Intermetallics in Solder Joints

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Introduction

Intermetallic compounds (IMCs) are generally considered a bad thing in solder joints, though this is not always the case. Excessive IMCs in solder joints are a bad thing since they significantly alter both the composition and the mechanical performance of the solder joint. Interfacial IMC layers can be an indication of the quality of the solder joint and the lack of them would indicate a solder process or possibly a material problem.

What are intermetallic compounds? They are stoichiometric combinations of two or more metal atoms where the atomic fractions of the metals are generally fixed (for example Cu3Sn). This can be contrasted with solid solutions where the atomic fractions can sometimes very as widely as 0 - 100%. Metals and alloys exhibit metallic bonding between the atoms, whereas IMCs exhibit a more covalent character. This is why IMCs tend to be much harder and have much higher elastic moduli than either of their respective metallic elements (from the previous example Cu or Sn).

The intermetallic compounds that have been most important in our work performing microstructural evaluations on solder joints are described briefly in the sections below.

Cu_6Sn_5

The intermetallic Cu6Sn5 is important due to the large number of tin-lead and lead-free solder joints formed directly to copper. This IMC forms an interfacial layer and can be found in the bulk microstructure of tin-lead solder joints where excessive time and temperature are involved during the soldering process. In addition, the Cu6Sn5 intermetallic is a primary feature in the microstructure of lead-free solder joints such as SAC 305 alloy (96.5Sn-3Ag-0.5Cu). Fig. A is an example of a Cu_6Sn_5 IMC needle in the bulk microstructure of a SAC alloy BGA solder joint.

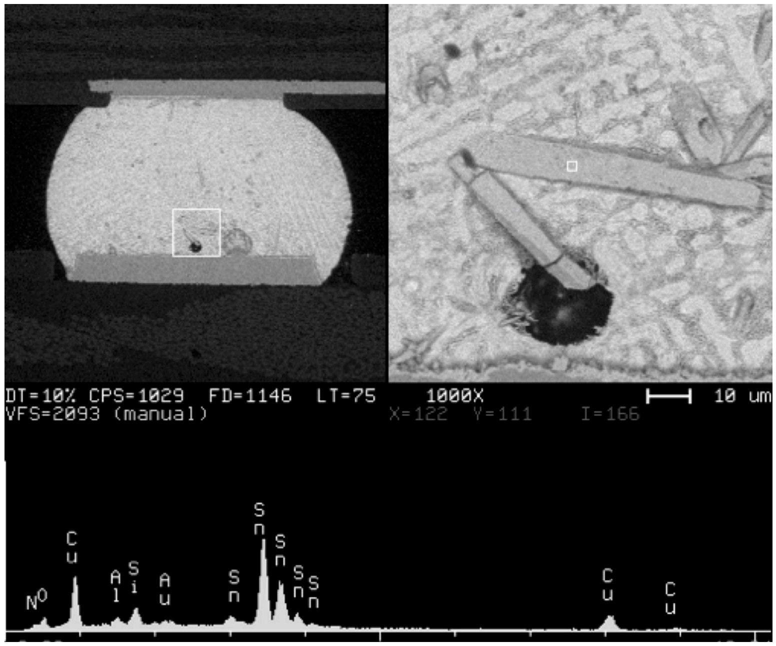

Figure A: Example of a Cu_6Sn_5 IMC needle in the bulk microstructure of a SAC alloy BGA solder joint.

Cu_3Sn

The intermetallic Cu_3Sn is important as it forms an interfacial layer between the copper and Cu_6Sn_5 IMC layer in tin-lead and lead-free solder joints formed directly to copper. The combination of the Cu_3Sn & Cu_6Sn_5 layers seems to result in a very strong bond between the solder and the copper.

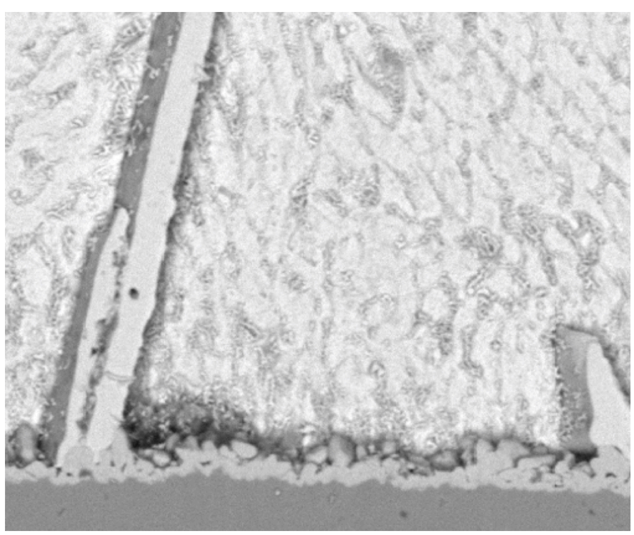

Figure B: Example of a Cu_3Sn interfacial IMC of a SAC alloy BGA solder joint on OSP board.

