The Massachusetts Pb-Free Consortium

TOXICS USE REDUCTION INSTITUTE

Testing and Analysis of Surface Mounted Pb-Free Soldering Materials and Processes

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OUTLINE

- Drivers for Pb-free Electronics
- Massachusetts TURI – Toxics Use Reduction Institute
- Previous Reported Results
- Current Design of Experiments
- Current Results
- Statistical Analyses
- Discussion
- Conclusions to Date
- Continuing Work
- Acknowledgements

Drivers for Pb-free Electronics

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Environmental Responsibility
(Recycling & Reuse)
(Minimize, Eliminate Toxic Wastes)

Legislation
WEEE
RoHS
Japan Guidelines
EPA & State Regulations

TOXICS USE REDUCTION INSTITUTE

Massachusetts TURI (Toxics Use Reduction Institute)

- Mission – Assist Companies in Toxics Use Reduction & Elimination
- Goals – Sustain, Safeguard, Promote Competitive Advantage of MA Businesses & Advance Innovation in Toxics Use Reduction and Management.
- Provides Training, Information, Workshops.
- Conducts Research and Development towards such Innovations.

Located at University of Massachusetts Lowell

www.turi.org

Massachusetts Lead Free Consortium

Goal:

Development of Pb-free process capabilities, guidelines, and recommendations, using DOE techniques and commercial equipment to help enable Pb-free assembly in industry.

Massachusetts Lead Free Consortium

Current Members

- Air Products and Chemicals
- Analog Devices
- BTU International
- Raytheon Company
- Schneider Electric
- Texas Instruments
- TURI
- University of Massachusetts Lowell
- Tyco Electronics – M/A-COM

Previously Reported Information
Initial Testing

- Comparisons: 95.5Sn-3.8Ag-0.7Cu vs. 96.5Sn-3.5Ag
- High, Medium and Low solids (residue) fluxes
- Ramp and Soak versus Linear Ramp Reflow Profiles
- High versus Low Peak Reflow Temperatures
  - 250 vs. 230 °C with 60 seconds above Liquidus for the ramp and soak
  - 235 vs. 225 °C with 90 – 120 seconds above Liquidus for the linear ramp profile

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Previously Reported Information
Initial Testing Results

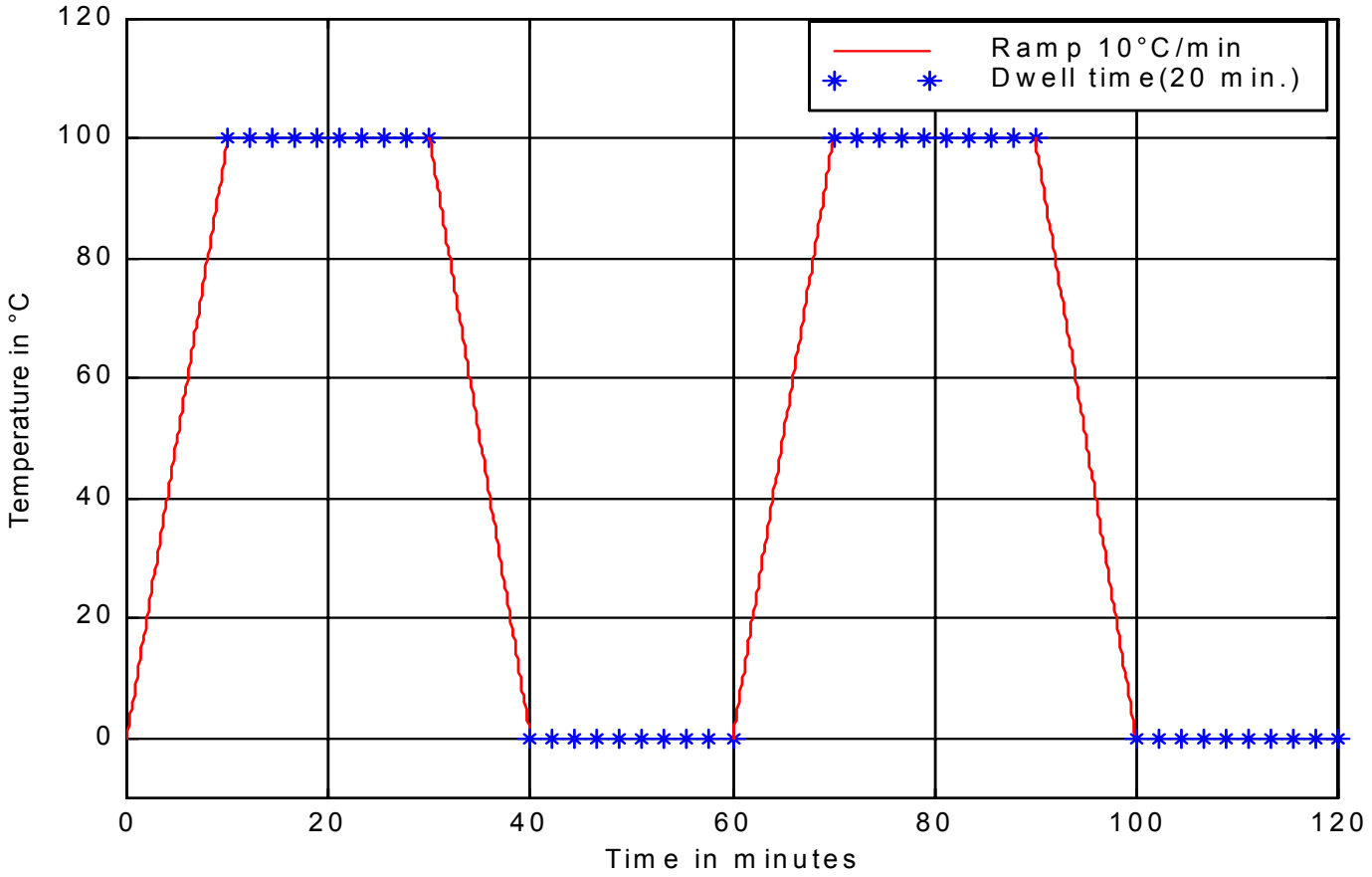
- Flux was the most critical factor with high solids content providing the most protection.
- The linear profile with the 235 °C peak produced the fewest number of visual defects.
- Optimal results were obtained using these two conditions with the Sn-Ag-Cu solder alloy.
- It was also determined that the linear profile approach decreases the process window requiring tighter controls but used less energy and thus is more cost effective.

Previously Reported Information
First DOE

- Three lead-free solders
  - 95.5Sn-3.8Ag-0.7Cu
  - 96.5Sn-3.5Ag
  - 57Sn-43Bi
- Two board surface finishes
  - ENIG - Electroless Nickel-Immersion Gold
  - OSP – Organic Solder Preservative
- Two atmosphere conditions - air versus nitrogen
- Two reflow profiles - ramp and soak versus linear ramp
- Three times above liquidus 60, 90 120 seconds

- Assess effects on visual defects and on solder joint pull-test strength as reflowed and after thermal cycling.

Previously Reported Information
First DOE



- 10 Minute Ramp
- 0 – 100 °C
- 20 Minute Dwell
- 2000 Cycles

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Previously Reported Information
First DOE Results

- No solder joint failures throughout the entire 2000 thermal cycles test.
- Solder paste composition was the most significant factor with Sn-Ag-Cu yielding the highest strengths and Sn-Bi the lowest.
- OSP board finish yielded slightly higher pull strengths, perhaps due to gold-tin intermetallic formation
- Slightly higher strengths were achieved with the linear ramp profile
- Strength increased after thermal cycling, as indicated by conventional wisdom, due to changes in the inter-metallic composition of the copper migrating through the alloy towards the components.

Previously Reported Information
First DOE Results

Solder Paste	Surface Finish	Time Above Liquidus	Soak	Nitrogen
Sn/Ag/Cu	*ENIG*	90sec	No	yes
Sn/Ag/Cu	*ENIG*	*120sec*	Yes	yes
Sn/Ag	*ENIG*	60sec	Yes	yes
Sn/Ag	*ENIG*	90sec	No	yes

Process Conditions Yielding Zero Visual Defects

Current DOE….

Five Board Finishes…

- SMOBC / HASL (Sn)
- OSP
- ENIG
- Matte Sn
- Immersion Ag

Four Lead Finishes…

- Matte Sn
- Ni-Pd-Au
- Ni-Au
- Sn-Ag-Cu

Three Solder Pastes…

- Supplier “A”
- Supplier “B”
- Supplier “C”

Two Reflow Atmospheres…

- Air
- Nitrogen

Solder – NEMI “Recommended” 95.5Sn-3.8Ag-0.7Cu

Sn – Pb Controls

Two Replicates

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Experimentation Matrix (partial)

(Two (2) Circuit Boards per Trial)

Bd.	PWB Finish	Solder paste	*Reflow Atmosphere	Component Finish
1	SMOBC/ HASL	“A”	Air	Pb- free
2	SMOBC/ HASL	“A”	Nitrogen	Pb- free
3	SMOBC/ HASL	“B”	Air	Pb- free
4	SMOBC/ HASL	“B”	Nitrogen	Pb- free
5	SMOBC/ HASL	“C”	Air	Pb- free
6	SMOBC/ HASL	“C”	Nitrogen	Pb- free
7	SMOBC/ HASL	Standard Sn-Pb	Air	Sn-Pb Leads
8	OSP	“A”	Air	Pb- free

Current DOE….

