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SERDP Tin Whisker Testing and Modeling: Low Stress Conditions

Stephan Meschter*, Polina Snugovsky#, Jeff Kennedy, Zohreh Bagheri# and Eva Kosiba#
*BAE Systems Endicott, NY, USA
#Celestica, Toronto, Ontario Canada
stephan.j.meschter@baesystems.com

SERDP Lead-Free Projects

- **Strategic Environmental Research and Development Program (http://www.serdp.org/)**
  - **SERDP performs research related to environmental challenges faced by the US Department of Defense**
- **WP-1751, J. Nielsen, The Role of Trace Elements in Tin Whisker Growth**
- **WP-1752, P. Borgesen, Microstructurally Adaptive Constitutive Models for Lead Free Solder Joints**
- **WP-1753, S. Meschter, Tin-Whisker Testing and Modeling**
- **WP-1754, E. Hoffman, Stress State and Metallic Whisker Growth**
- **WP-2212, D. Hillman, Tin Whiskers Inorganic Coatings Evaluation**
- **WP-2213, S. Meschter, Composite coating for whisker mitigation**

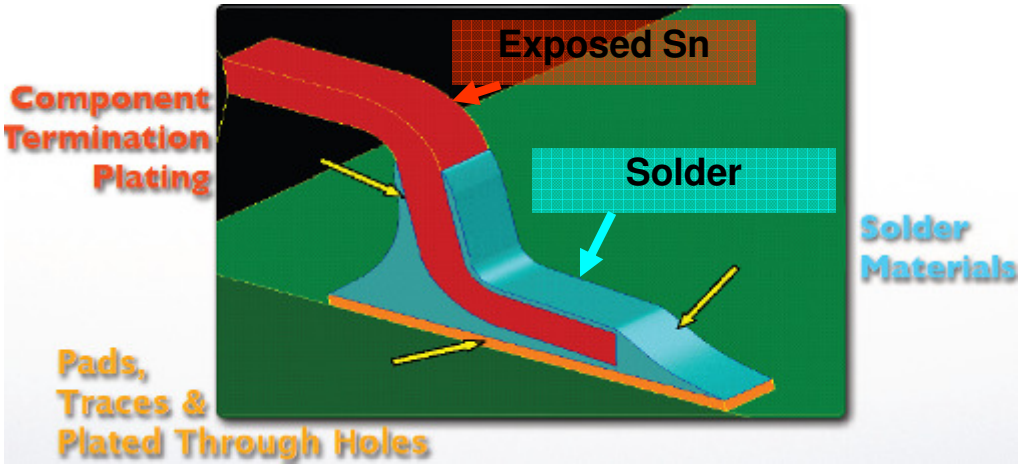
SERDP Project WP1753 Technical objective

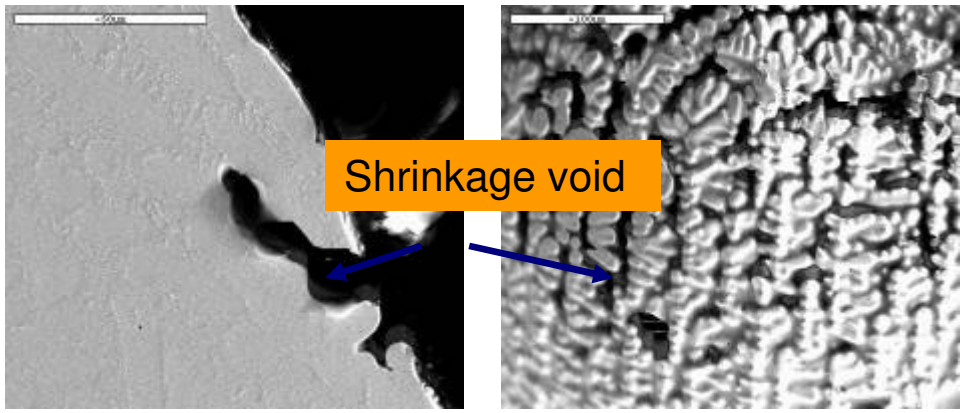
- **Perform systematic tin-whisker testing to improve the reliability of military electronics**
  - **Assess combinations of whisker growth variables**
    - **Design, manufacturing, and environments**
  - **Evaluate conformal coating for mitigation effectiveness**
  - **Provide metallurgical analysis of tin whiskers for nucleation and growth-mechanism formulation**

- **Provide an analytical framework to assess functional risk of whiskers to military electronic systems**
  - **System function risk assessment through integration of whisker distribution data and circuit details**

Whiskers in typical Pb-free solder joints

- No lead(Pb) in electroplated Sn finish – *propensity for whisker formation*
- Poorer wetting – *more exposed Sn plating for same type of components*
- More aggressive fluxes to improve wetting – ionic contamination, oxidation and corrosion *promoting whisker growth*
- Sn-Ag-Cu solder – *what about whisker growth?*
  - Rough surface – trapped contamination, difficult to clean – *higher propensity to whisker*

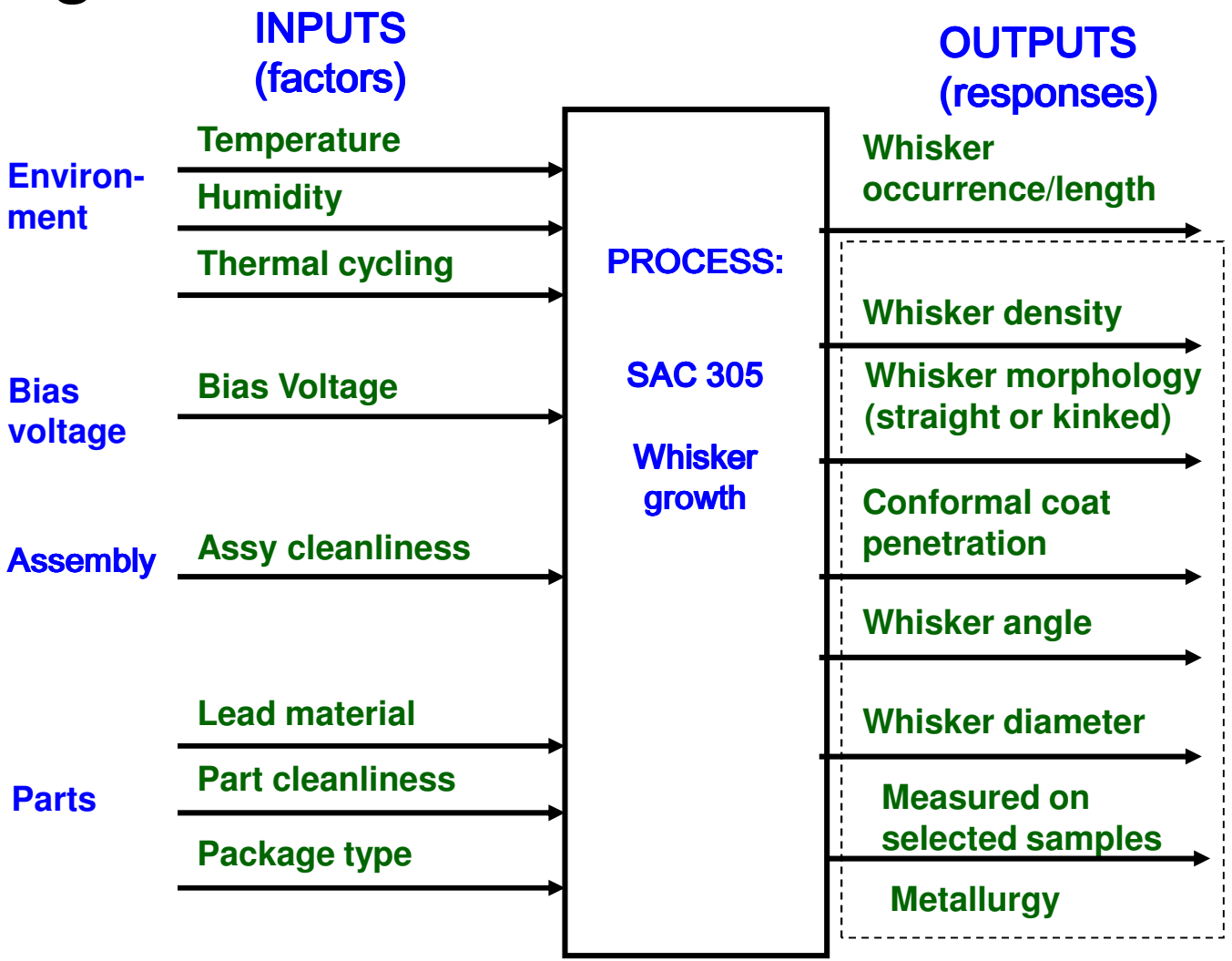




cross-section top view

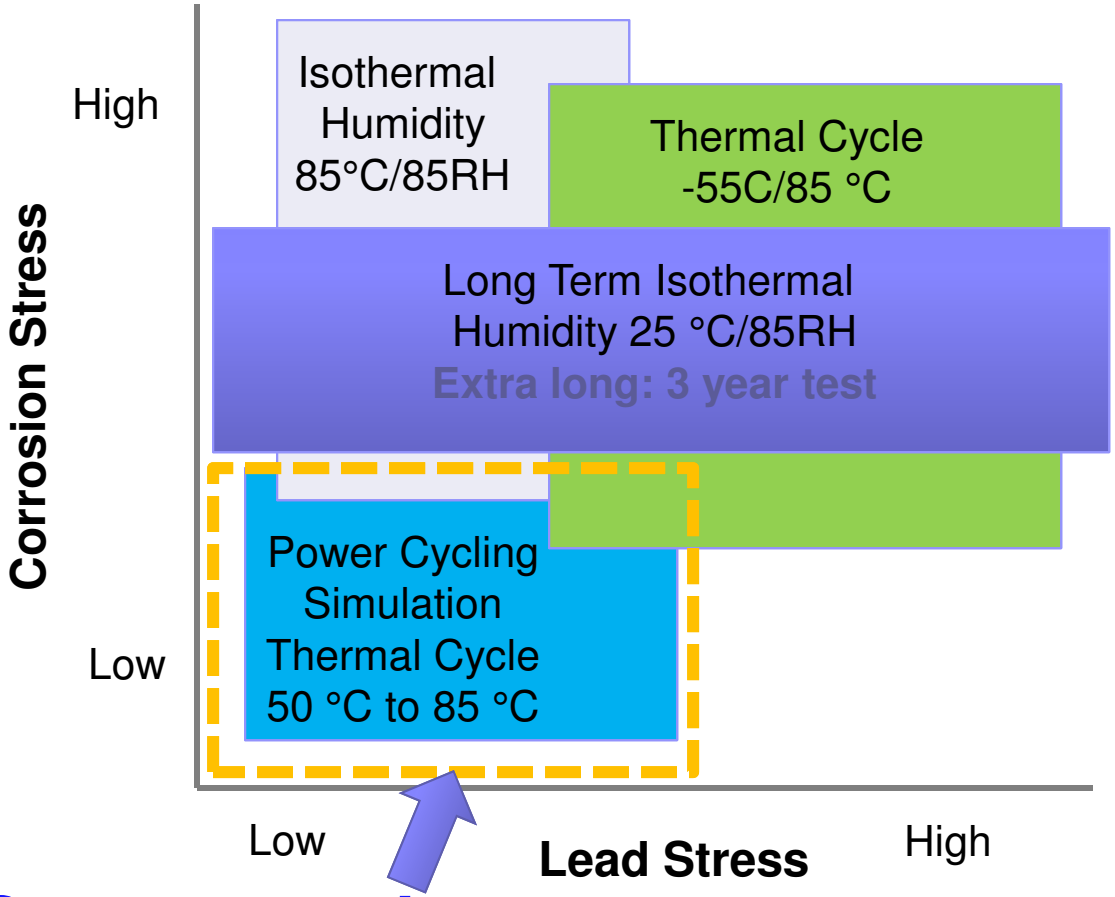
Lead-Free joint roughness, SEM

Testing overview



Test matrix includes variable combinations expected to yield low, medium and high whisker propensities in order to evaluate conformal coat mitigation

Variable stress whisker testing



Lead IMC stress:
- Higher → with intermetallic growth
- Higher → with long test duration
- *Montoring IMC thickness on both board and leads during test*

Lead thermal cycle CTE stress:
- Higher → with larger delta T
- Higher → with tin on alloy 42
- Lower → with tin on copper

