Thermal Cycling Reliability of Doped SnAgCu Solder Alloys After Long-term Aging

ESTABLISHED 1856

FINAL EXAM

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Motivation

☐ Electronic packages are used in harsh environments

- ✓ Subjected to several thermal cycles per day, based on application
- ✓ Continuous exposure causes fatigue that gradually results in failure

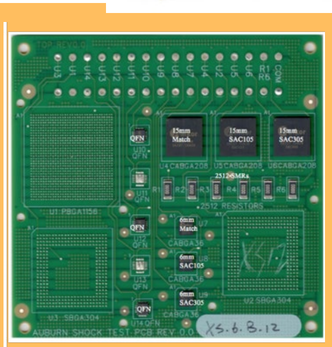
☐ Lead (Pb) free electronics

- ✓ Eutectic Tin (Sn) – Lead (Pb) solders were used in electronics till late 1900s
- ✓ As harmful effects of Pb were discovered, it was banned from electronics from early 2000s
- ✓ Since then, several new materials have been tested to find a replacement for SnPb based solder alloy and their reliability has been the main concern

Electronic Package

❑ Different levels of packaging

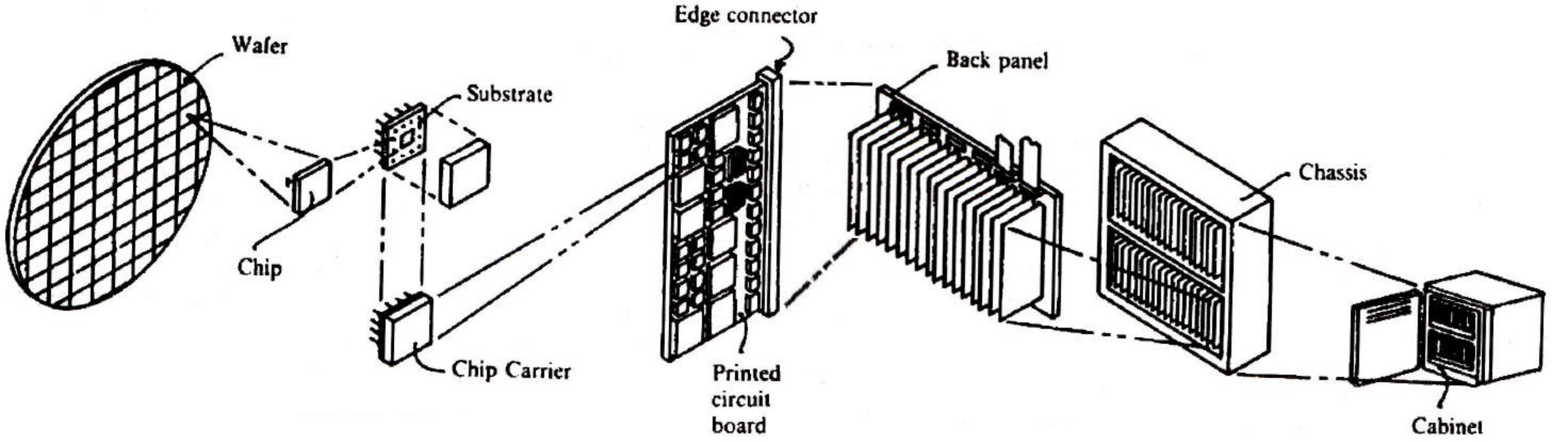
- ✓ Level 0: Interconnection between the devices on the circuit on the silicon die
- ✓ Level 1: Interconnection between the silicon die and the package
- ✓ Level 2: Interconnection between the package and the circuit board
- ✓ Level 3: Interconnection between different boards in the electronic system



PCB with components

❑ Functions

- ✓ Mechanical support
- ✓ Handling convenience
- ✓ Thermal management
- ✓ Protect the circuits on the die



Different levels of packaging

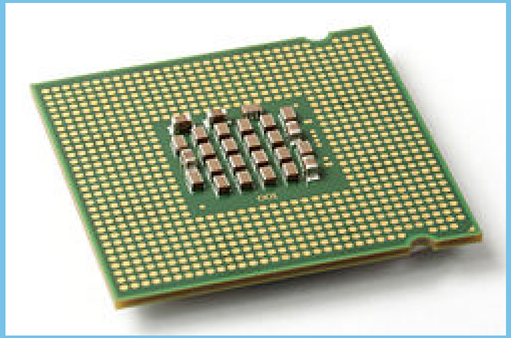
Area array components

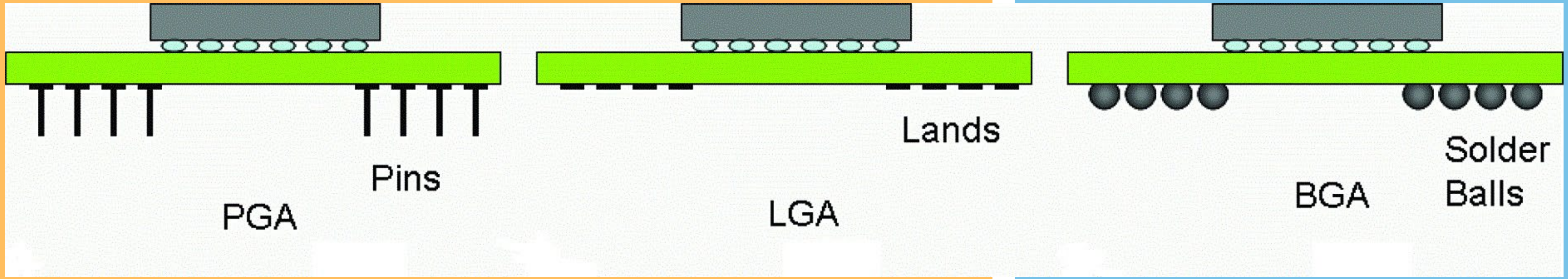
Pin Grid Arrays

- The solder spheres in BGA are replaced with an array of metallic pins
- Inserted in to the PCB through hole technique or using a socket
- PGAs were a standard package for most 2nd though 5th generation processors

Land Grid Arrays

- Solder spheres in BGA are replaced with a grid of flat contacts
- Are attached to PCB using LGA socket or by soldering them onto PCB surface





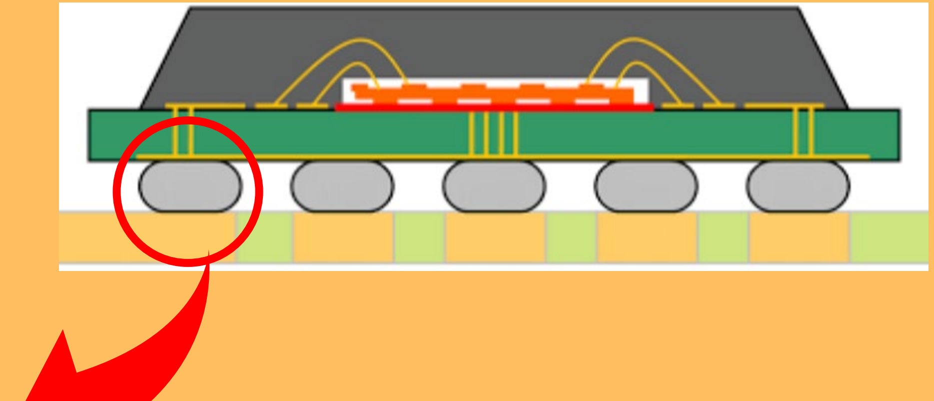
Comparison of different packages

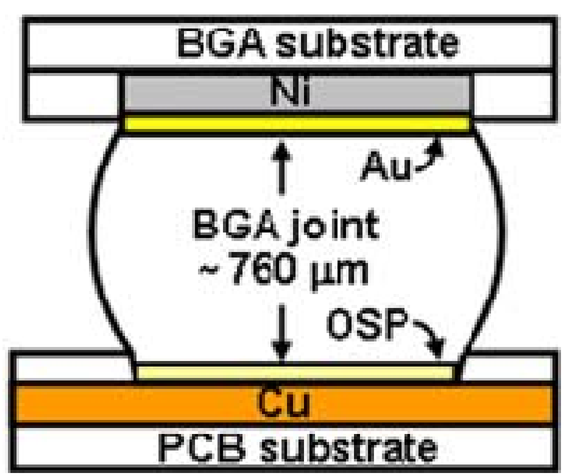
Packages on PCB

Electronic Assembly

A typical electronic assembly consists of:

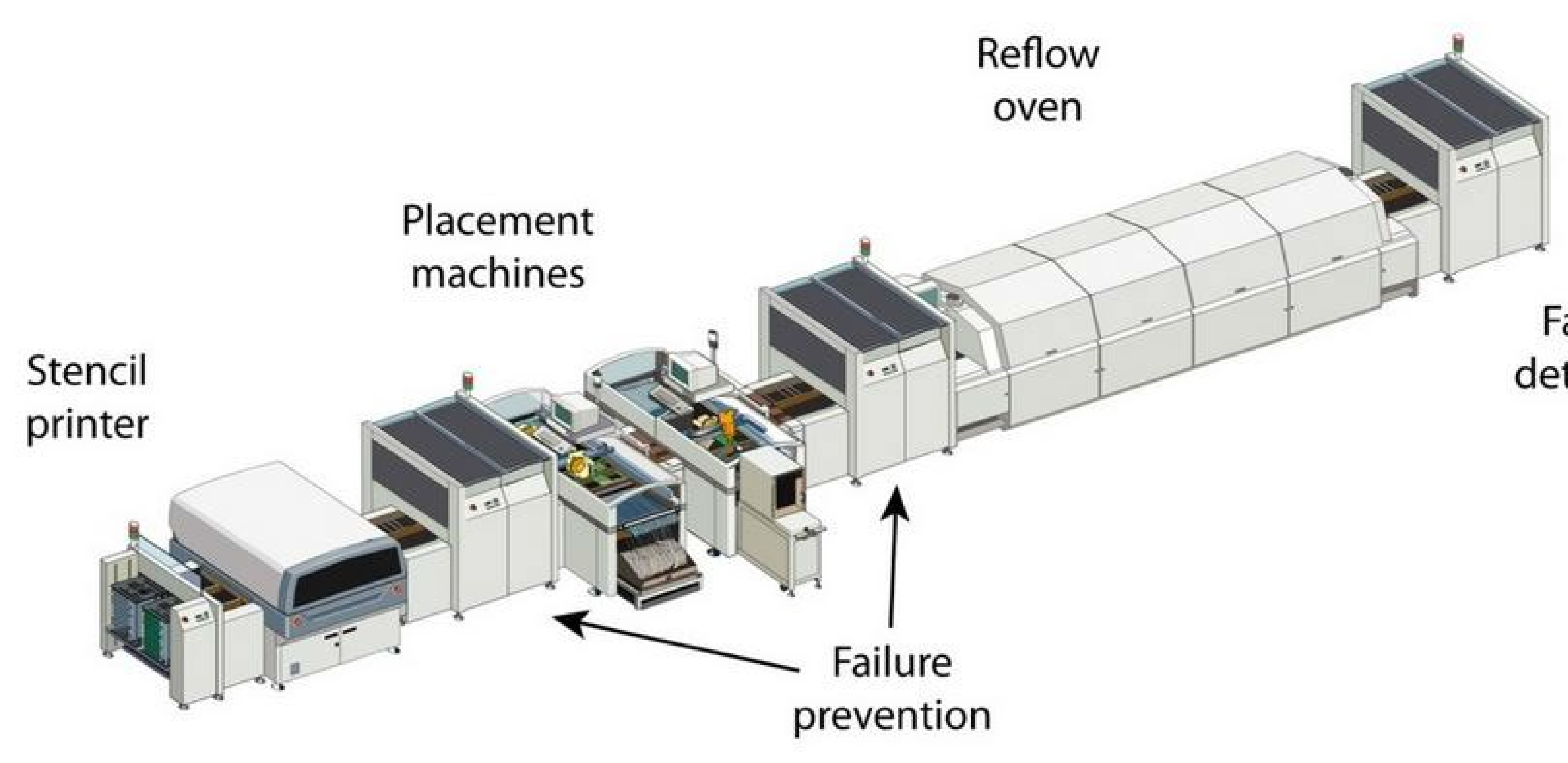
- Substrate material
- Solder mask
- Surface finish
- Solder alloy



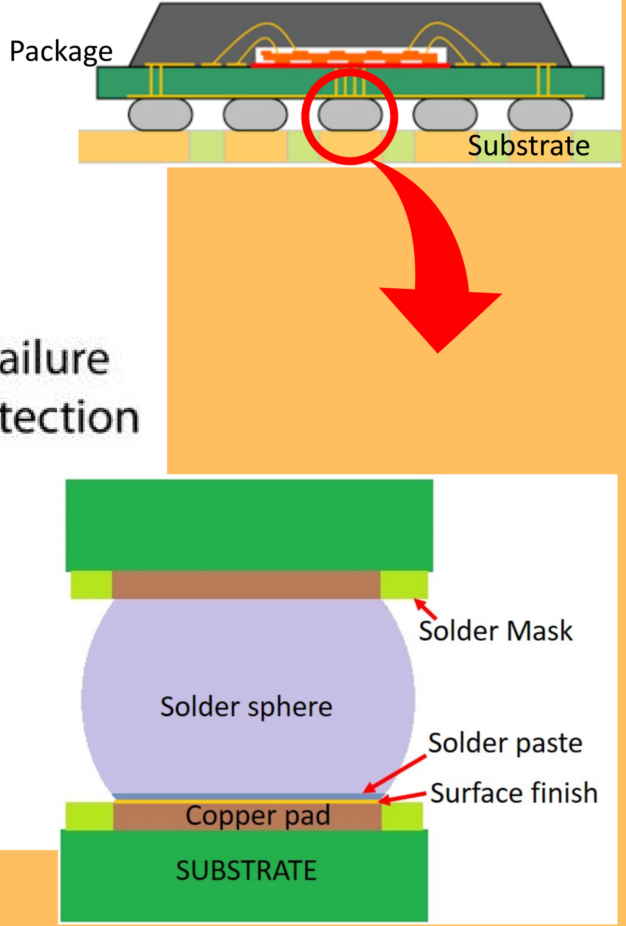


Packages on PCB

SMT Assembly Line



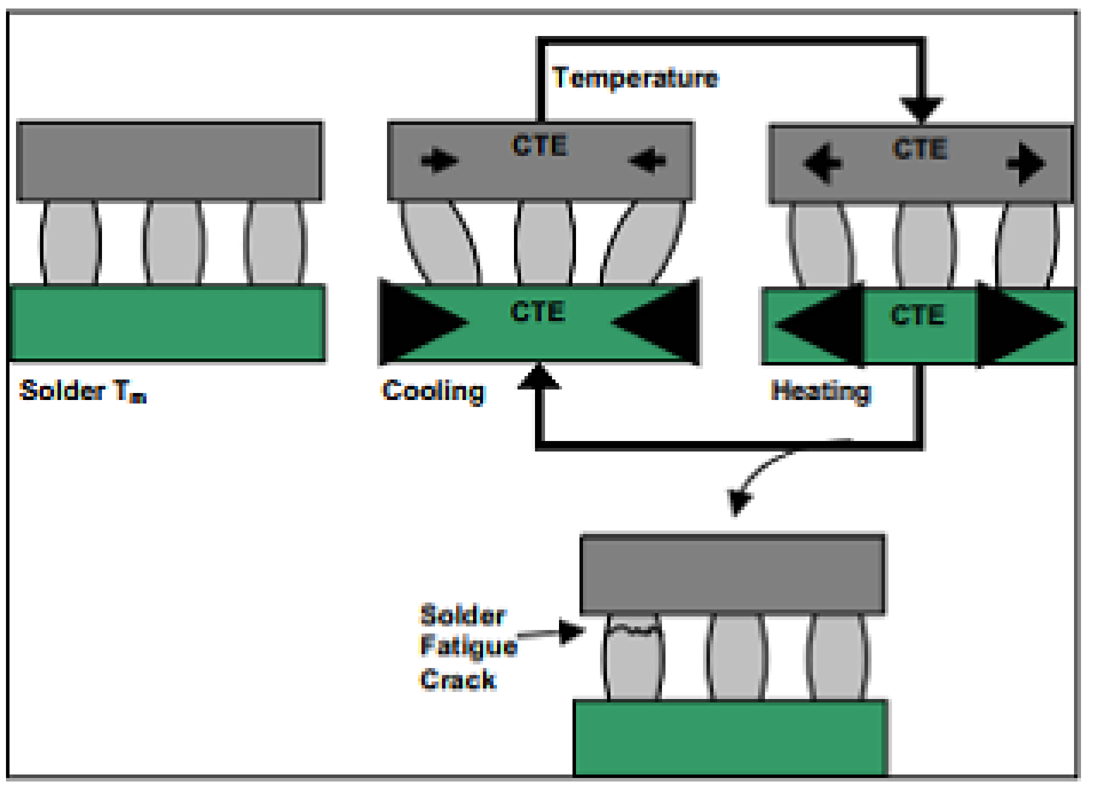
Typical SMT assembly production line



Typical solder joint

Solder Joint Reliability

- Coefficient of thermal expansion (CTE) mismatch between different materials
- When exposed to a temperature variation, these materials expand at different rates corresponding to their CTE.
- Thermal stress is induced at the weakest point, which is a solder joint.
- Exposure to several thermal cycles develops fatigue that finally results in the failure of the solder joint.

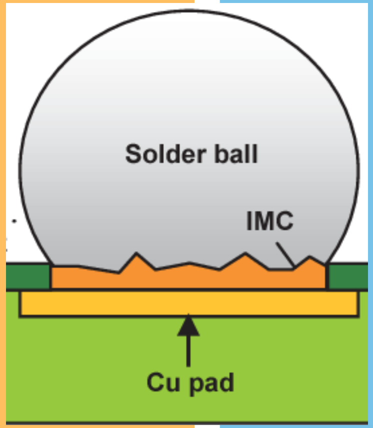


Failure due to CTE mismatch

Solder Joint Reliability

Precipitate coarsening

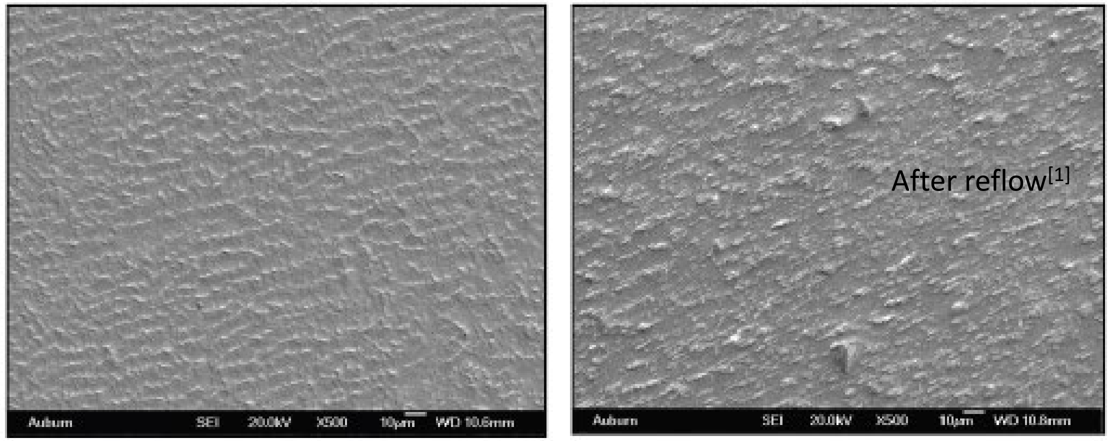
- After reflow, the bulk solder consists of fine dendrite structures
- During aging, fine precipitates coalesce and get coarsened
- Interparticle space increases and weakens the material



Solder joint for shear test[3]

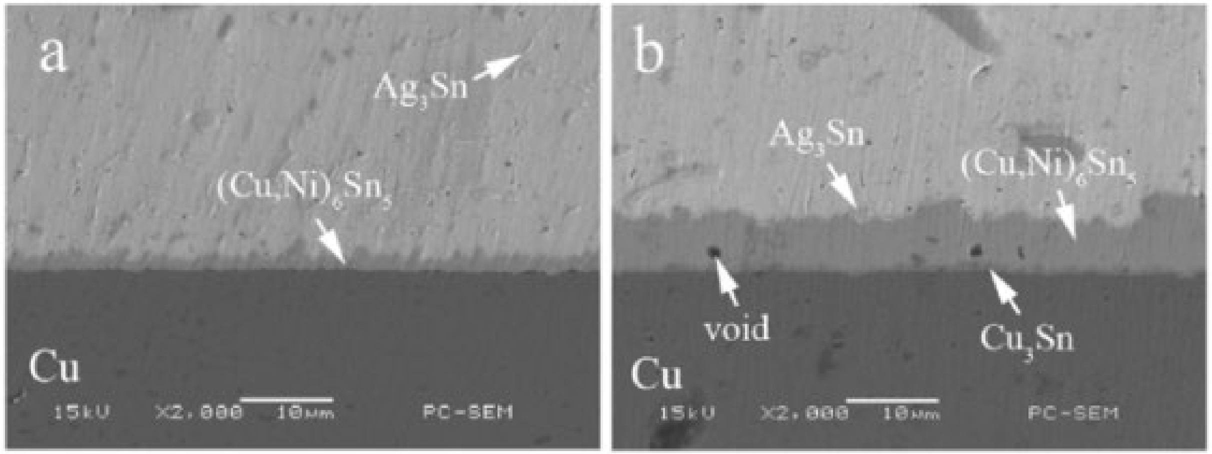
Intermetallic compound (IMC) growth

- At reflow, the copper from the pads dissolve into the bulk solder and form IMC layer at the copper/solder sphere interface, which is required for the mechanical bond.
- Over time, the brittle IMC layer grows thick and becomes the weakest part of the solder joint, where failure occurs.



After reflow[1]

(a) No aging. (b) 20 days of aging at 125 °C.



IMC layer growth before and after aging for 24 hours at 150°C[2]

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[1] N. Fu, J. C. Suhling, and P. Lall, "Cyclic Stress-Strain Behavior of SAC305 Lead Free Solder: Effects of Aging, Temperature, Strain Rate, and Plastic Strain Range," in 2016 IEEE 66th Electronic Components and Technology Conference (ECTC), pp. 1119–1127, IEEE, may 2016.

[2] Liu, Yang & Meerwijk, Joost & Liangliang, Luo & Zhang, Honglin & Sun, Fenglian & Yuan, Cadmus & Zhang, G.Q.. (2014). Formation and evolution of intermetallic layer structures at SAC305/Ag/Cu and SAC0705-Bi-Ni/Ag/Cu solder joint interfaces after reflow and aging. Journal of Materials Science: Materials in Electronics. 25. 10.1007/s10854-014-2257-8.

[3]. Yang, L. et al. "Shear strength and brittle failure of low-Ag SAC-Bi-Ni solder joints during ball shear test." *2013 14th International Conference on Electronic Packaging Technology* (2013): 750-753

Thermal Reliability

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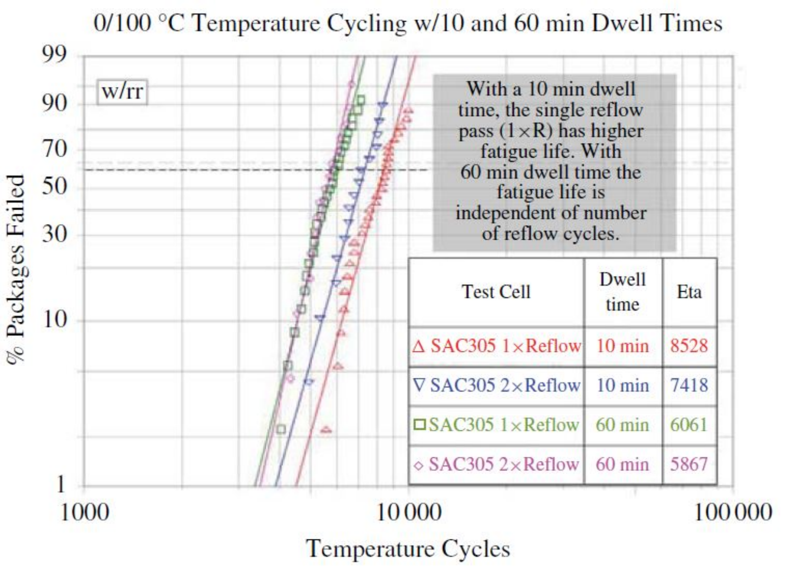
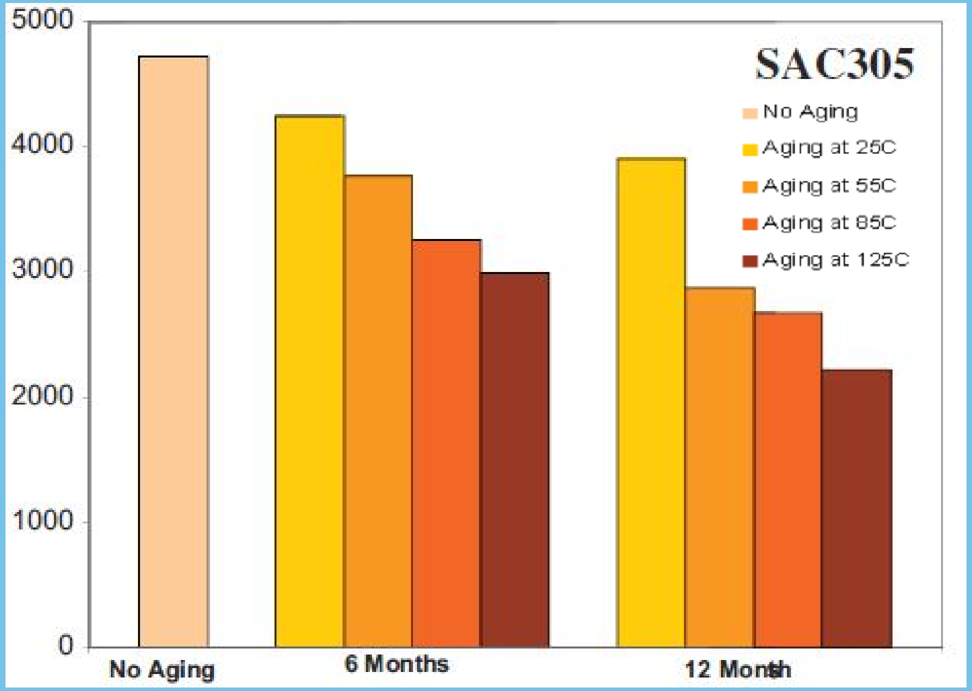
Effect of dwell time and number of reflows[1]


0/100 °C Temperature Cycling w/10 and 60 min Dwell Times

With a 10 min dwell time, the single reflow pass (1×R) has higher fatigue life. With 60 min dwell time the fatigue life is independent of number of reflow cycles.

- In the case of 10 minute dwell, more coarsening was found for sample with 2 reflows.
- For 60 minute dwell, the coarsening was comparable for both reflows.
- Initial morphology had less influence with increased thermal cycling exposure.