Ni_3Sn_4

The intermetallic Ni_3Sn_4 forms between tin and electroplated nickel and electroless nickel (e.g. Ni-P) plating layers. Electroless-nickel immersion-gold (ENIG) PWB finishes have become increasingly common and nickel barrier plating is also quite common making the Ni_3Sn_4 an important consideration.

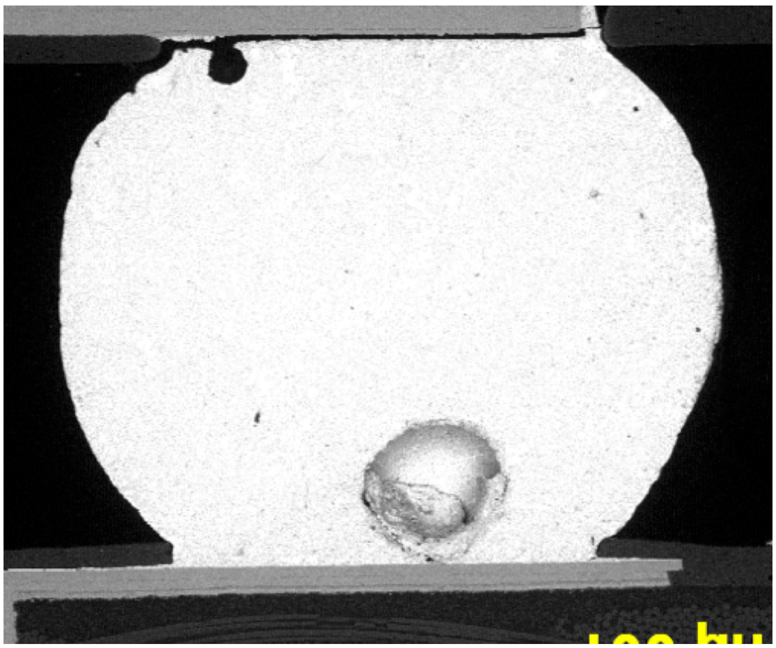

Figure C: Example of black pad syndrome, interfacial failure between Ni_3Sn_4 and Ni-P.

$AuSn_4$

The intermetallic AuSn4 is generally a concern when it forms at too high a volume fraction in bulk Sn-based solder joints [1], which is referred to as gold embrittlement. Since four tin atoms are consumed for each gold atom, the volume fraction can increase rapidly with increasing gold concentration.

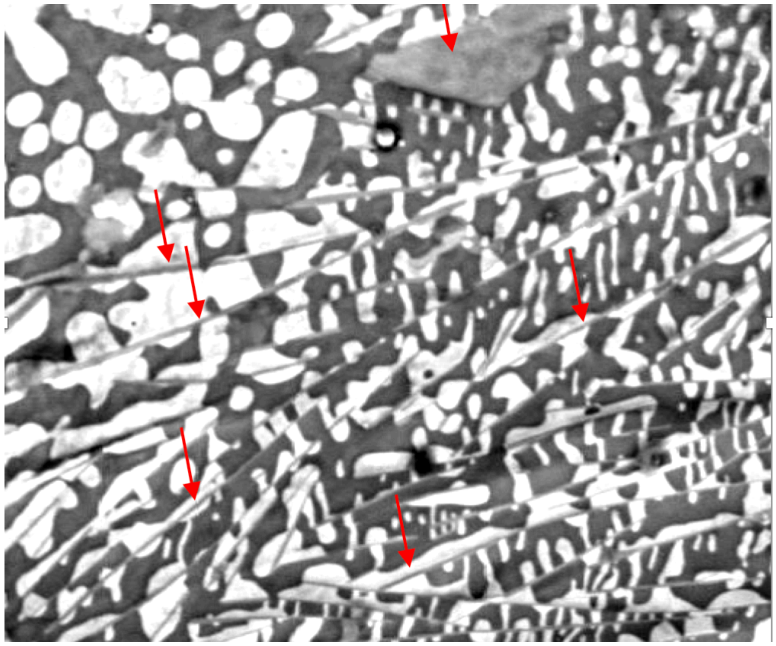

Figure D: Eutectic tin-lead microstructure with gold embrittlement. Bright areas are Pb-phase, darker areas are Sn-phase, and intermediate contrast areas are Au-Sn IMC ($AuSn_4$ - red arrows). Image processing was used to estimate the area fraction of IMC in this image, which was calculated at 20.5% corresponding to a severely embrittled solder joint.

