Update of Global Trends in Lead-Free Soldering

Agilent Technologies, Inc.

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Purposes

To present global trends regarding lead-free soldering and technology.

Emphasis is placed on costs, regulations, definitions, designs, materials, processes, tests, inspections, and reliability of components, printed circuit boards (PCBs), tin whiskers, and solder joints.

Contents

New Exemptions Under Consideration by EU (Due early 2005)

(1) Lead used in compliant-pin VHDM (Very High Density Medium) connector systems.

(2) Lead as a coating material for a thermal conduction module c-ring.

(3) Lead and cadmium in optical and filter glass.

(4) Lead in optical transceivers for industrial applications.

(5) Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in proportion to the tin-lead content (proposed exemption until 2010).

(6) Lead in solders to complete a viable electrical connection internal to certain Integrated Circuit Packages ('Flip Chip') (proposed exemption until 2010).

(7) Lead in lead-bronze bearing shells and bushes.

EU RoHS
Maximum Concentration Values (MCV)

For the purposes of Article RoHS-5(1)(a): a maximum concentration value of 0.1% by weight in ‘homogeneous materials’ for lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) and of 0.01% weight in ‘homogeneous materials’ for cadmium shall be tolerated.

What does ‘Homogeneous material’ means?

Definitions and Interpretations of ‘Homogeneous Materials’

(1) ‘Homogeneous material” means a material that cannot be mechanically disjointed into different materials.

(2) The term ‘homogeneous’ is understood as “of uniform composition throughout”, some examples of “homogeneous materials” would be individual types of plastics, ceramics, glass, metals, alloys, paper, board, resins, and coatings.

(3) The term “mechanically disjointed” means that the materials can be, in principle, separated by mechanical actions such as unscrewing, cutting, crushing, grinding, and abrasive processes.

(4) Using these interpretations, a plastic cover (for example) would be a ‘homogeneous material’ if it consisted exclusively of one type of plastic that was not coated with or had attached to it (or inside it) any other kinds of materials. In this case, the MCV of the RoHS Directive would apply to the plastic.

(5) On the other hand, an electric cable that consisted of metal wires surrounded by non-metallic insulation materials would be an example of something that is not ‘homogenous material’ because mechanical processes could separate the different materials. In this case the MCV of the RoHS Directive would apply to each of the separated materials individually.

(6) A semi-conductor package (as a final example) would contain many homogenous materials, which include the plastic molding material, the tin-electroplating coatings on the lead frame, the lead frame alloy and the gold-bonding wires.

How to Test or Measure a Product and Determine It is a Lead-Free Product?

One of the most promising equipments is the energy dispersive x-ray fluorescence (EDXRF) spectrometers:

Hand-held (for screening test)

Desktop (for verification test)

It is a matter of convenience (hand-held) against detailed measurement resolution (desktop).

Various factors such as shape, thickness, and matrix of target item affect the measure values.

International Efforts on Testing of Lead-Free Products

Standardization of the sample preparation needs to be discussed and agreed on.

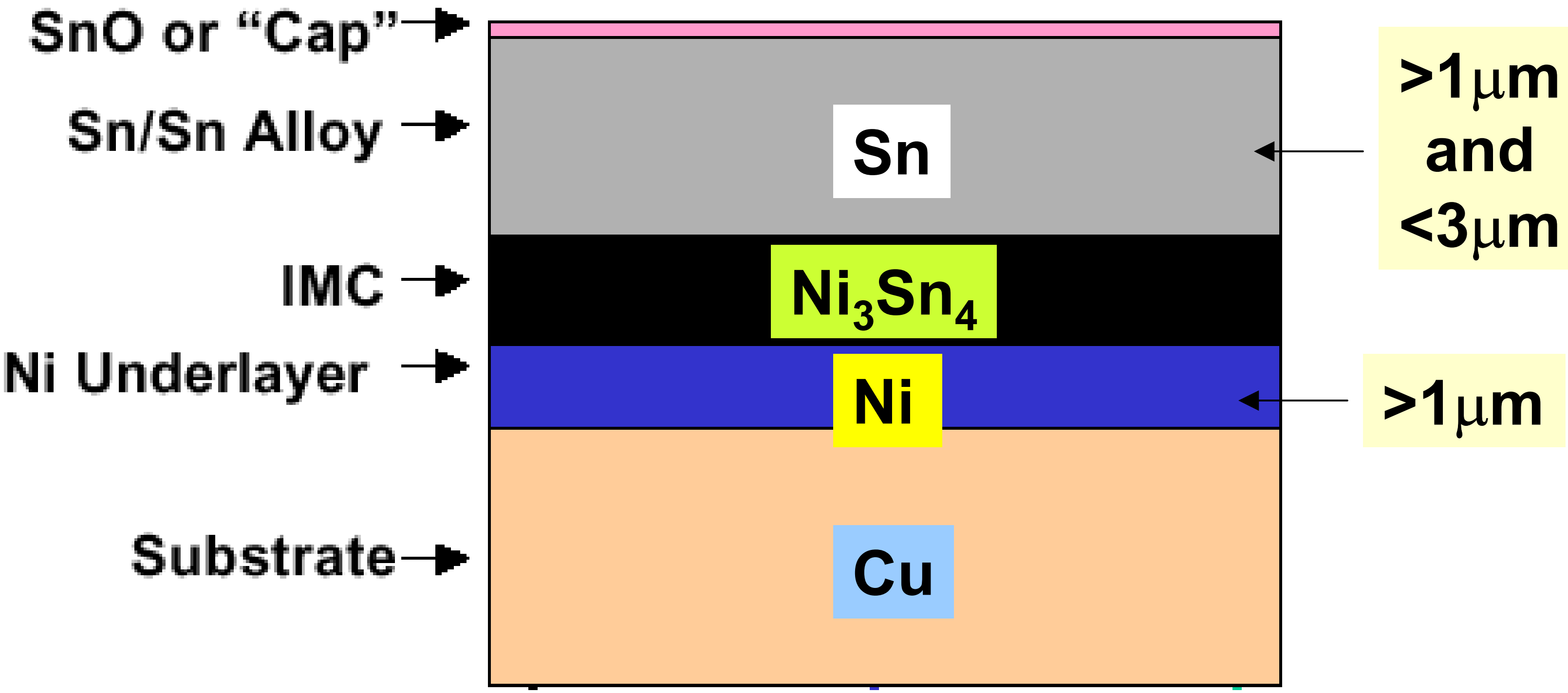
Currently, IEC (International Electrotechnical Commission) ACEA (Advisory Committee Environmental Aspects) ad hoc Working Group is working very hard in this area and published (July 2004) their very first report stating their mission, goal, scope, test procedure, and schedule.

Schedule

• Outline document	June 30, 2004
• Working Draft (WD)	Nov. 16, 2004
• Commenting period	
• Committee Draft (CD)	March 31, 2005
• Commenting period	
• Committee Draft for Voting	Dec. 31, 2005

RoHS July 1, 2006

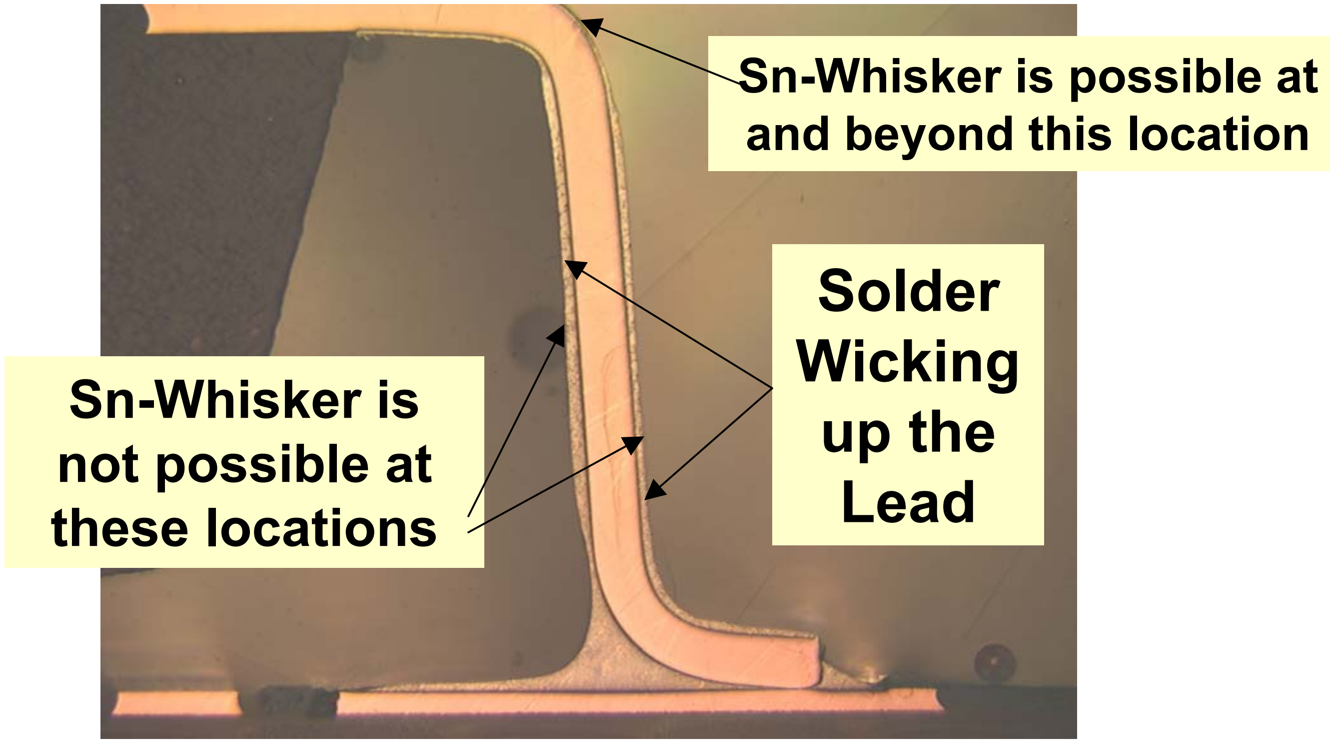
Sn-Whisker for Very High-Rel Components



On leaded components, the Ni underlayer should be >1µm and the Sn plating layer should be >1µm (for solderability purpose) and <3µm. Why 3µm? The stress measurements for different thickness of Sn plating found that the Sn layer right above the Ni_3Sn_4 inter-metallic compound (IMC) is in tension. But this tensile stress is reducing as the Sn layer is further away from the IMC. For Sn plating thickness >3µm, compressive stresses are observed at the extreme Sn layer.

Solder Wicking and Sn Whisker

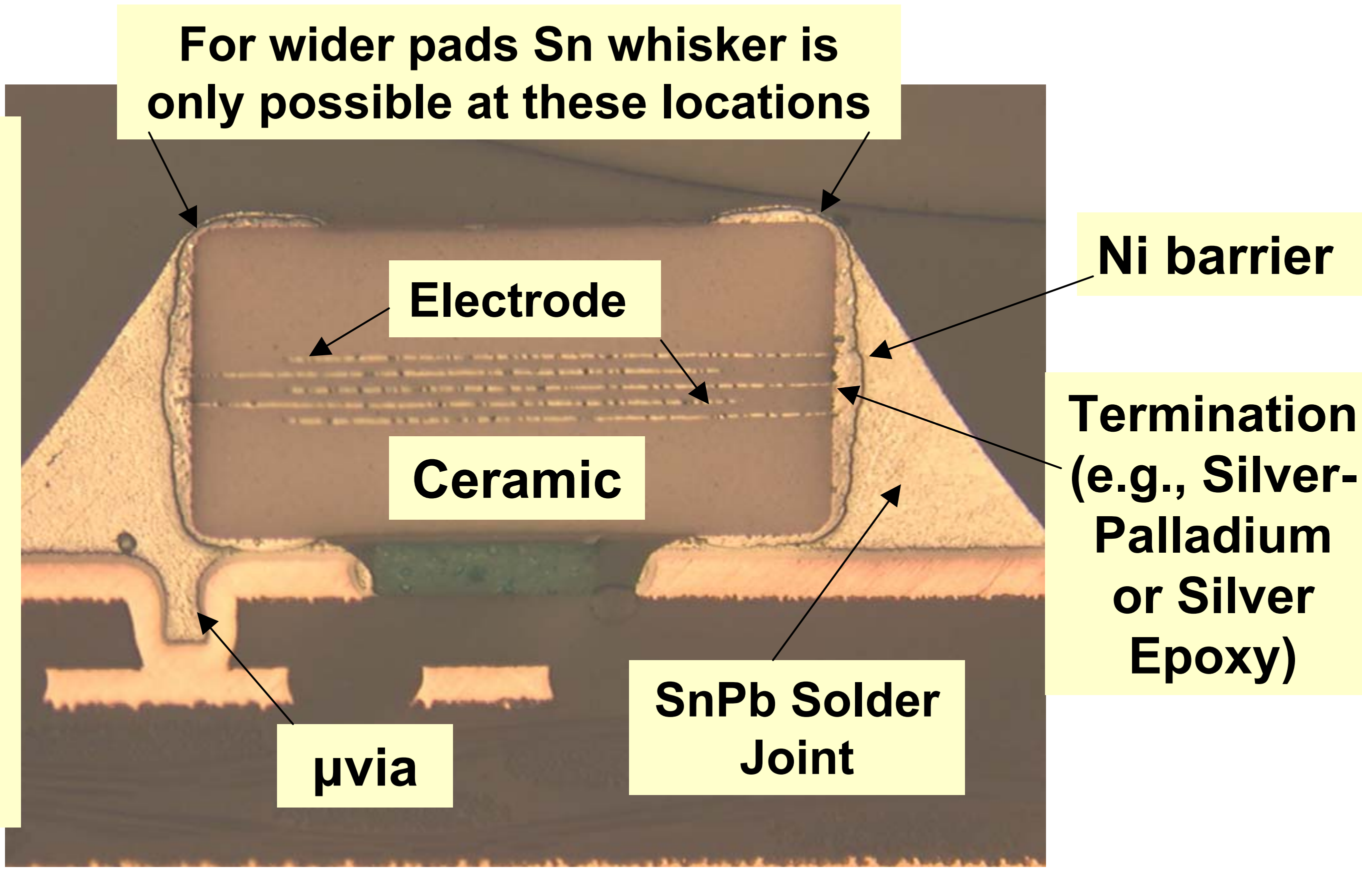
208-Pin PQFP with Matte Sn-plated Leads



During reflow the molten solder wicking up the lead. This is because the lead's temperature is higher than that on the board and its smaller curvature. The plated Sn on the lead will be dissolved in the wick-up molten solder. (The dissolution rate of Sn > 90µm/s at 220^{o}C)