Components from…

M/A-COM
Texas Instruments
Analog Devices

(also Topline – Pb-free chip caps and resistors)

Board Layout…

M/A-COM

Board Production…

Sanmina – SCI (formerly Hadco)

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Current DOE….
Processing Completed
Current Analysis Effort

Assembly…
Schneider Electric
using
MPM Screen Printer
Siemens Pick and Place Equipment

Reflow Oven…
BTU Pyramax 98N

Nitrogen…
Air Products & Chemicals

Inspection & X-rays…
M/A-COM
UMass – Lowell

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Current DOE….
In Progress and Future

Stress Testing Chambers…
Raytheon

Pull Tests / Shear Tests…
UMass – Lowell
M/A-COM

Analysis & Presentations
UMass – Lowell
ALL

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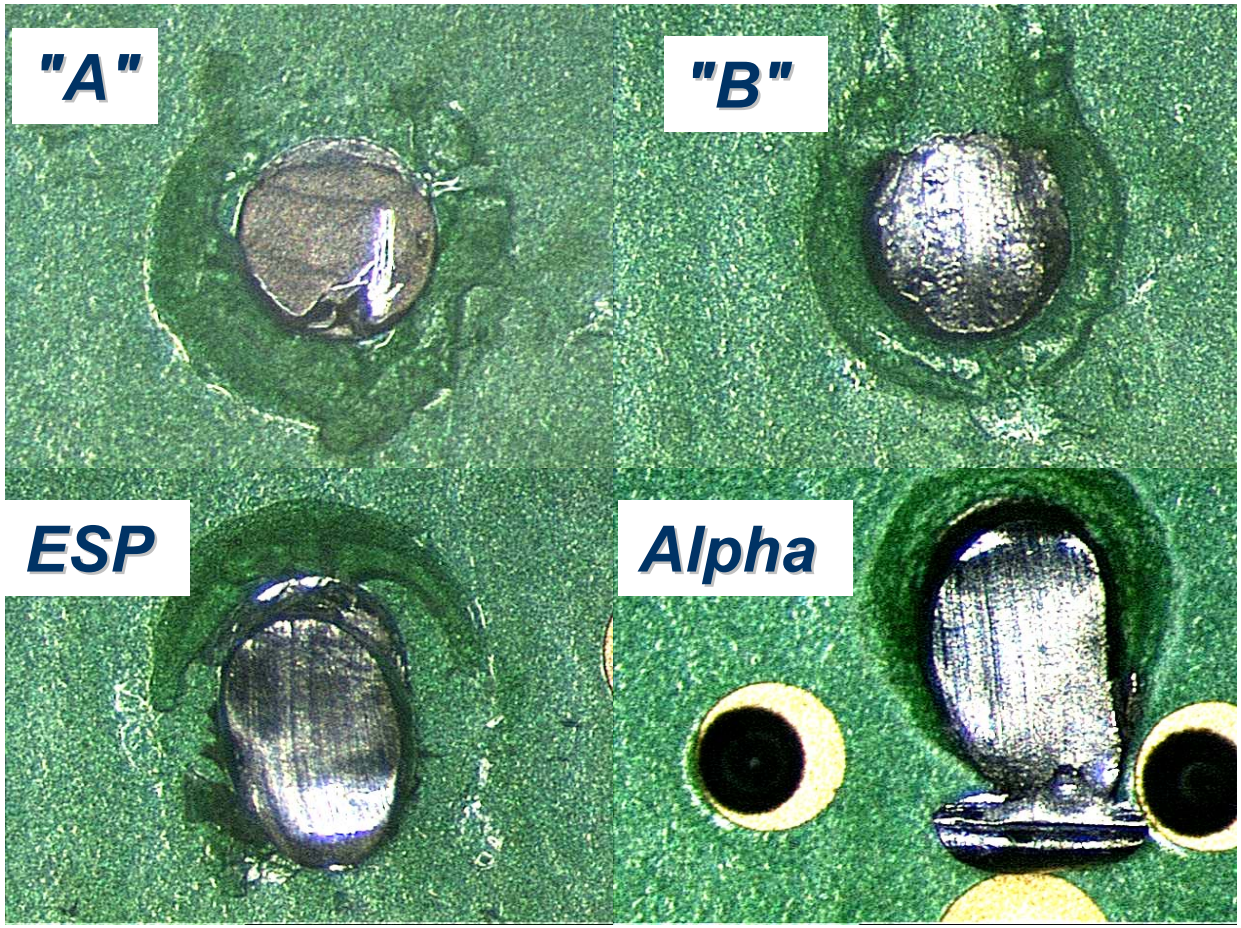
Current DOE….Pb-free BGA

Pb-Free SW-461 Mechanical Sample Optimization					
#	Sphere Source	Flux	#	Sphere Source	Flux
1	"A"	"A"	5	"B"	"A"
2	"A"	"B"	6	"B"	"B"
3	"A"	No Clean “D”	7	"B"	No Clean “D”
4	"A"	Water Soluble “E”	8	"B"	Water Soluble “E”

Interestingly, both batches of spheres had the same Lot Number….

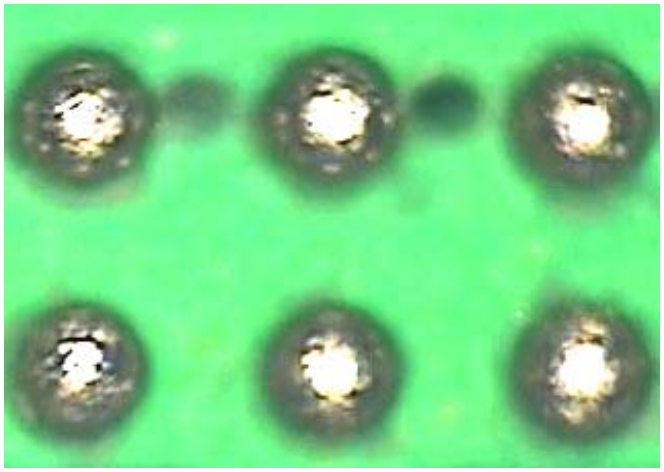
Spheres mounted with all 4 Fluxes exhibited ductile fracture.



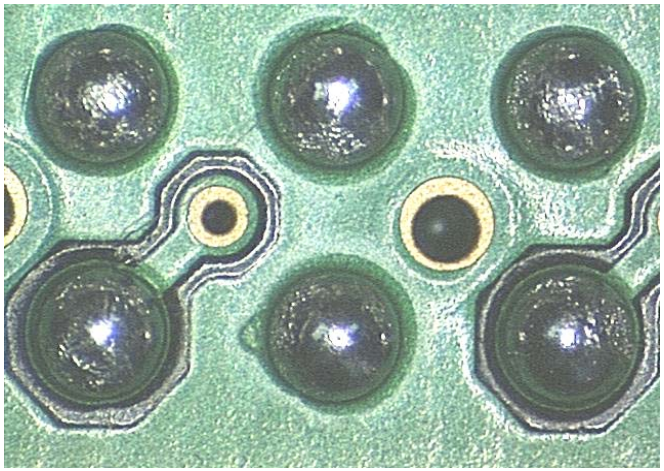
Ball Shear Test Results – Average Values

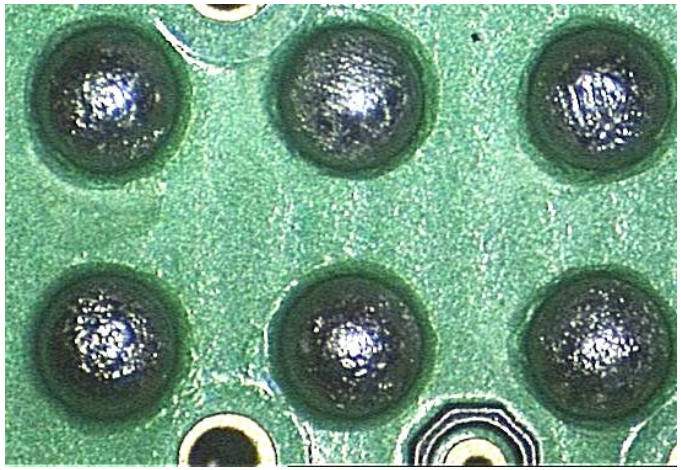
"B" Flux – 1.825 Kg "E" Flux – 1.650 Kg Sn-Pb Control – 1.60 Kg

