Medalist

The Transition to Lead-Free:

Lead-Free Soldering and the 5DX

5DX User Group Meeting

Loveland, Colorado

March 2005

Agilent Technologies

Agenda

Lead-free is becoming a reality

Lead-free Issues and Resulting Defects

Test Strategy Considerations for Lead-free

Lead-free Test and Inspection studies

5DX C & A

Discussion of *your* experiences

Question:

Lead-free soldering at you sites:

1) In production now

2) In limited production now

3) Experimentation and process development

4) No activity yet

Lead-free is becoming a reality

Lead-Free is a Law!

- **EU (European Union)**
  - WEEE (Waste Electrical and Electronic Equipment)
  - RoHS (Restriction of Hazardous Substances)
- **China**

Implementation Date is July 1, 2006

Restriction of Hazardous Substances (RoHS)

- Lead
- Mercury
- Cadmium
- Hexavalent chromium
- PBB / PBDE

Lead - the most common material that must be eliminated

Leading Lead-Free Solder Alloys

- **US: NEMI & SMTA: Sn3.9Ag0.6Cu** ***(SAC396)***
- **Europe: Sn(3.4 - 3.9)Ag(0.5-0.9)Cu**
- **JEIDA: Sn3.0Ag0.5Cu** ***(SAC305)***

Converging on the metallurgical range:

Sn-(3.0-4.0)Ag-(0.5-1.0)Cu

Melting Point ~ 217 C

(34º C higher than Sn/Pb at 183 C)

Numbers are in weight percent

Sn = Tin
Ag = Silver
Cu = Copper

Affected products and exemptions

Products affected:

Electronic toys, Electronic tools, Radios, TVs, VCRs, telecom etc. DVDs, Household items, IT equipment

Exemptions:

Network Infrastructure, Medical, Instruments, Automotive, Defense, Aerospace, etc. *High reliability*

Lead is allowed in:

Glass, CRT (TV tubes), X-ray shielding

Exemptions may be reconsidered…

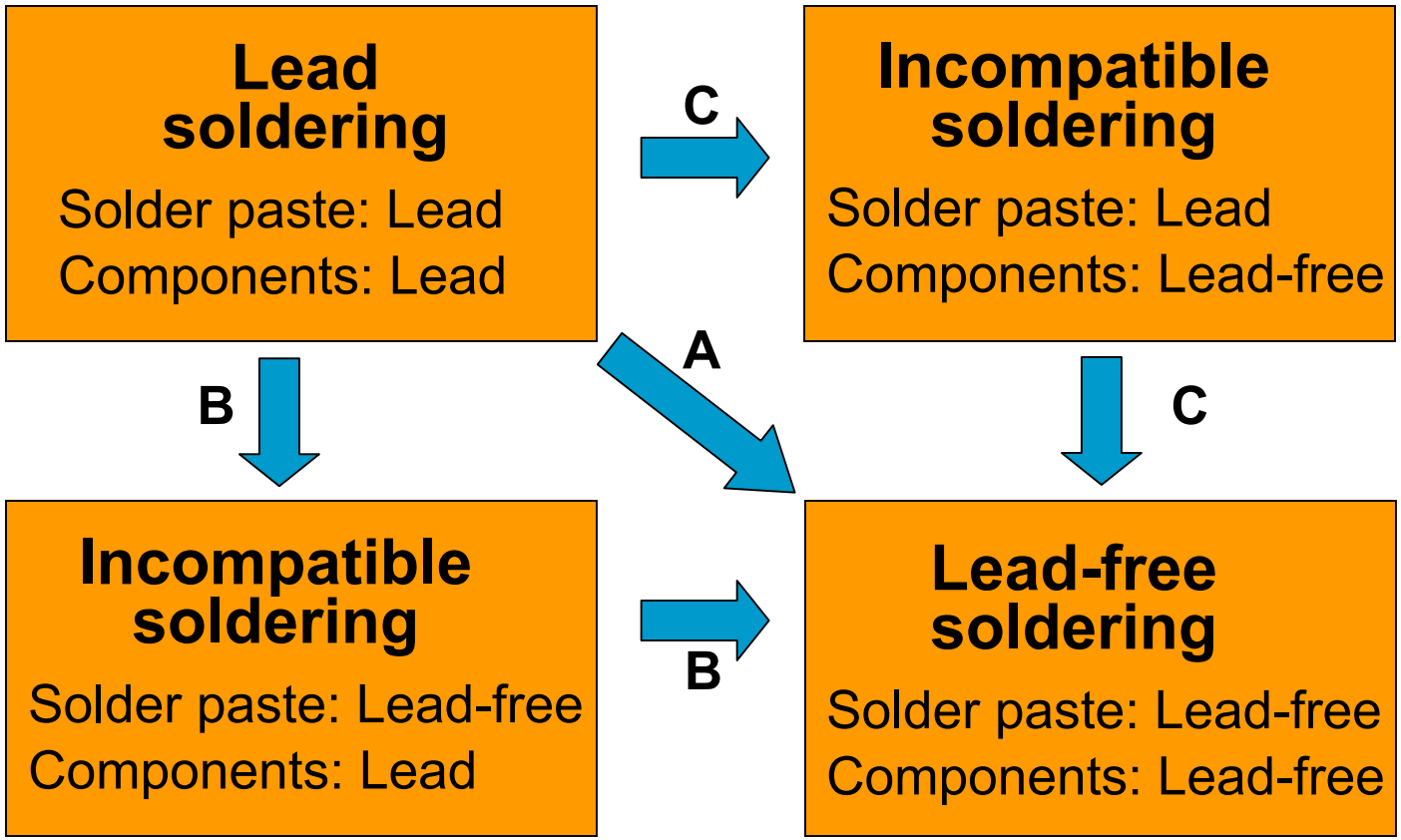
…..*more as it develops*

Lead in many areas of the PCBA

- **Solder**
- **Components**
- **Board finish**

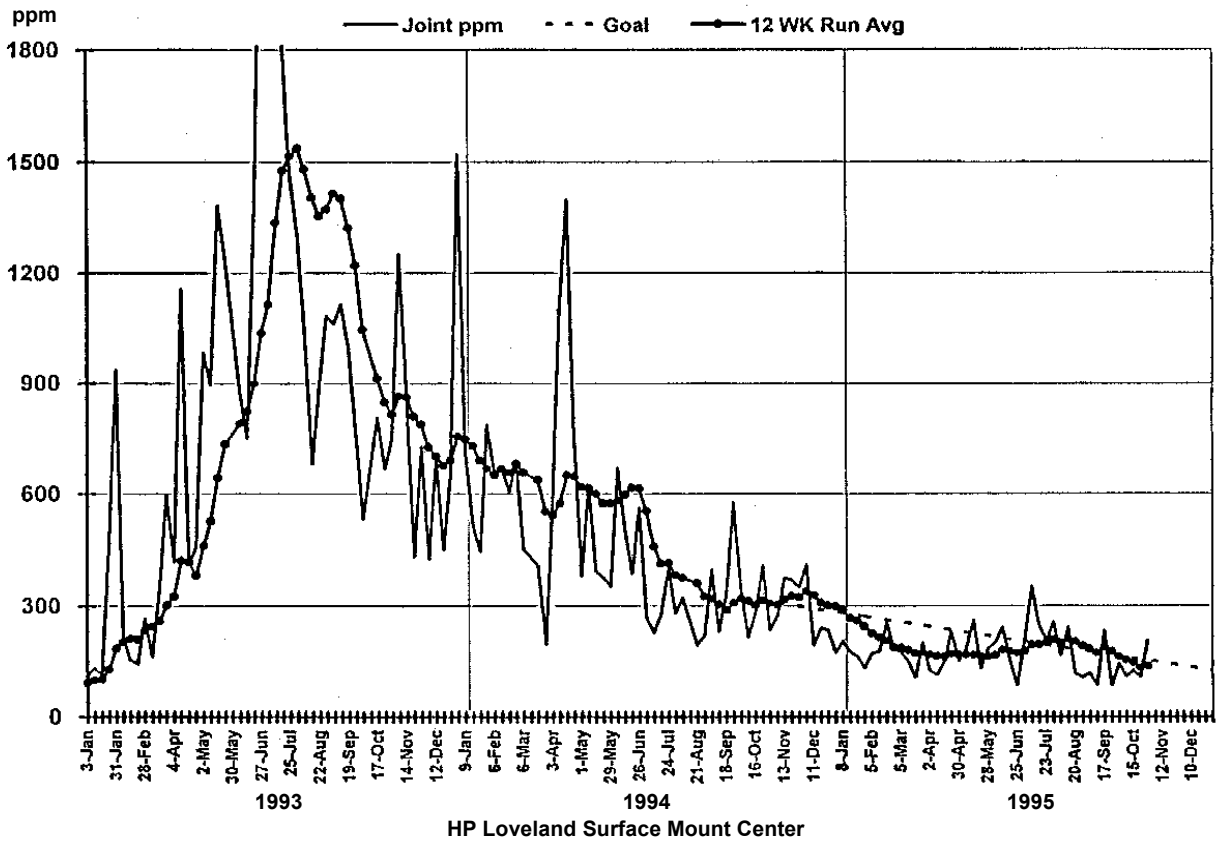
It will not be a clean switch –
There will be many issues!

Lead-free transition issues



Defect levels - one data point

No-clean transition



Some manufacturing sites and boards will see little difference.

Lead-free Issues

and Resulting Defects

Issues

Logistics: Lead and lead-free components in the process
…..***often with no change in part number!***

SMT: Higher reflow temperature

Higher defect levels & more process variation

Slightly different defect spectrum

Driven by differences in **wetting**

Wave: Need to retrofit equipment

Higher defect levels (insufficient barrel-fill)

Rework: Fewer rework attempts

Higher rework temperatures

Reliability: Solder joints generally higher reliability

Components? - higher temperatures

Tin whiskers

Other: Board complexity

Solder Joint Defects

Predictions

Defects	Comparison
OPENS	Lead-Free > SnPb
SHORTS (Bridging)	Lead-Free > SnPb
VOIDS	Lead-Free > SnPb
MISALIGNMENT	Lead-Free > SnPb
INSUFFICIENT SOLDER	About the same
EXCESS SOLDER	About the same

Some manufacturing sites and boards will see little difference.

Wetting: What is it?

Definitions of Wetting:

The adherence of a film or a liquid to coat or cover the surface of a solid completely. PQ Corporation

The spontaneous spreading of one phase over the surface of another. About.com

The wetting characteristics of molten solder and the surfaces it is joining determine how well the solder covers pads and leads, and determines the shape of solder joints.

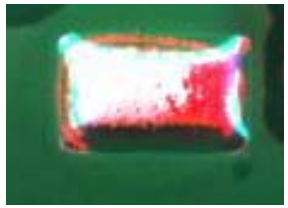
The wetting force of Sn/Ag/Cu lead-free solders is not strong as for Sn/Pb solders.

What does this mean in manufacturing?