0201 Chip Capacitor with Pure Sn and Ni Under-layer Barrier (SnPb Reflow Process)

A Ni barrier is usually applied over the Pd-Ag or Ag-epoxy terminations to prevent silver leaching, and a final Sn coating is applied over the Ni to preserve its solderability.



During reflow the pure-Sn will be dissolved in the molten solder. (The dissolution rate of Sn > 90μm/s at 220°C)

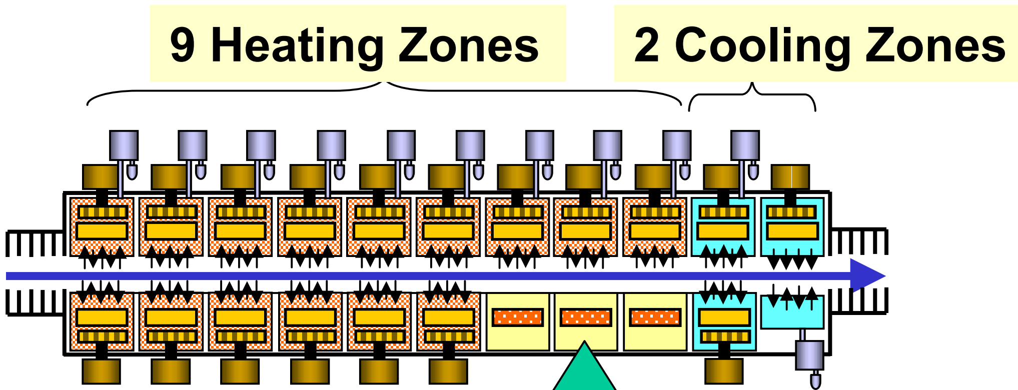
Lead-Free PCB Requirements

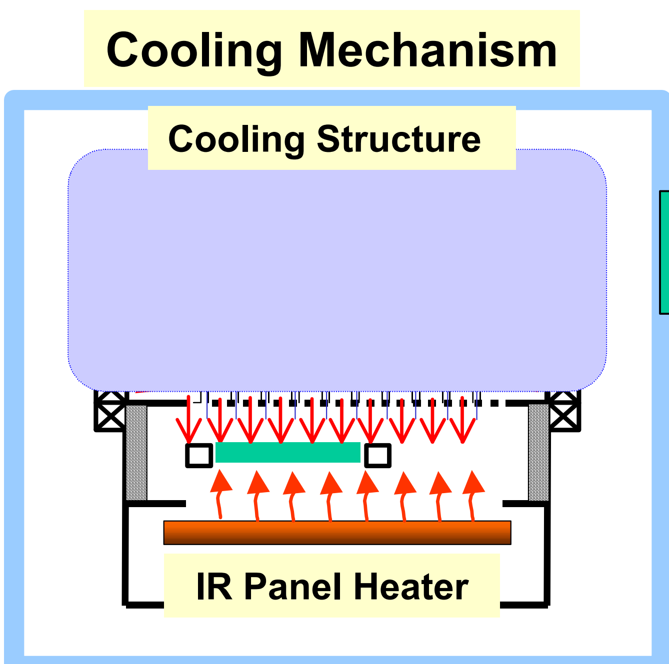
(1) Temperature of decomposition,
(2) Time to delamination,
(3) Stiffness,
(4) Glass transition temperatures,
(5) Young's module,
(6) Peel strength,
(7) Solder-mask adhesion strength,
(8) Thermal stability,
(9) Moisture absorption,
(10) x-, y-, z-axis thermal expansion,
(11) Warpage,
(12) Ionic contamination

PCB Surface Finishes Recommended by NEMI on March 2004

Surface Finish	Recommend	Risky	Not Acceptable	No Vote
ImAg	6	2	0	1
ImSn	5	3	0	1
OSP (Entek)	5	2	1	1
ENIG	4	2	2	1
HASL-SnCu	2	4	0	3

Oki/Furukawa's Lead-Free Component Temperature Control Reflow Technology

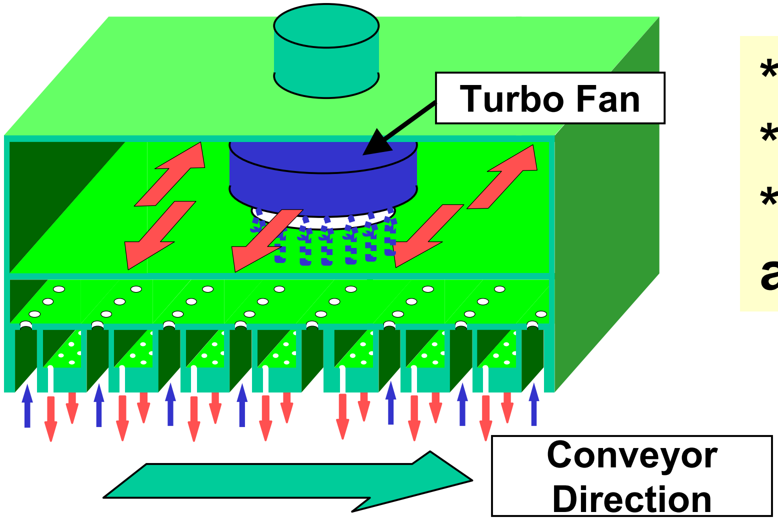




Convection/IR Dual Heating System + Cooling Construction

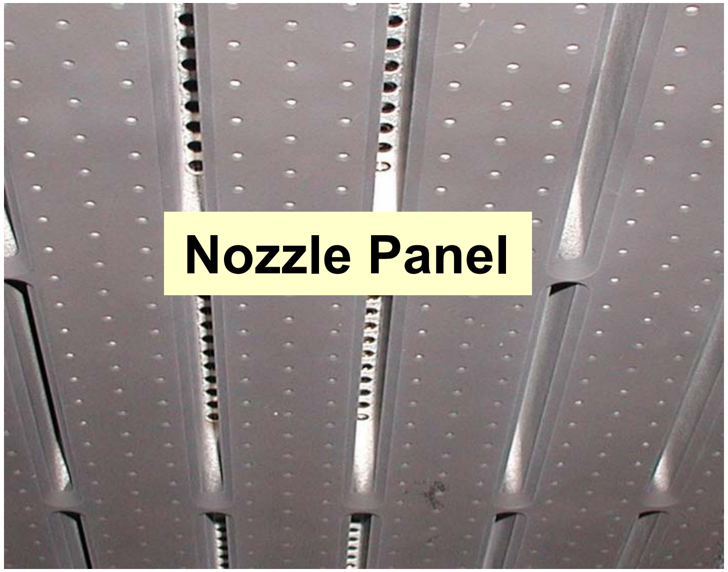
By adding a cooling mechanism to the convection heating area, the thermal effects of IR (infrared radiation) heating can be controlled, making large temperature differential setting possible.

Oki/Furukawa's Reflow Technology



*Isolated Zone Circulation
*Smooth Jet Steam
*Optimization of Nozzle Diameter and Blower Distance

1. Elimination of colliding currents and poor heat transfer turbulence layer.
2. Eliminates horizontal airflow to prevent component displacement.
3. Improved nozzle formation/convection mechanism resulting in high pressure, high density, even convection current.



Lead-Free Solder Joint Inspections

For Visual Inspections, the IPC-610 is being updated to include lead-free solder joints. It is scheduled to be published by the end of 2004.

For X-ray Inspections of lead-free solder joints, the existing x-ray machines should be able to do the job by re-adjusting the threshold values.

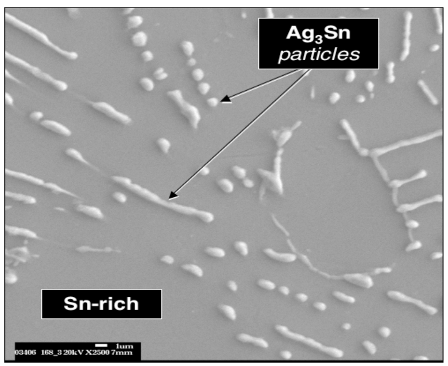
Non-Destructive Lead-Free Solder-Joint Inspections (Visual Inspection)

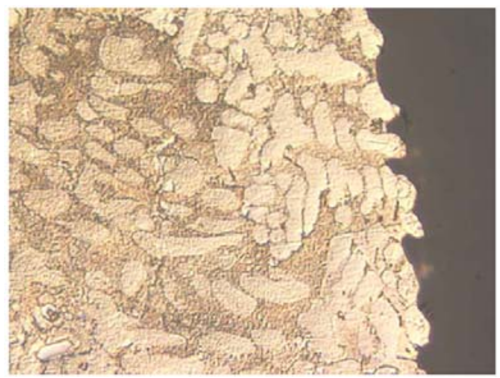
- Simple
- Low Cost
- Limitations of Human Eyes:

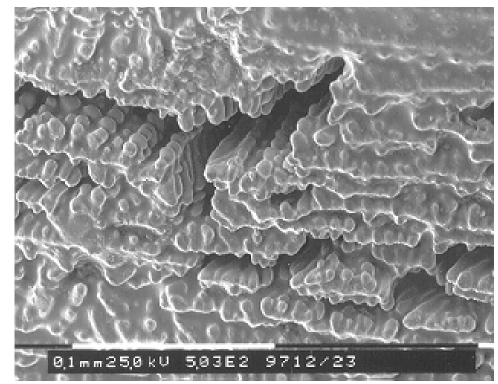
  Visual inspection can only observe the surface portions of the solder joints explored in front of our eyes. The solder joints underneath the dies, package substrate, PCBs, etc., can only be observed through x-ray inspections.

