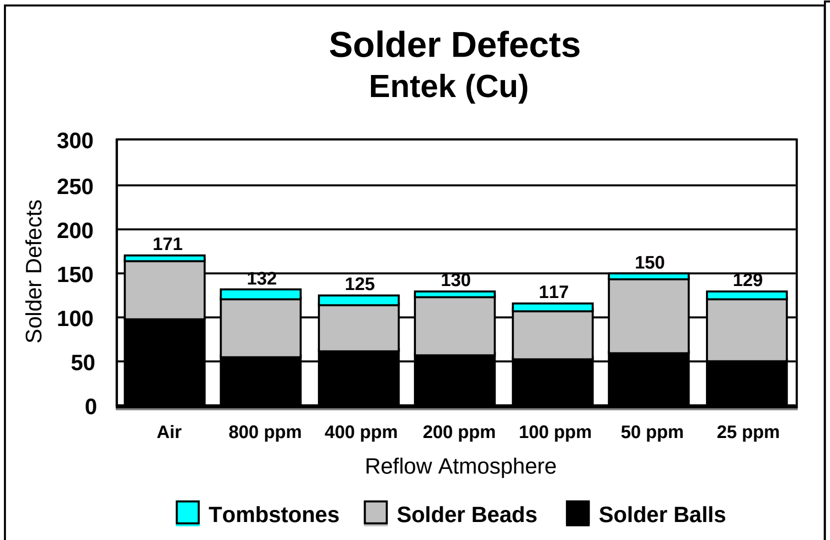


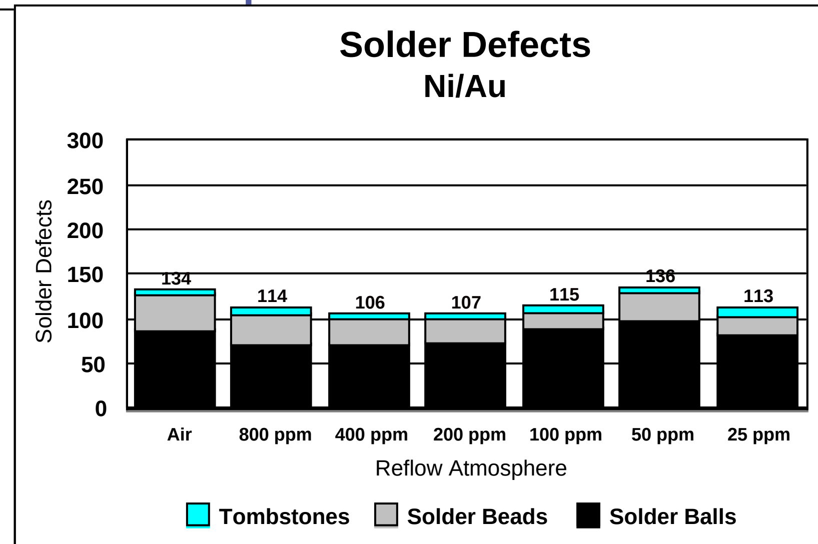
Sn

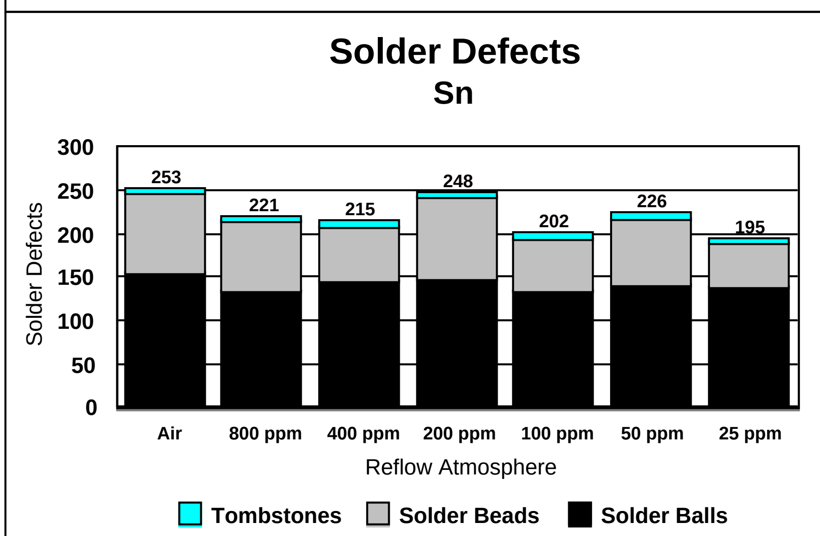


