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Low Temperature Solders – *Déjà vu*

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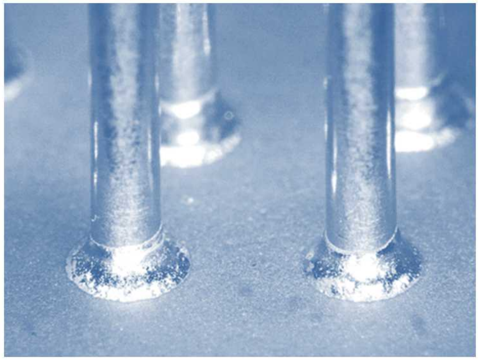

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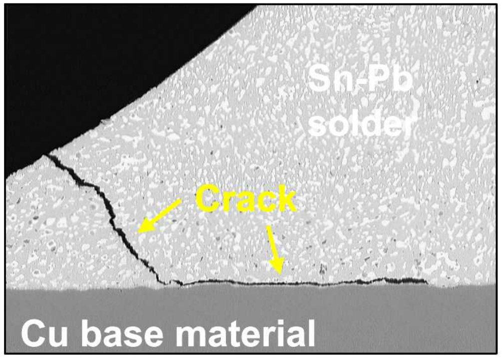
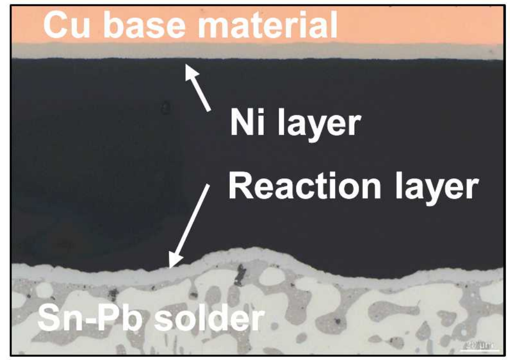
Mechanical Metallurgy

- **In the past, base materials were usually stronger than Sn-Pb solders.**
  - **Solder joint failures occurred in the filler metal or at an interface.**

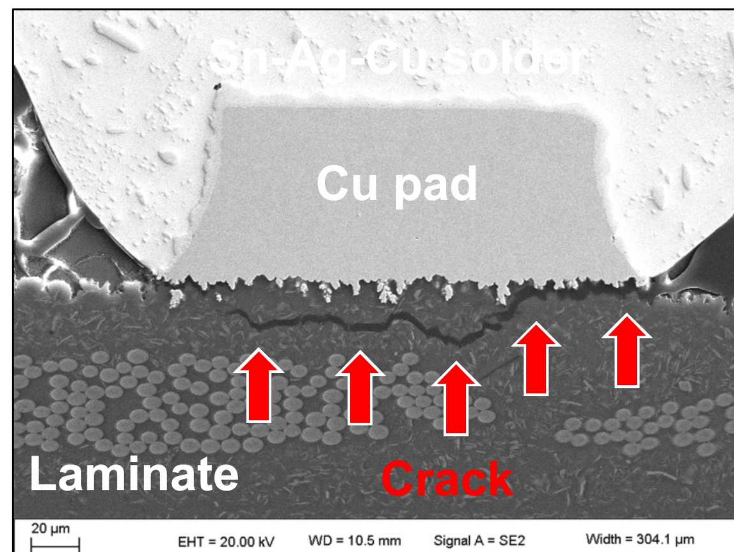


Solder (bulk) failure



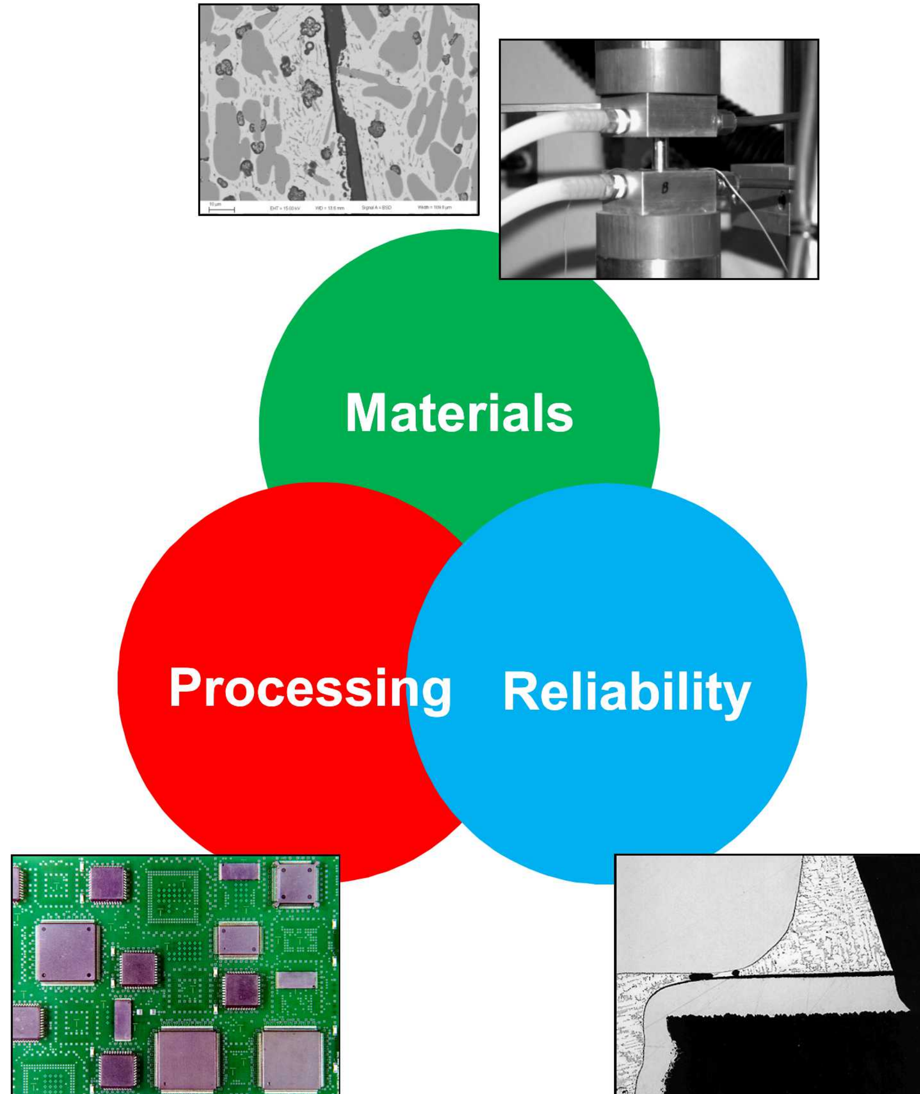
Interface failure

- **However, high strength solders can "push" the failure into printed circuit board (PCB) or component structures.**
  - **As the strength of the solder increases, so does the risk of this "collateral damage."**



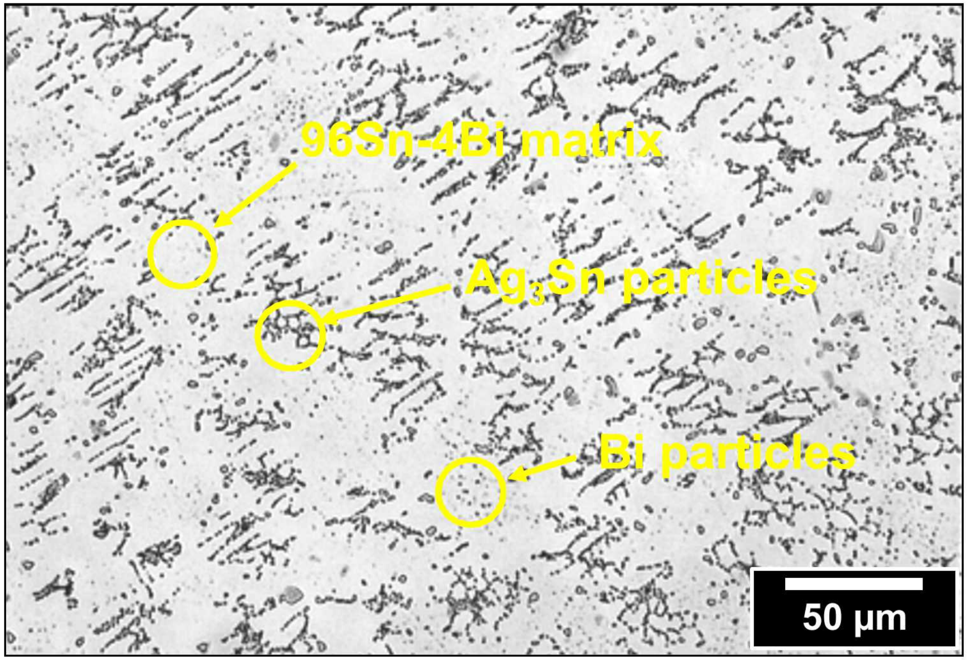
Current Low Temperature Solders – Sn-Ag-Bi

- **Materials**
  - Alloy microstructure
  - Mechanical performance
- **Processing**
  - Solderability performance
- **Reliability**
  - Interface reactions
  - Solder joint fatigue
  - *Pb-contamination effects*
- **Summary**



Current Low Temperature Solders – Sn-Ag-Bi

- The as-cast microstructure is shown below for the 91.84Sn-3.33Ag-4.83Bi (T_s - 212°C) alloy:

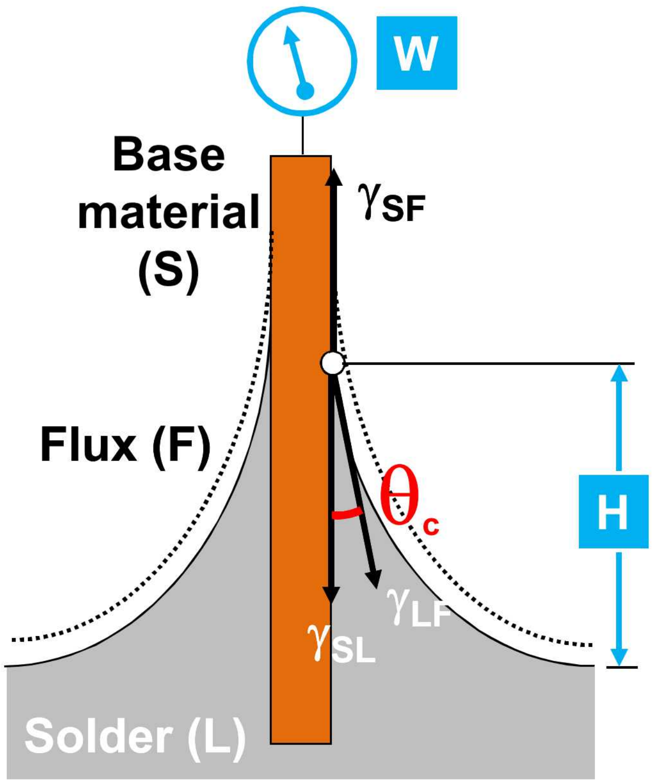


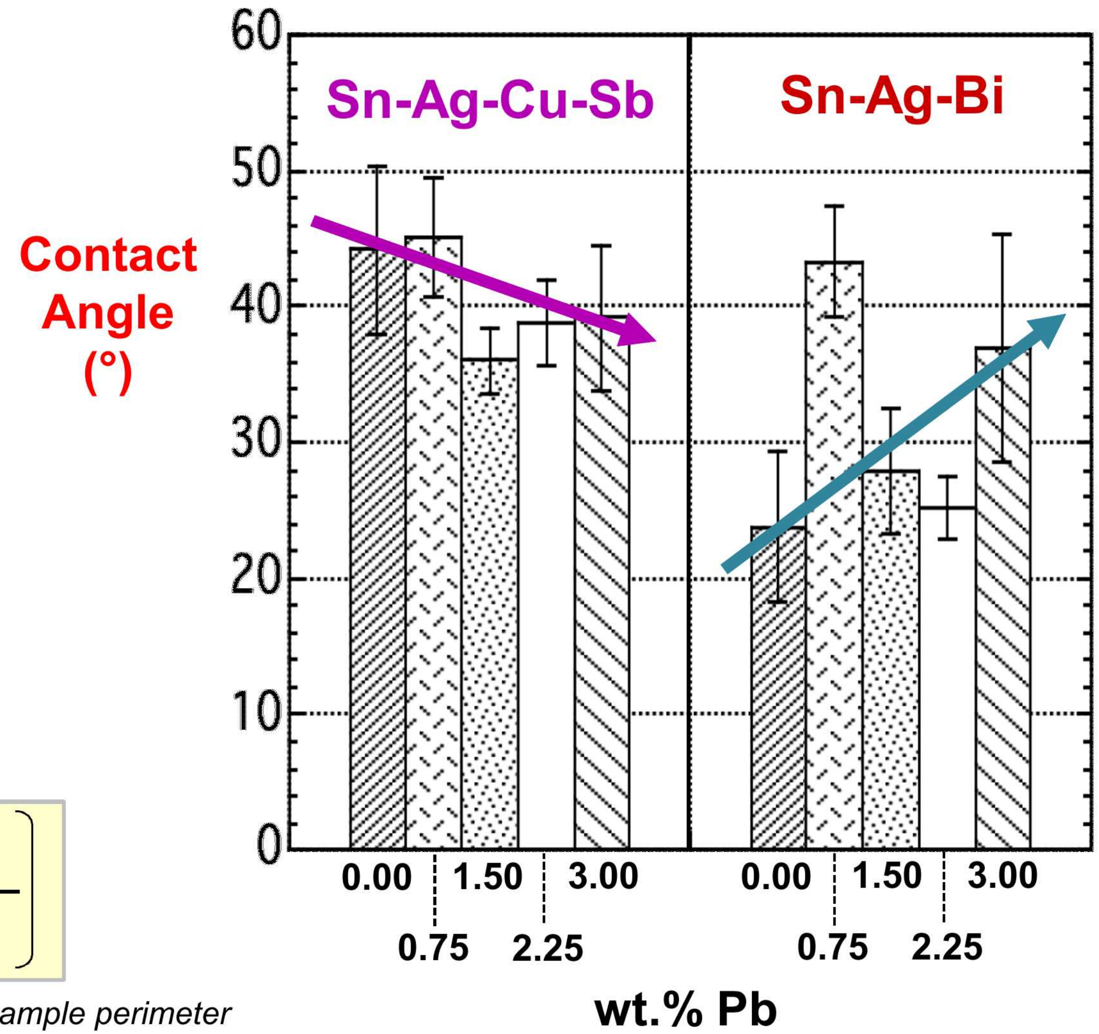
P. Vianco, et al., JEM 28 (1999).

- This solder was engineered to have the same strengthening mechanisms that are found in high-performance alloys:
  - Precipitation hardening
  - Solution strengthening

Current Low Temperature Solders – Sn-Ag-Bi

- **Careful … alloy additions also affect solderability.**



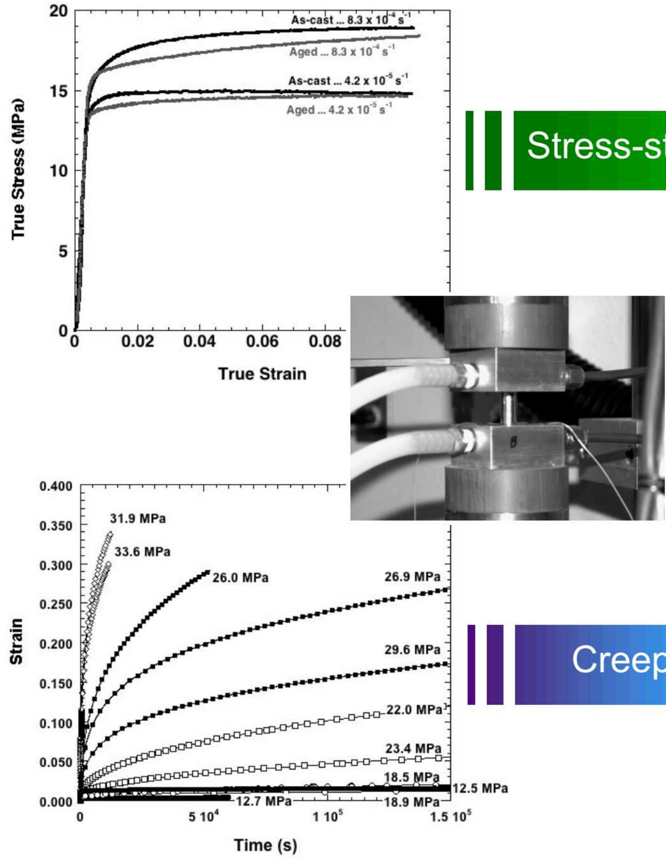


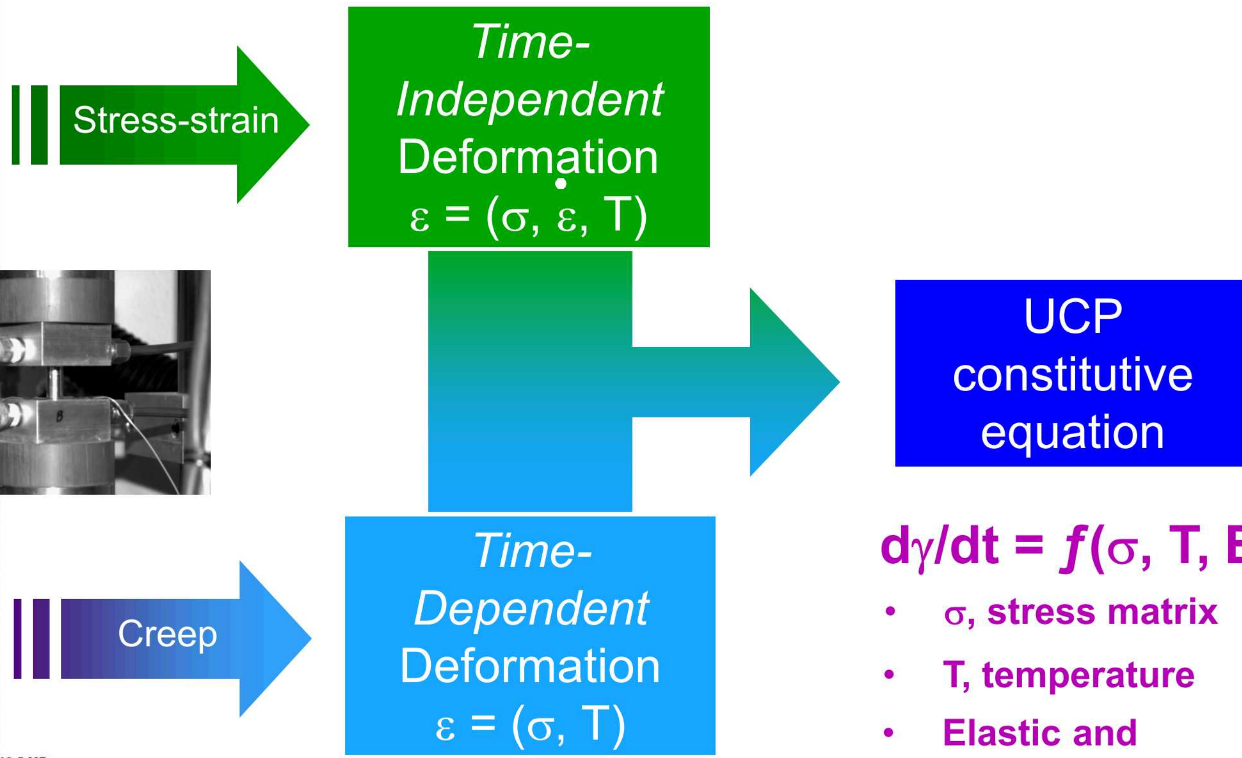
$$\theta_c = \arcsin\left(\frac{4W^2 - (\rho\, g\, P\, H^2)^2}{4W^2 + (\rho\, g\, P\, H^2)^2}\right)$$

ρ = solder density; g = accn. due to gravity; P = sample perimeter

Traditional Low Temperature Solders

- The computational modeling approach was used, which was based upon the **unified creep-plasticity (UCP) equation**.
  - Combine time-independent and time-dependent deformation behaviors into a single UCP constitutive equation; $d\gamma/dt = f(\sigma, T, E)$.





