

Reliability of Pb-Free Solder Assemblies for Non-Implantable, Medical Device Applications

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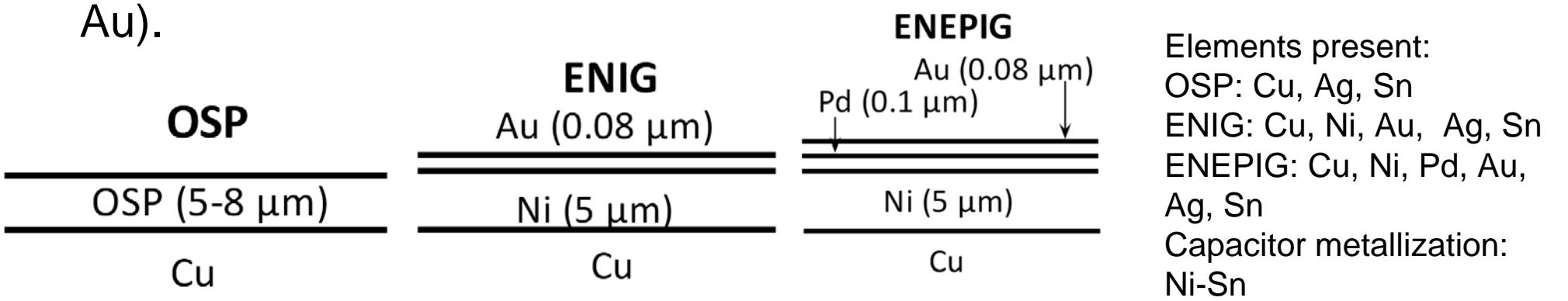
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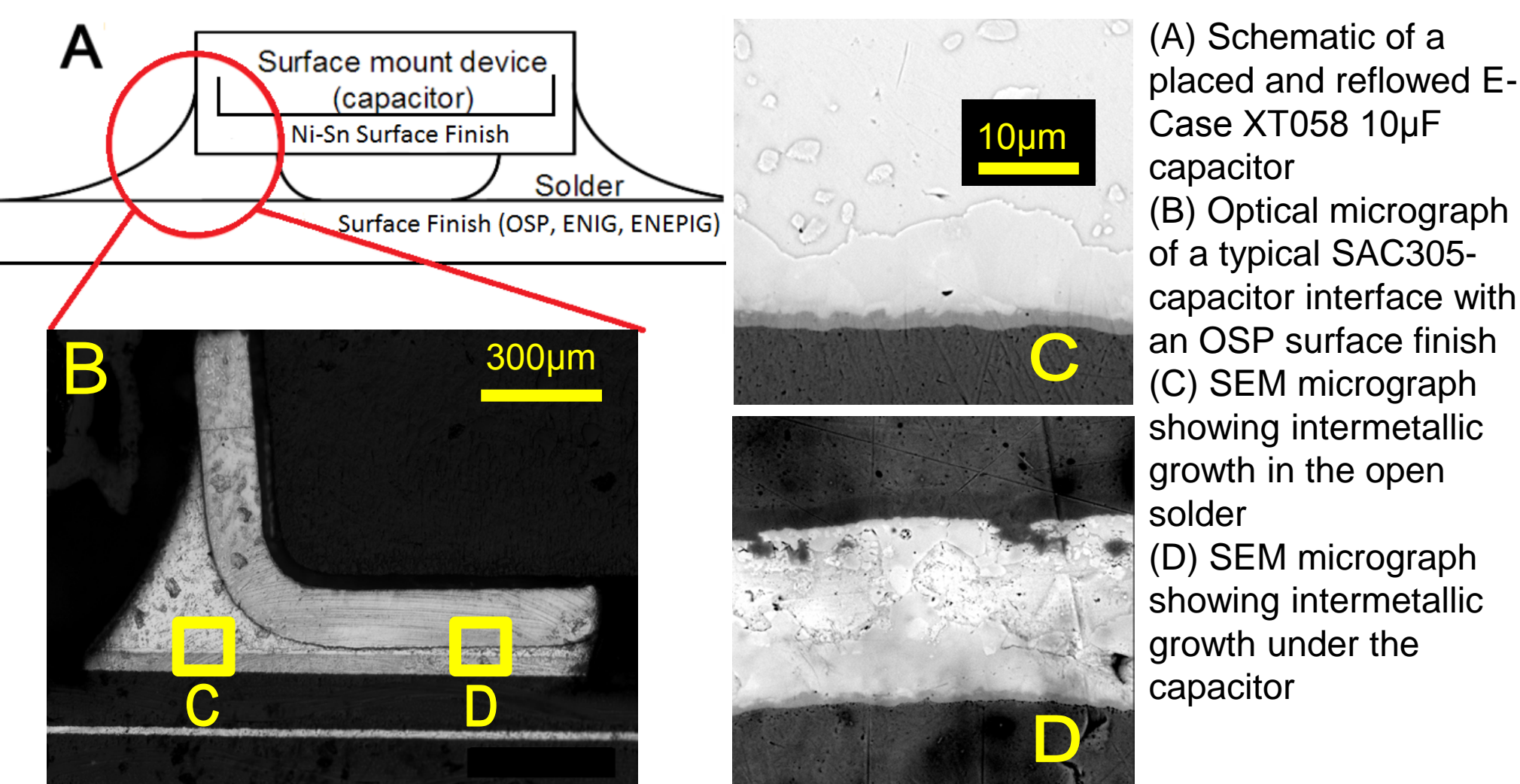
Medtronic is pursuing the use of Pb-free solders in their non-implantable/disposable medical devices in response to legislative action in the European Union which bans the sale of Pb containing electronics. All medical devices have previously been exempt from the EU RoHS directive, but the exemption for non-implantable devices is being phased out. The high Sn alloy SAC305 (Sn-3wt%Ag-0.5wt%Cu) is the most widely used lead free solder, and is therefore of primary interest to Medtronic. Due to the highly demanding application and need for high reliability in the medical device industry, extensive understanding of the system is needed to show that SAC305 will perform closely to Sn-Pb solders to be considered a viable alternative for use. Medtronic additionally desires to know how the choice of board surface finish affects the performance of SAC305 solder joints in typical Medtronic assemblies. When solder is flowed over a circuit board, intermetallic compounds (IMCs) form from the elements in the system. The senior design team conducted isothermal aging studies at 75°C, 100°C, 125°C, and 150°C at 500hrs, 1000hrs, 1500hrs, and 2000hrs for 3 surface finishes (OSP, ENIG, ENEPIG) to complement Medtronic's studies that include thermal cycling and mechanical reliability. The IMC growth at each solder interface was characterized for all conditions to detect trends and determine reliability. The team ultimately recommends OSP or ENEPIG over ENIG due to more consistent growth patterns between samples, lower overall IMC growth, and reduced porosity and cracking.