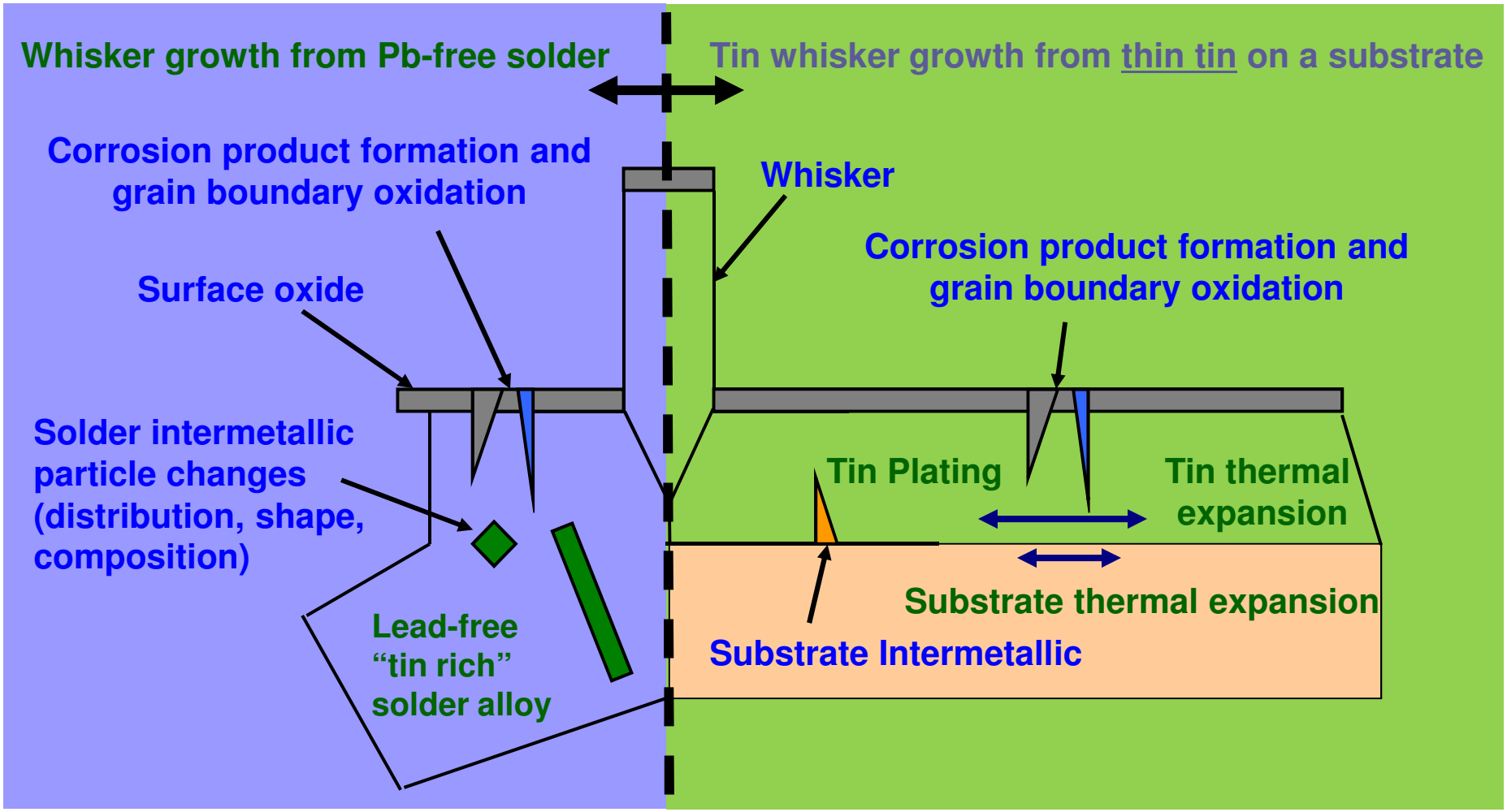
Current work

Power Cycling Simulation

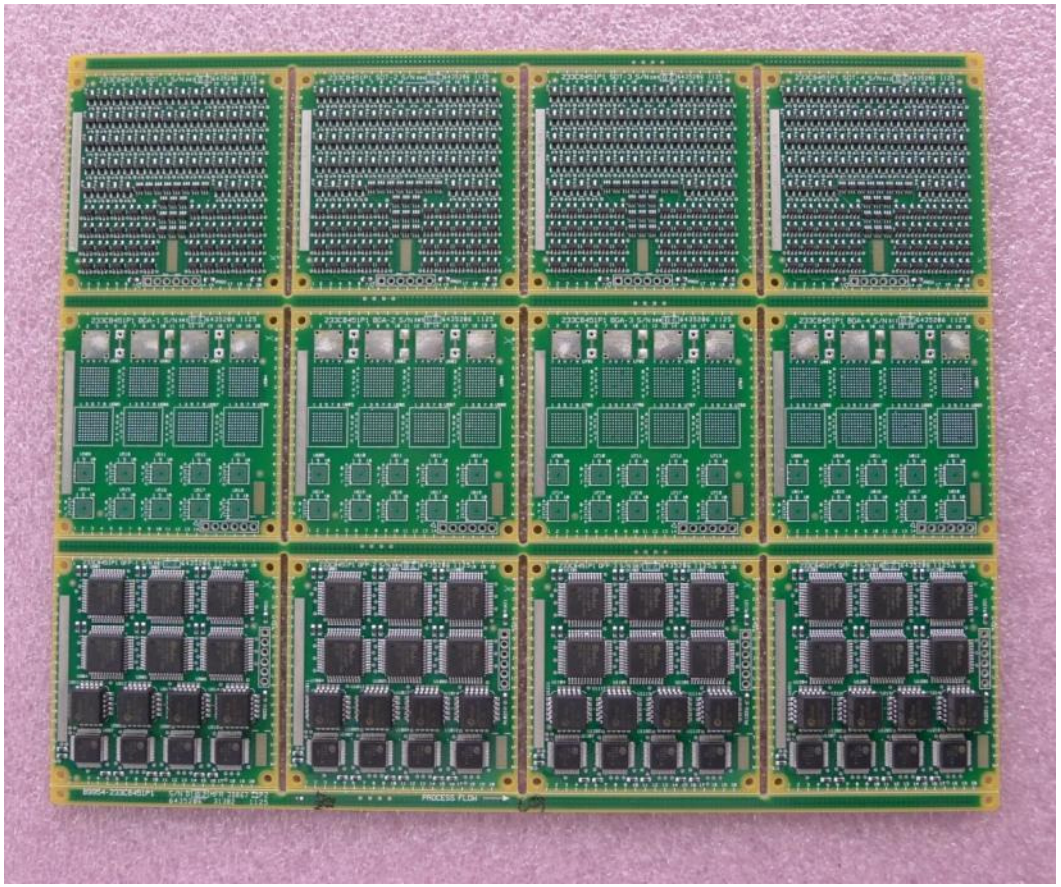
Evaluating a broad range of stress combinations suspected to promote whisker growth

Factors contributing to whisker growth

Compressive stress in tin is believed to cause to whisker growth.



Test vehicle panel



24.7 x 20 cm 0.236 mm thick panel

Board Types

SOT (Small outline transistor)

Current work

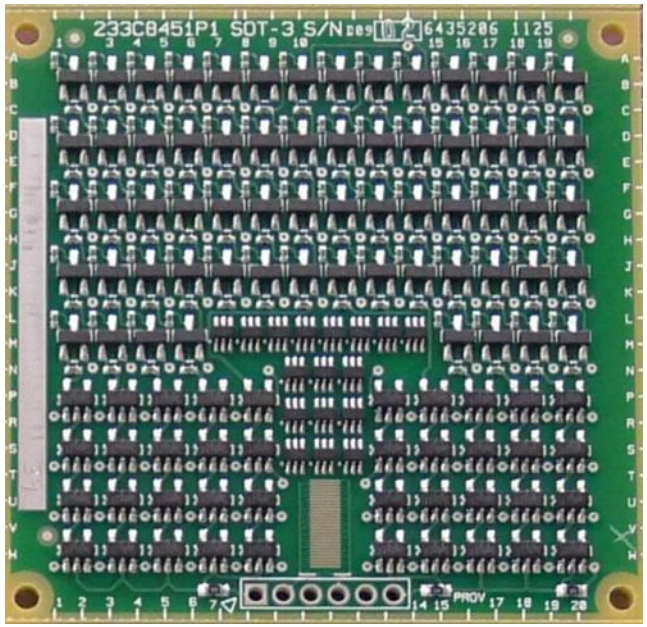
BGA (Ball grid array)

QFP/PLCC
(Quad flat pack/
Plastic leaded chip carrier)

Test Vehicle

6 cm square

Can be inspected entirely in the SEM

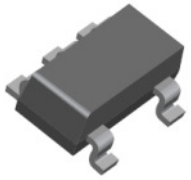


Immersion tin finish printed wire board

Designation Part No. Package	Lead Frame Material	Plating Material	Number of Leads/ number of parts
SOT3 2N7002 SOT23-3	Alloy 42	Matte Sn	3/64
SOT5 NC7S08M5X SOT23-5	Cu194	Matte Sn	5/40
SOT6 2N7002DW-7-F SOT363	Alloy 42	Matte Sn	6/17

Alloy 42	Fe-42Ni
C194	Cu2.1-2.6Fe-0.015-0.15P-0.05-0.2Zn

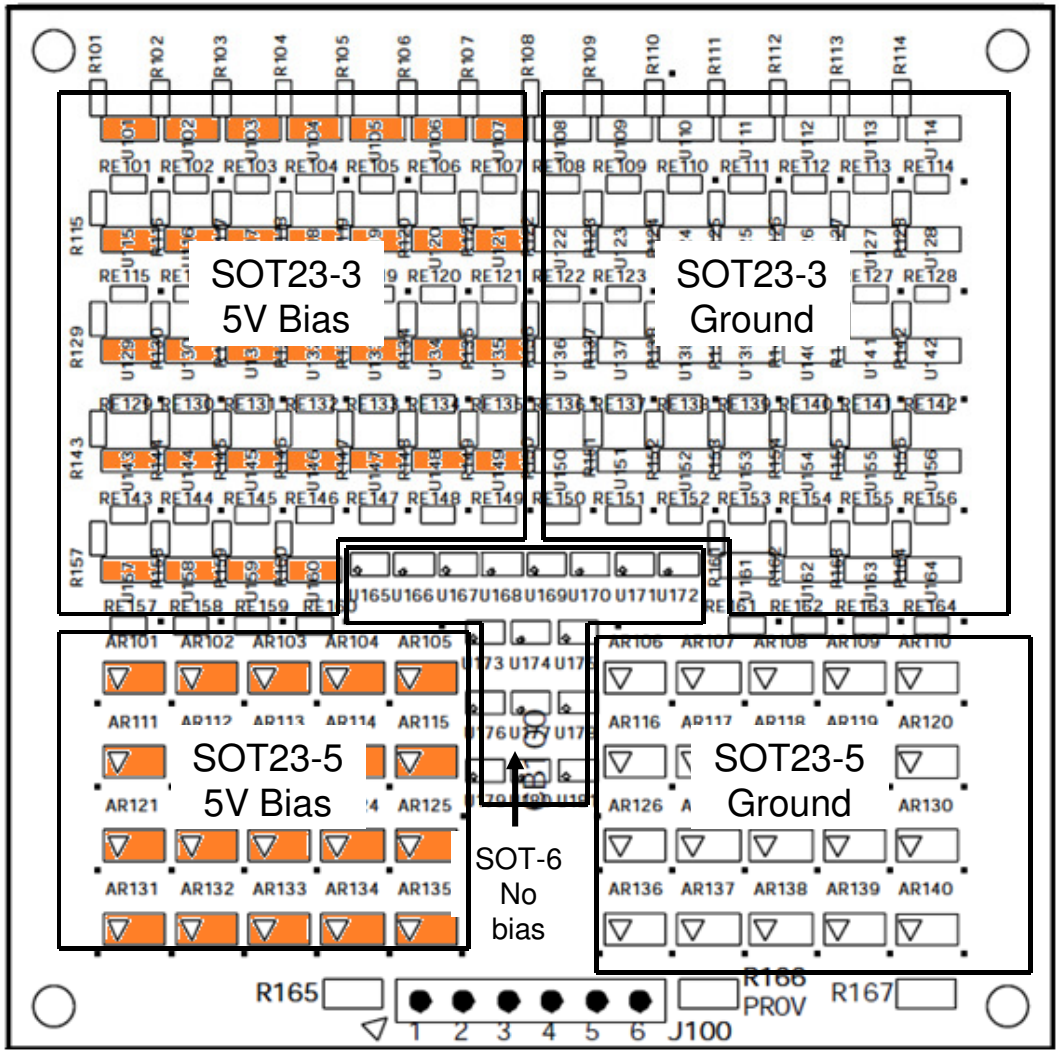
SOT3

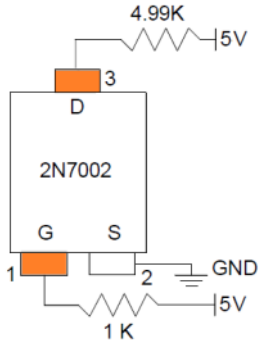


SOT5

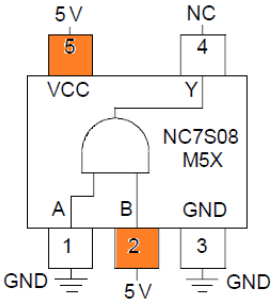
SOT6

Electrical Bias

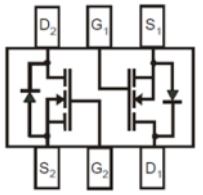




SOT3



SOT5



No connect

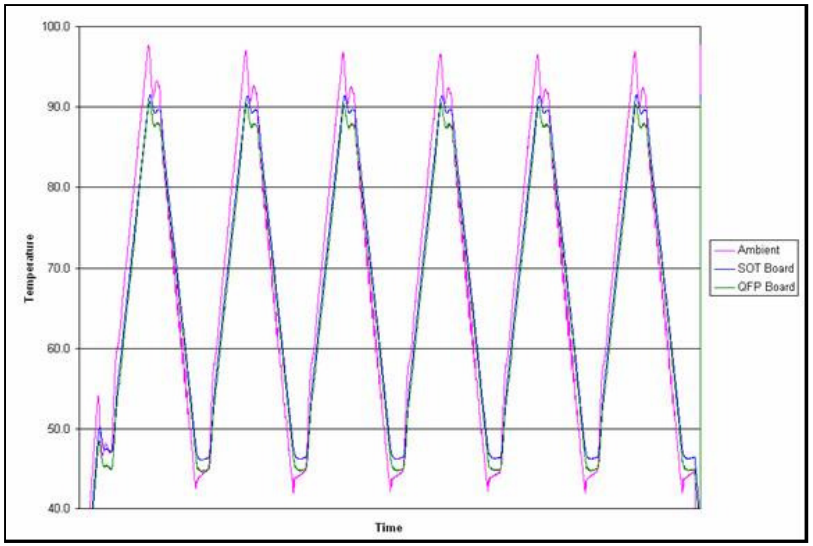
SOT6

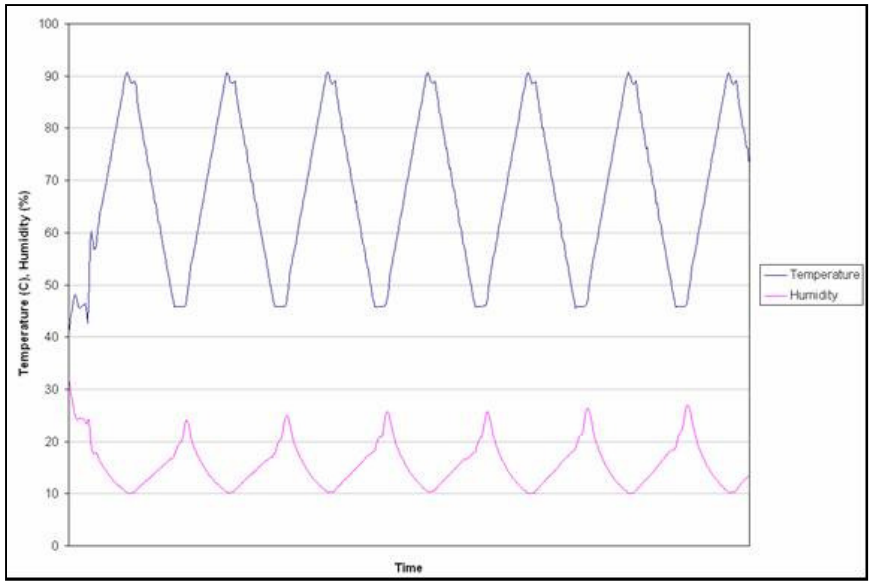
5V applied to Qty = 32 SOT23-2, Qty = 20 SOT23-5