Non-Destructive
Lead-Free Solder-Joint Inspections

The wetting of SnAgCu alloys is not as good as that of the SbPb solder alloys:



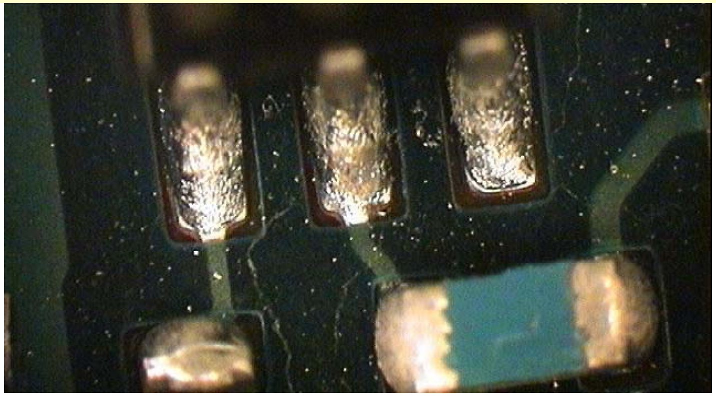




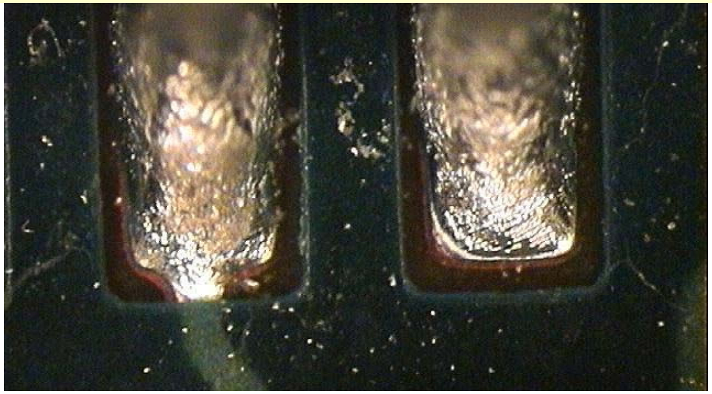
The wetting angels are somewhat different between these two kinds of solder joints

The lead-free solder joints are not as shining as the SnPb solder joints

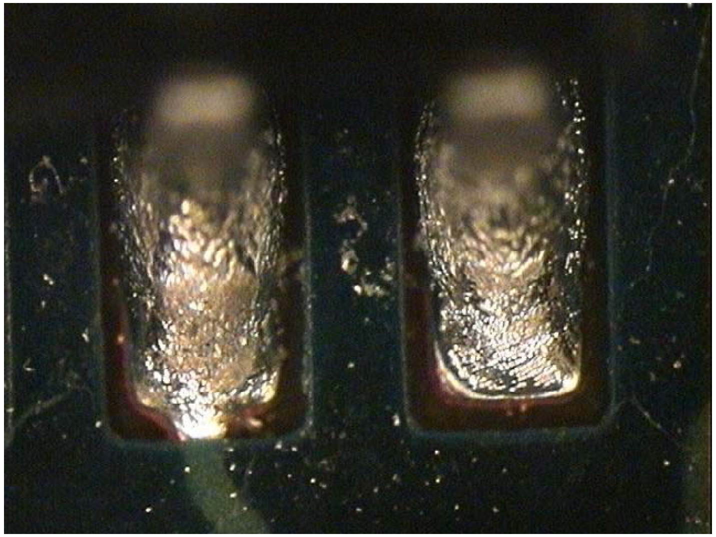
95.5Sn3.8Ag0.7Cu (Type 3, 89.3%)



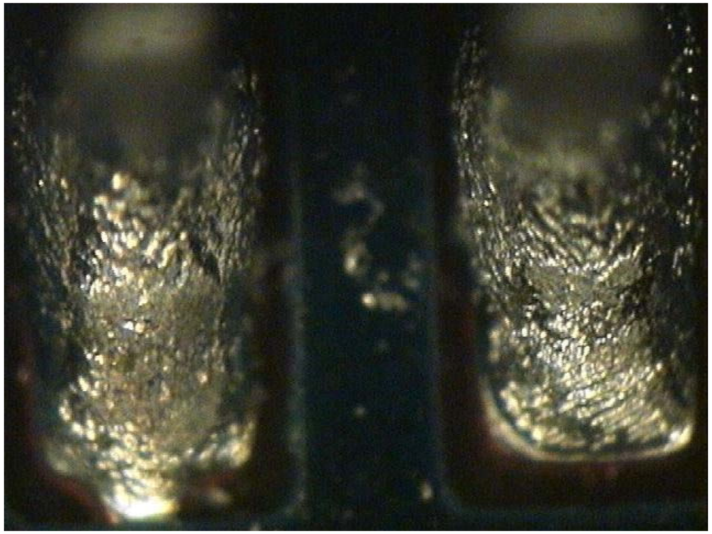
100x



200x



200x



300x

Lead-Free solder joints typically exhibit a rough, grainy, and rugged appearance. This is mainly attributed to the high Sn contents, which tend to develop dendrites easily.

Non-Destructive Lead-Free Solder-Joint Inspections (X-Ray Inspection)

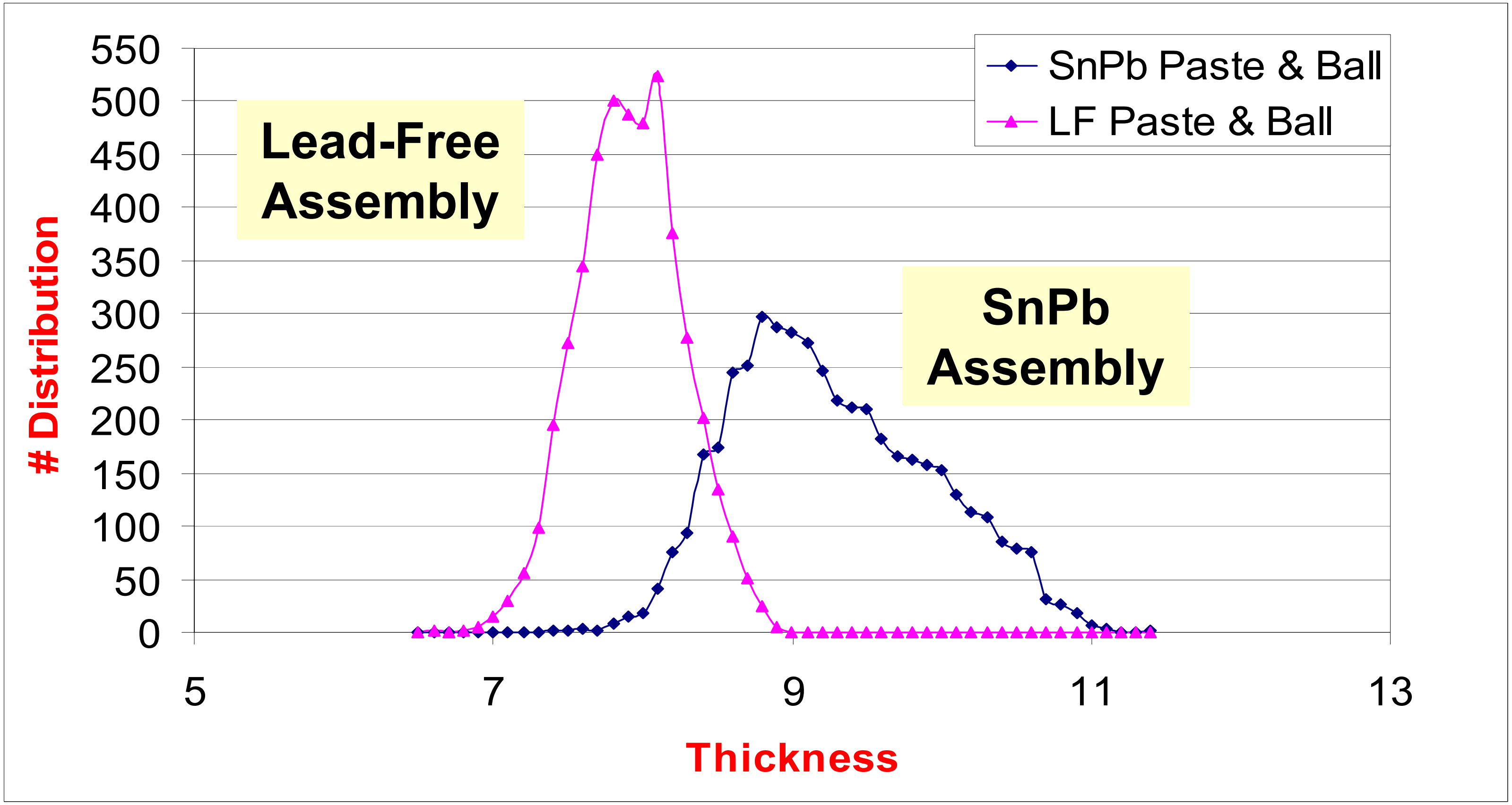
In general, the x-ray addressable defects are: (1) opens, (2) shorts, (3) voids, (4) misalignments, (5) insufficient solders, and (6) excess solders.

Since there is no lead in the lead-free (mostly tin) solder joints, the reflections of the x-ray from the lead-free solder joints are different from the tin-lead solder joints.

One of the frequently asked questions is: can we use the existing machine to do x-ray inspections of lead-free solder joints and what do we have to change to make it works?

Thickness Measurement (Ball Slice)

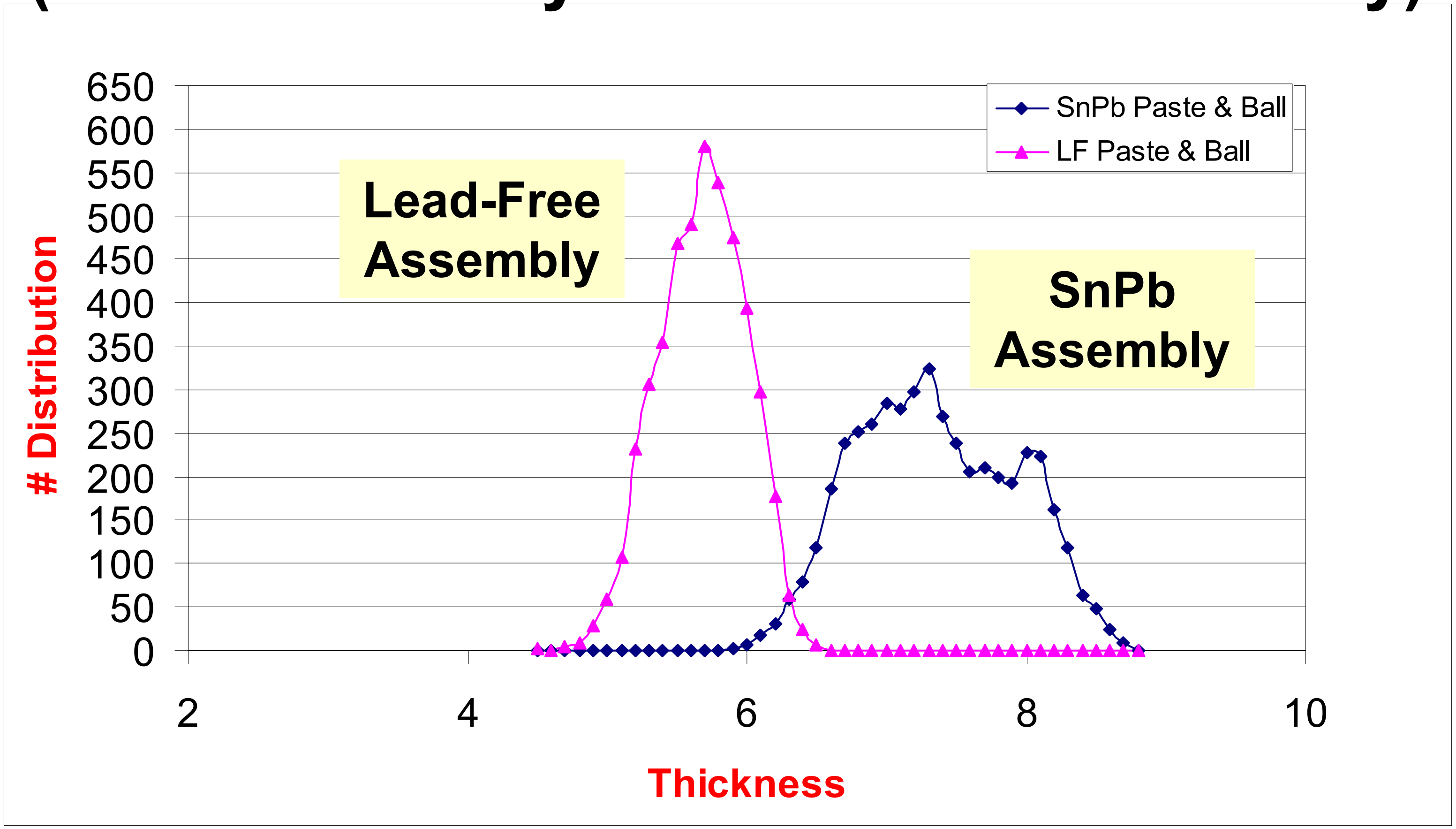
(SnPb Assembly vs. Lead-Free Assembly)



SnPb Assembly = SnPb Solder Ball & SnPb Solder Paste
Lead-Free Assembly = SnAgCu Solder Ball & SnAgCu Solder Paste

Thickness Measurement (Pad Slice)

(SnPb Assembly vs. Lead-Free Assembly)



SnPb Assembly = SnPb Solder Ball & SnPb Solder Paste
Lead-Free Assembly = SnAgCu Solder Ball & SnAgCu Solder Paste

Lead-Free Solder Reliability

(1) Are lead-free solder joints reliable for certain components, with certain Ag-alloy contents, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

(2) What are the failure mechanisms, failure modes, acceleration models, and acceleration factors of lead-free solder joints for certain components, with certain Ag-alloy contents, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

(3) Are lead-free solder joints more or less reliable than tin-lead solder joints for certain components, with certain Ag-alloy contents, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

(4) Are the failure mechanisms, failure modes, acceleration models, and acceleration factors of lead-free solder joints the same as tin-lead solder joints for certain components, with certain Ag-alloy contents, on certain substrates or PCBs, under certain operating conditions, and for certain periods of time?