Project Background

- Medtronic is evaluating the reliability of SAC305 solder (Sn-3wt%Ag-0.5wt%Cu), a common alternative to Pb-Sn solder. The solder joints interact with multiple elements present in the component metallization, solder and surface finish. The microstructure developed as a result of the presence of these elements will determine reliability.
- The objective is to simulate the 10+ year service life at room temperature typical of a non-implantable, medical, electronic device. The goal of the study is to characterize the solder interface and determine the surface finish impact on reliability. This study complements Medtronic's thermal cycling and mechanical reliability studies for the same systems.
- E-Case XT058 10µF capacitors were isothermally aged at four temperatures (75°C, 100°C, 125°C, 150°C) and four times (500hrs, 1000hrs, 1500hrs, 2000hrs) to track the IMC growth for the 3 surface finishes.
- One of three surface finishes are applied to the circuit board to improve electrical contact and protect from oxidation. These surface finishes are OSP (Organic Solderability Preservative), ENIG (Electroless Ni Immersion Au), and ENEPIG (Electroless Ni Electroless Pd Immersion Au).

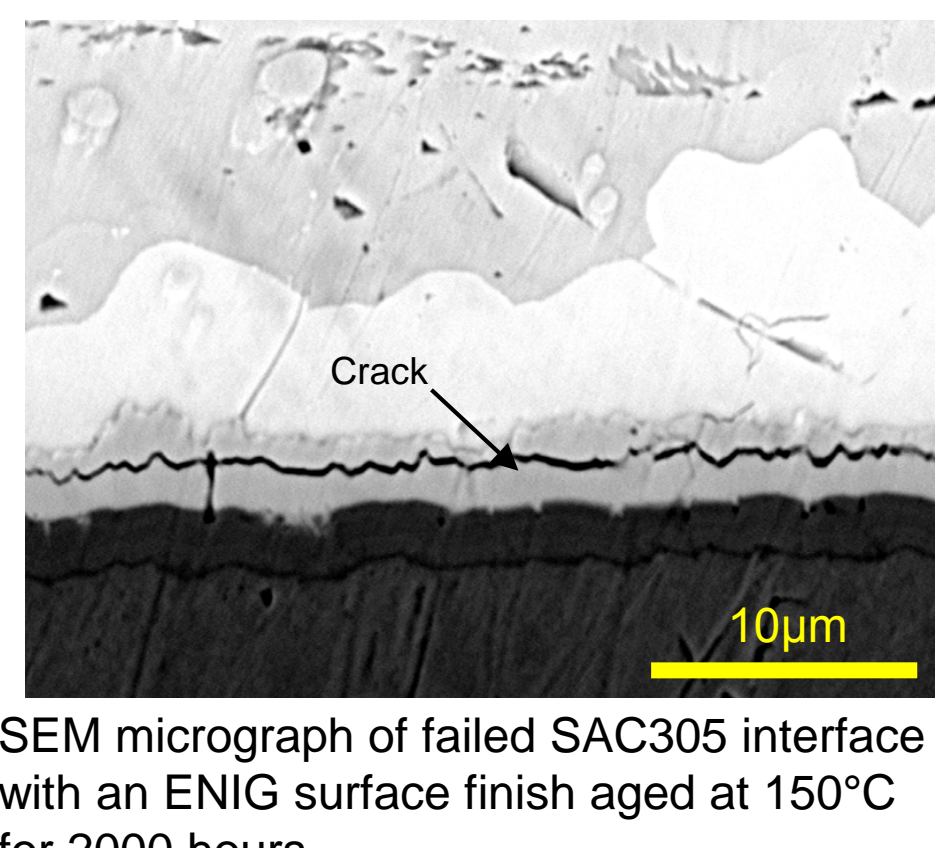


(Above) Schematic of the 3 surface finishes studied. Solder paste is deposited then components are placed on top of the surface finish and reflowed to secure the components to the board.