10

Simulated power cycling environment

- 50 °C ambient on-off simulation
- Chamber air determines board temperature
  - Constant voltage applied
  - 31 mA board current draw @ 5V = 155 mW
  - Low power yields small temperature gradients
- Low range thermal cycling
  - Target 50 to 85 °C, 35 °C
  - Measured 48 °C to 88 °C, ΔT=40 °C
- Humidity was recorded
  - Cycling 25%RH at 88 °C to 10%RH at 48 °C

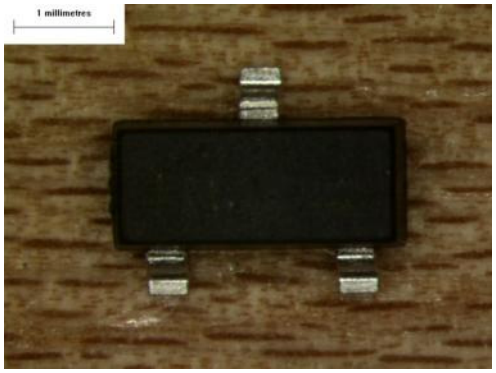


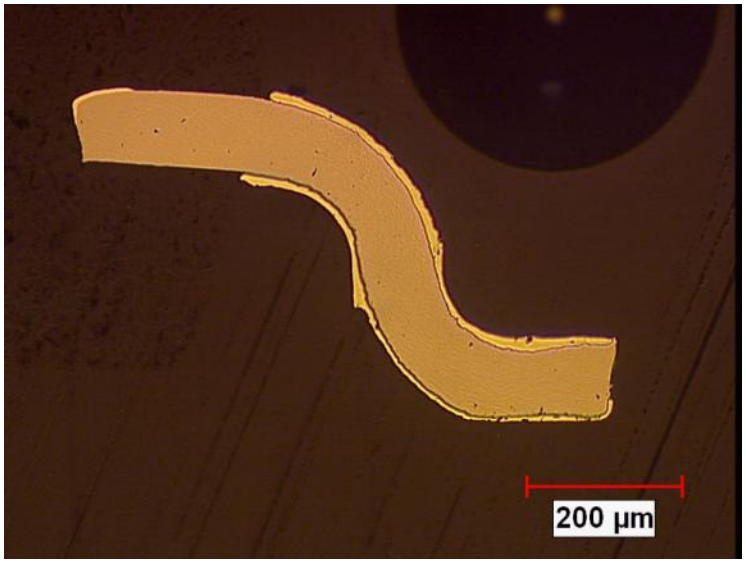


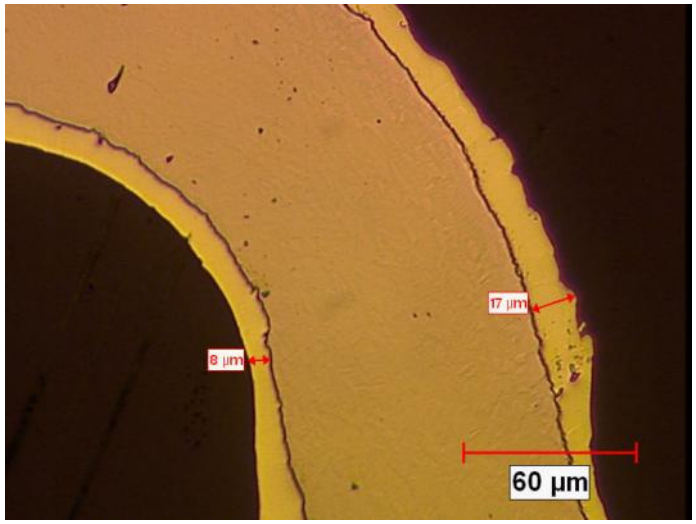
COMPONENTS, AS RECEIVED

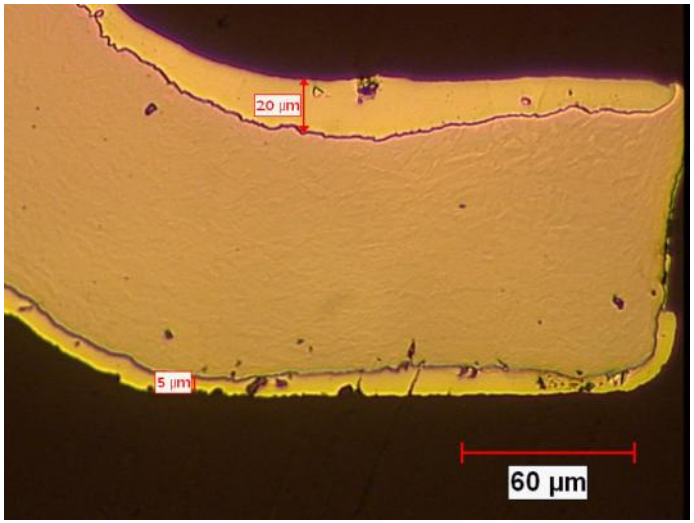
Components, SOT23-3 as received

- Sn plating thickness varies from 5 to 20 µm depending on lead area



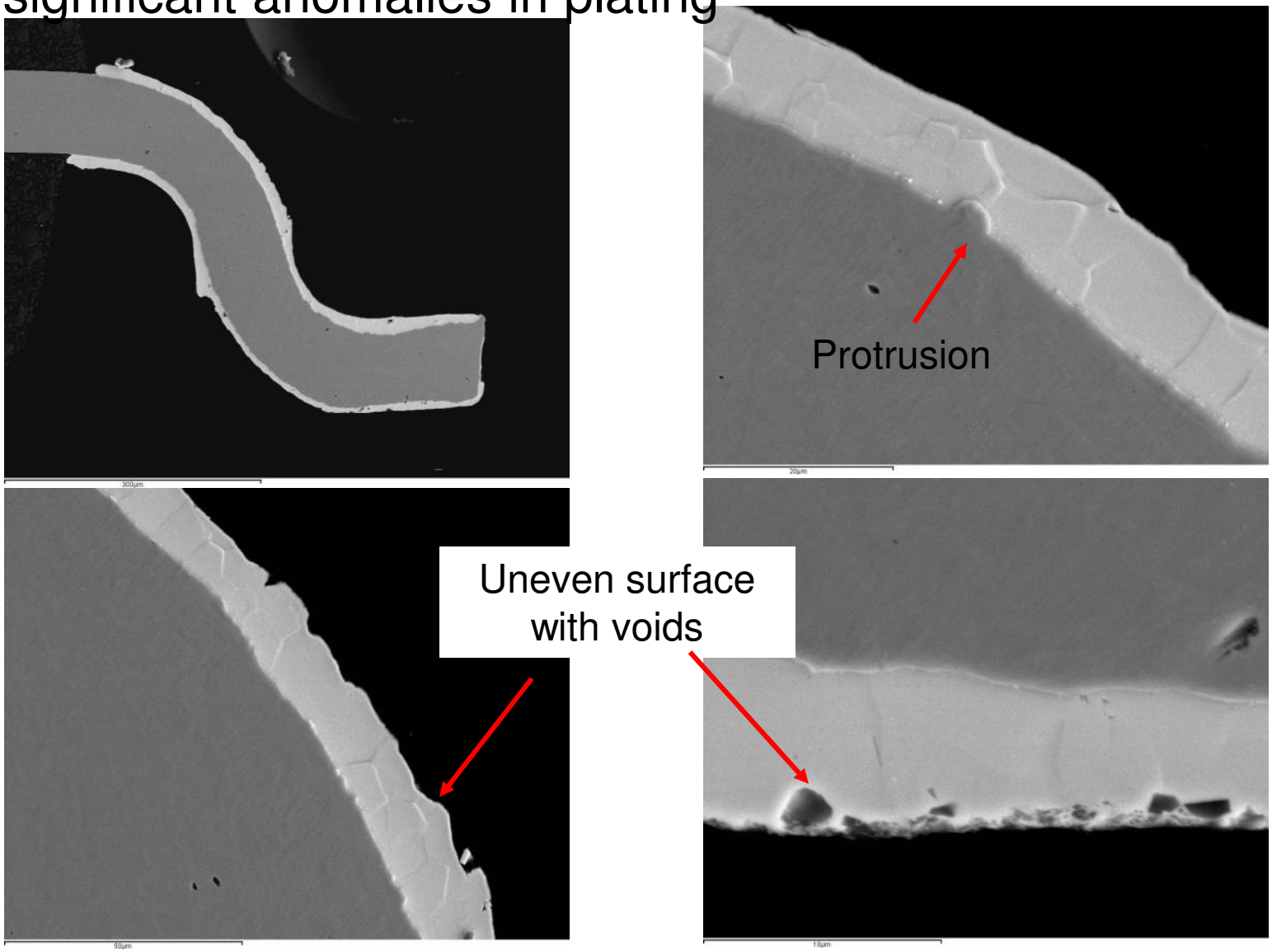




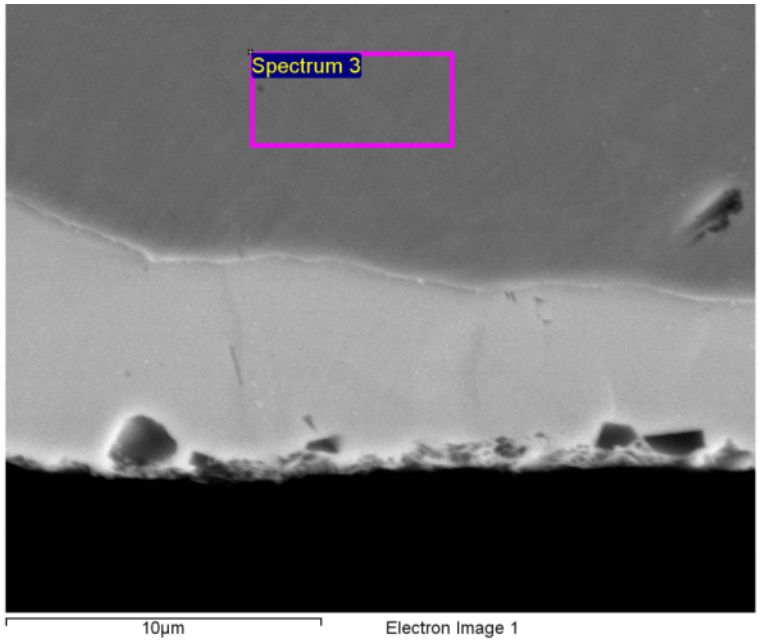


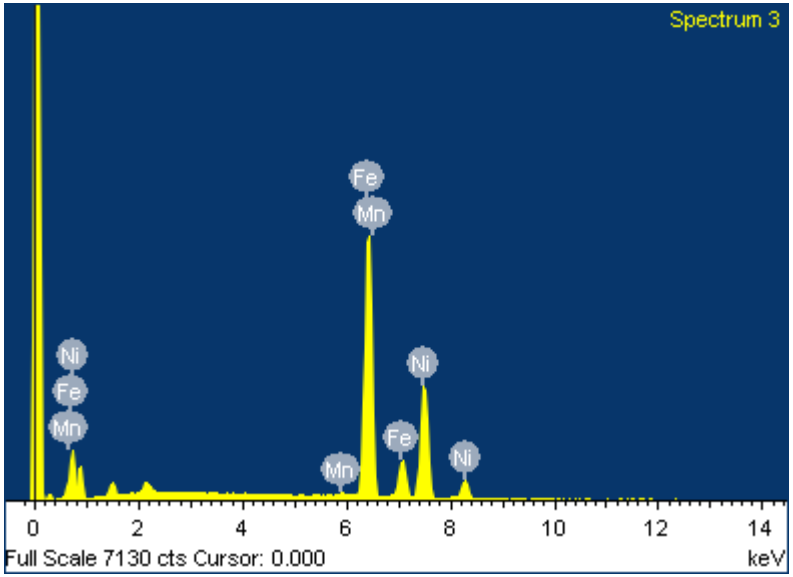
Components, SOT23-3 as received (cont.)

- No significant anomalies in plating



Components, SOT23-3 as received (cont.)

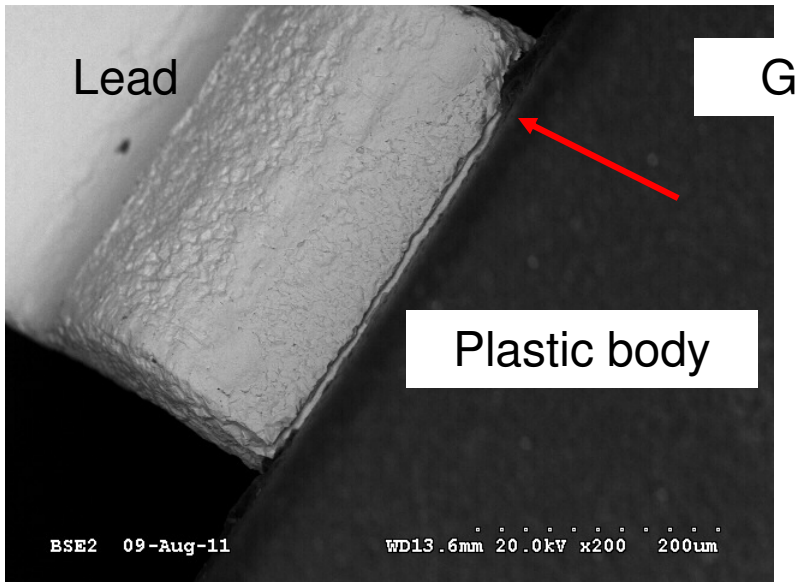


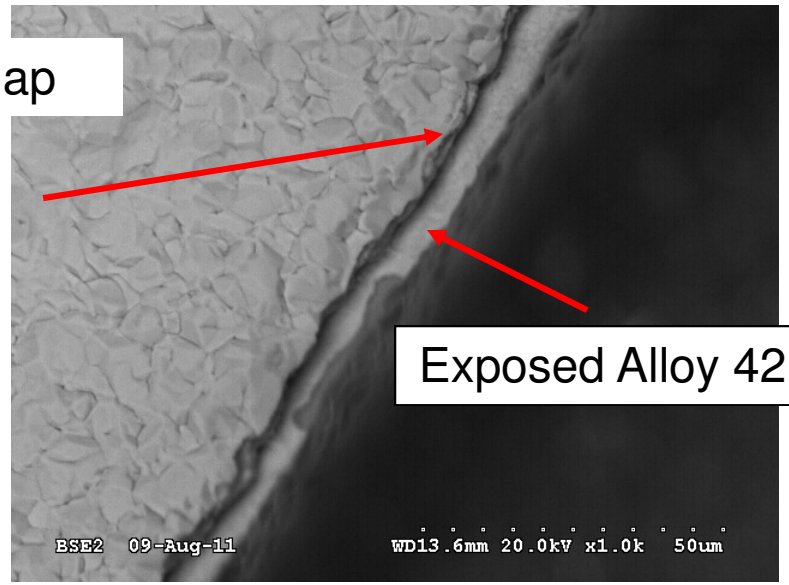


EDX on Alloy 42 Leadframe Material

Element	Weight%	Atomic%
Mn K	0.56	0.58
Fe K	59.12	60.30
Ni K	40.33	39.13
Totals	100.00	

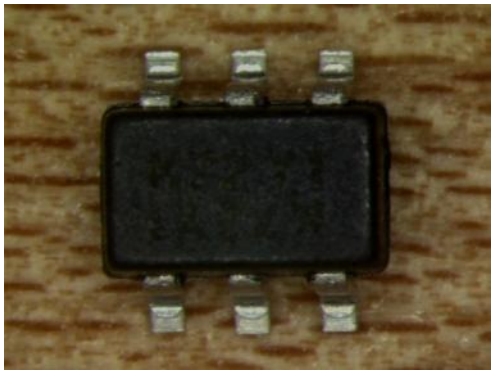
Components, SOT23-3 as received (cont.)