45 mm x 45 mm BGA



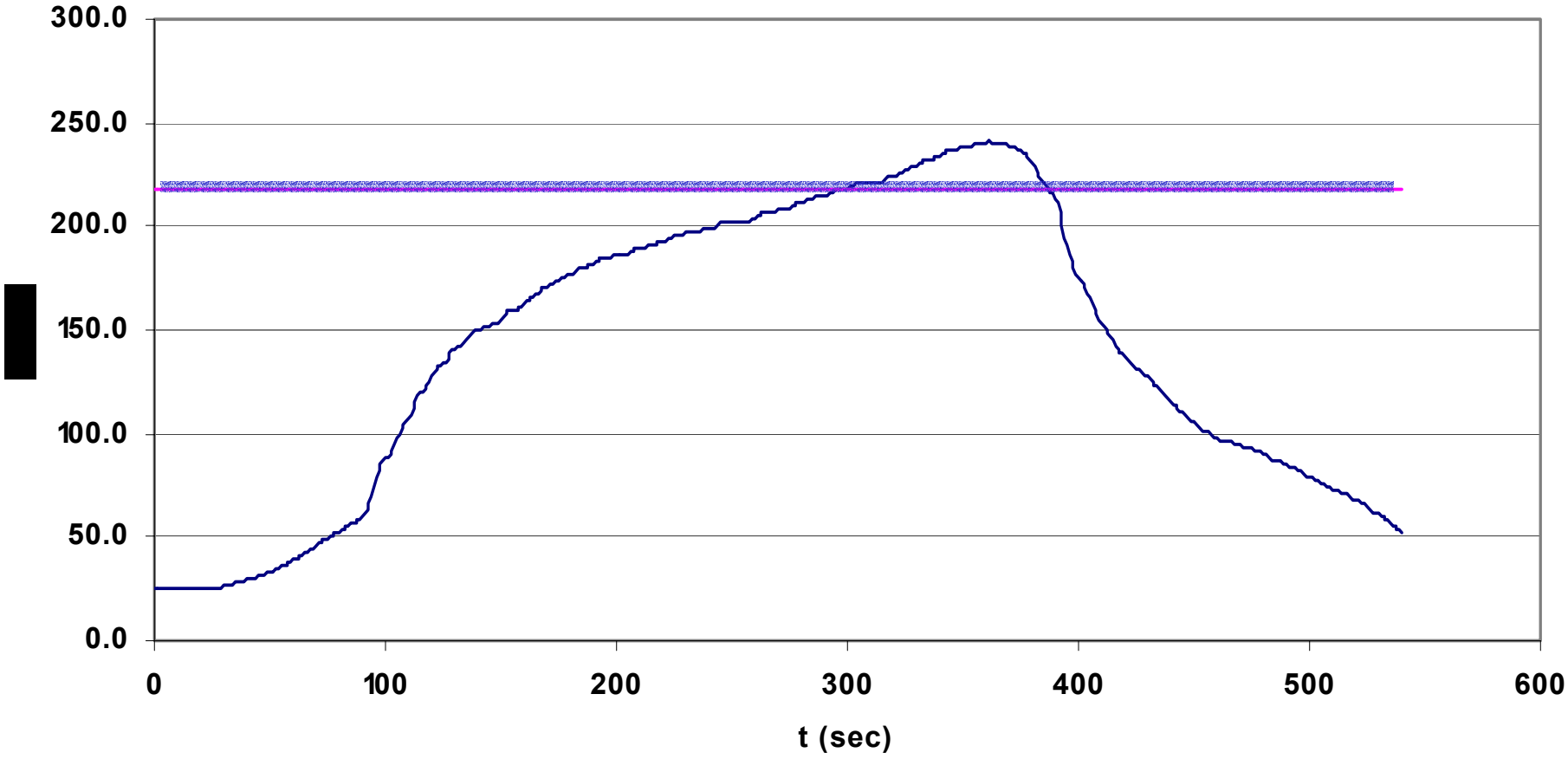
Appearance
The Pb-Free
reflowed spheres
(below)
have a dull, faceted
finish compared to
Sn-Pb (left).





311 - 0.75 mm spheres – 1.5 mm pitch

Current DOE Reflow Profile Used



Based on Paste Suppliers Recommendations

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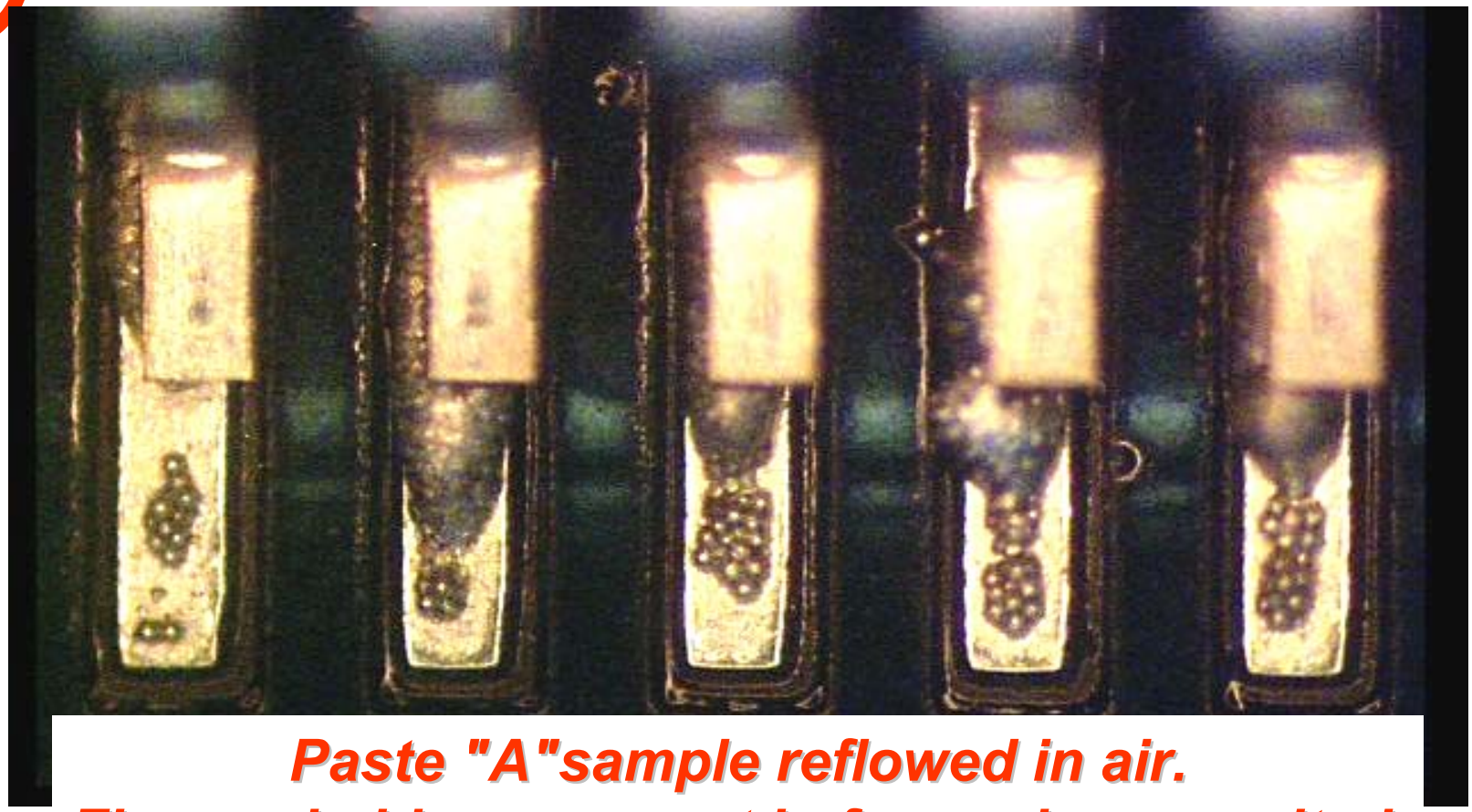
Assembly Observations…

- "A" Paste did not "roll" well on stencil resulting in irregular prints on fine pitch.
- "B" Paste clogged stencil after 4 prints.
- Air versus nitrogen may be more important at the higher reflow temperatures required for Pb-free.
- Placement vision system had difficulty "recognizing" Sn-Pb balls after being programmed using Pb-free BGAs – may require re-programming when going to Pb-free.
- Voiding issues may have to be address with experiment to reach Sn-Pb void-free status – if necessary.
- "B" flux for BGA sphere attach had an "unpleasant" odor….



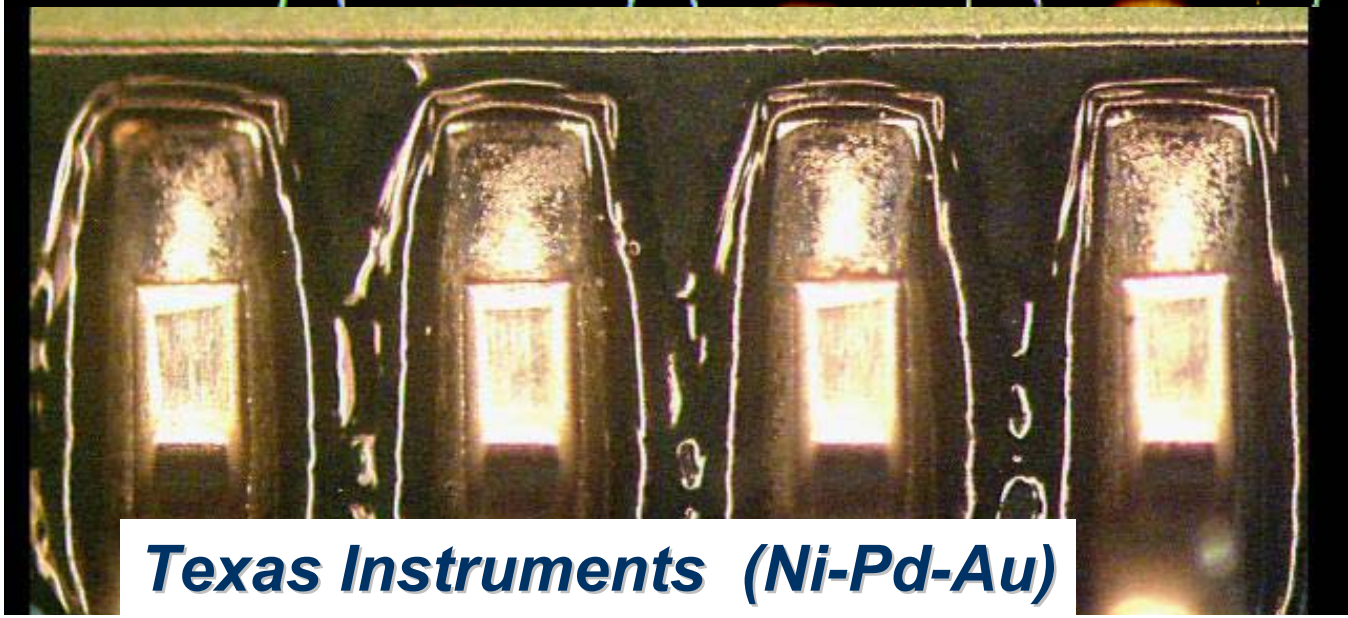
Paste "A"sample reflowed in air.
Flux probably was spent before spheres melted allowing re-oxidation of surface.
This occurred only on fine-pitch prints and is apparently a volume to surface area effect.