During reflow, elements present at the solder joint interact to form IMCs such as Cu_3Sn , Cu_6Sn_5 , $(Cu,Ni)_3Sn$, $(Cu,Ni)_6Sn_5$, and $(Cu,Ni,Au)_6Sn_5$ [1][2]. Their growth is thermally activated.

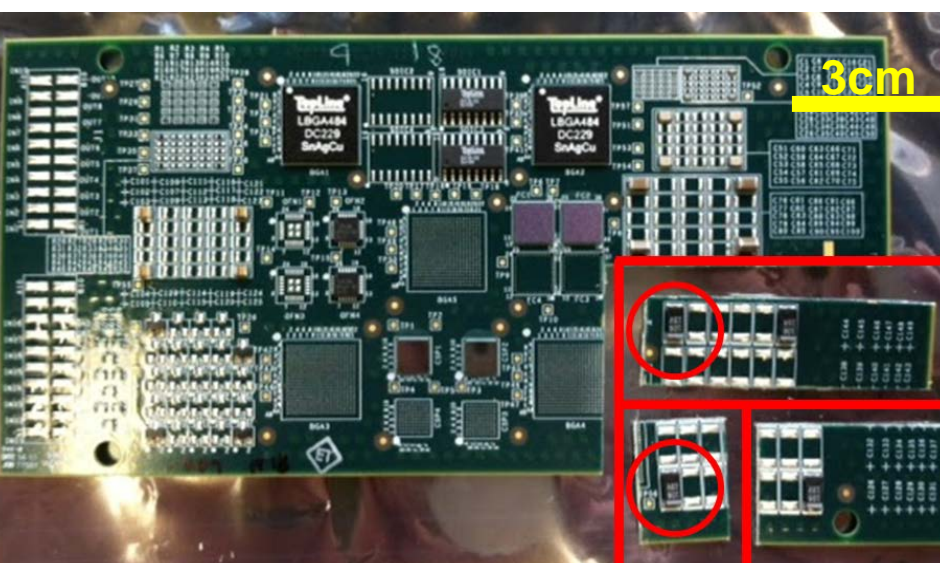
IMCs are more brittle than the solder and can cause mechanical failure. Failed joints limit device reliability because electrical continuity is lost.[3]



SEM micrograph of failed SAC305 interface with an ENIG surface finish aged at 150°C for 2000 hours.

Experimental Procedure

- Test vehicles were aged at 75°C, 100°C, 125°C, and 150°C to 500hrs, 1000hrs, 1500hrs and 2000hrs then sectioned along the solid red lines as shown at right. For each time, temperature, and surface finish combination a 10µF capacitor was cut from the board. The capacitors were sectioned, mounted in cold set epoxy, and polished.
- Phenom SEM used in backscattered electron mode to obtain images and to confirm multiphase IMC presence and identify phases formed, the team used Energy Dispersive X-ray Spectroscopy (EDS). Charging effects mitigated by painting with graphite suspension, grounding with Cu tape and use of a charge dissipative sample holder specific to the Phenom SEM.



Sectioning plan for aged test vehicles. The circled components are the capacitors of interest to this study.

ImageJ software characterized three parameters— average, maximum, and minimum IMC thickness. The total area occupied by each IMC was traced and measured. The area was divided by the length of interface observed in order to produce the average thickness for each IMC layer.

$$\text{average IMC thickness} = t_i = \frac{\text{area of phase}}{\text{length of interface}}$$

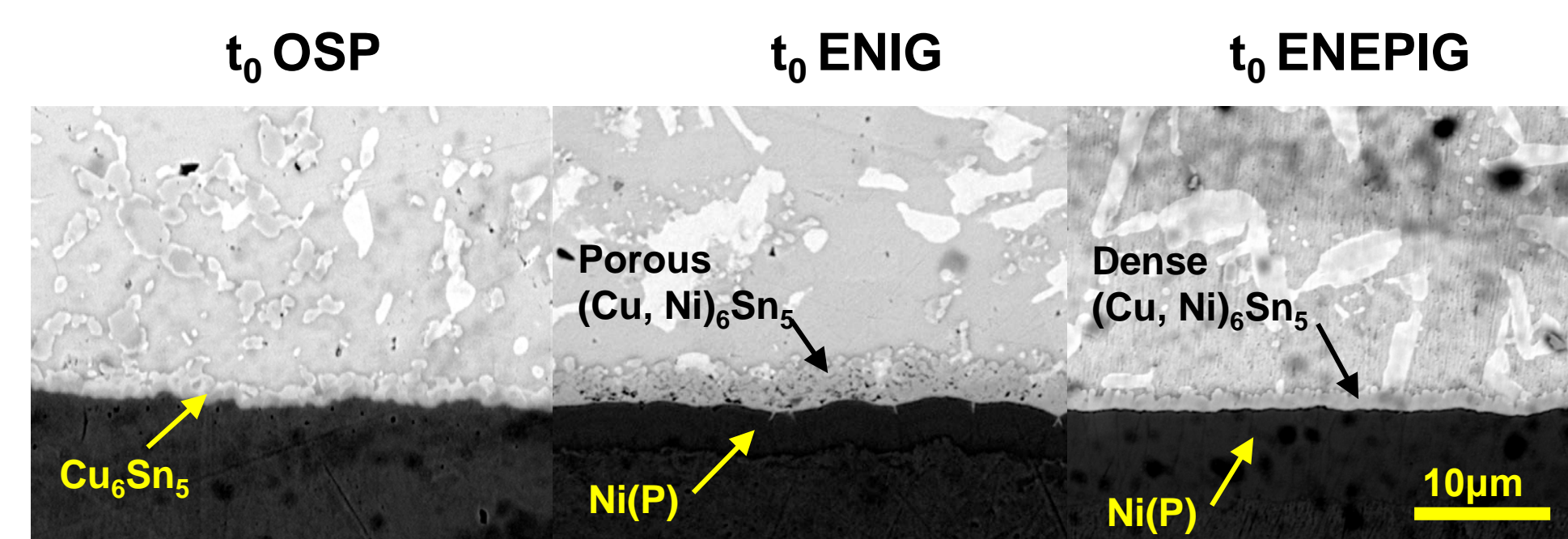
The total IMC thickness is the sum of individual average thicknesses for all IMC species present in a given sample.