Effect of aging periods and aging temperatures [2]



- Characteristic life decreases with aging periods and aging temperature

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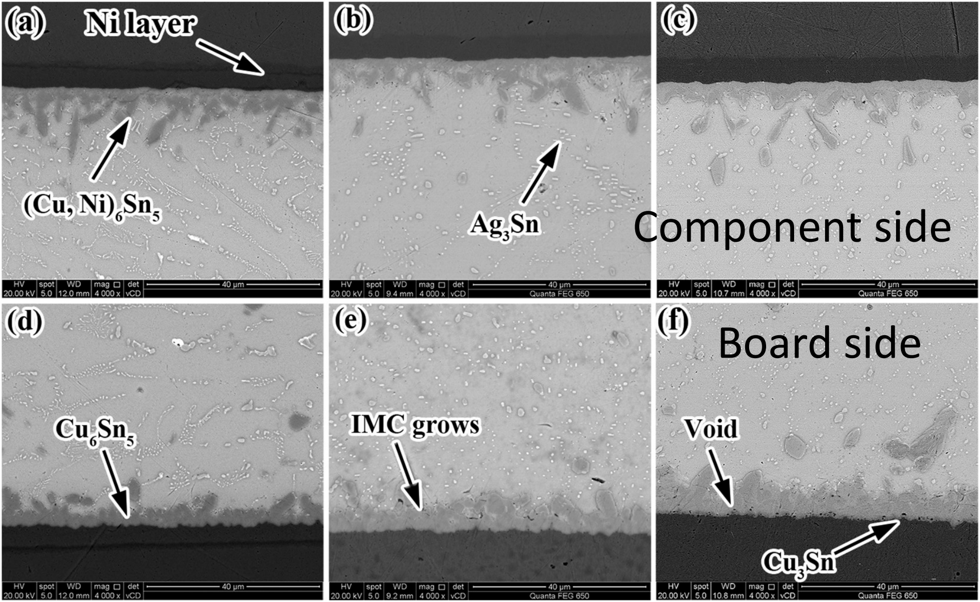
[1]. R. Coyle, J. Osenbach, M. N. Collins, H. McCormick, P. Read, D. Fleming, R. Popowich, J. Punch, M. Reid, and S. Kummerl, "Phenomenological study of the effect of microstructural evolution on the thermal fatigue resistance of Pb-free solder joints," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 1, no. 10, pp. 1583– 1593, 2011

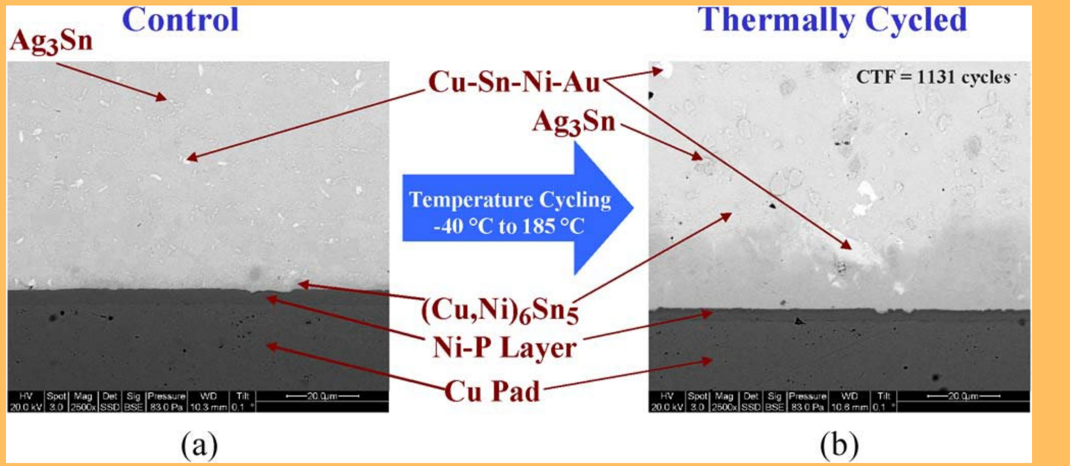
[2]. J. Zhang, Z. Hai, S. Thirugnanasambandam, J. L. Evans, M. J. Bozack, Y. Zhang, and J. C. Suhling, "Thermal aging effects on the thermal cycling reliability of lead-free fine pitch packages," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 3, no. 8, pp. 1348–1357, 2013

Microstructure Evolution

- ☐ Evolution is such that the stress induced by the external thermo-mechanical conditions are relaxed[1].
- ☐ IMC layer formation also relaxes the stress induced.



(a,d) as reflowed, (b,e) after thermal cycling (c,f) after aging



- ☐ Needle shaped structures due to the presence of $(Cu,Ni)_6Sn_5$ on package side[2]
- ☐ Thinner IMC layer due to Ni layer

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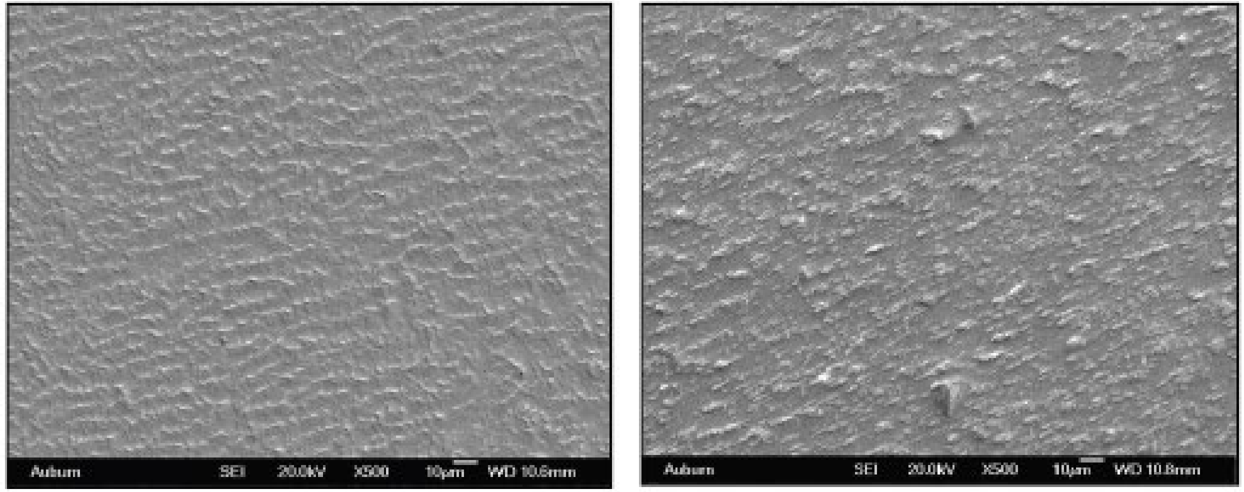
[1] E. George, D. Das, M. Osterman, and M. Pecht, “Thermal cycling reliability of lead-free solders (SAC305 and Sn3.5Ag) for high-temperature applications,” IEEE Transactions on Device and Materials Reliability, vol. 11, no. 2, pp. 328–338, 2011.
[2] J. Gu, J. Lin, Y. Lei, and H. Fu, “Experimental analysis of Sn-3.0Ag-0.5Cu solder joint board-level drop/vibration impact failure models after thermal/isothermal cycling,” Microelectronics Reliability, vol. 80, pp. 29–36, jan 2018.

Microstructure Evolution - Aging

SAC 305 solder joint as micro cylinder shaped uniaxial sample



(a) No aging.

(b) 20 days of aging at 125 °C.

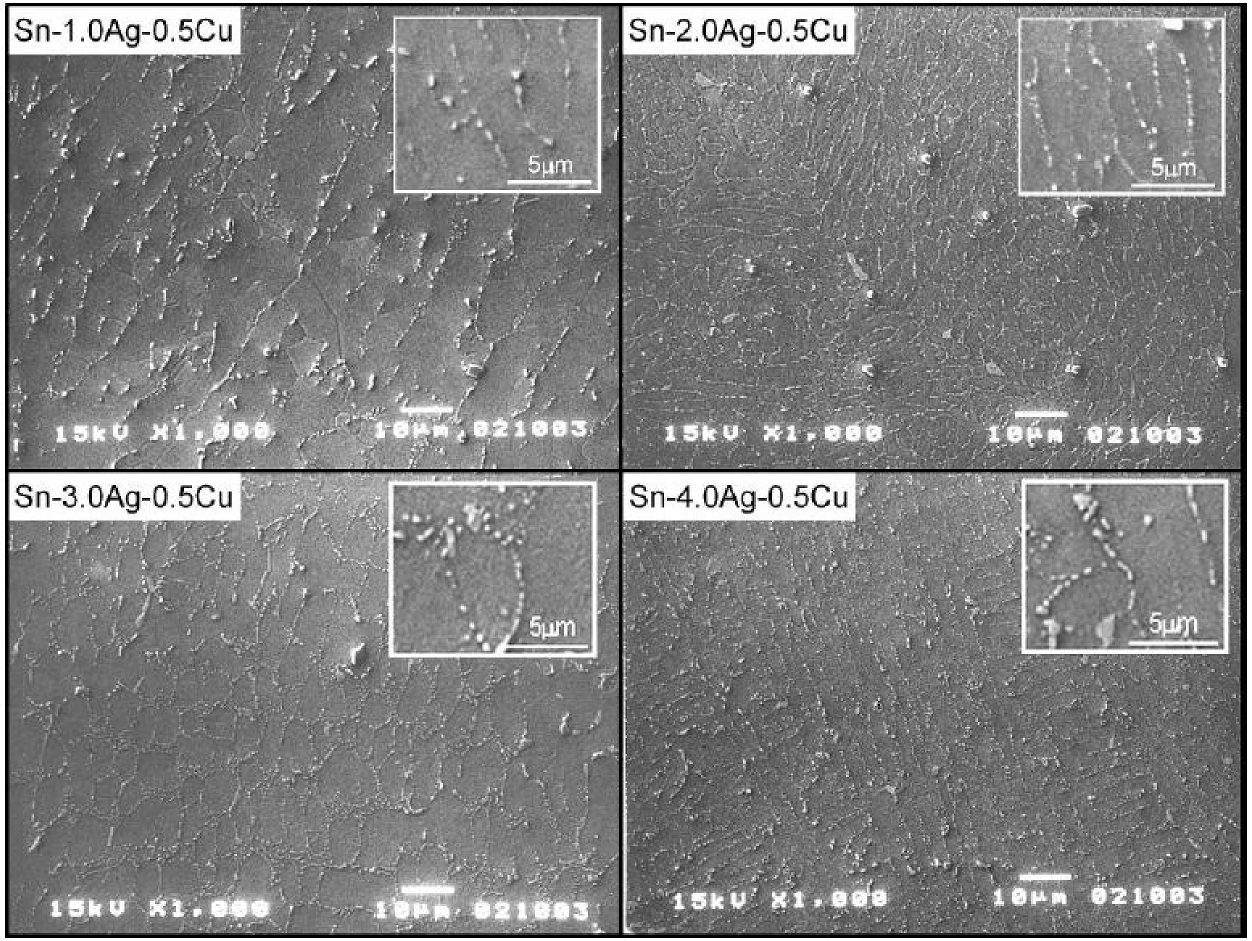
- Dendrite structure before aging is effective in blocking dislocation movements
- After aging, these structures disappear and the IMC coalesce and coarsen, which leads to increased dislocation movements.

N. Fu, J. C. Suhling, and P. Lall, “Cyclic Stress-Strain Behavior of SAC305 Lead Free Solder: Effects of Aging, Temperature, Strain Rate, and Plastic Strain Range,” in 2016 IEEE 66th Electronic Components and Technology Conference (ECTC), pp. 1119–1127, IEEE, may 2016.

Effect of Silver (Ag) content

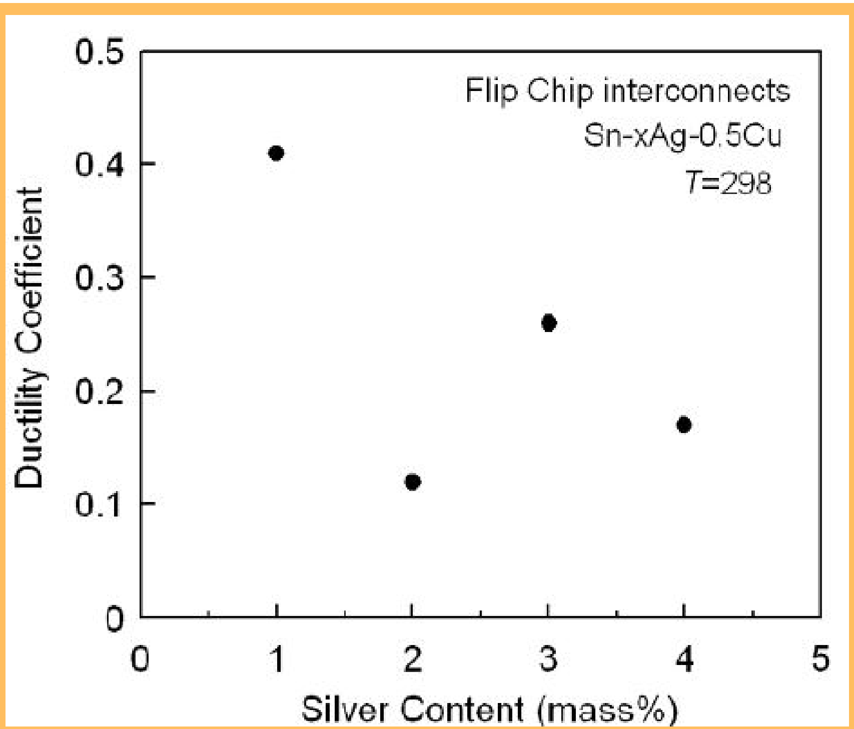
- ✓ SAC 105 has relatively large Sn grains with more coarsened interparticle space of the intermetallics.
- ✓ SAC205 has cell like Sn grains decorated with fine IMCs.
- ✓ For SAC305, the IMCs appear around the Sn grains with a network structure and the Sn grains appear to be larger than that of SAC205 solder.
- ✓ In the case of SAC405, the microstructure is very fine and the IMCs appear dense with in the matrix, when compared with the other alloys.

- ➢ In general, the interparticle space and the grain size seem to decrease with increasing Ag content. which might increase the strength of the solder alloy.



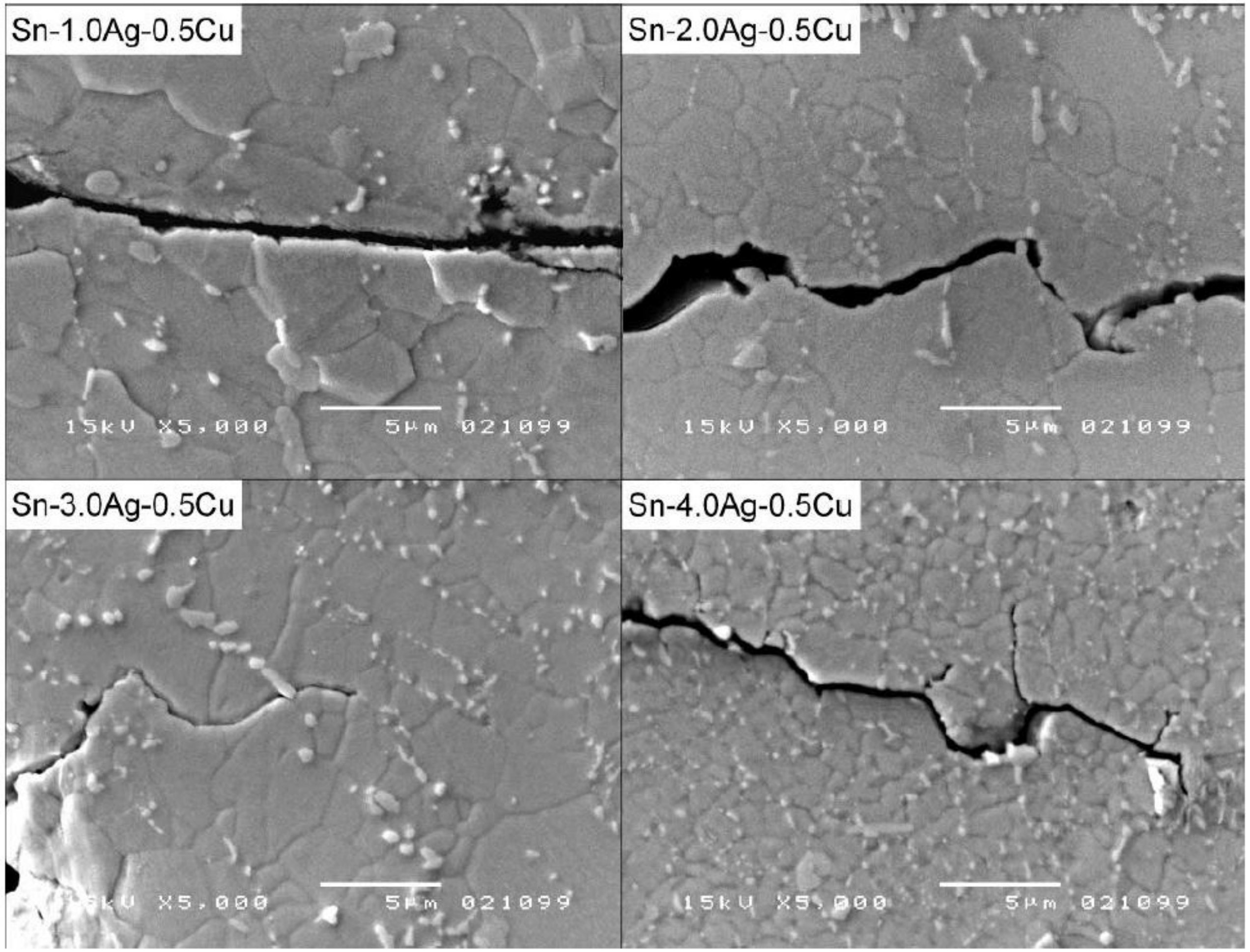
Y. Kariya, T. Hosoi, S. Terashima, M. Tanaka, and M. Otsuka, “Effect of Silver Content on the Shear Fatigue Properties of Sn-Ag-Cu Flip-Chip Interconnects,” Journal of Electronic Materials, vol. 33, no. 4, pp. 321–328, 2004..

Effect of Silver (Ag) content



Effect of %Ag on ductility

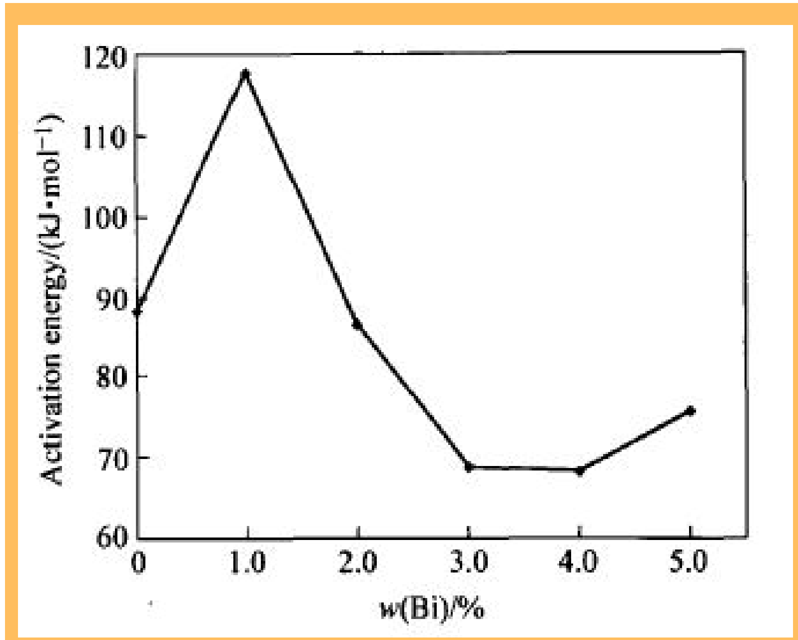
- ➢ Ductility decreases with increase with Ag content
- ➢ SAC 305 is recommended for flip chip bumps as strength and ductility is well balanced.



After shear fatigue test

Y. Kariya, T. Hosoi, S. Terashima, M. Tanaka, and M. Otsuka, “Effect of Silver Content on the Shear Fatigue Properties of Sn-Ag-Cu Flip-Chip Interconnects,” Journal of Electronic Materials, vol. 33, no. 4, pp. 321–328, 2004..

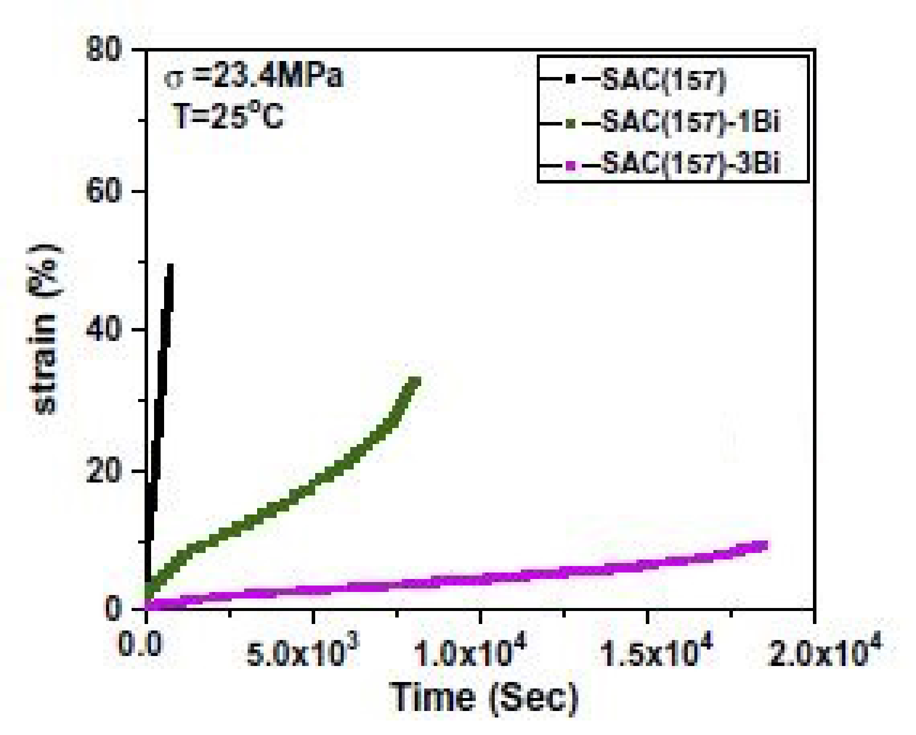
Effect of dopants - Bismuth



Effect of %Bi on activation energy[1]

- ☐ Thickness of IMC layer decreased with increase in Bi composition till 2%
- ☐ IMC growth rate was lowest at 1% Bi

- ☐ The melting point of SAC-3Bi was around 6.8°C lower than the SAC alloy
- ☐ Bi addition increased the creep resistance of the SAC alloy, due to solid solution strengthening effect of Bi atoms and Bi precipitates.



Effect of %Bi on creep rate[2]

- ☐ Higher the activation energy, lower the atomic diffusion, less IMC layer growth

[1] G.-y. LI and X.-q. SHI, "Effects of bismuth on growth of intermetallic compounds in Sn-Ag-Cu Pb-free solder joints," Transactions of Nonferrous Metals Society of China, vol. 16, pp. s739–s743, jun 2006..
[2] A. A. El-Daly, A. M. El-Taher, and S. Gouda, "Development of new multicomponent Sn-Ag-Cu-Bi lead-free solders for low-cost commercial electronic assembly," Journal of Alloys and Compounds, vol. 627, pp. 268–275, 2015.

Effect of dopants – Antimony(Sb)

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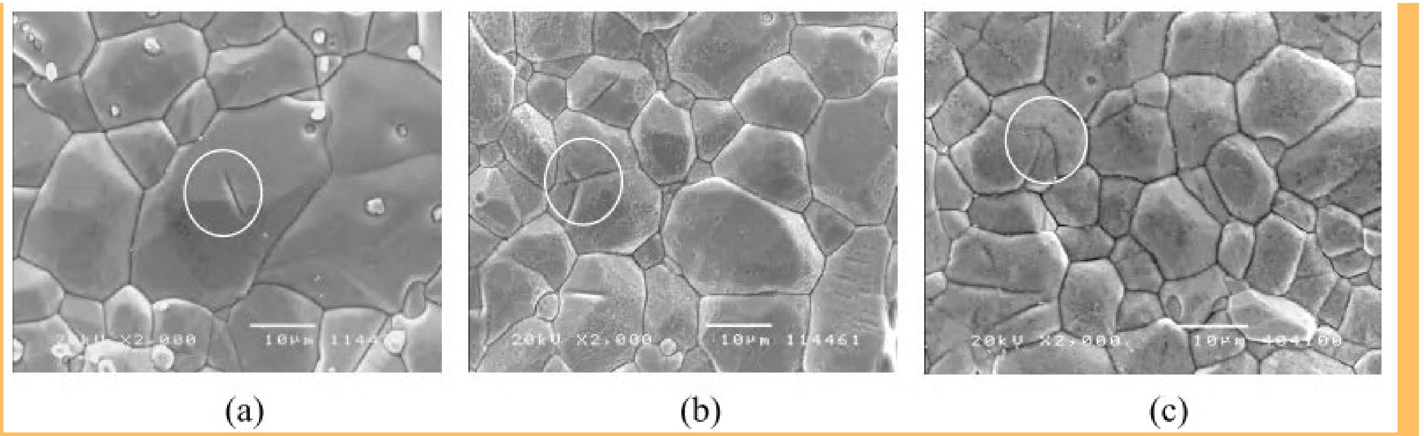
☐ The grain size of IMC layer decreases with increase in Sb content

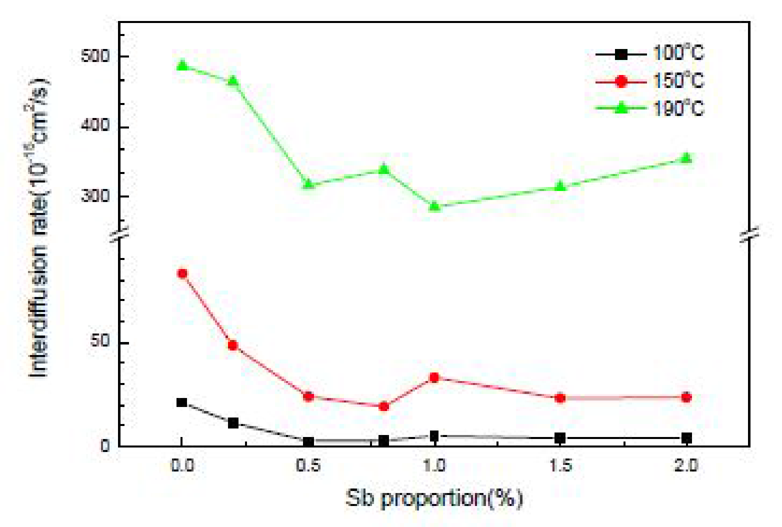
☐ The refining of the IMC grain size improves the mechanical properties

☐ The IMC growth rate is the lowest at 0.8% Sb

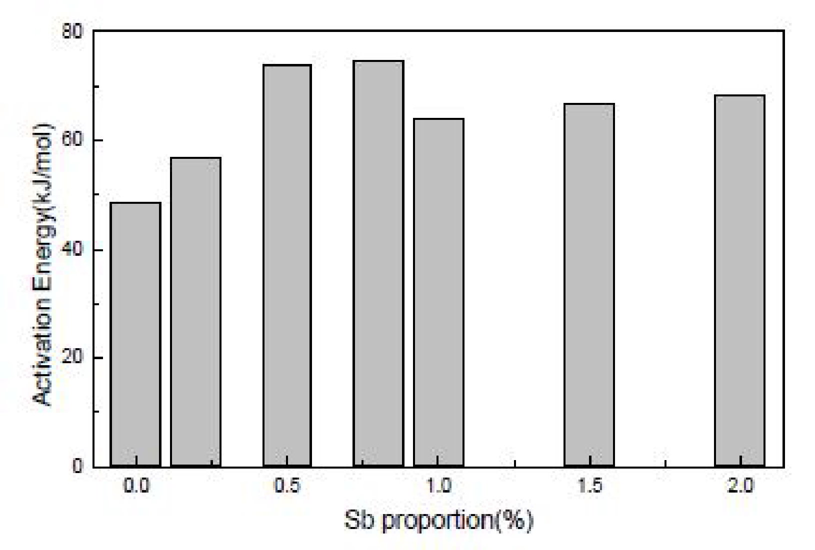
☐ The activation energy is the highest at 0.8% Sb



SEM images of top view of IMC layer of Sn-3.5Ag-0.7Cu-xSb solder joints aged at 190ºC for 600 hours. (a) x = 0, (b) x = 0.2, and (c) x = 0.8 wt%



Effect of % Sb on IMC growth rate



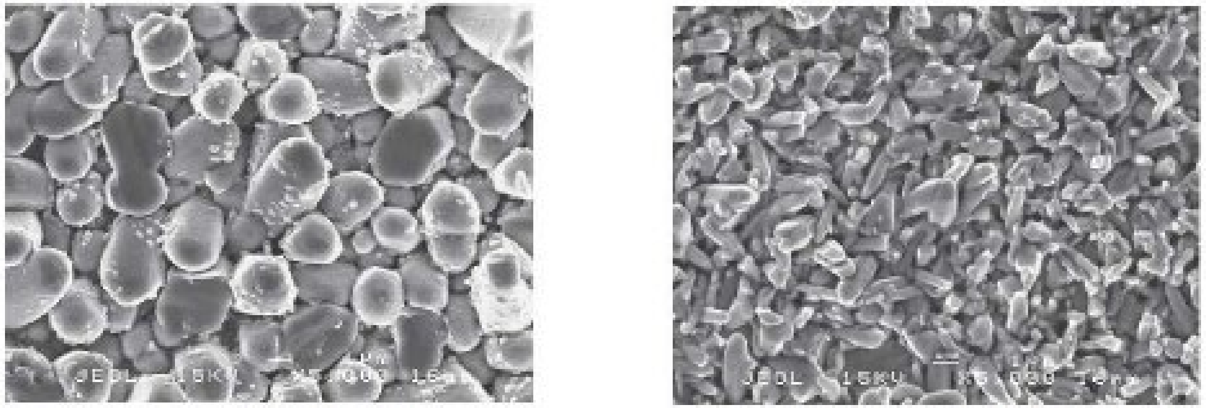
Effect of % Sb on activation energy

Li, G. Y. et al. "Influence of Dopant on IMC Growth and Mechanical Properties of Sn-3.5Ag-0.7Cu Solder Joints." *2007 International Symposium on High Density packaging and Microsystem Integration* (2007): 1-4..