"A"Paste in air. Larger pitch components and pads do not exhibit this phenomenon…

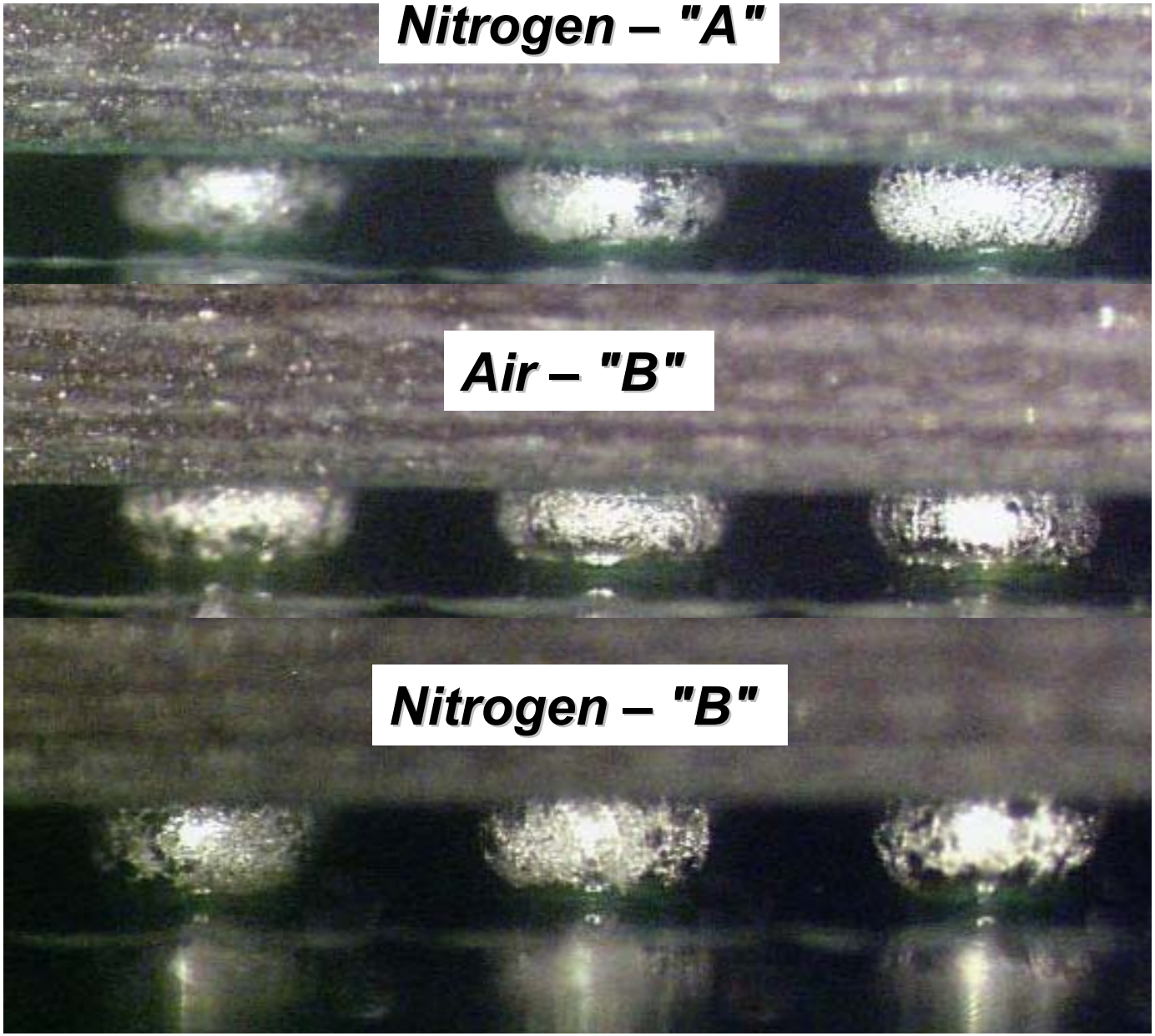
possibly confirming the volume to surface area hypothesis.

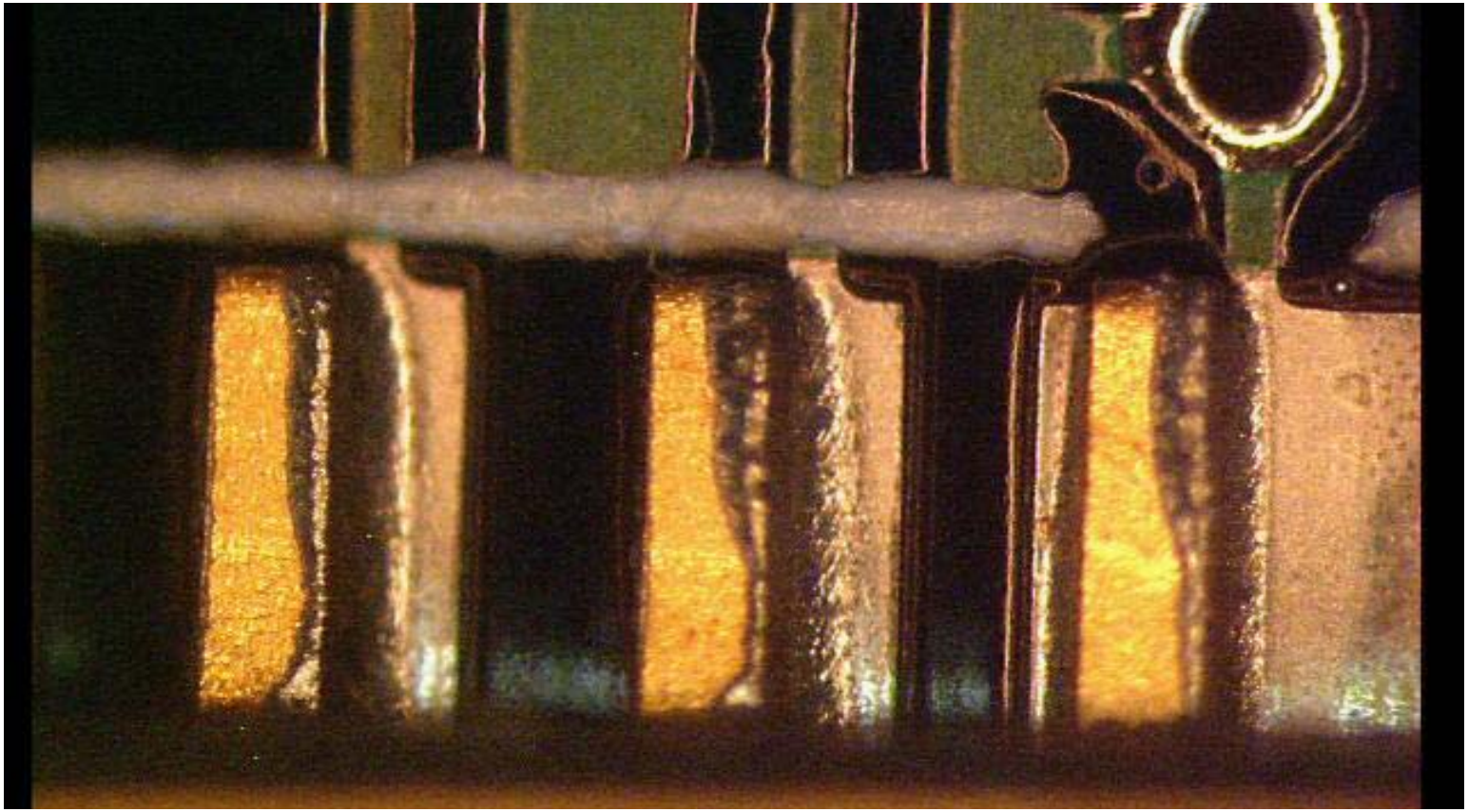
Lead finish had no effect.

Analog – Matte Sn



Texas Instruments (Ni-Pd-Au)


Nitrogen – "A"
Air – "B"
Nitrogen – "B"



As expected – thick gold leads can halt solder flow.
M/A-COM ceramic SOIC.