$$\text{total IMC thickness} = \sum_{i=1}^n t_i$$

Maximum and minimum phase thicknesses for each IMC species were measured directly from the scaled image in ImageJ. The range of these readings approximates irregularity of the interface shape.

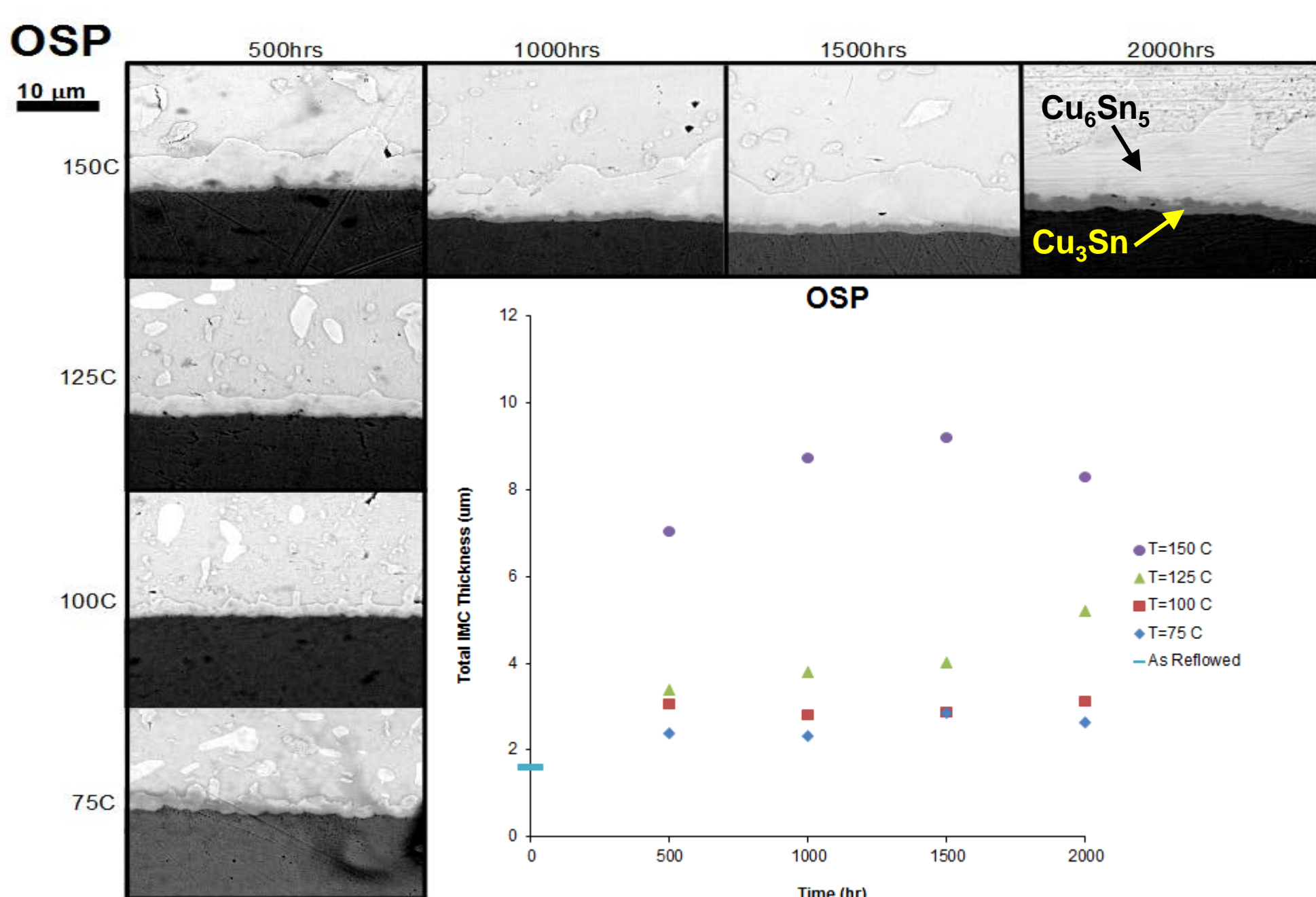
Each micrograph was investigated for cracks and microvoids. While a crack in a 2-D image could be representative of a 3-D separation, it does not fully capture the interface. The presence of cracks and microvoids indicate further investigation required and a larger sample size to characterize fully.