Reduced Wetting: Pad Coverage

Paste as stenciled

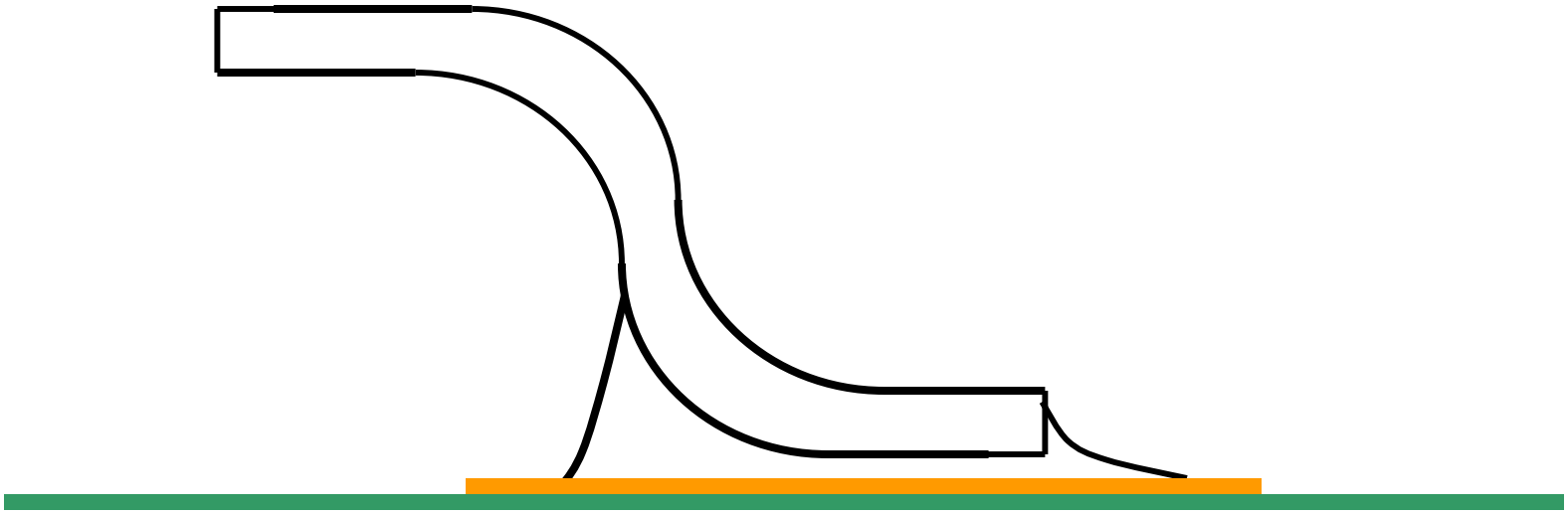
Sn/Pb, reflowed



Pb-free, reflowed

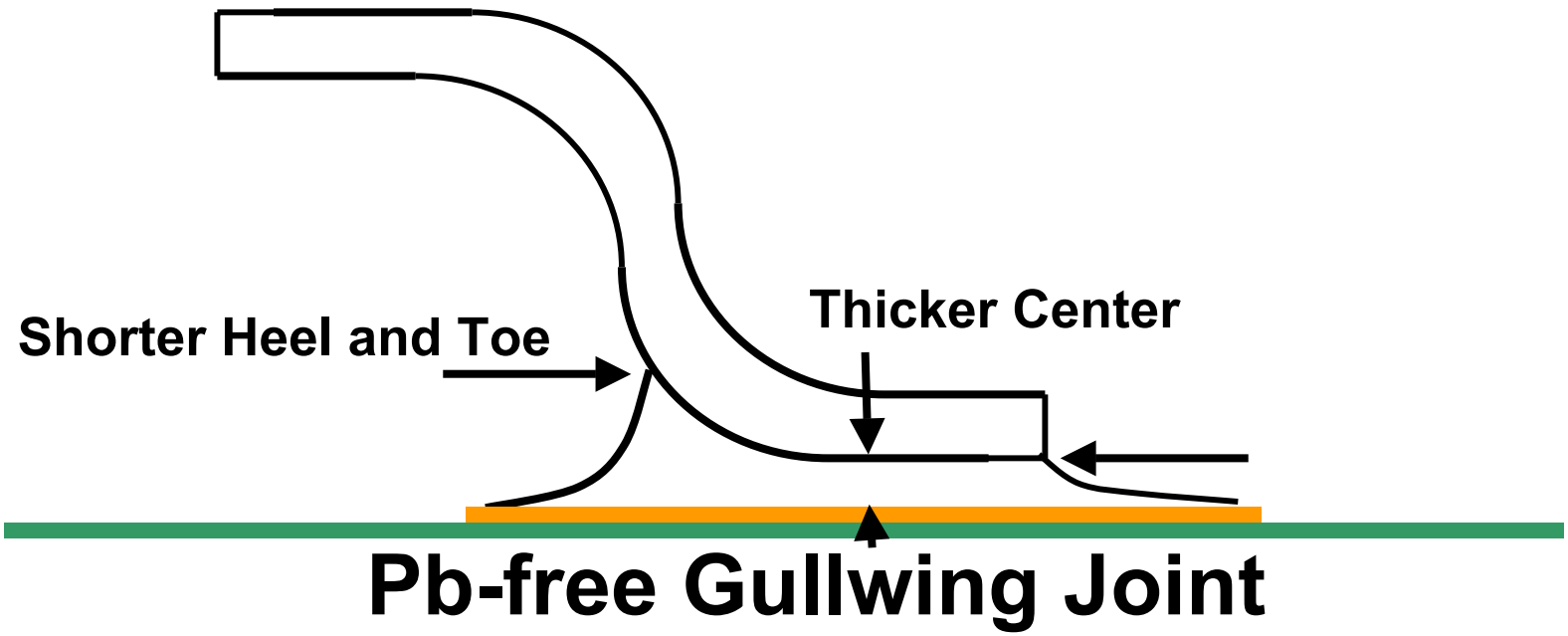
Entire pad not covered

Reduced Wetting: Joint Shape

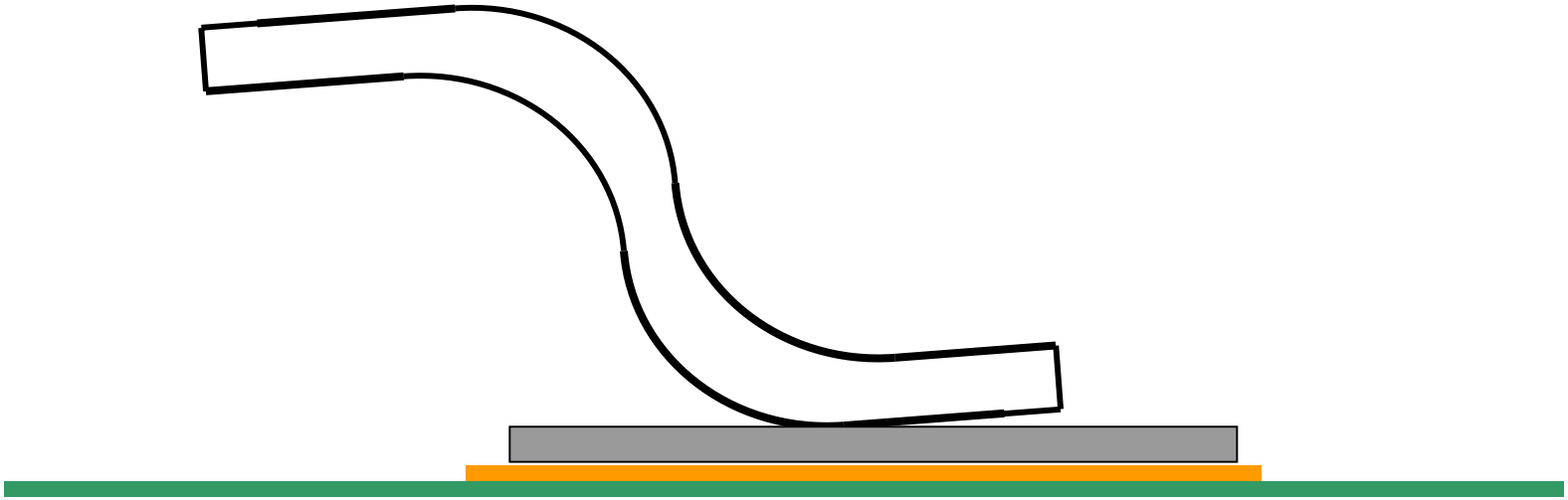


Sn/Pb Gullwing Joint

Reduced Wetting: Joint Shape

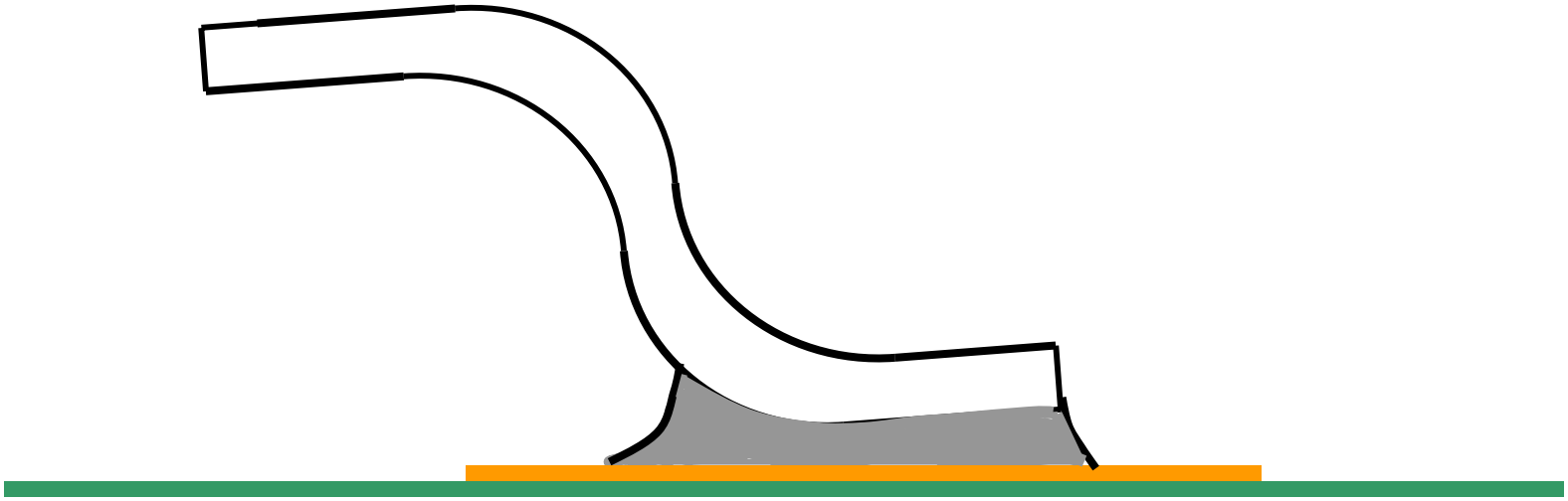


Reduced Wetting: Bent Lead



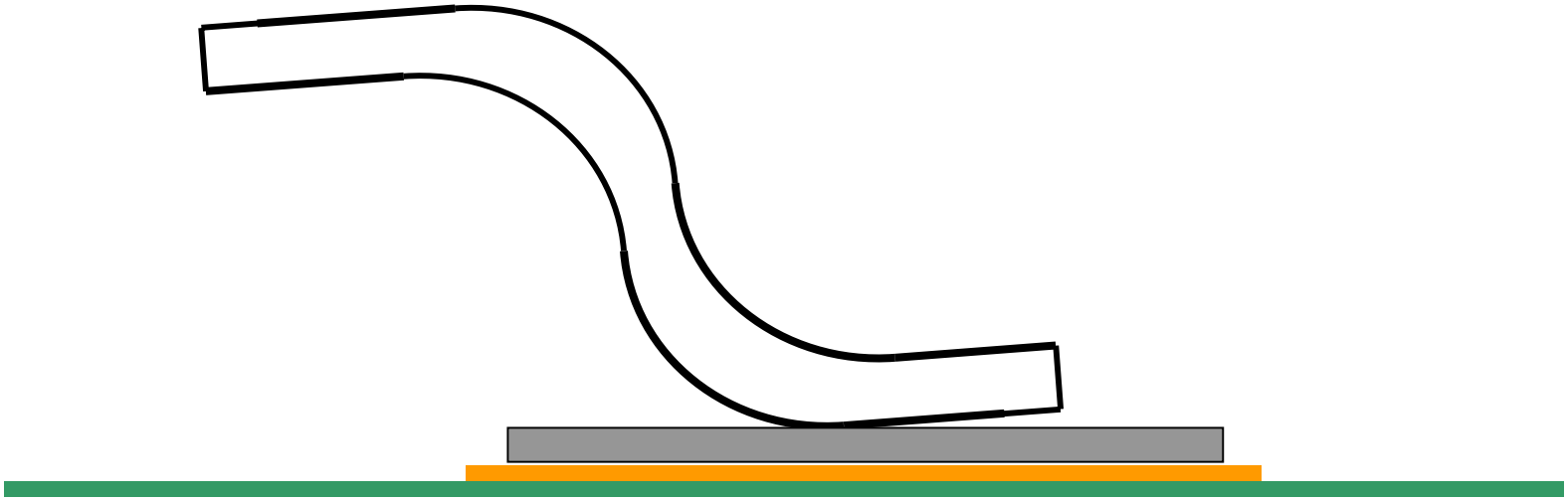
Bent lead on Sn/Pb paste

Reduced Wetting: Bent Lead



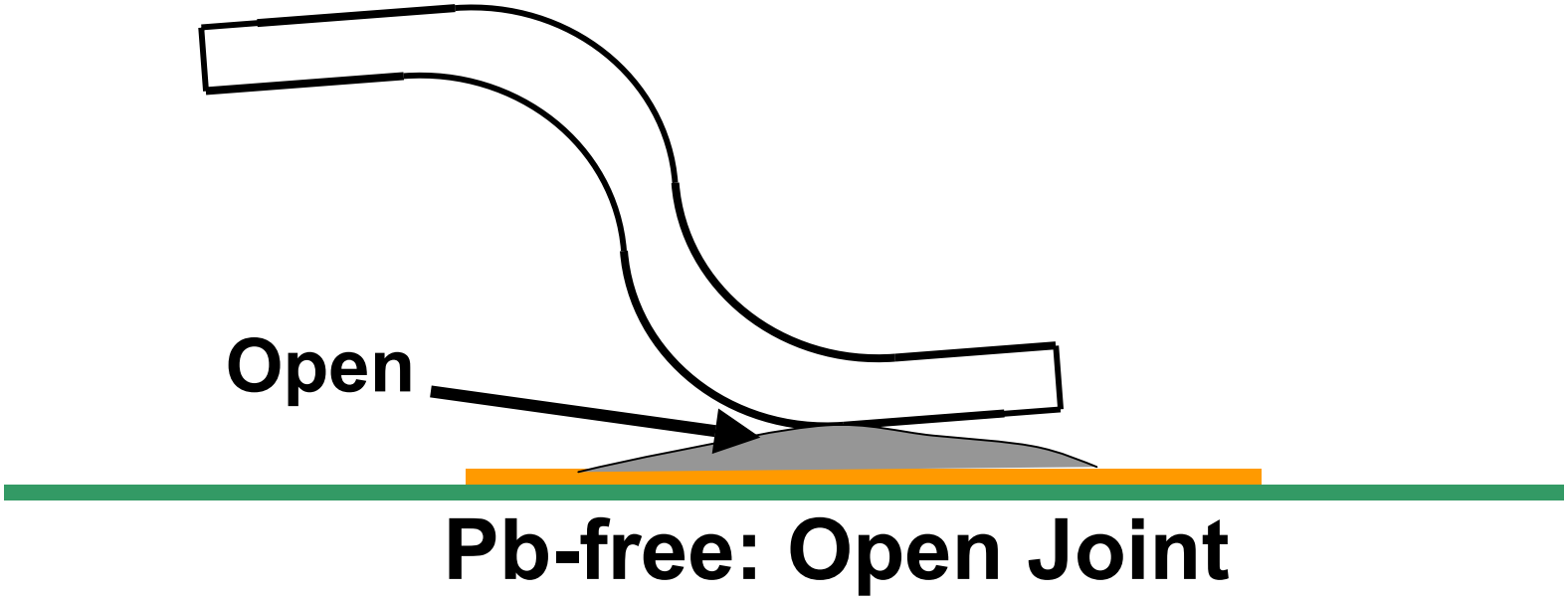
Sn/Pb: Acceptable Joint

Reduced Wetting: Bent Lead



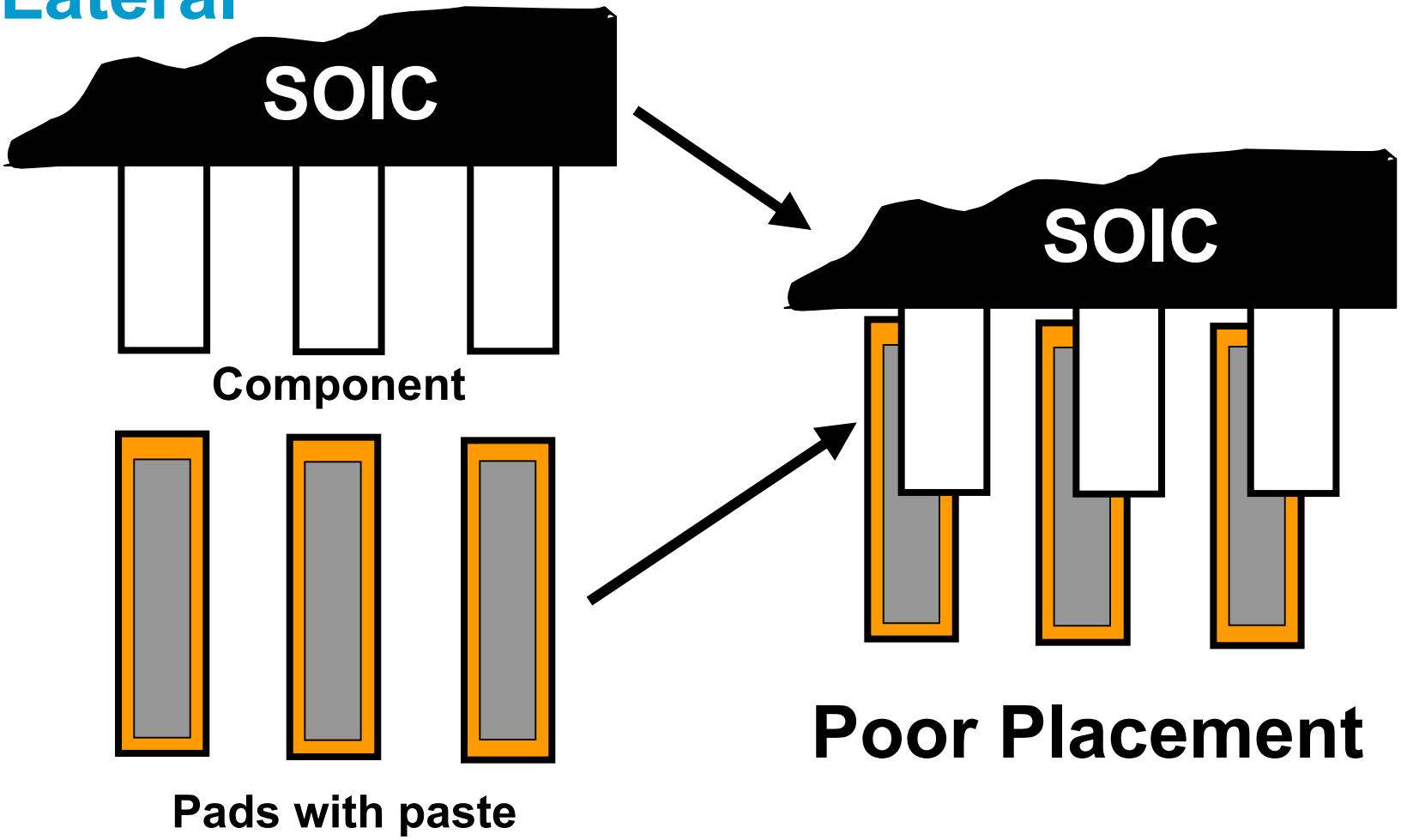
Bent lead on Pb-free paste

Reduced Wetting: Bent Lead

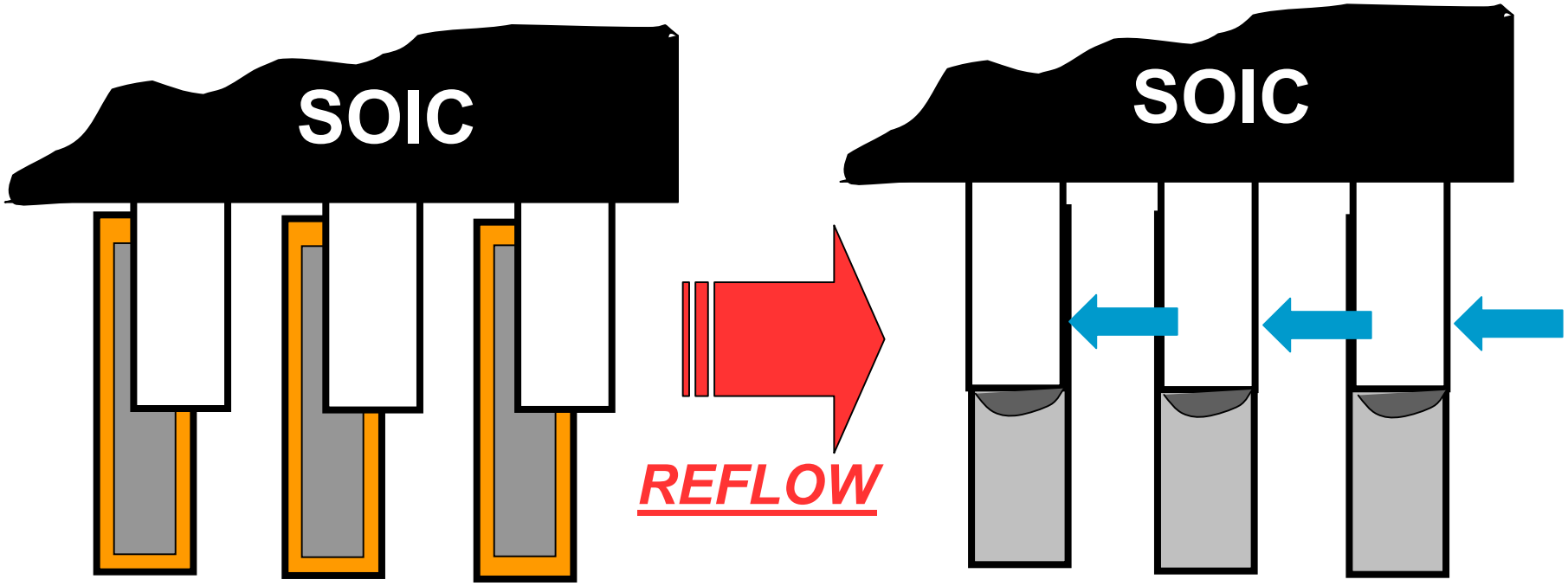


Pb-free: Open Joint

Reduced Wetting: Self-alignment of parts: Lateral



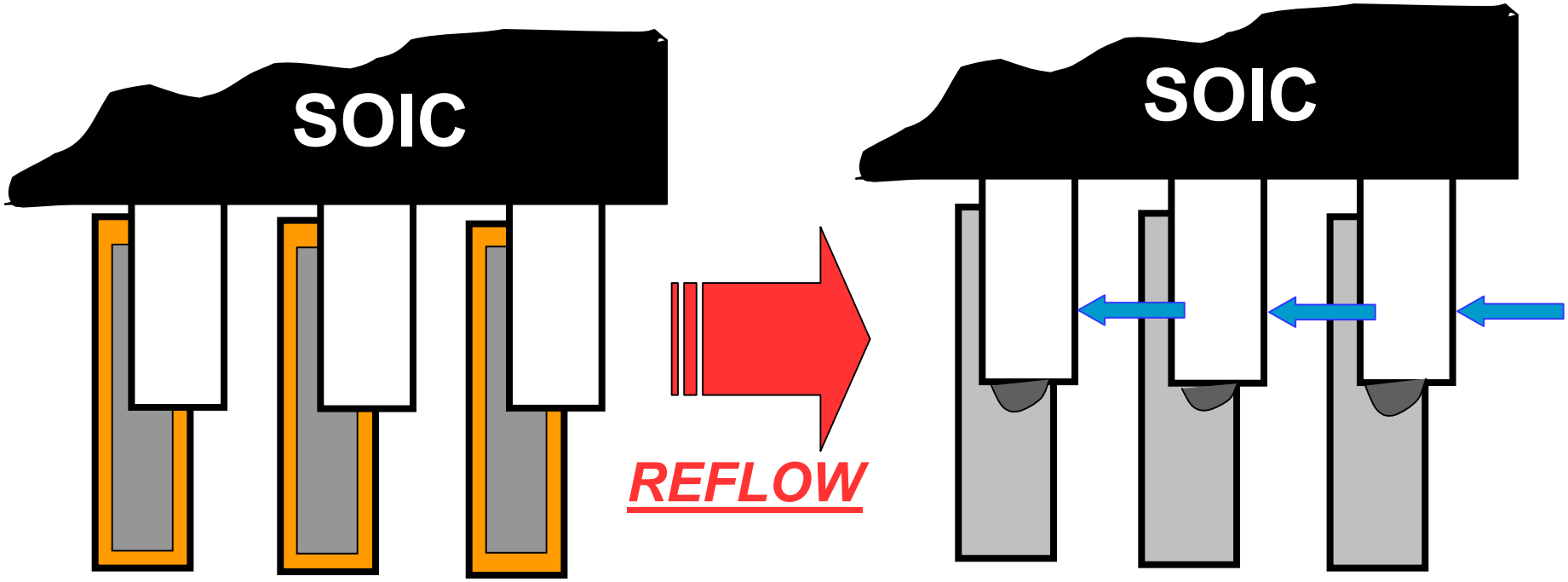
Reduced Wetting: Self-alignment of parts with Sn/Pb Solder



Poor Placement (Pre-reflow)

Self-aligned in reflow by wetting forces (Blue arrows)