Effect of dopants

Nickel (Ni)

- ✓ Ni Addition suppresses Cu_3Sn
- ✓ Cu_3Sn phase existed only when the aging temperature was above 130°C[1]
- ✓ With 5-15 at% Ni, an increased growth rate of $(Cu,Ni)_6Sn_5$ was observed
- ✓ Grain coarsening was significantly suppressed



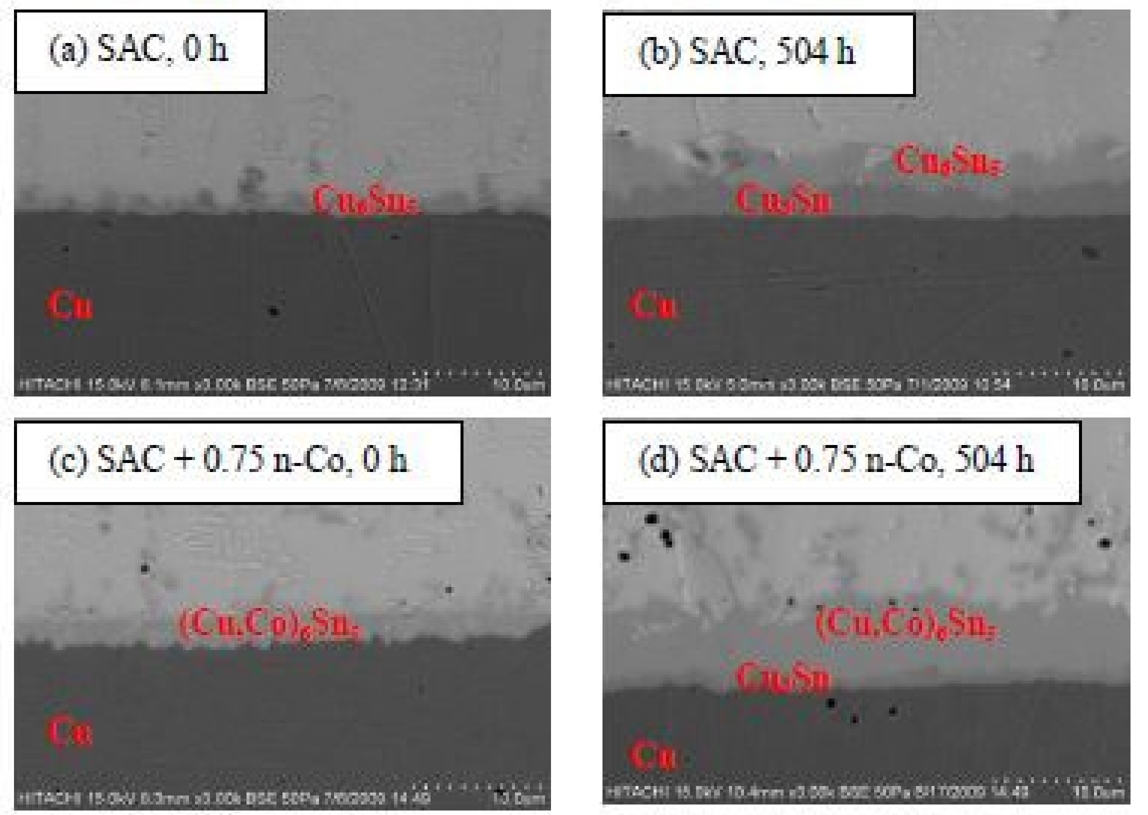
(a) Sn-3.5Ag/Cu

(b) Sn-3.5Ag-0.2Co-0.1Ni/Cu

Top view of IMC after reflow at 250°C for 1 minute

Cobalt (Co)

- ✓ Co addition improves ductility, thermal fatigue and creep resistance, reduces brittle failure mode
- ✓ Co suppresses the growth of Cu_3Sn[2]
- ✓ Interdiffusion coefficient for Cu_3Sn is smaller in SAC+0.75 n-Co



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[1] F. Gao, T. Takemoto, H. Nishikawa, and A. Komatsu, "Microstructure and mechanical properties evolution of intermetallics between Cu and Sn-3.5Ag solder doped by Ni-Co additives," Journal of Electronic Materials, vol. 35, no. 5, pp. 905–911, 2006.

[2] S. L. Tay, A. S. Haseeb, and M. R. Johan, "Effect of addition Cobalt nanoparticles on Sn-Ag-Cu lead-free solder," 2010 12th Electronics Packaging Technology Conference, EPTC 2010, pp. 433–436, 2010.

Problem statement

- The reliability of solder joint is crucial for the electronic device to function as expected throughout the required period, which in turn is influenced by aging, solder paste, solder sphere, surface finish and other factors that constitute the joint.

- Researches that has been going on focuses on one or two factors with one or utmost two levels of each factor. So, it doesn’t encompass all the factors that come into play in the solder joint reliability.

- In high reliability applications where ten or more years of product life is expected (e.g. automotive, military, aerospace), thermal fatigue has been the major cause of failure of solder joints. In these applications, the failures could be fatal. Therefore, insight on thermal cycling reliability of new solder materials considering the different factors is crucial.

- From the results of the research, packaging industry would be able to better understand the effect of different factors and dopants on solder joint reliability, there by allowing them to determine the best combination for harsh applications.

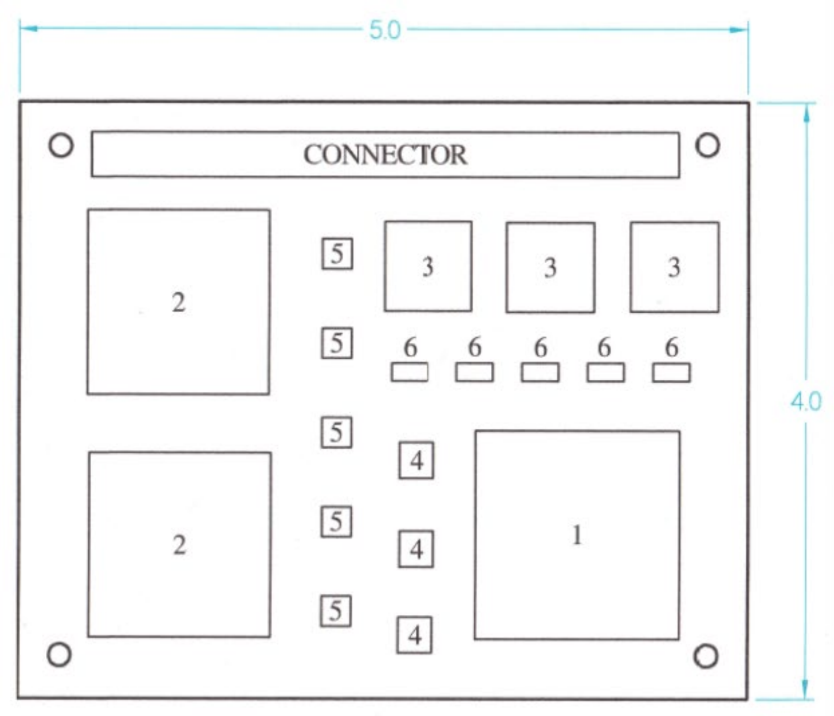
Research Objectives

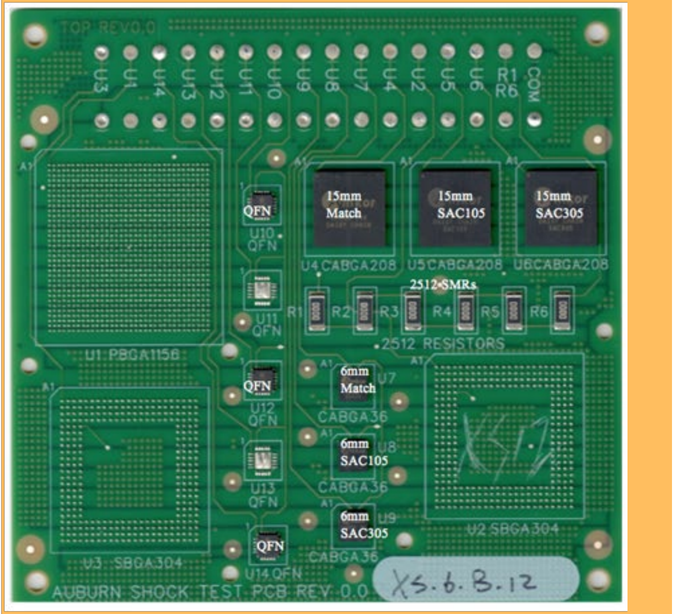
- ✓ Develop and conduct tests to study the thermal cycling reliability
- ✓ Analyze the data statistically to find out the different patterns/trends
- ✓ Analyze the failed samples for various failure modes
- ✓ Study the effect of surface finish on the solder joint fatigue life
    - Investigate the influence of different factors on the IMC layer growth and its effect on the solder joint reliability
- ✓ Study the effect of micro-alloying new elements on component reliability

Test vehicle design

Components

- 3 large perimeter BGAs (15x15mm with 0.8mm pitch)
- 3 small full array BGAs (6x6mm with 0.8mm pitch)
- 3 small QFNs (5x5 mm with 0.65mm pitch)
- Six 2512 SMT resistors



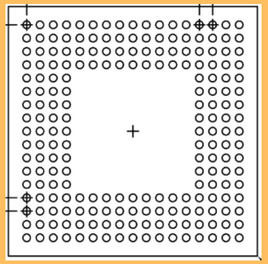


5 replicates for each solder paste – surface finish combination

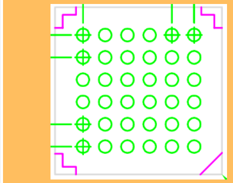
Test vehicle design

Component Specifications

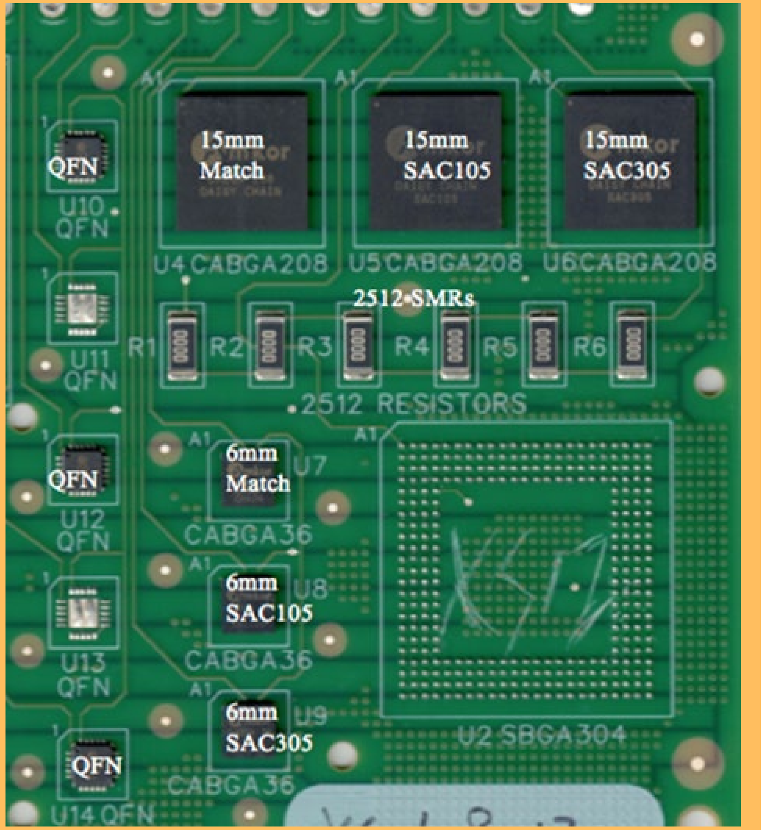
Package Type	Package Size (mm)	Pitch Size (mm)	Ball Diameter (mm)	Ball Arrangement	Solder Joint
BGA	15x15	0.8	0.46	Perimeter	SAC 105, SAC305, Match
BGA	6x6	0.8	0.46	Full Array	SAC 105, SAC305, Match
QFN	5x5	0.65	--	--	Paste only
SMR	2.5x1.2	--	--	--	Paste only



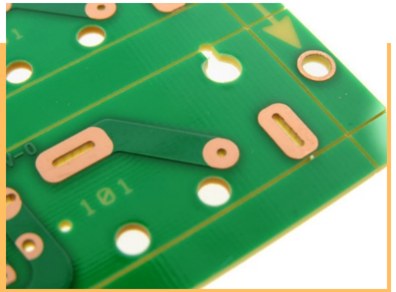
15mm BGA



6mm BGA

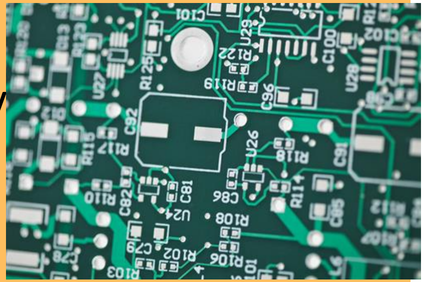


Surface finishes



Organic Solderability Preserve (OSP)

- ✓ Water based organic finish, with a thin layer of carbon-based organic compound over copper.
- ✓ Advantages: Low cost, superior co-planarity and solderability
- ✓ Disadvantage: Handling sensitivity, poor shelf life, easy degradation with temperature, non-conductive coating

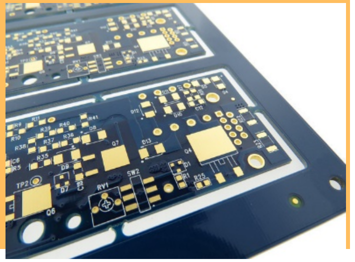


Immersion Silver (ImAg)

- ✓ Has excellent solderability, long shelf life, easy probe testing, good thermal and mechanical reliability
- ✓ Could generate creep corrosion in high Sulphur and humid environment

Electroless Nickel Immersion Gold (ENIG)

- ✓ Two-layer metallic coating over catalyzed copper with Ni layer acting as a diffusion layer to copper, covered by gold that protects Ni from oxidation during storage.
- ✓ Provides excellent shelf life, good wettability, great co-planarity, easy in-circuit testing, good product reliability
- ✓ But higher cost per unit



Solder paste composition

Paste name	Paste Code	Paste Alloy Composition	BGA Pre-Balling Sphere	
			15mm BGA	6mm BGA
Indium Material 1	Ind_1	98.47Sn-0.5Ag-1.0Cu-0.03Mn	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Indium Material 2	Ind_2	SAC + Sb	SAC105 SAC305	SAC105
Alpha Innolot	A_Inn	90.95Sn-3.80Ag-0.70Cu-0.15Ni-1.40Sb-3.00Bi	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Alpha Maxrel +	Ap_Mx	Sn-3.8Ag-0.8Cu-Bi-X	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Accurus CycloMax	Ac_Cyx	92.77Sn-3.41Ag-0.52Cu-3.3Bi	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Accurus Ecolloy	Ac_Ely	96.62Sn-0.92Cu-2.4Bi	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Heraeus Innolot	Hs_Inn	Sn-3.5Ag-0.7Cu-0.125Ni-1.5Sb-3Bi	SAC105 SAC305	SAC105
Heraeus HT 1.02	Hs_HT	Sn-2.5Ag-0.5Cu-2In-0.03Nd	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Senju M794	Sj_94	Sn-3.4Ag-0.7Cu-3.2Bi-3.0Sb-Ni-Co	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Senju M758	Sj_58	Sn-3.0Ag-3Bi-0.8Cu-Ni	SAC105 SAC305 MATCH	SAC105 SAC305 MATCH
Henkel K	Hk_K	90.98Sn-3.8Ag-0.7Cu-0.02Ni-1.5Sb-3Bi	SAC105 SAC305	SAC105
Henkel L	Hk_L	90.98Sn-3.8Ag-0.7Cu-0.02Ni-1.5Sb-3Bi	SAC105 SAC305	SAC105

SMT Assembly

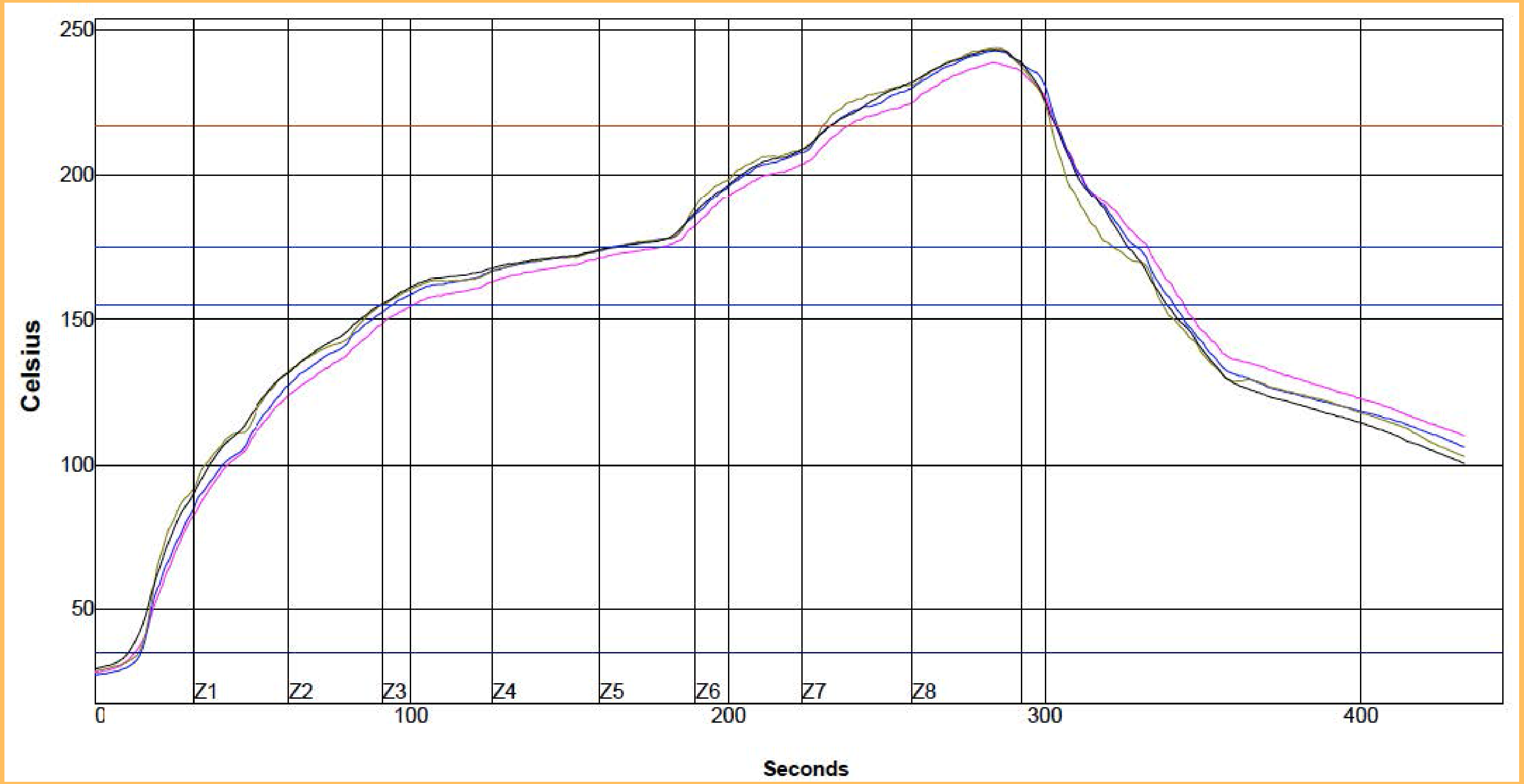
- ✓ The boards were assembled at Electronics Packaging Lab, University of Alabama, Huntsville.
- ✓ An E-FAB Electroform stencil with thickness of 6 mils was used
- ✓ MPM UP2000HiE was used for solder paste printing
- ✓ After inspection, the Universal GSM-1 pick and place machine with tray feeder is used to pick and place all the components.
- ✓ The assembly is inspected, after which it is reflowed in a 13 zone Rehm V7 convection reflow oven

Assembly line at UAH

Reflow oven

Reflow profile

- ✓ The thermal profile is selected such that the solder joints have the best wetting with least board damage.



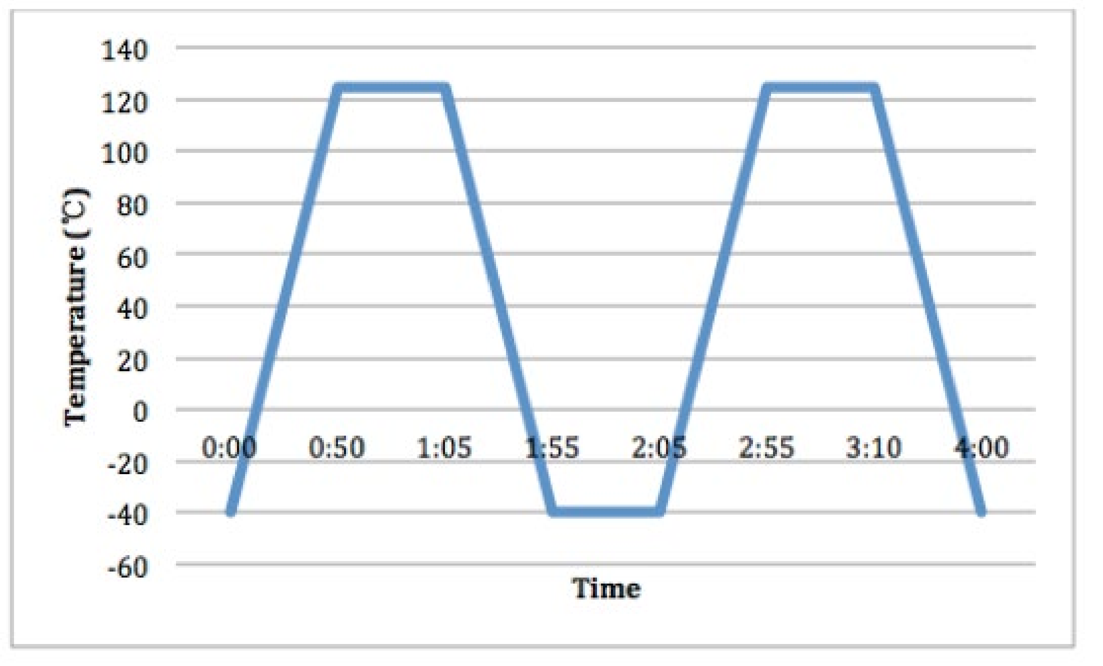
Thermal Test

Aging

- The boards were aged for twelve months at 125°C after the build.

Thermal Cycling

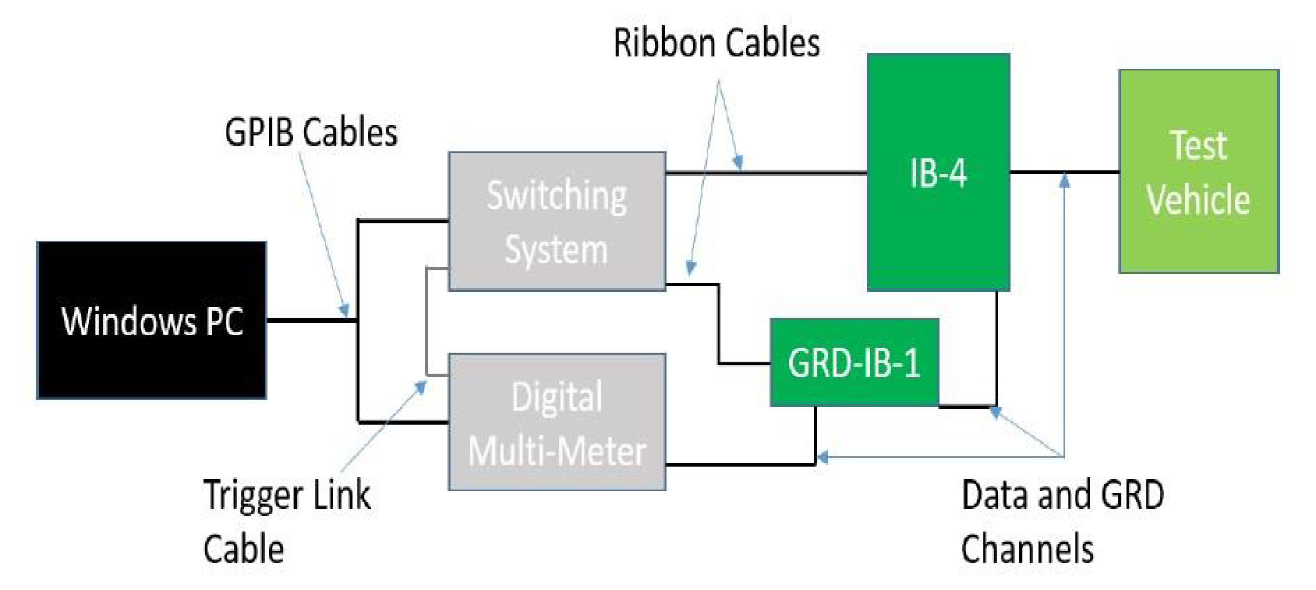
- The aged boards are cycled between -40°C and +125°C
- Ramp time of 50 minutes (ramp rate = 3.3 °C per minutes)
- Dwell times of 15 minutes at +125°C and 10 minutes at -40°C
- Total cycle time equals to 125 minutes.