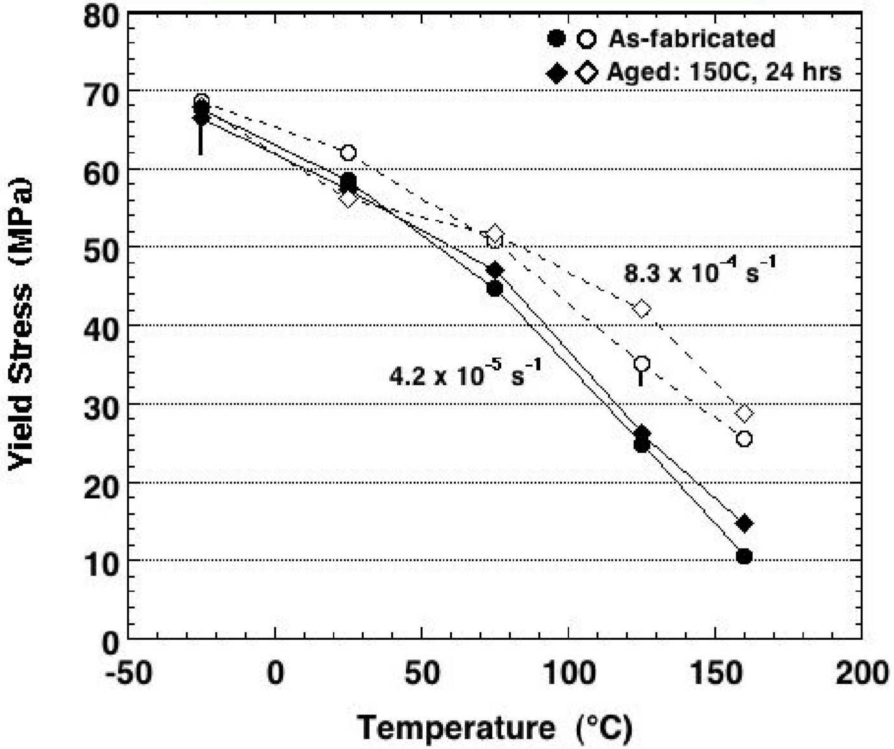
$d\gamma/dt = f(\sigma, T, E)$

- σ, stress matrix
- T, temperature
- Elastic and physical properties

Current Low Temperature Solders – Sn-Ag-Bi

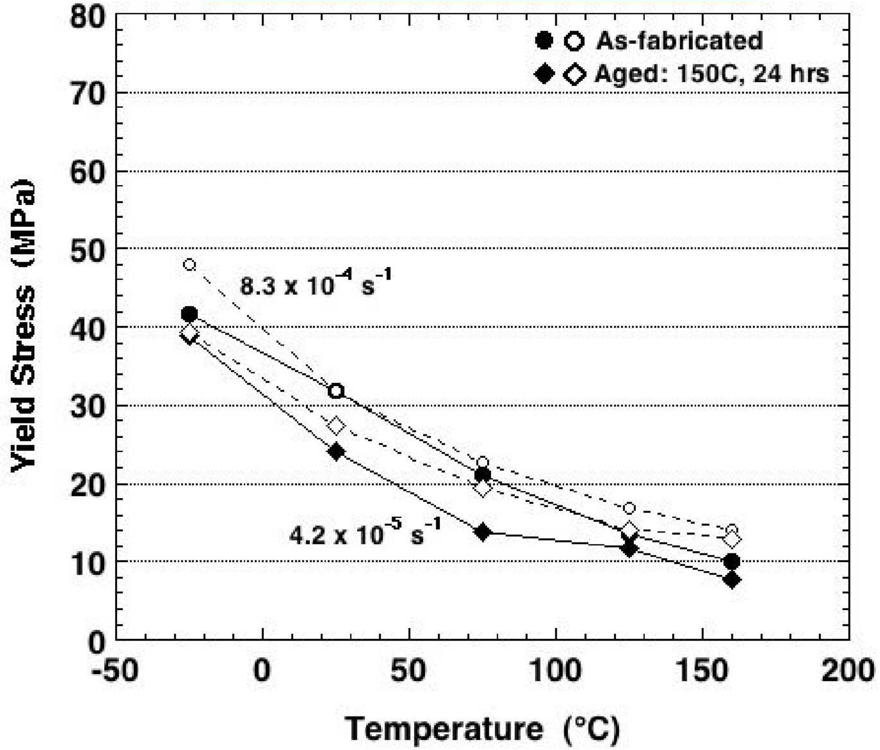
- **The improved strength of Sn-Ag-Bi is evidenced by its yield stress properties when compared to those of the SAC396 alloy.**
  - **The Sn-Ag-Bi maintains a higher strength over temperature and shows little sensitivity to aging (125°C or 150°C, 24 hours).**

91.84Sn – 3.33Ag – 4.83Bi



P. Vianco, et al., JEM 28 (1999).

95.5Sn – 3.9Ag – 0.6Cu

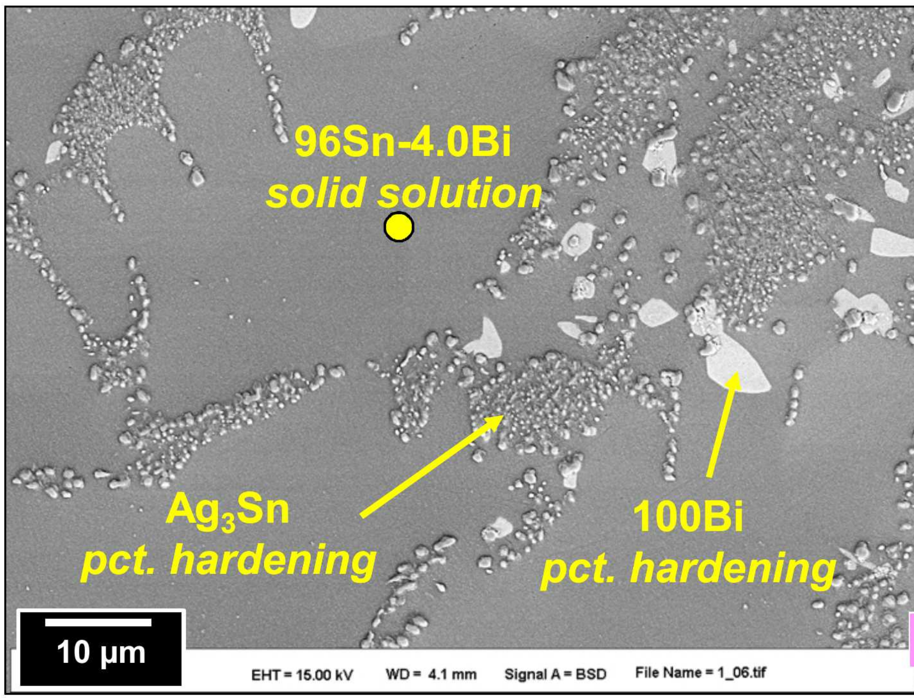


P. Vianco, et al., JEM 32 (2003).

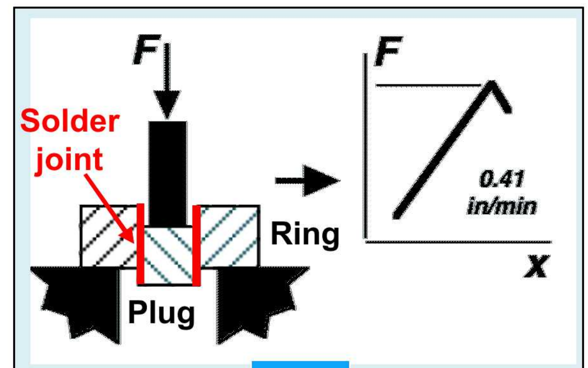
Current Low Temperature Solders – Sn-Ag-Bi

- **The solder is tested in joint configurations to include the effects of gap thickness and (area) footprint on mechanical performance.**
  - **The ring-and-plug shear test provides a method to measure the shear strength of Sn-Ag-Bi *solder joints*.**

91.84Sn – 3.33Ag – 4.83Bi



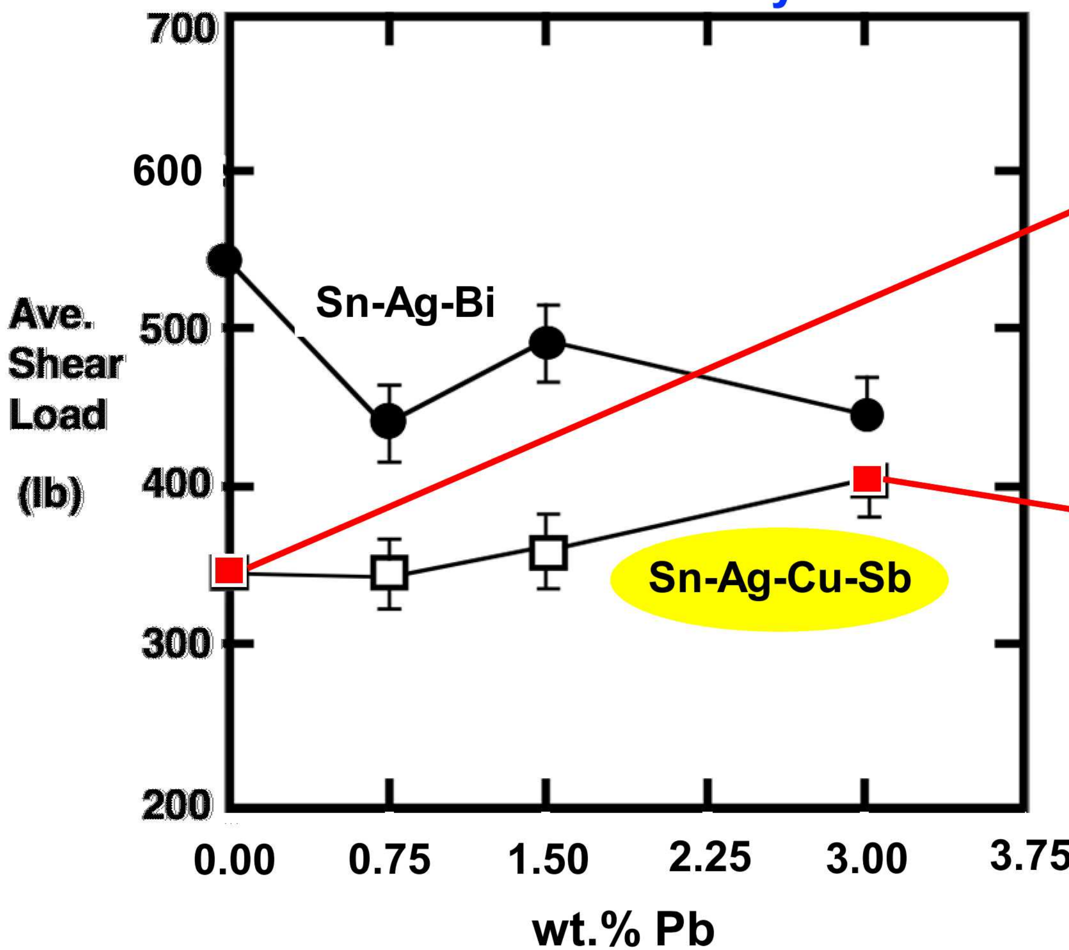
Ring-and-Plug Shear Test

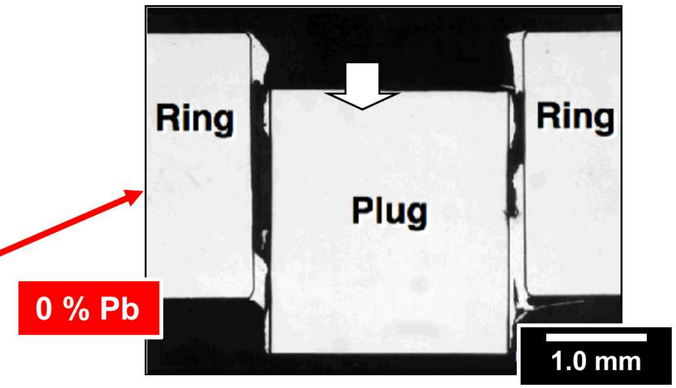


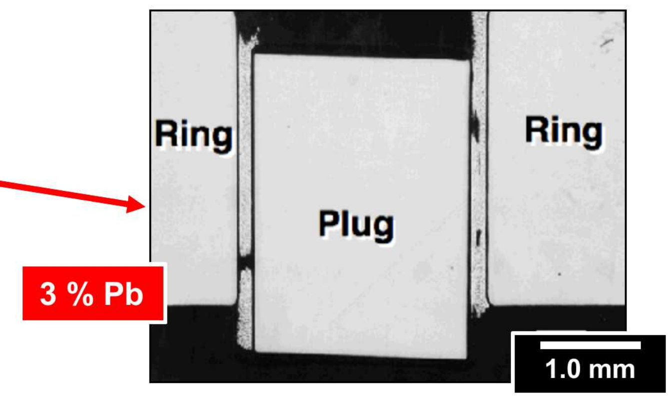
Solder	Stress (psi)
Sn-Pb	5840
Sn-Ag	7970
Sn-Ag-Bi	11800

Current Low Temperature Solders – Sn-Ag-Bi

- **Alloy additions affect the mechanical properties of the solder.**
  - Additions of 0 – 3.75 wt.% Pb were made to two alloys.