Results and Discussion



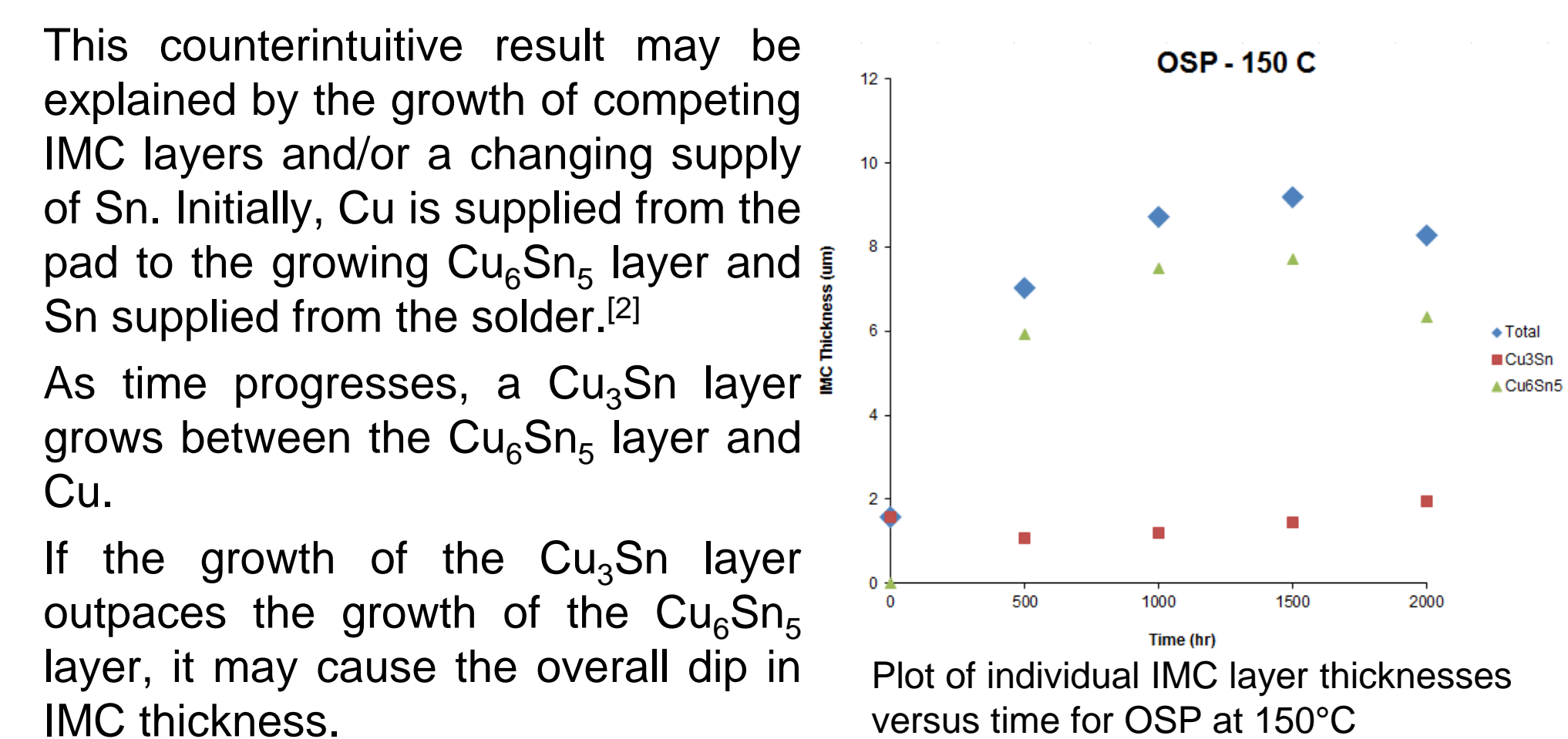
As reflowed samples for all three surface finishes show the initial IMC growth that occurs during reflow.

- EDS results indicate Cu_6Sn_5 is present in OSP, and $(Cu,Ni)_6Sn_5$ is present in ENIG and ENEPIG. There is also a small solubility of Au indicated in the initial $(Cu,Ni)_6Sn_5$ layer for ENIG and ENEPIG. As expected from review of the literature, ENIG and ENEPIG exhibit a Ni(P) layer below the solder interface due to the electroless deposition process of the Ni layer.
- The microstructures for as reflowed samples show great variability in the shape of the IMC interface. Edges vary from needle-like to scalloped to nearly planar.
- In addition to irregular morphology, ENIG shows significant porosity in the $(Cu,Ni)_6Sn_5$ layer. Porosity in the other surface finishes is less pronounced.