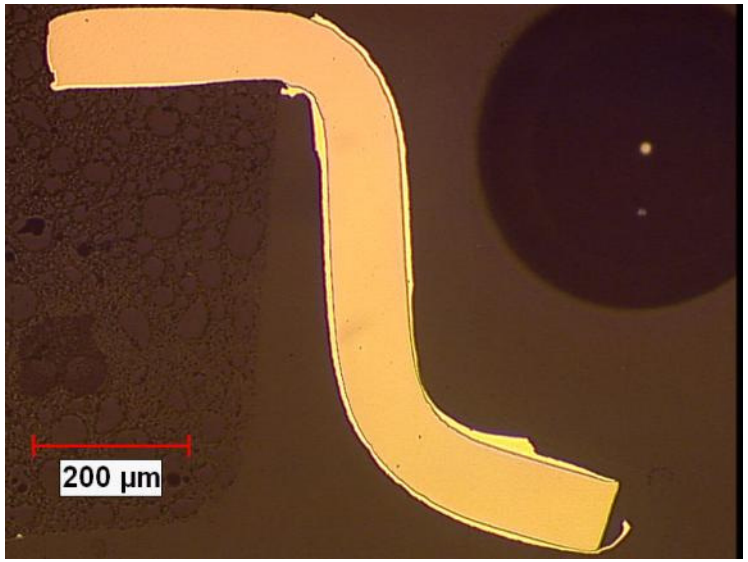


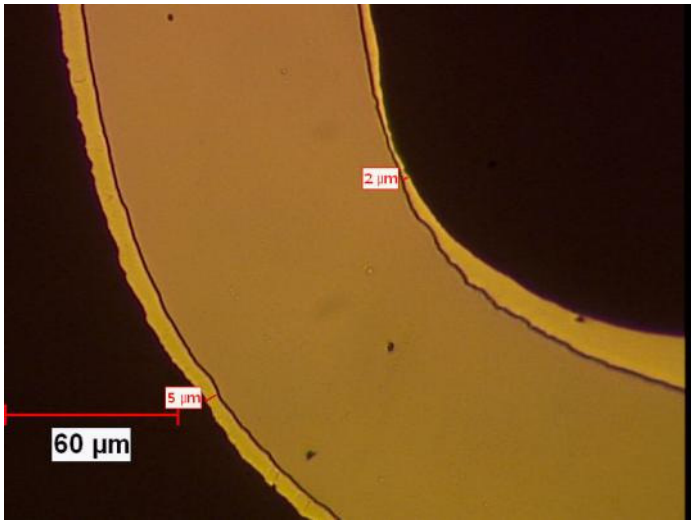


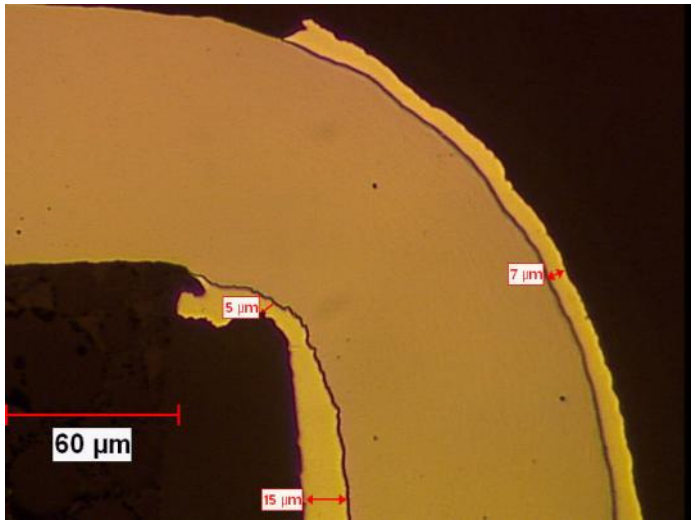
Components, SOT363 as received

- Sn plating thickness varies from 2 to 25 µm depending on lead area



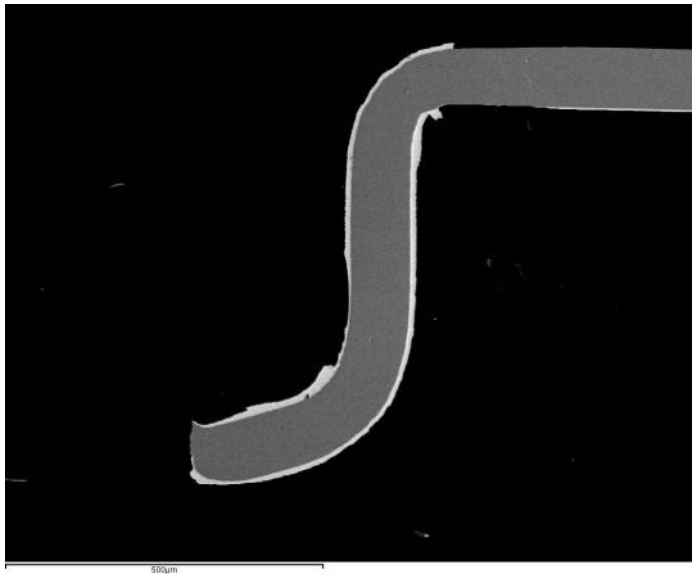


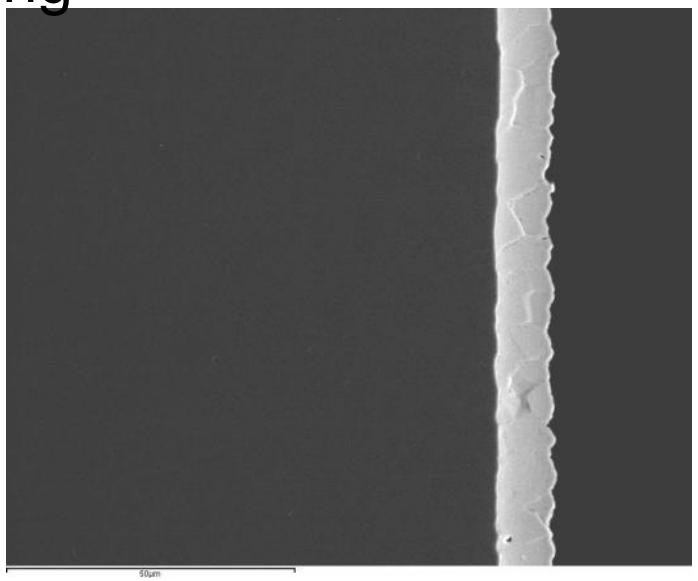


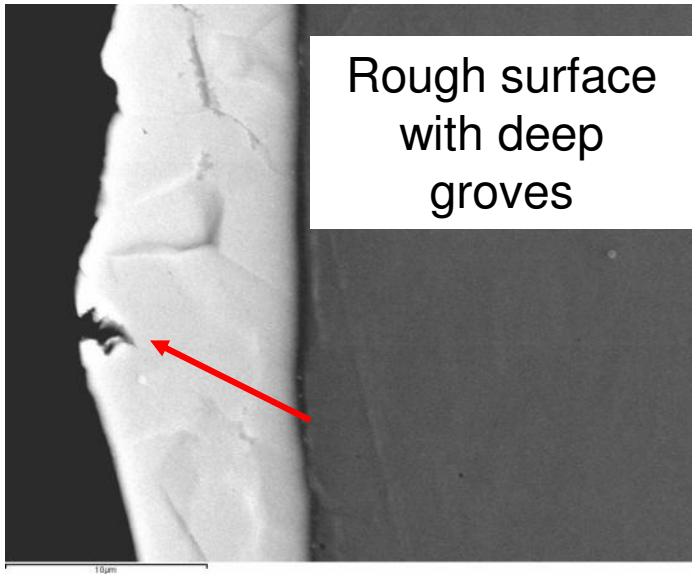


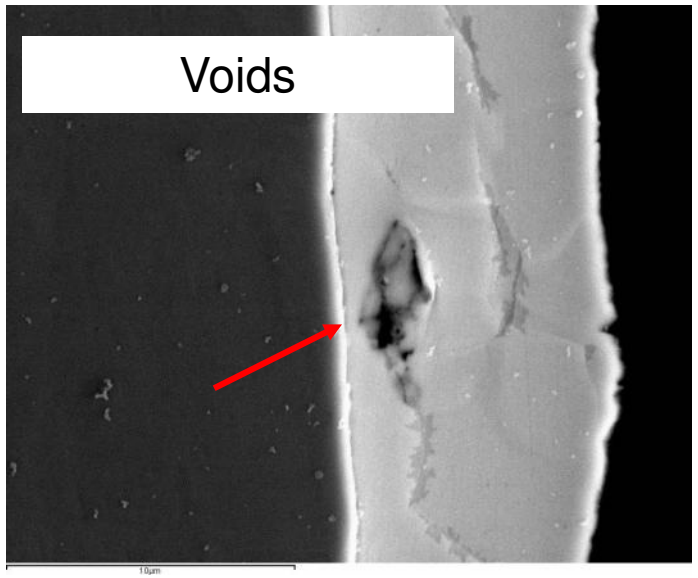
Components, SOT363 as received (cont.)

- No significant anomalies in plating

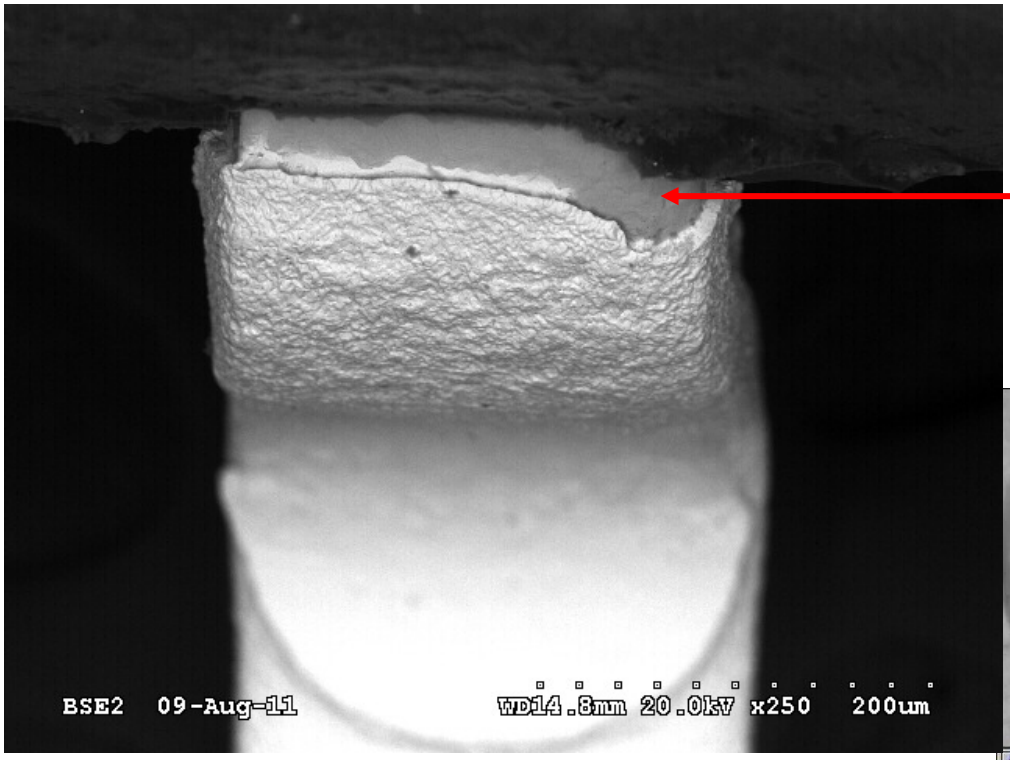




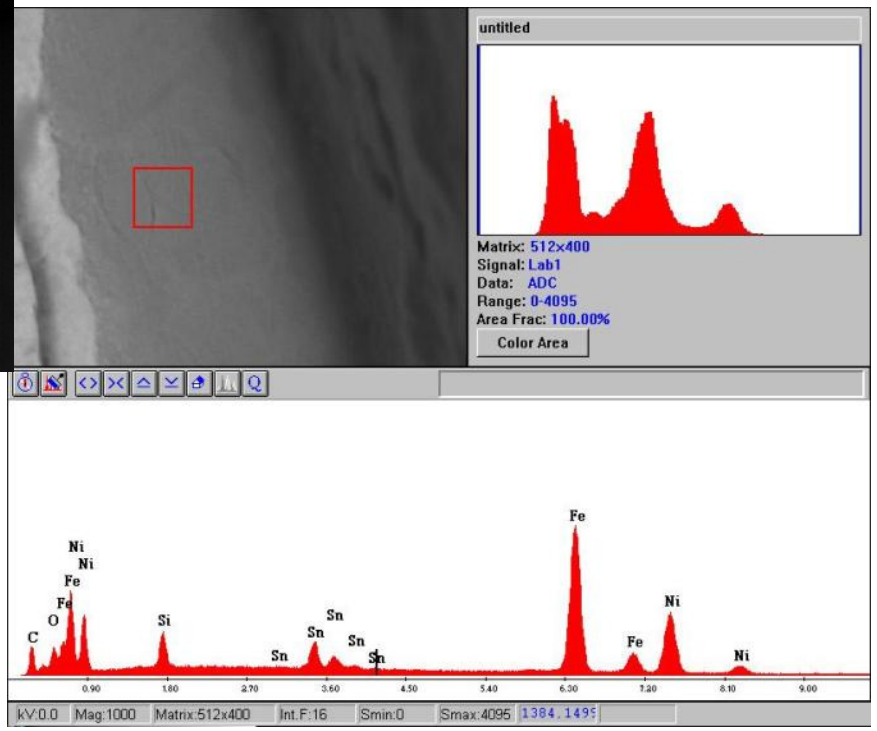




Components, SOT363 as received (cont)