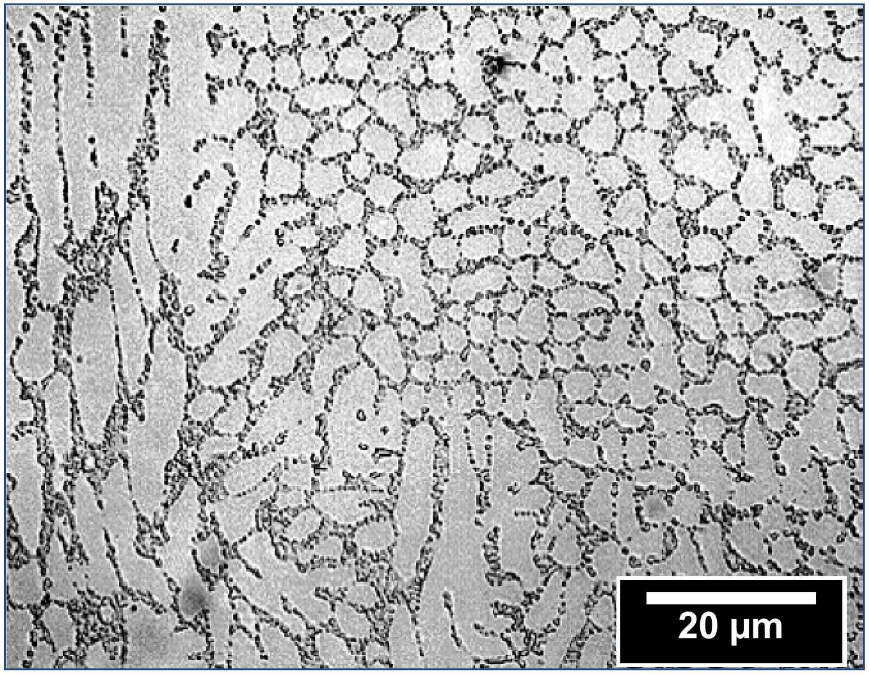


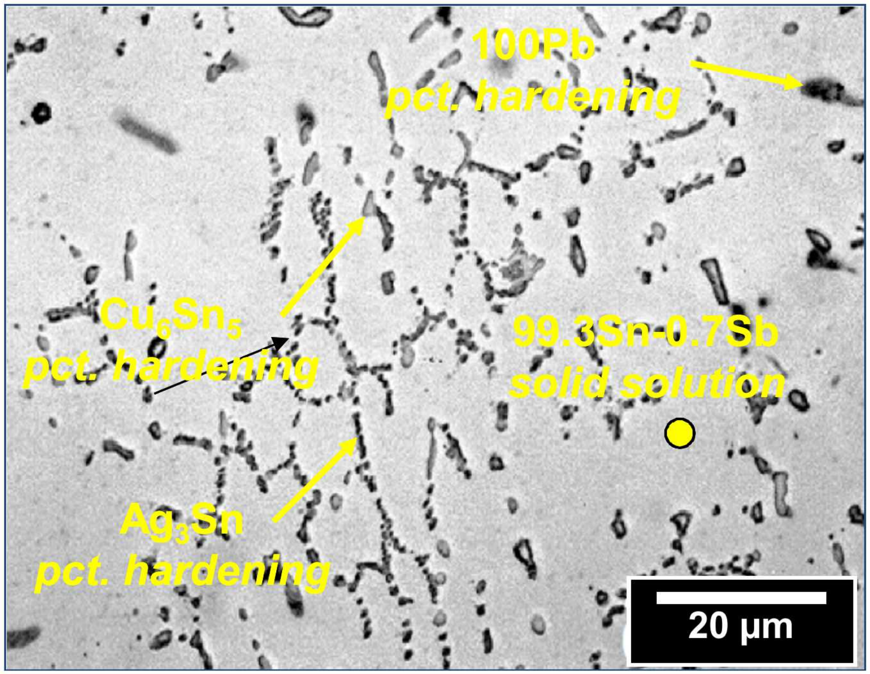


The strength increase was accompanied by a change of failure mode, from the bulk solder to the interface.

Current Low Temperature Solders – Sn-Ag-Bi

- **Sn-Ag-Cu-Sb:** **The addition of Pb broke up the Ag_3Sn particle network,** ***thereby enhancing the precipitation hardening effect.***



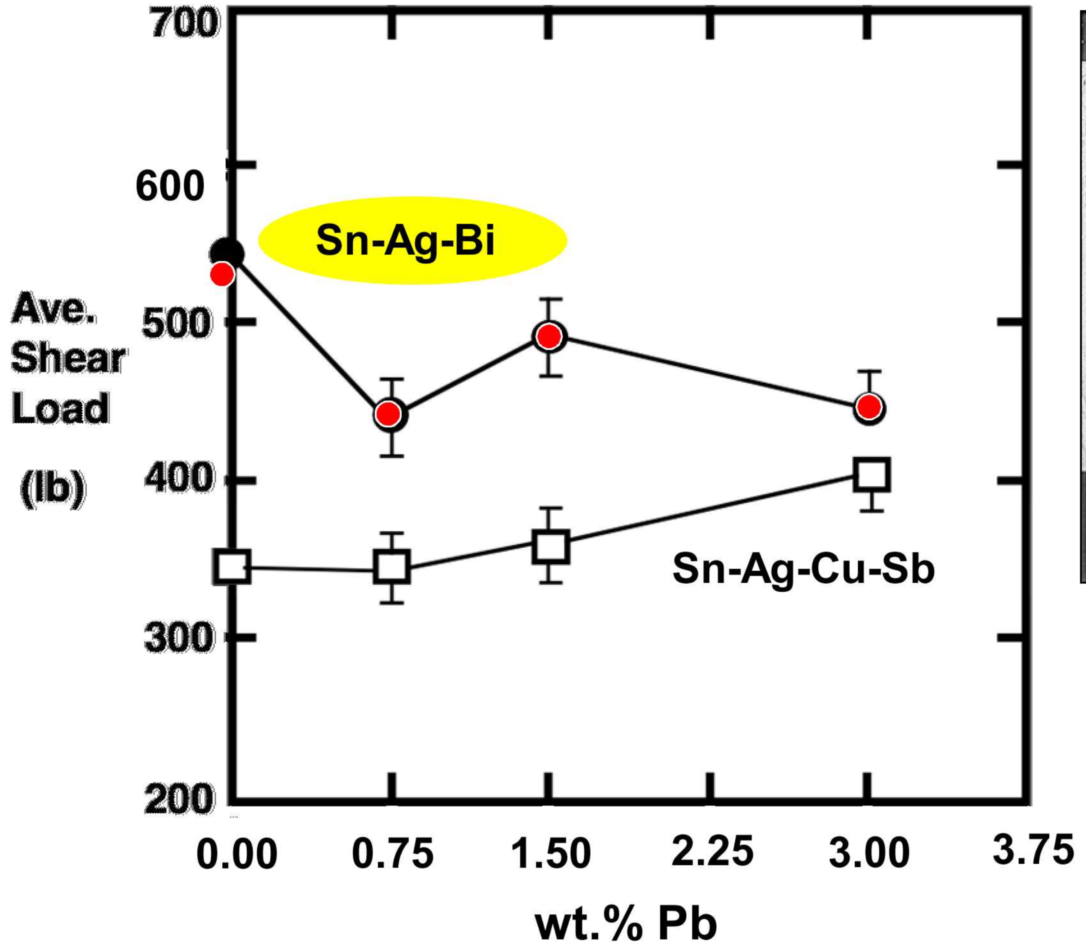


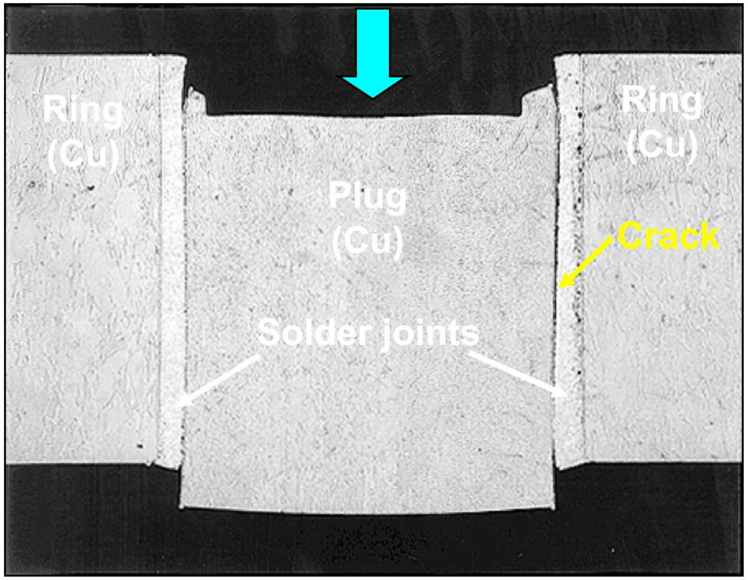
0.00 % Pb

3.00 % Pb

Current Low Temperature Solders – Sn-Ag-Bi

- **Sn-Ag-Bi:** **The fracture path remained along the solder/base material interface for all Pb additions.**

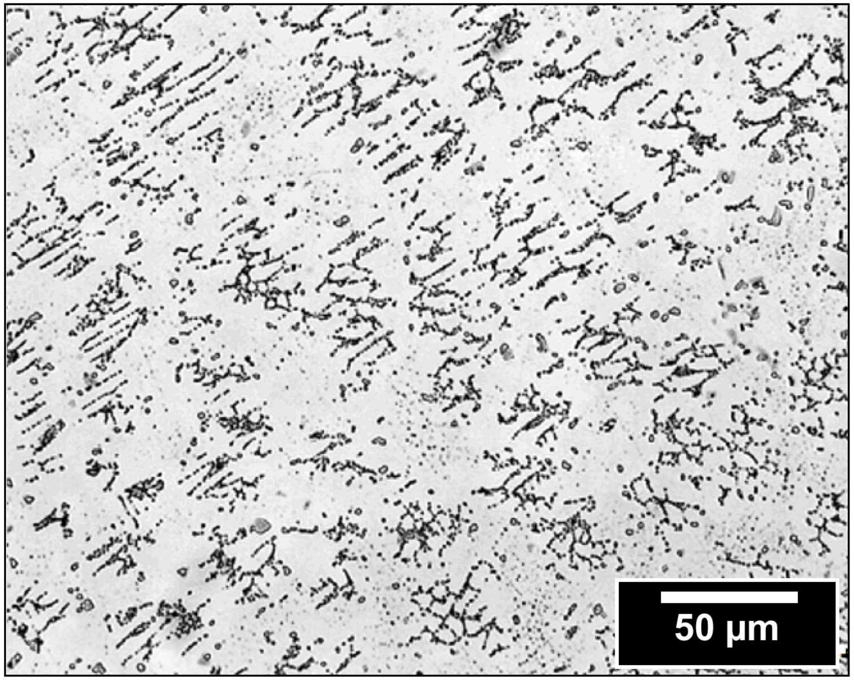




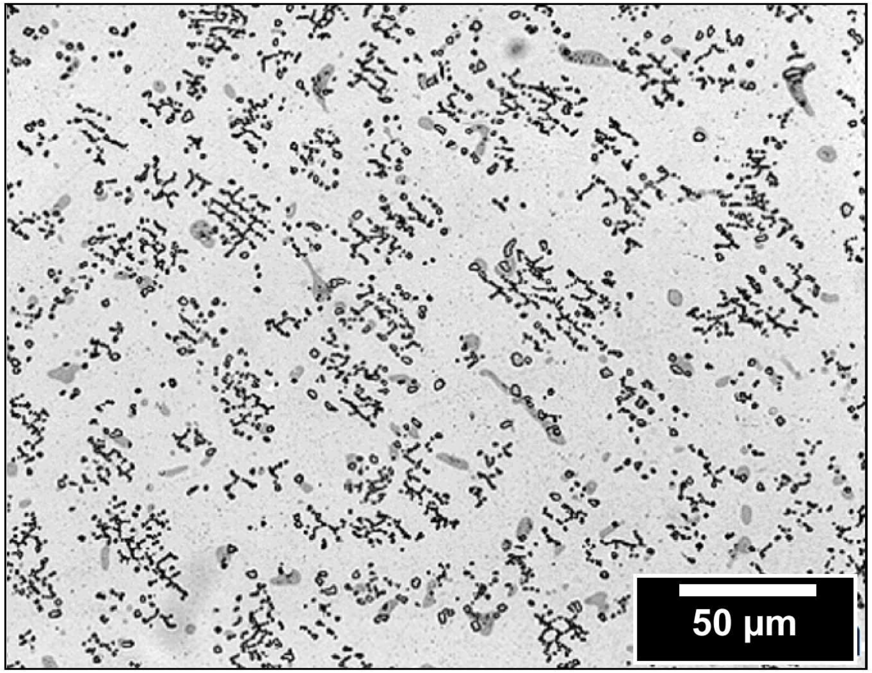
The nominal strength remained greater than the ≈ 400 lb. level above which failure occurs typically at the interface.