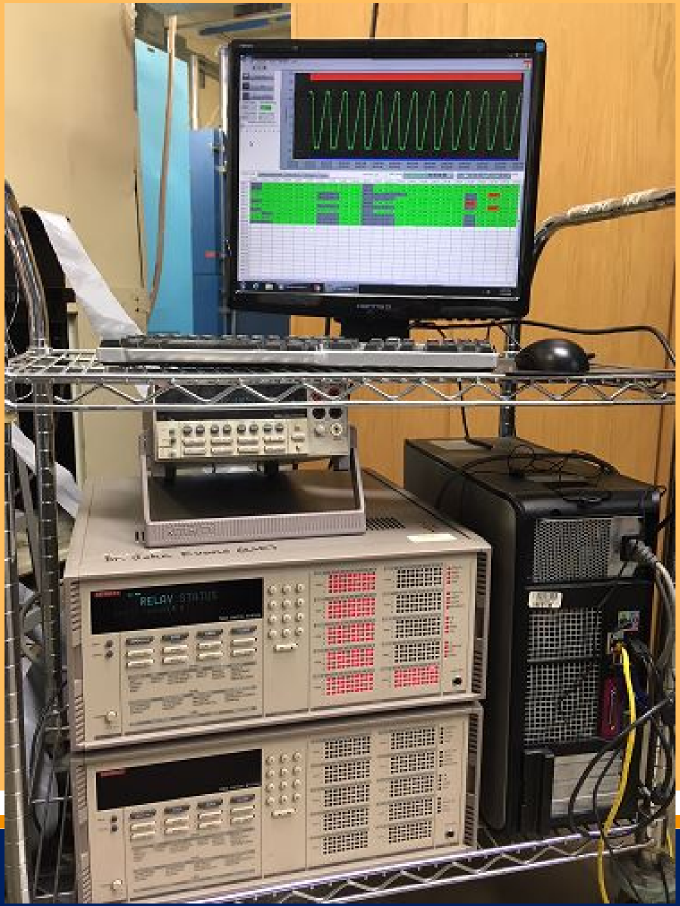


Thermal profile

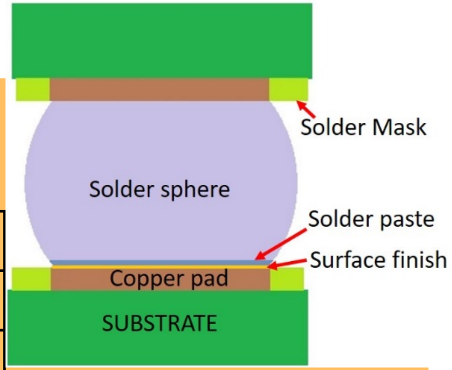
Data acquisition system

- Keithley 7002 switch scanning system and Keithley 2001 digital multimeters which are interconnected using LabView software
- The “failure” is defined as when the resistance increases by over 100 ohms for the five consecutive measurements





Component matrix – CABGA208



Aged components

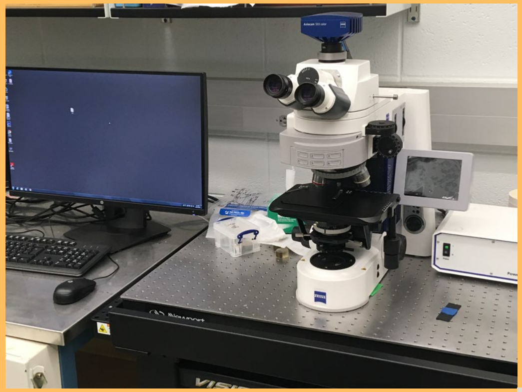
Finish	OSP			ImAg			ENIG		
Sphere	SAC105	SAC305	Match	SAC105	SAC305	Match	SAC105	SAC305	Match
Ind 1	5	5	5	5	5	5	5	5	5
A Inn	5	5	5	5	5	5	5	5	5
Ind 2	5	5	0	5	5	0	5	5	0
Sj 94	5	5	5	5	5	5	5	5	5
Ap Mx	5	5	5	5	5	5	5	5	5
Ac Cyx	5	5	5	5	5	5	5	5	5
Ac Ely	5	5	5	5	5	5	5	5	5
Hs Inn	5	5	0	5	5	0	5	5	0
Hs HT	5	5	5	5	5	5	5	5	5
Sj 58	5	5	5	5	5	5	5	5	5
Hk K	5	5	0	5	5	5	5	5	0
Hk L	5	5	0	5	5	0	5	5	0

Failure Analysis

Metallurgical sample preparation

- After the test, the failed samples were used for microstructure analysis.
- The sample is mounted in epoxy and left to cure.
- The sample for analysis is prepared by grinding and polishing.

Automated grinding/polishing machine



ZEISS Axio Imager.M2m

Microscopy

- The prepared sample is analyzed using ZEISS Axio Imager.M2m optical microscope with Axiocam 503 color microscope camera and ZENCore software.
- Extend of recrystallization was also analyzed from the polarized images.
- For further analysis, Hitachi S-2460N Scanning Electron Microscope is used.
- Chemical composition of the sample of interest is determined by EDX analysis.

Hitachi S-260N SEM

Data Analysis

Two parameter Weibull plot

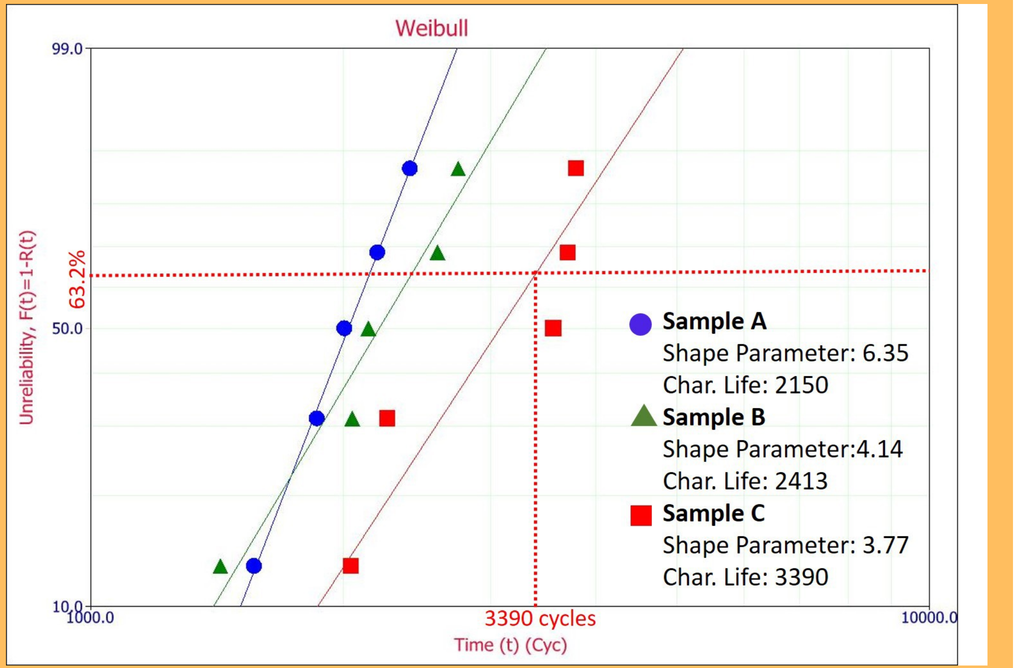
- Weibull analysis is done to quantify the performance of each combination.

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

where R(t) is the reliability at time ‘t’, β is the shape parameter and θ is the characteristic life, which is the time at which 63.2% of the samples are expected to fail.

- B10 life is also calculated for comparison of early failures.
- Right censoring is done for the samples that did not fail by the end of the test.

Percentage failure analysis is done to determine the time around which most of the failures occurred.

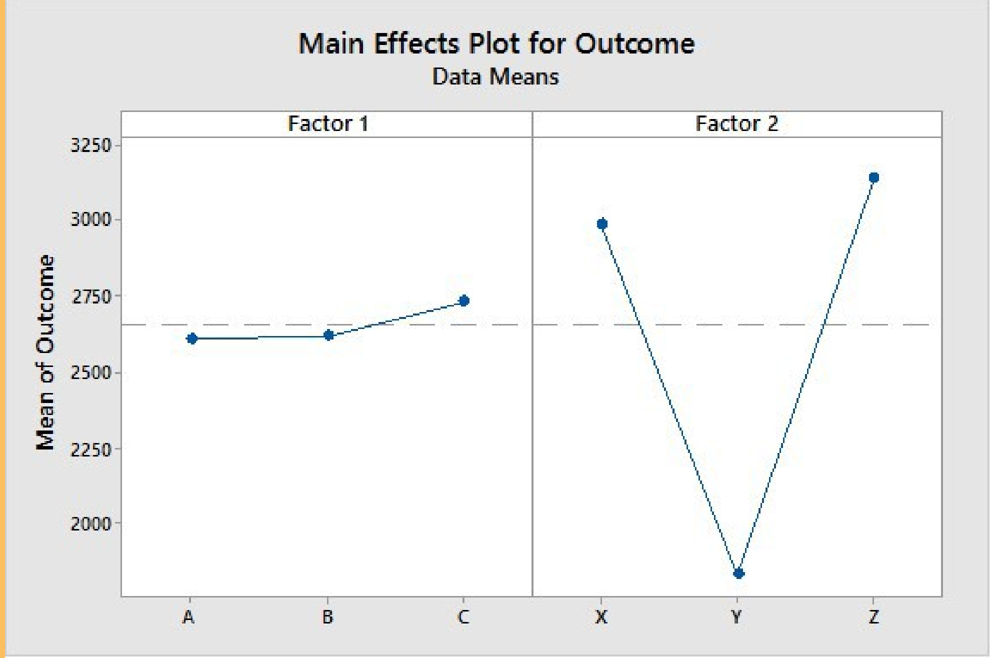


Weibull analysis for samples A, B and C

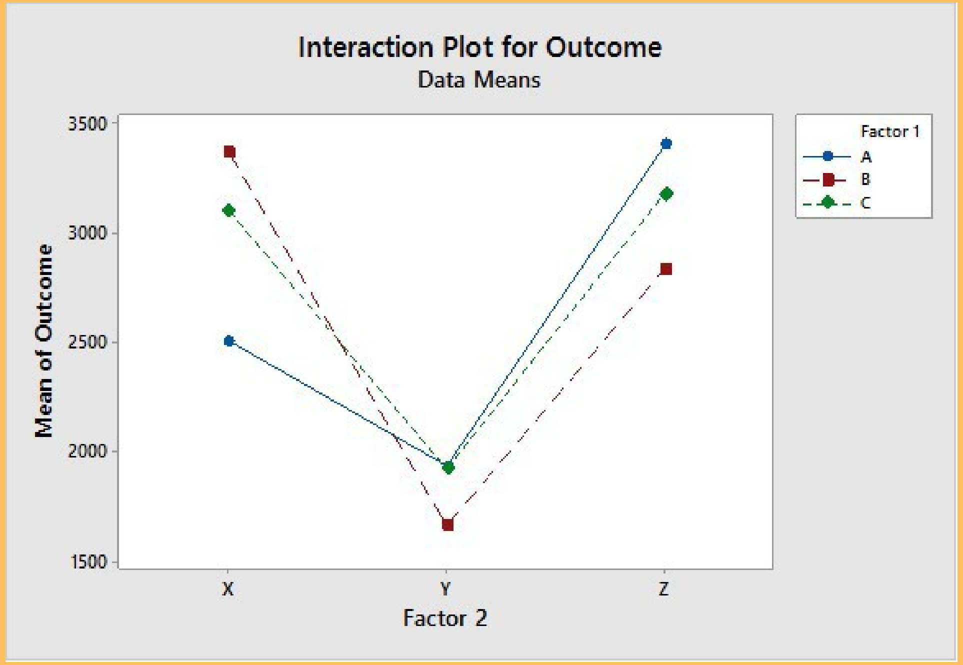
Data Analysis

ANOVA analysis

- ANOVA analysis is done to determine the most and least influential factors.
- In main effect plot, the influence of each factor on the outcome is considered separately and other factors are ignored.
- In reality, there would be always interaction between factors which could be analyzed using interaction plots.



Main effect plot for two factors, each with three levels.

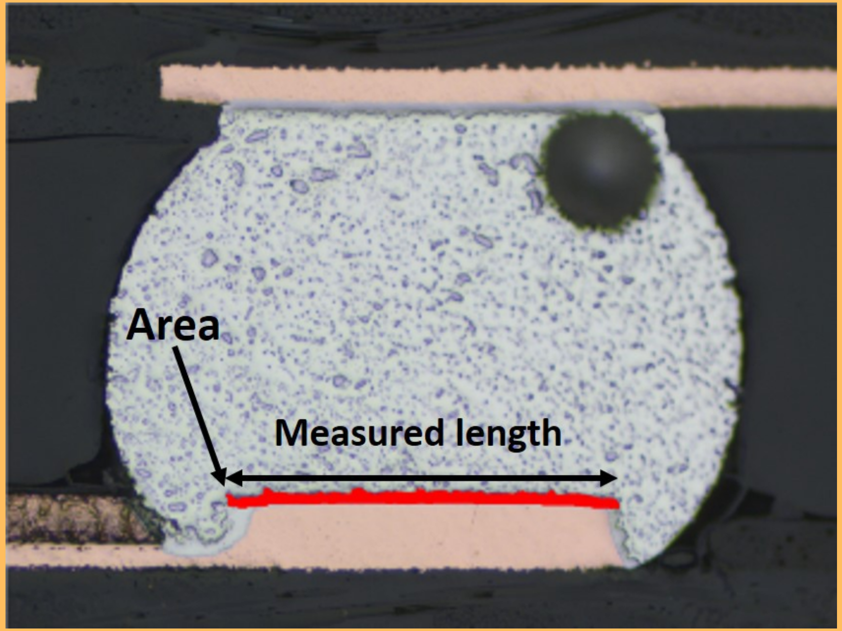


Interaction effect plot for two factors, each with three levels

IMC layer analysis

ANOVA analysis

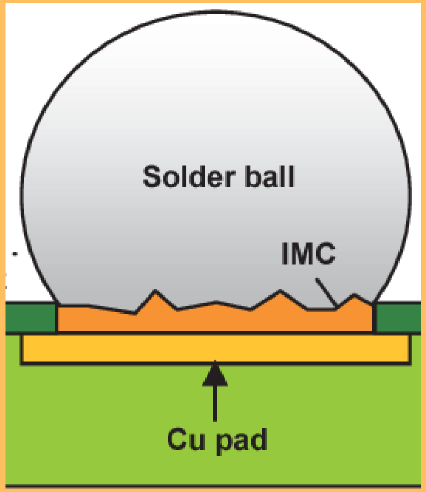
- The IMC layer thickness for each combination is measured to study its role on the component reliability.
- ANOVA analysis on IMC thickness is done to determine the factors responsible for IMC layer growth.
- The thickness is found by using the image processing tools in ZENCore software by ZEISS.



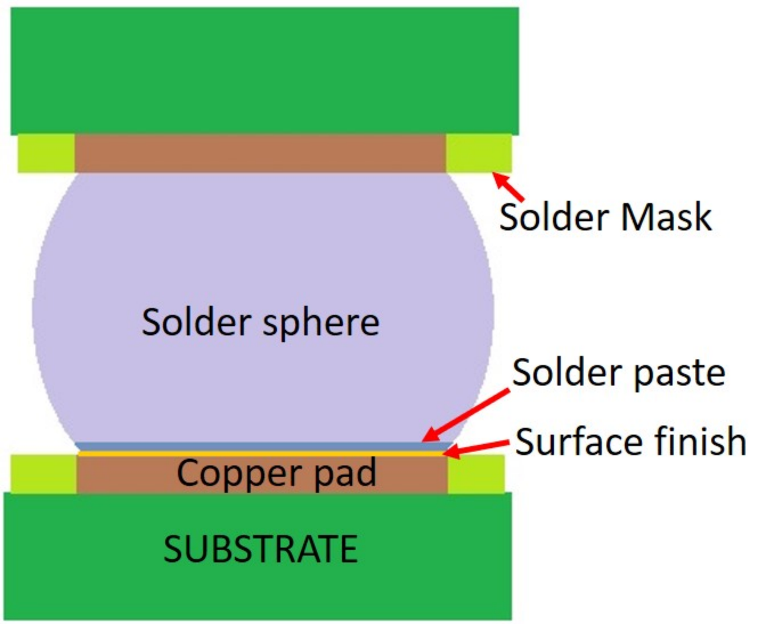
IMC layer thickness measurement

Effect of Surface Finish

AIM: To study the effect of surface finish on the component reliability



After reflow[1]



Parts of a solder joint

Surface finish

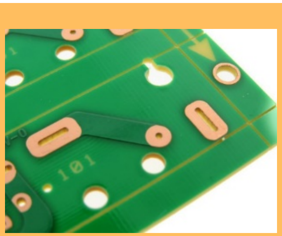
- Protect the copper pads prior to assembly
- During assembly, finish becomes a part of the solder joint
- Influence the reliability of the solder joint

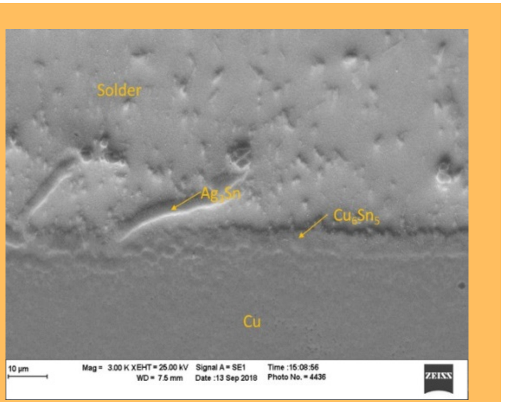
[1] Yang, L. et al. “Shear strength and brittle failure of low-Ag SAC-Bi-Ni solder joints during ball shear test.” *2013 14th International Conference on Electronic Packaging Technology* (2013): 750-753.

Surface Finishes

Organic Solderability Preserve (OSP)

- ✓ Water based organic finish, with a thin layer of carbon-based organic compound over copper.

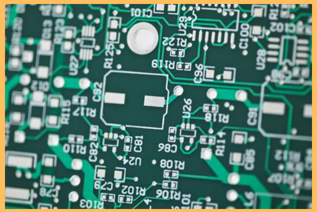


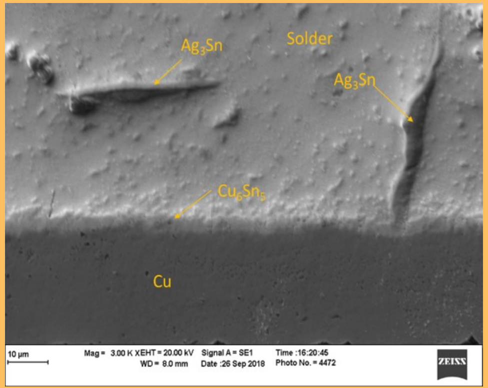


OSP finish[1]

Immersion Silver (ImAg)

- ✓ Has excellent solderability, long shelf life, easy probe testing, good thermal and mechanical reliability

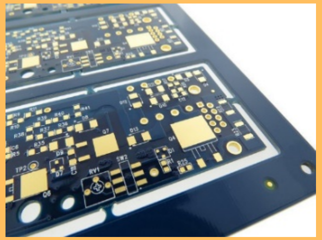


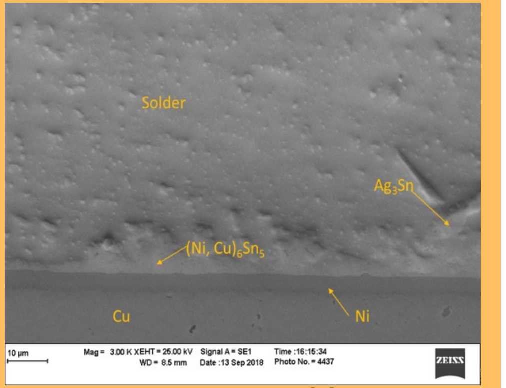


ImAg finish[1]

Electroless Nickel Immersion Gold (ENIG)

- ✓ Two-layer metallic coating over catalyzed copper; with Ni layer acting as a diffusion layer to copper, covered by gold that protects Ni from oxidation during storage.





ENIG finish[1]

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[1] S. Su, S. Hamasha and K. Hamasha, "Effect of Surface Finish on the Shear Properties of SnAgCu-Based Solder Alloys," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 9, no. 8, pp. 1473-1485, Aug. 2019, doi: 10.1109/TCPMT.2019.2928267.

Test setup

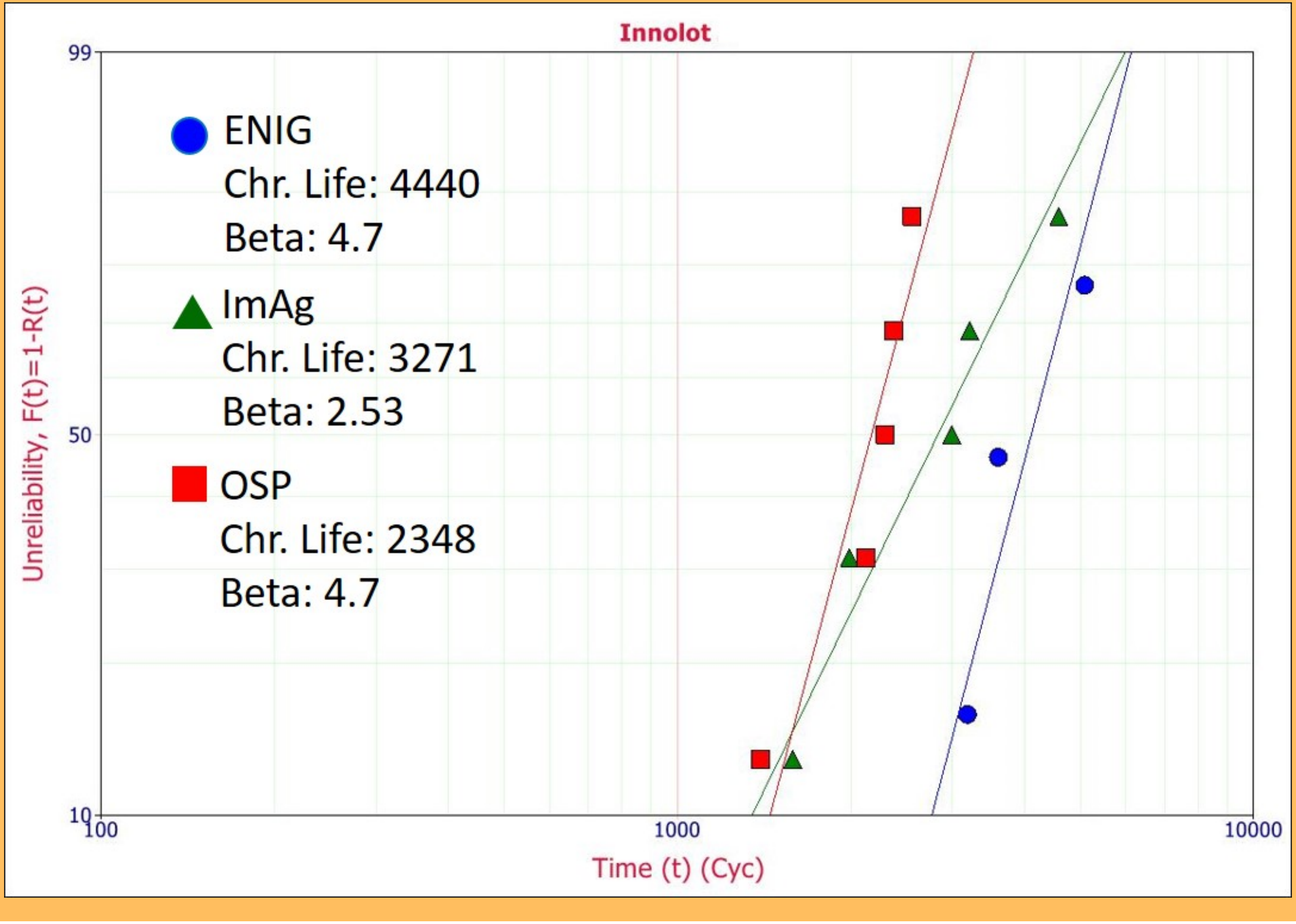
Solder alloys involved:

Solder paste	Label	Composition
A_Inn	Innolot	Sn-3.80Ag-0.70Cu-0.15Ni-1.40Sb-3.00Bi
A_Mx	SAC-Bi	Sn-3.8Ag-0.8Cu-2.8Bi
SAC305	SAC305	Sn-3.0Ag-0.5Cu

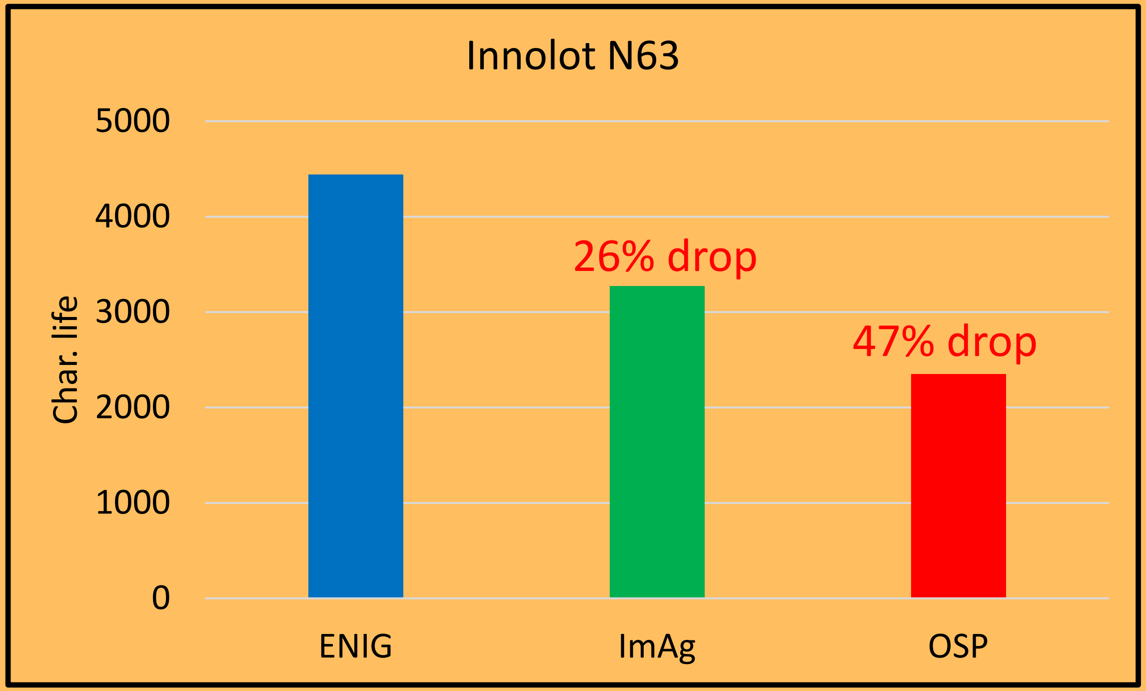
Test matrix:

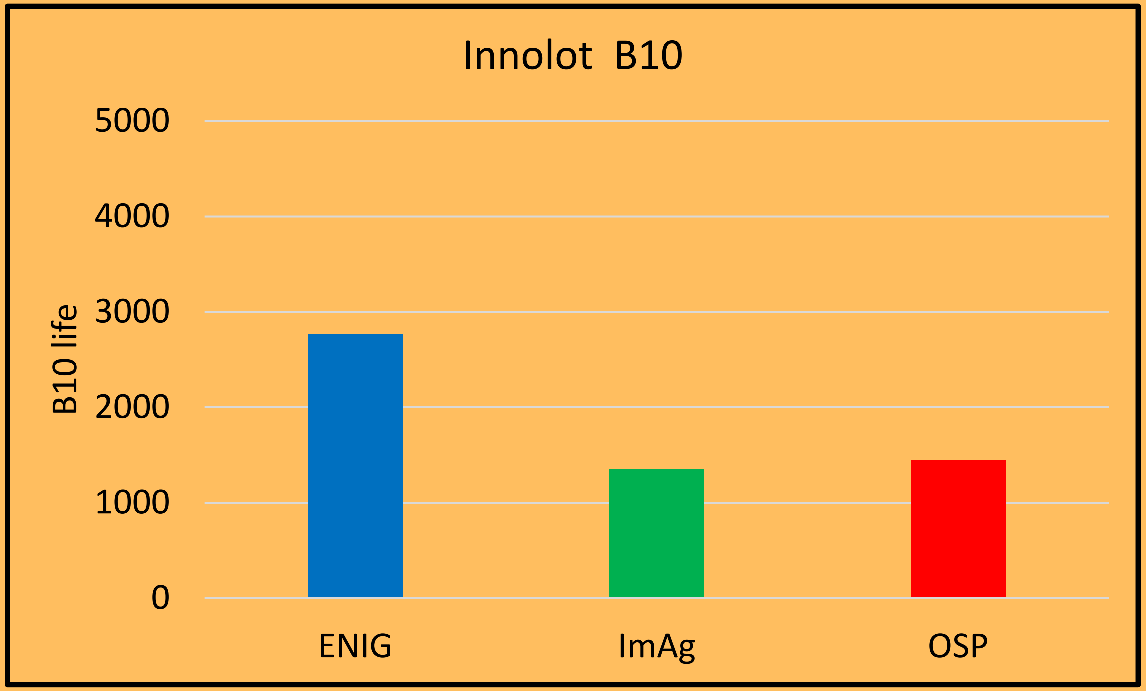
Component	Solder paste/sphere	Surface Finish
CABGA208	Innolot	ENIG
		ImAg
		OSP
	SAC-Bi	ENIG
		ImAg
		OSP
	SAC 305	ENIG
		ImAg
		OSP

Results (Innolot alloy)

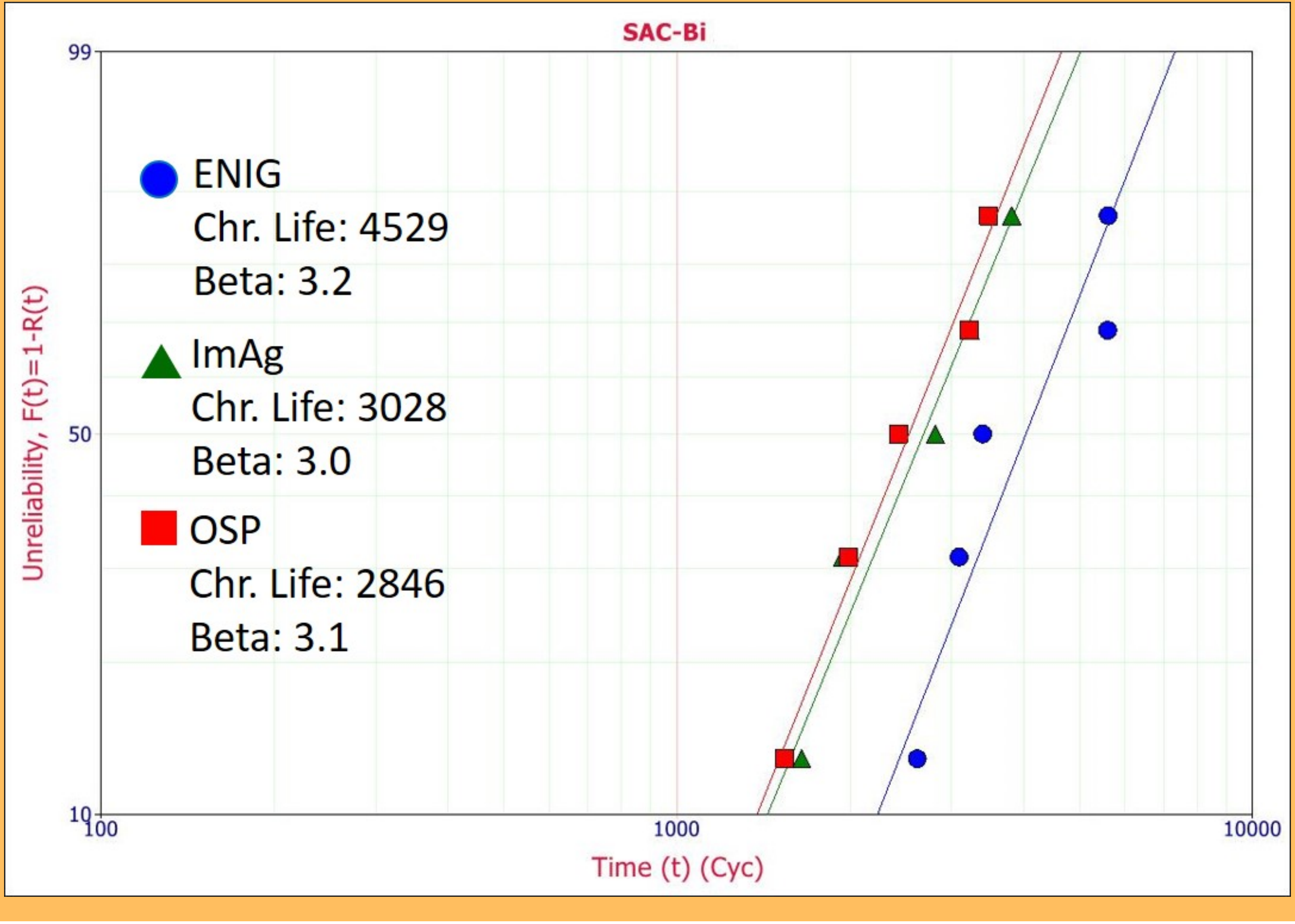


Results (Innolot alloy)

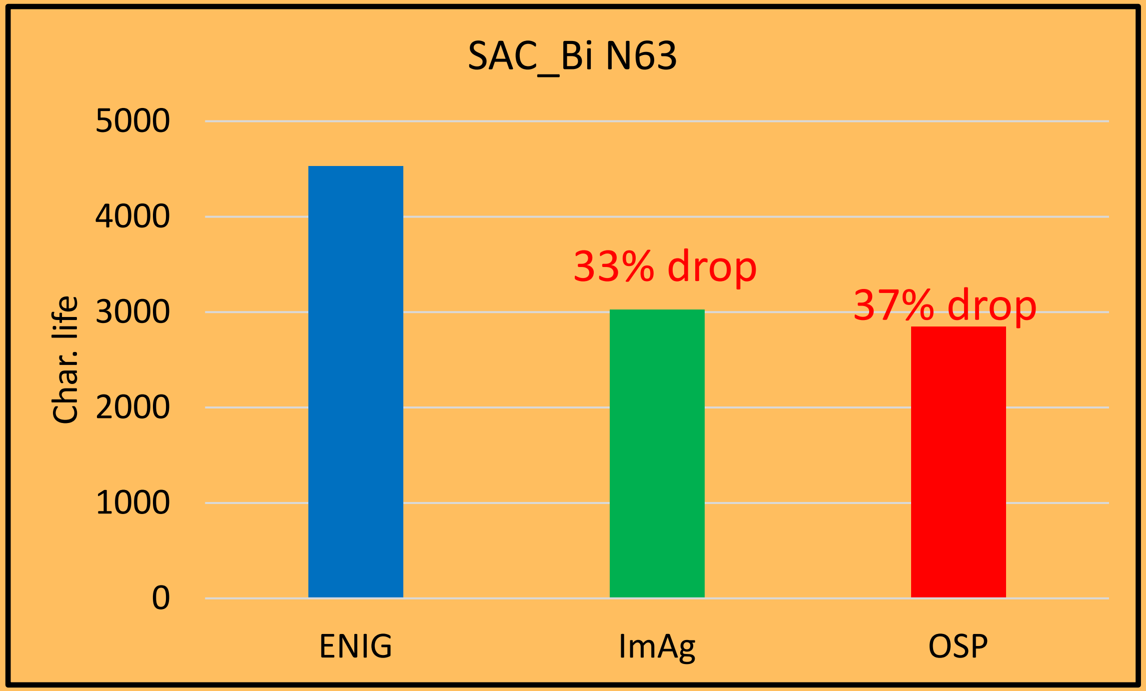


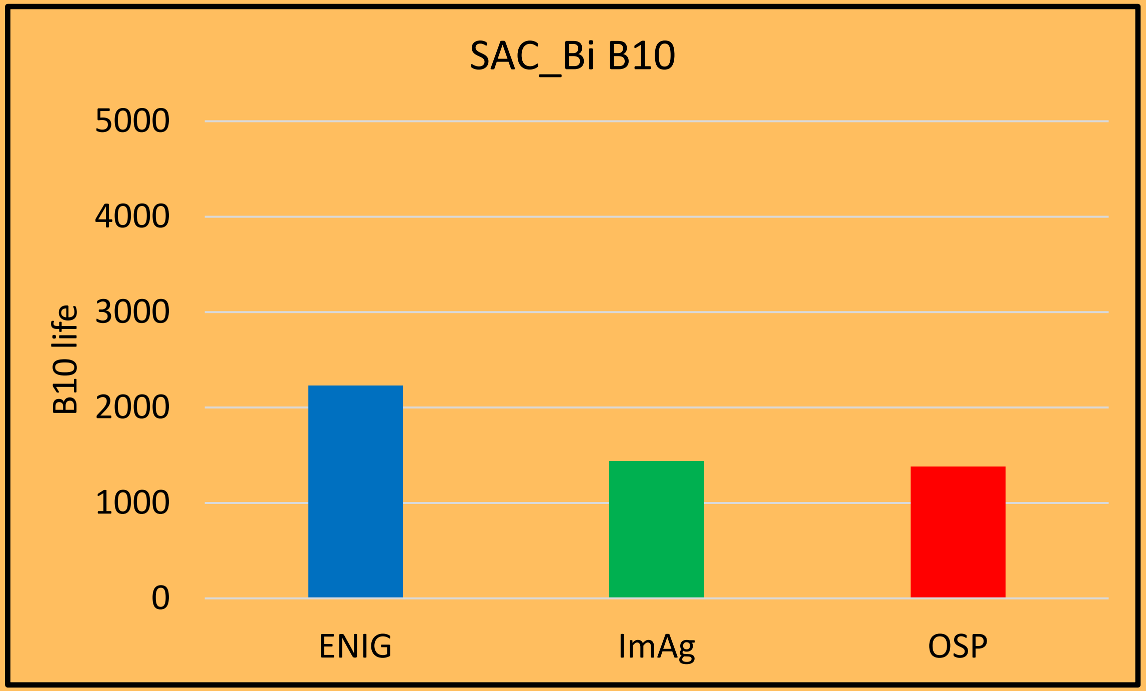


Results (SAC-Bi alloy)

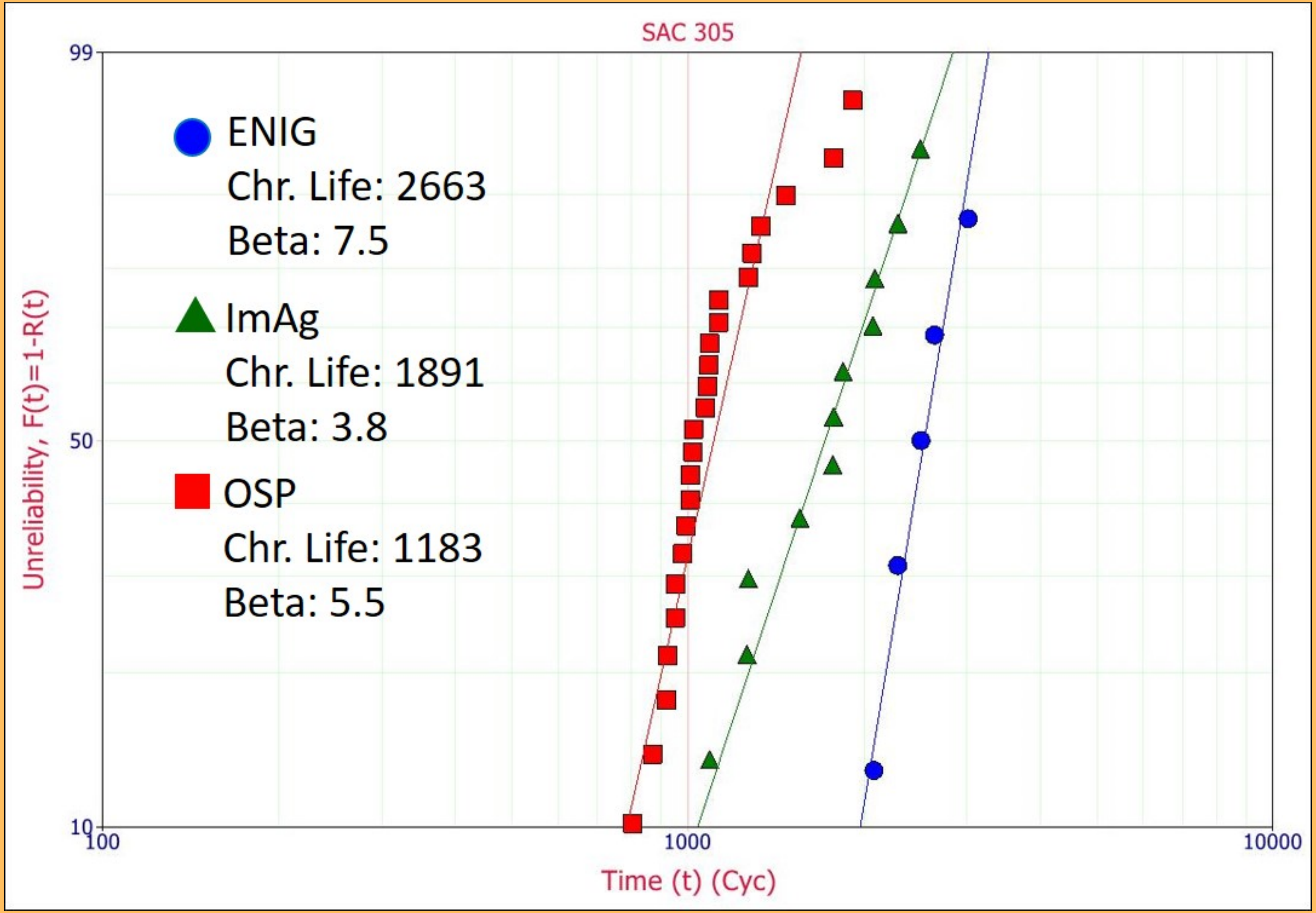


Results (SAC-Bi alloy)

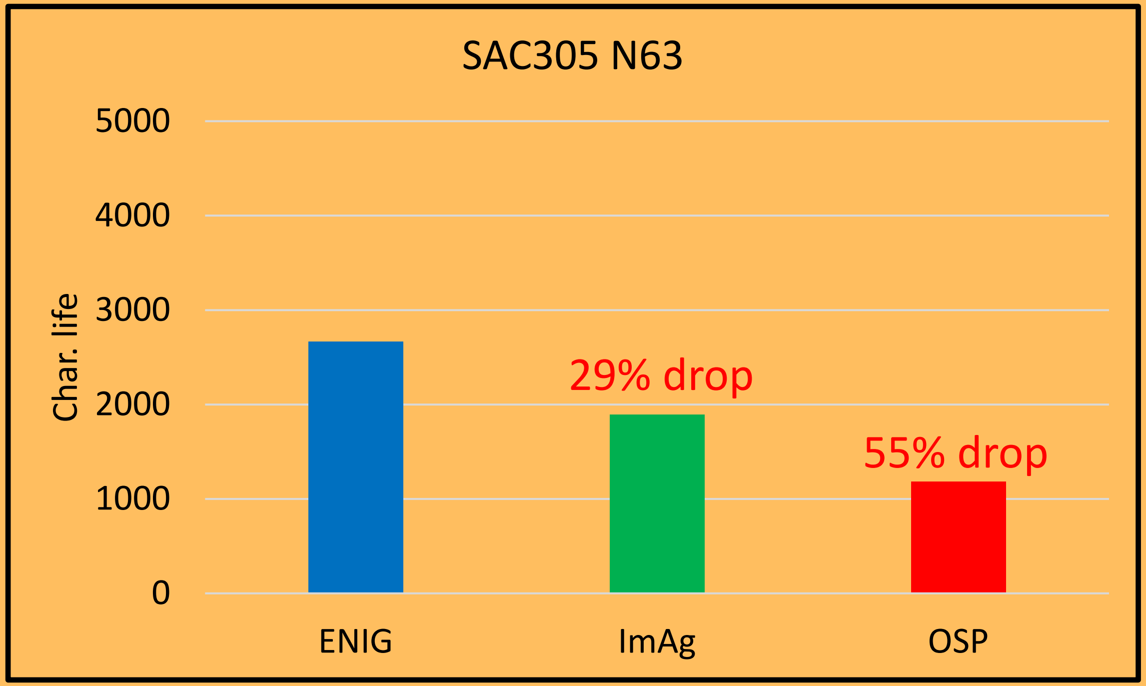


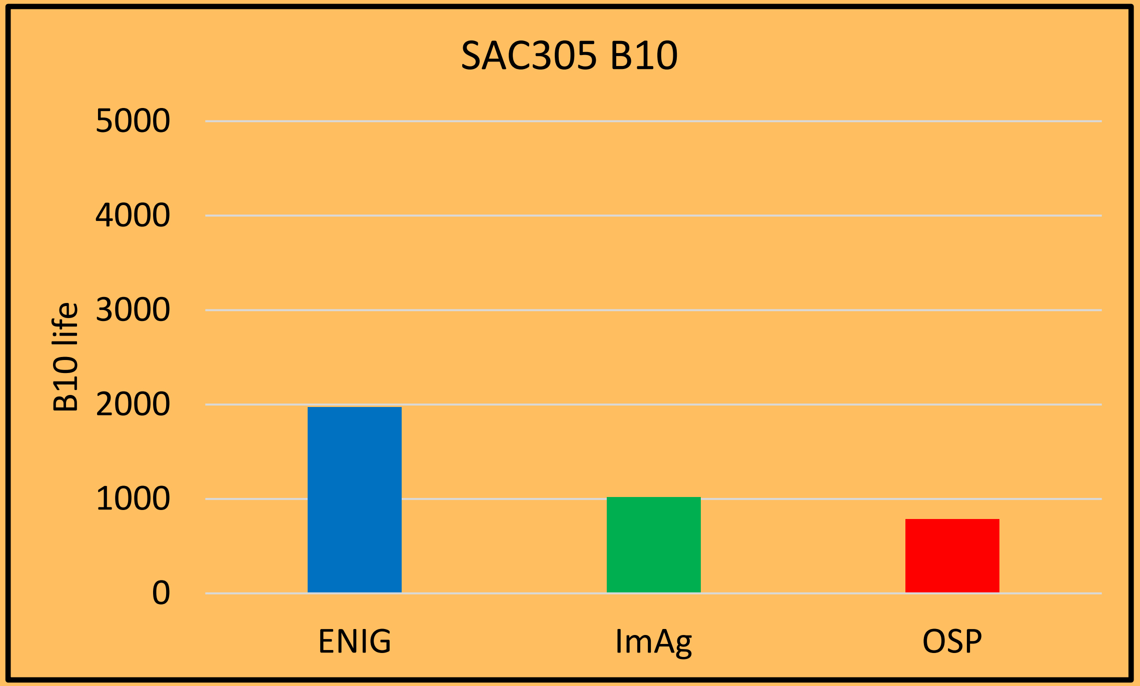


Results (SAC305 alloy)

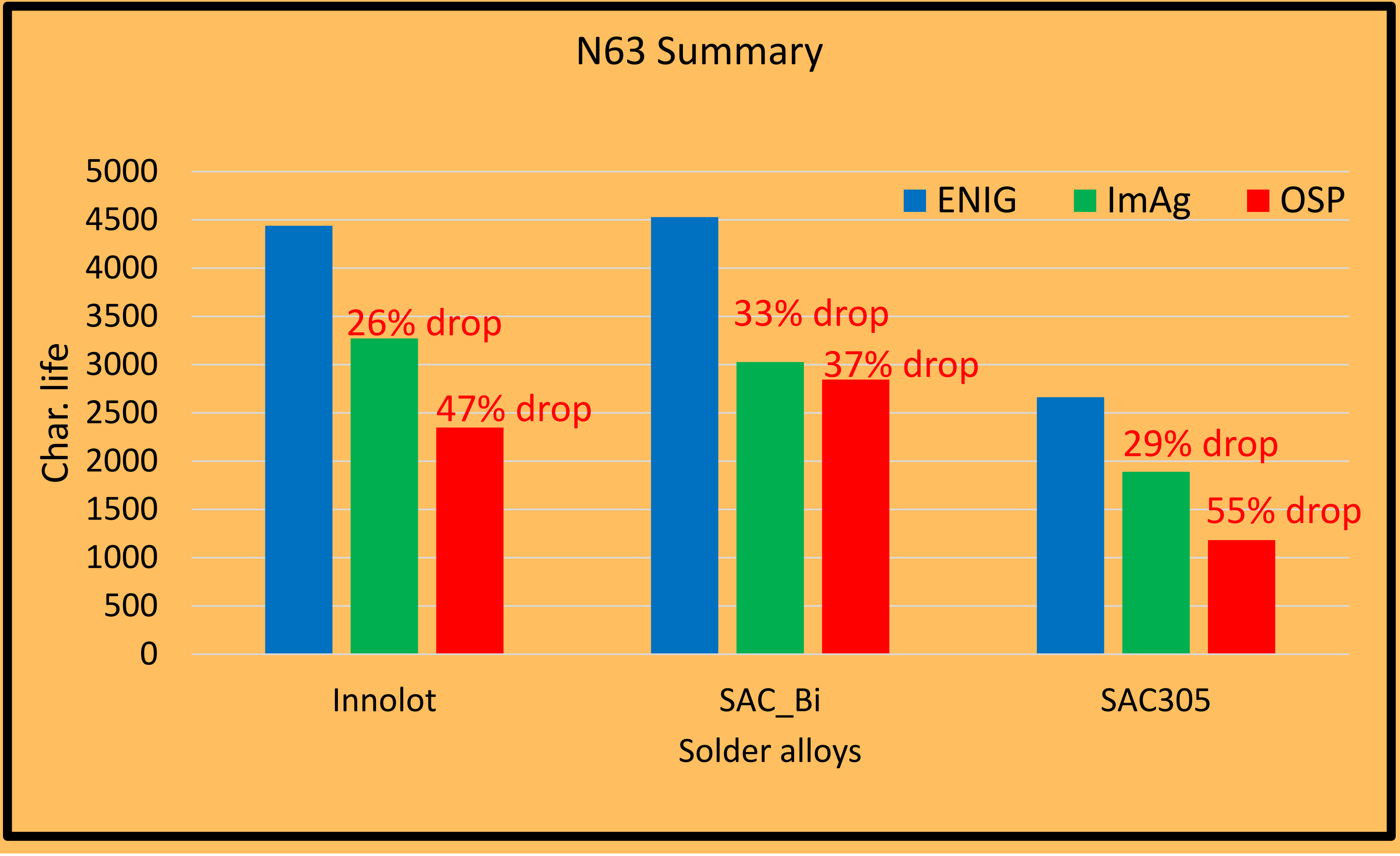


Results (SAC305 alloy)

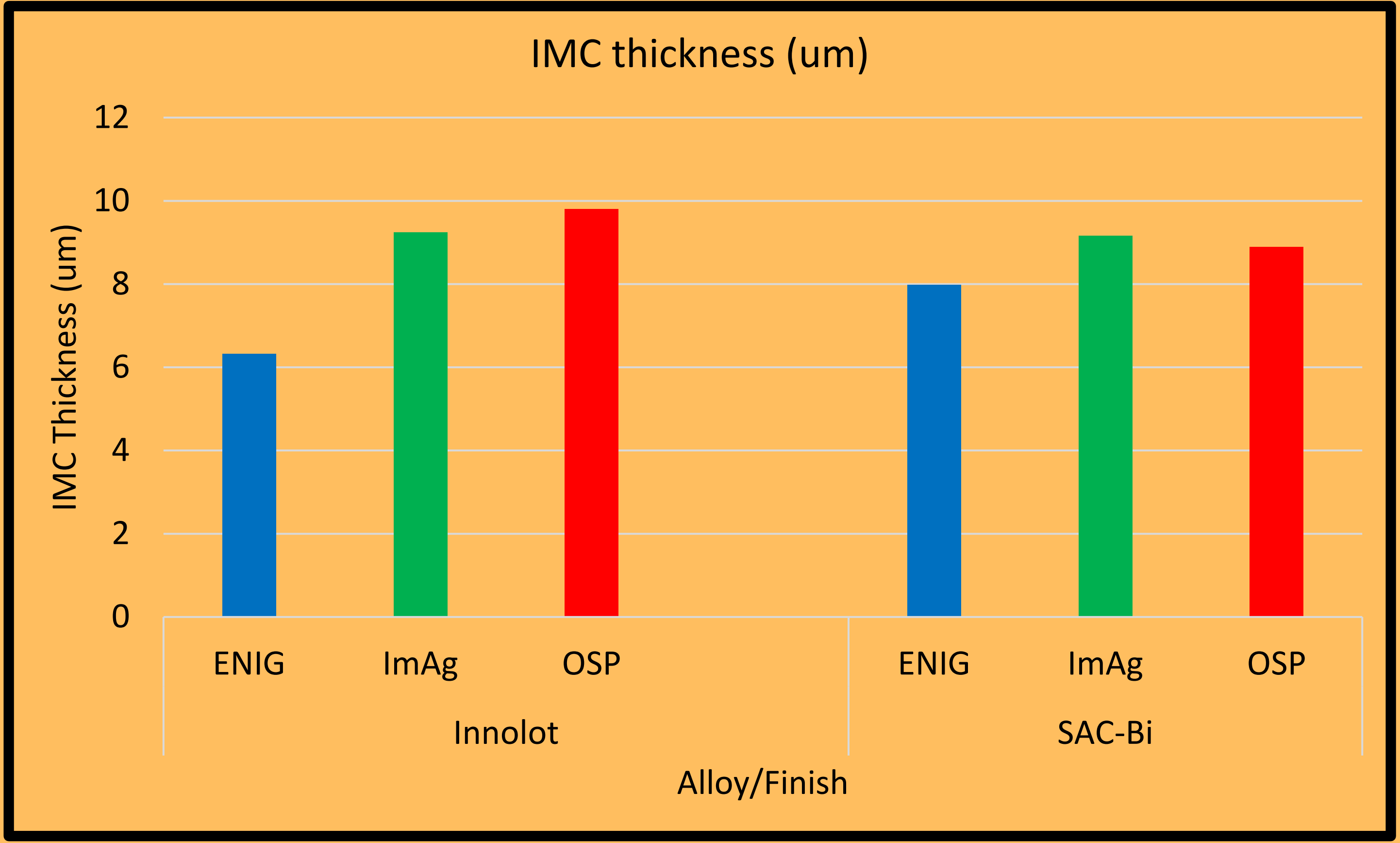


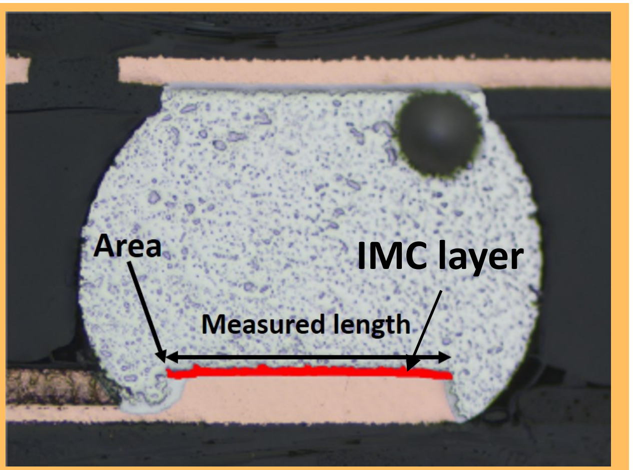


Results (Char. Life summary)