Reduced Wetting: Self-alignment of parts with Lead-free Solder

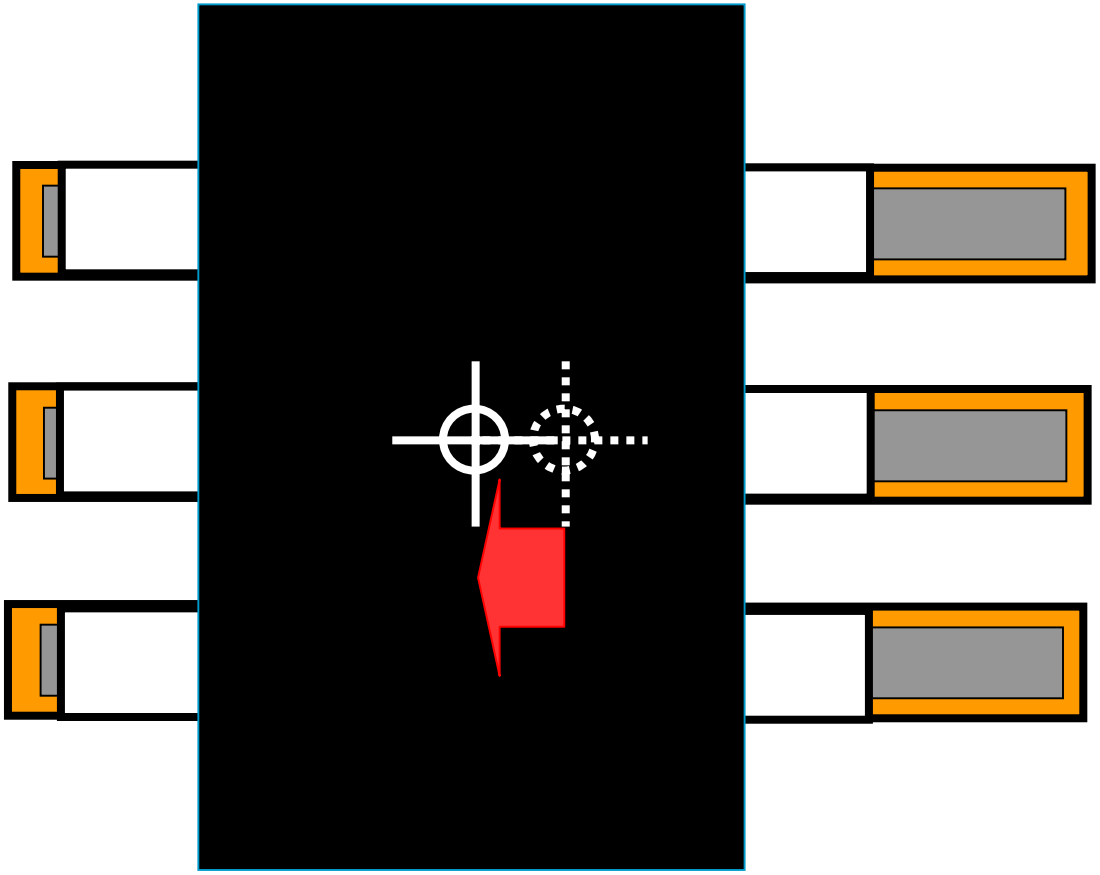


Poor Placement (Pre-reflow)

Reduced self-alignment in reflow by reduced wetting forces (Blue arrows)

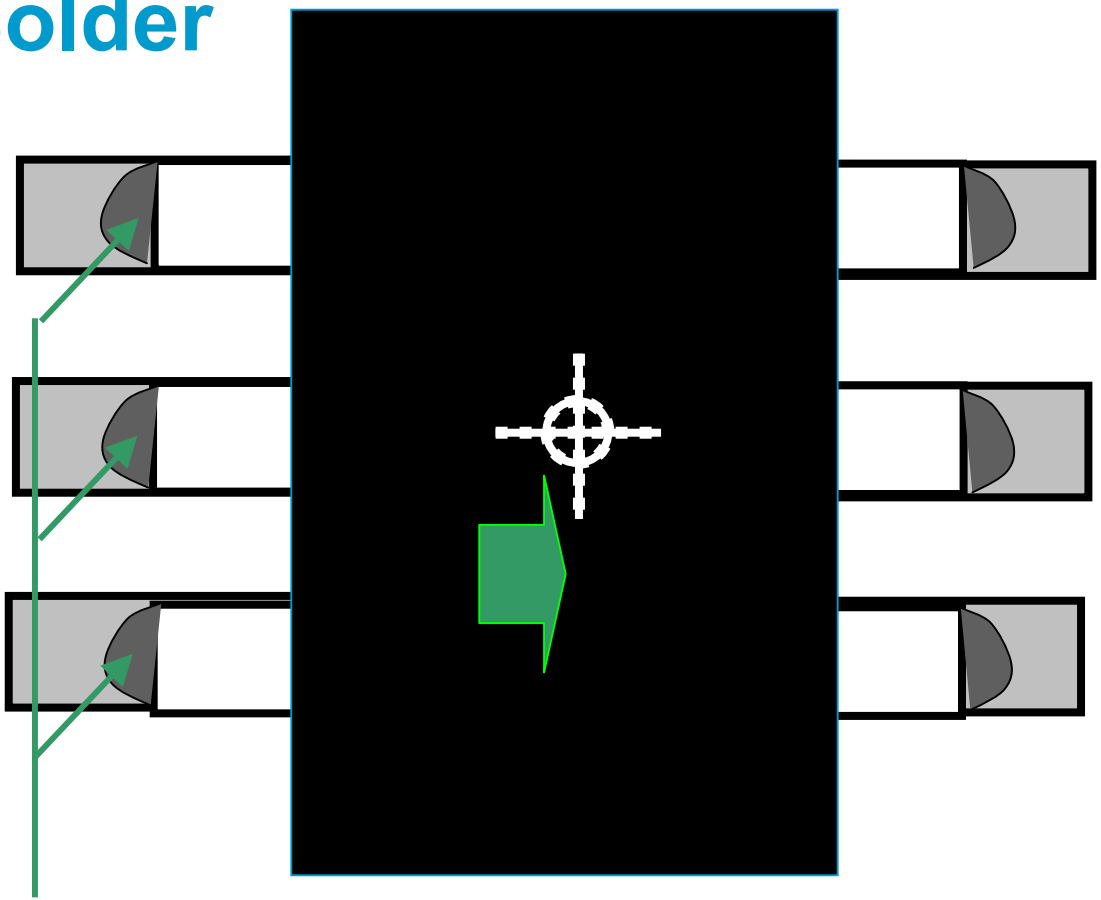
Reduced Wetting: Self-alignment of parts: Axial

Poor Placement



Reduced Wetting: Self-alignment of parts with Sn/Pb Solder

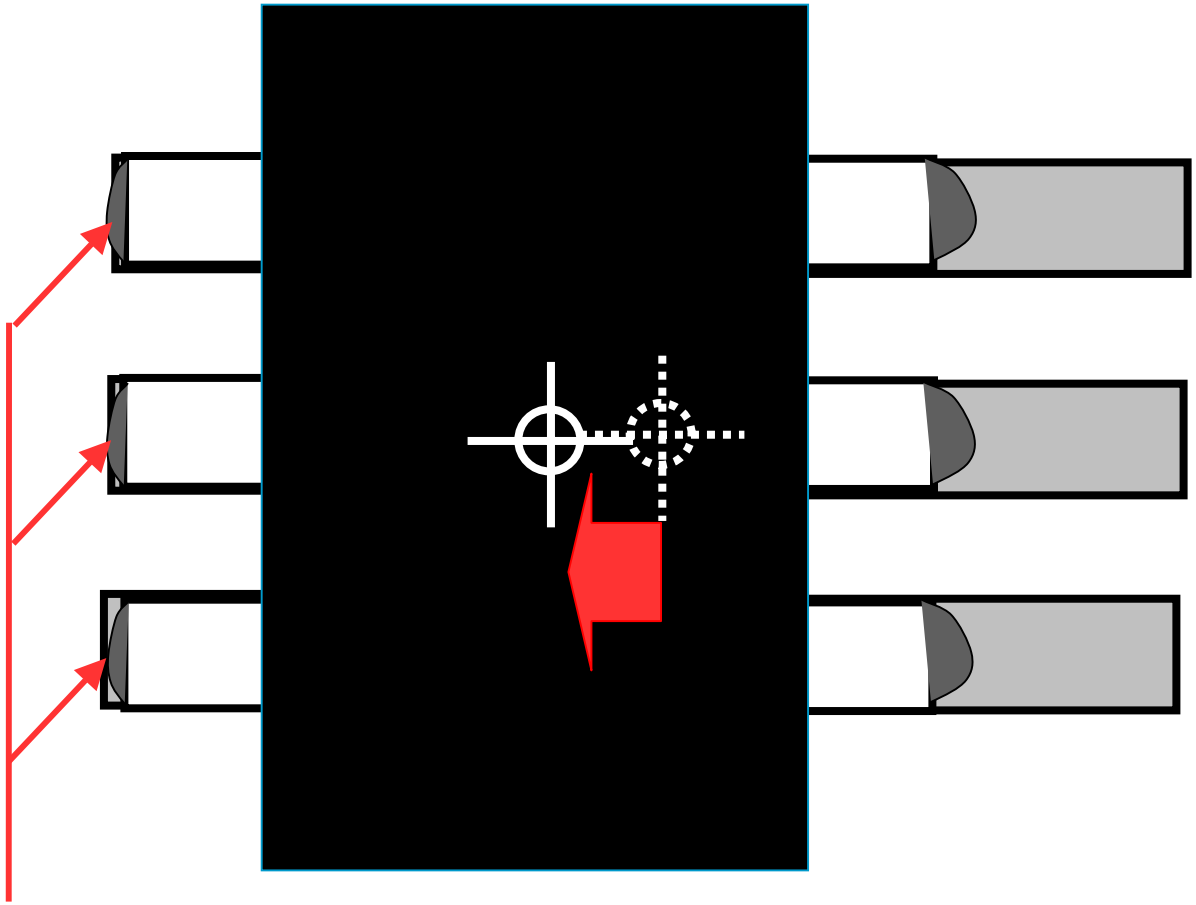
Self-aligned in reflow (Sn/Pb)



Note large solder fillets

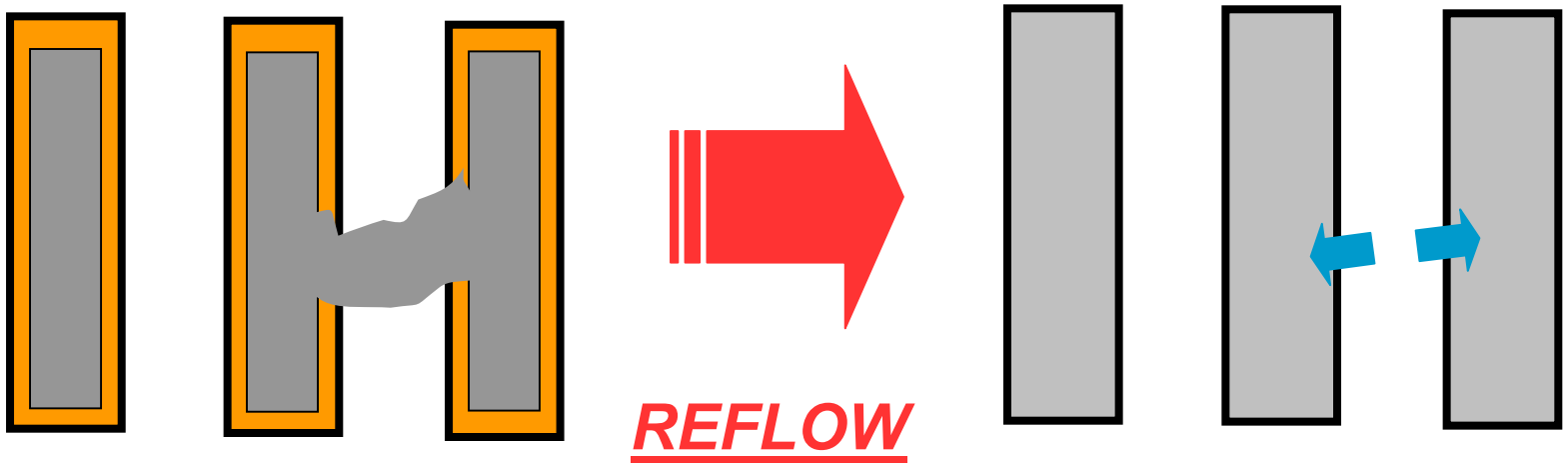
Reduced Wetting: Self-alignment of parts with Lead-free Solder

Does *NOT* Self-align in reflow (Lead-free)



Note very small solder fillets

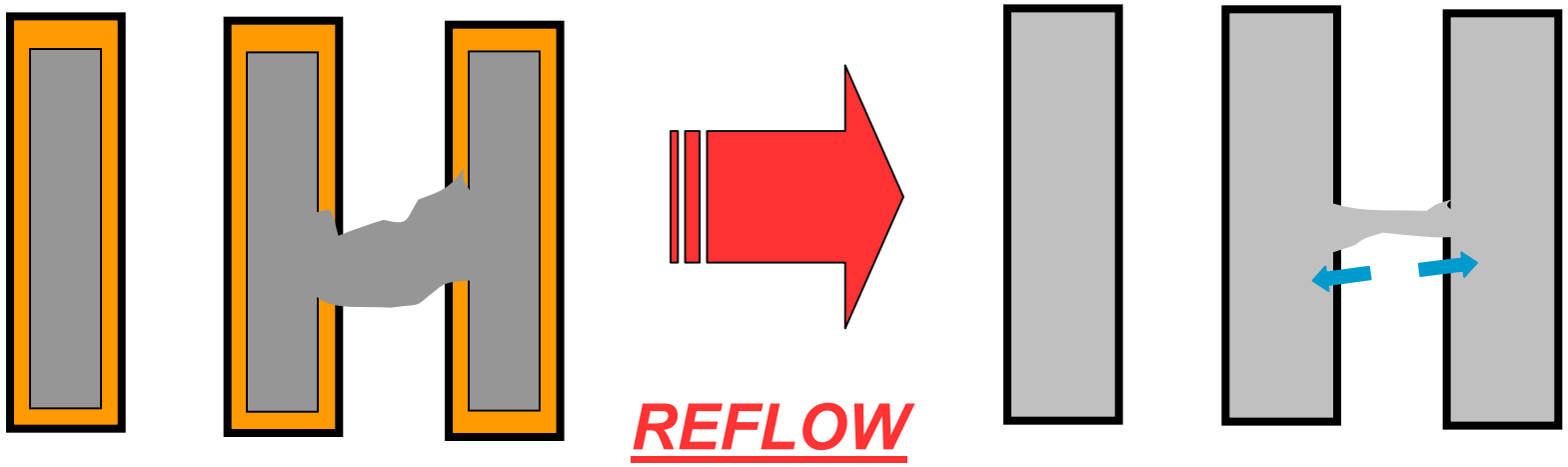
Reduced Wetting: Solder Bridges Sn/Pb Solder



Solder bridge formed at stencil

Wetting forces clear solder bridge during reflow (Blue arrows)

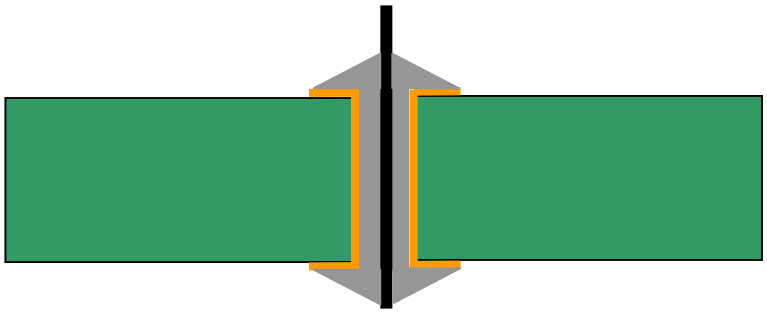
Reduced Wetting: Solder Bridges Lead-free Solder



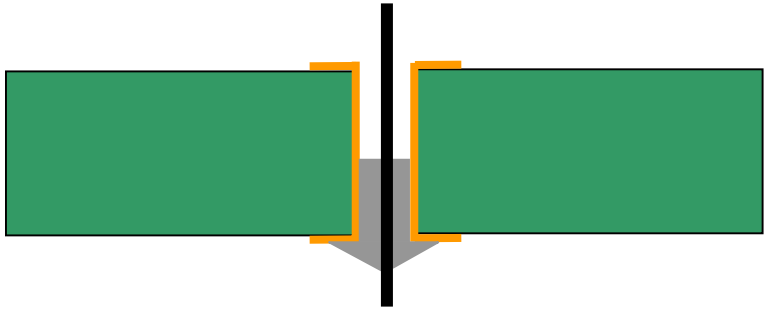
Solder bridge formed at stencil

Reduced wetting forces do not clear solder bridge during reflow (Blue arrows)