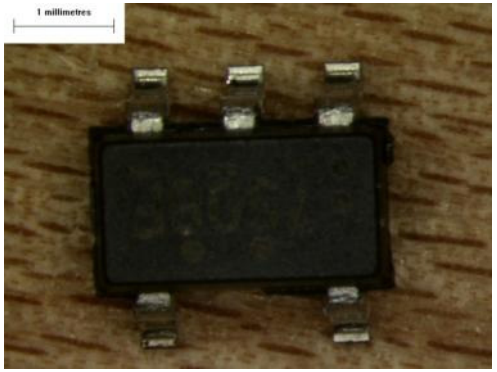


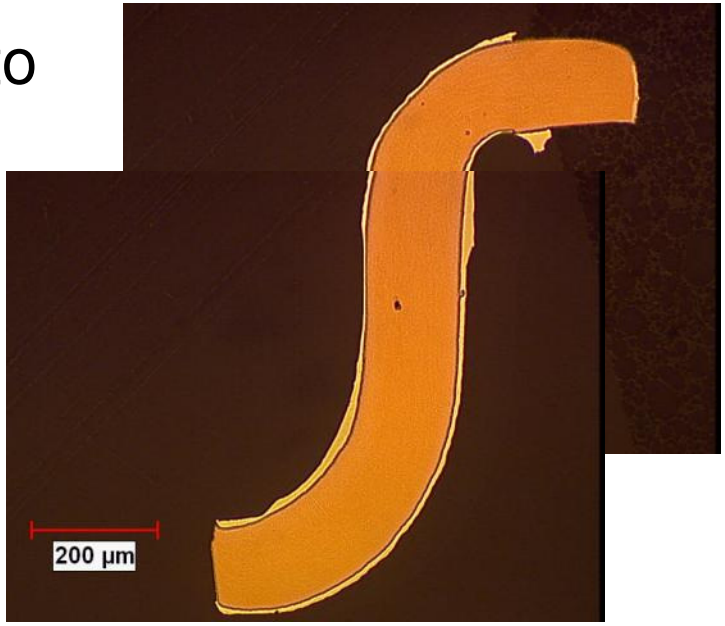
Exposed Alloy 42

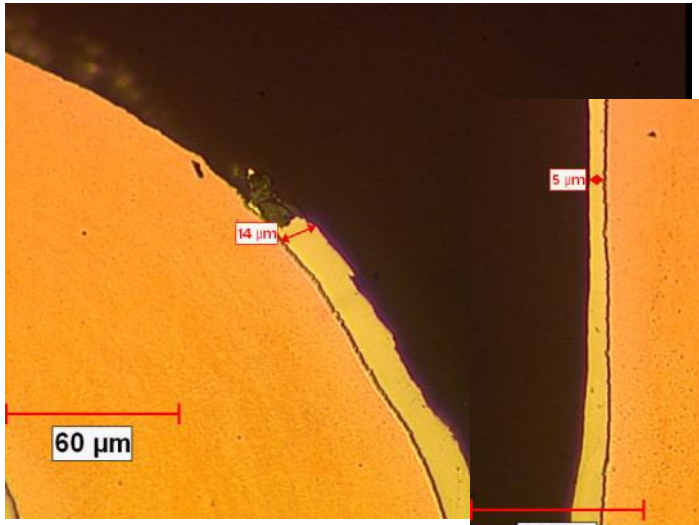


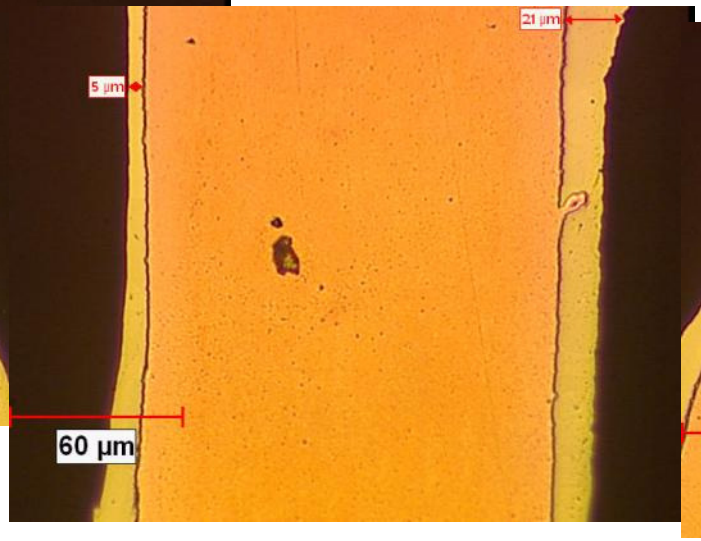
Components, SOT23-5 as received

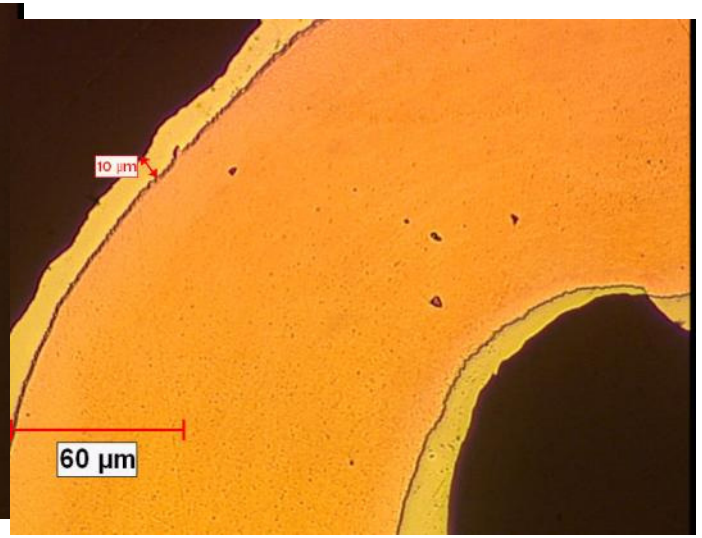
- Sn plating thickness varies from 5 to 29 µm depending on lead area





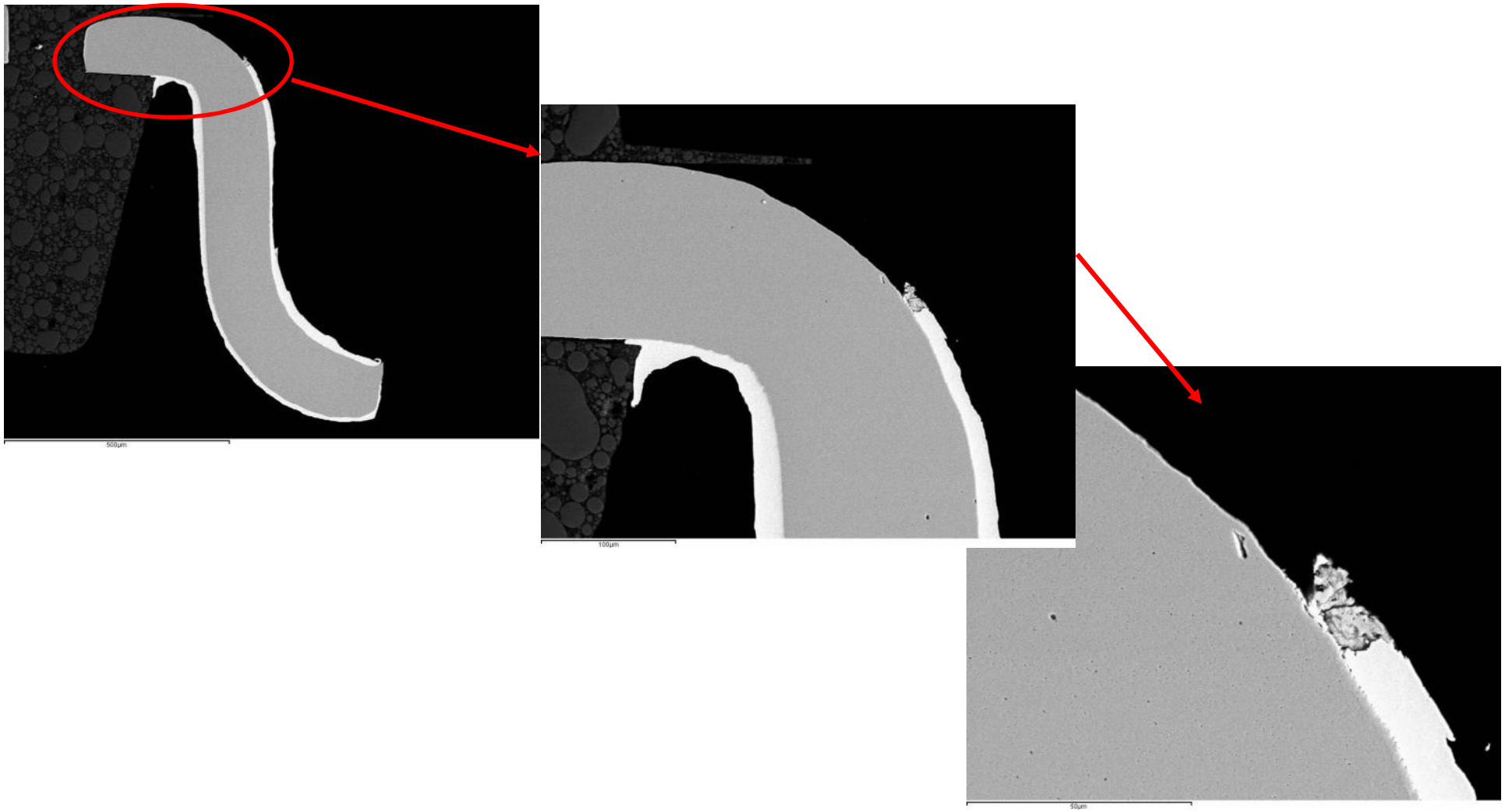






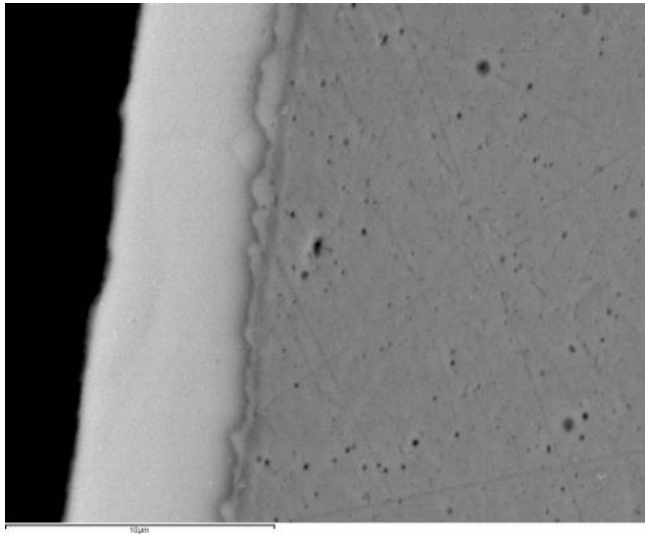
Components, SOT23-5 as received

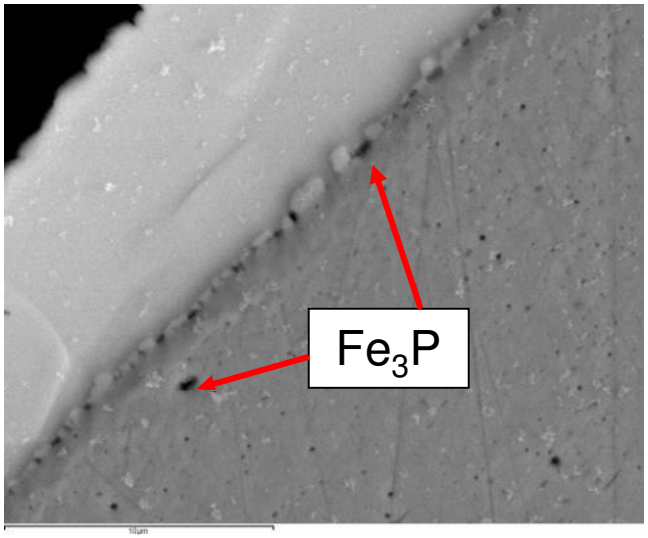
- Skipped Sn plating

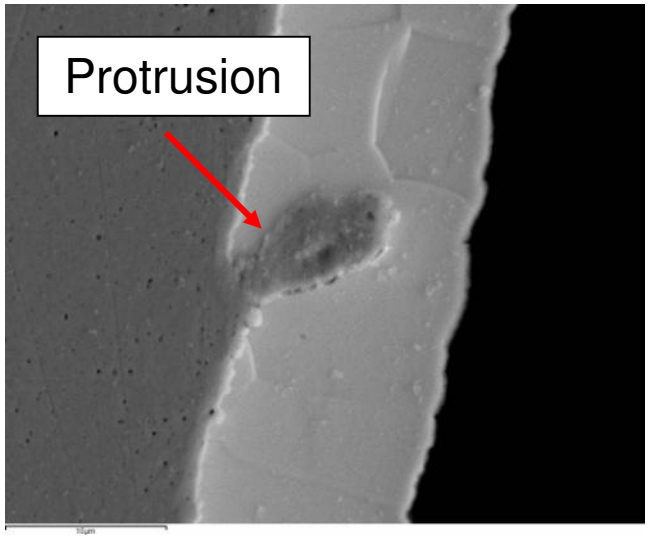


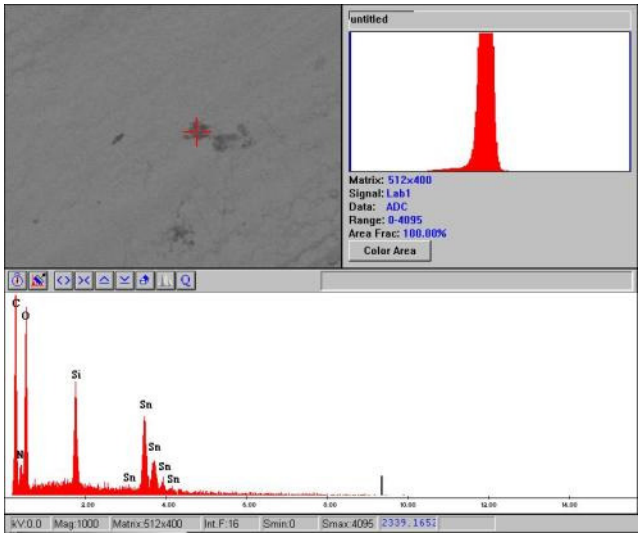
Components, SOT23-5 as received

- Sn plating is more uniform and smother than on SOT23-3 and SOT363
- Defects the Intermetallic layer related to Fe_3P