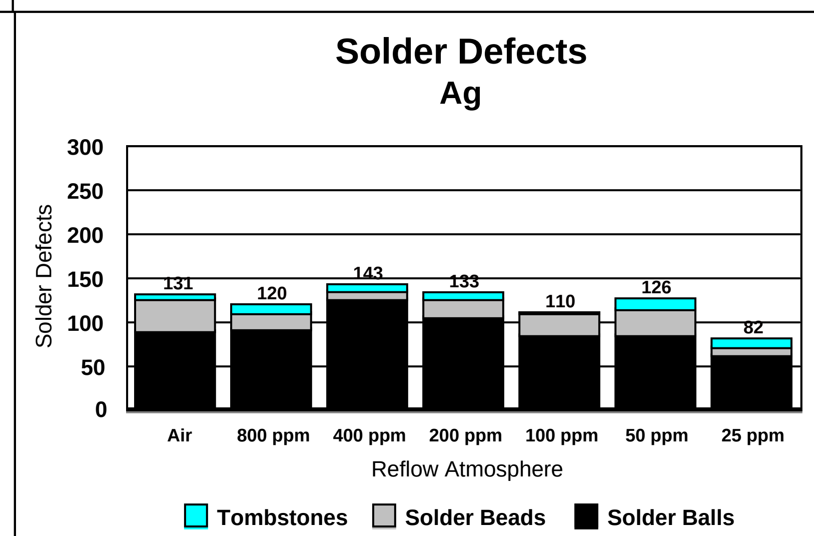
Ag

Solder Defect Performance in Optimal Profile