Current Low Temperature Solders – Sn-Ag-Bi

- **Microstructural effect:** **The Pb additions did not alter the microstructure on the *large size scale*.**



0.00 % Pb

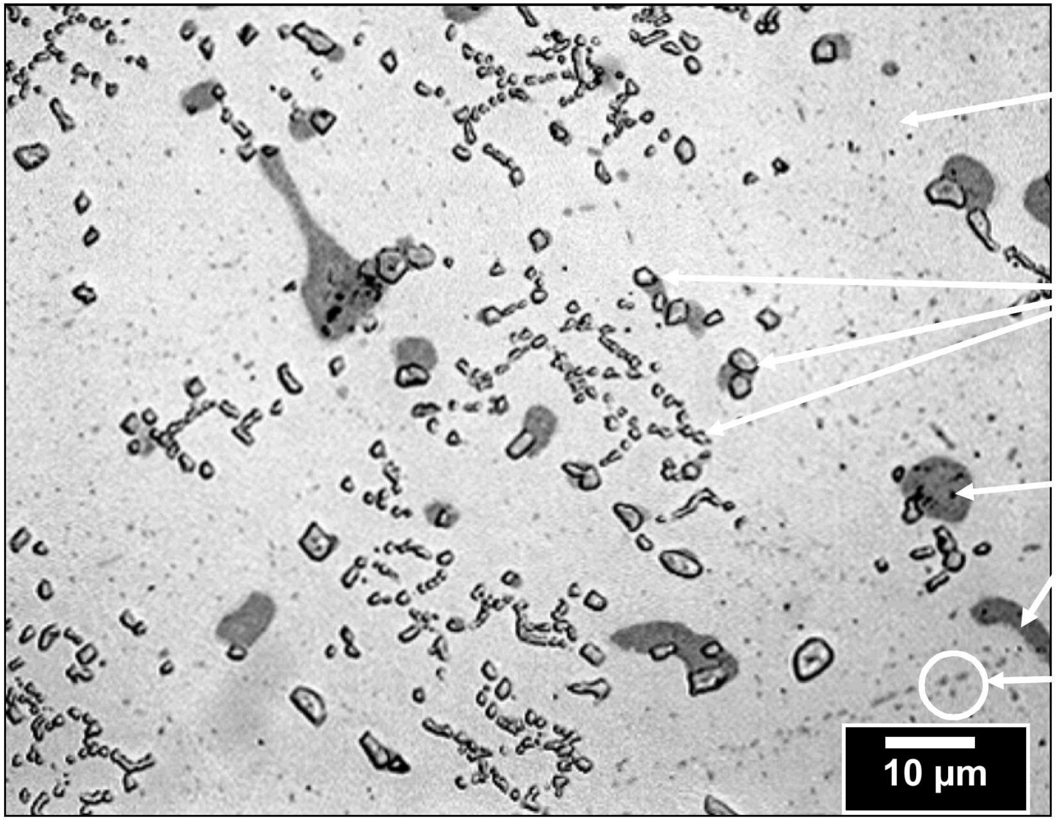


3.00 % Pb

- **On the other hand …**

Current Low Temperature Solders – Sn-Ag-Bi

- … The Pb additions altered the small-scale phase distributions within the Sn-Ag-Bi microstructure.



96.5Sn-3.5Bi
Solid solution

Ag_3Sn

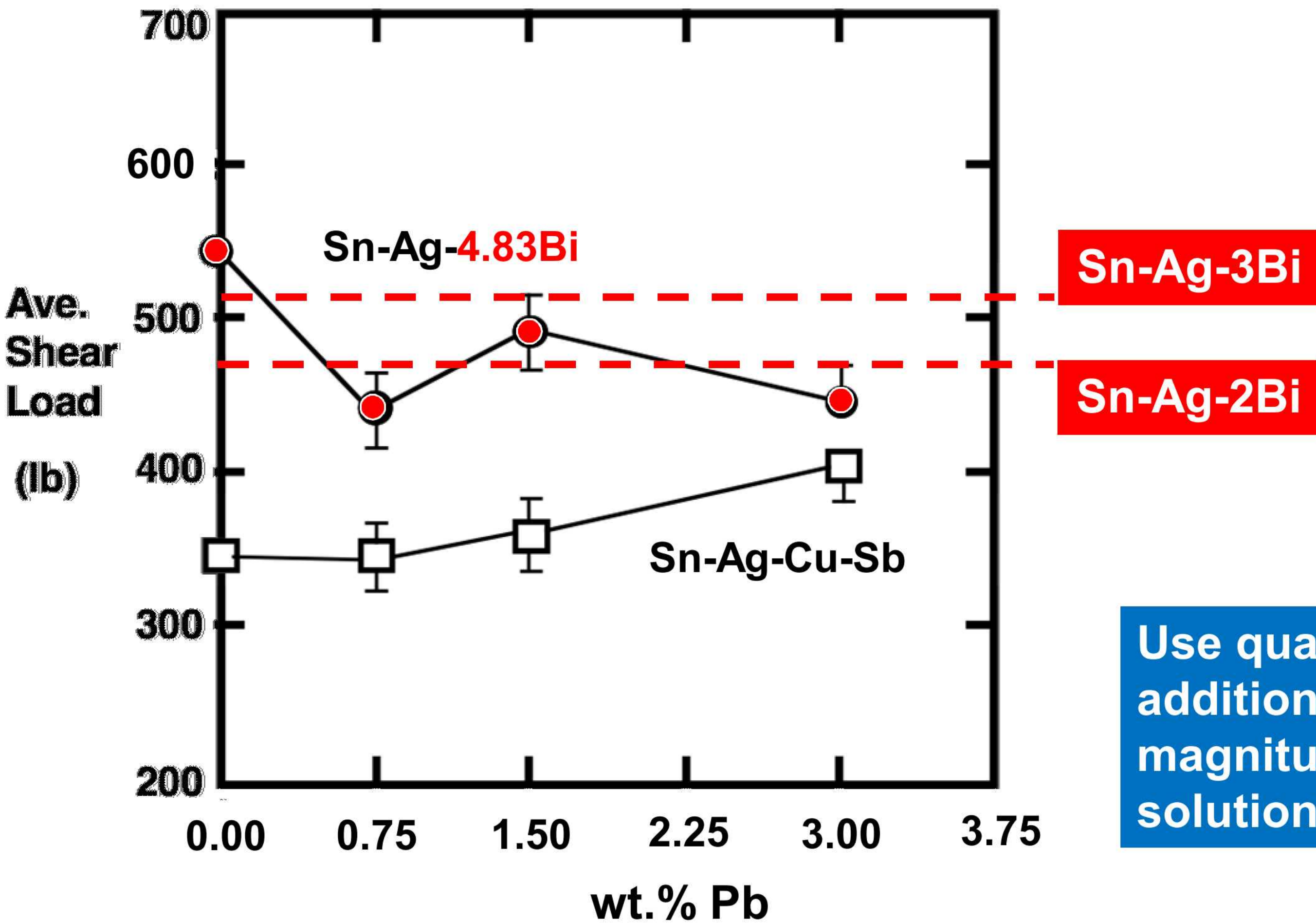
64Pb-33Bi-3Sn

63Sn-24Pb-13Bi

The Pb scavenged Bi from the matrix phase, thus reducing the solid-solution strengthening effect.

Current Low Temperature Solders – Sn-Ag-Bi

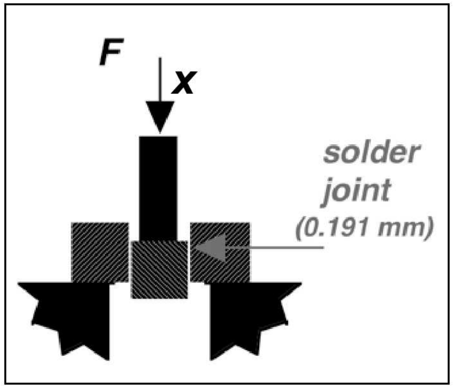
- Ring-and-plug shear tests performed on Sn-Ag-XBi (X = 2, 3 wt.%) confirmed a similar drop of strength.



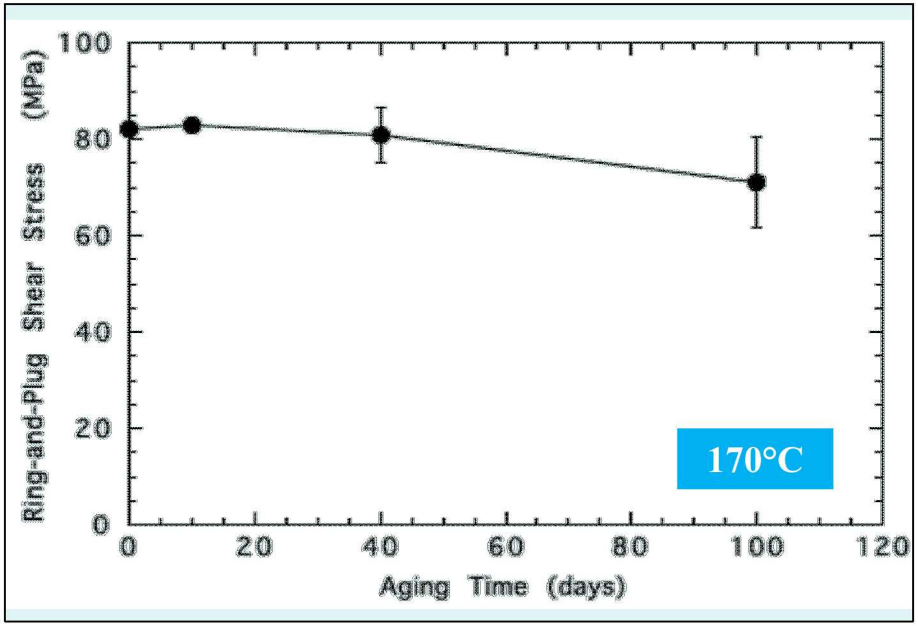
Use quaternary element additions to adjust the magnitude of the solid-solution strengthening.