Ag_3Sn

The intermetallic Ag_3Sn is a constituent phase in SN62 solder (62Sn-36Pb-2Ag) and in SAC alloys. It is also important when tin-based solder is used on immersion silver (IAg) finished printed wiring boards and silver terminated chip components.

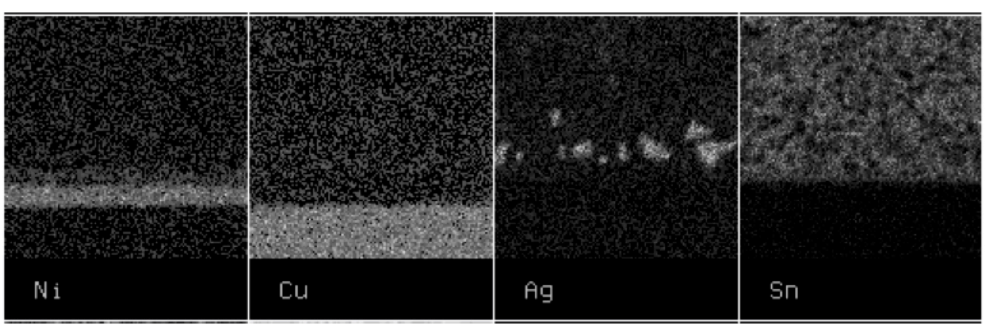

Figure E(a): X-ray dot map of Ag_3Sn that settled onto the Ni_3Sn_4/solder interface. (b) This is a Ag_3Sn IMC needles growing into the bulk solder from the PWB mounting pad on an IAg

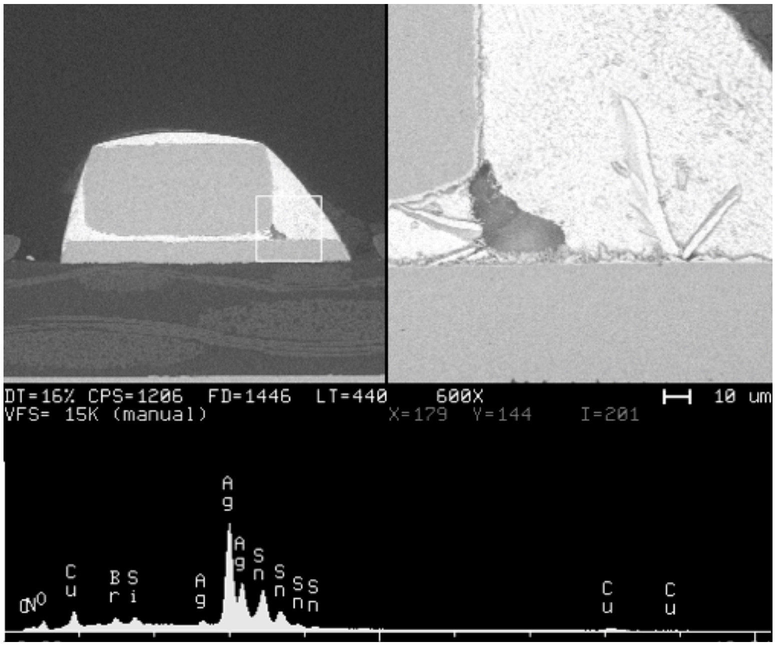

Figure E(b): This is a Ag_3Sn IMC needle growing into the bulk solder from the PWB mounting pad on an IAg finished PWB.

Volume Fractions

The gold-tin system will be used in this section to illustrate the volume fraction of IMC that results when tin reacts with gold in bulk solder. Using eutectic tin-lead solder in the example we can write this reaction as ...