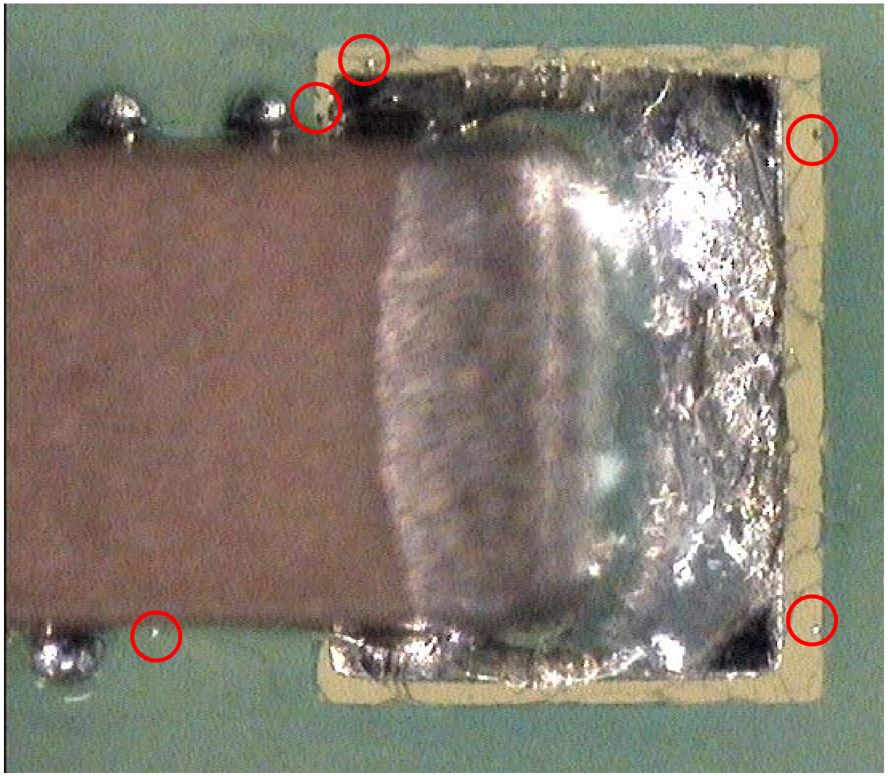




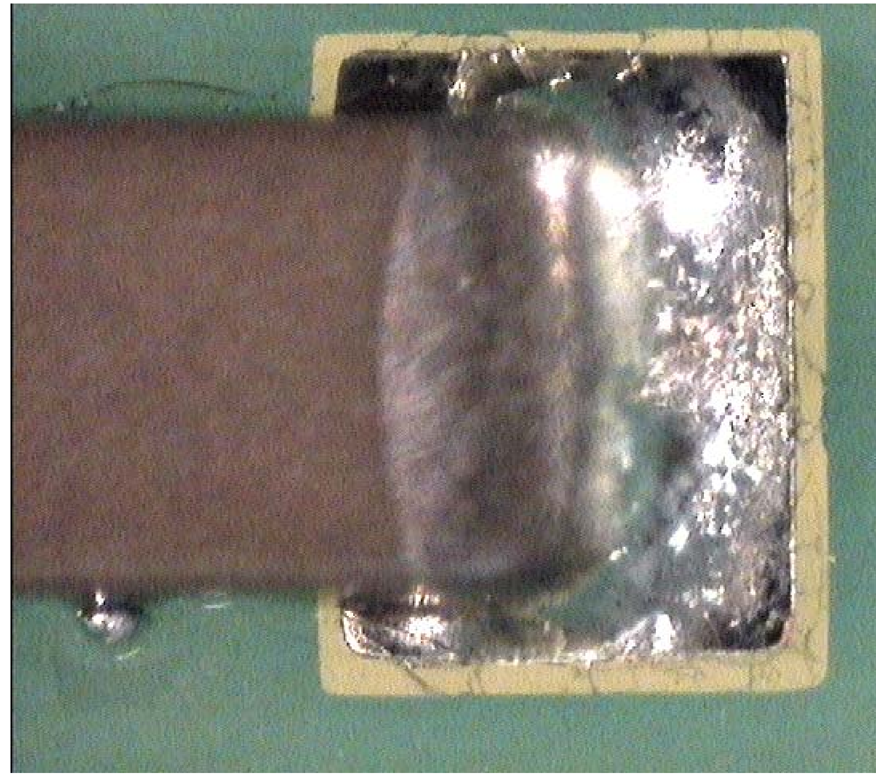




Solder Balling in Nitrogen (25ppm O_2)