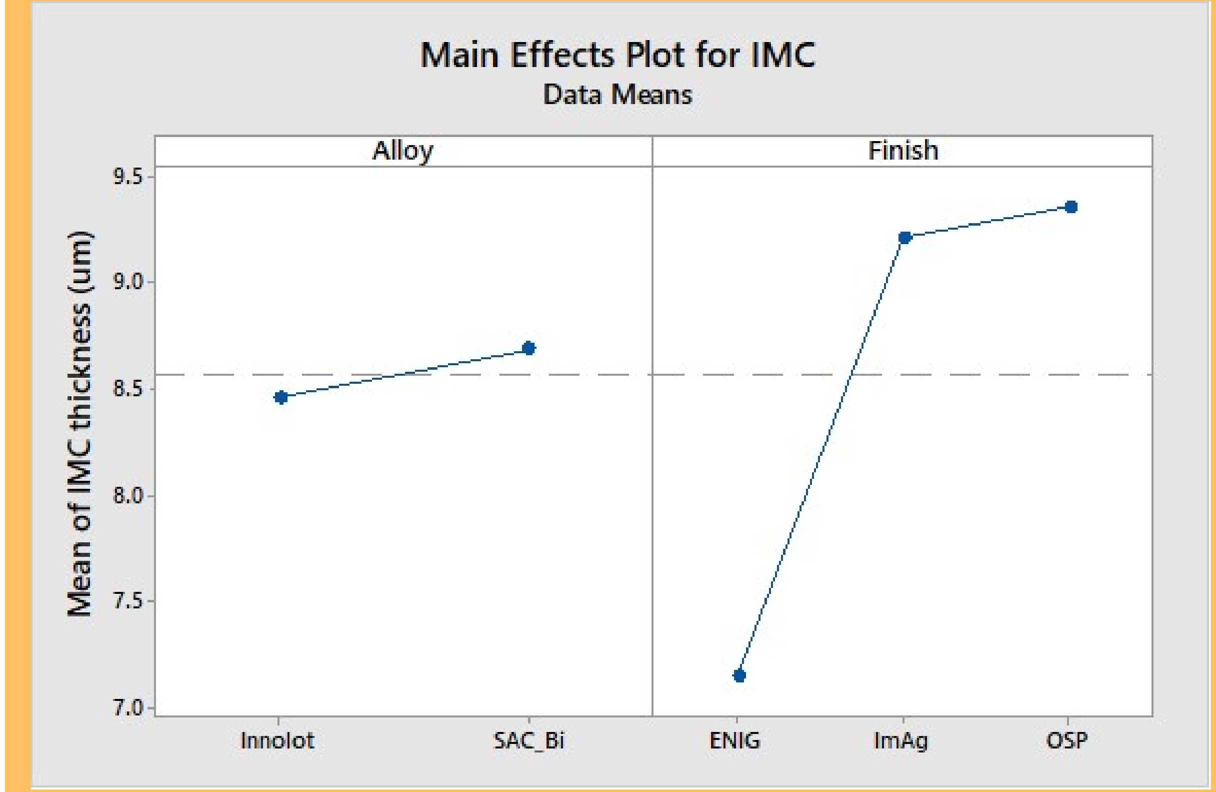
Results (IMC layer thickness)

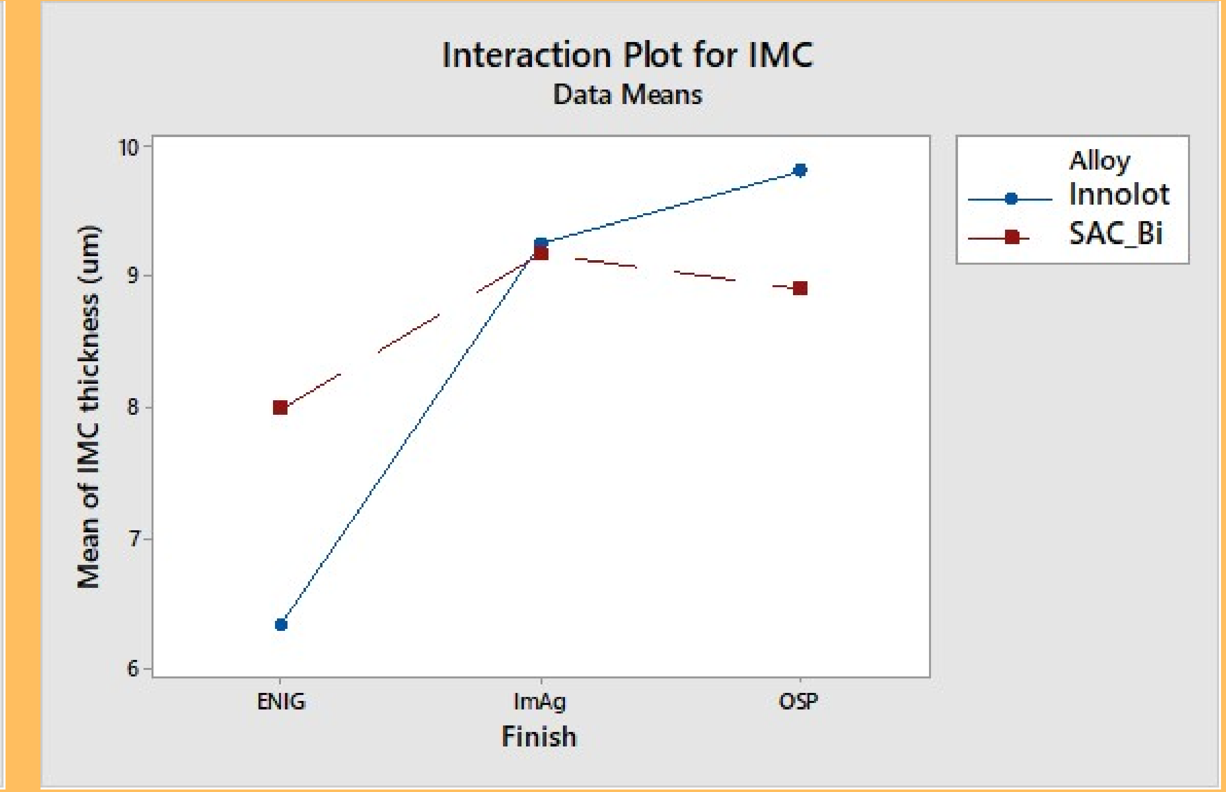




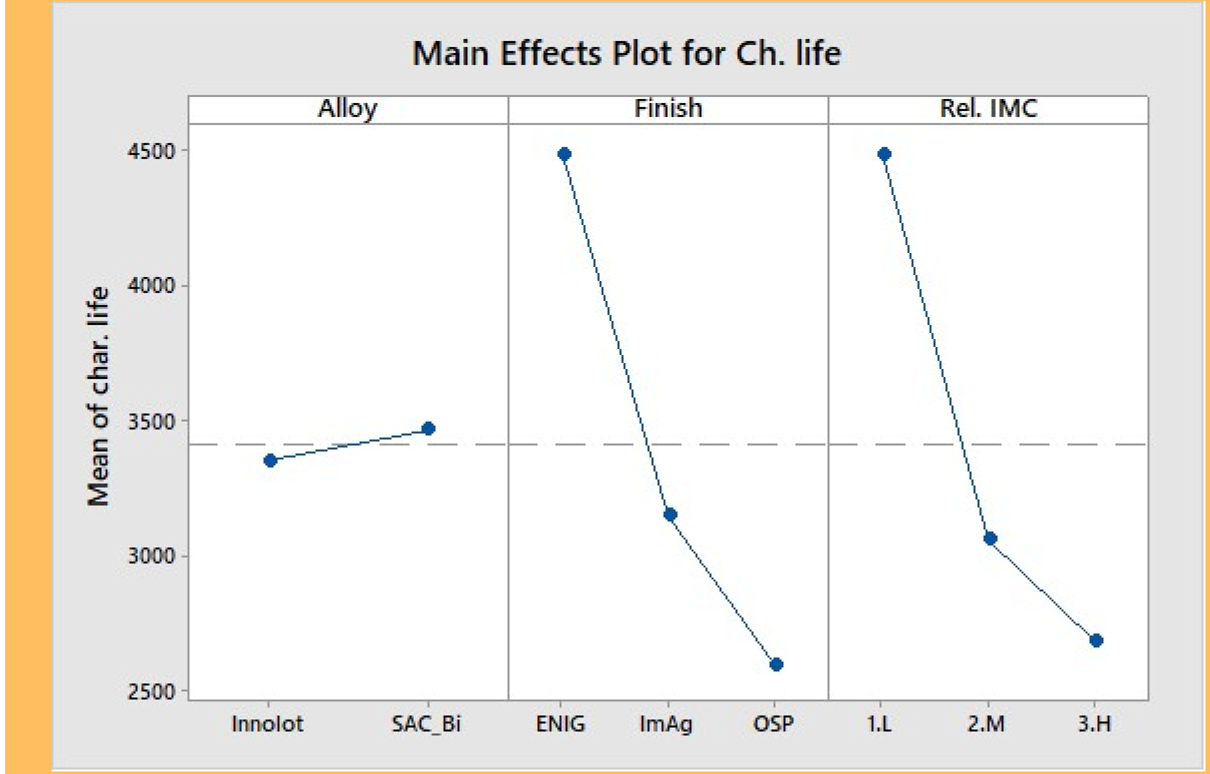
At least three measurements for each alloy-finish combination.

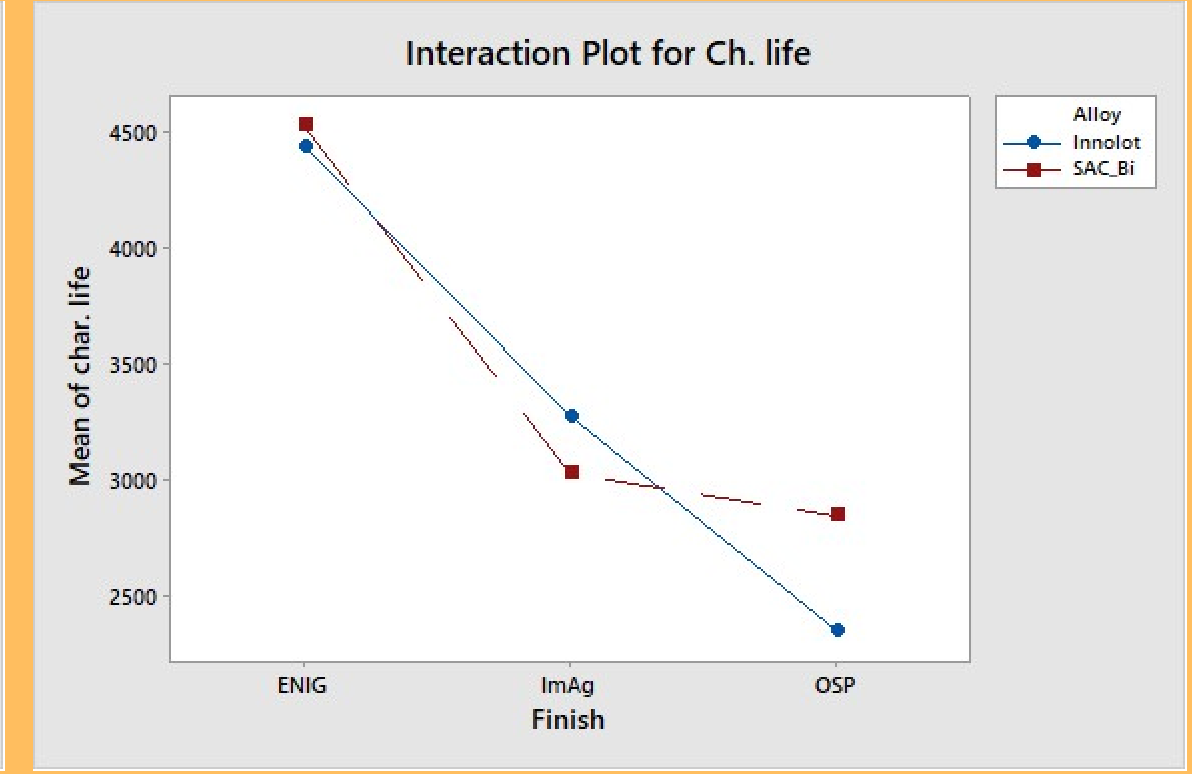
Results (ANOVA – IMC thickness)





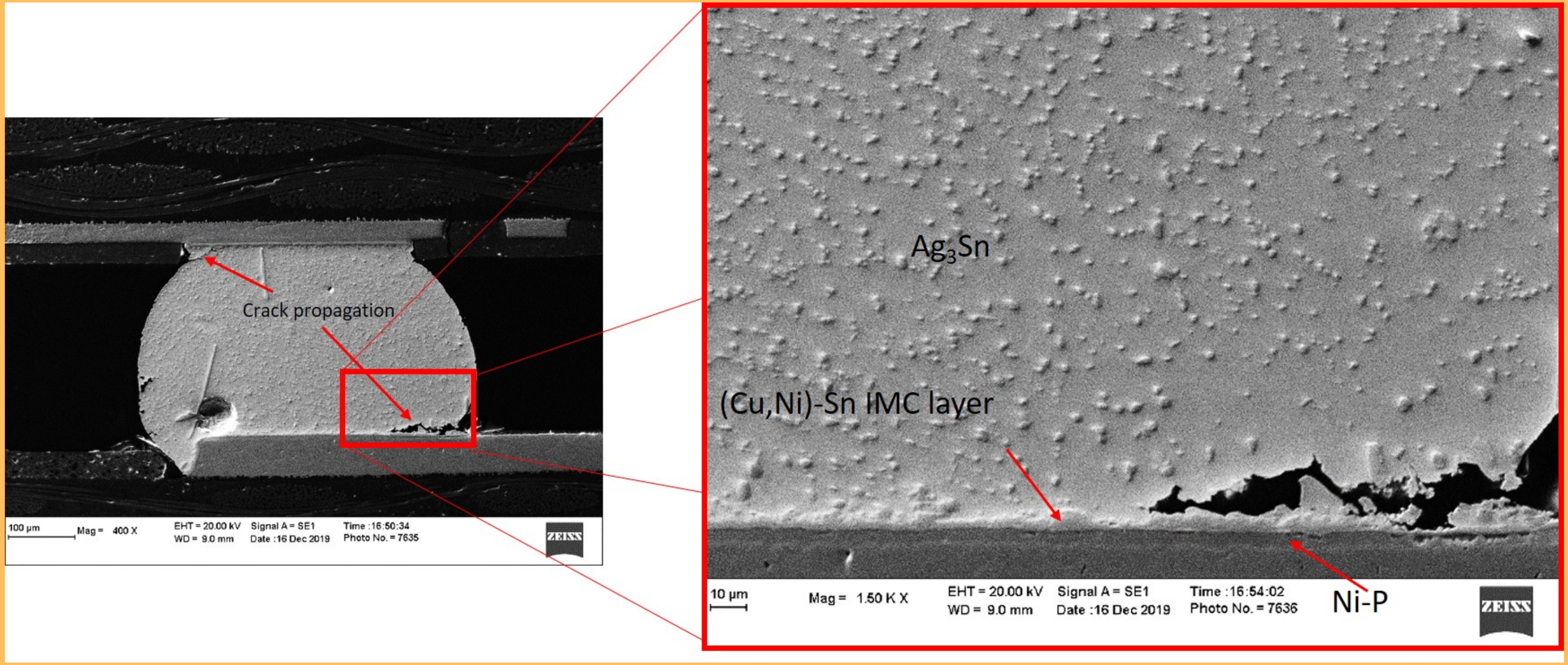
Results (ANOVA – char. life)





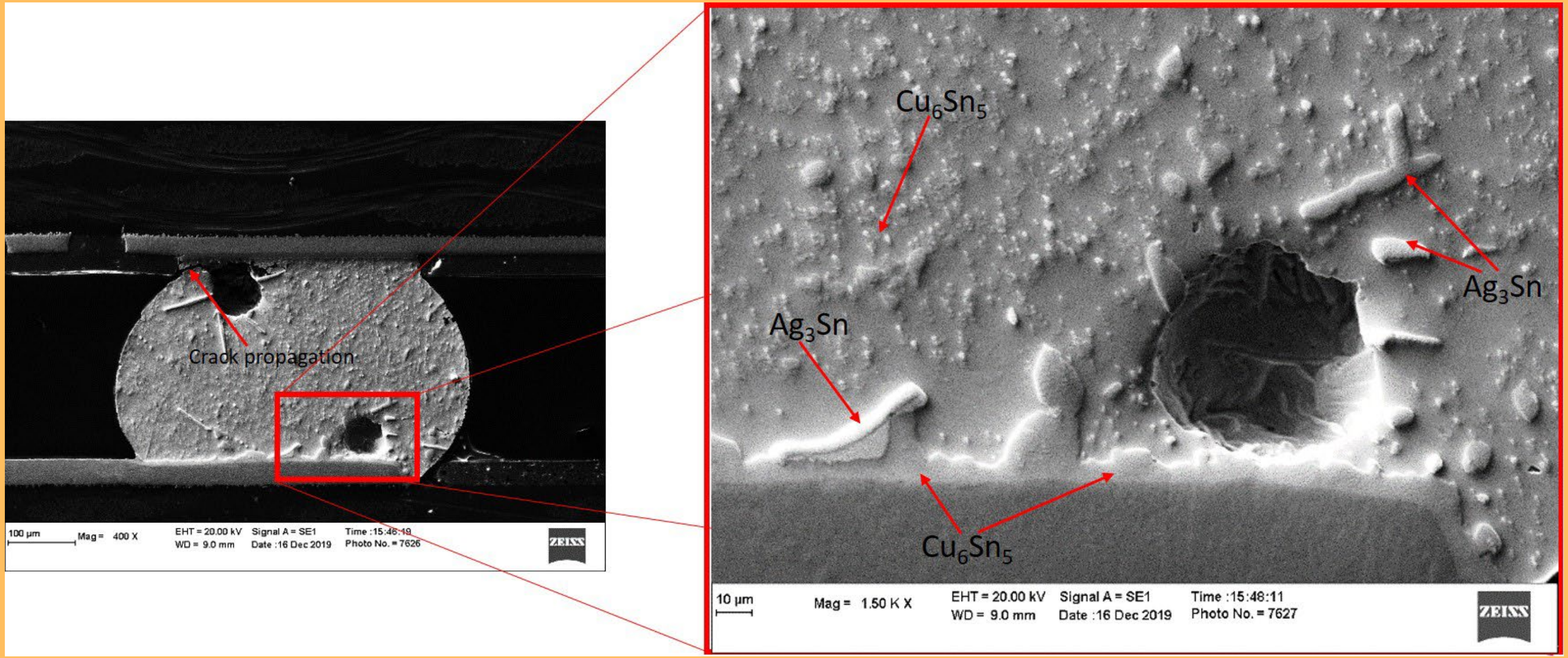
Rel. IMC: Relative IMC layer thickness in each alloy

Failure Analysis



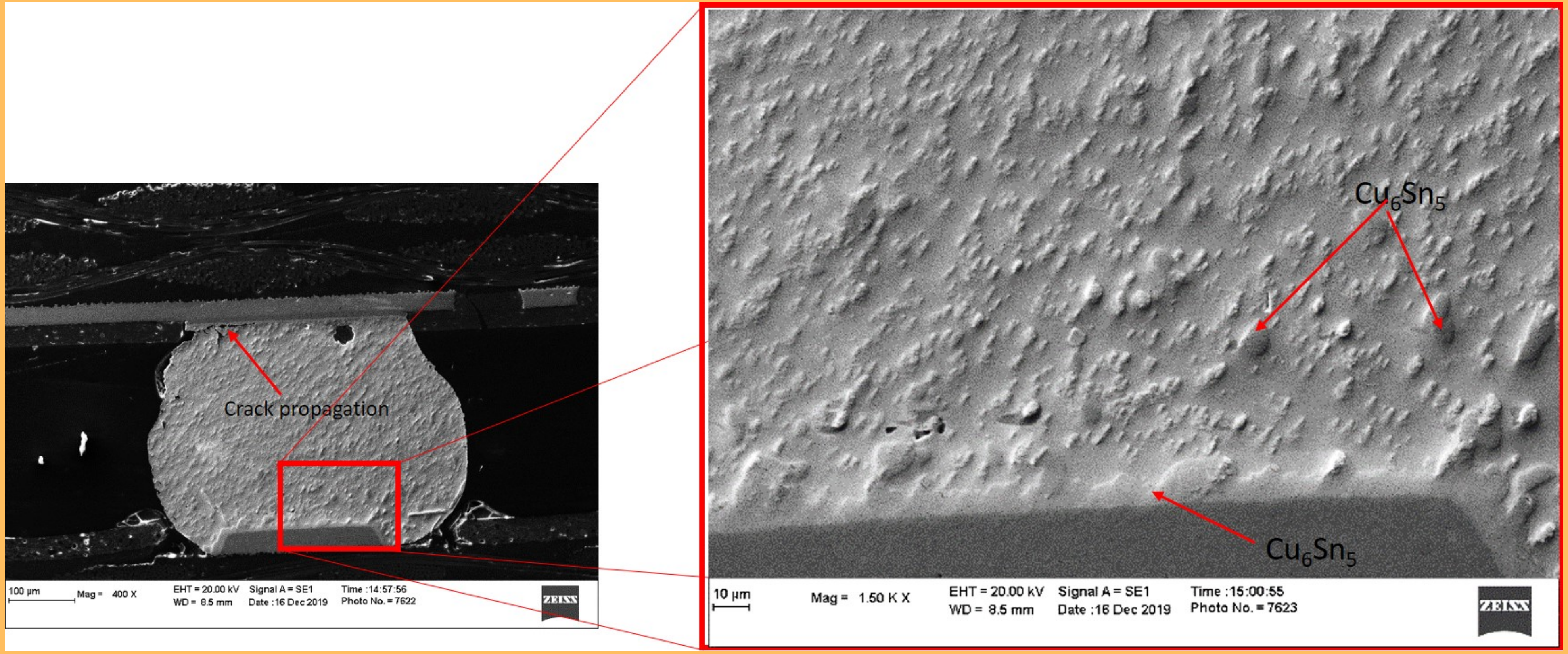
SEM image of SAC-Bi with ENIG finish

Failure Analysis



SEM image of SAC-Bi with ImAg finish

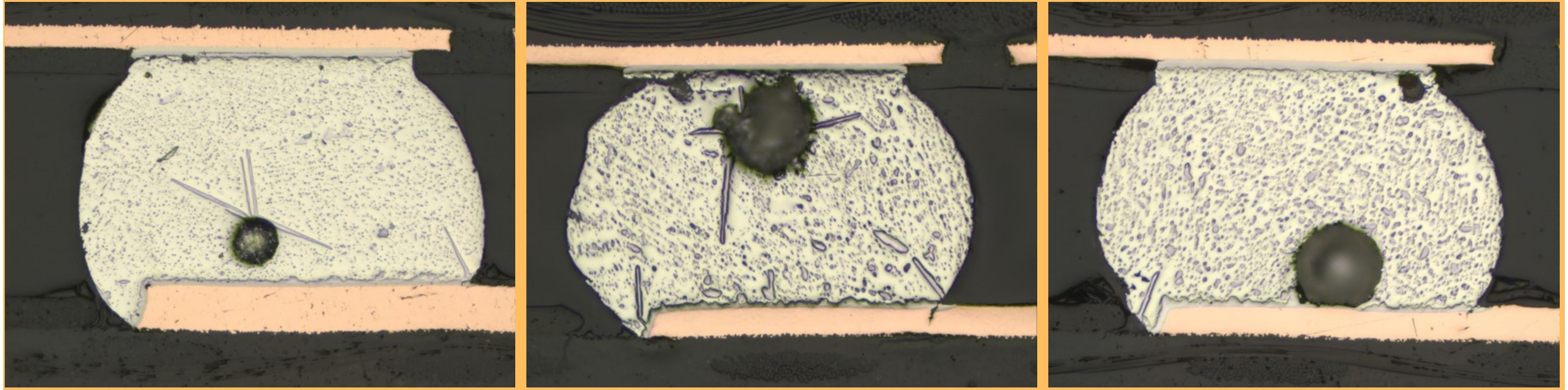
Failure Analysis



SEM image of SAC-Bi with OSP finish

Failure Analysis

Dark field images of SAC-Bi solder joint with different finishes



ENIG ImAg OSP

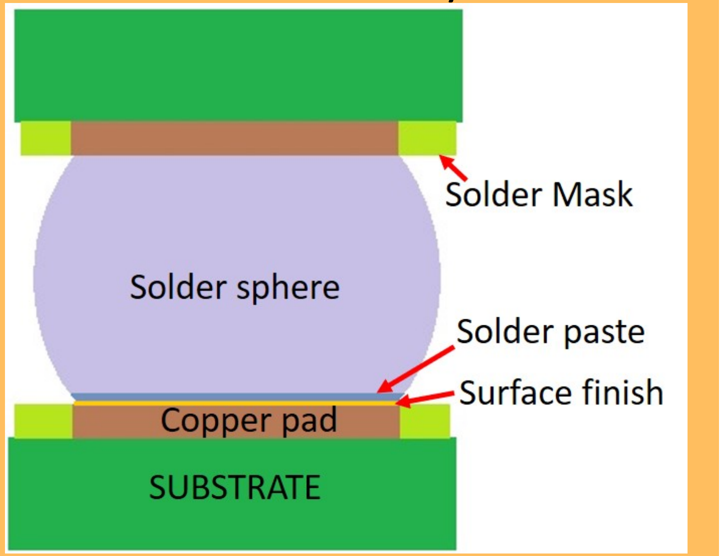
Conclusion

- The effect of different surface finishes were studied with Innolot and SAC-Bi solder alloys
- Significant improvement in reliability was found when ENIG was used with either of the alloys in the study
- ENIG was followed by ImAg and OSP
- Among the alloys, micro-alloyed Innolot and SAC-Bi outperformed SAC305 alloy
- The effect of surface finish was clearly visible in the case of microstructure as solder joint with ENIG had finer and uniformly distributed IMC precipitates.