Au-Sn Phase Diagram

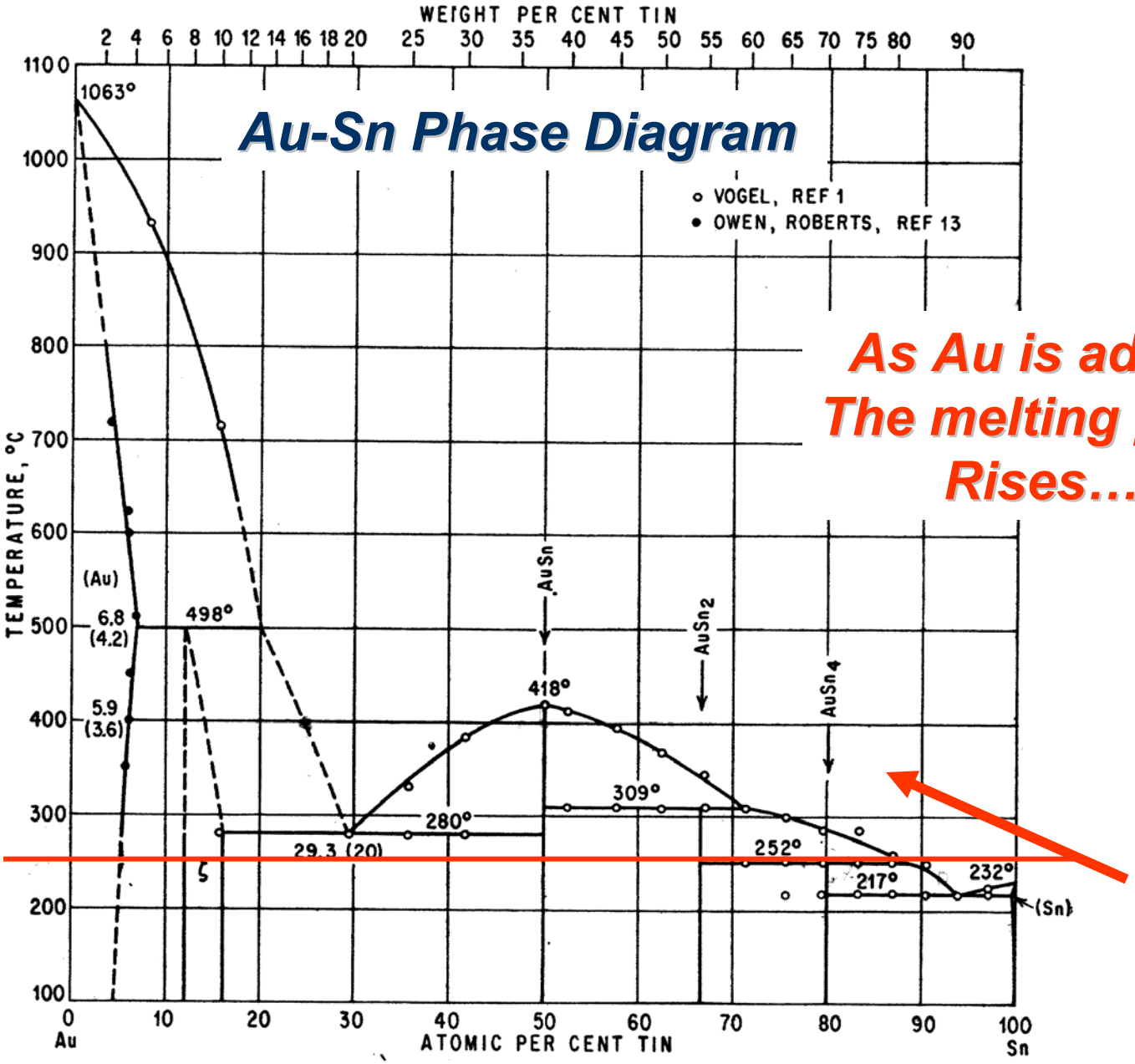
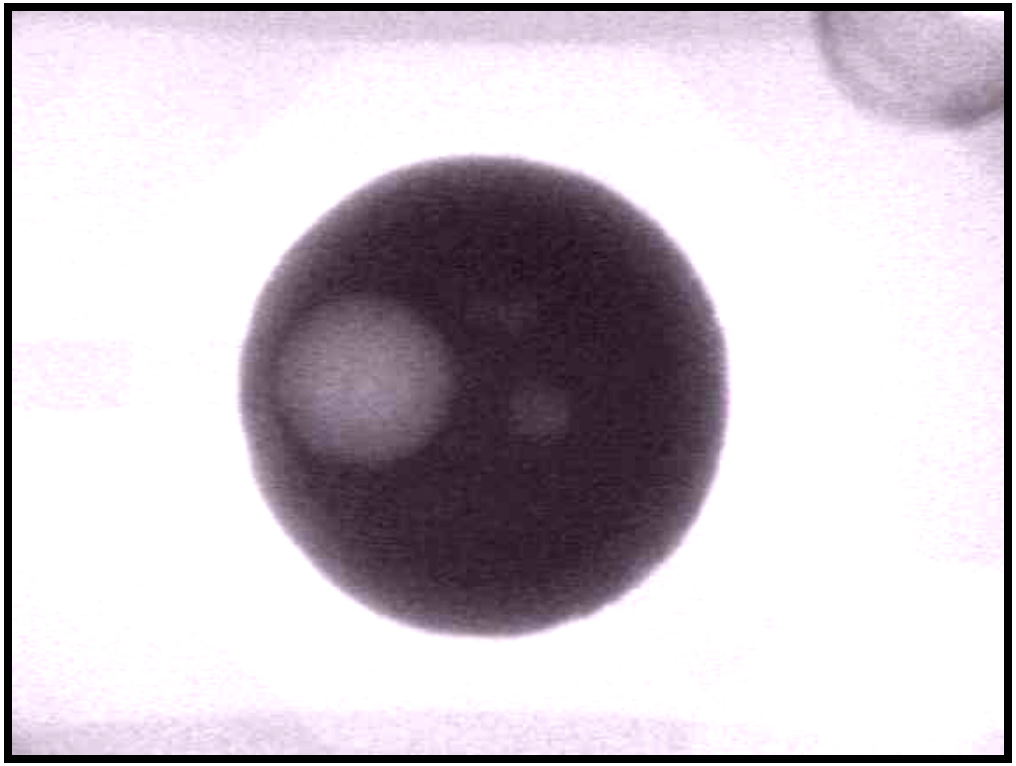


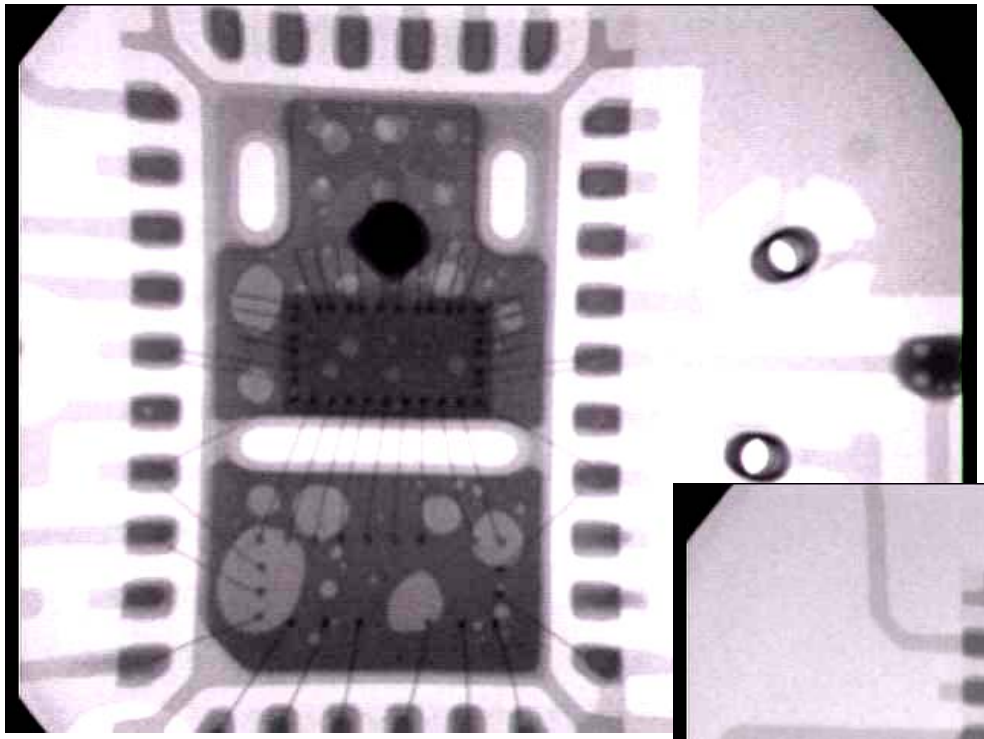
Fig. 135. Au-Sn

As Au is added The melting point Rises….