Lead-Free Solder Joint Reliability

Due to the immaturity of SnAgCu lead-free solder joints, the industry does not have enough data to answer these equations right now.

More lead-free reliability data are needed and field data must be collected, especially for high-reliability and long life-cycle products.

Thus, the reliability of lead-free solder joints is currently under scrutiny.

Material Properties of SnAgCu

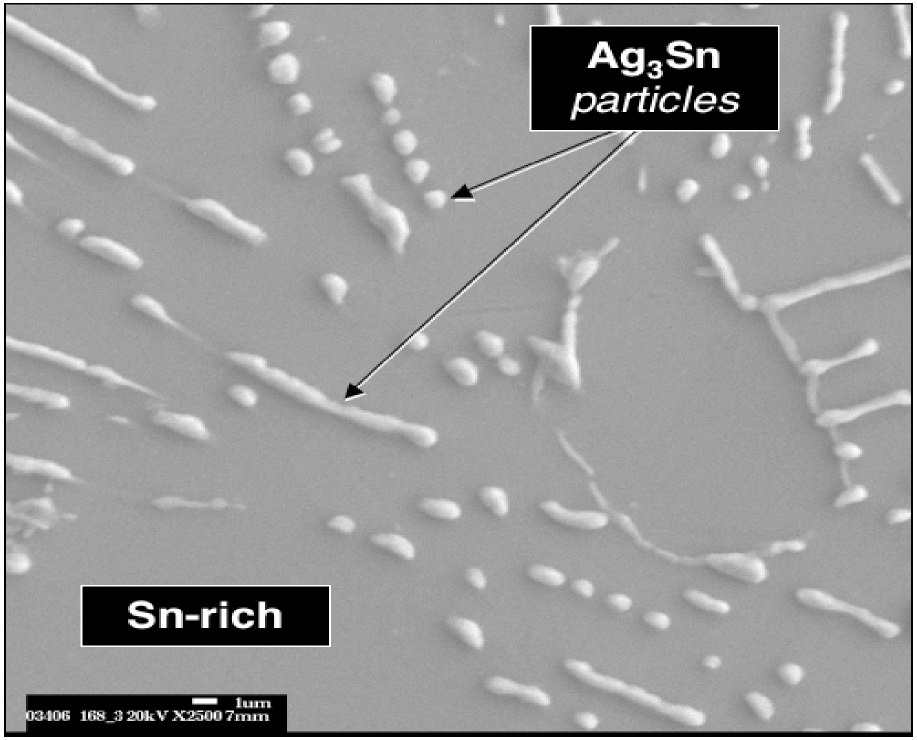
(1) Young's Mosulus

(2) Coefficient of Thermal Expansion

(3) Creep Deformations

(4) Fatigue Crack Growth Equation

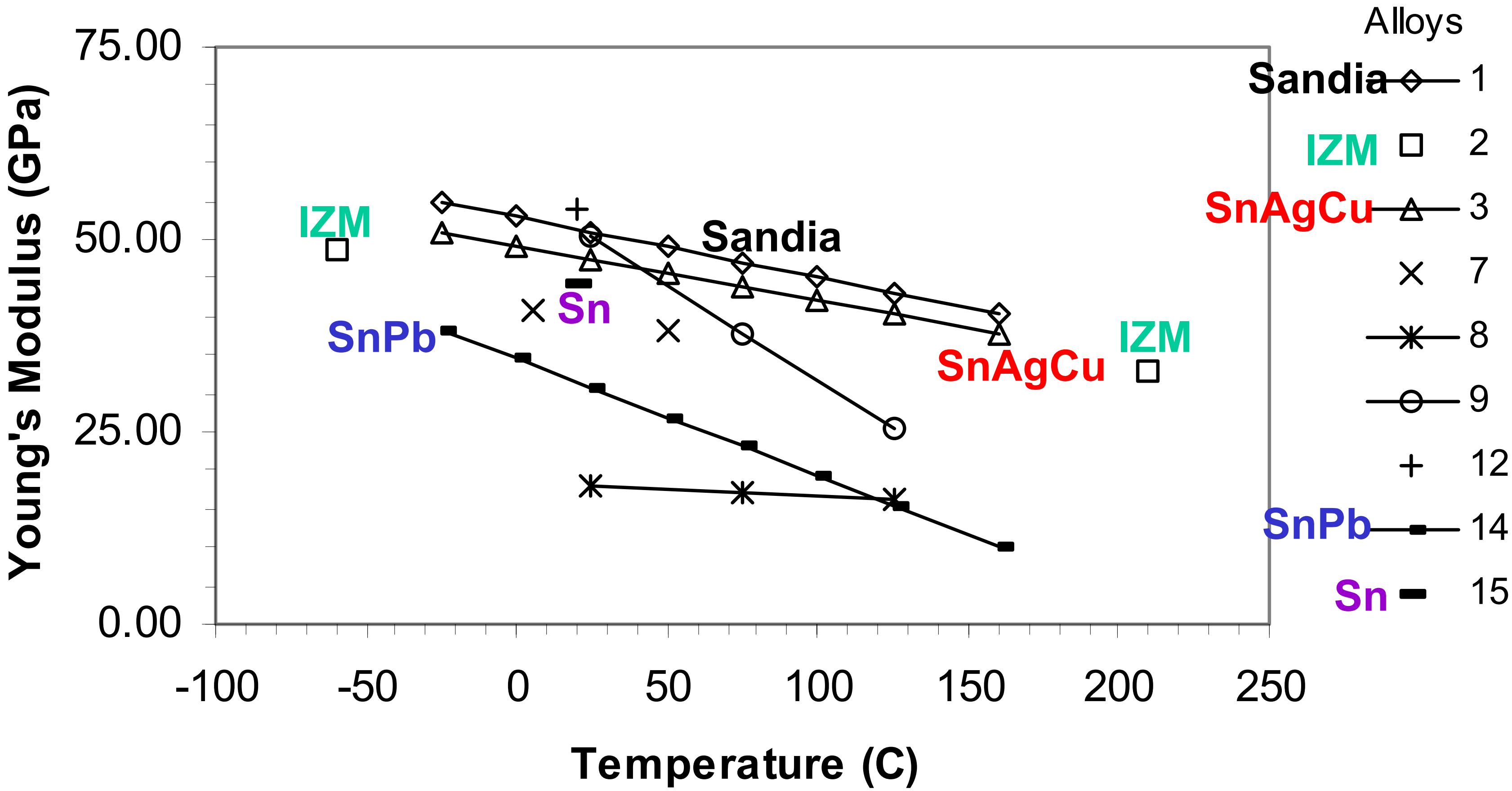
Microstructure of SnAgCu



Scanning electron micrograph illustrating the Ag_3Sn particle morphology within the inter-Sn-rich phase regions.

Young's Modulus of SnAgCu vs. SnPb

(The Young's modulus of SnAgCu is larger than that of SnPb, thus the stresses in lead-free solder joints are larger than those in tin-lead solder joints.)



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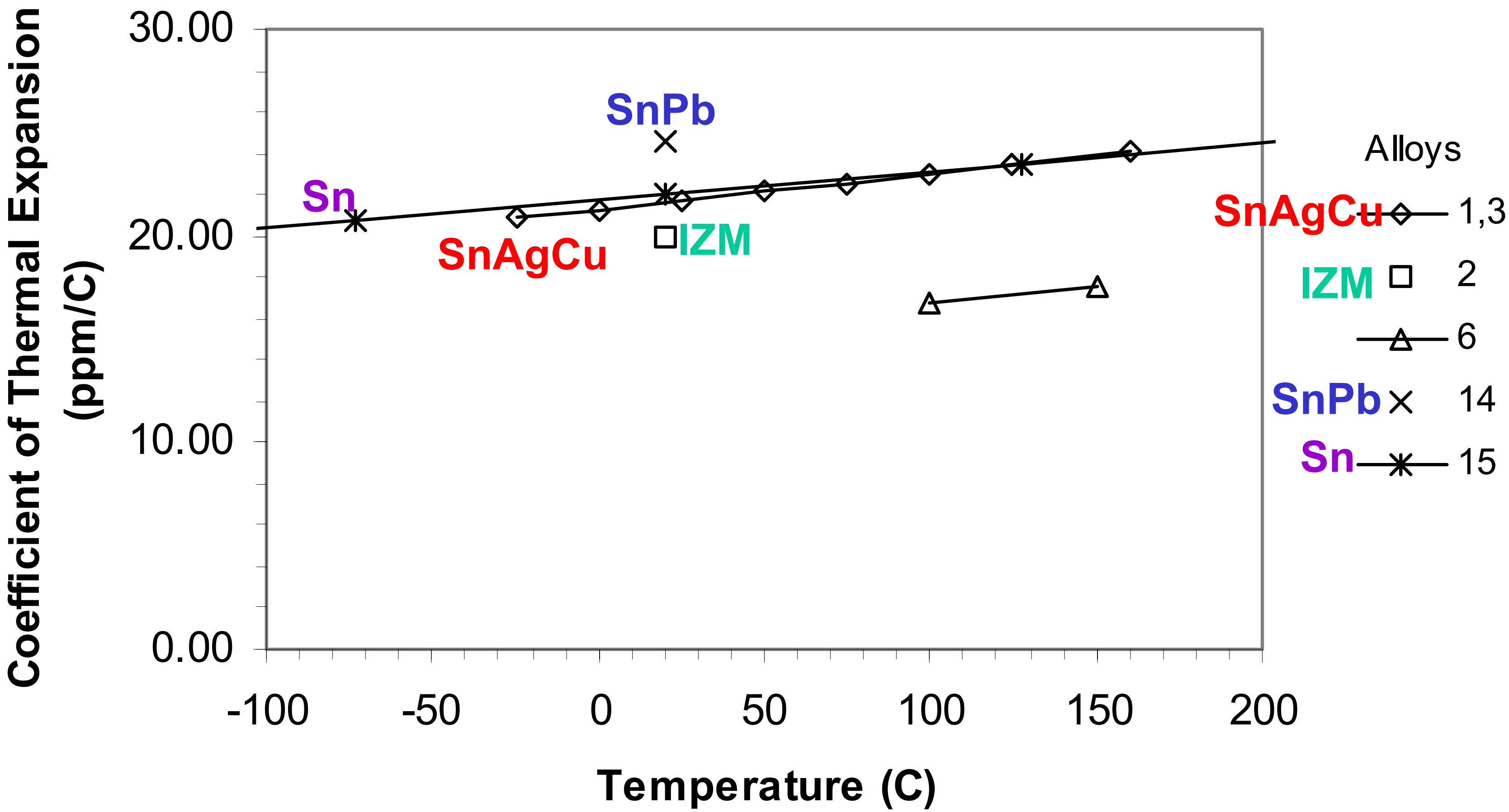
Coefficient of Thermal Expansion of Lead-Free Solders