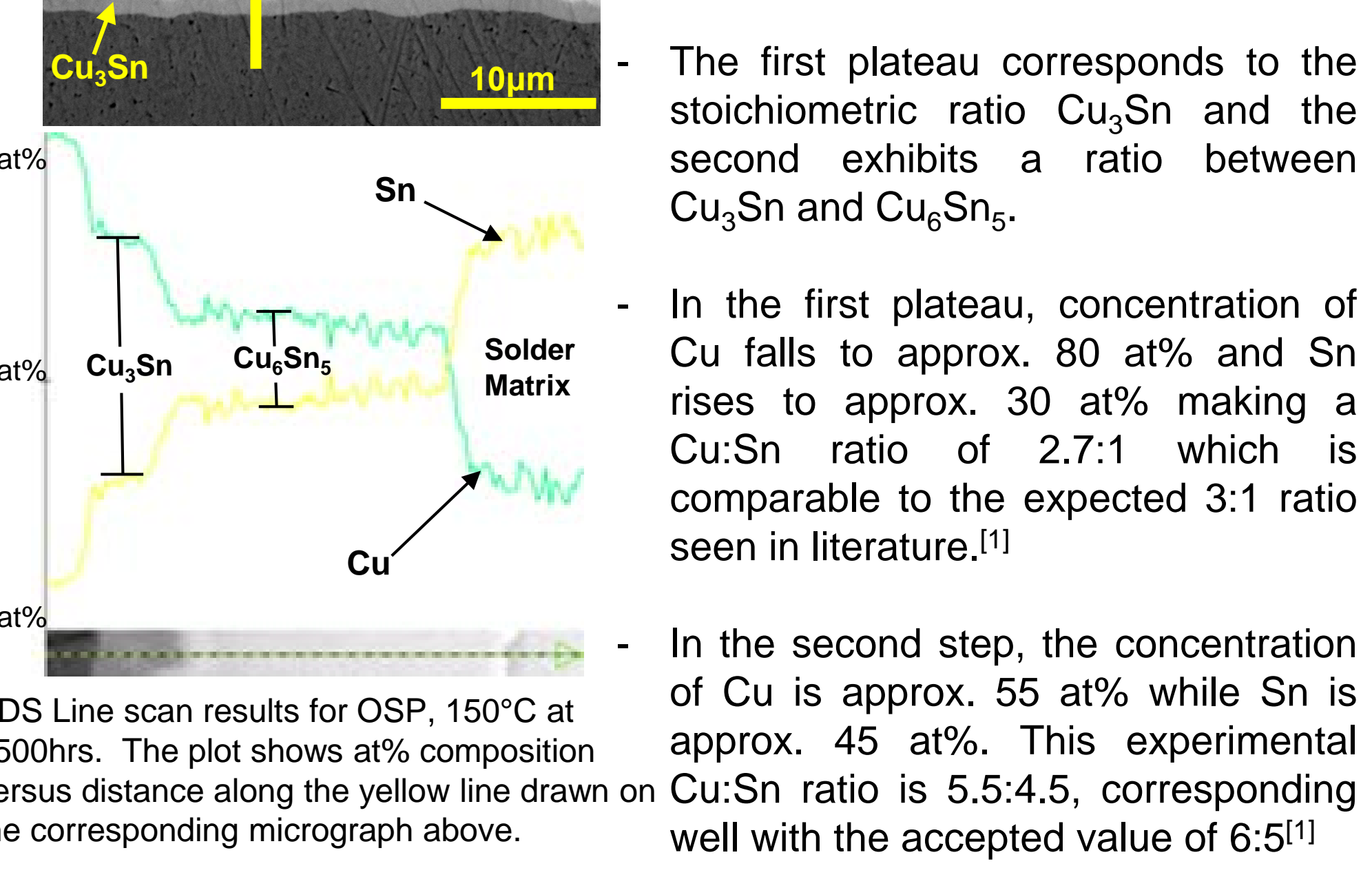


SEM micrographs of the OSP system for the 150°C series and the 500hr series. (Inset) Plot of average total IMC thickness over time for the four temperatures.