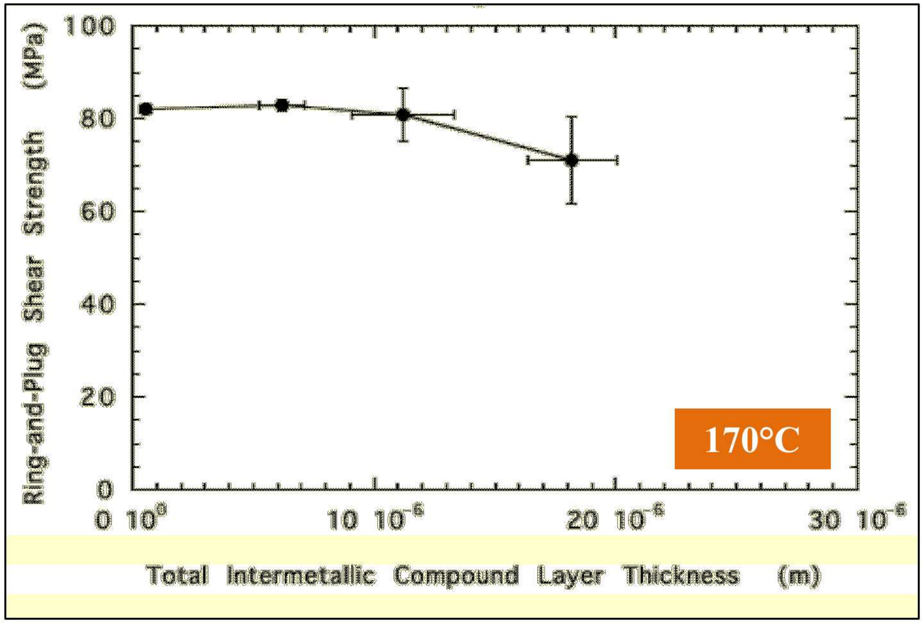
Current Low Temperature Solders – Sn-Ag-Bi

- **The effect of solid-state IMC layer growth on joint strength was examined for Sn-Ag-Bi/Cu couples using the *ring-and-plug shear test.***
  - **Isothermal aging did not cause a significant shear strength loss to the solder joints.**
  - ***Moreover, the development of the IMC layer caused a small strength loss, but only when the IMC thickness exceeded ≈10 µm.***



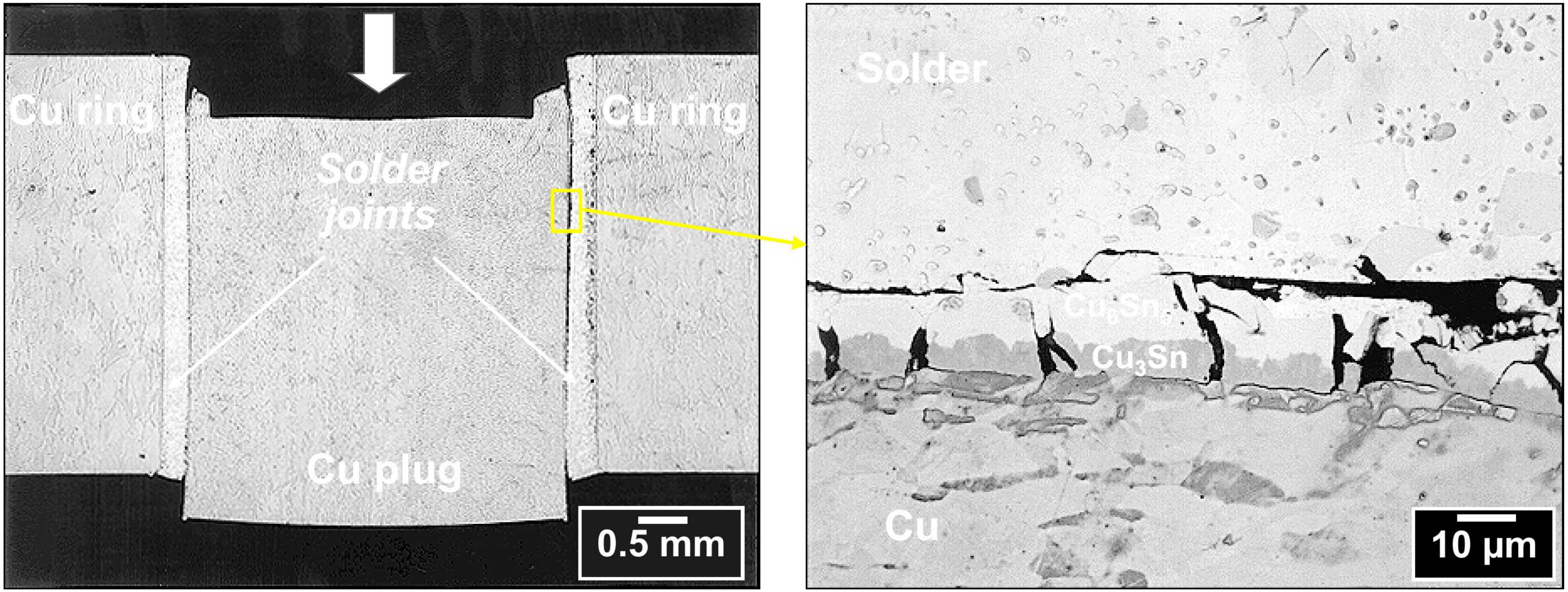
Ring-and-plug shear test





Current Low Temperature Solders – Sn-Ag-Bi

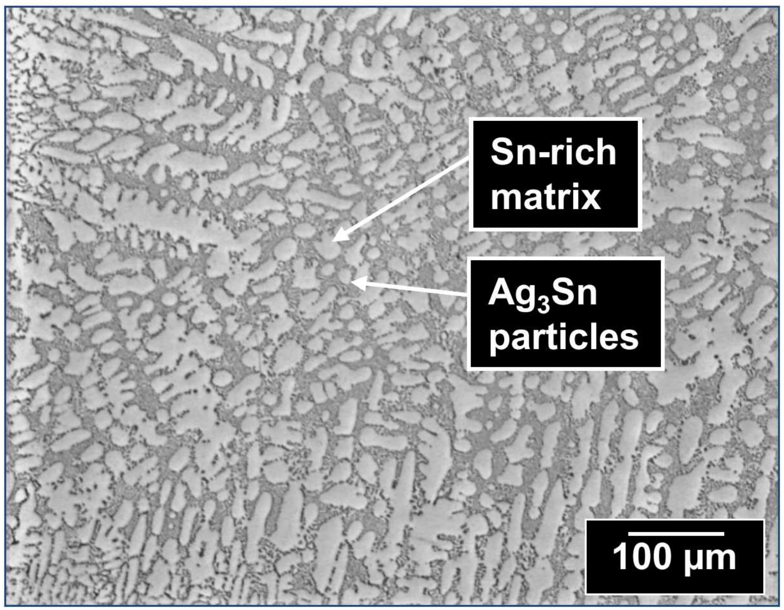
- **The strength study included a failure mode analysis.**
  - **The crack path followed the IMC/solder interface, which is often the case at this displacement rate.**
  - **However, the concurrent presence of cracks in the IMC layer implies that Bi at the IMC/solder interface did not, itself, reduce solder joint strength.**

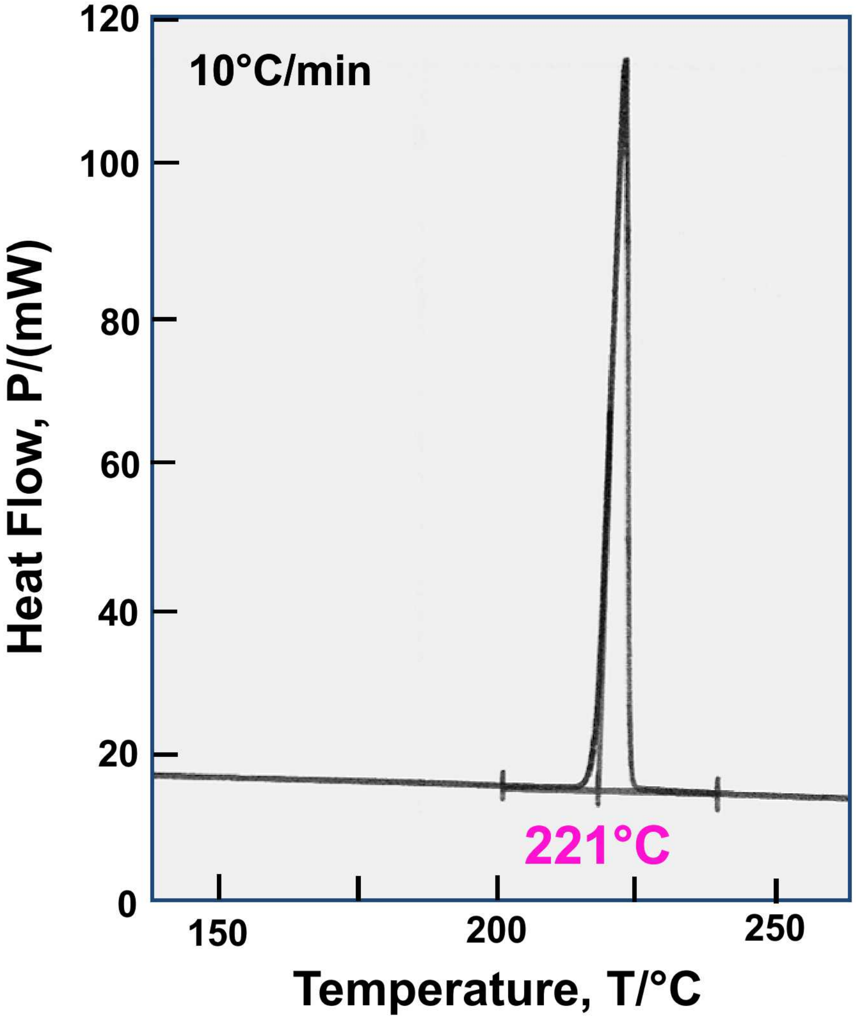


170°C, 100 days

Novel Low Temperature Solders

- **Objective:** *"Develop a Pb-free solder having solidus and liquidus temperatures close to the* ***183°C eutectic temperature*** *of 63Sn-37Pb."*
- **The starting point was the eutectic 96.5Sn-3.5Ag alloy (T_e = 221°C).**