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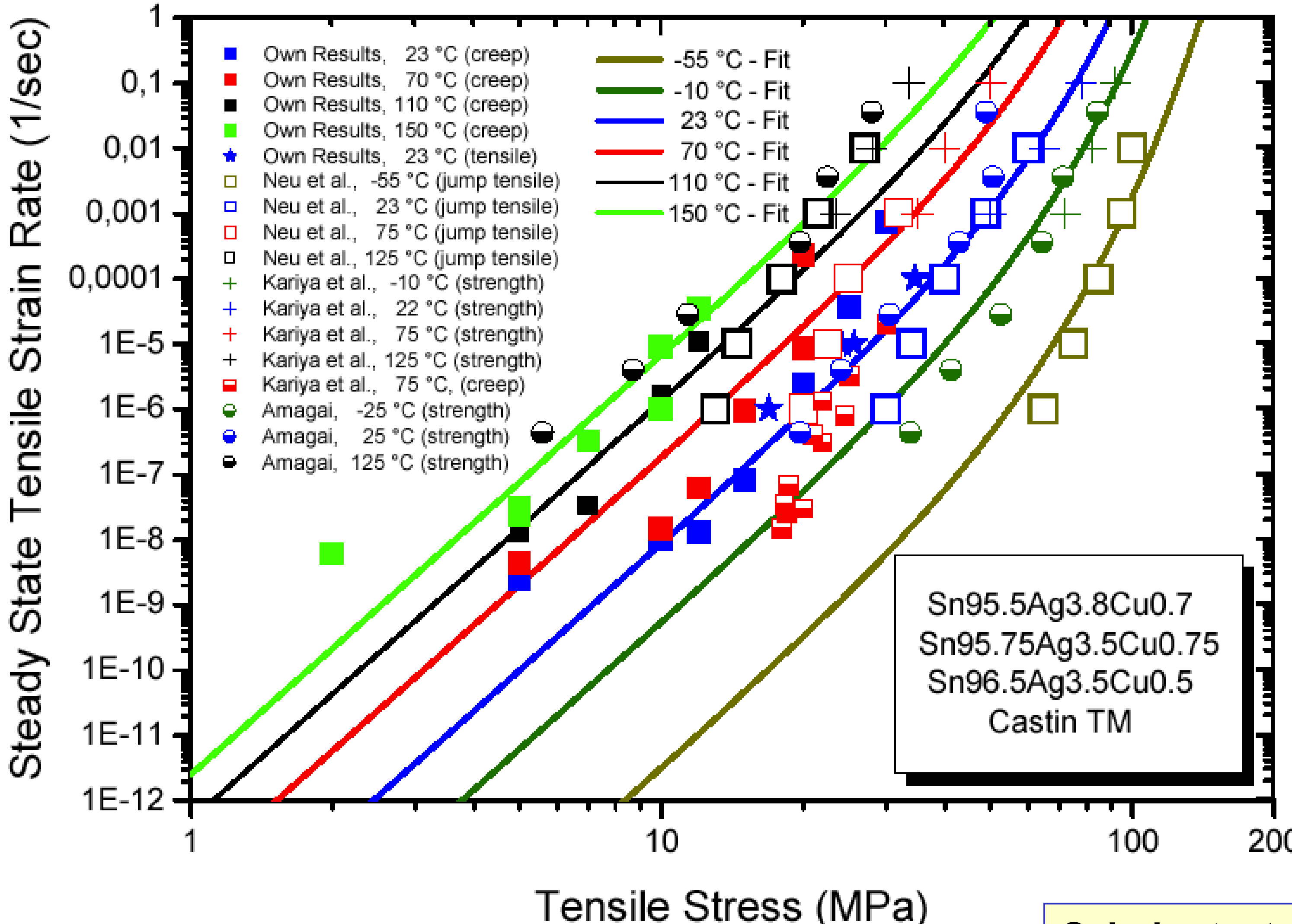
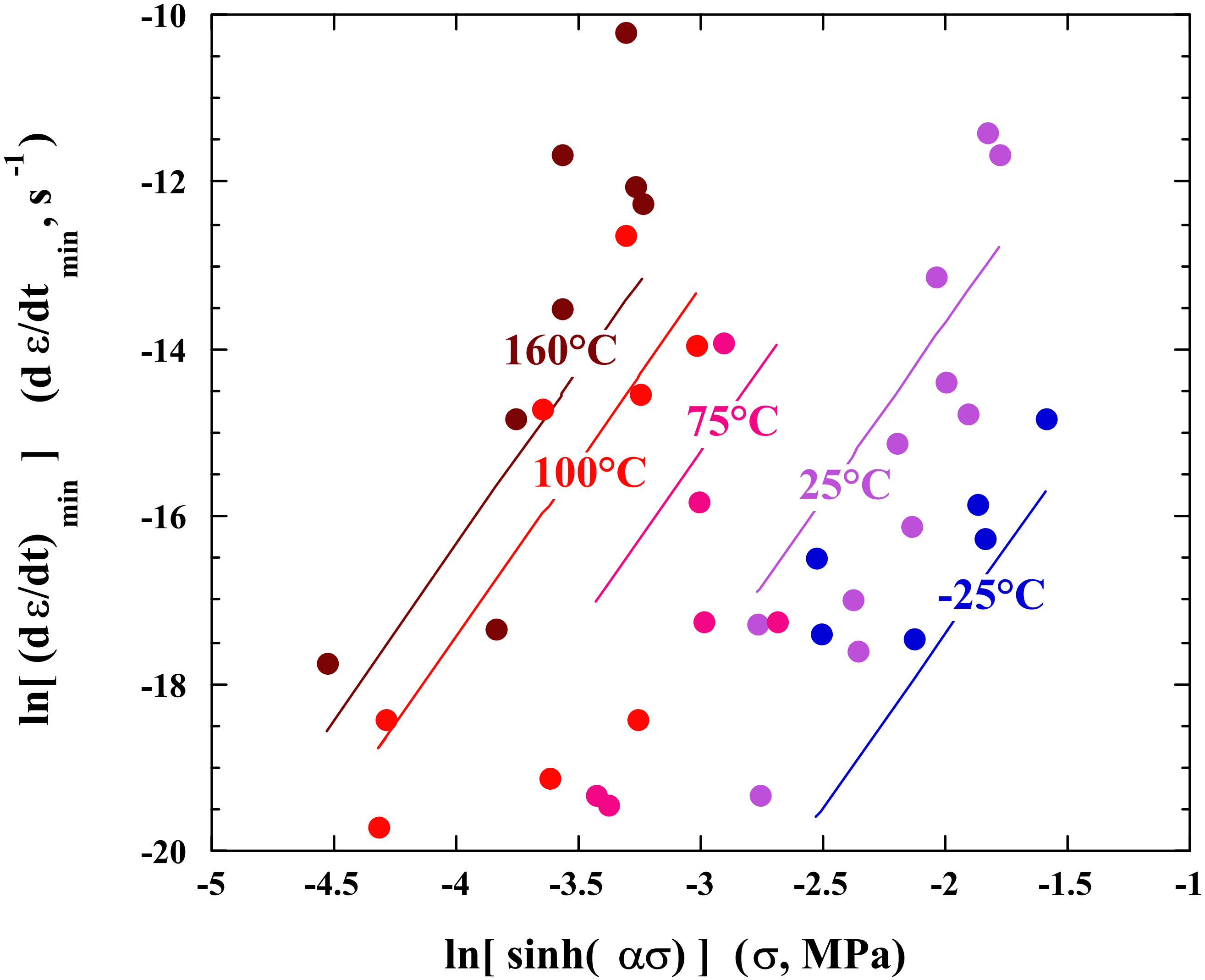
Creep of SnAgCu Solders Based on 108 Data Points (IZM)



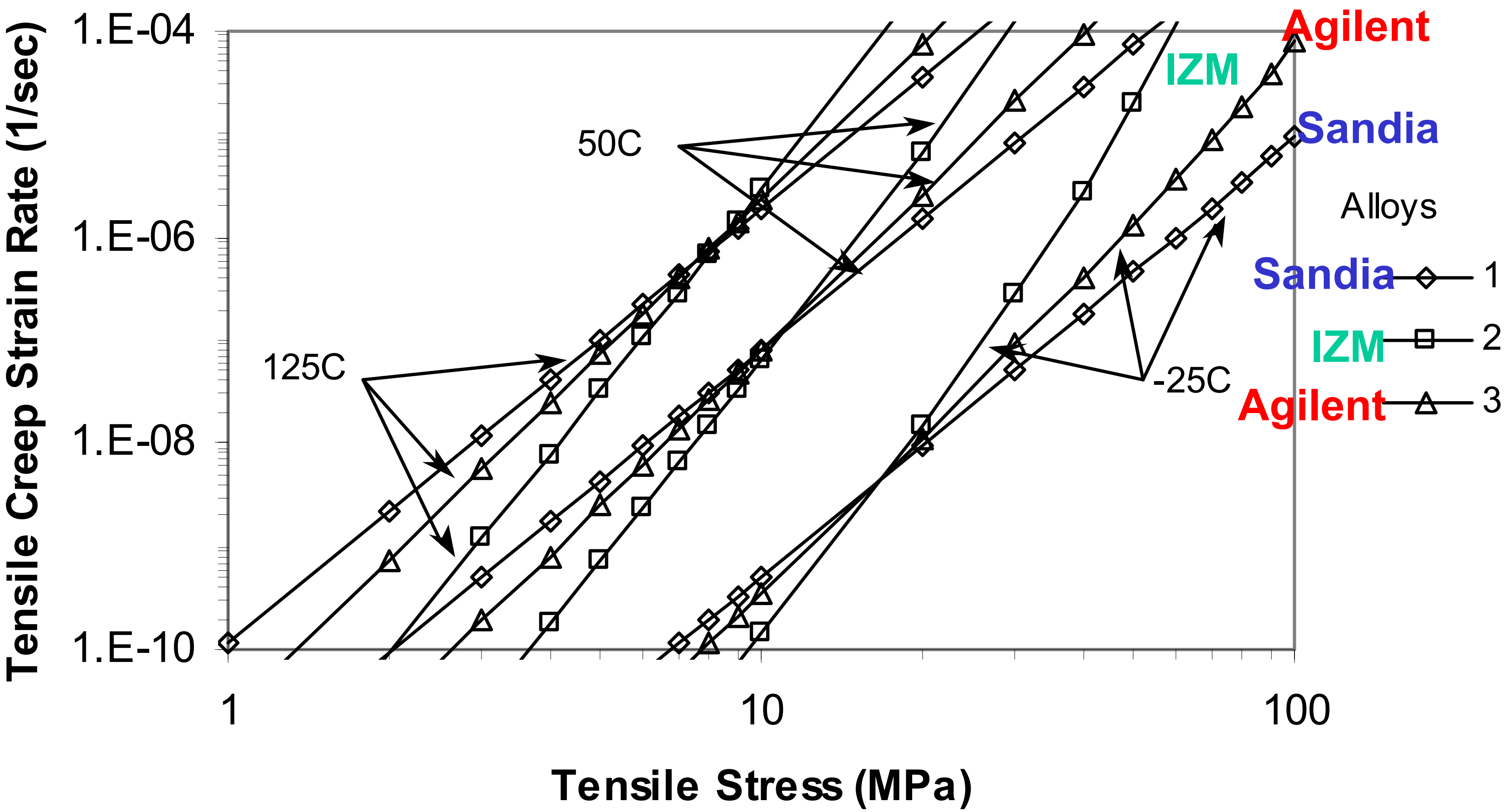
Schubert, et.al., IZM

95.5Sn-3.9Ag-0.6Cu Creep Test Data



Sandia

Lau, Dauksher, and Vianco, "Acceleration Models, Constitutive Equations, and Reliability of Lead-Free Solders And Joints", *IEEE Electronic Components and Technology Conference*, June 2003, pp. 229-234.