Reduced Wetting: Plated Through Hole Fill



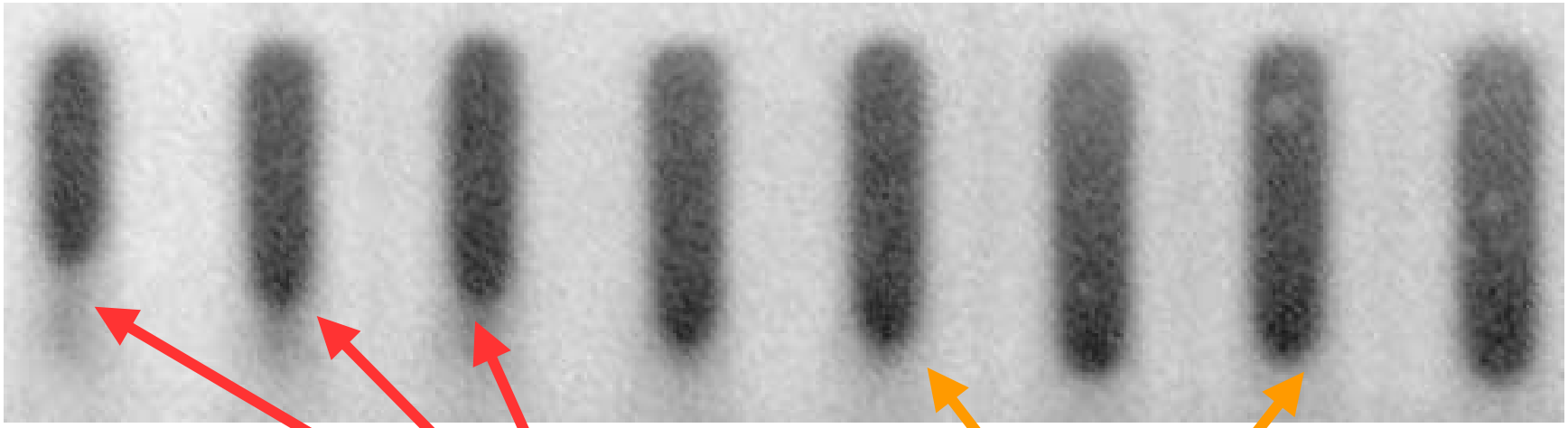
Sn/Pb Solder:
100% fill



Pb-free solder:
Poor fill

Defects: SMT Connector Opens

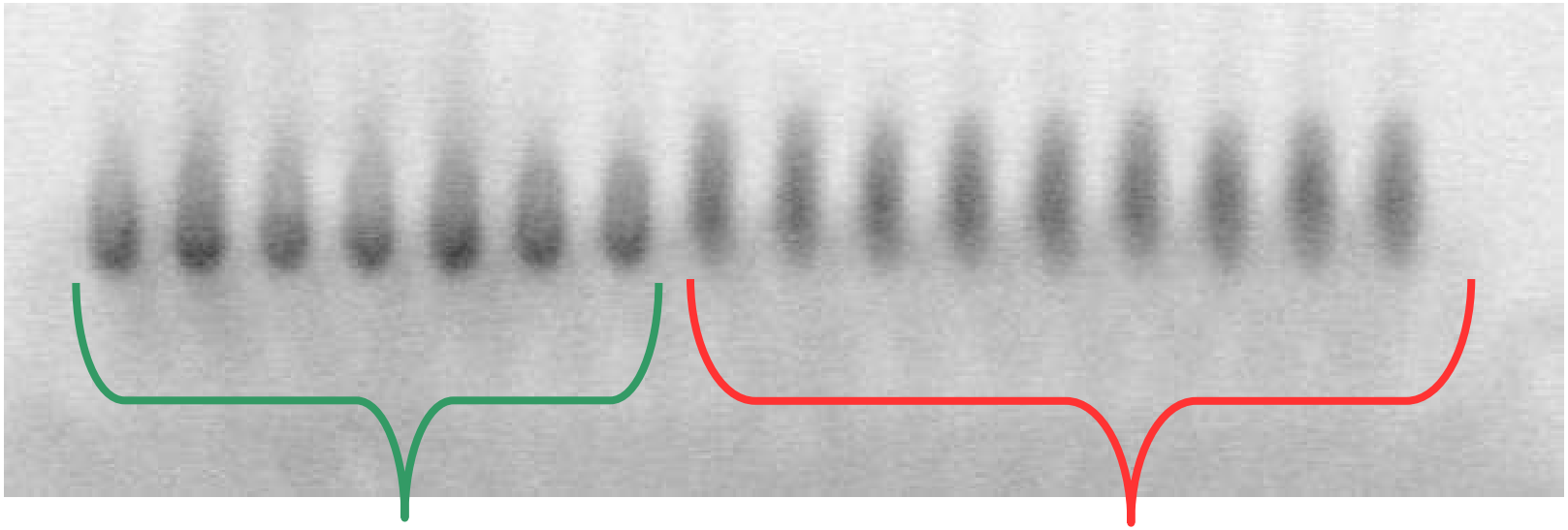
Note: *All images shown are lead-free joints unless stated*



Open Joints (No Heels)

Marginal Joints: Small heels

Defect: Many Opens on a QFP



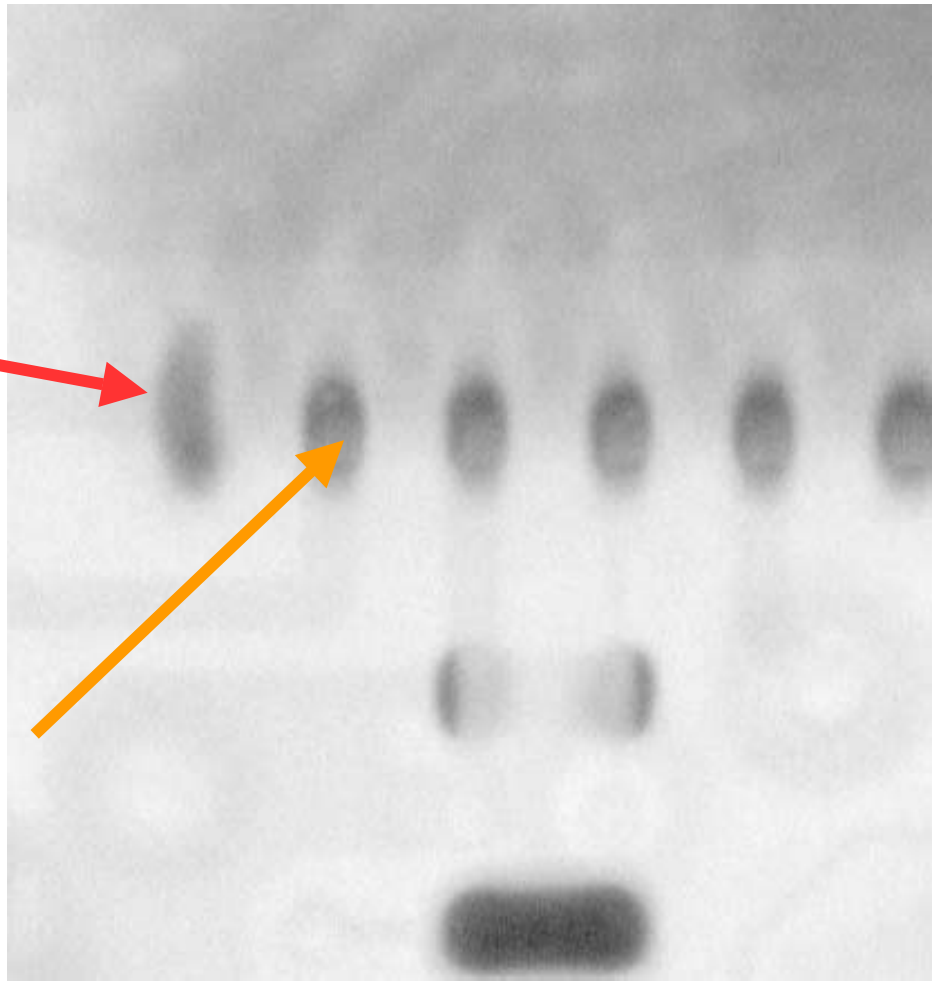
Acceptable Joints:
(Strong heels, toes, and side fillets)

Open Joints:
(No heels, toes, or side fillets)

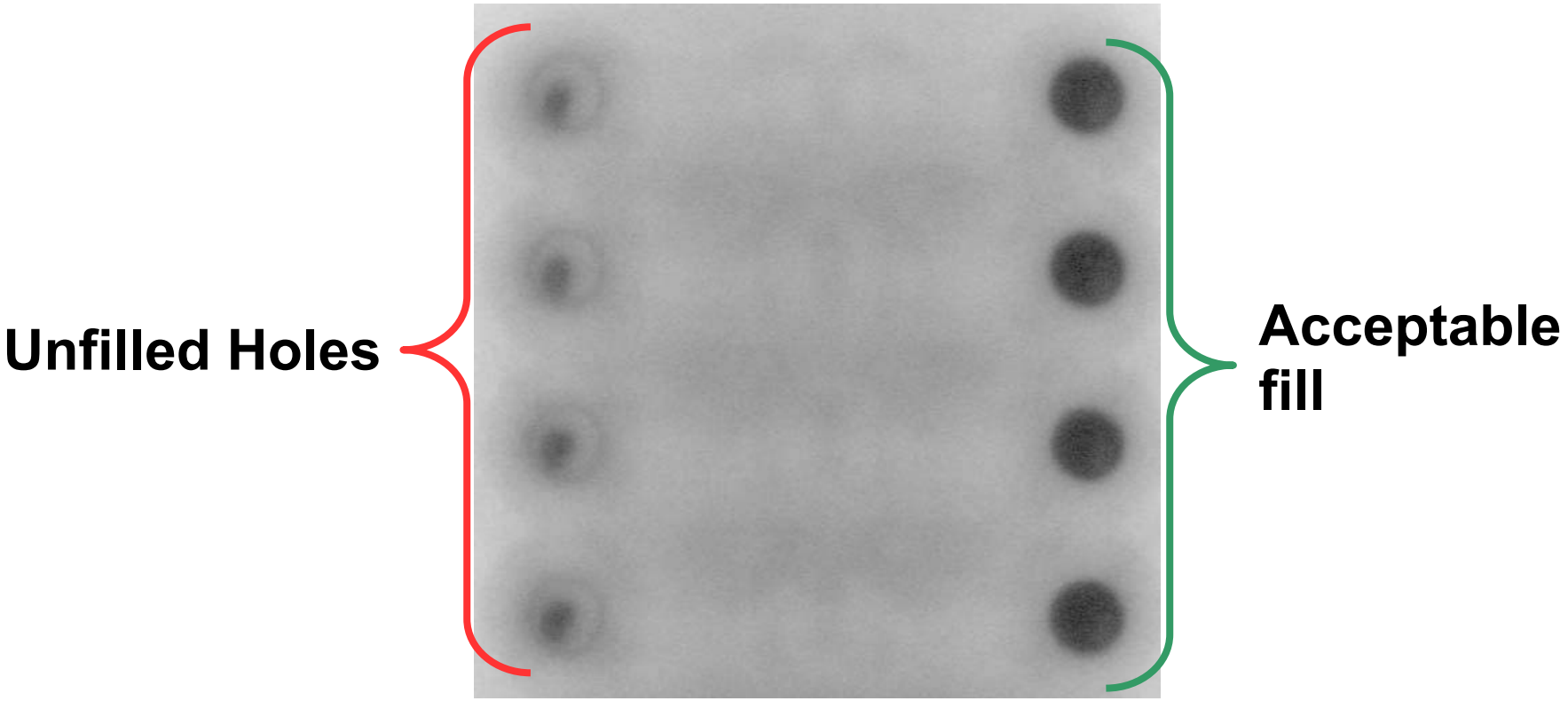
Defect: Open on a TSOP

Open: no heel, toe, or side fillets

Void: Probably not a defect

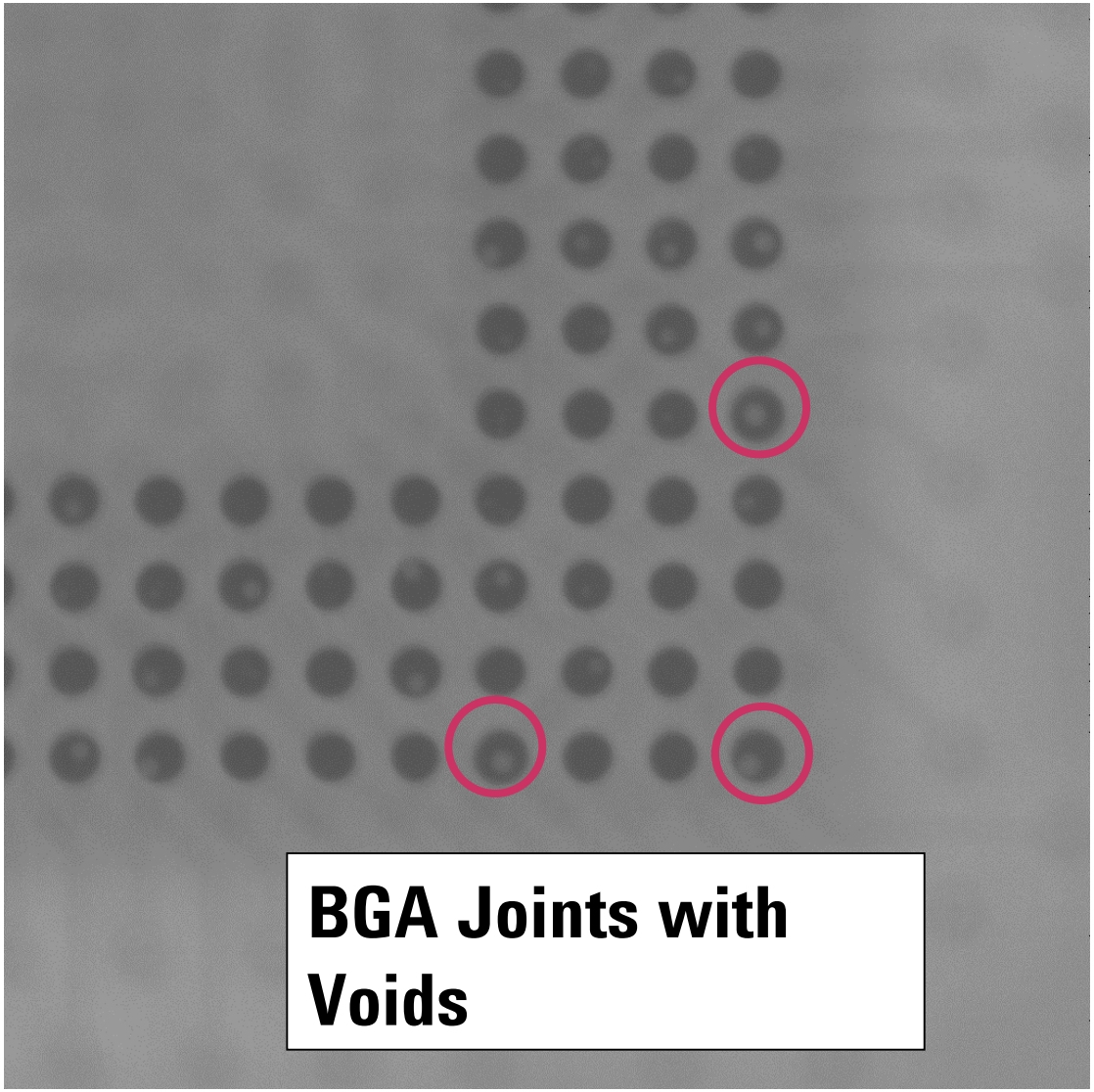


Defect: Open plated through holes

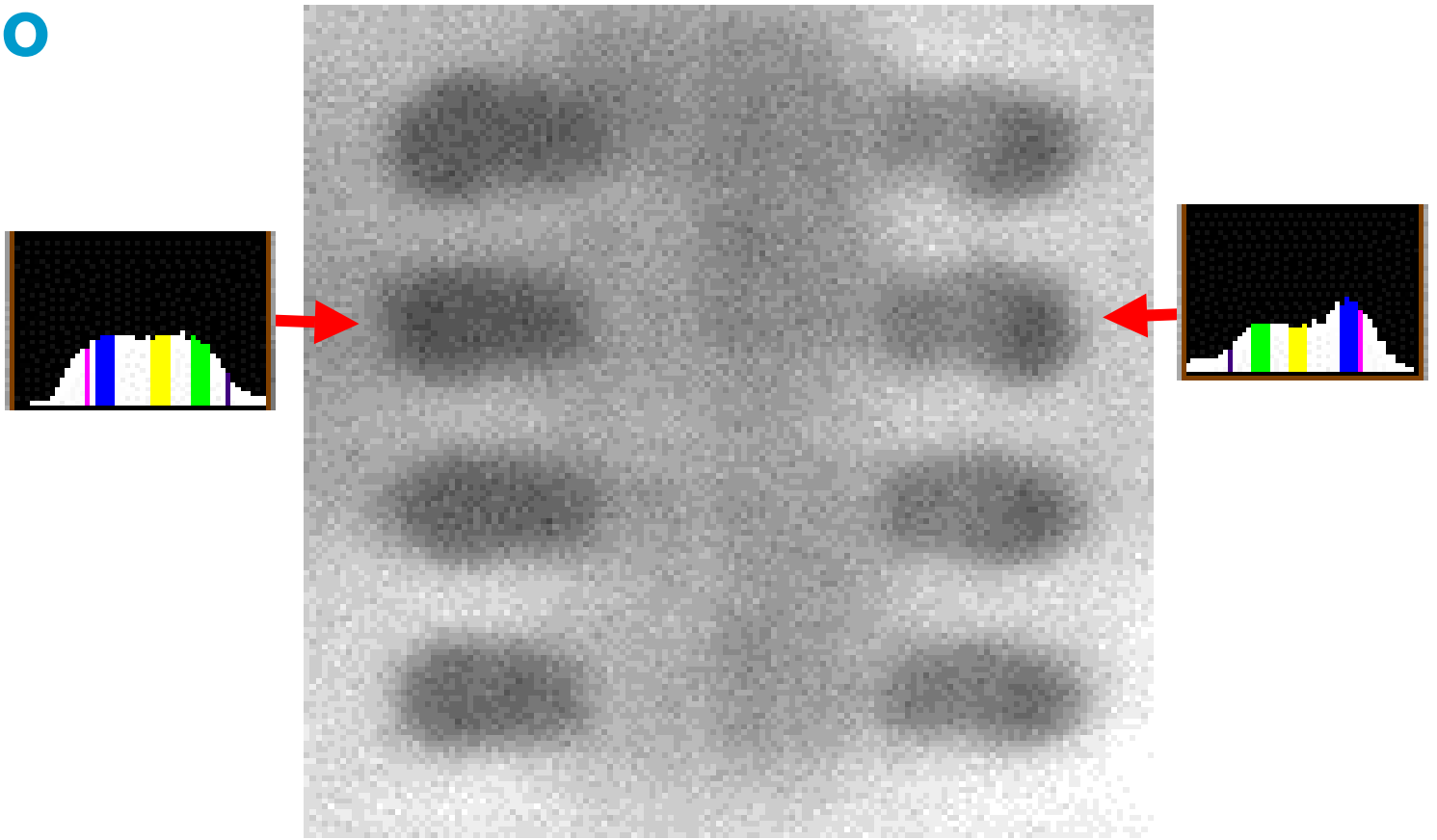


Increased Voids

Tin/Silver/Copper solder used in a Ball Grid Array



Process Variation: 1206 R-Pack: Gullwing Algo



Heels on left side are small, but both joints are acceptable. Good process indicator.

Process Indicator or False Call?

Many calls will be made on acceptable joints due to the large variations in joints made in a lead-free process still under development.

These "Process Indicators" found by the 5DX are not conventional "False Calls."

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Test Strategy Considerations for Lead-free

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Test strategies for lead-free

Establish a good picture of the current lead-tin process

DPMO values for similar board types

If possible measure and establish benchmarks for

- **Defects**
- **Potential defects**
- **Process indicators**

The purpose is to establish benchmark values to compare to the lead-free process

Test strategies for lead-free

Best Practices

Switch first over only one line to lead-free

Very tight test and inspection should be implemented

Implementing good process characterization

Implement good test strategies after reflow to capture all defects.

Data gathered from test and inspection should be used to improve the process and to eliminate systematic defects.

Test strategies for lead-free

Best Practices

If faults and defects are increasing significantly, adding test and inspection capability should be considered.

When all issues have been resolved and defect levels and quality levels are acceptable, switching lead-free manufacturing to the next line should be considered.

Note that there are likely to be big variations from site to site, between board type and board type, and component type to component type.

Process Characterization for Lead-Free: Examples

Use automated imaging technologies to characterize lead-free assembly processes.