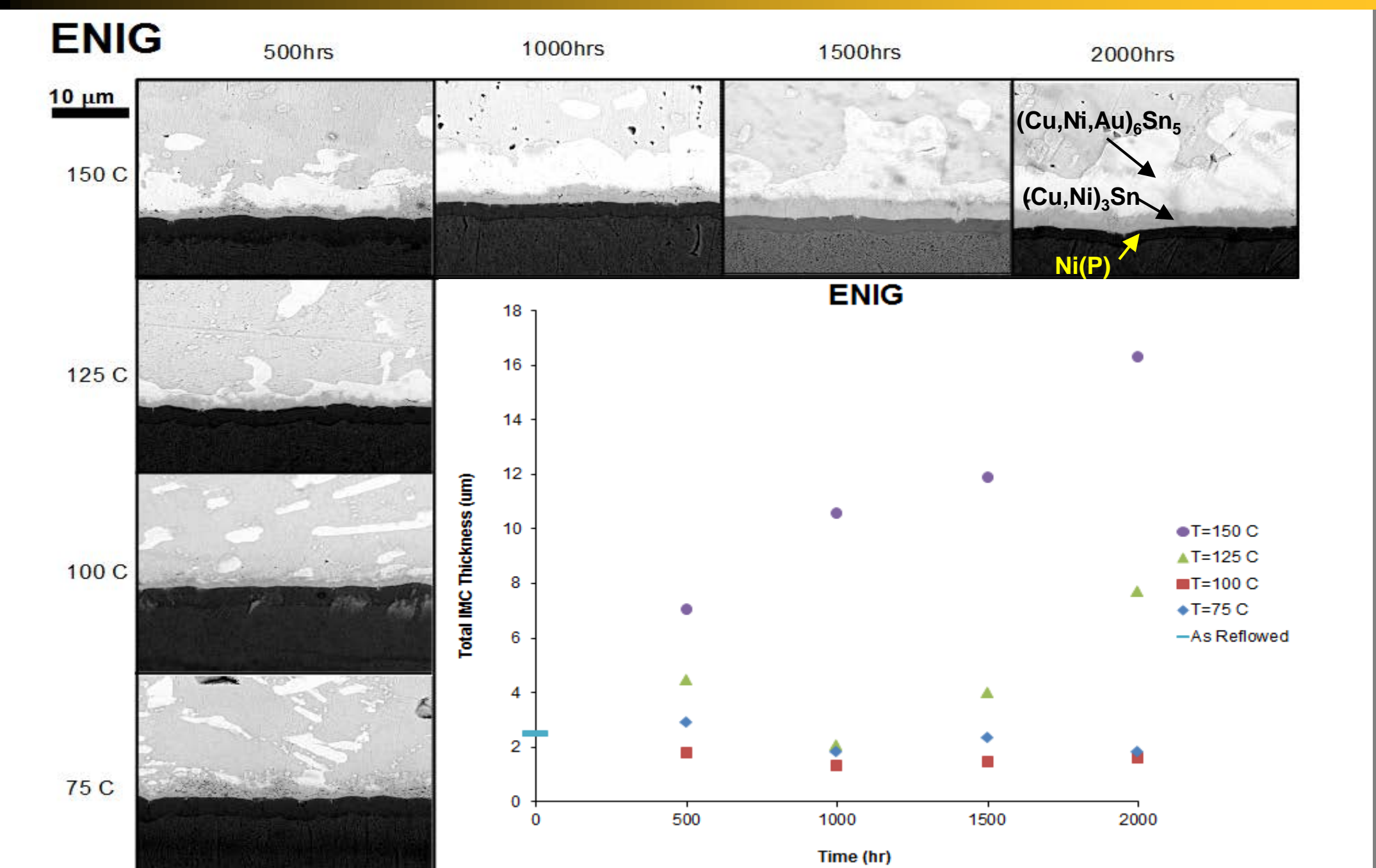
- Minimal total IMC growth is seen in samples aged at 75°C and 100°C but observation of the interface morphology shows a smoothing of the scalloped IMC edge with increasing time and temperature. What little porosity that is present initially is densified fully over the 2000hrs studied.
- Samples aged at 125°C exhibited minimal growth until 1500hrs where growth was initiated suddenly. Total growth by 2000hrs, however, was still minimal.
- Samples aged at 150°C show a growth pattern that is roughly parabolic with time. This is one typical growth rate seen in the literature for this system.[1] A counterintuitive dip in overall IMC thickness is seen at 2000hrs.



This counterintuitive result may be explained by the growth of competing IMC layers and/or a changing supply of Sn. Initially, Cu is supplied from the pad to the growing Cu_6Sn_5 layer and Sn supplied from the solder.[2] As time progresses, a Cu_3Sn layer grows between the Cu_6Sn_5 layer and Cu. If the growth of the Cu_3Sn layer outpaces the growth of the Cu_6Sn_5 layer, it may cause the overall dip in IMC thickness.