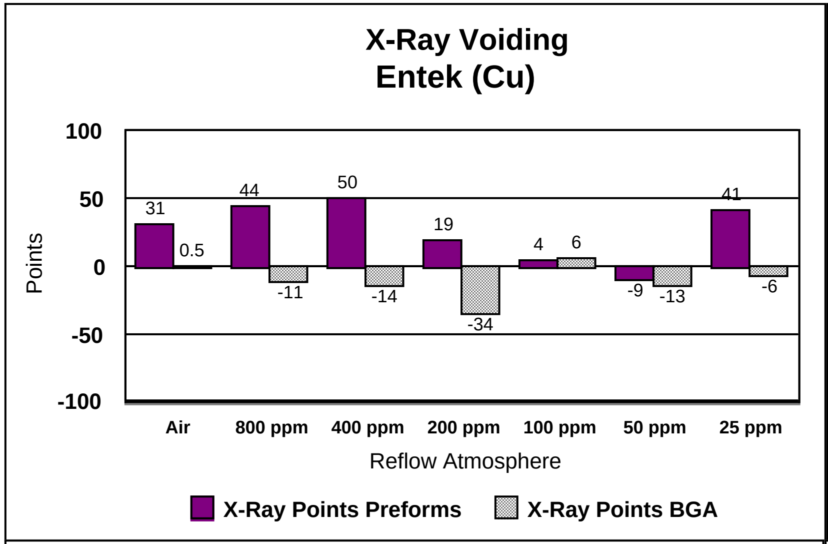
Immersion Tin

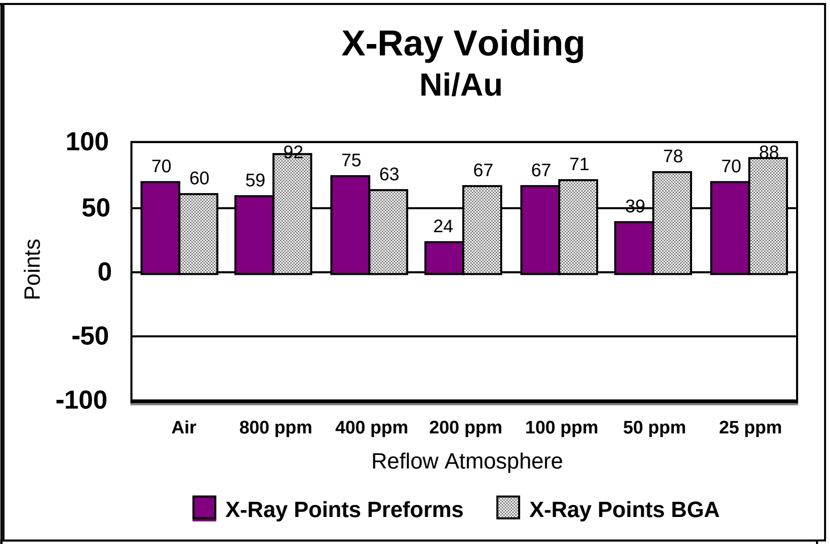


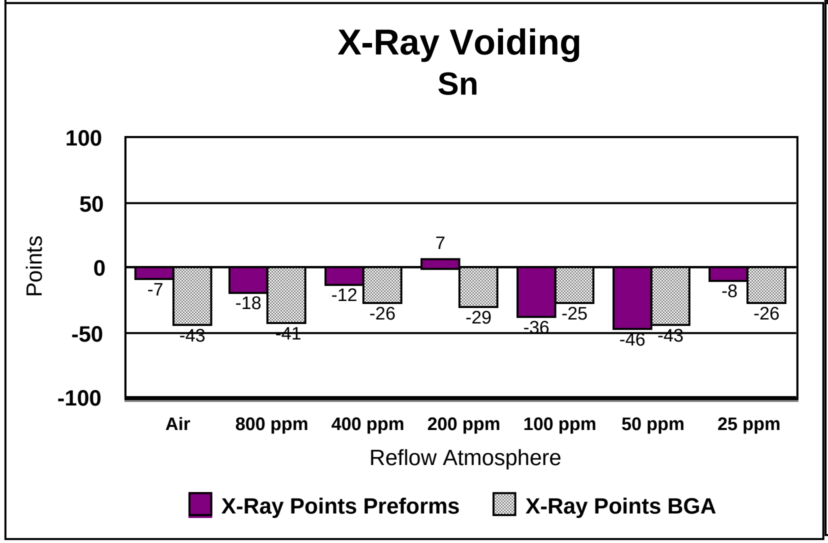
Entek over Copper

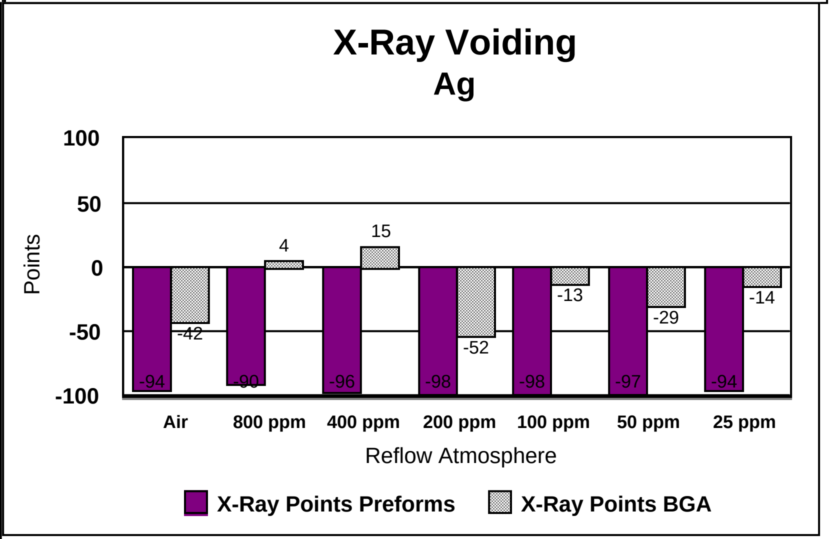