Examples:

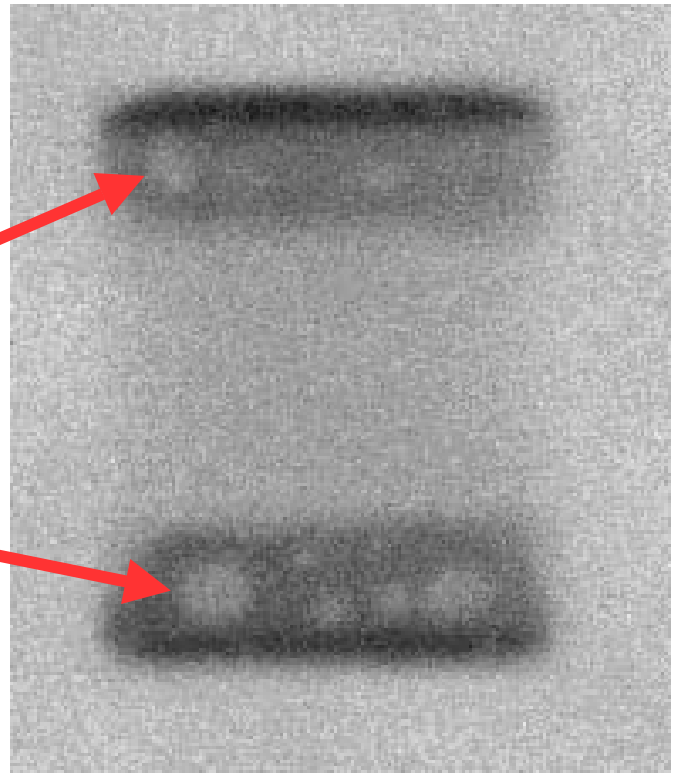
- **Void reduction**
- **Optimize solder wetting**

Process Characterization: Void Reduction

Voids can be found automatically with algorithms in AXI, or identified by the inspector in Manual X-ray Inspection.

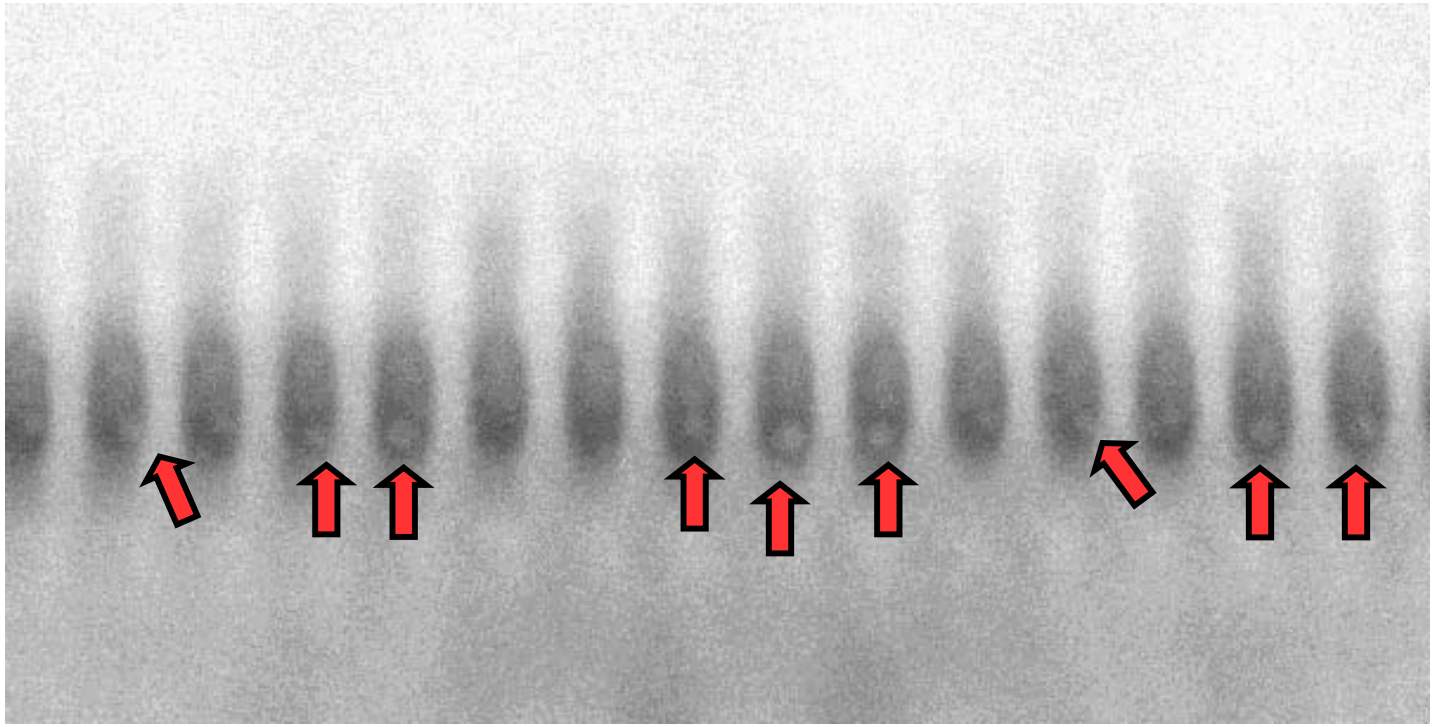
Use these results to

optimize your soldering process.



Large voids in the lead-free solder joints of a 1210 resistor. These are *not* defects, but are indicators that the soldering process is not optimized.

Process Characterization: Void Reduction



Voids in the heels of lead-free solder joints on a QFP.

Usually Not **considered defects, but process indicators.**

Process Characterization: Optimize Solder Reflow Process

Designed experiments can help optimize the soldering process.

Examples of variables:

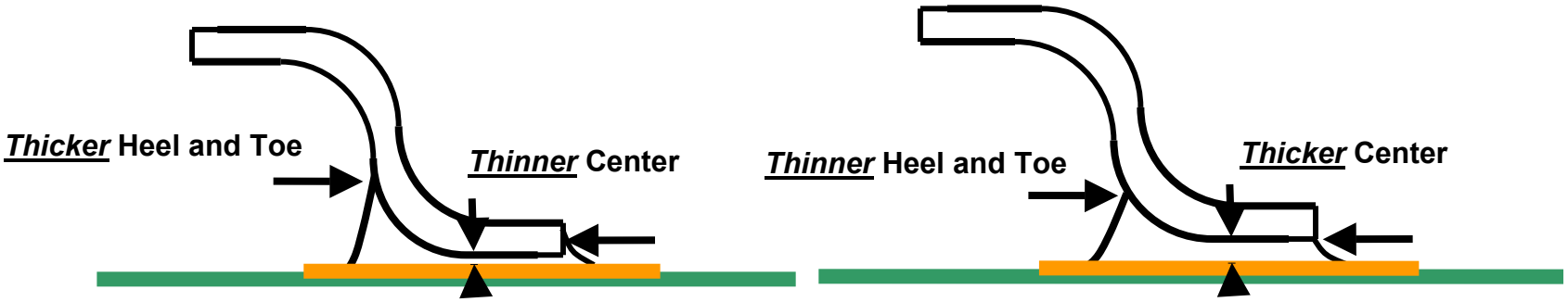
- **Solder paste manufacturers**
- **Reflow and cooling profiles**
- **Stenciling parameters**
- **PCB surface finishes**
- **Component termination finishes, etc.**

A continuous variable (vs. a pass/fail attribute) is needed to keep the samples sizes small and manageable.

What variable can we use?

Process Characterization: Optimize Solder Reflow Process

Optimize the Solder Wetting



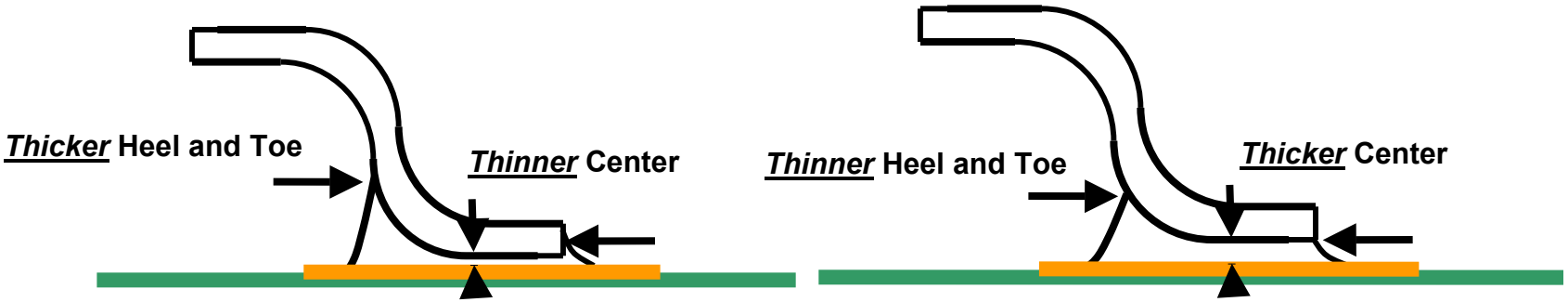
Sn/Pb Gullwing Joint

Pb-free Gullwing Joint

Joints with good wetting have *more* solder forming the heels and toes, and *less* solder remaining under the lead.

Process Characterization: Optimize Solder Reflow Process

Optimize the Solder Wetting



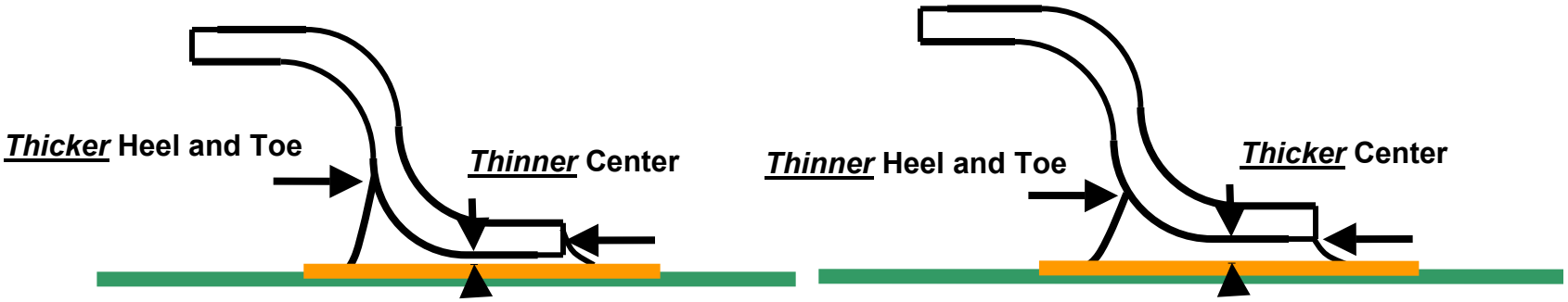
Sn/Pb Gullwing Joint

Pb-free Gullwing Joint

How can the thicknesses of the joints be measured?

Process Characterization: Optimize Solder Reflow Process

Optimize the Solder Wetting



Sn/Pb Gullwing Joint

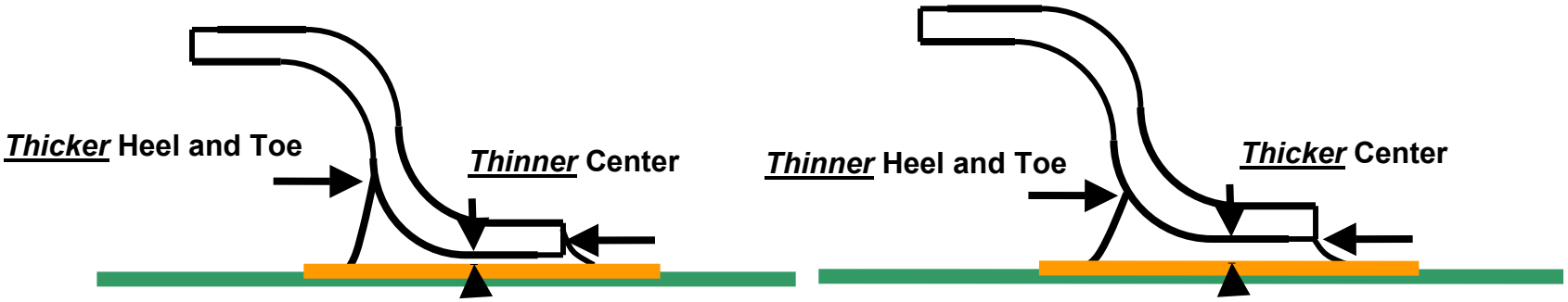
Pb-free Gullwing Joint

Use the ratio of the heel thickness to the center thickness of one type of gullwing joint to define how well wetting is occurring.

The larger the ratio, the better the solder wetting.

Process Characterization: Optimize Solder Reflow Process

Optimize the Solder Wetting



Sn/Pb Gullwing Joint

Pb-free Gullwing Joint

This technique was successfully used to characterize several process variables during one SMT manufacturer's transition to *no-clean* manufacturing.

Automated X-ray Inspection

AXI measures the relative solder thickness in regions of the solder joints.

It uses those measurements to determine if a each solder joint is acceptable or defective.

Those measurements can also be used for process characterization.

Summary of AXI in Test Strategy for Lead-free Transition

Automated X-ray Inspection is a powerful tool for process characterization during the transition to lead-free solder.

There is less difference between acceptable open solder joints with lead-free due to the reduced wetting of lead-free solders.

Increased variation in size and shape of acceptable joints in lead-free may cause an increase in false calls.

Also, Automated solder paste inspection (SPI) and post-reflow AOI are also valuable in-process tools.

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Lead-free Test

and Inspection Studies

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Results from

- 3 5DX AXI Customers and 1 AOI Customer
- Customer experiments & prototype runs
- Data from customer production
- Only low complexity boards so far
- Will be more difficult for high complexity boards.

Lead-free example 1

Production results - high volume board (AOI Customer)

- Major CM in Asia
- World Class Manufacturing
  - Very low DPMO values
- DPMO ~ 2 X for lead-free (still very impressive)
- Defect spectrum
  - Increase for lead-free
    - Tombstone (significant increase)
    - Misalignment
    - Opens
  - Decrease for lead-free
    - Solder bridges
    - Insufficient solder

Board Characteristics

Consumer product - High volume

Lead-free board

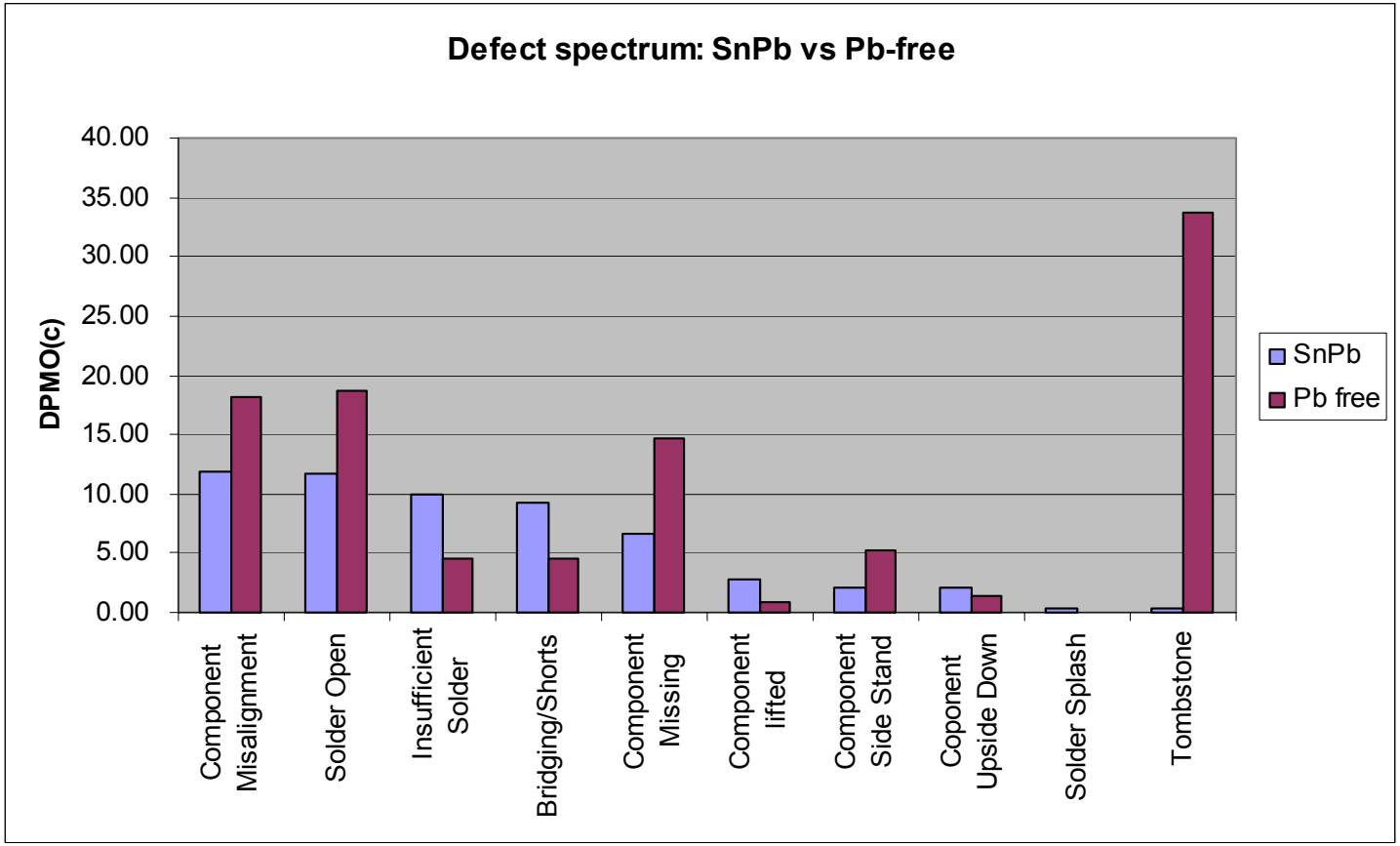
- Technology Type:
  - -BGA: smallest pitch 19.6 mils
  - -Gullwing: smallest pitch 15.75 mils
  - -SMT Connector:
    - smallest pitch 17.71 mils
  - -Chip: smallest size 0402
- Solder Paste: Pb-free
- Board Finish: OSP
- Number of Components = 560
- Number of Solder Joints = 2600
- Board Dimension: 3.9 * 2.0 inches

Tin / lead board

- Technology Type:
  - -BGA: smallest pitch 19.6 mils
  - -Gullwing: smallest pitch 15.7 mils
  - -SMT Connector:
    - smallest pitch 19.6 mils
  - -Chip: smallest size 0402
- Solder Paste: Tin / Lead
- Board Finish: OSP
- Number of Components = 270
- Number of Solder Joints = 1300
- Board Dimension: 2.1 * 2.3 inches

Defect Spectrum

High volume - consumer product



One month's volume, Sn/Pb ~ 75,000 boards, Pb-free ~ 50,000 boards)