Sn + Pb + Au >>> Sn + Pb + $AuSn_4$

The density of these constituent phases can be used to calculate the volume fraction. Tin has a small amount of Pb in solid solution (and vice versa), but for our purposes we can use the density of pure tin and pure lead. The density of the constituent phases and atomic or formula weights of the elements are listed below.

pAu = 19.3 g/cm^3

pSn = 7.3 g/cm^3

pPb = 11.34 g/cm^3

$pAuSn_4$ = 8.985 g/cm^3 [1]

AWAu = 196.97 g/mole

AWSn = 118.71 g/mole

AWPb = 207.2 g/mole

$FWAuSn_4$ = 671.81 g/mole

We can set up a spreadsheet for calculating the volume fraction of IMC versus the weight percentage of gold using a mass balance approach and generate Fig. F below. Fig. F shows that the volume fraction of AuSn4 increases rapidly with weight percent gold and the primary tin phase is consumed.

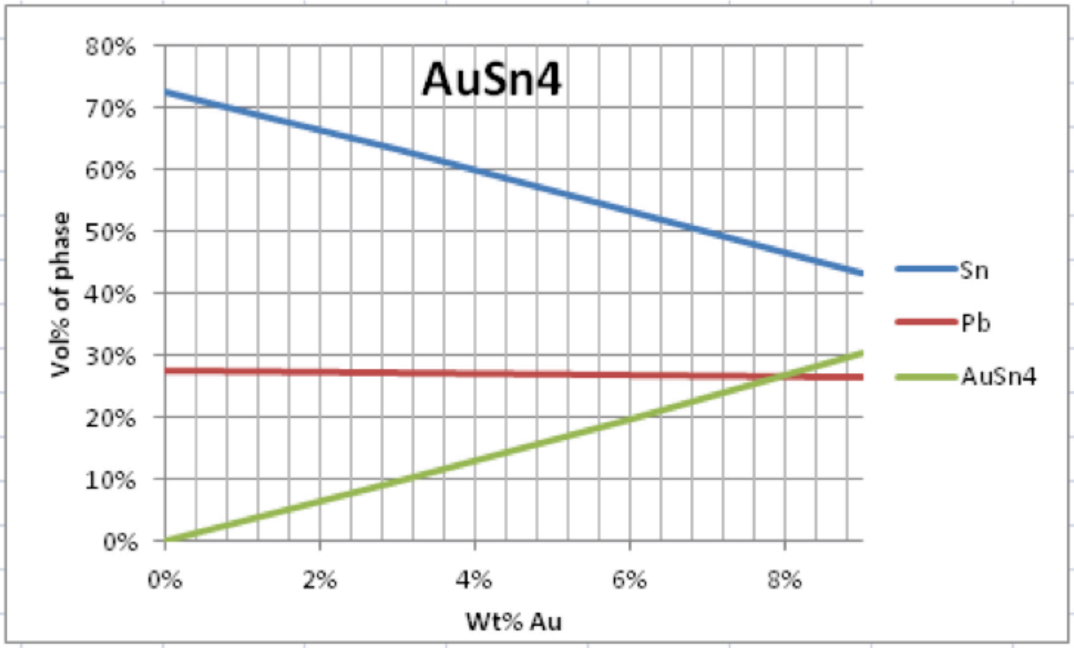

Figure F: Volume percentage of $AuSn_4$ in bulk eutectic tin-lead versus weight percent gold.

The same approach was used for Ag_3Sn and Cu_6Sn_5 IMCs in bulk eutectic tin-lead solder as shown in Fig. G. The AuSn4 is worst case for generating volume of IMC since the Au:Sn ratio is 1:4. The Cu6Sn5 is also a concern since the atomic weight of copper is ~ 1/3 that of gold so it takes less copper weight to generate more IMCS. Solder joints are referred to as "overheated" when too much copper is dissolved into the solder making it "gritty".