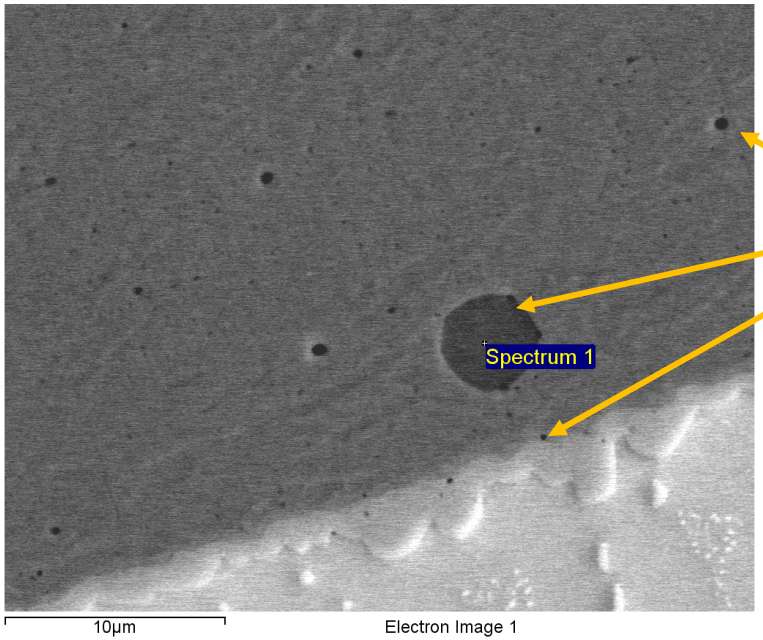




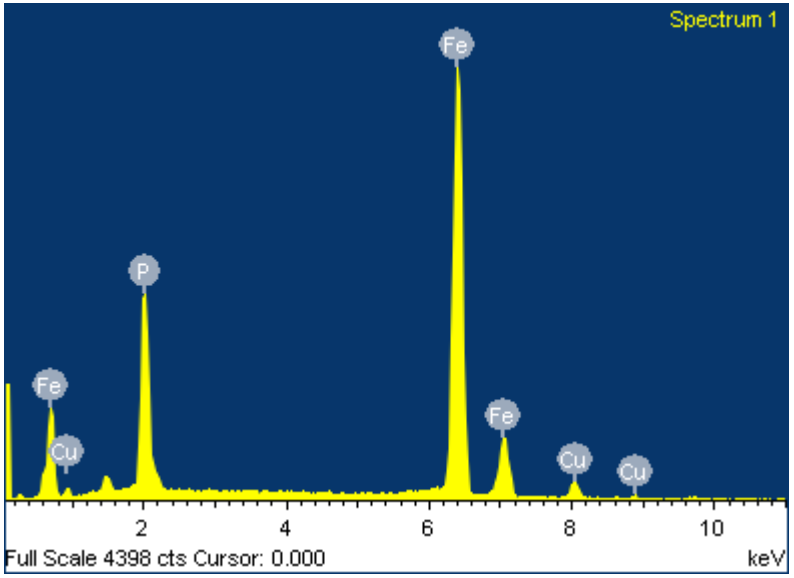




Components, SOT23-5 as received

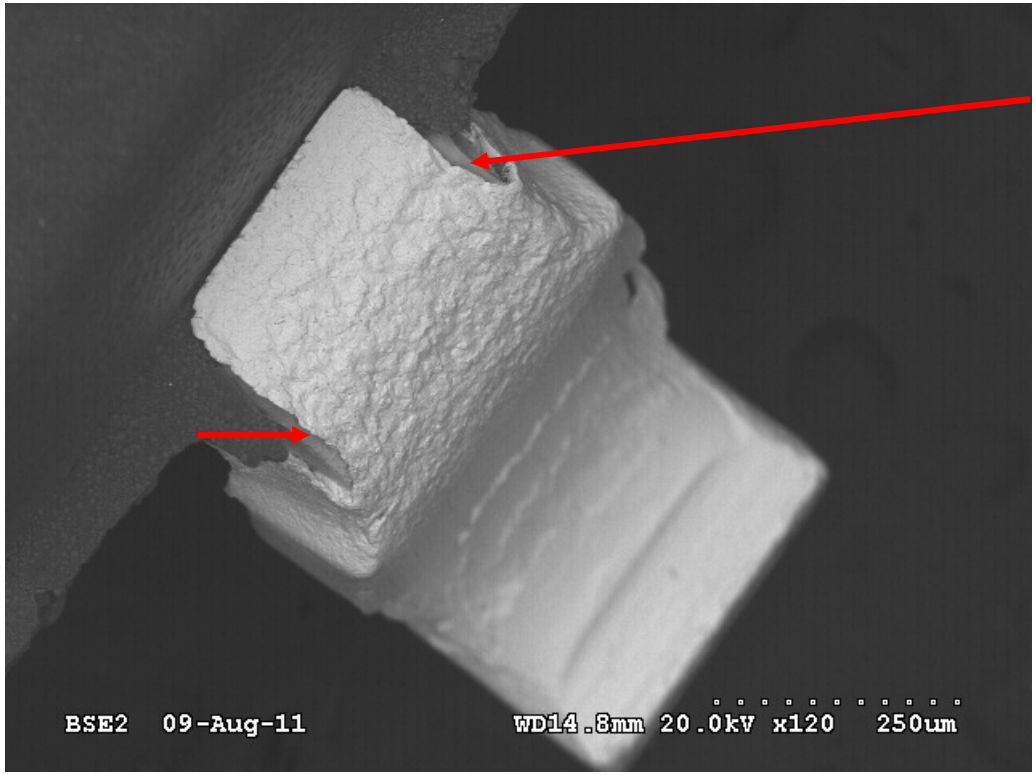


Fe_3P

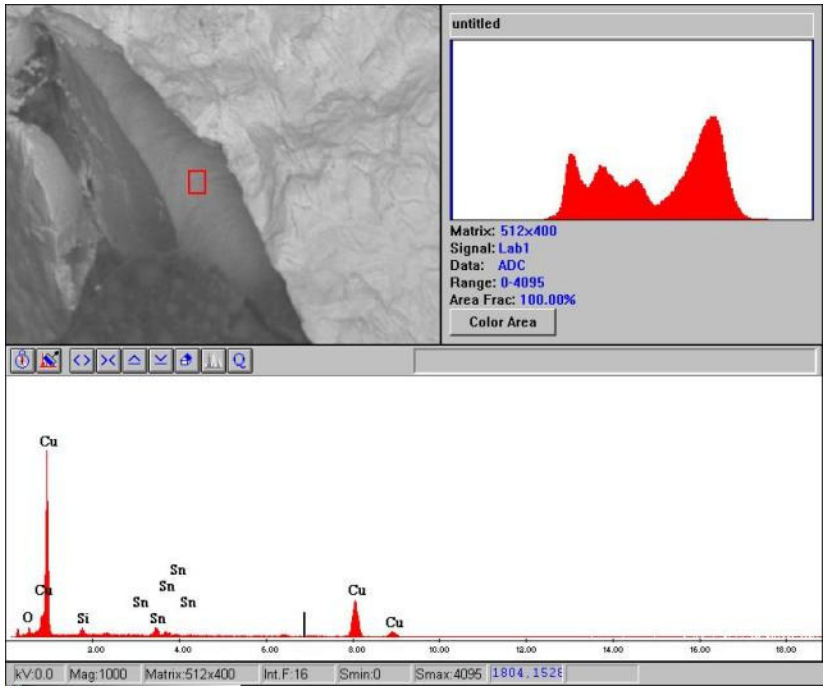


Element	Weight%	Atomic%
P K	13.26	21.74
Fe K	81.00	73.67
Cu K	5.74	4.59
Totals	100.00	

Components, SOT23-5 as received



Exposed Cu Alloy C194



Components For Assembly

- Before Assembly components were divided into 2 groups
  - The first group was cleaned
    - Method developed in Screening Experiments was used
  - The second croup was contaminated with NaCl
    - Method developed in Screening Experiments was used
      - 3µg/in^2 intended

- Each group was assembled using SAC305 solder paste and washed after assembly

- Assembled boards were divided into two groups
  - The first group was left clean
    - Cleaned Components/Clean Boards – 0-0
    - Contaminated Components/ Clean Boards – 1-0
  - The second group was contaminated with NaCl
      - 10µg/in^2 intended
    - Cleaned Components/Contaminated Boards – 0-1
    - Contaminated Components/ Contaminated Boards – 1-1

COMPONENTS, CLEANED

Components Before Cleaning

Component Name	Component ID	Total Inorganic anions (µg/in²)	Total Organic anions (µg/in²)
SOT 23-3	2N7002(3 leads)	0.4	3.3
SOT 23-5	NC 7S 08 M5X (5 leads)	0.3	0.0
SOT 363	2N7002DW(6 leads)	0.2	3.5
QFP 64	LQFP 64	0.4	3.1
QFP 44	QFP 44	0.2	2.4
PLCC 20	PLCC 20	3.7	0.0

Components After Cleaning

- Cleaning:
  - The samples were cleaned twice
    - Placed in a KPak® bag with a solution of 10% IPA / 90% v/v deionized water and sealed.
    - 40 minutes in steam bath at 80° C and
    - 40 minutes on shaker table and then
  - Baked at 60° C for 10 minutes.

Component	Concentration of Inorganic anions in μg/in^2						
	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulphate	Total inorganic
SOT 23-3	0.0	0.0	0.0	0.0	0.2	0.2	0.4
SOT 23-5	0.1	0.0	0.0	0.0	0.1	0.0	0.3
SOT 363	0.1	0.0	0.0	0.0	0.1	0.0	0.2
QFP 64	0.1	0.0	0.0	0.0	0.2	0.1	0.4
QFP 44	0.1	0.0	0.0	0.0	0.1	0.0	0.2
PLCC 20	0.2	0.2	0.0	0.0	0.1	3.1	3.7

The level of contamination is much below the recommended minimum

Cleanliness Requirements

Terry Manson: Foresite table

TEST PROCEDURE – ION CHROMATOGRAPHY (IPC-TM-650, METHOD2.3.28)

Foresite Recommended Levels for Typical Ionic Residue Species *All values are in µg/in²*				
Ionic Species	**Bare Board**	**Component**	**No-clean Assembly**	**Cleaned Assembly**
Anion Species always tested for (Based on NIST Controls)				
Fluoride (F^-)	NA	NA	NA	NA
Acetate ($C_2H_2O_2$)	3.0	3.0	3.0	3.0
Formate (CH_2O_2)	3.0	3.0	3.0	3.0
Chloride (Cl^-)	2.0	1.0	3.0	6.0
Nitrite (NO_2^-)	3.0	3.0	3.0	3.0
Bromide (Br^-)	6.0	6.0	12.0	12.0
Nitrate (NO_3^-)	3.0	3.0	3.0	3.0
Phosphate (PO_4^{2-})	3.0	3.0	3.0	3.0
Sulfate (SO_4^{2-})	3.0	3.0	3.0	3.0
WOA (Weak Organic Acid)	NA	NA	SMT 25 Wave 150	25
Cation Species always tested for (Based on NIST Controls)				
Lithium (Li)	3.0	3.0	3.0	3.0
Sodium (Na)	3.0	1.0	3.0	3.0
Ammonium (NH_4)	3.0	3.0	3.0	3.0
Potassium (K)	3.0	3.0	3.0	3.0
Magnesium (Mg)	NA	NA	NA	NA
Calcium (Ca)	NA	NA	NA	NA

Industry accepted limit of contamination (our customers' requirements) - 10.75 µg/in^2 total inorganic

COMPONENTS, CONTAMINATED

Components After Pre-build Contamination

- Intention was to have SOT23-3 level of contamination 3.0µg/in² Cl^-
- More contamination was trapped by SOT363 and SOT23-5 because of rougher surface and more gaps than in SOT23-3

Component Name	Component ID	Total Inorganic anions (µg/in²)	Total Organic anions (µg/in²)
SOT 23-3	2N7002(3 leads)	1.9	0.0
SOT 23-3 repeat	2N7002(3 leads)	2.3	0.0
SOT 23-5	NC 7S 08 M5X (5 leads)	8.7	0.0
SOT 363	2N7002DW(6 leads)	7.4	0.0
QFP 64	LQFP 64	7.9	0.0
PLCC 20	PLCC 20	25	0.0

Components After Pre-build Contamination (cont.)