Lead-free example 2

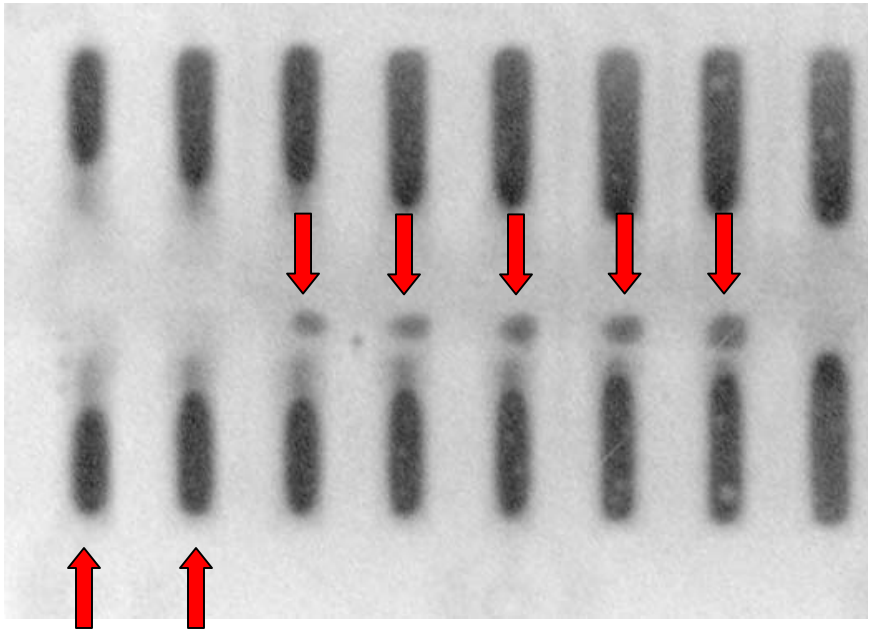
- Following slides are from another lead-free board

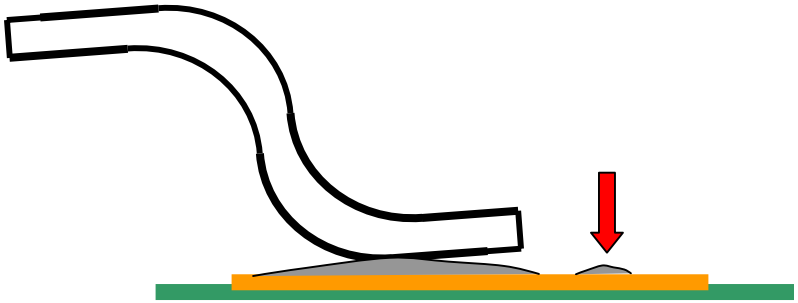
- The x-ray images illustrates many of the expected difficulties with lead-free

  - Wetting problems
  - Insufficient barrel fill
  - Opens

Lead-free examples

Wetting problems



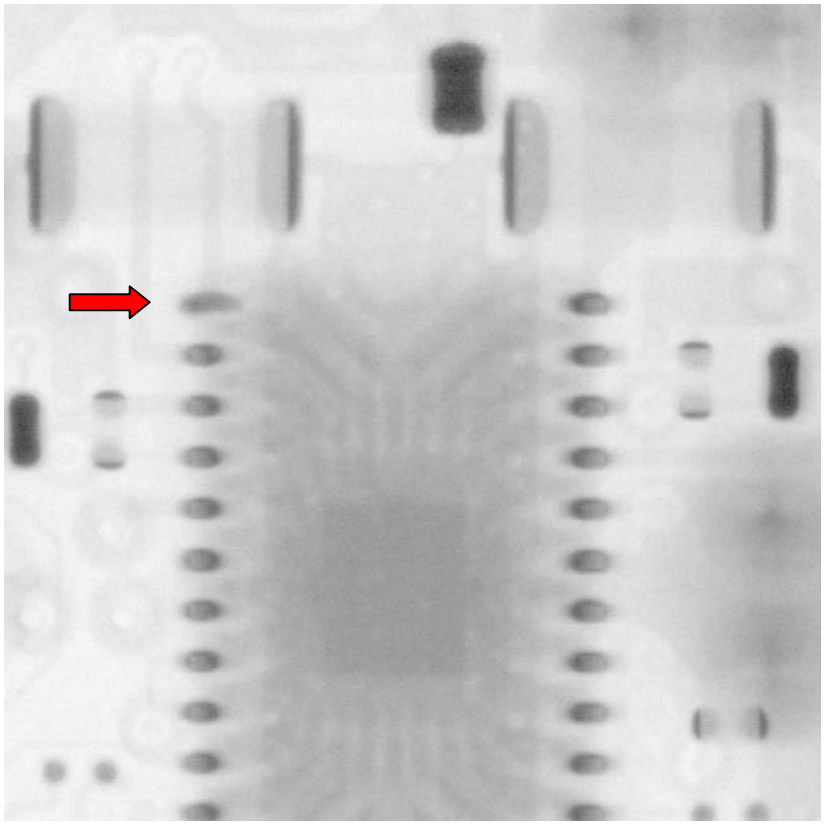


Pb-free: Bad wetting

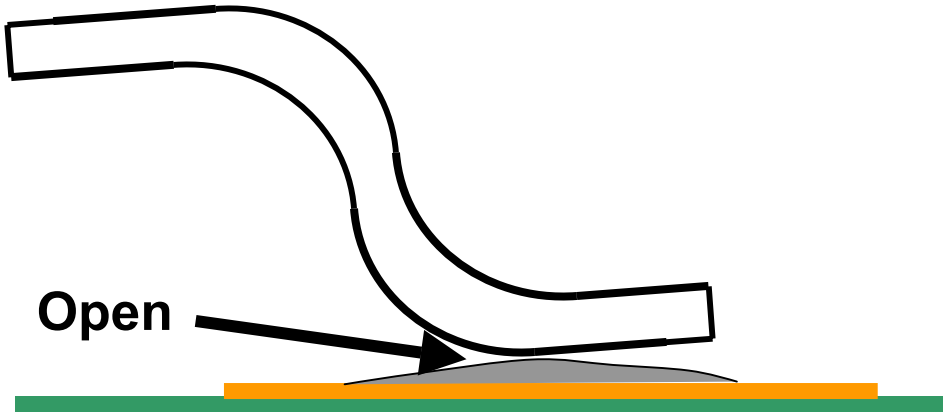
Opens

Numerous voids can also be seen

Lead-free examples

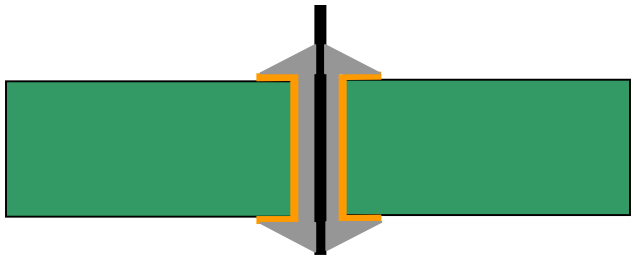


Open pin

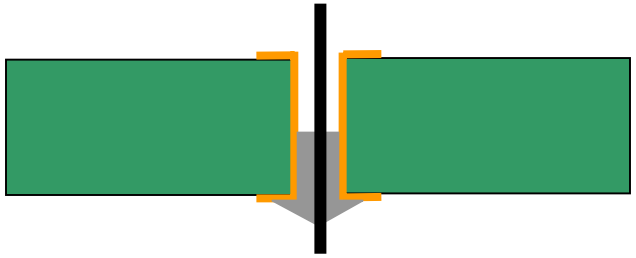


Pb-free: Open Joint

Lead-free examples



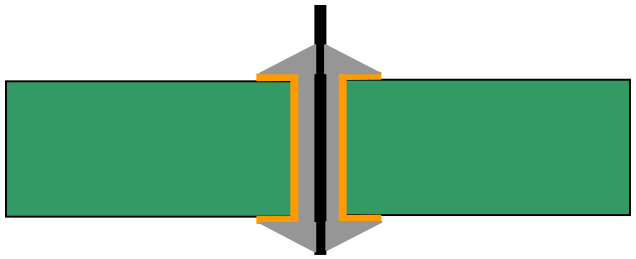
100% fill



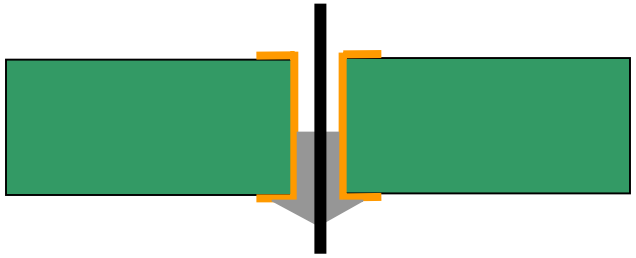
Pb-free solder:
Poor fill

Through-hole insufficient

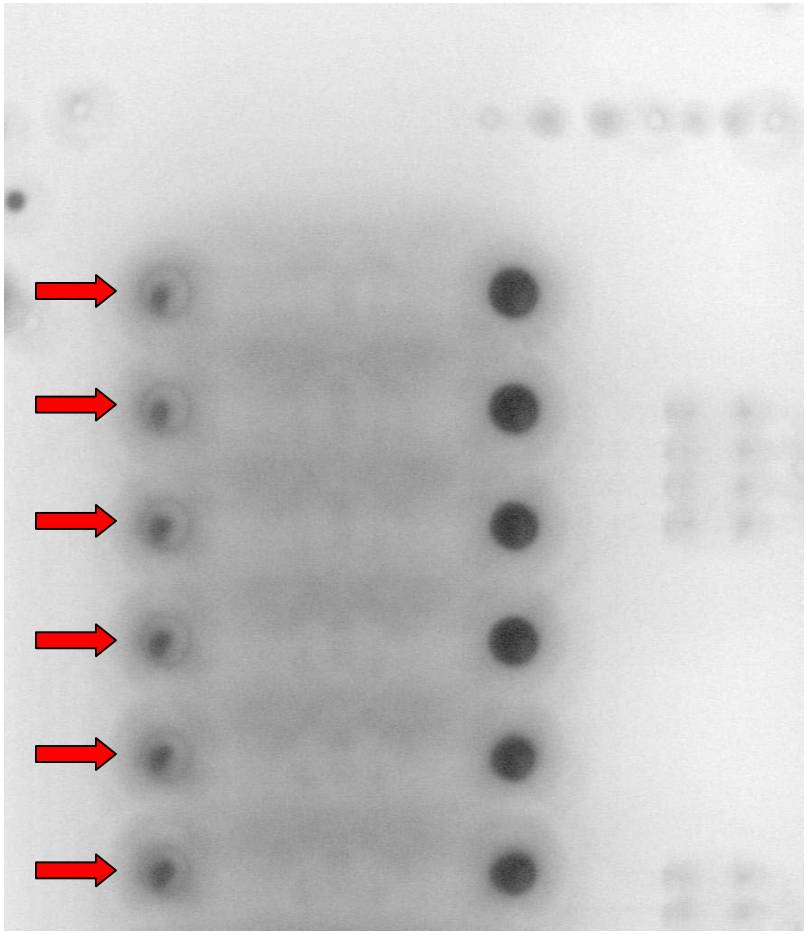
Lead-free examples



100% fill



Pb-free solder:
Poor fill



Through hole insufficient

Lead-free example 3

- Following slides are from another lead-free board.

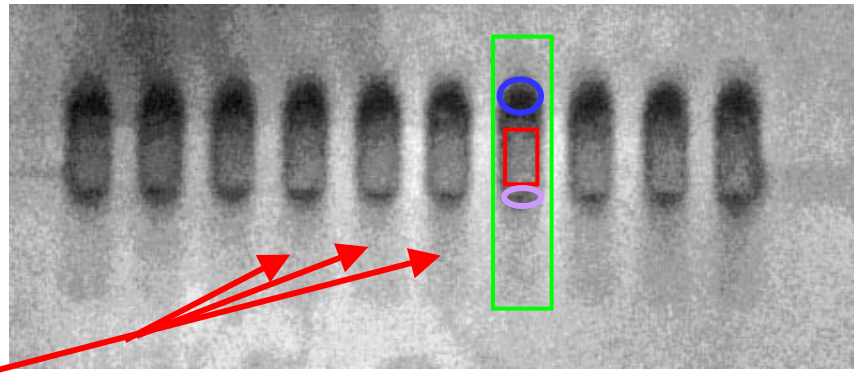
- Small batch experiment

- The x-ray images illustrates many of the expected difficulties with lead-free

Lead-free vs. Sn/Pb examples:

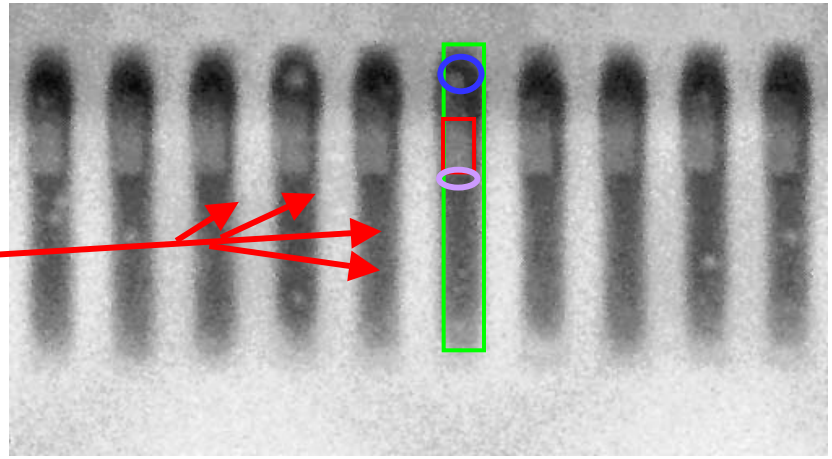
QFP Joints

Pad outline: Green boxes
Area under lead: Red boxes
Heel area: Blue ellipse
Toe area: Purple boxes



Sn/Pb solder flows into the joint. Very little left on the pads.

Sn/Pb



Lead-free solder does not flow into the solder joint as much with lead-free: Solder stays distributed on the pads.

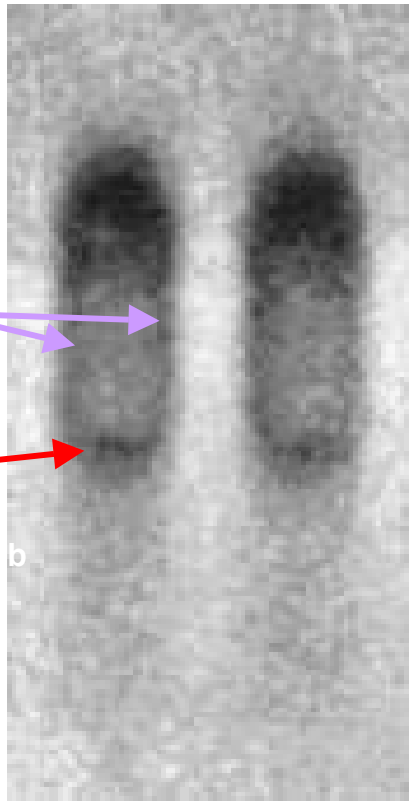
Lead-free

Lead-free vs. Sn/Pb examples:

Close-up of QFP Joints

Sn/Pb solder aligns the part on the pad. Side fillets are the same size.

Note good toe formation.

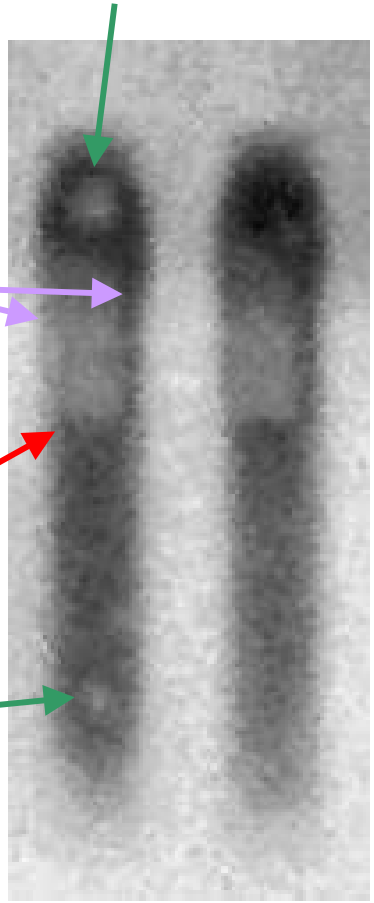


Sn/Pb

Lead-free solder does not align the part. Side fillets are different sized since part is shifted to the left.

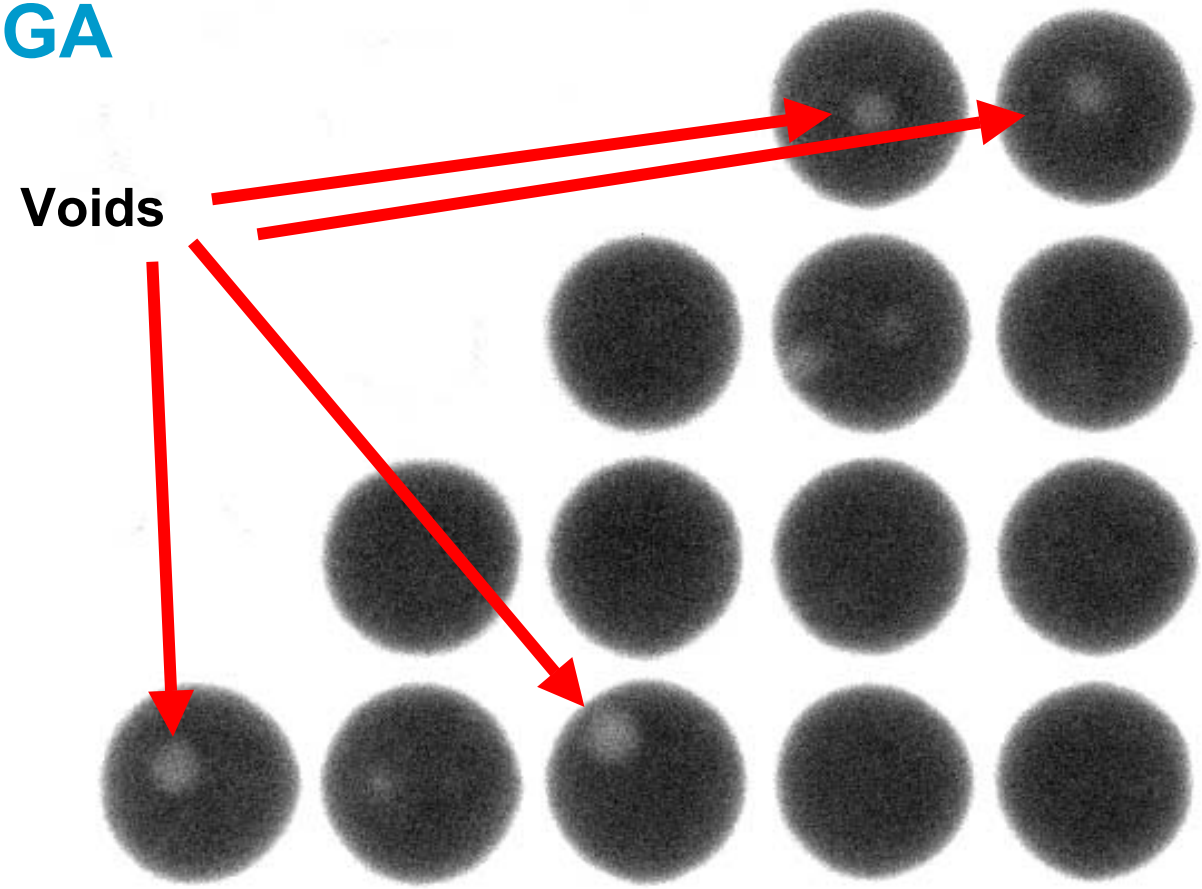
Note poor toe formation.