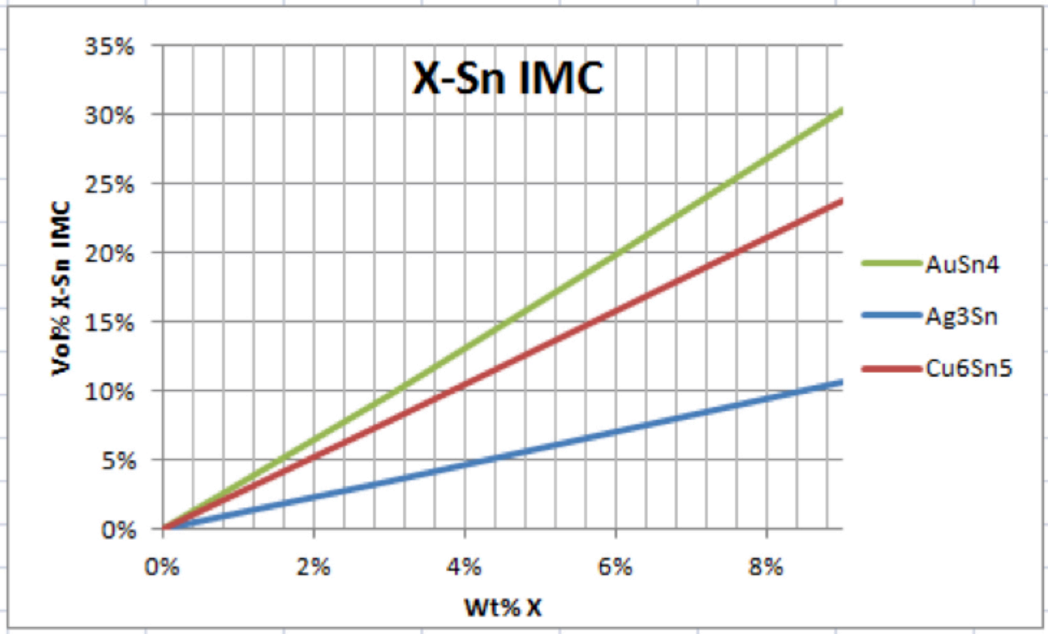

Figure G: Volume percentage of X-Sn IMC in bulk eutectic tin-lead versus weight percent "X".

Ternary IMCs

Zribi et a [3] found that a ternary intermetallic phase, $Au0.5Ni0.5Sn_4$, grows at the Ni_3Sn_4/solder interface during annealing. The presence of this ternary phase was shown to decrease the toughness of the solder joints. Marks [9] demonstrated failures at the Ni_3Sn_4/ solder interface after aging.

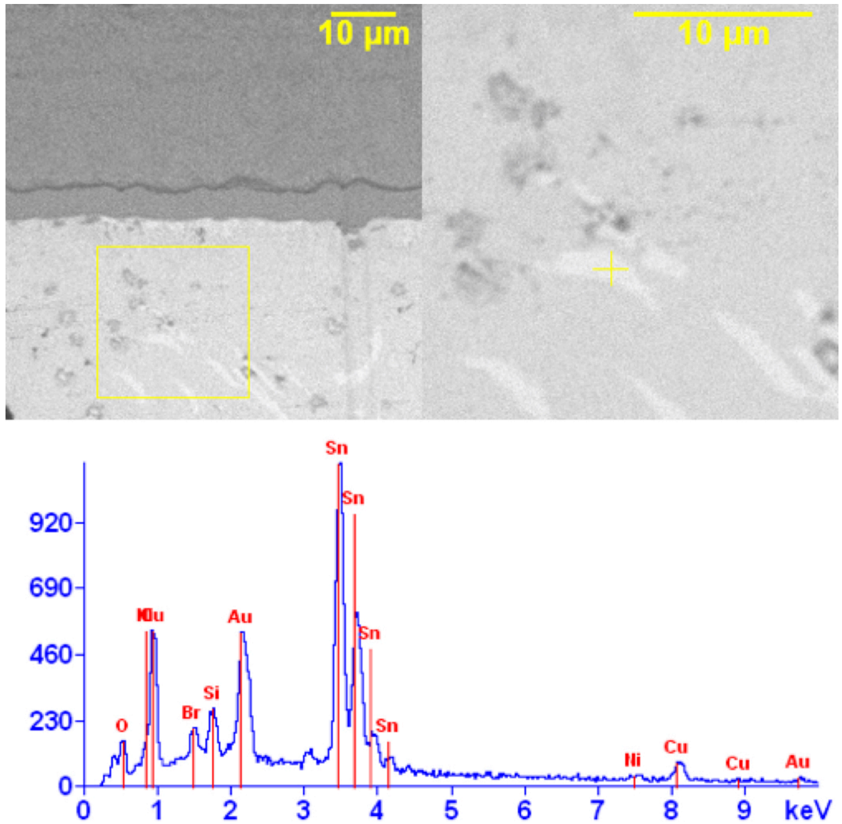

Figure H: Apparent $Au_{0.5}Ni_{0.5}Sn_4$ phase in bulk SAC solder joint.

Yoon-Chul Sohn et al [10] identified ternary phases including $(Ni,Cu)_3Sn_4$, $(Cu,Ni)_6Sn_5$, and Ni_3SnP in solder joints utilizing SAC alloy. The Ni_3SnP phase was identified as the phase likely responsible for brittle interfacial fracture at Ni-P/solder interfaces.

Conclusions

This paper highlighted some of the conditions, microstructures, and metallurgical considerations involving intermetallic compounds in solder joints.

References

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