Effect of micro-alloying new elements

AIM: To study the effect of micro-alloying new elements on the component reliability in thermal cycling

- Microstructure with fine and uniformly distributed IMC precipitates could be co-related with better reliability
- Factors influencing the microstructure of the solder joint (considered in the study):
  - ✓ Solder sphere alloy
  - ✓ Solder paste alloy
  - ✓ Surface finish

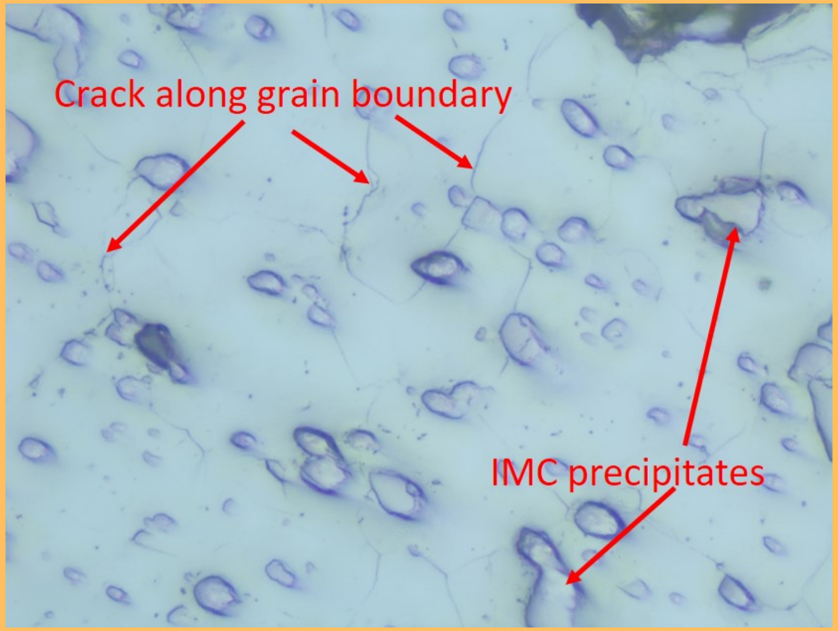


Parts of a solder joint

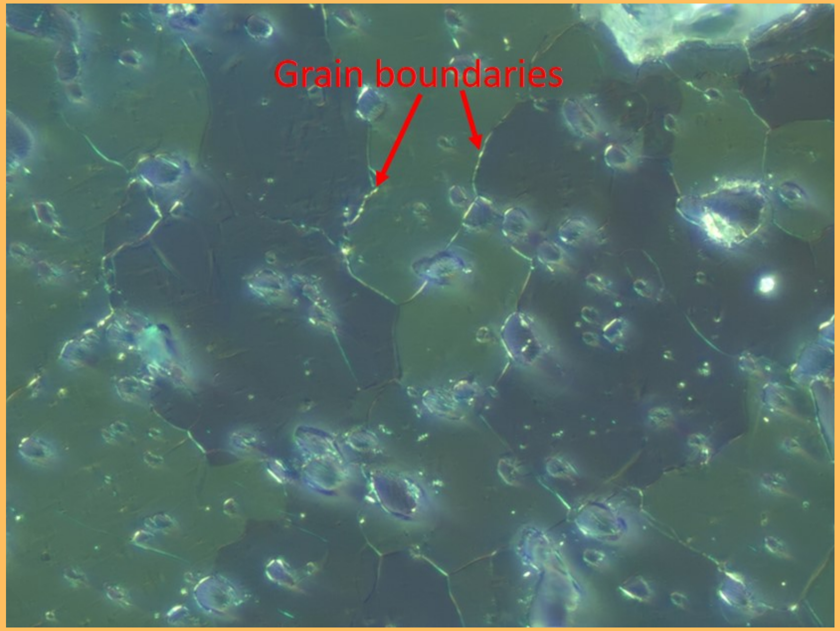
Theory

When the solder joints are exposed to thermal cycling:

- Stress develops in the solder joints due to CTE mismatch between package and PCB
- The joints are fatigued after exposure to several thermal cycles



Bright-field image

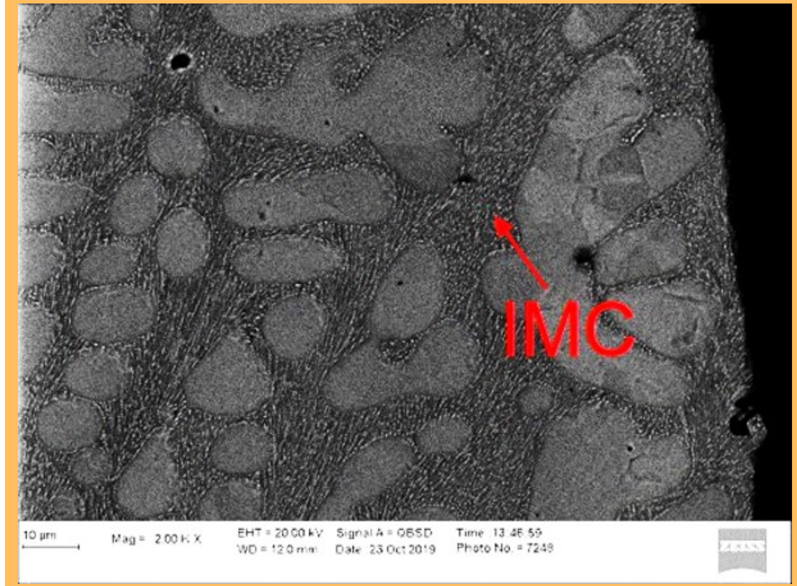


Polarized image

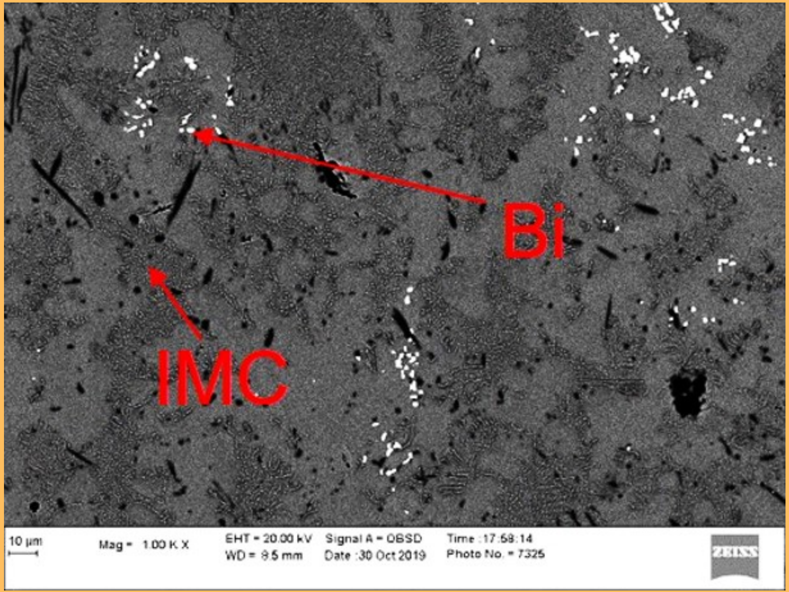
- Recrystallization occurs in the regions of strain concentration and micro-cracks develop along the grain boundaries
- Once the crack is initiated, it propagates along these grain boundaries and gradually leads to failure

Theory

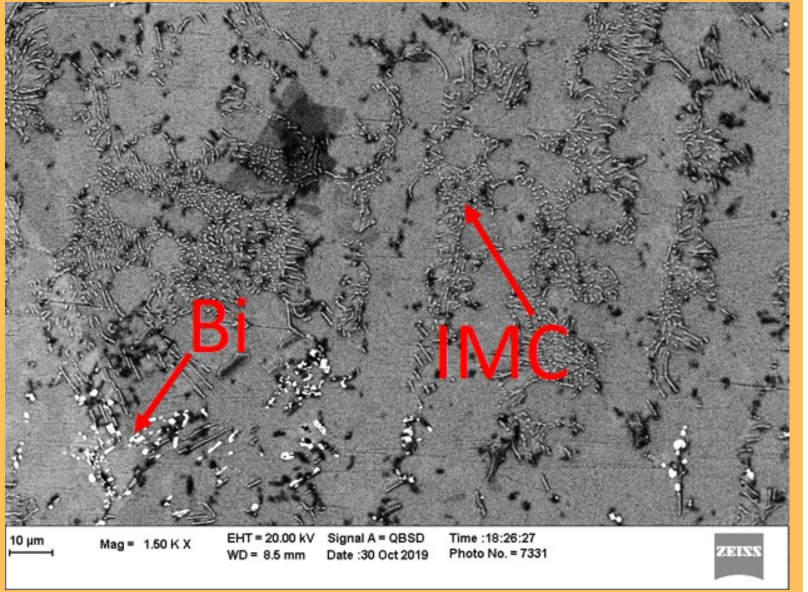
Comparison of microstructure after assembly



SAC305



SAC-Bi



Innolot

Test setup

Solder alloys involved

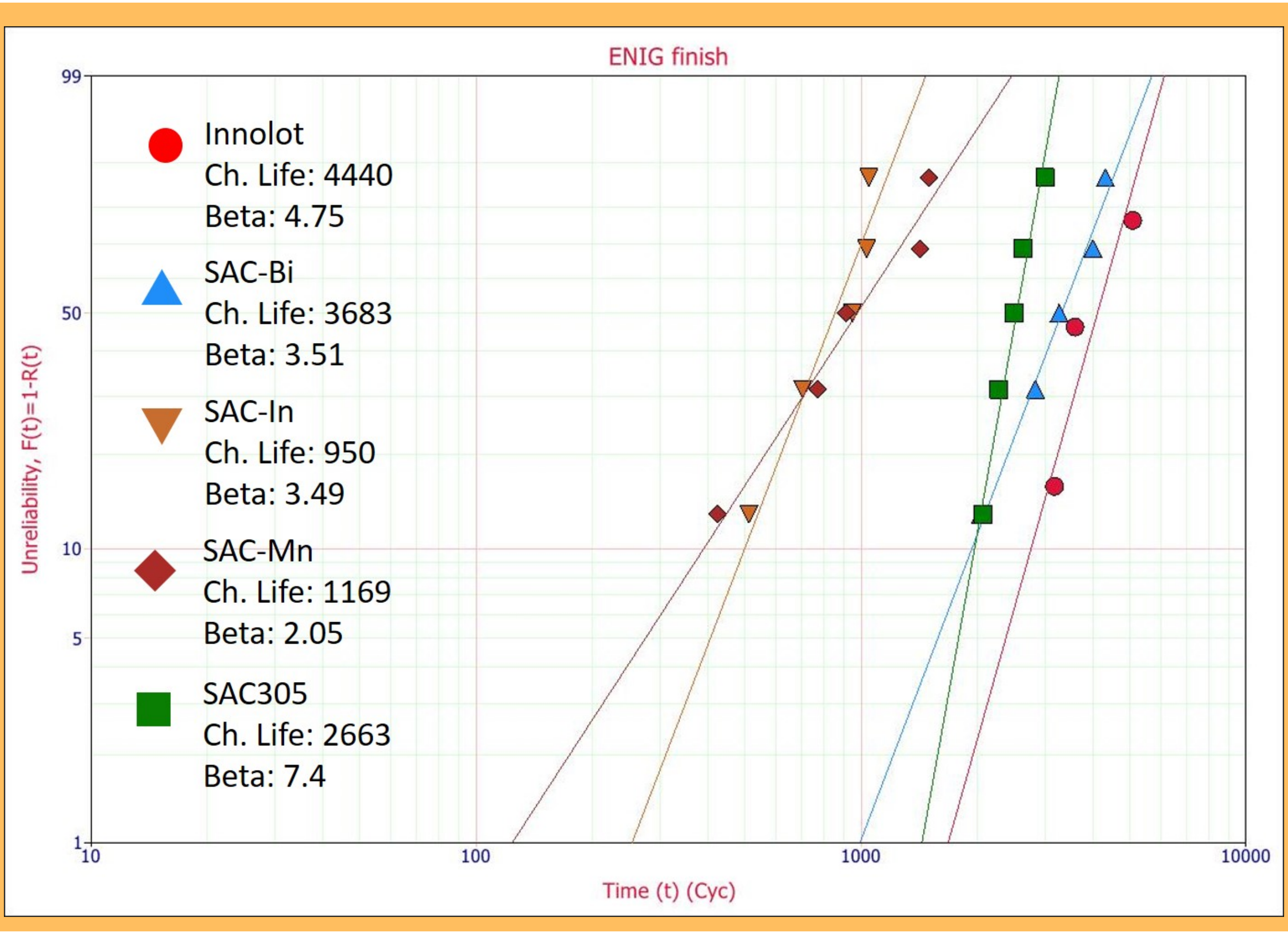
Paste	Label	Composition
A_Inn	Innolot	90.95Sn-3.80Ag-0.70Cu-0.15Ni-1.40Sb-3.00Bi
Ac_Cyx	SAC-Bi	92.77Sn-3.41Ag-0.52Cu-3.3Bi
Hs_HT	SAC-In	Sn-2.5Ag-0.5Cu-2In-0.03Nd
Ind_1	SAC-Mn	98.47Sn-0.5Ag-1.0Cu-0.03Mn
SAC305	SAC305	Sn-3.0Ag-0.5Cu

Test setup

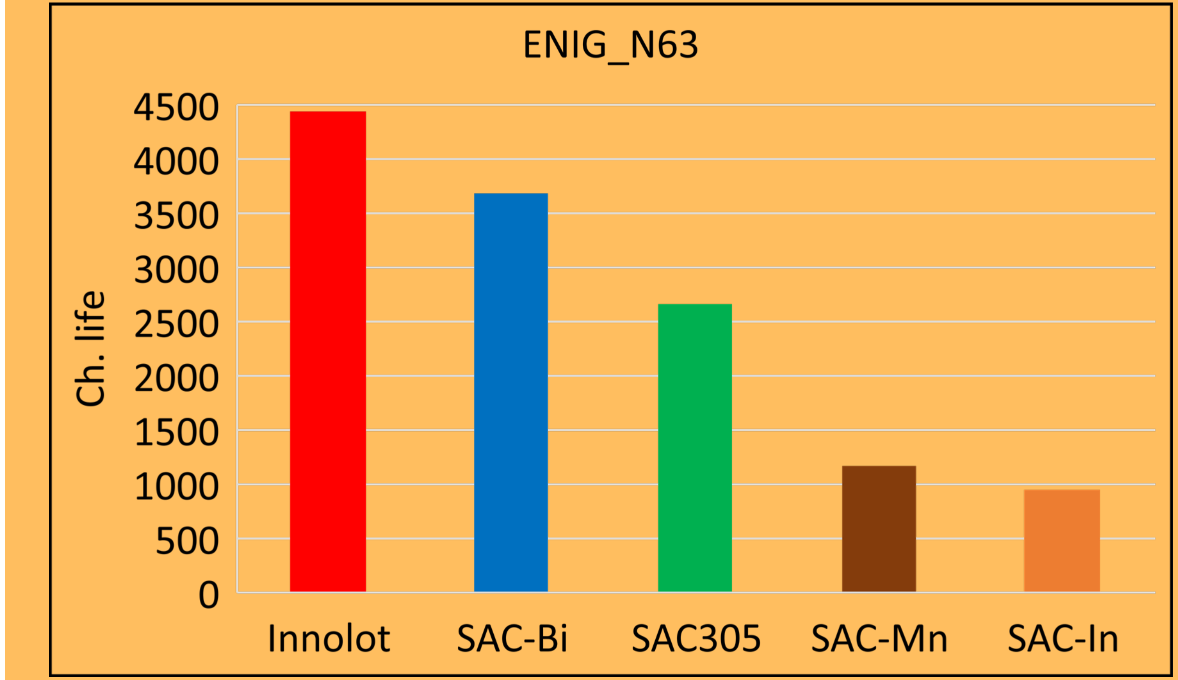
Test matrix

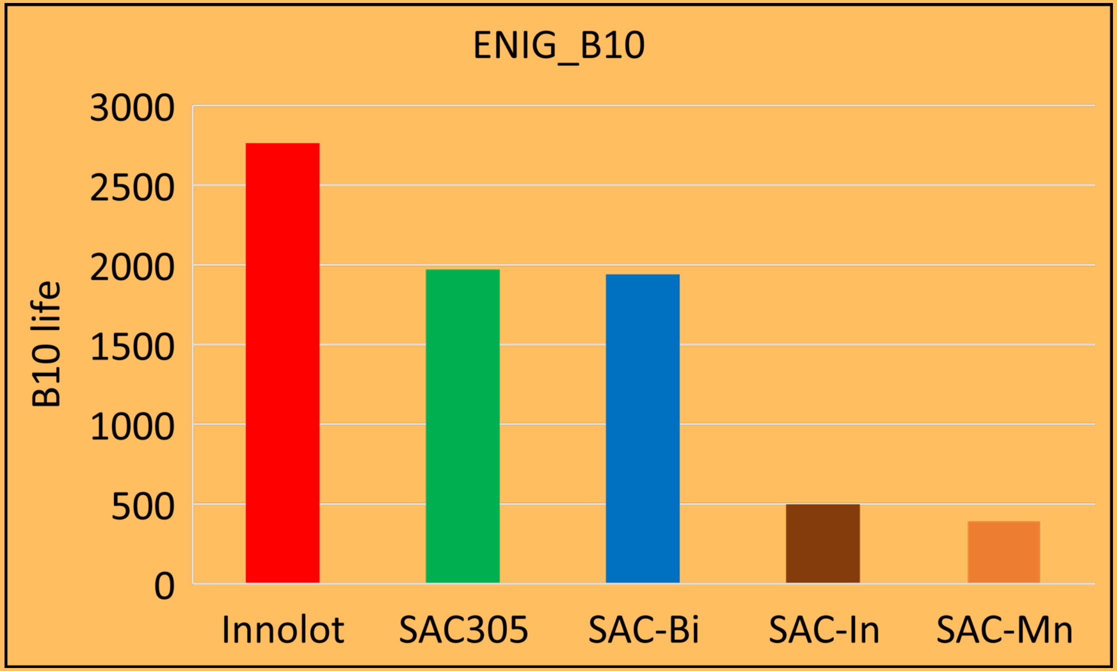
Component	Surface finish	Solder alloy
CABGA208	ENIG	Innolot
		SAC-Bi
		SAC-In
		SAC-Mn
		SAC305
	ImAg	Innolot
		SAC-Bi
		SAC-In
		SAC-Mn
		SAC305
	OSP	Innolot
		SAC-Bi
		SAC-In
		SAC-Mn
		SAC305

Results (ENIG finish)



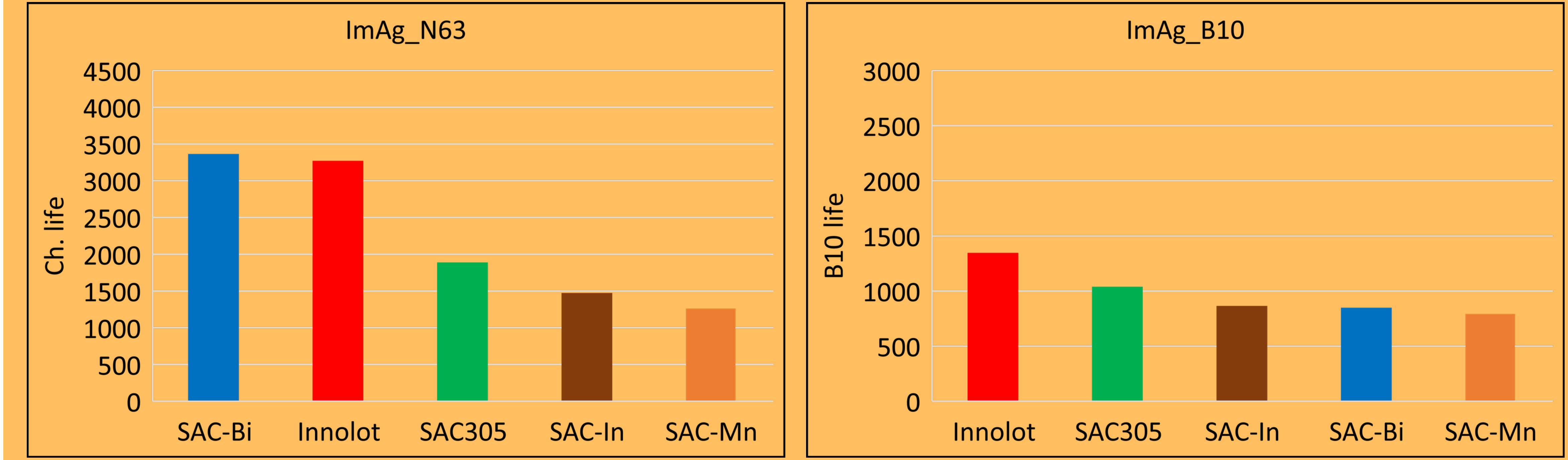
Results (ENIG finish)



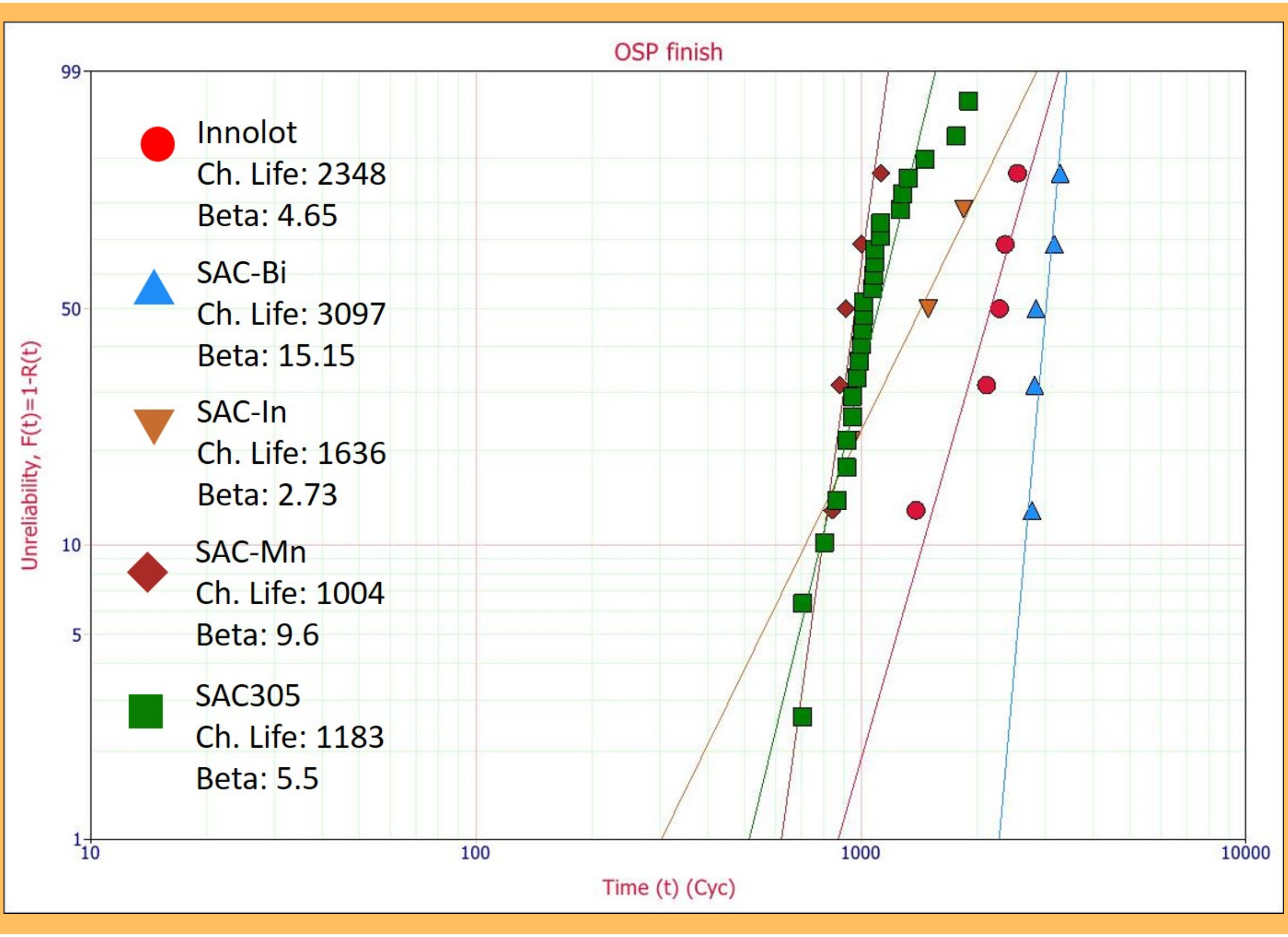


Results (ImAg finish)

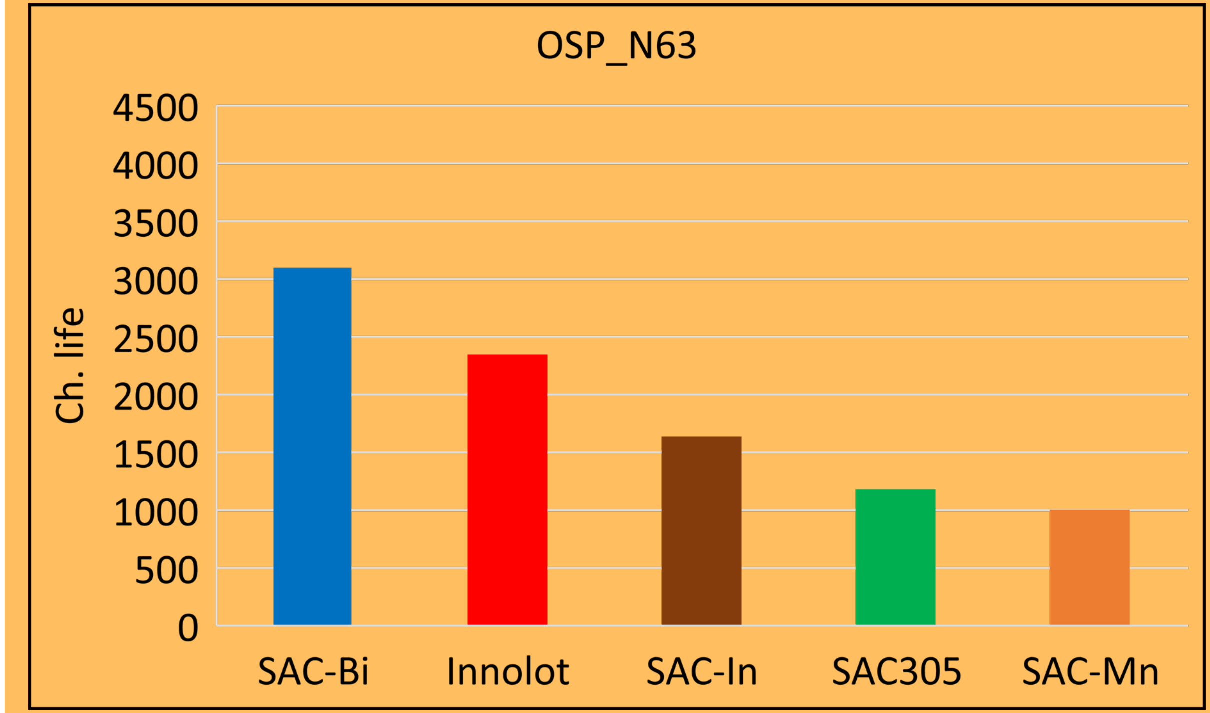
Results (ImAg finish)