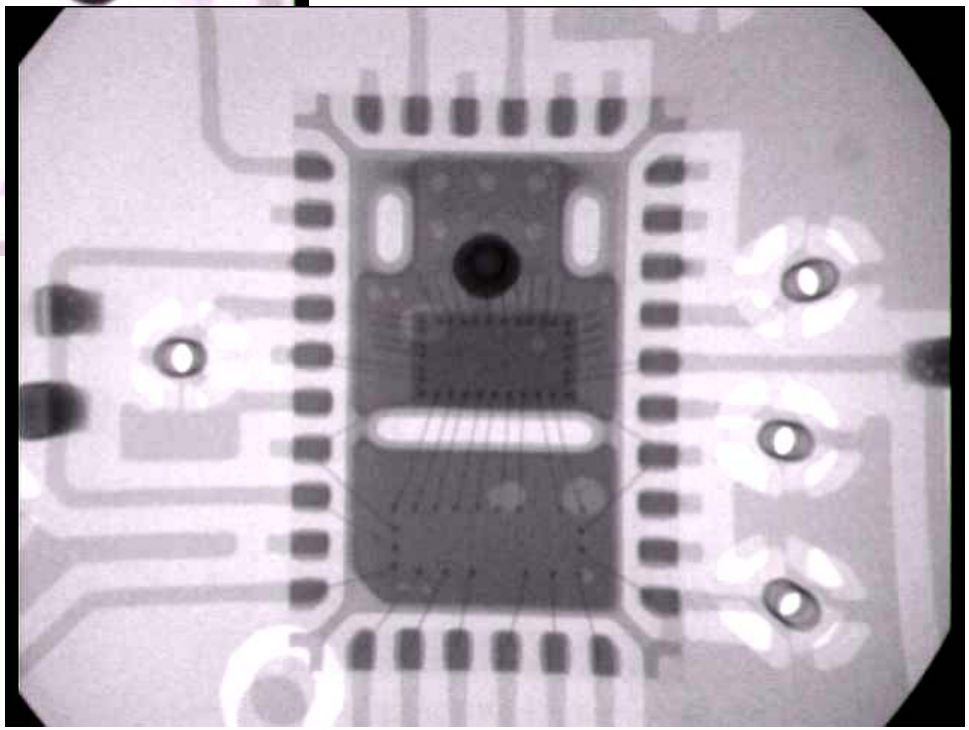
Tmax



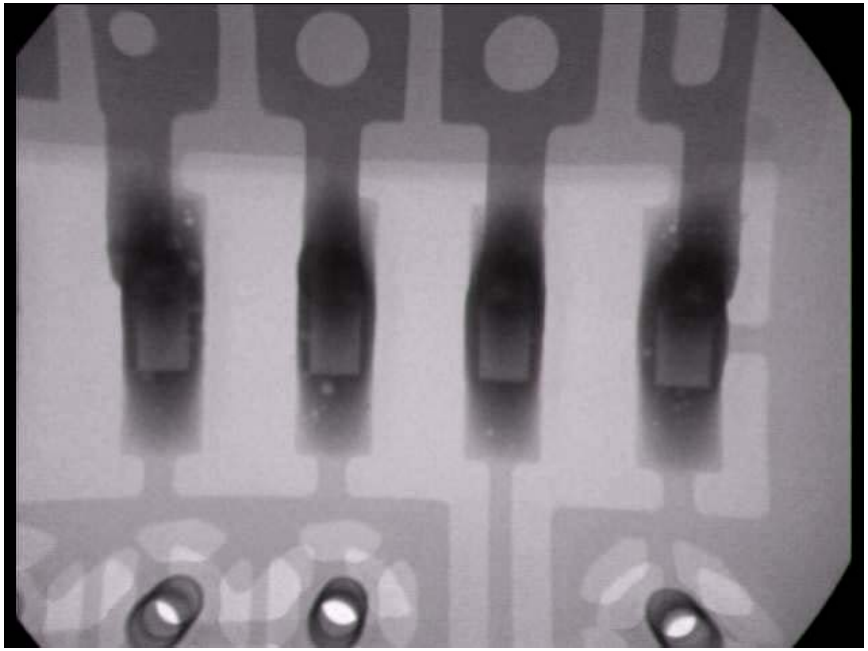
Pb-free solder is "known" for its tendency to form voids – especially in BGA joints.
Only a few voids this size have been found to date.
These are not cause for rejection unless they are greater than 25% of the solder volume.



Some pastes, finishes, or processes produced many voids…



Others resulted in many less voids as well as smaller voids,



Some finishes / prints / process conditions showed excellent results in terms of appearance both visibly and in x-ray.

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Visual Inspection Criteria

(H. Pasquito – M/A-COM – IPC Certified Class A Instructor / Inspector

- Criteria Developed using IPC-A-610C – Acceptability of Electronic Assemblies
- "Modified" to Account for Differences in Appearance of Pb-free Solder Joints
- Class 2 Length, Height, Alignment Criteria
- Inspectors – Joey Pang & Pat Ratelle – UMass Lowell
- Guidance – H. Pasquito, K. Walters – Team Members

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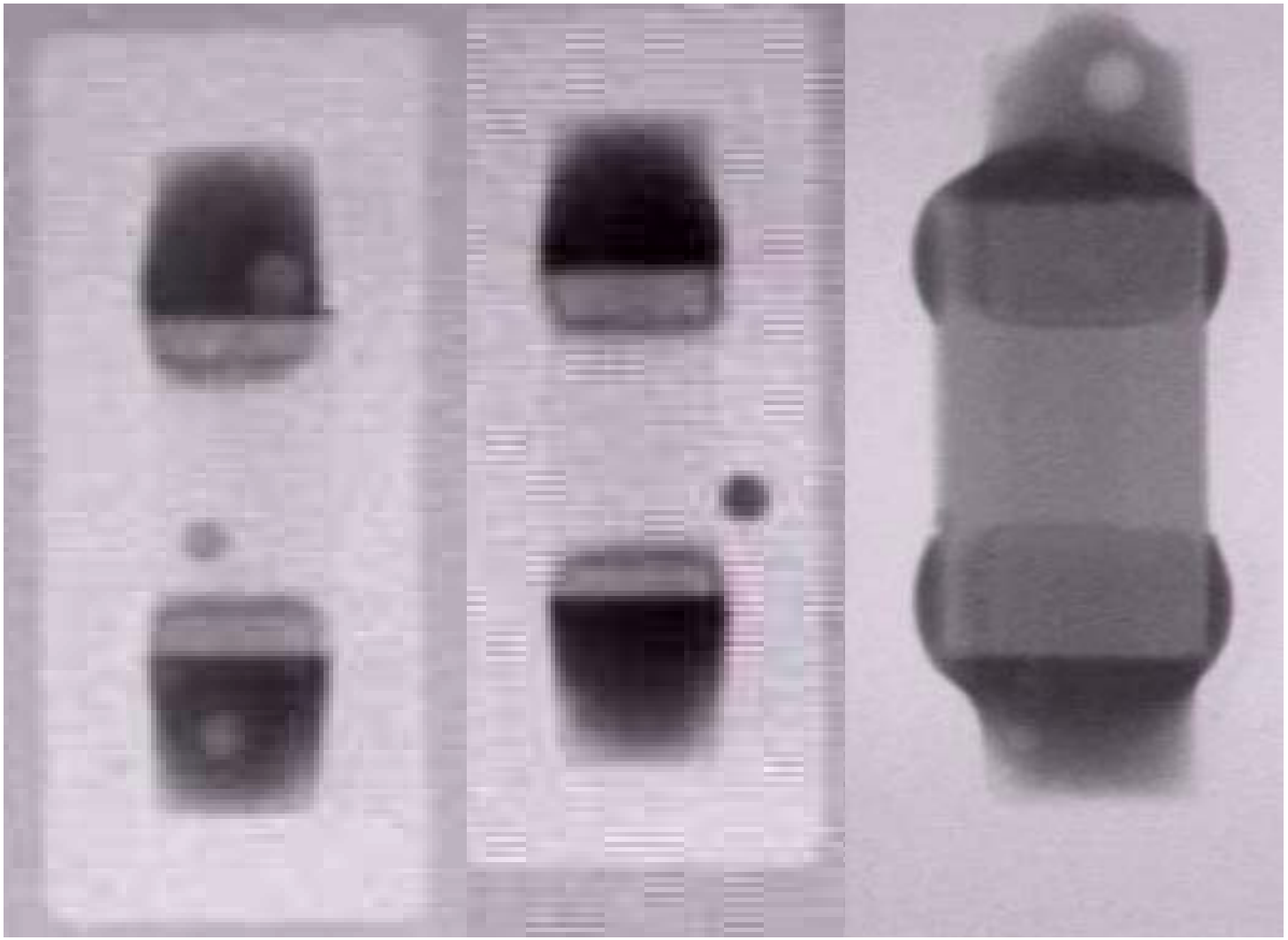


Voids, solder beads, and potential solder beads on chip Caps and Resistors.

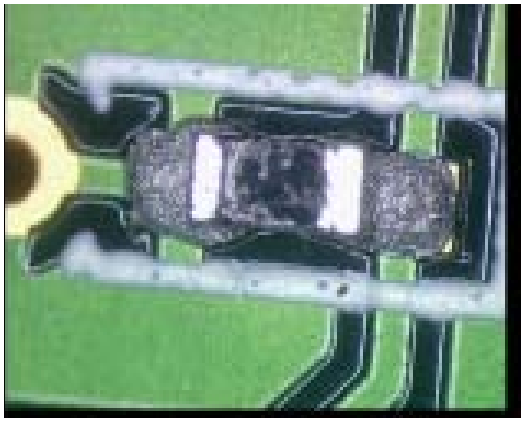
Visual Inspection Criteria (continued)

Property
Total Defects
Cold Solder Joining
Nonwetting
Solder Balls
Dewetting
Bridging
Pin/Blow Holes*
Shiny**
Residue**
Smooth**

** - none observed*

*** - qualitative inspection criteria*

Visual Inspection Criteria (continued)



COLD SOLDER JOINT

Evidence of solder not melting, thus maintaining original bead shape

NO COLD SOLDER JOINT

Solder has fully melted, thus not maintaining original bead shape

Visual Inspection Criteria (continued)

NONWETTING

Not properly wetted joint
Showing no evidence of fillet at contact

DEWETTING

Not properly wetted joint
Showing evidence of receded wetting at contact

WETTING

Properly wetted joint
Showing evidence of fillet at contact

Visual Inspection Criteria (continued)

SOLDER BALL (TYPE 1)

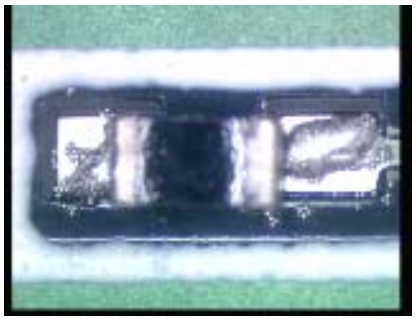
Few balls of solder off the land, Type one is for 1-5 solder balls

recorded as 1 solder ball

SOLDER BALL (TYPE 5)