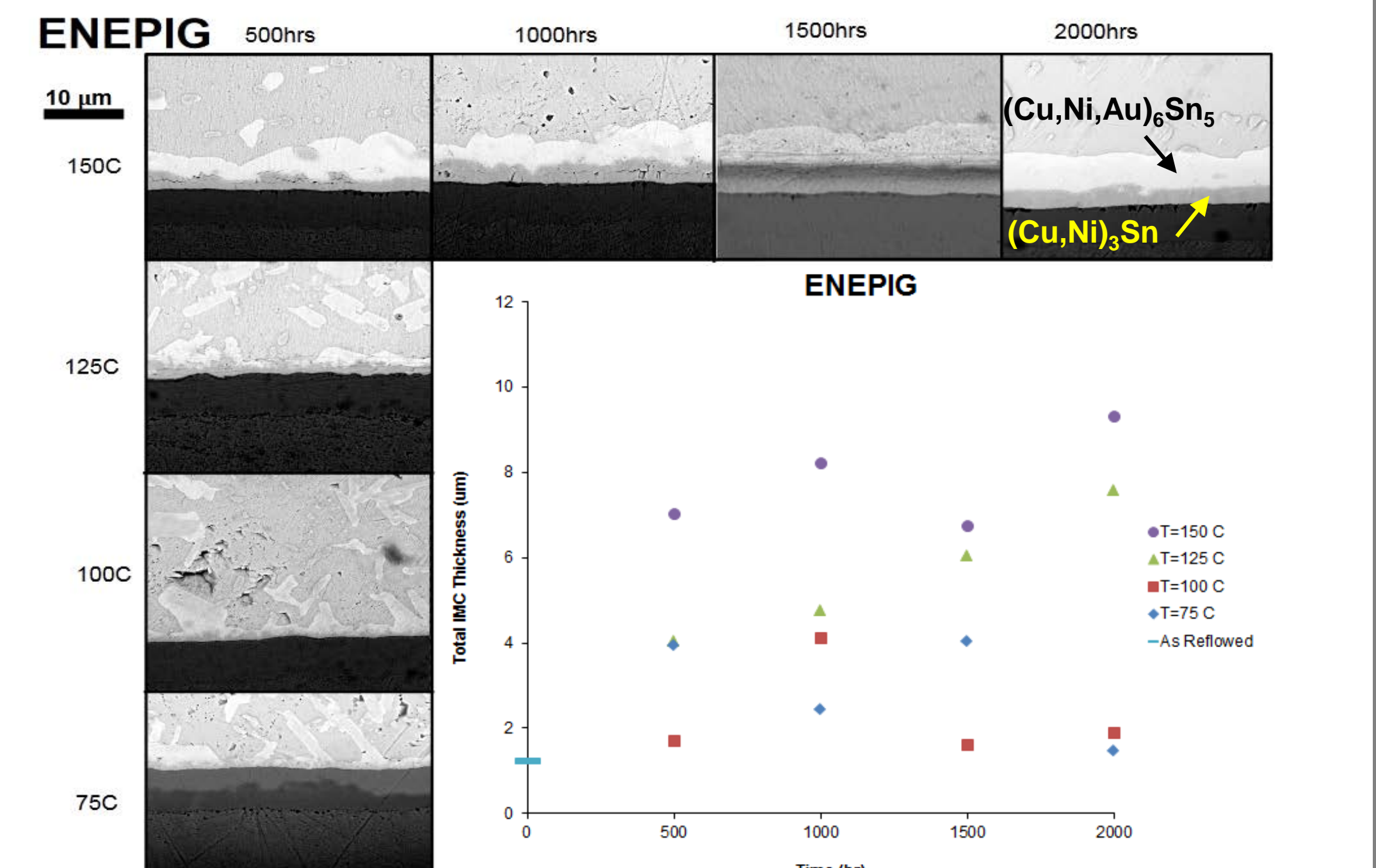


EDS Line scan results for OSP, 150°C at 1500hrs. The plot shows at% composition versus distance along the yellow line drawn on the corresponding micrograph above.



SEM micrographs of the ENIG system for the 150°C series and 500hr series. (Inset) Plot of total IMC thickness over time for the four temperatures.

- Like OSP, ENIG samples aged at 75°C and 100°C do not exhibit much growth and in some cases even show a decrease in IMC thickness compared to the t_0 case. This is caused by the densification of the porosity originally present in the Cu_6Sn_5 layer over time at these temperatures.
- The 125°C trend is unusual compared to the expected parabolic growth rate reported by Yoon et al.[2] The 150°C trend shows a monotonically increasing growth pattern that is roughly linear.
- Like OSP, the morphology of the Cu_6Sn_5 interface becomes more planar with increasing time and temperature but to a lesser degree than OSP. ENIG samples, even after aging, still exhibited large ranges in layer thicknesses.
- Incidence of cracking was observed more frequently in ENIG than other surface finishes but few total samples exhibited any cracking at all.



SEM micrographs of the ENEPIG system for the 150°C series and 500hr series. (Inset) Plot of average total IMC thickness vs time for the four temperatures.

- IMC growth for 75°C and 100°C samples is highly irregular; we would expect uniform, consistent growth over time instead of what was observed.
- 125°C samples exhibit almost linear growth. 150°C samples exhibit irregular growth as observed in the 75°C and 100°C samples.
- Morphologies vary greatly across the board with jagged peaks at low temps and time (t_{500} 75°C) transforming to highly planar, smooth surfaces at higher temps and time (t_{2000} 150°C). Porosity is minimal in all samples.

Conclusions

- OSP and ENEPIG IMC growth patterns were far more predictable and correlated better with literature than ENIG.
- Initial IMC formation is significant to overall IMC layer thickness for samples that were aged at low temperatures (75°C, 100°C) but not as significant for high temperature aged samples (125°C, 150°C) for all surface finishes.
- For the OSP, ENIG and ENEPIG surface finishes, an aging temperature of at least 125°C was necessary to detect significant IMC growth in 2000 hours.
- Observations of cracking and voiding proved inconclusive (but more frequent in ENIG) due to the small sample population size of the study.
- For all surface finishes, porosity diminishes within the IMC layer and IMC morphology become less irregular with increasing time and temperature.

Recommendations

- Selection of OSP or ENEPIG is advised as ENIG shows the greatest variation and maximum in IMC thickness as well as increased porosity and more frequent voiding and cracking relative to the other surface finishes.
- Further study to substantiate these results by expanding the sample population size is advised.
- Consideration of these results in context of the larger Medtronic study is advised.

References
[1] Kumar, S., Handwerker, C., and Dayananda, M. *Intrinsic and Interdiffusion in Cu-Sn System*. Phase Equilibria and Diffusion, 32, 309-319 (2011).
[2] Yoon, Jeong-Won et al. *Comparative Study of ENIG and ENEPIG as Surface Finishes for a Sn-Ag-Cu Solder Joint*. Electronic Materials, 40, 9, 1950-1955 (2011).
[3] Zeng, G. et al. *A Review on the Interfacial Intermetallic Compounds between Sn-Ag-Cu Based Solders and Substrates*. Material Science: Material Electronics, 21, 421-440. (2010).

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