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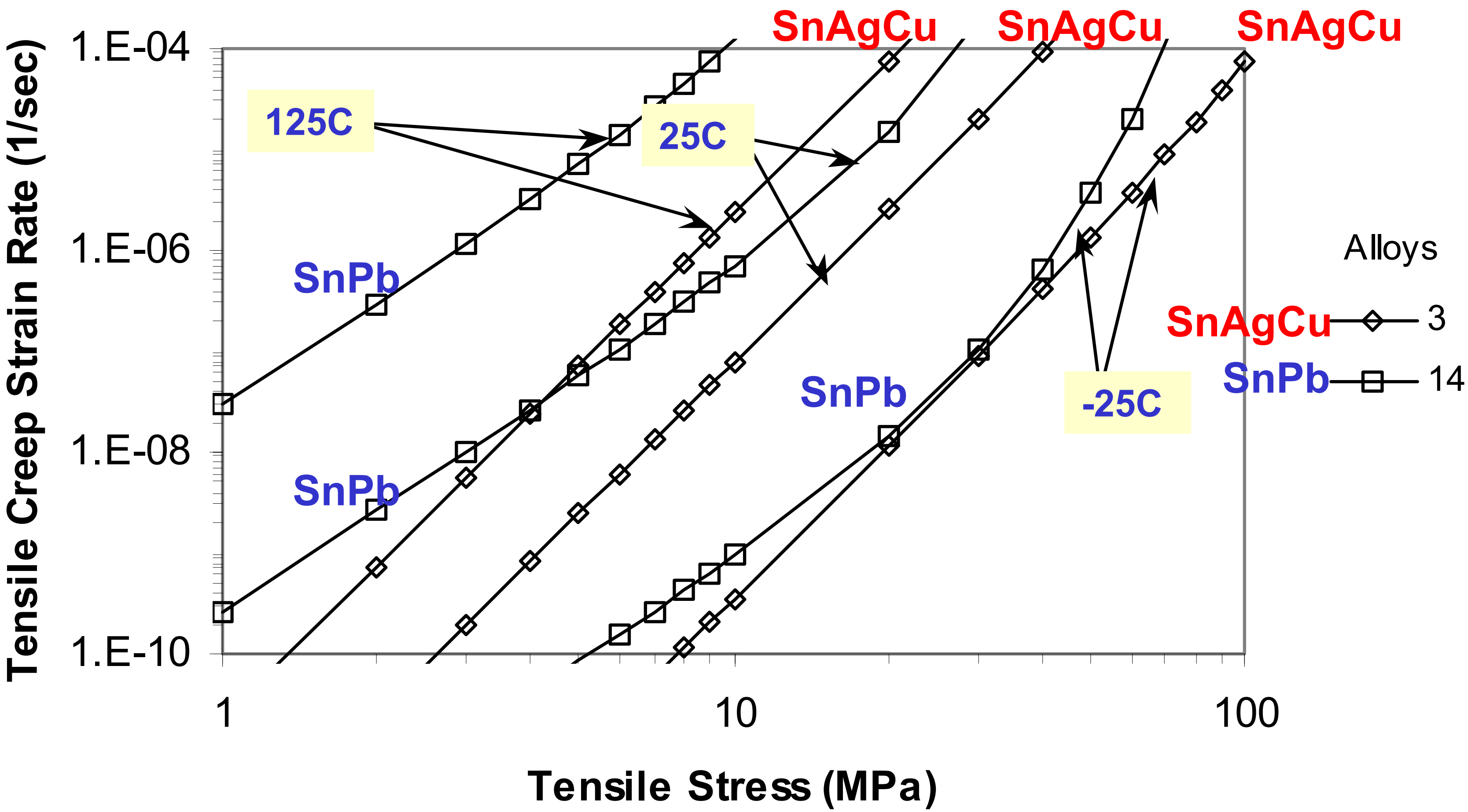
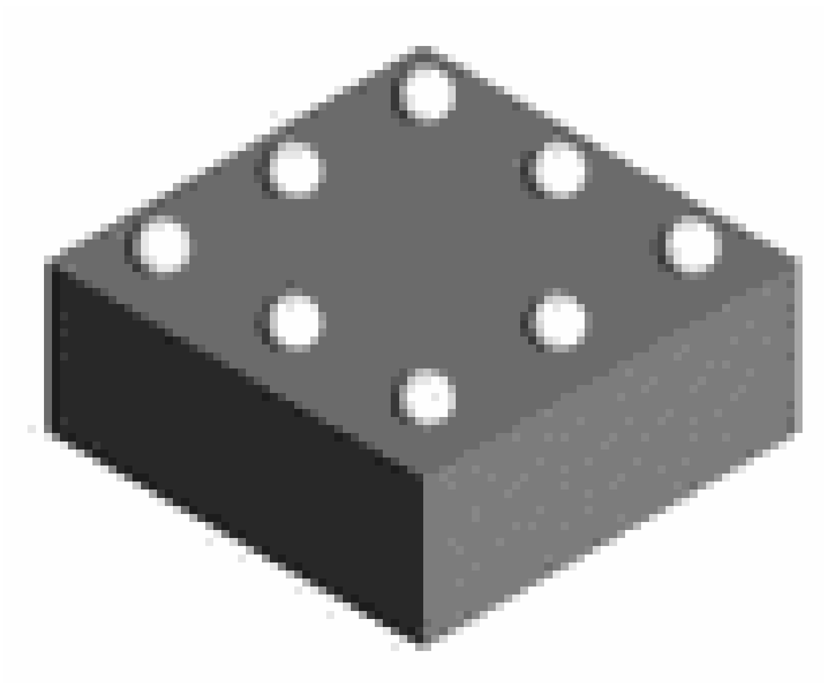
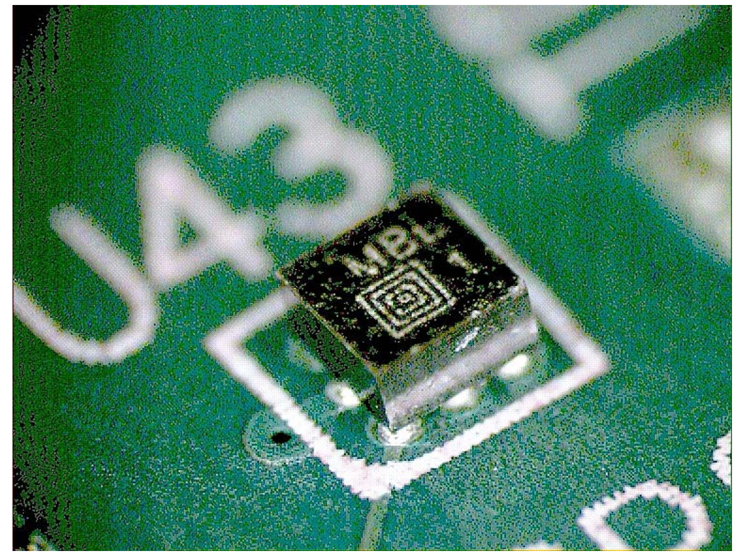
Sn(3.5-3.9)Ag(.5-.8)Cu vs. Sn37Pb

(The creep rate of SnPb is faster than that of SnAgCu, thus the creep deformations in the SnPb solder joints should be larger than those in the SnAgCu solder joints.)



WLCSP with Lead-Free Solder Bumps

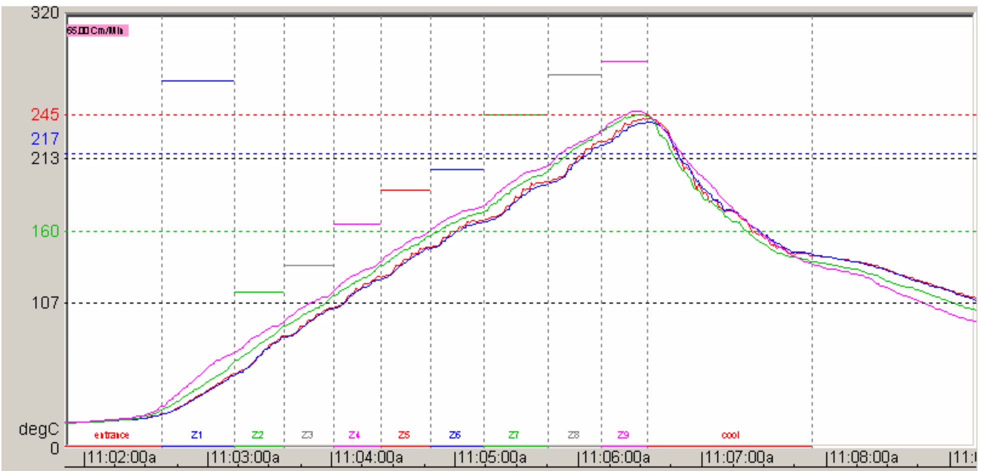


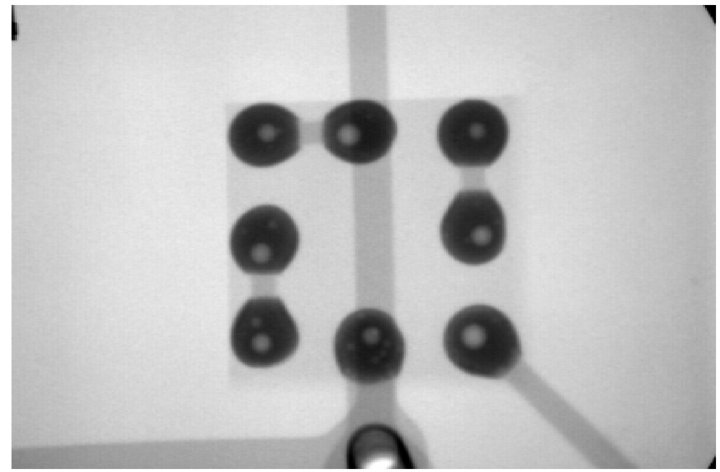


*1.29 x 1.29 x 0.85mm WLCSP
*8 bumps at 0.5mm pitch
*Bump diameter is 0.17mm
*Solder alloys are Sn4Ag0.5Cu

*PCB is 1.6mm thick
*FR-4 fiber-glass laminate
*Cu pads are 30~44μm thick
*Cu pads are 0.3mm in diameter
*Cu pads are NSMD (0.45mm)
*EN(4.5~5.6μm)IG(~0.08μm)