Several balls of solder off the land, Type 5 is for 6-10 solder balls

recorded as 5 solder balls



SOLDER BALL (TYPE 10)

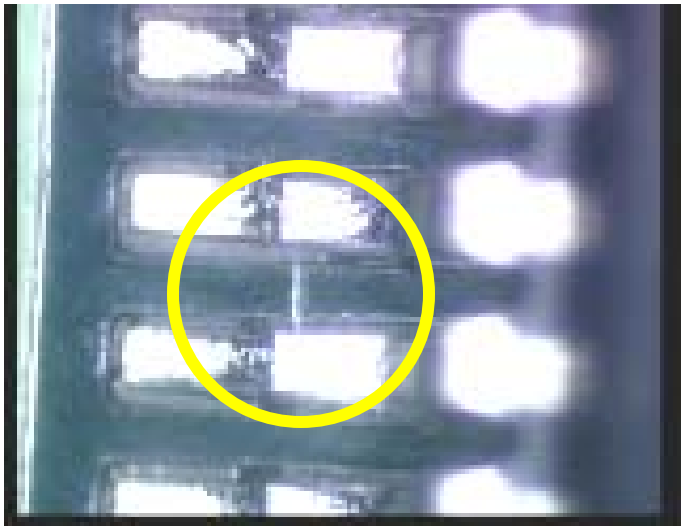
Many balls of solder off the land, Type 10 is for >10 solder balls

recorded as 10 solder balls

NO SOLDER BALL

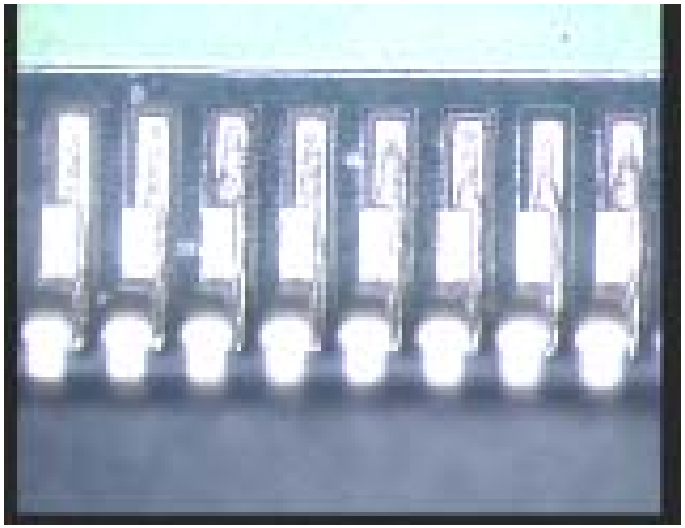
No balls of solder off the land

Visual Inspection Criteria (continued)



BRIDGE

Evidence of solder joining two leads



NO BRIDGE

No Evidence of solder joining two leads

Visual Inspection Criteria (continued)

PIN/BLOW HOLE

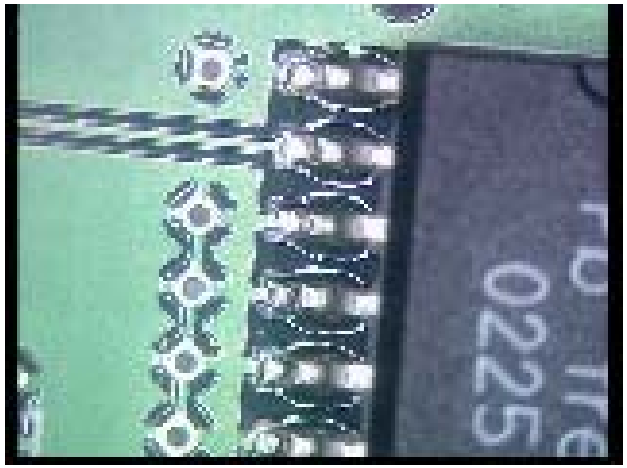
Evidence of blow hole in solder

NO PIN/BLOW HOLE

No evidence of blow hole in solder

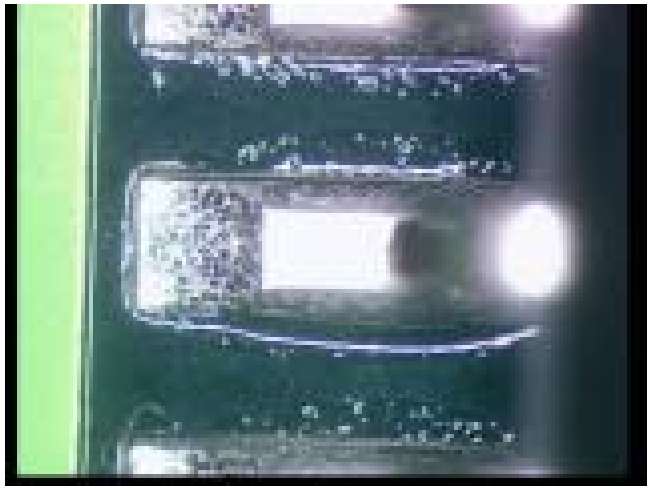
None Found

Visual Inspection Criteria (continued)



RESIDUE

Evidence of halo caused by residue



NO RESIDUE

No evidence of halo caused by residue

Visual Inspection Criteria (continued)

Visual "Judgment"

SMOOTH

NO PICTURE PROVIDED

Surface of solder has smooth texture

LUMPY

NO PICTURE PROVIDED

Surface of solder has lumpy texture

Visual "Judgment"

SHINY

NO PICTURE PROVIDED

Surface of solder has shiny appearance (high reflectivity)

DULL

NO PICTURE PROVIDED

Surface of solder has dull/gray appearance (low reflectivity)

Current DOE Statistics

Property	Main Effects			2 Factor Interactions			3 Factor Interaction
	Finish	Paste	Atmosphere	Finish*Paste	Finish*Atmosphere	Paste*Atmosphere	Finish*Paste*Atmosphere
Total Defects	Y - 3	Y - 2	Y - 1	N	N	Y	N
Cold Solder Joining	Y - 3	Y - 2	Y - 1	N	N	Y	N
Nonwetting	N	Y - 2	Y - 1	N	N	N	N
Solder Balls	Y	N	N	N	N	N	N
Dewetting	N	N	N	N	N	N	N
Bridging	Y	N	N	N	N	N	N
Pin/Blow Holes*	N	N	N	N	N	N	N
Shiny**	Y - 1	Y - 2	N	N	N	N	N
Residue**	N	Y - 1	Y - 2	N	N	N	N
Smooth**	N	N	N	N	N	N	N

Based on ANOVA Calculations

Current DOE Statistics

Property	Atmosphere	
	Air	Nitrogen
Total Defects	150.30	6.00
Cold Solder Joining	102.70	1.10
Nonwetting	33.30	1.60
Solder Balls	9.07	2.83
Dewetting	5.10	0.43
Bridging	0.13	0.03
Pin/Blow Holes*	0.00	0.00
Shiny**	0.63	0.43
Residue**	0.83	0.47
Smooth**	0.80	0.97

Current DOE Statistics

Property	Pb-Free Paste B	A	C
Total Defects	11.35	171.25	51.90
Cold Solder Joining	0.20	137.45	18.10
Nonwetting	2.60	20.25	29.50
Solder Balls	8.00	6.35	3.50
Dewetting	0.50	7.15	0.65
Bridging	0.05	0.05	0.15
Pin/Blow Holes*	0.00	0.00	0.00
Shiny**	0.80	0.30	0.50
Residue**	0.85	0.70	0.40
Smooth**	0.95	0.90	0.80

Current DOE Statistics

Property	Finish				
	ENIG	Imm. AG	Matte Sn	OSP	SMOBC/HASL
Total Defects	20.42	29.67	62.92	107.58	170.25
Cold Solder Joining	5.83	13.83	43.75	101.75	94.42
Nonwetting	7.75	13.42	6.50	3.50	56.08
Solder Balls	6.08	2.00	1.33	1.67	18.67
Dewetting	0.75	0.42	11.33	0.67	0.67
Bridging	0.00	0.00	0.00	0.00	0.42
Pin/Blow Holes*	0.00	0.00	0.00	0.00	0.00
Shiny**	0.17	0.75	0.50	0.67	0.58
Residue**	0.83	0.58	0.42	0.67	0.75
Smooth**	0.83	0.92	0.75	0.92	1.00

Current DOE Statistics (Board Finish)

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Ryan-Einot-Gabriel-Welsch Multiple Range Test for Total Defects
Means with the same REGWQ Grouping letter (A, B) are not significantly different.

REGWQ Groupings	Mean	N	Finish
A	170.25	12	SMOB/HASL
B	107.58	12	OSP
B			
B	62.92	12	Matte Sn
B			
B	29.67	12	Imm. AG
B			
B	20.42	12	ENIG

Interpretation: The Board Finish level SMOBC/HASL significantly differs from all other finishes.
No other finishes were found to be statistically different from one another at the 0.05 level.

tyco Electronics MACOM

Current DOE Statistics (Paste)

Ryan-Einot-Gabriel-Welsch Multiple Range Test for Total Defects
Means with the same REGWQ Grouping
letter (A, B) are not significantly different.

REGWQ Grouping	Mean	N	Paste
A	171.25	20	A Pb-Free
B	51.90	20	C Pb-Free
C	11.35	20	B Pb-Free

Interpretation:

All Pastes were found to differ significantly from all other pastes.
B Pb-Free performed best.