Heraeus

Solder Void Performance in Optimal Profile





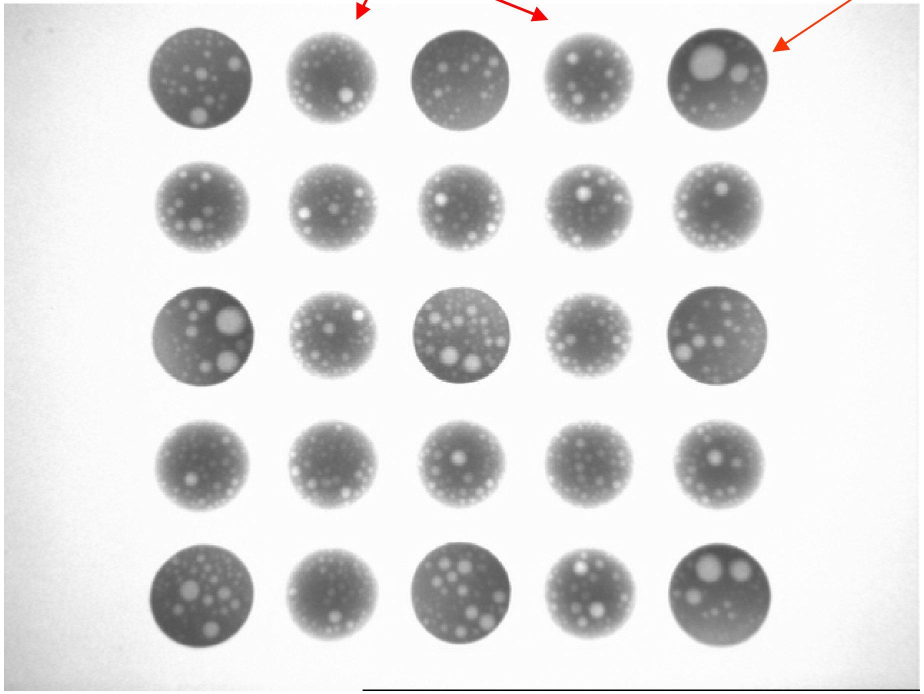




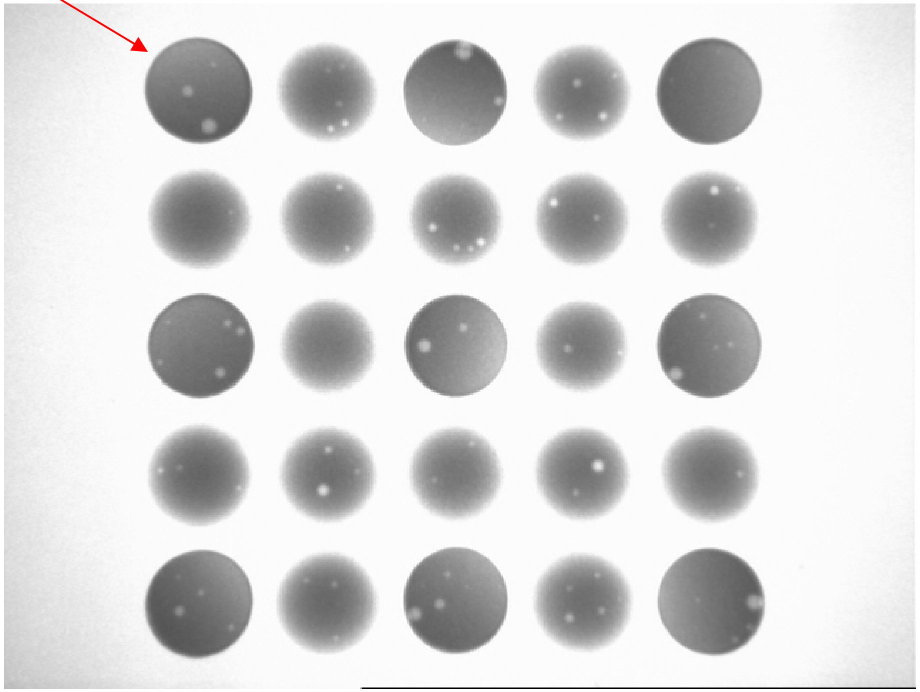
Solder Voiding in Nitrogen (25ppm O_2)