Lead-Free Reflow Temperature of WLCSP

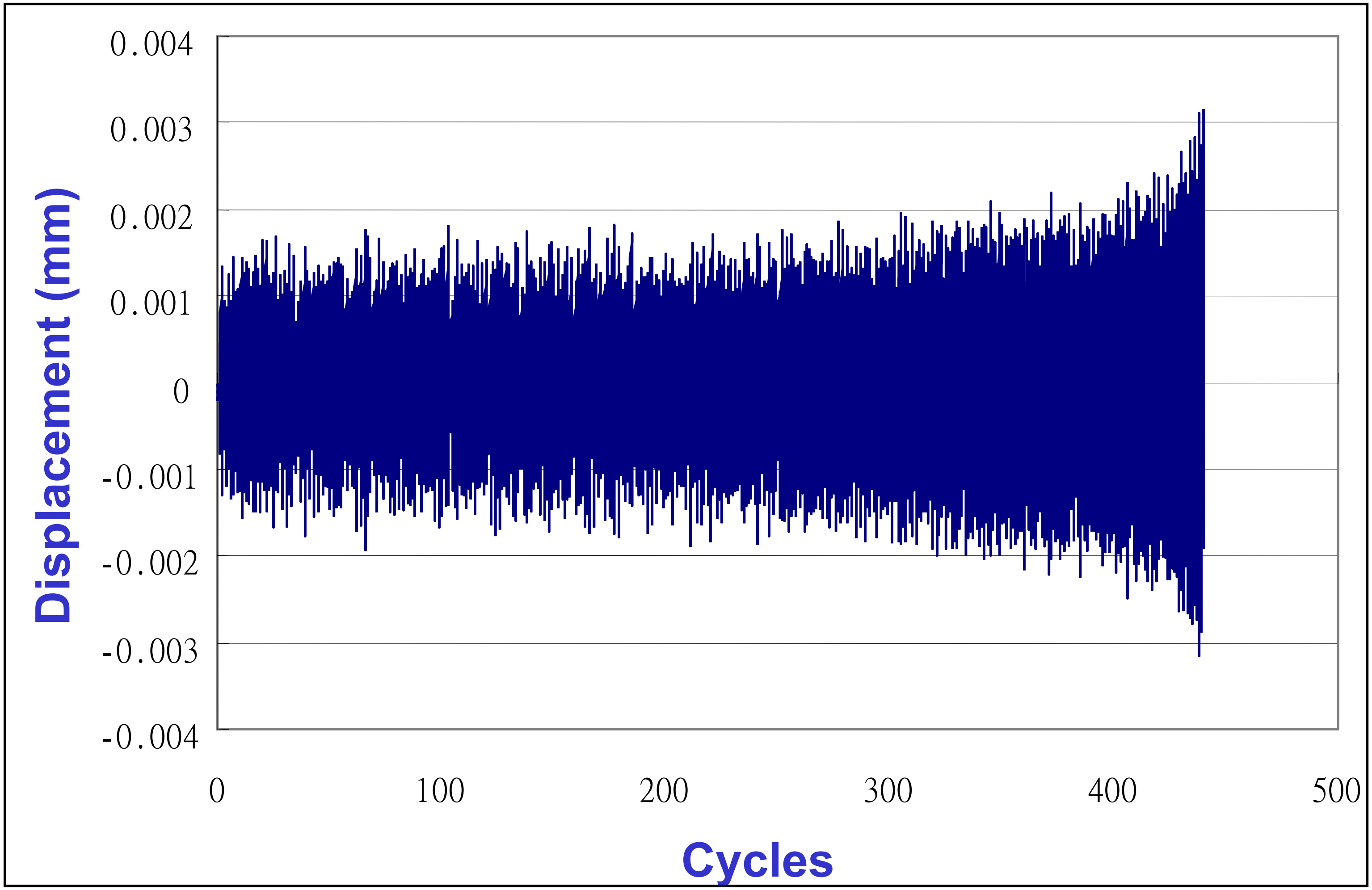




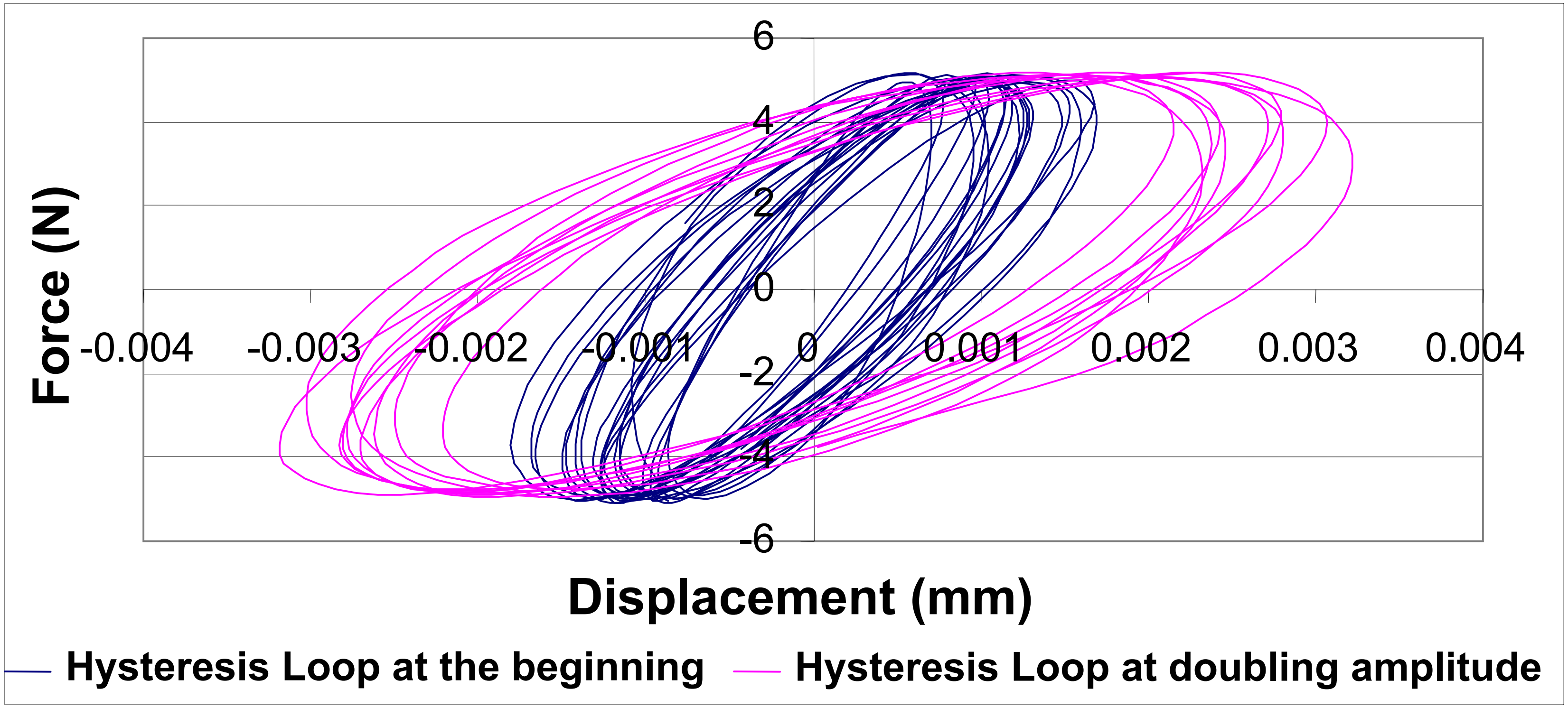
Peak Temperature = 245°C
Solder Paste = Sn3.9Ag0.6Cu

X-Ray Image showing Voids

Displacement-Increase Curve



Force-Displacement Hysteresis Loops for Sample G1



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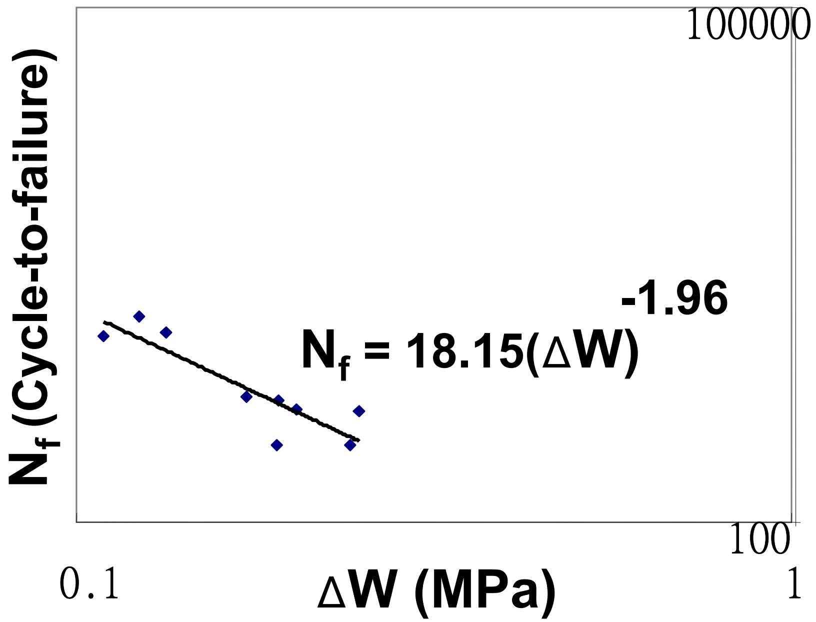
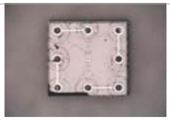
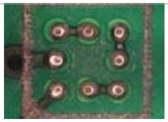
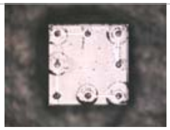
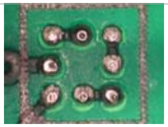
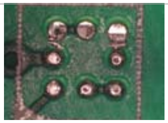
Number of Cycle-To-Failure vs. Strain Energy Density per Cycle



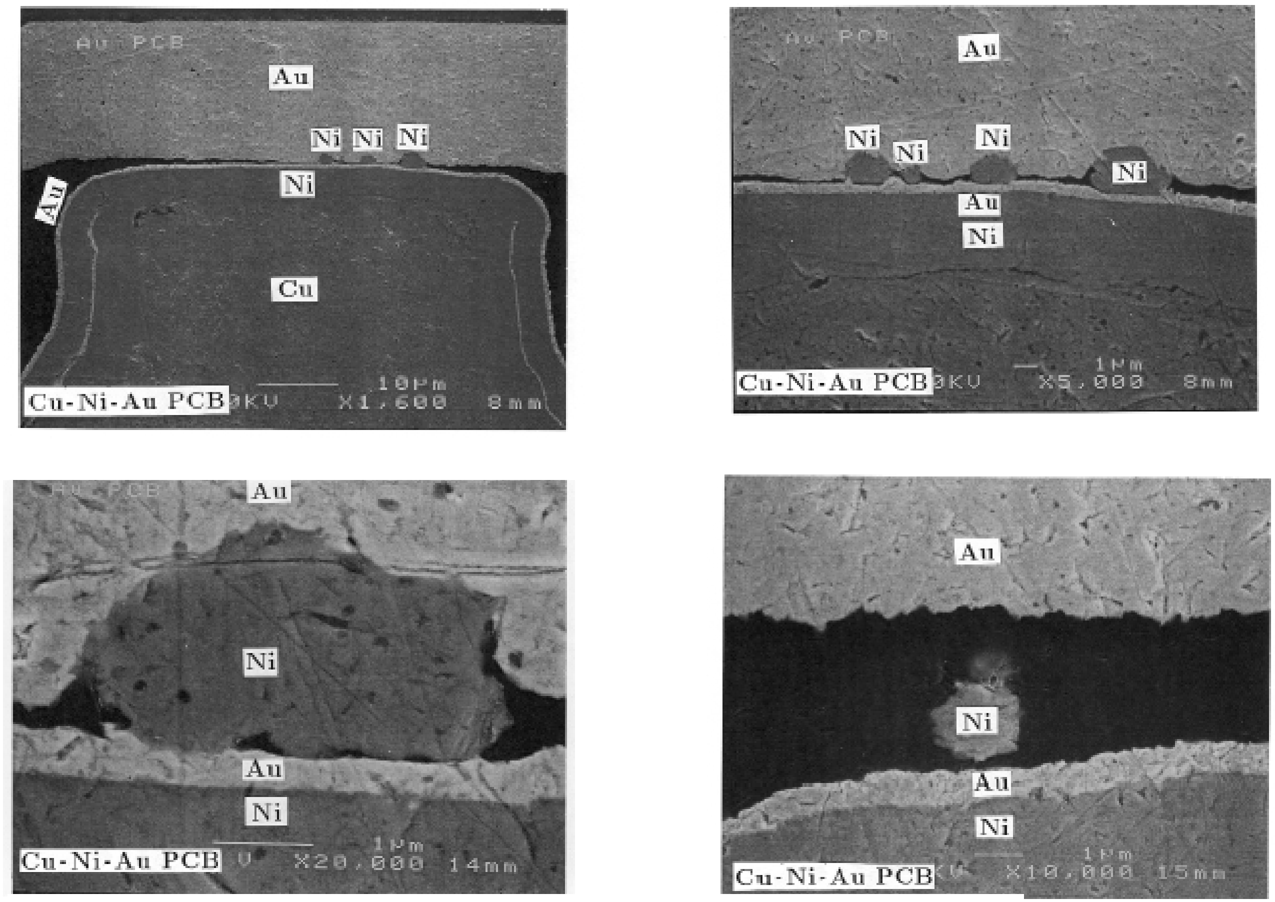
$$N_f = 18.15(\Delta W)^{-1.96}$$

N_f is the No. of cycle-to-failure
ΔW is the strain energy density per cycle

Test Results and Failure Surface with Applied Force = 4.15N

Cycles to total separation of the package	Cycles to double displacement amplitude	ΔW (Strain energy density per cycle, MPa)	ΔW (Area of hysteresis loop of the whole package)	Picture taken after total failure	
				Package-side	PCB-side
1214	1098	0.109	0.0146		
1265	1240	0.133	0.0179		
1569	1550	0.122	0.0164		

ACF (Anisotropic Conductive film)-bonded flip chip with Au bumps on ENIG PCB



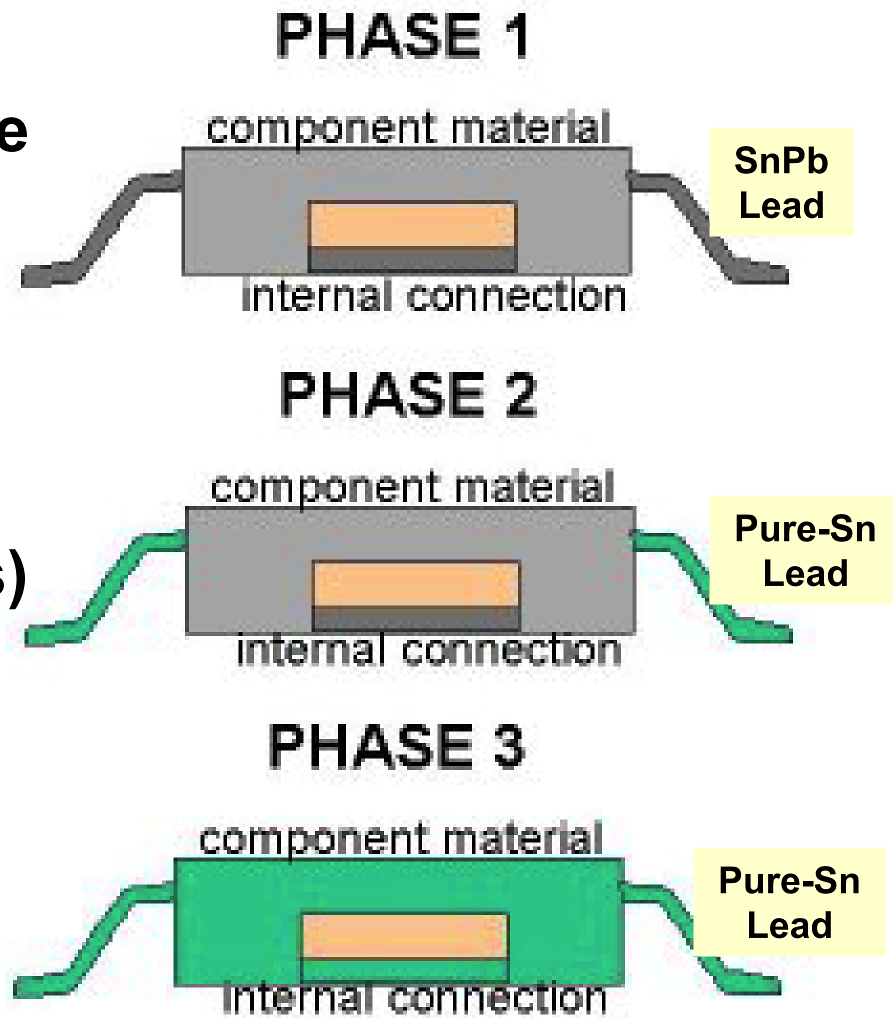
The Ni conductive particles penetrate into the electroplated Au bumps.
A wasted Ni conductive particle