Note voids.



Lead-free

Lead-free examples:
Voids in BGA



Summary of issues during transition

- **Poor wetting and increased variation in solder joint shape and size *driving…..***
- **Higher defect levels**
- **More “Process Indicator” calls**
- **New and traditional defect types**
- **Many process issues**
- **Fewer allowed repair attempts**

You need many tools in the toolbox:

The 5DX is a Valuable Tool

5DX C&A for Leadfree

- Lead-free vs. Sn/Pb C&A Tables:
- *What are the differences?*

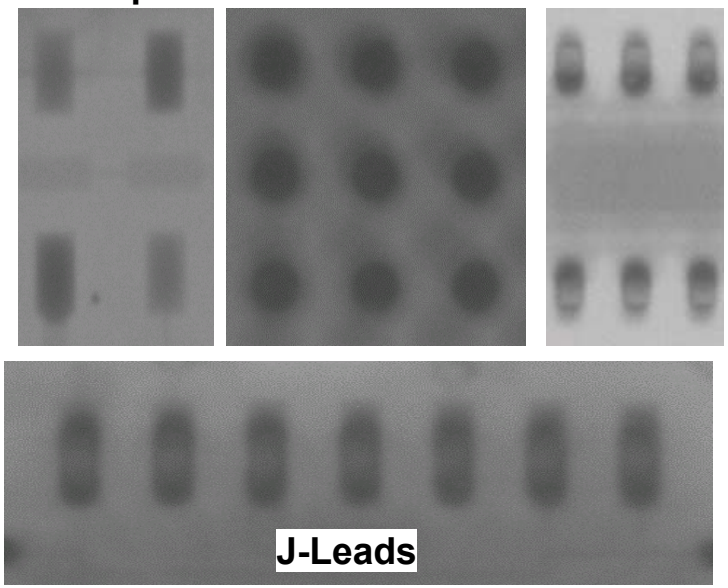
Does AXI work with lead-free solders?

Yes!

X-ray Image Comparisons
Sn/Pb and Lead-Free Solders

SnPb

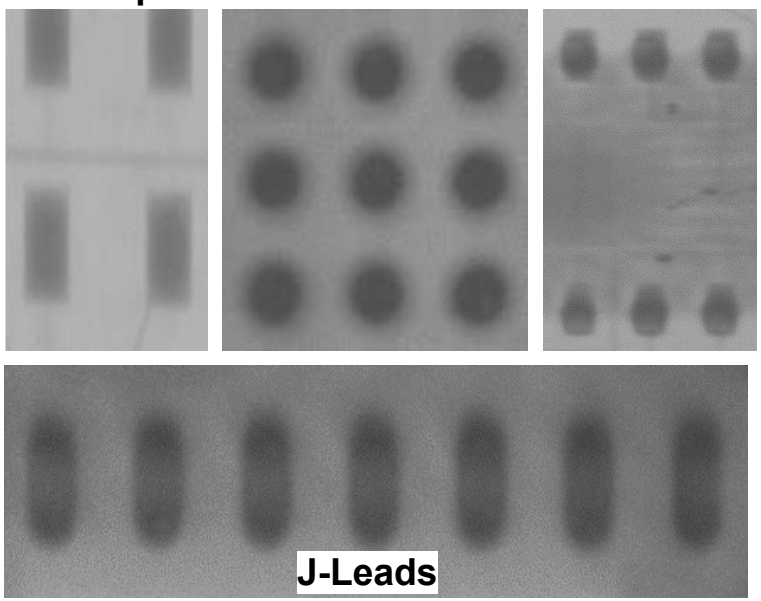
Solder pads BGAs SOIC



Sn/Pb 63/37

Lead-Free

Solder pads BGAs SOIC



Sn4Ag1Cu
(SAC4010)

Objective of Tests

On a lead-free board:

Compare thickness measurement differences on lead-free solder joints when using Sn/Pb and lead-free (SAC396) C&A tables.

Determine if there is any difference in BGA diameter measurement when using the Sn/Pb and lead-free solder (SAC396) C&A tables.

Examine the repeatability of the measurements.

Methodology

5DX was set-up with both Sn/Pb and Lead-free C&A panels

A lead-free board was tested multiple times (6 to 10) using the Sn/Pb C&A tables, and multiple times using the Sn/Pb C&A tables.

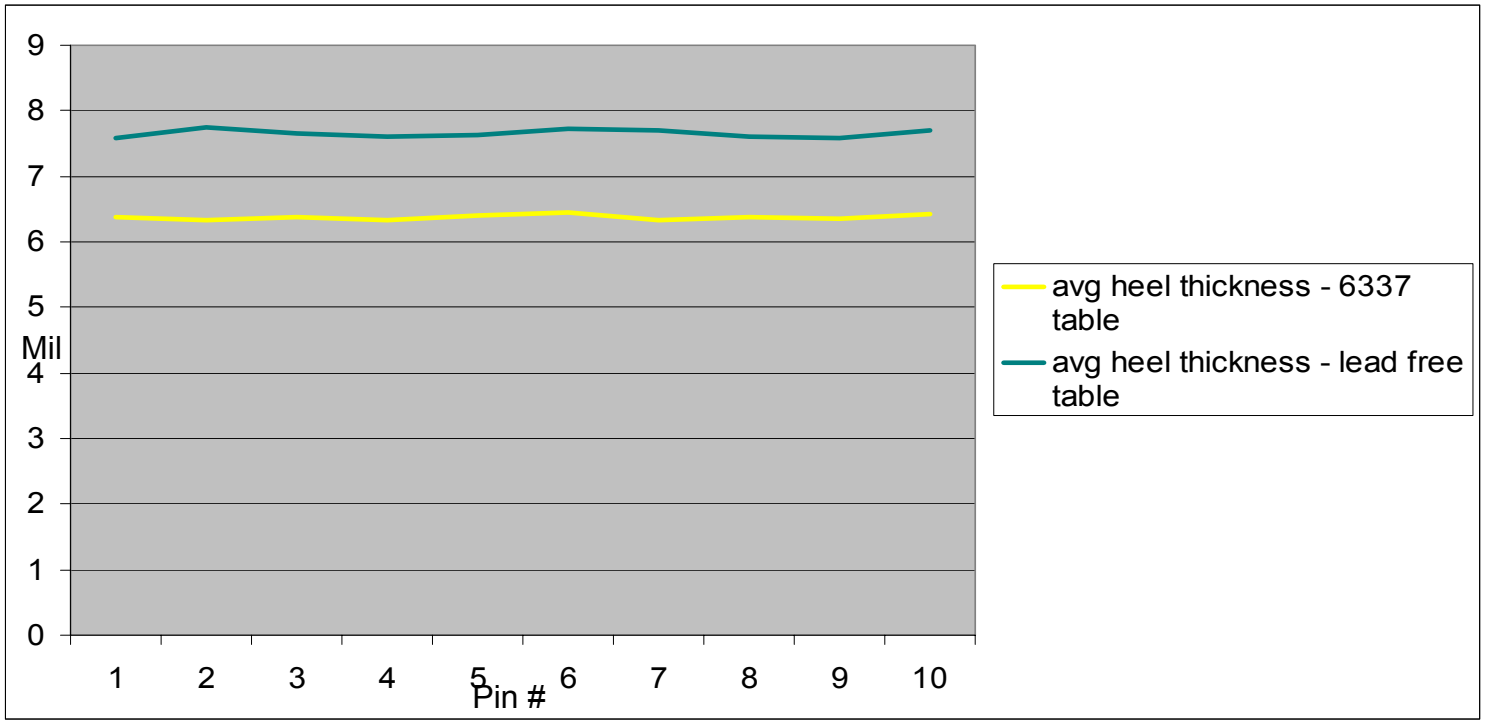
Thickness data of ROIs of a single joint of each type (BGA, Gullwing, J-lead, Chip, Res) were analyzed and standard deviations computed.

Results were graphed.

Observations and recommendations were made.

Measured solder thickness differences

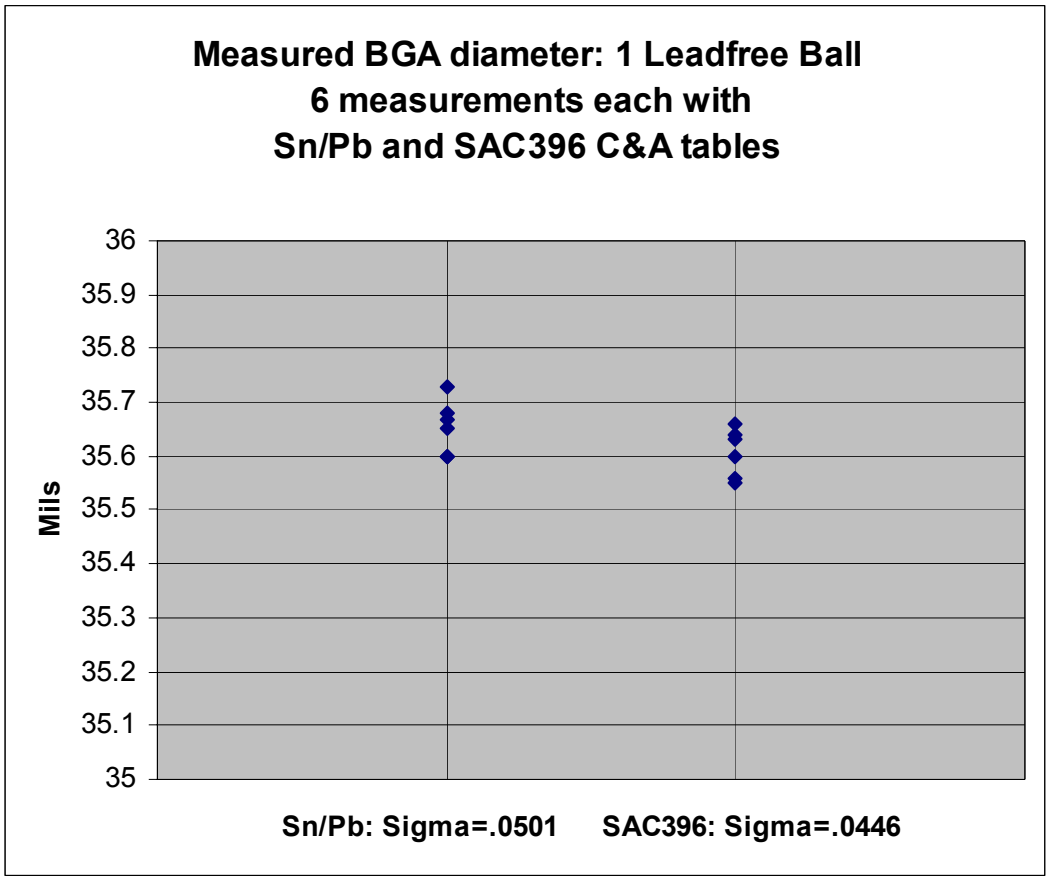
First Observation*: New lead-free solder joints will measure lower thickness measurement: *around 20% less



Gullwing lead-free solder joint measured with regular and lead-free calibrations. Similar results for J-lead, BGA, Chip components, and through-hole.

BGA Mid-ball Diameter: (1 ball, 6 measurements)

Diameter

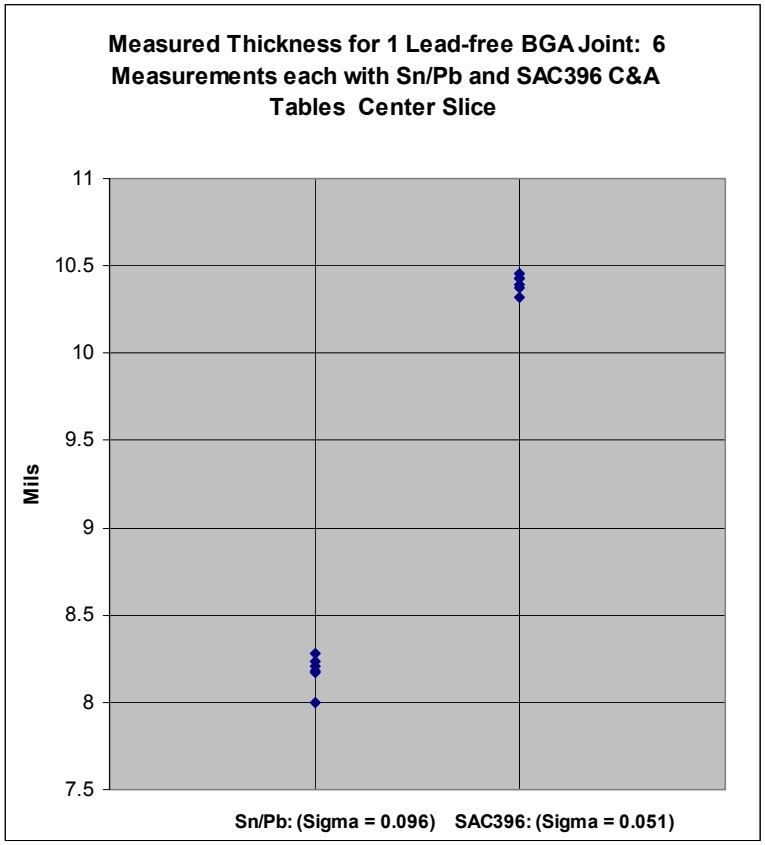


	Average	Sigma
Sn/Pb	35.655	.0501
SAC396	35.607	.0446
Delta	*0.1%*	

No Significant Difference

BGA Mid-ball Thickness: (1 ball, 6 measurements)

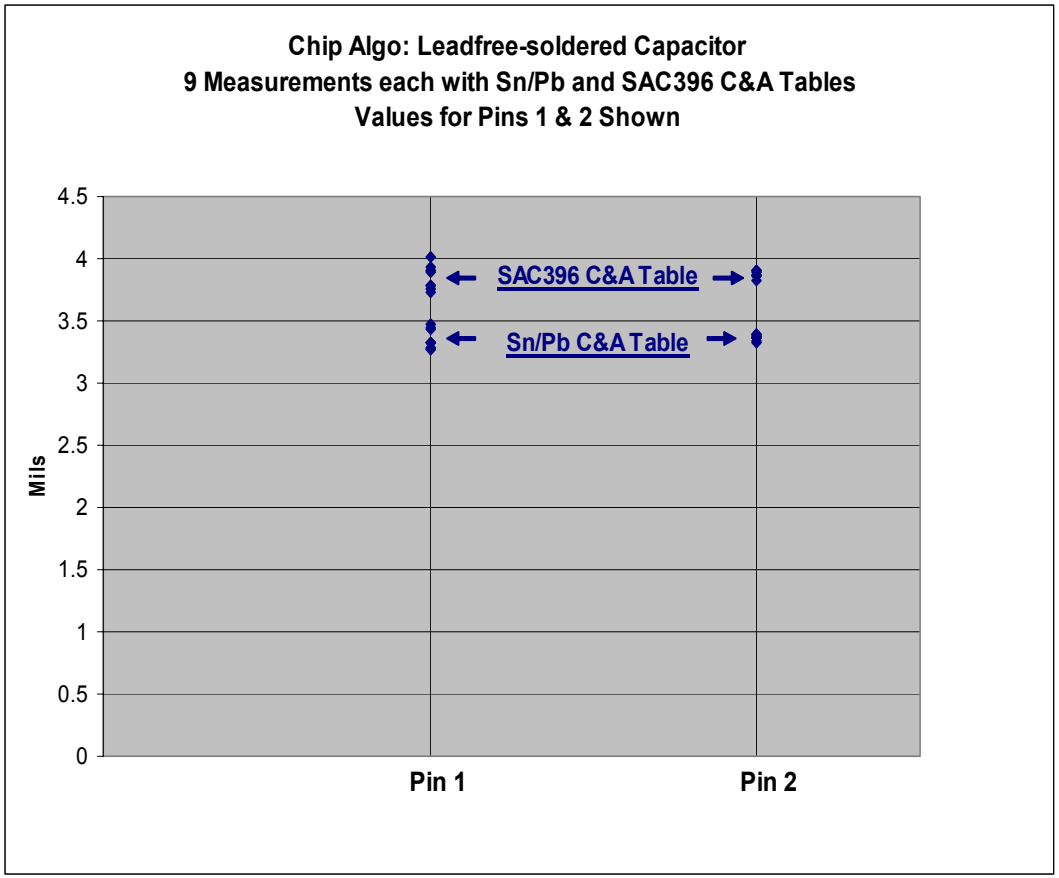
Thickness (Center slice)



	Average	Sigma
Sn/Pb	8.178	0.098
SAC396	10.400	0.061
Delta	*21.3%*	

Really large difference in thickness measurements

Chip (1 capacitor, 2 pins, 9 measurements each)



Pin 1

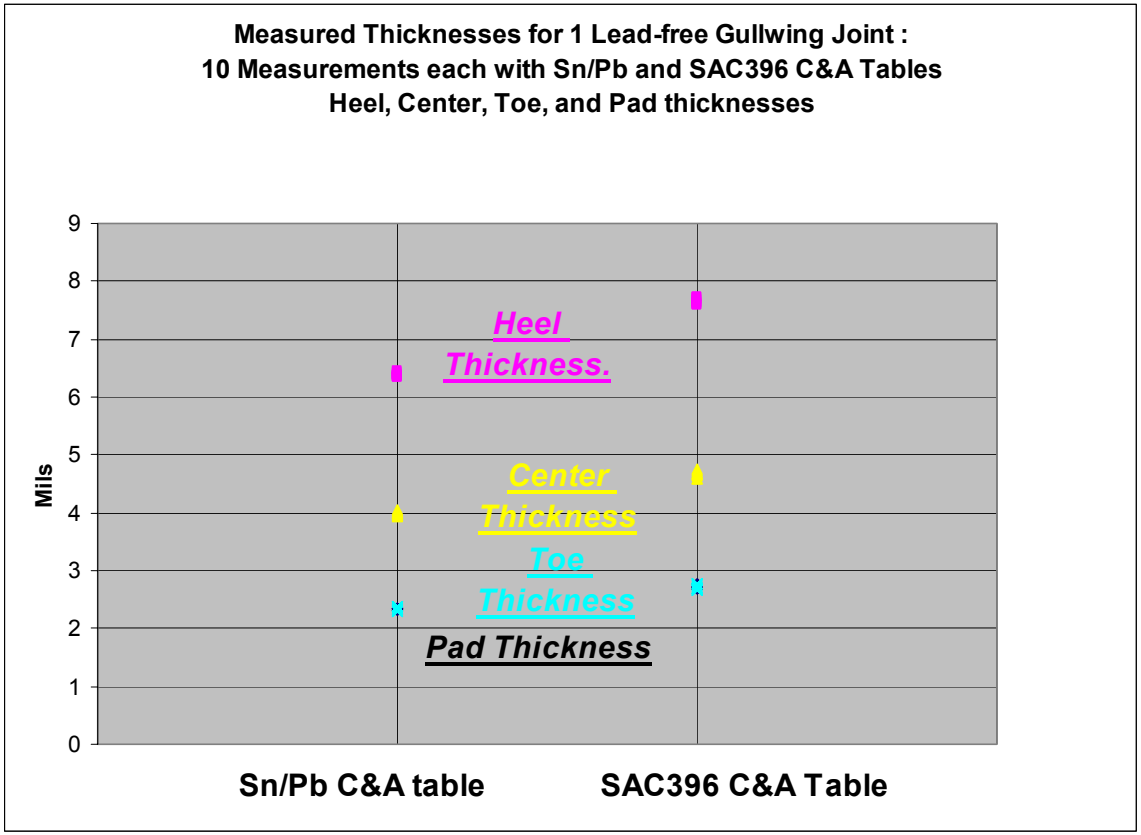
	Average	Sigma
SnPb	3.363	0.078
SAC396	3.858	0.095
Delta	*12.8%*	

Pin 2

	Average	Sigma
SnPb	3.364	0.021
SAC396	3.865	0.025
Delta	*12.9%*	

Large difference in Thickness measurement (not as big as for BGA)

Gullwing (1 pin, 10 measurements for Heel, Center, Toe, and Pad Avg.)