No Preform

Copper Preform

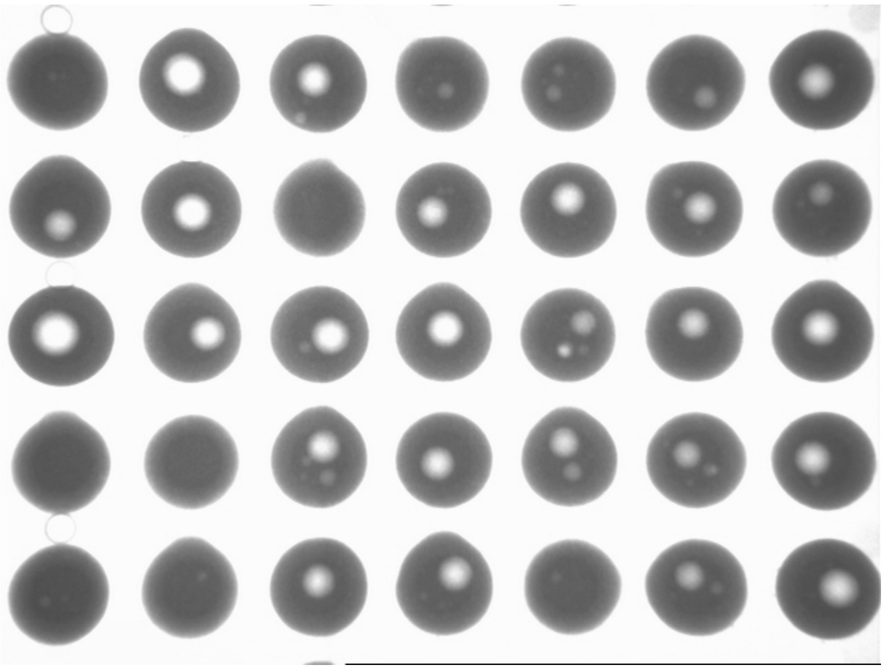


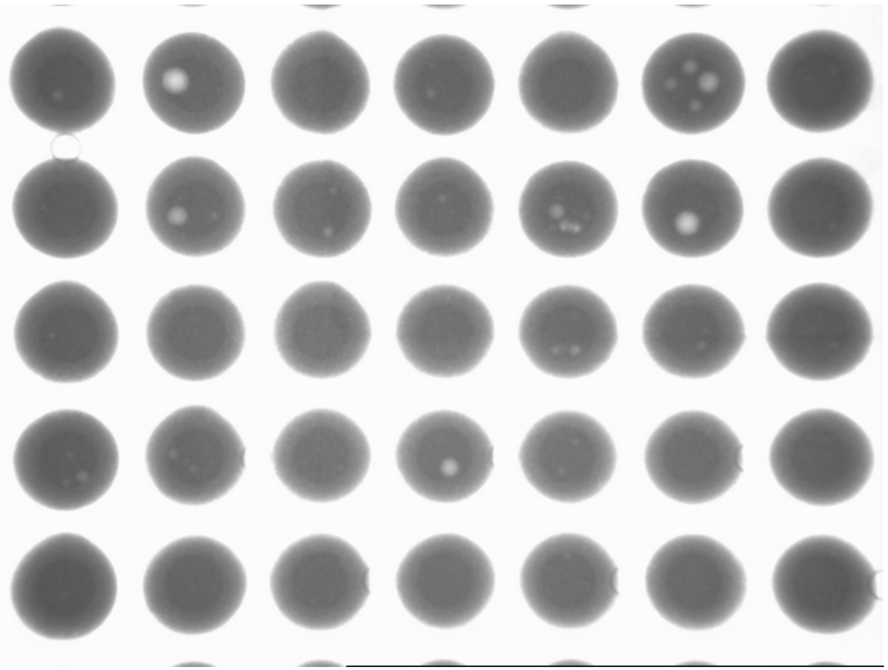
Immersion Silver



Immersion Gold

BGA Voiding in Nitrogen (25ppm O_2)