Lead-Free Compatible, Lead-Free, and <u>Green (RoHS Compliant)</u> Components

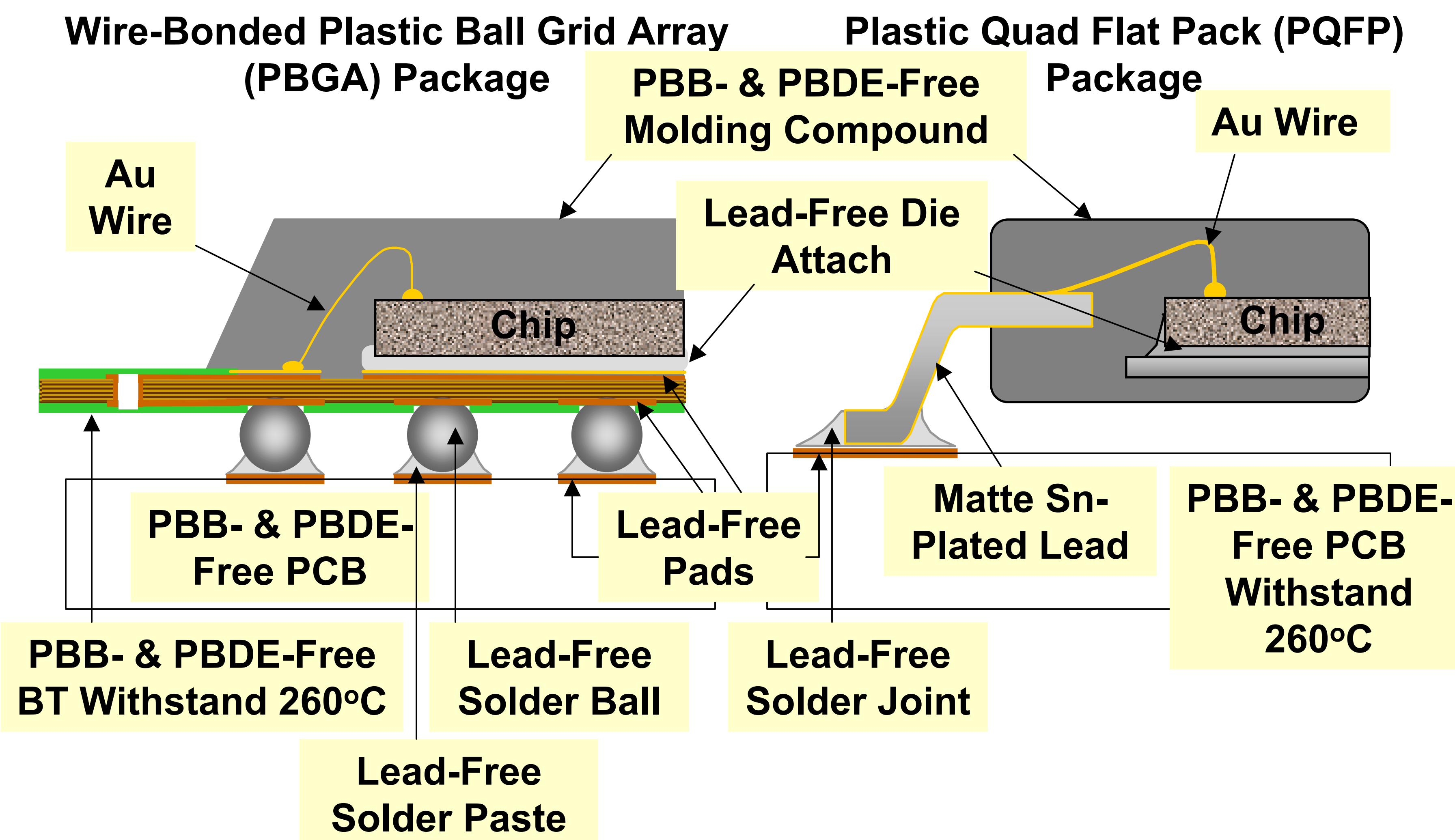
Lead-Free Compatible Components (Withstand 260°C)

Lead-Free (Termination Finishes) Components

Green components (PBB- & PBDE-Free Molding Compound)



Green (RoHS Compliant) Components



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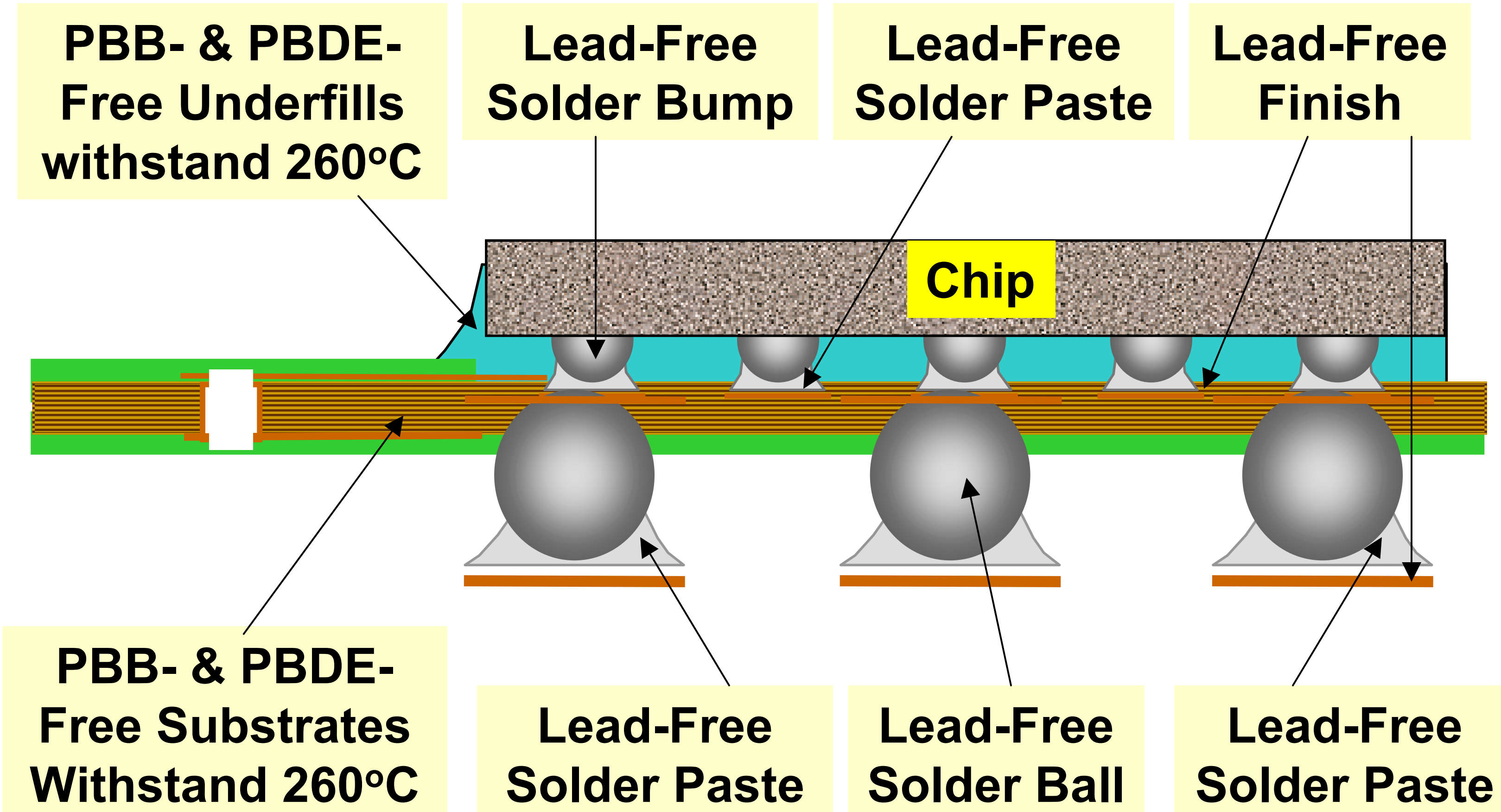
Green (RoHS Compliant) Flip Chip in PBGA Package



Lead-Free Supplier Status

Solder Suppliers: Ready (SnAgCu)

Component Suppliers: Today <30% are lead-free

1/1/2005 ~50% are lead-free

1/1/2006 ~75% are lead-free

PCB Suppliers: Ready (ENIG, OSP, ImAg, ImSn, HASL)

EMS: Today, most of the leading companies, e.g., Flextronics, Solectron, Sanmina, Celestica, Jabil are ready, except rework of high density area array packages.

Conclusions and Recommendations

(1) Lead-free is not a lie anymore and is here to stay. Either you jump on the lead-free bandwagon or are left behind.

(2) Lead-free has been a law in EU since February 13, 2003, and the implementation date is July 1, 2006. China will formally publish her own RoHS on September 18th, 2004 and the implementation date is also July 1, 2006.

(3) A maximum concentration value of up to 0.1% by weight in 'homogeneous materials' (please see text for definitions and interpretations) for lead will be permitted in the manufacture of new EEE.

(4)Standards for sampling and testing or measurement procedures and methods of lead-free products are desperately needed.

(5) EDXRF spectrometer is one of the most promising equipments to test/measure lead-free products.

(6) The leading solder alloys are Sn(3-4wt%)Ag(0.5-0.7wt%)Cu with melting point ~ 217^{o}C, which is 34^{o}C higher than Sn37wt%Pb.

Conclusions and Recommendations

(7) The components and PCBs will exhibit higher assembly temperatures and thus their costs, performance, and reliability are of great concerns.

(8) The lead-free roadmap for component suppliers is the end of 2004, after which all lead-free components should be qualified.

(9) The qualification specifications for lead-free (moisture-sensitive) components have been updated and given in IPC/JEDEC J-STD-020C.

(10) System houses are requiring that all the lead-free components should be able to withstand 260^{o}C soldering temperature.

(11) Most lead-free components for consumer products are with pure matte Sn plating, thus Sn whiskers (to short circuits) are possible. For some methods to mitigate the Sn whiskers, please see, e.g., [105].

(12) For lead-free components for high-end and high-reliability products, a Ni layer (>1µm) underneath the Sn layer is necessary. The thickness of the Sn layer is larger than 1µm for solderability purpose and less than 3µm for stresses at Sn layer in a state of tension.

Conclusions and Recommendations

(13) In order to find out if the Sn whiskers on a particular component post a reliability (short circuits) problem of a real product, one has to determine the stress state at the Sn layer of the component within the whole product (structure) subjected to the specificed boundary conditions, e.g., temperature cycling, bending, twisting, sharing, shock and vibration, etc.

(14) A combination of the local and global TEM effects of a real product results in compressions in the Sn layer of its components will enhance the initiation and growth of the Sn whiskers.

(15) Due to solder wicking, the risk of Sn-whisker should be reduced.

(16) Whisker-free matte Sn-plating chemical solutions, and acceleration test methods and their corresponding acceleration factors and models of tin whiskers are desperately needed.

(17) The leading surface finishes for lead-free PCBs are: (a) OSP, (b) ENIG, (c) ImAg, (d) ImSn, and (e) HASL SnCu. ImAg stands out among the others.

(18) Higher glass transition temperatures, temperature of decomposition, time to delamination, stiffness, solder-mask adhesion strength, and thermal stability, and higher resistant in moisture absorption, thermal expansion, warpage, and ionic contamination PCB materials are desperately needed.

Conclusions and Recommendations

(19) More research and development works need to be done on component temperature control reflow technologies by re-designing (modifying) the reflow machine for lead-free soldering.

(20) IPC-610 is being updated to include visual inspections of lead-free solder joints and scheduled to be published before the end of 2004.

(21) 5DX is able to perform 3D x-ray inspection of lead-free solder joints by re-adjusting the threshold values.

(22) Basic material properties such as Young's modulus, CTE, and creep of SnAgCu have been reported.

(23) The Young's modulus of the SnAgCu solders is higher than that of the SnPb solder, thus the SnAgCu solder is stiffer than the SnPb solder and higher stresses should be expected in the lead-free solder joints.

(24) The creep strain rate of the SnAgCu solders is slower than that of the SnPb solder, thus lower creep deformations should be expected in the SnAgCu solder joints.

(25) Acceleration test methods and their corresponding acceleration factors and models of lead-free PCBs, lead-free components, and lead-free solder joint are desperately needed.

Conclusions and Recommendations

(26) Fatigue crack-growth constants, which can be determined by isothermal fatigue tests, for real lead-free solder joints are desperately needed in order to make quantitative solder-joint thermal-fatigue life predictions.

(27) A set of fatigue crack-growth constants has been given for a WLCSP.

(28) It is clear that the shortest transition to totally lead-free is the best for the electronics industry, provided that all of the reliability and temperature related concerns are adequately addressed.

(29) More research and development works (see [106] for precise topics) need to be done on lead-free substitutes, such as the metal-bumped flip chip with adhesive technologies.

(30) It should be noted and emphasized that lead-free is only a necessary condition to make/ship EEE in/to EU and China, but not sufficient! The other five materials (Hg, Cd, Cr6+, PBBs, and PBDEs) have to be free also! In those cases, they are called RoHS complaint (or green) products. For examples, Figure 16 shows PBB-free, PBDE-free, and lead-free PBGA and PQFP packages, lead-free soldered on PBB-free, PBDE-free, and lead-free PCBs. Figure 17 shows a lead-free solder-bumped flip chip, lead-free soldered on a PBB-free, PBDE-free, and lead-free BT substrate (which can withstand 260°C maximum reflow temperature) with lead-free solder balls, lead-free soldered on a PBB-free, PBDE-free, and lead-free PCB (which is not shown). The underfill encapsulant between the chip and BT substrate is PBB-free and PBDE-free, and is able to withstand 260°C maximum reflow temperature.