Component	Concentration of Inorganic anions in μg/in^2						
	Fluoride	Chloride	Nitrite	Bromide	Nitrate	Sulphate	Total inorganic
SOT 23-3	0.1	1.7	0.0	1.0	0.0	0.1	1.9
SOT 23-3 repeat	0.1	2.2	0.0	0.0	0.0	0.0	2.3
SOT 23-5	0.3	6.7	0.0	0.0	0.0	0.7	8.7
SOT 363	0.1	7.2	0.0	0.0	0.1	0.1	7.4
QFP 64	0.1	7.7	0.0	0.0	0.0	0.1	7.9
PLCC 20	0.1	24.7	0.0	0.1	0.0	0.1	25.0

The level of contamination is above the recommended minimum

Chloride content:

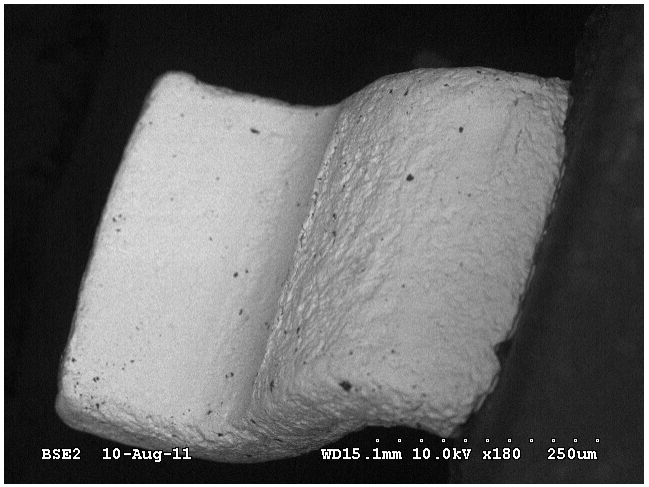
SOT23-3 – 2X above recommendation, but 2X below the level previously encountered in production

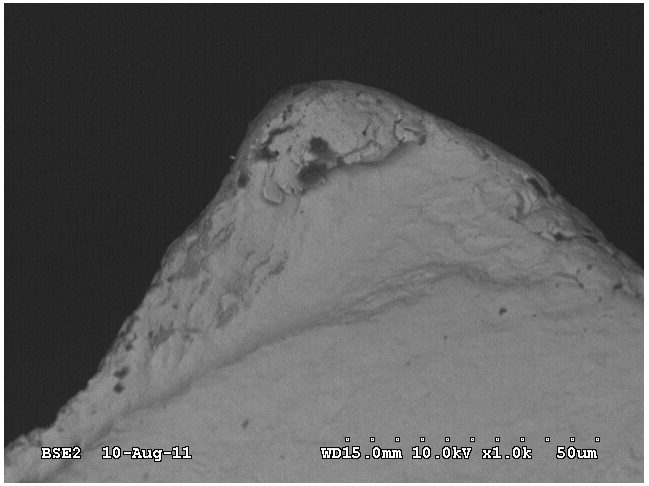
SOT23-5, SOT363, and QFP624 – comparable to what may happen in production

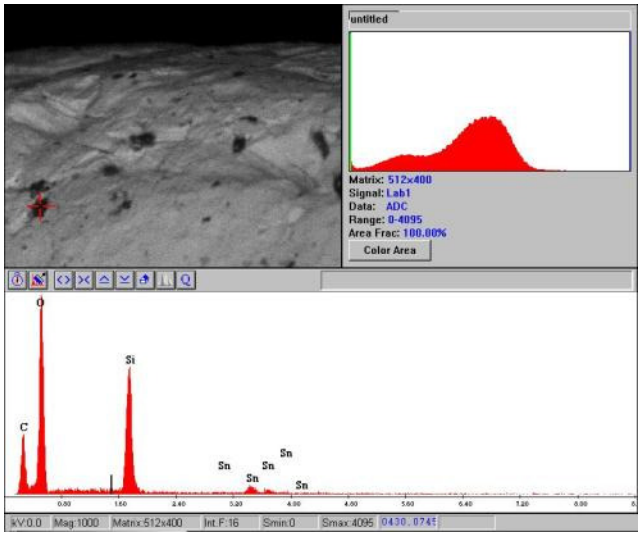
PLCC20 – very high level

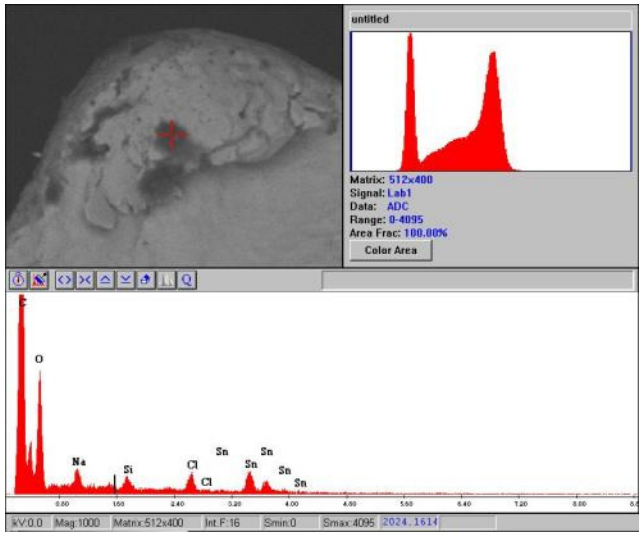
Components Pre-build Contamination:
SOT23-3, Cl^- - 1.7-2.2µg/in²

- Mostly silicon containing contamination was detected
- Chloride was found only in several occasions



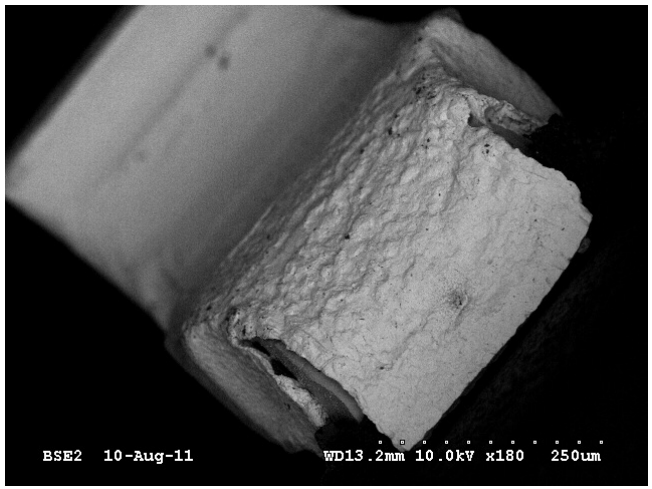


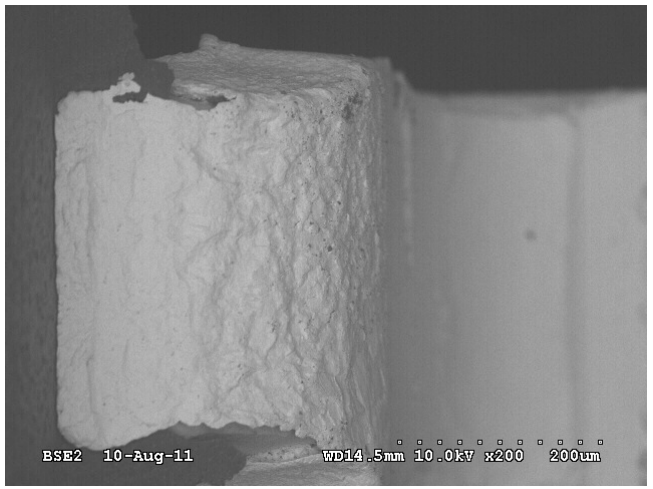


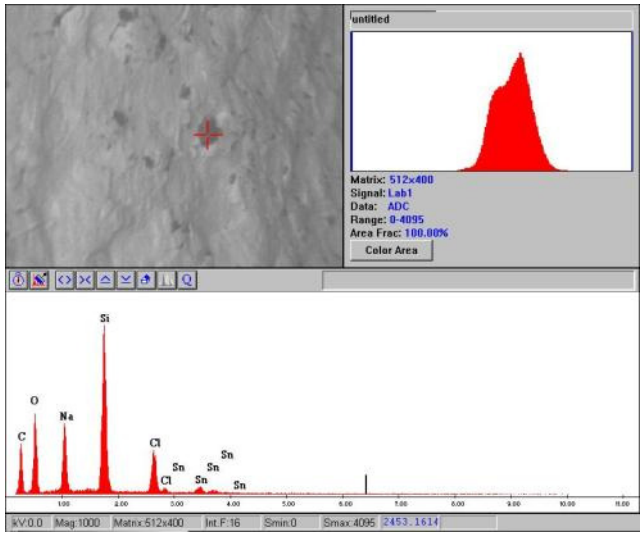


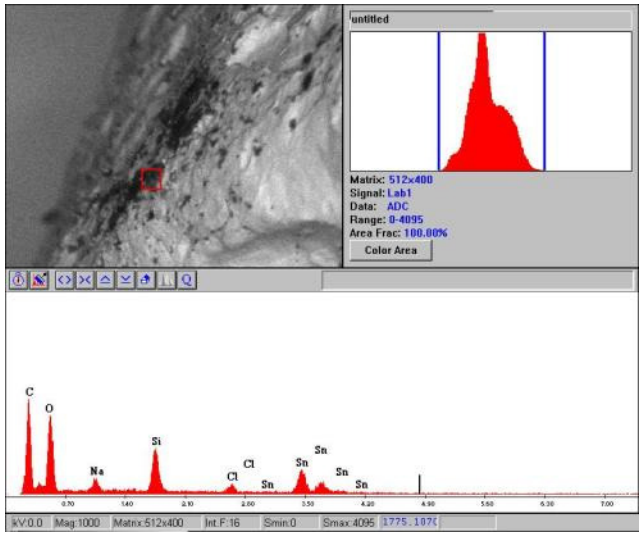
Components Pre-build Contamination: SOT23-5, Cl^- - 6.7µg/in^2

- Chloride containing contamination in surface roughness and gaps



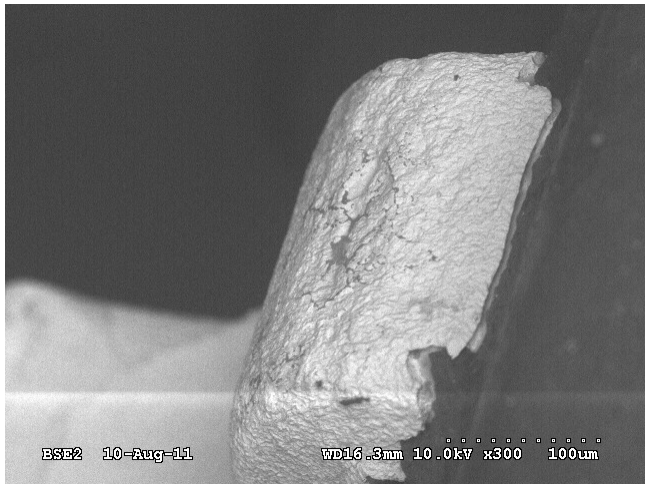


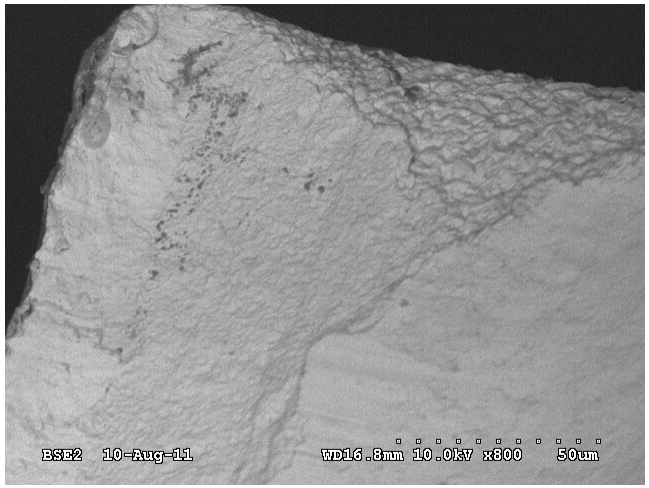


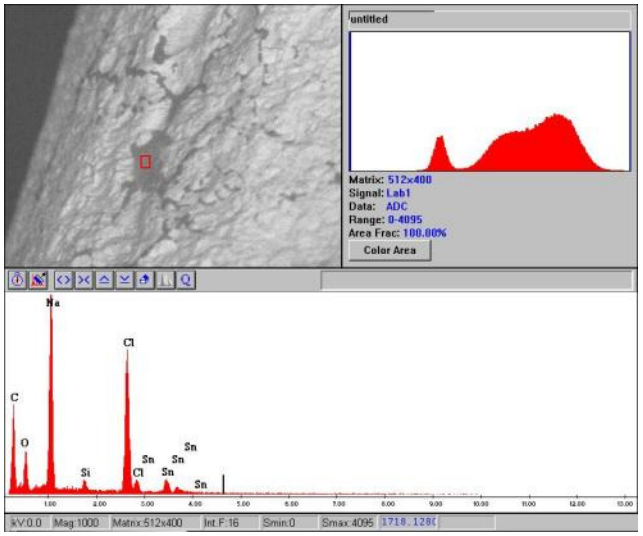


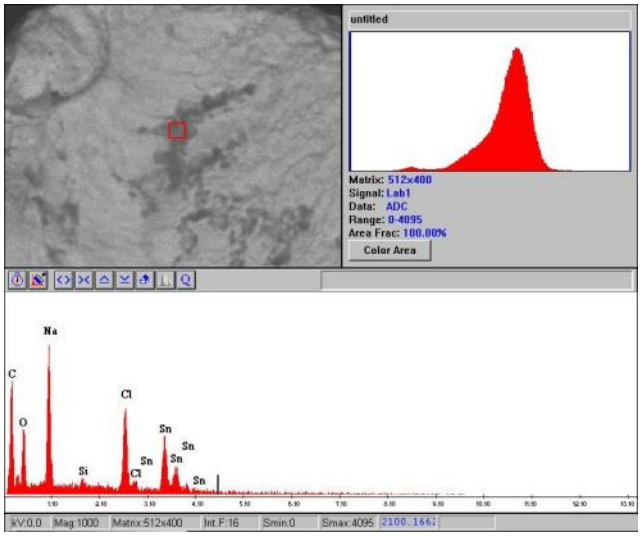
Components Pre-build Contamination: SOT363, Cl^- - 7.2µg/in²

- Chloride containing contamination are widely spread in surface roughness, grain boundaries and gaps









ASSEMBLY

Assembled Boards

- Cleaned and Contaminated components were assembled using SAC305 solder paste and washed after assembly
- Assembled boards were divided into two groups
  - The first group was left clean
    - Cleaned Components/Clean Boards – 0-0 no conformal coating
    - Contaminated Components/ Clean Boards – 1-0 no conformal coating
  - The second group was coated using UV40
    - Cleaned Components/Clean Boards – 0-0 with conformal coating
    - Contaminated Components/ Clean Boards – 1-0 with conformal coating

  - Each of four types of SOT boards was divided into two groups
    - The first group is left clean
    - The second group was contaminated with NaCl
      - $10\mu g/in^2$ intended
      - Cleaned Components/Contaminated Boards – 0-1
      - Contaminated Components/ Contaminated Boards – 1-1