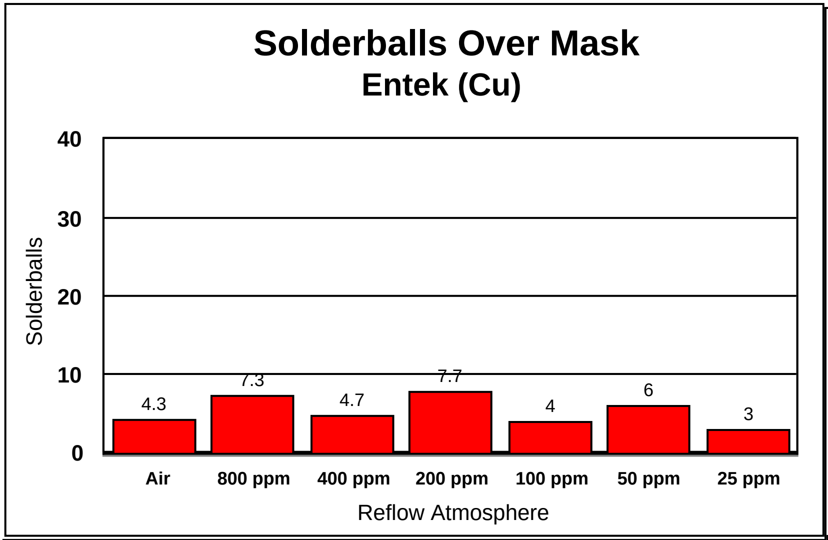


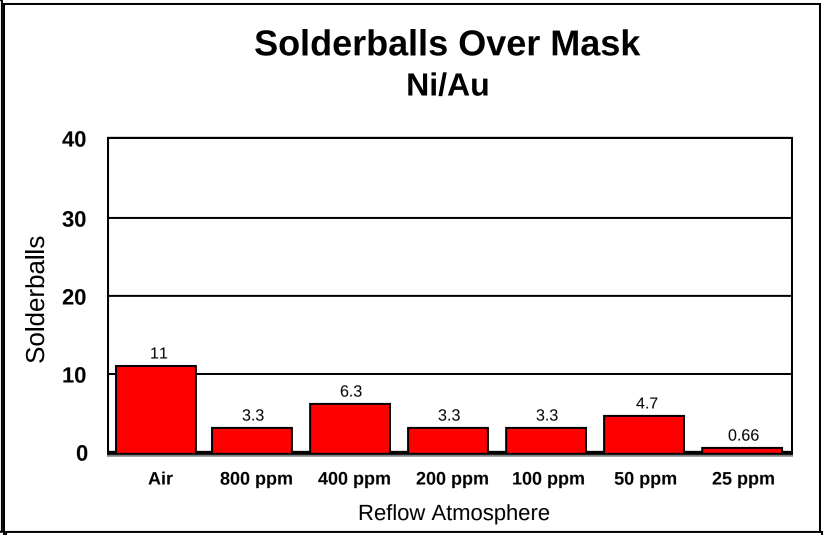


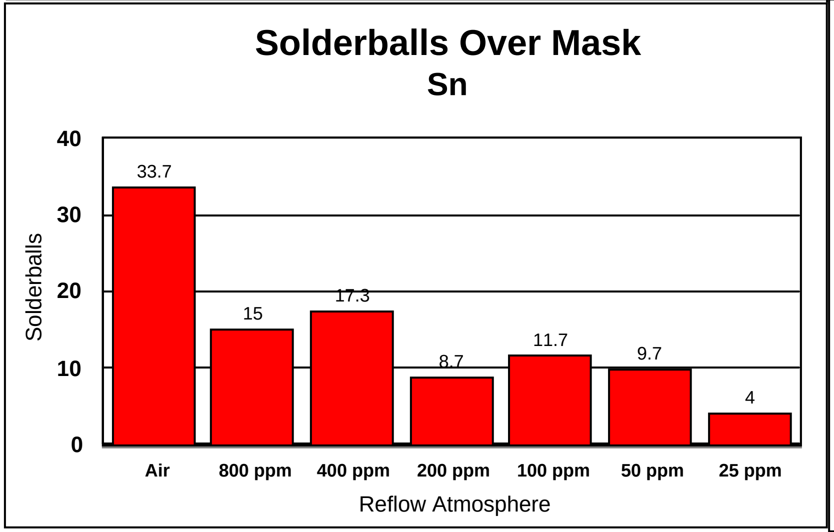
Immersion Tin

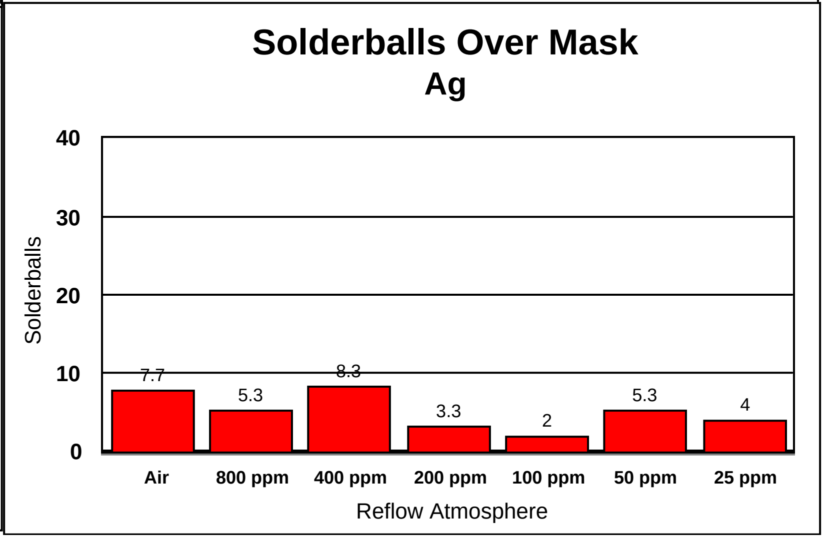
Immersion Gold

Solder Balling Performance in Optimal Profile









Conclusions

- Ramp-to-spike profile with long liquidous time was the best overall optimal profile.
- Board $\boxed{\text{surface finish}}$ had the most influence on F620 performance and the reflow atmosphere O_2 content the least.
- Ni/Au exhibited over 100X the wetting of immersion Ag.
- Atmosphere had little or no effect on solder voiding.
- Ni/Au overall best $\boxed{\text{surface finish.}}$