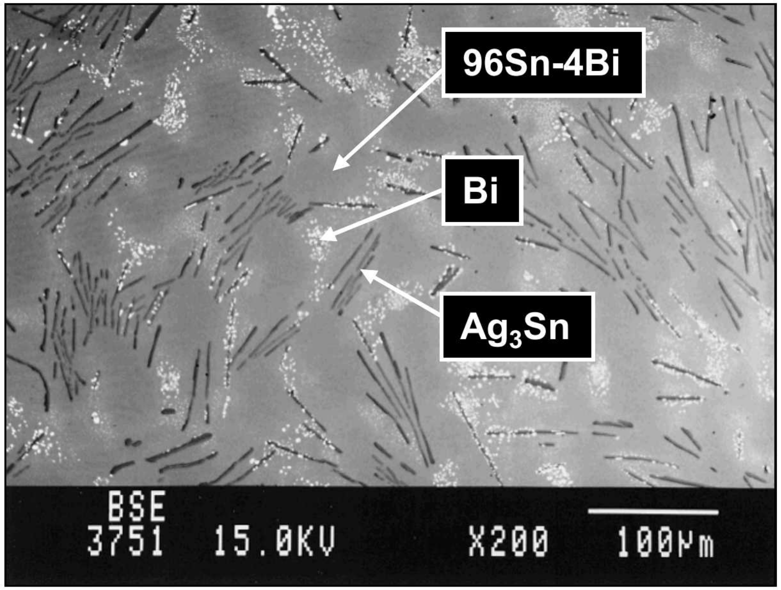


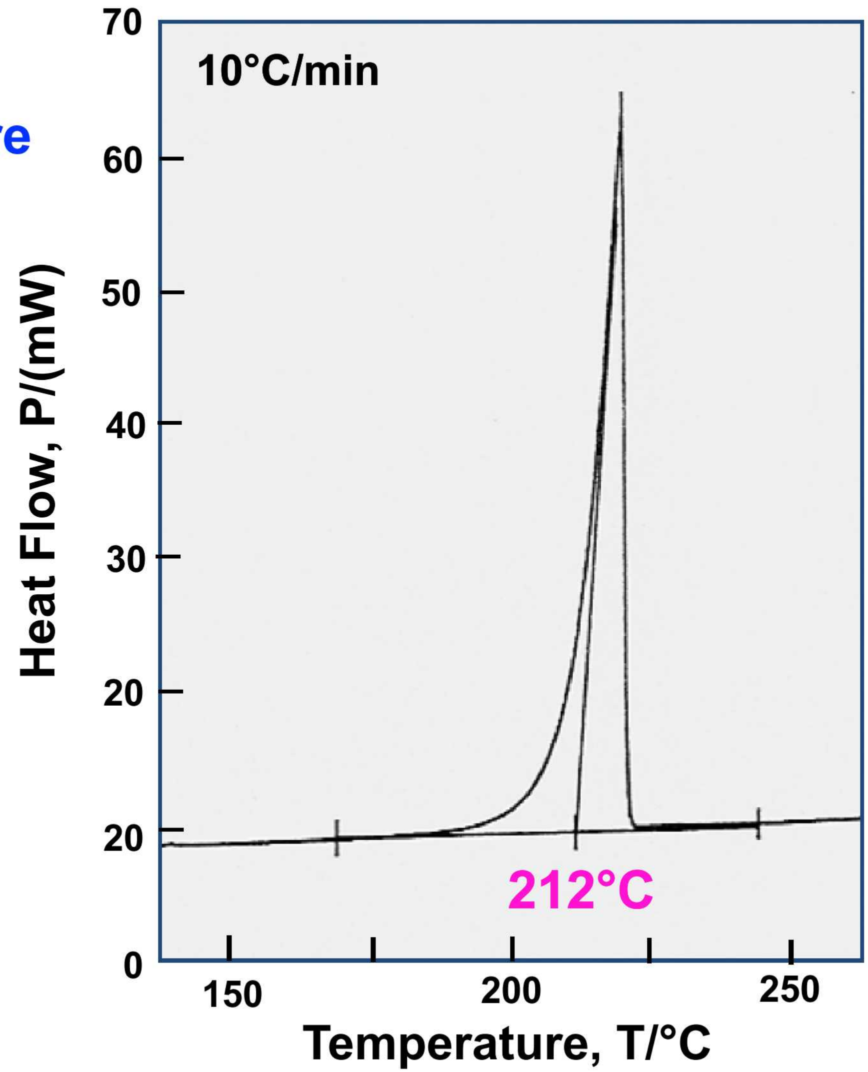


P. Vianco, et al., Mater. Trans of JIM (2004)

Novel Low Temperature Solders

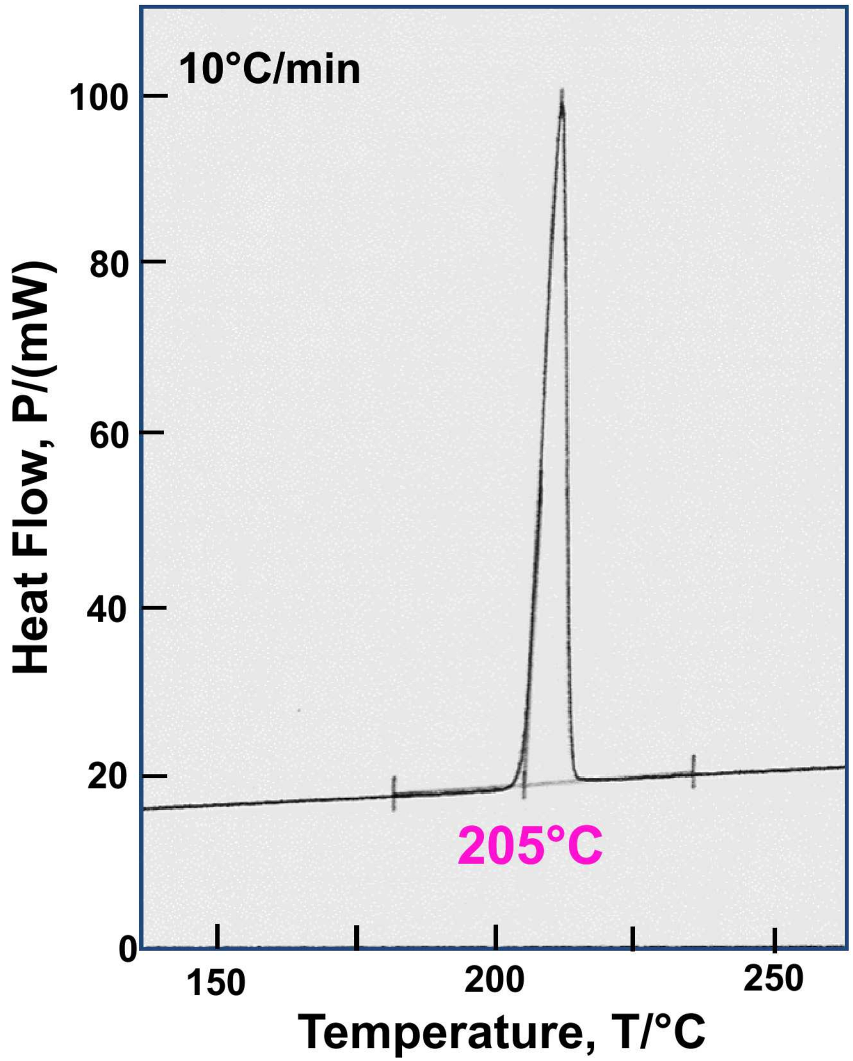
- An extensive development effort led to the 91.84Sn-3.33Ag-4.83Bi alloy having a solidus temperature of 212°C (ΔH = 55 J/g).





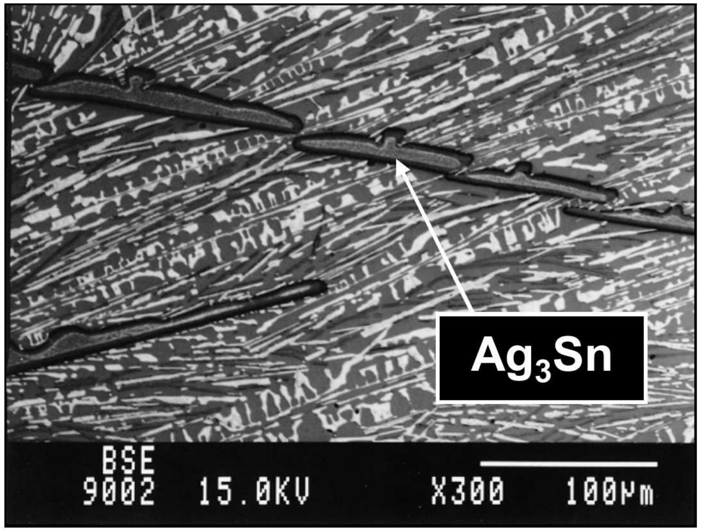
Novel Low Temperature Solders

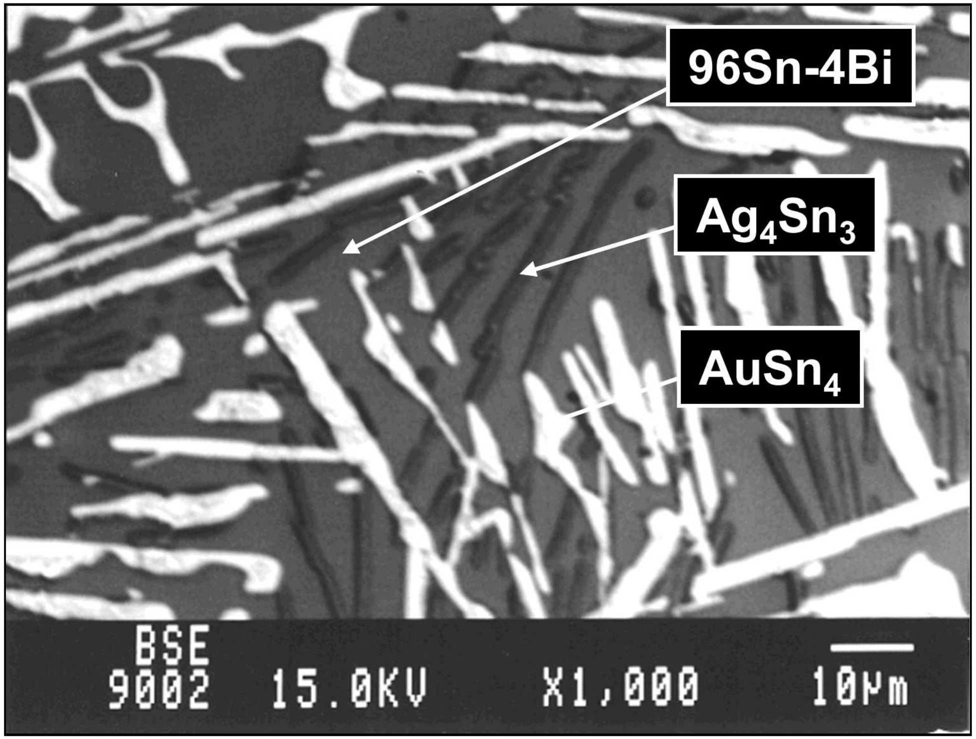
- Two ternary alloys were developed that confirmed the effectiveness of gold (Au) as a melting point depressant.
- The 86.4Sn-5.1Ag-8.5Au was developed from this precept:
  - 95% confidence intervals (mass%) were: Sn, 1.5; Ag, 0.33; and Au, 0.06
  - T_s = 205°C; ΔH = 55 J/g
- The very sharp peak implies that: *T_l - T_s is less than 5°C*.