- Eight types of SOT boards were recieved:
  - 0-0, 1-0, 0-1, 1-1 no conformal coating
  - 0-0, 1-0, 0-1, 1-1 with conformal coating

Assembled Boards: Post Assembly Contamination

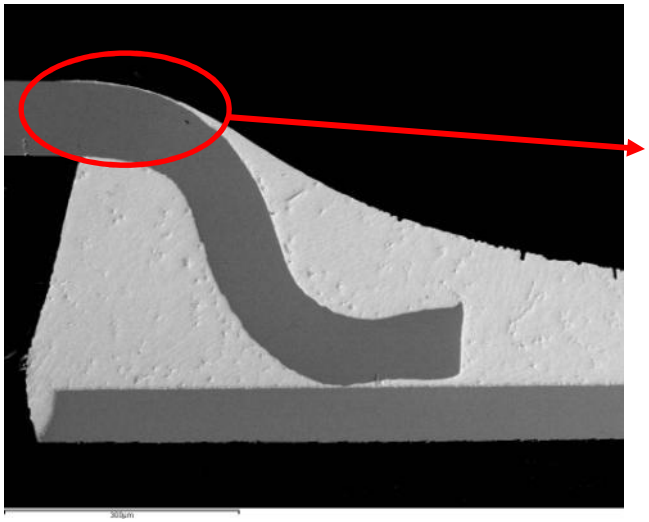
- Two solutions for post assembly contamination:
  - 250 +/- 10 ppm for
    - SOT boards with conformal coating
  - 160 +/- 10 ppm for
    - SOT boards no conformal coating
    - QFP boards without conformal coating
    - QFP boards with conformal coating

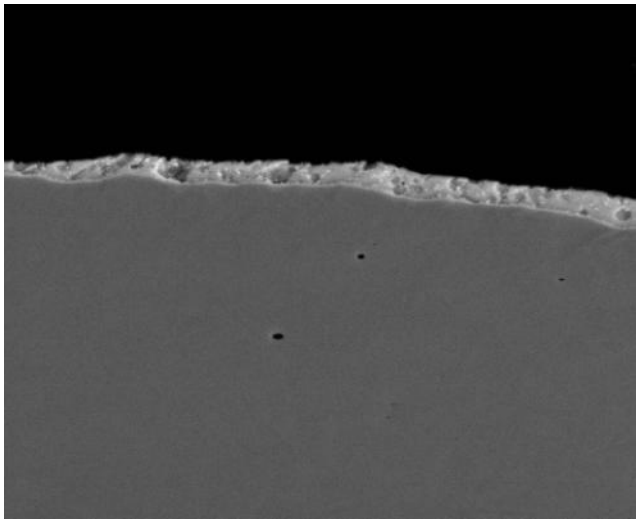
- Ion Chromatography results (IC)
- Chloride in ppm – about 5 ppm
- Chloride in µg/in^2 - 9.6 to 12.8 µg/in^2

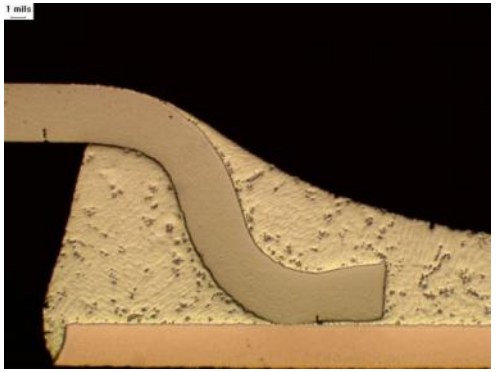
Sample ID	IC – Chloride, ppm	Chloride Conc. µg/in^2)
Board 237 - SOT - not coated	**5.2**	**12.5**
Board 217 – SOT - coated	**5.3**	**12.8**
Board 219 - SOT - coated	**4.0**	**9.6**

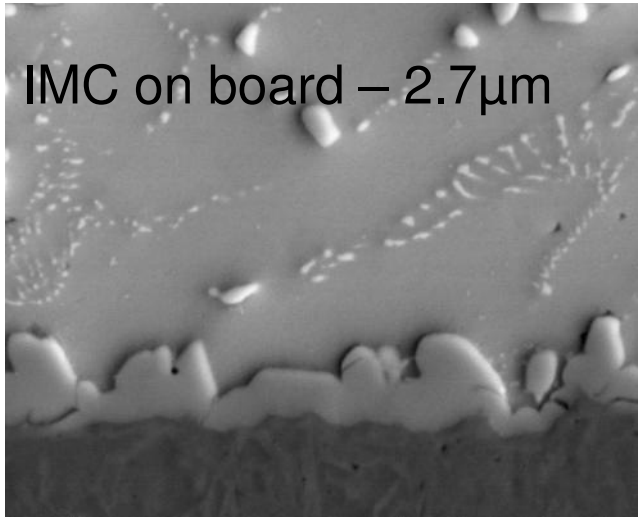
Solder Coverage:SOT23-3

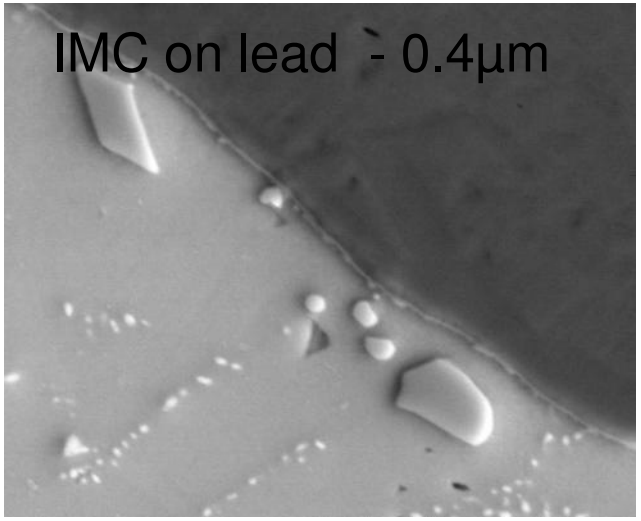
- SOT23-3 is fully covered with solder





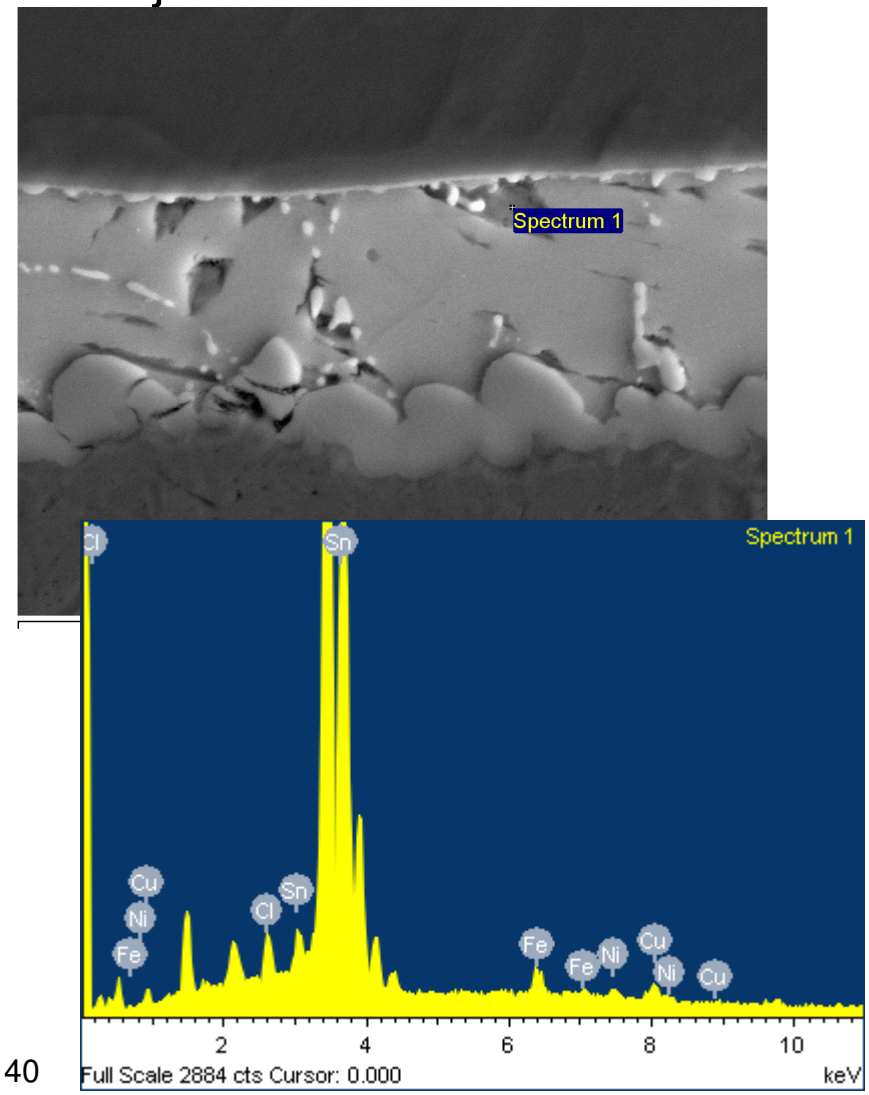






Solder Coverage: SOT23-3

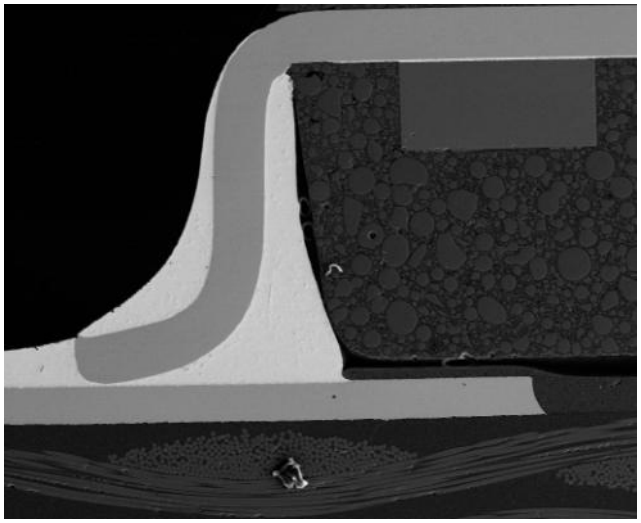
- Some Cl was found trapped at the thinnest part of the joint between the lead and Cu pad

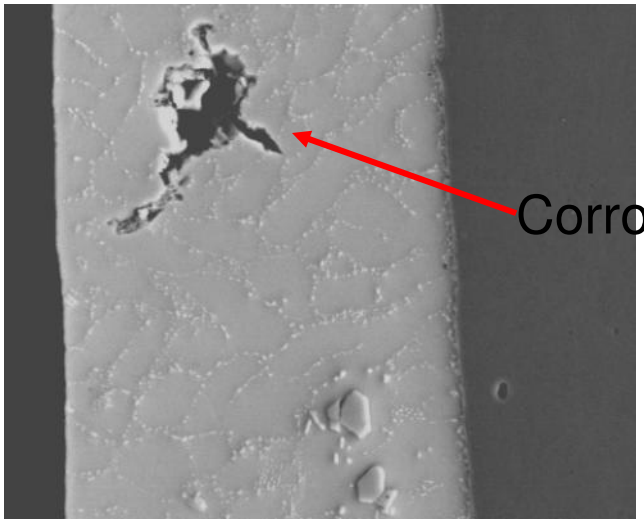


Element	Weight%	Atomic%
Cl K	1.21	3.78
Fe K	2.07	4.08
Ni K	0.95	1.78
Cu K	1.59	2.77
Sn L	94.18	87.59
Totals	100.00	

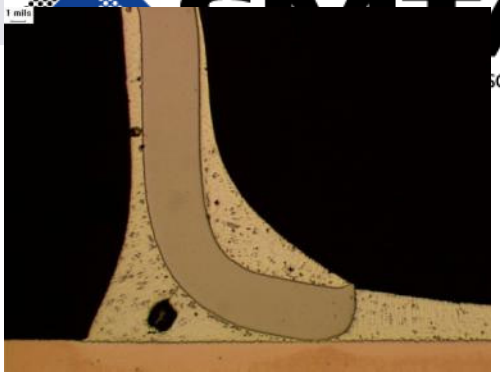
Solder Coverage: SOT363

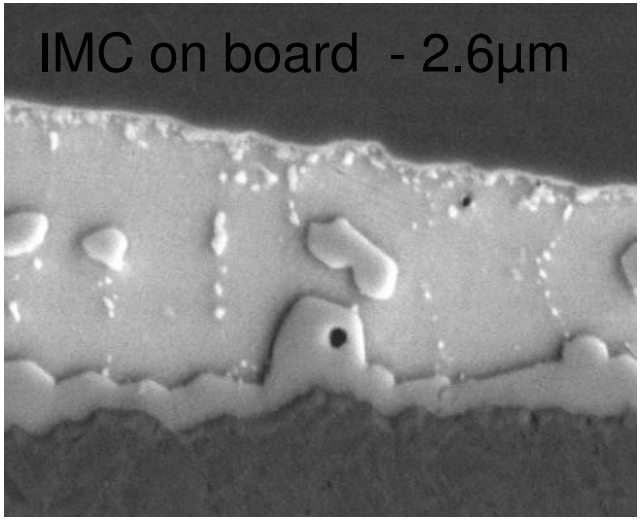
- SOT363 is fully covered with solder

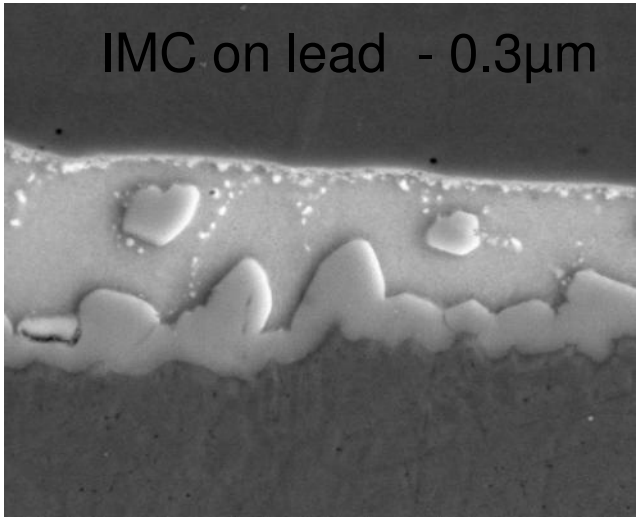




Corrosion ?







Solder Coverage: SOT23-5

- The top part of the leads of SOT23-5 is not covered with solder