Current DOE Statistics (Atmosphere)

Ryan-Einot-Gabriel-Welsch Multiple Range Test for Total Defects
Means with the same REGWQ Grouping
letter (A, B) are not significantly different.

REGWQ Grouping	Mean	N	Atmosphere
A	150.33	30	Air
B	6.00	30	Nitrogen

Interpretation:

Nitrogen preformed significantly better than Air.

Current DOE Statistics (Paste x Atmosphere Interaction)

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Ryan-Einot-Gabriel-Welsch Multiple Range Test for Total Defects
Means with the same REGWQ Grouping
letter (A, B) are not significantly different.

REGWQ Grouping	Mean	N	Interaction
A	337.10	10	A with Air
B	98.70	10	C with Air
C	15.20	10	B with Air
C			
C	7.50	10	B with Nitrogen
C			
C	5.40	10	A with Nitrogen
C			
C	5.10	10	C with Nitrogen

Interpretation: The A Pb-Free, Air combination was significantly worse than all other combinations.
The C Pb-Free, Air combination was significantly worse than all other remaining combinations.
The bottom four combinations could not be told statistically apart from each other within the limitations of the current study.

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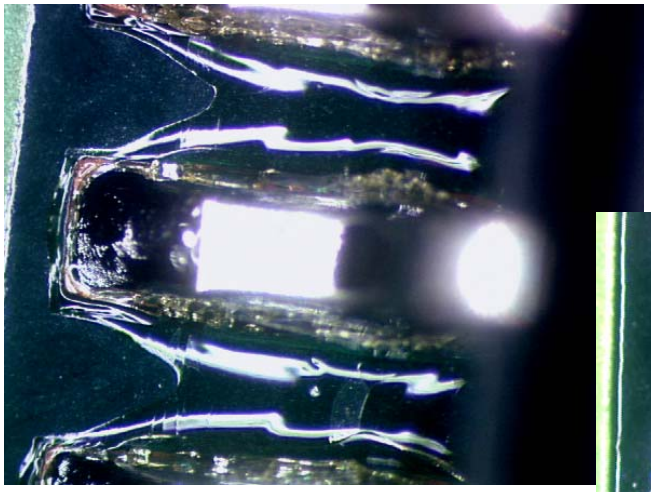
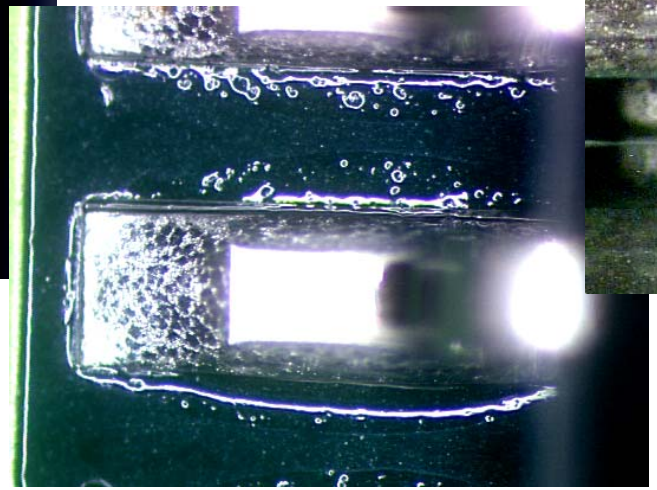
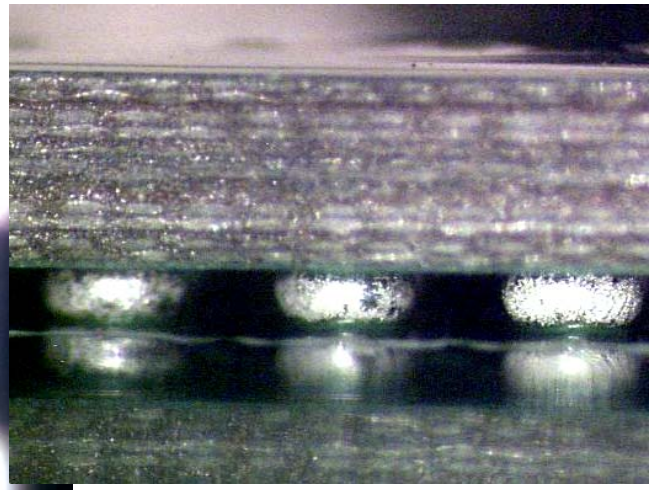
Current DOE
Shiny and Flux Residue Analysis

One goal was to establish inspection criteria for Pb-free solder joints.





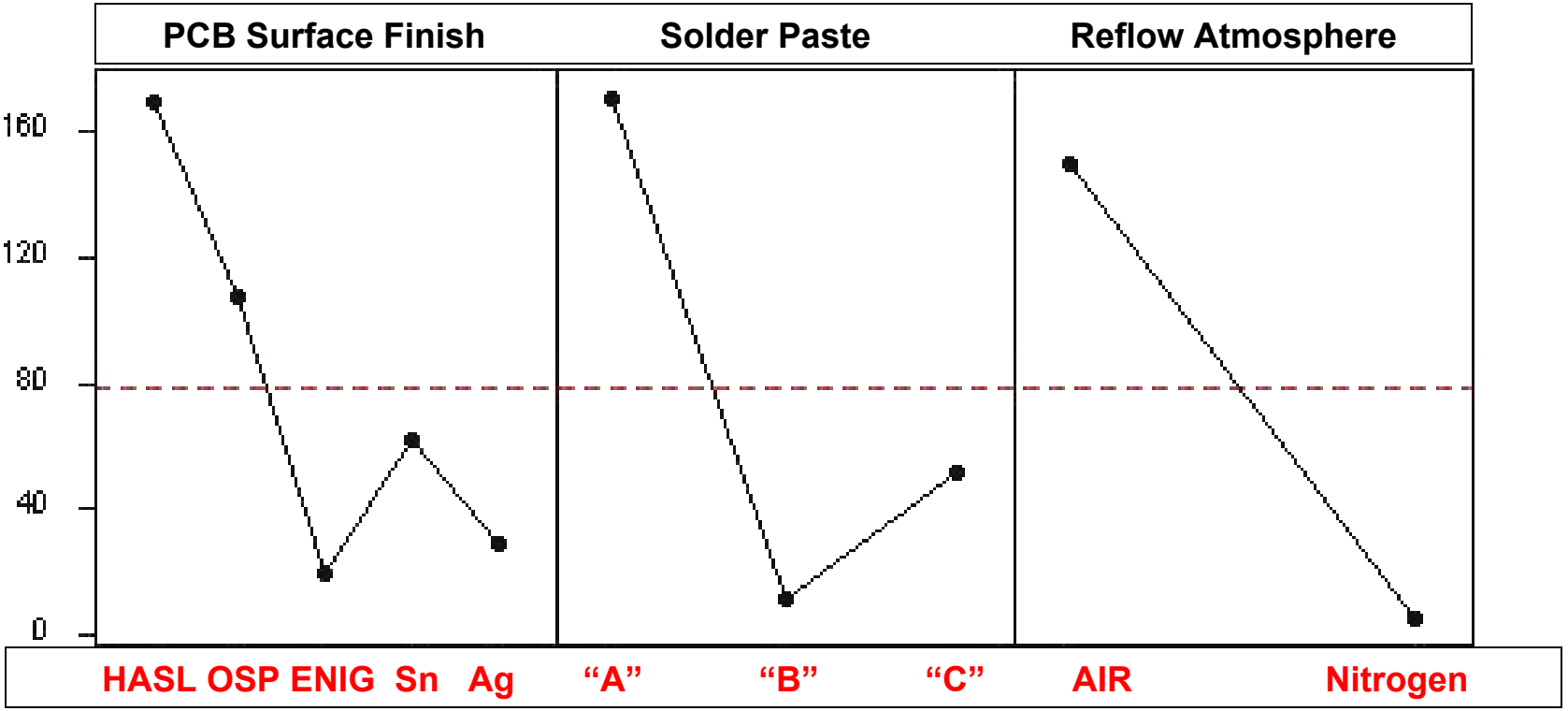


- Flux Residue is often “glossy.”
- Dry joints may look dull in some lighting schemes.
- Air reflow may “burn” or darken some fluxes.
- Residue prevents oxidation – shinier joint.
- Residue may crack on cooling.

Current DOE Discussion

- This assembly process was not optimized for any of the variable options or solder pastes provided.
- Further, throughput and cost can be significant issues that may override some of these results.
- These data show it is possible to obtain visually acceptable solder joints using a variety of board finishes, lead finishes, paste formulations and Air/Nitrogen combinations.
- Must correlate data to be taken with these findings for further clarification of the effects of these variables on solder joint reliability and yield.

Current DOE - Discussion



- *Demonstrated the effects of atmosphere, paste selection, and surface finish on visible defects and appearance for these process conditions.*
- *Nitrogen and paste "B" yielded the fewest visible defects.*
- *SMOBC – HASL board finish yielded significantly more visual defects.*

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Future Work….

Complete X-ray Inspection – Document Findings

Baseline Mechanical Pull and Shear Tests

Thermal Cycling Tests – (1000 hrs. = 6 weeks)

Electrical Testing Where Possible

Mechanical Testing of Stressed Parts

Data Analysis and Photographs

Develop Results and Conclusions

To Date….

Demonstrated Robust Assembly Processes

(provided paste print and reflow atmosphere effects addressed)

Demonstrated Diverse Assembly Processes

(lead finish, board finish, component type)

Identified Caveats

(joint appearance, gold concentration effects,
Voiding issues, paste area/volume - in air)

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