Heel	Average	Sigma
SnPb	6.38	.041
SAC396	7.65	.060
Delta	16.6%	

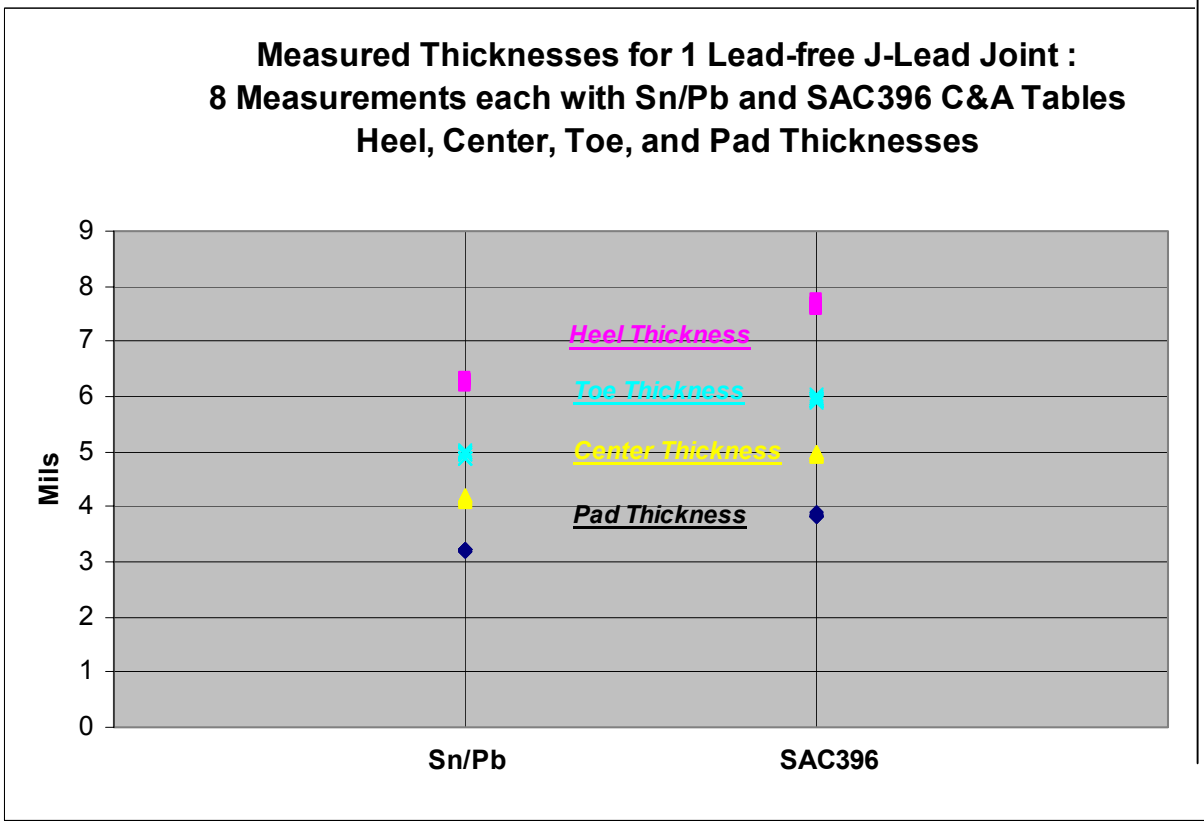
Center	Average	Sigma
SnPb	3.99	.039
SAC396	4.66	.059
Delta	14.3%	

Toe	Average	Sigma
SnPb	2.34	.037
SAC396	2.70	.040
Delta	13.3%	

Pad	Average	Sigma
SnPb	2.34	.012
SAC396	2.71	.039
Delta	13.6%	

Differences vary with ROI

J-Lead (1 pin, 8 measurements for Heel, Center, Toe, and Pad Avg.)



Heel	Average	Sigma
SnPb	6.26	.068
SAC396	7.64	.061
Delta	18.6%	

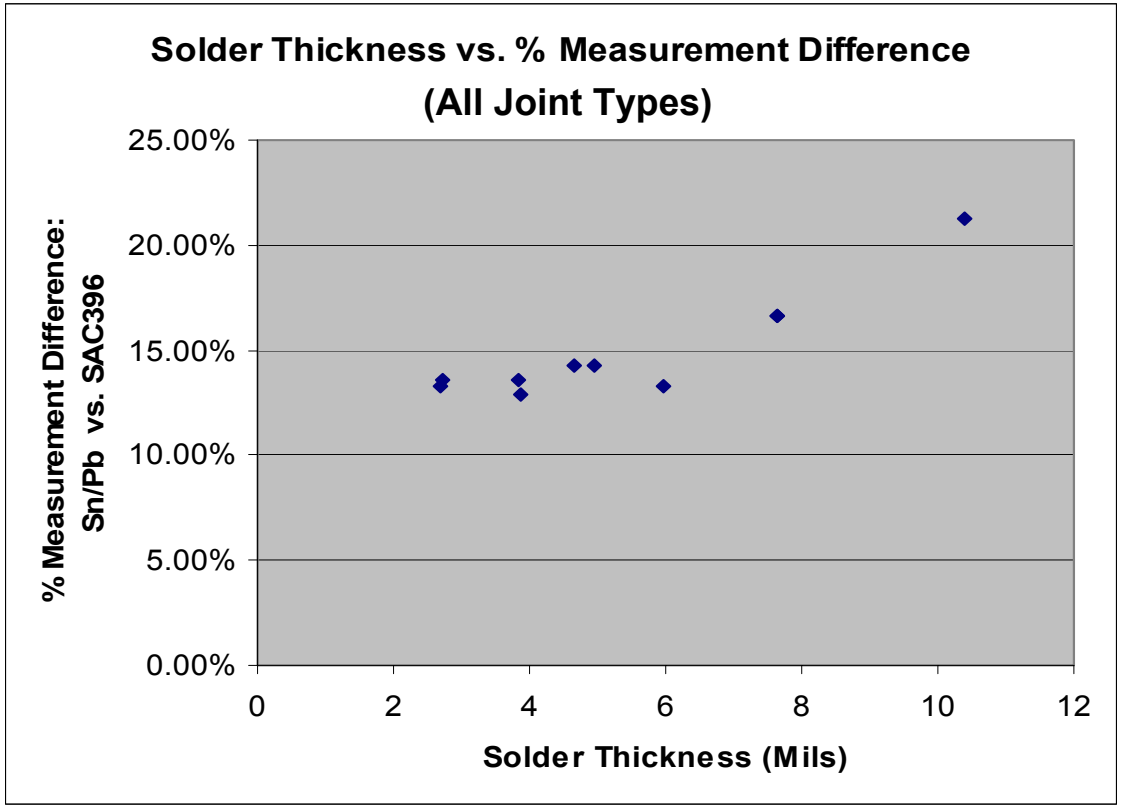
Center	Average	Sigma
SnPb	4.16	.041
SAC396	4.95	.021
Delta	16.0%	

Toe	Average	Sigma
SnPb	4.94	.060
SAC396	5.96	.049
Delta	17.1%	

Pad	Average	Sigma
SnPb	3.22	.021
SAC396	3.83	.027
Delta	15.9%	

Differences vary with ROI, very similar to Gullwing

Correlation:
Measurement Differences to Solder Thickness



Measurement differences are greater when the solder is thicker.

Linear? Exponential? We don't know yet. Investigating.

Open Signal Comparison: J-lead and Gullwing

Open Signal (OS) = Heel Thickness – Center Thickness

J-lead:

OS_{SAC396} = 7.64 – 4.95 = 2.69 (mils)

OS_{SnPb} = 6.26 - 4.16 = 2.10 (mils)

Gullwing:

OS_{SAC396} = 7.65 – 4.66 = 2.99 (mils)

OS_{SnPb} = 6.38 – 3.99 = 2.39 (mils)

Measurement Repeatability
(Data from Sn/Pb and SAC396 tests)

Joint Type & Region	+/- 3 Sigma
BGA Diameter	+/- 4.5%
BGA Thickness	+/- 6.1%
Gullwing Heel	+/- 6.0%
Gullwing Center	+/- 6.0%
Gullwing Toe	+/- 4.0%
Gullwing Pad Average	+/- 2.7%
J-lead Heel	+/- 6.8%
J-lead Center	+/- 2.1%
J-lead Toe	+/- 4.9%
J-lead Pad Average	+/- 2.7%
Chip Pad Average	+/- 2.5%

Observations:

Measured thicknesses are different when using the Sn/Pb and Lead-free C&A tables on lead-free joints.

Thickness differences varied from about 13% to 21% depending on joint an the thickness of the ROI.

3 Sigma repeatability of the thickness measurements is +/- 2% to 6% of measured thickness.

Differences between Sn/Pb and SAC396 C&A were larger when the solder was thicker.

This drives the “Open Signal” (Heel Thickness – Center Thickness) for J-lead, Gullwing, FPGullwing, Res, and Chip joints to be larger when using the lead-free C&A tables for lead-free solder.

Lead-free C&A conclusions so far……

Overall joint formation of SnAgCu solder alloys is similar to Sn/Pb solder alloys

AXI can test lead-free solder alloys successfully

Lead-Free joint formation generates a significant number of voids and more variation in the shapes of the solder joints.

AXI Sn/Pb C&A can be used to test lead-free PCBAs by compensating for the expected grayscale or thickness measurements

We recommend using the lead-free C&A panel when testing lead-free boards.
(See your Agilent sales rep for details.)

Overall Conclusions: The 5DX and Lead-free

New lead-free soldering processes will produce more defects and more variability in acceptable joints, causing increased "process indicators."

Increases in BGA voids in lead-free will be addressed by the new BGA voiding algorithm in 8.3.

Lead-free C&A panel will improve opens calls.

Portfolio tools (URT, Coverage Analyst, etc.) will improve overall call effectiveness of test and inspection.

Future developments to improve lead-free performance are being investigated.

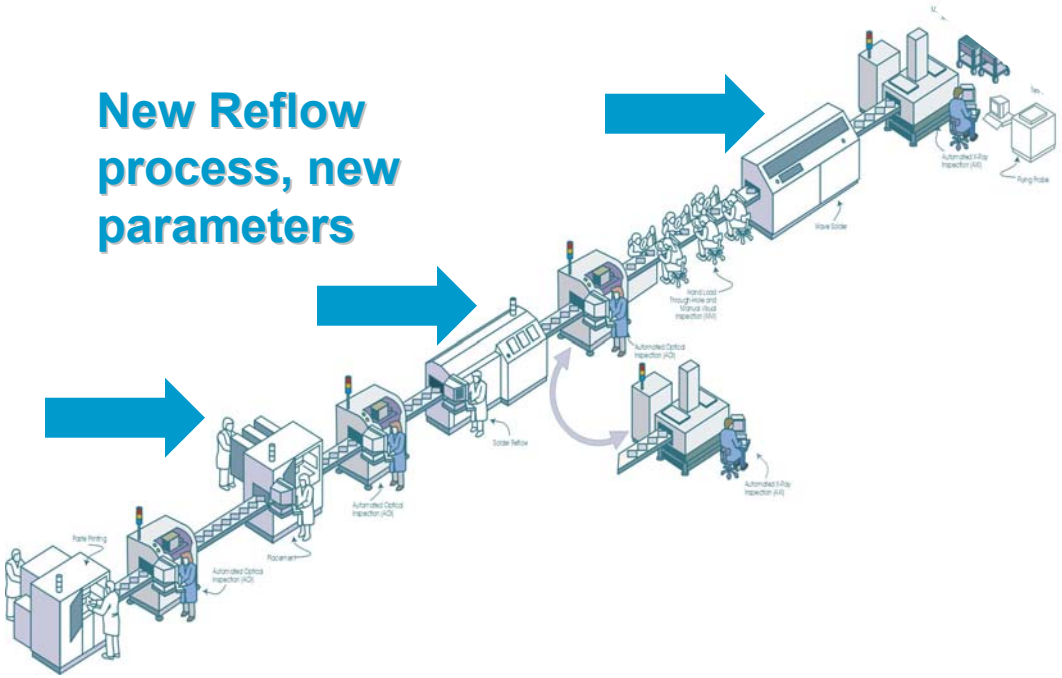
Implementing Lead-Free

New Wave soldering alloy, new parameters

New Reflow process, new parameters

Tighter component placement tolerances

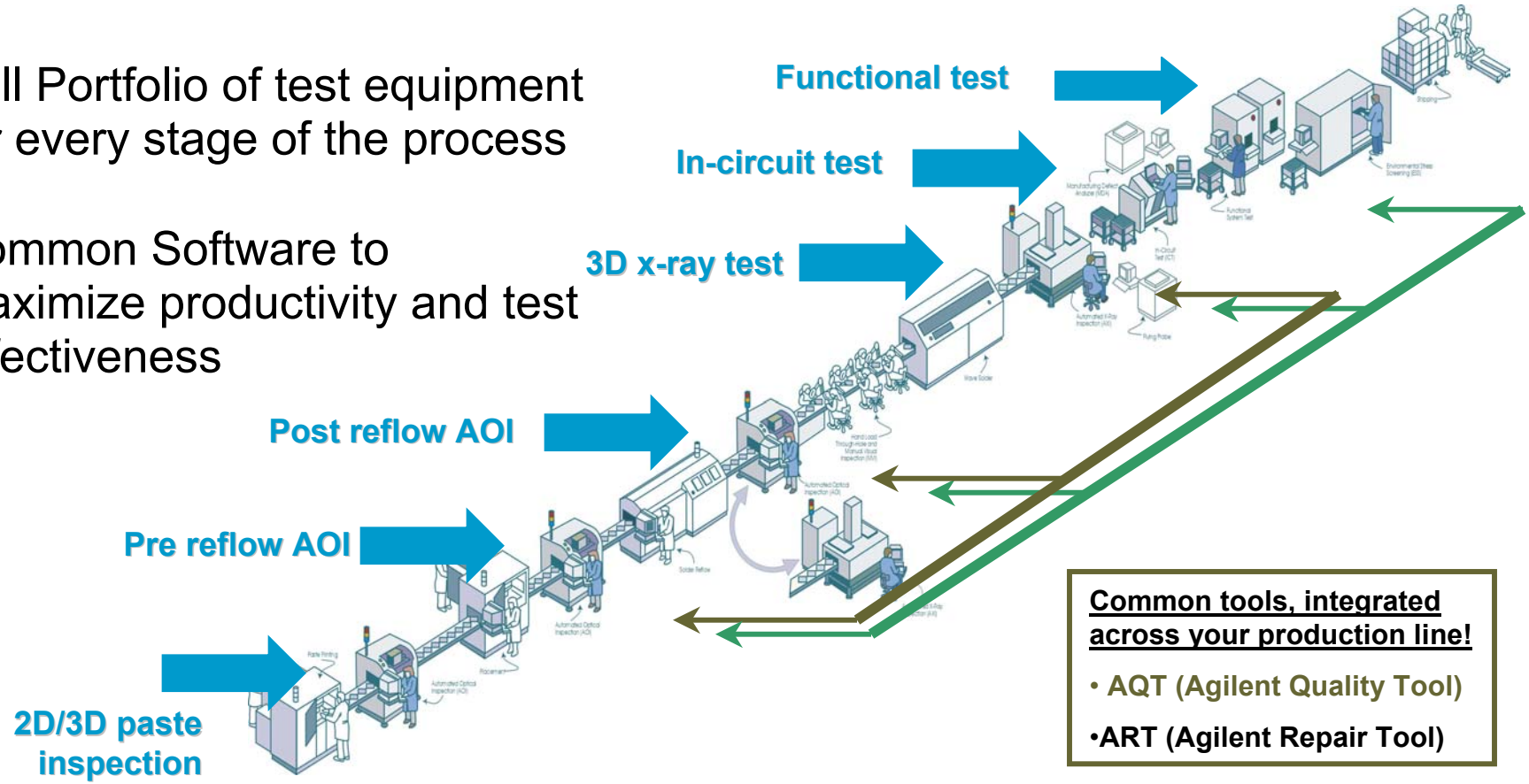
New printing parameter, new alloy and chemicals



Agilent Minimizes Your Risk When Implementing Lead-Free

Full Portfolio of test equipment for every stage of the process

Common Software to maximize productivity and test effectiveness



Common tools, integrated across your production line!

- AQT (Agilent Quality Tool)
- ART (Agilent Repair Tool)

Agilent Minimizes Your Risk When Implementing Lead-Free in 3 Ways

1 ***Most Complete Coverage and Flexible Solutions***

- With uncertainty of defect levels and defect types, Agilent's solutions cover the entire manufacturing line

2 ***Test and Inspection Solutions Are Lead-Free Ready***

- AOI and AXI proven as market leaders through customer and market studies

3 ***Experts to Help You Succeed!***

- Agilent has the expertise and can partner with you to deploy a lead-free test and inspection implementation

Technology	Product	Lead-Free Ready?
Solder Paste Inspection	SP50	✓
AOI:Optical Inspection	SJ50	✓
X-Ray Test	5DX	✓
In-Circuit Test	3070	✓