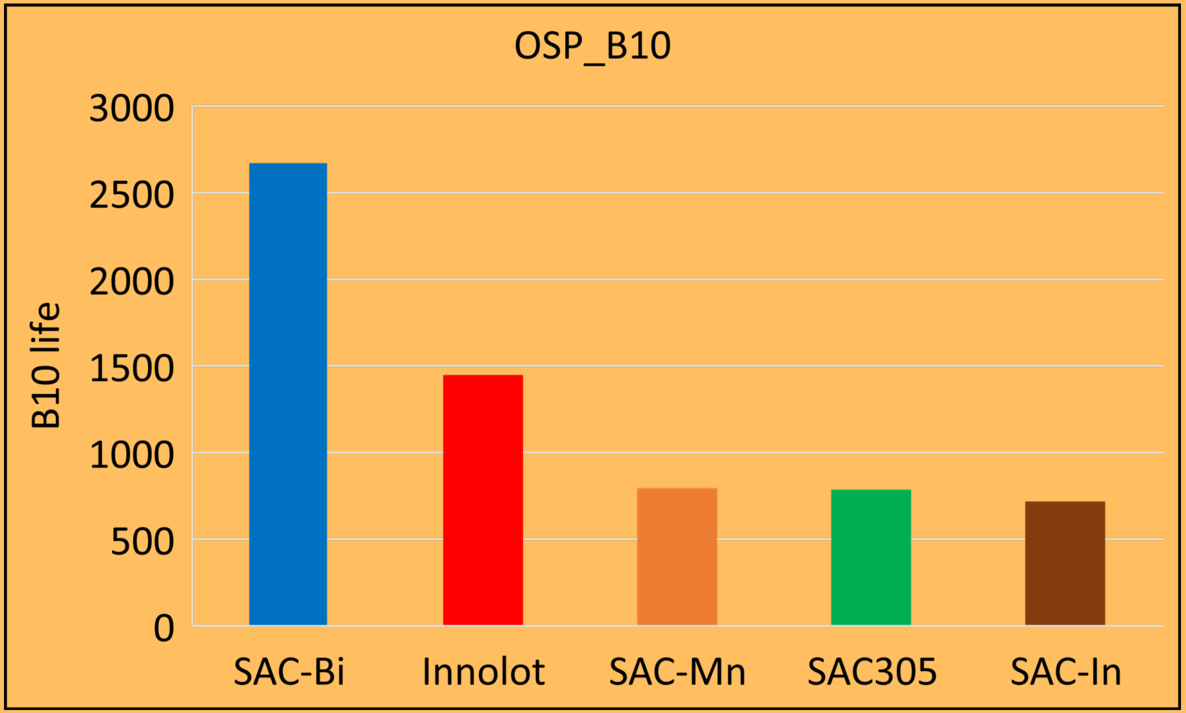


Results (OSP finish)



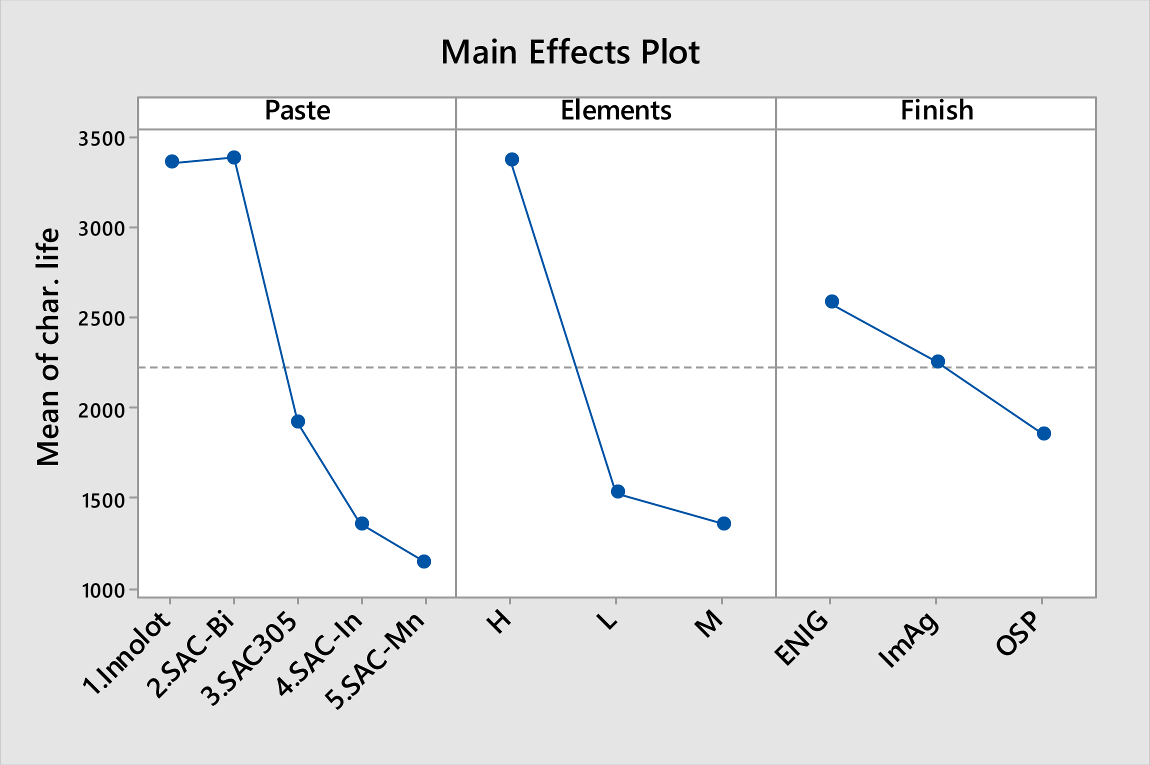
Results (OSP finish)

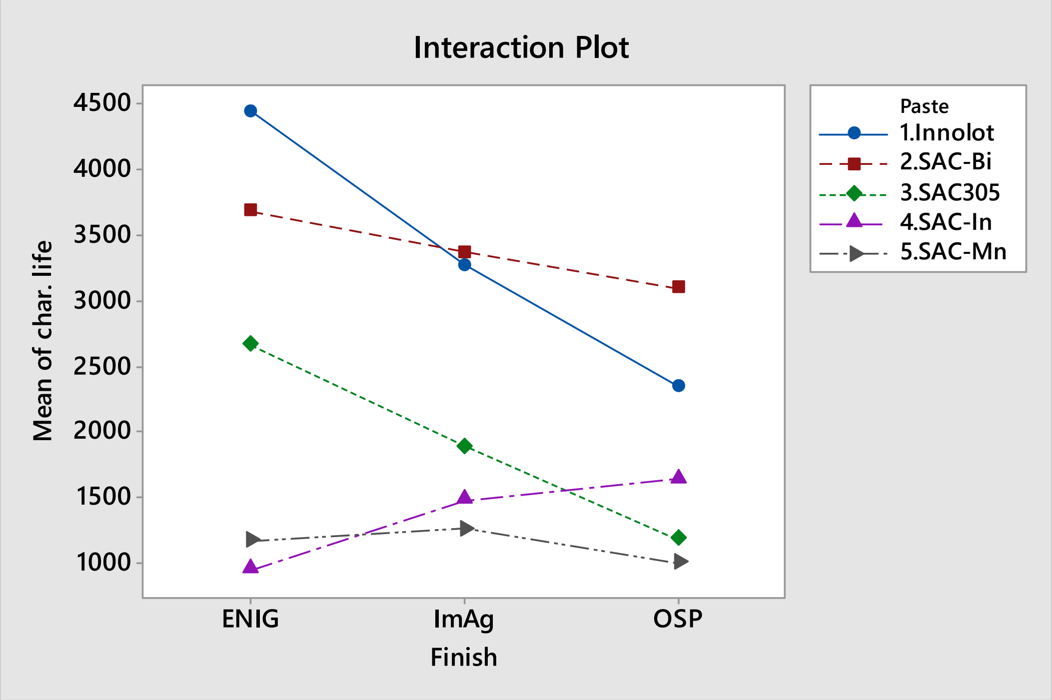




ANOVA analysis

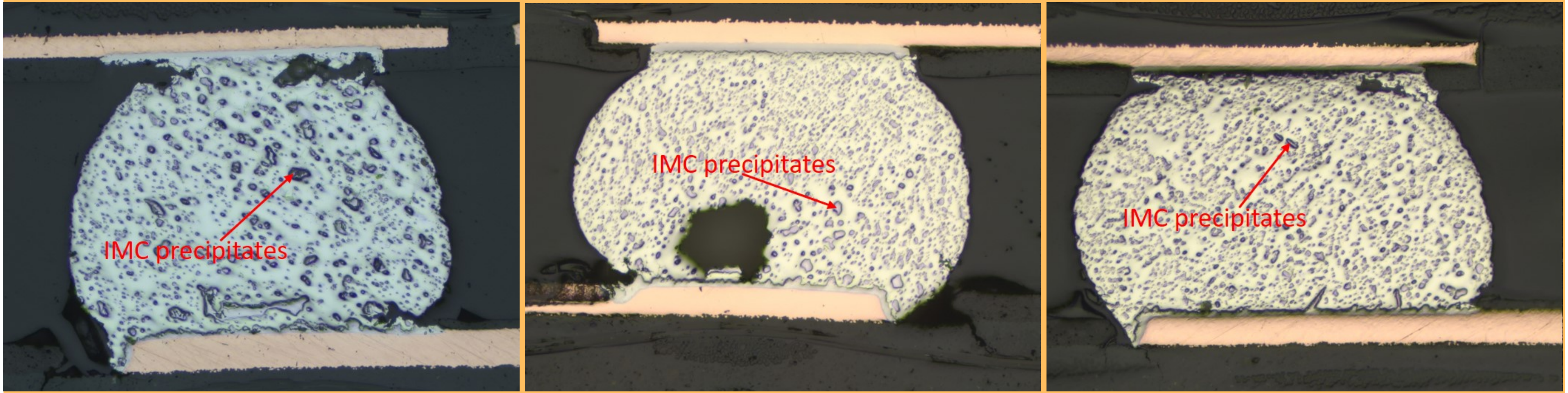
Alloy	(100-Sn)%	High/Med/Low
Innolot	9.05	H
SAC-Bi	7.2	H
SAC-In	5.03	M
SAC-Mn	1.53	L
SAC305	3.5	L





Failure Analysis

Bright field images of solder alloys with OSP finish

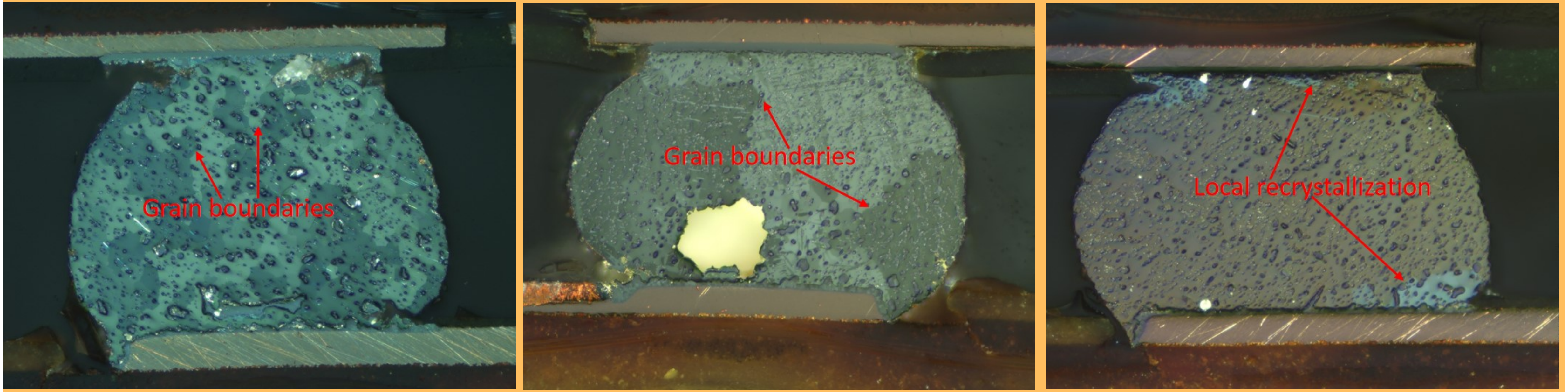


SAC-In SAC-Bi Innolot

IMC precipitate coarsening varies for each alloy

Failure Analysis

Polarized images of solder alloys with OSP finish



SAC-In

SAC-Bi

Innolot

Amount of recrystallization varies for each alloy

Conclusion

- The effect of alloy composition (micro-alloying) was studied with four different alloys and SAC305
- It could be concluded that alloys with higher amount of micro-alloyed elements performed better
- Innolot with elements Bi, Sb and Ni showed high thermal cycling reliability, followed by SAC-Bi
- Microstructure with fine, uniformly distributed precipitates that favor better reliability was found in the case of Innolot

Publications

- F. J. Akkara *et al.*, "Effect of Solder Sphere Alloys and Surface Finishes on the Reliability of Lead-Free Solder Joints in Accelerated Thermal Cycling," *2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, San Diego, CA, USA, 2018, pp. 1374-1380.

- F. J. Akkara *et al.*, "Effects of Long-Term Aging on SnAgCu Solder Joints Reliability in Mechanical Cycling Fatigue," *SMTA International*, Rosemont, IL, USA, 2017, pp. 419-425.

- F. J. Akkara *et al.*, "Effects of Mixing Solder Sphere Alloys with Bismuth-Based Pastes on the Components Reliability in Harsh Thermal Cycling," *SMTA International*, Rosemont, IL, USA, 2018.

- F. J. Akkara *et al.*, "Effect of Aging on Component Reliability in Harsh Thermal Cycling," *2019 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, Las Vegas, NV, USA, 2019, pp. 717-723.

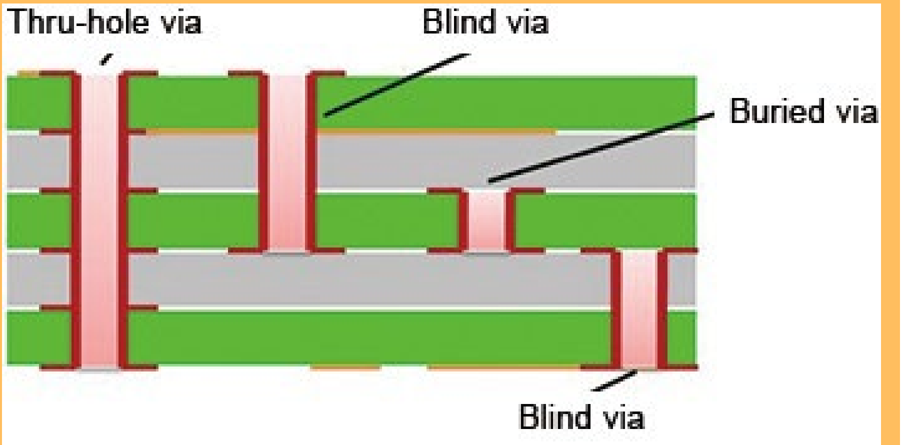
- F. J. Akkara *et al.*, “Thermal Cycling Reliability of Newly Developed Lead-Free Solders for Harsh Environments," *SMTA International*, Rosemont, IL, USA, 2019.

- F. J. Akkara *et al.*, "Effect of Combining Solder Pastes with SAC305 Spheres on Component Reliability in Harsh Thermal Cycling," *2020 19th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, Orlando, FL, USA, 2020, pp. 1322-1327.

Thank you!!

Electronic Assembly - Substrate

- Rigid material with metal traces
- Components are mechanically attached to the substrate
- Helps in thermal conduction and electrical isolation
- Vias are used for connections through different layers



Substrate material with vias

FR-4 (Flame Retardant)

- 4 indicates woven glass reinforced epoxy resin
- T_g ranges from 120°C to 180°C
- Good electrical insulator with considerable mechanical strength

Electronic Assembly – Solder mask

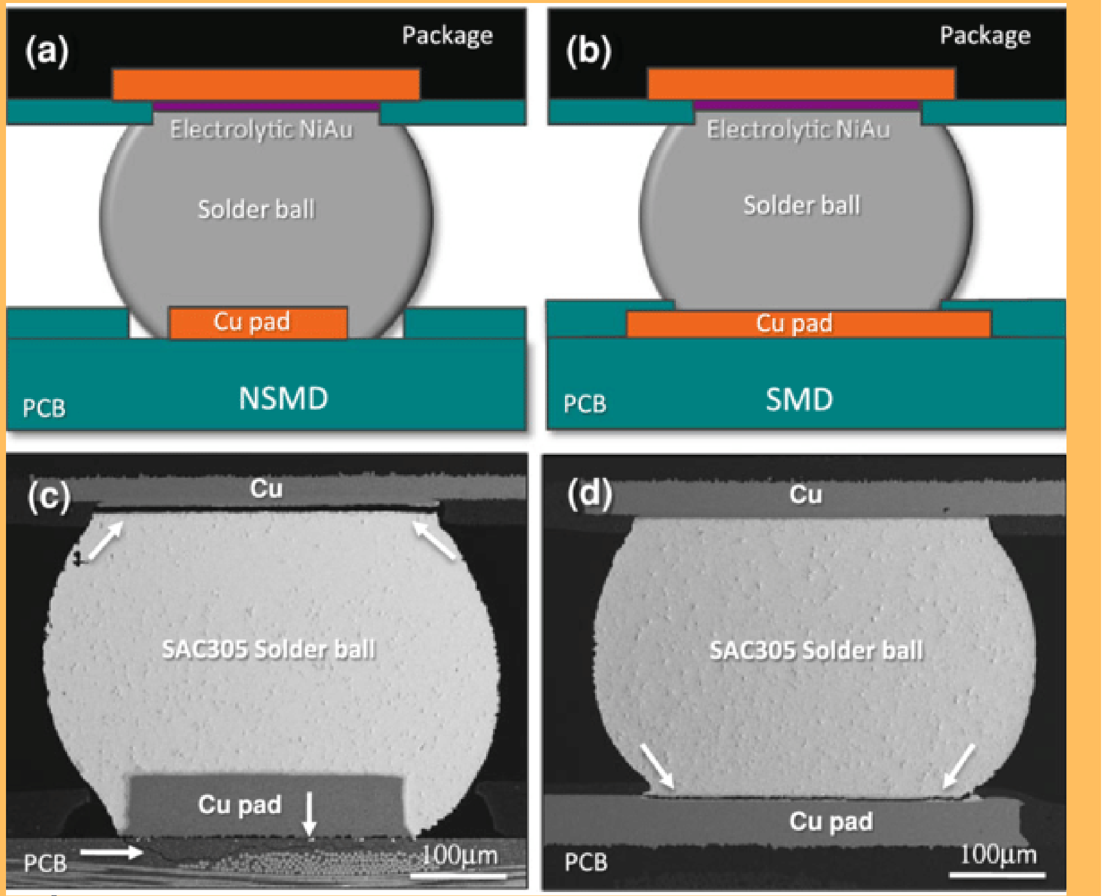
Solder mask

- Thin lacquer-like layer of polymer
- Protects the copper traces
- Prevents solder bridging
- Acrylic and epoxy polymers

✓ Solder mask defined pads (SMD)

✓ Non solder mask defined pads (NSMD)

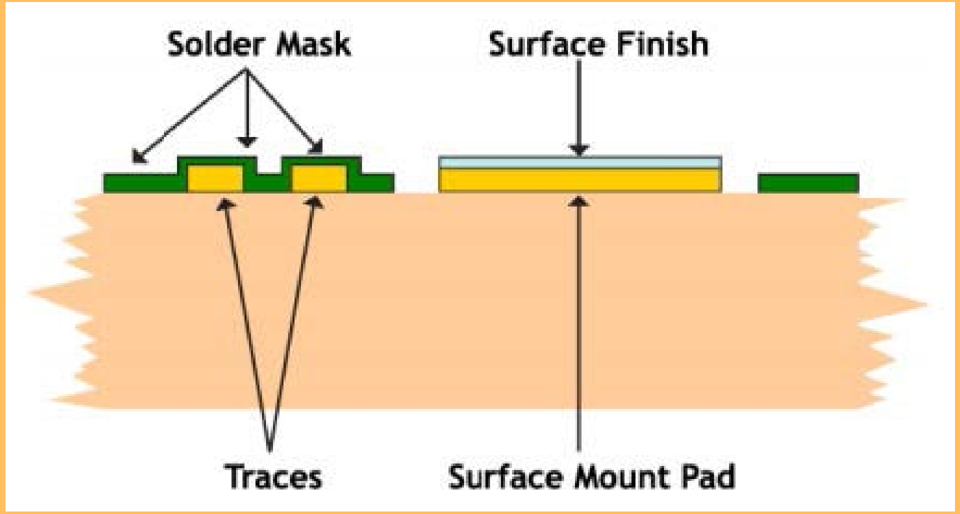
✓ Joints on NSMD are stronger than that on SMD pads



https://resources.pcb.cadence.com/blog/jbj-pcb-design-for-solder-mask-defined-footprints

Electronic Assembly – Surface finish

- Protects the copper pads from oxidation
- Improves solderability by dissolving outermost layer of surface finish while soldering



Examples of surface finish:

- HASL: Hot Air Solder Leveling
- ImSn: Immersion Tin
- OSP: Organic Solderability Preserve
- ImAg: Immersion Silver
- ENIG: Electroless Nickel Immersion Gold
- ENEPIG: Electroless Nickel Electroless Palladium Immersion Gold

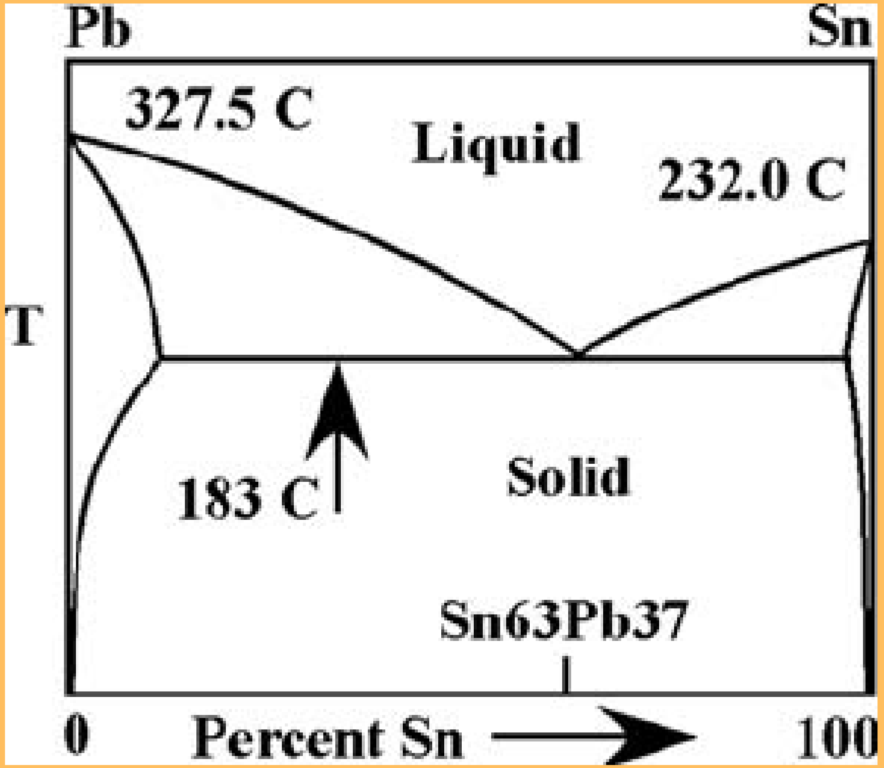
Electronic Assembly – Solder alloy

Eutectic SnPb solder

- Was used in electronics due to its favorable properties such as low surface tension, low melting point, ductility, strong intermetallic bonds with copper pads

- Banned from electronics after discovering the harmful effects

- Search for replacement lead to a series of near eutectic alloys based on tin(Sn)-silver(Ag)-copper(Cu), commonly known as SAC alloys
  - ❖ Sn99.3 Cu0.7
  - ❖ Sn96.5 Ag3.5
  - ❖ **Sn96.5 Ag3.0 Cu0.5 (SAC 305)**
  - ❖ **Sn98.5 Ag1.0 Cu0.5 (SAC 105)**
  - ❖ Sn95.5 Ag3.8 Cu0.7
  - ❖ Sn95.5 Ag3.9 Cu0.6



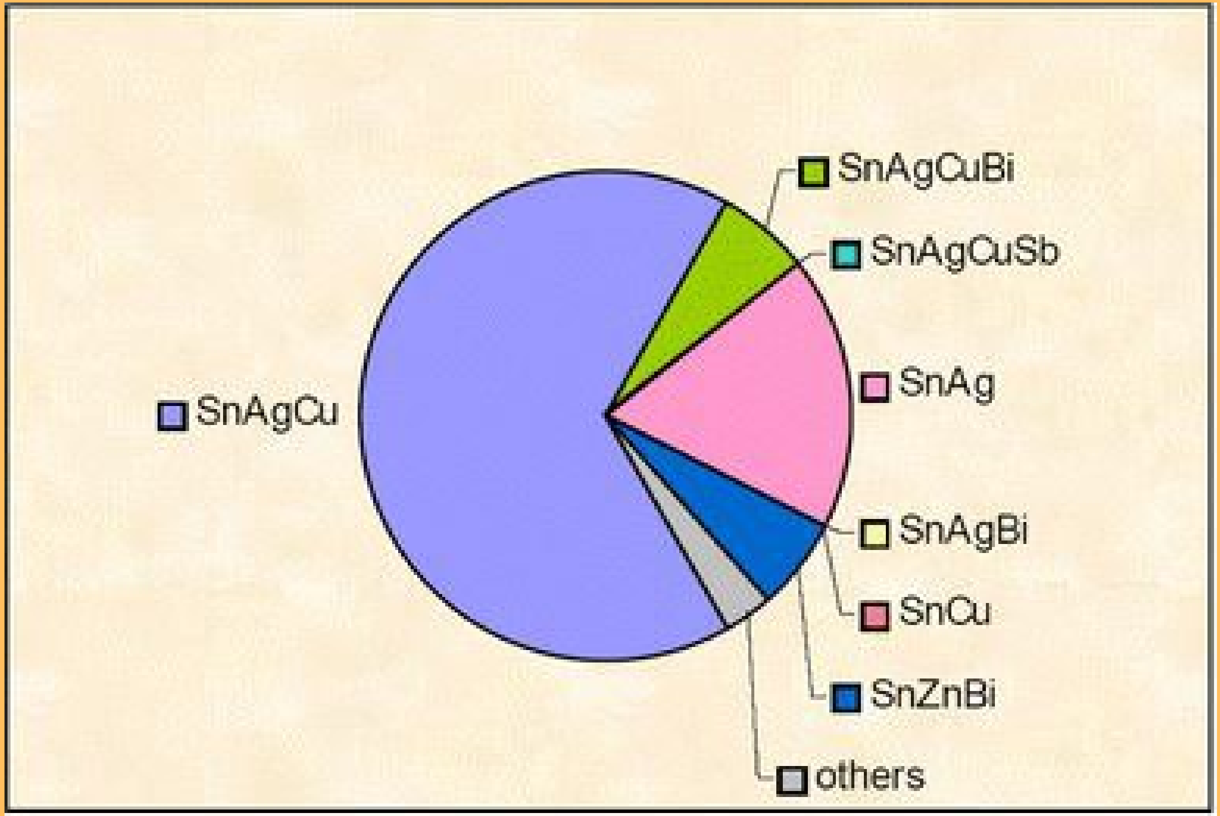
SnPb binary phase diagram

Electronic Assembly – Solder alloy

Micro-alloying/Doping

- In order to improve the SAC based alloys, several elements were micro-alloyed
- Elements includes Bismuth, Antimony, Cobalt, Nickel, Indium

- For special applications, copper or silver was replaced in SAC alloys. Such solder alloys include:
    - ❖ Sn42Bi58
    - ❖ Sn48In52
    - ❖ Sn20Au80
    - ❖ Sn95Sb05
    - ❖ Sn91Zn09



Market share of lead free alloys