Novel Low Temperature Solders

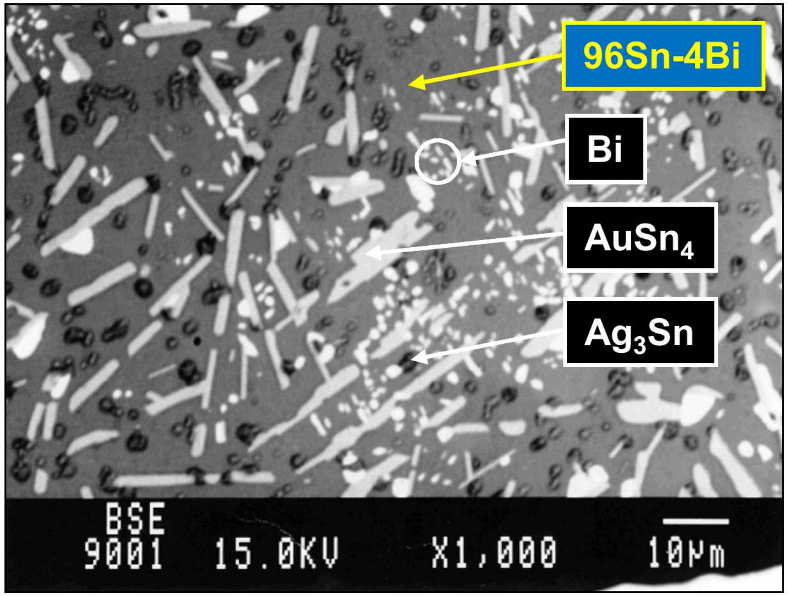
- The 86.4Sn-5.1Ag-8.5Au microstructure was comprised of a solid-solution (matrix) phase, 96Sn-4Bi, and three particle phases:
  - Ag_3Sn
  - Ag_4Sn_3
  - $AuSn_4$

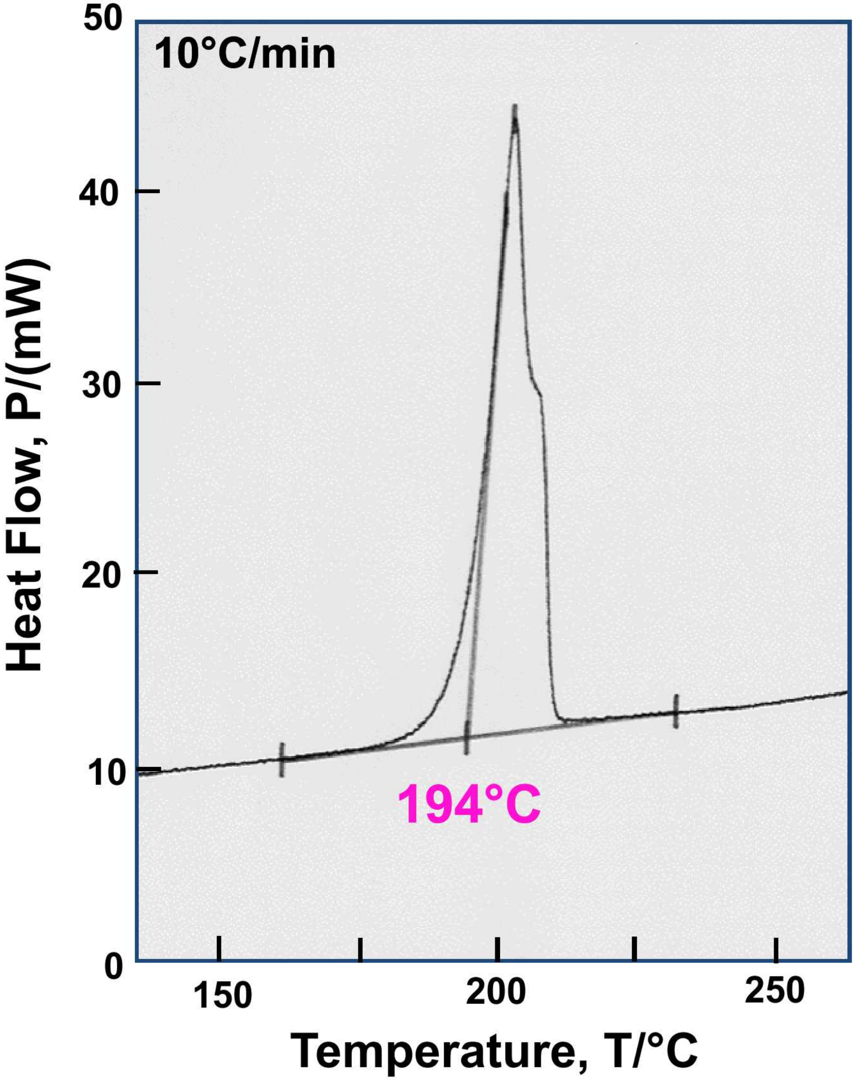




Novel Low Temperature Solders

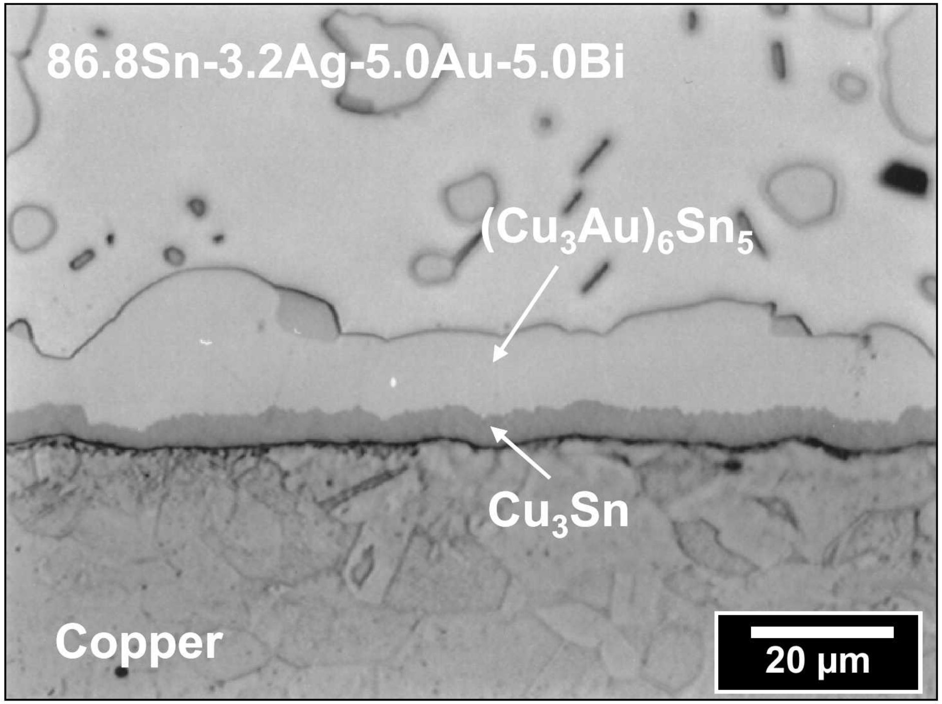
- The 86.8Sn-3.2Ag-5.0Au-5.0Bi exhibited a shoulder that is indicative of a liquidus point of ≈ *204°C*.
  - T_s = 194°C; ΔH = 53 J/g
  - Besides the particle phase, the matrix phase was a solid solution: 96Sn-4Bi.





Novel Low Temperature Solders

- An extensive amount of analysis was performed on the 86.8Sn-3.2Ag-5.0Au-5.0Bi alloy (T_s = 194°C).



170°C, 100 days

- The complexity of the solder composition *did not alter* intermetallic compound (IMC) layer development along the Sn-Ag-Au-Bi/Cu interface vis-à-vis other high-Sn solders.
  - The rate kinetics were similar to the Sn-Ag, 100Sn, etc. solders.

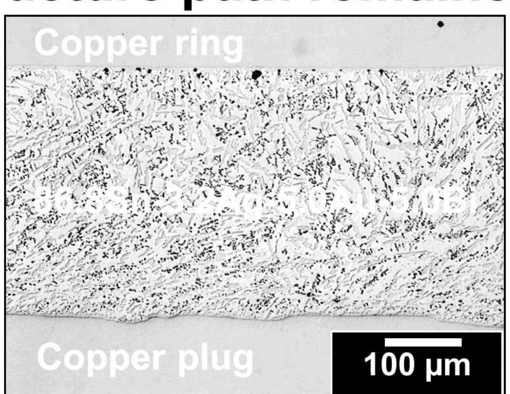
Novel Low Temperature Solders

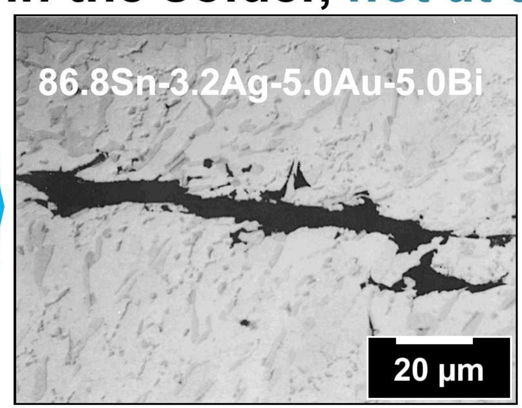
- **Ring-and-plug mechanical testing was performed using the 86.8Sn-3.2Ag-5.0Au-5.0Bi alloy (T_s = 194°C).**

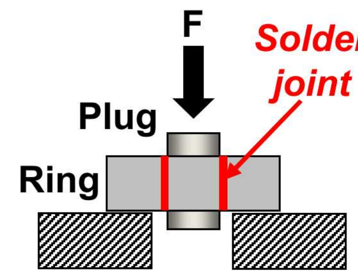
Solder alloy (mass%)	Ring-in-plug shear strength	
87.5Sn-5.0Bi-7.5Au	80 ± 2 (MPa)	11,600 ± 300 psi
86.8Sn-3.2Ag-5.0Bi-5.0Au*	84 ± 2 (MPa)	12,200 ± 300 psi
96.5Sn-3.5Ag	55 ± 1 (MPa)	8,000 ± 100 psi
60Sn-40Pb	40 ± 2 (MPa)	5,800 ± 300 psi
91.84Sn-3.33Ag-4.83Bi	80 ± 10 (MPa)	11,600 ± 300 psi

**The ring-and-plug shear strength of the Sn-Ag-Bi-Au alloy remains as the highest value recorded of any solder alloy.*

- **The fracture path remained in the solder, *not at the interface*.**



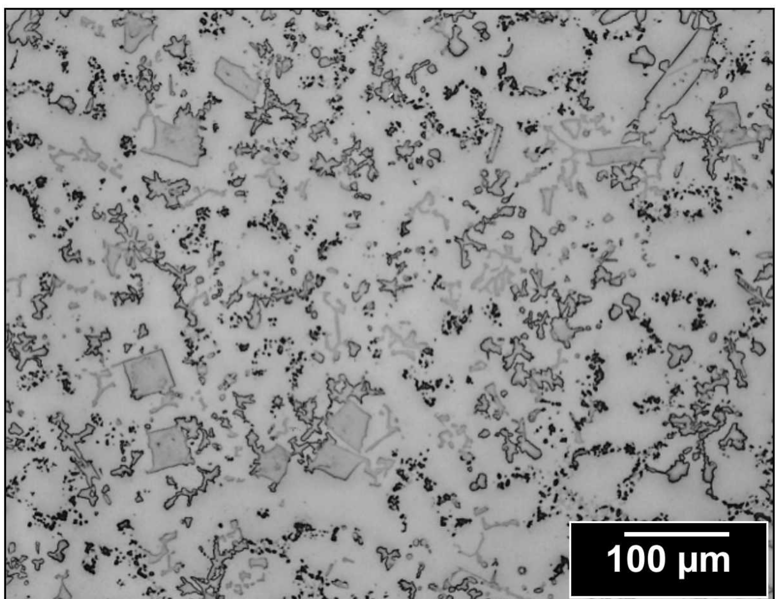


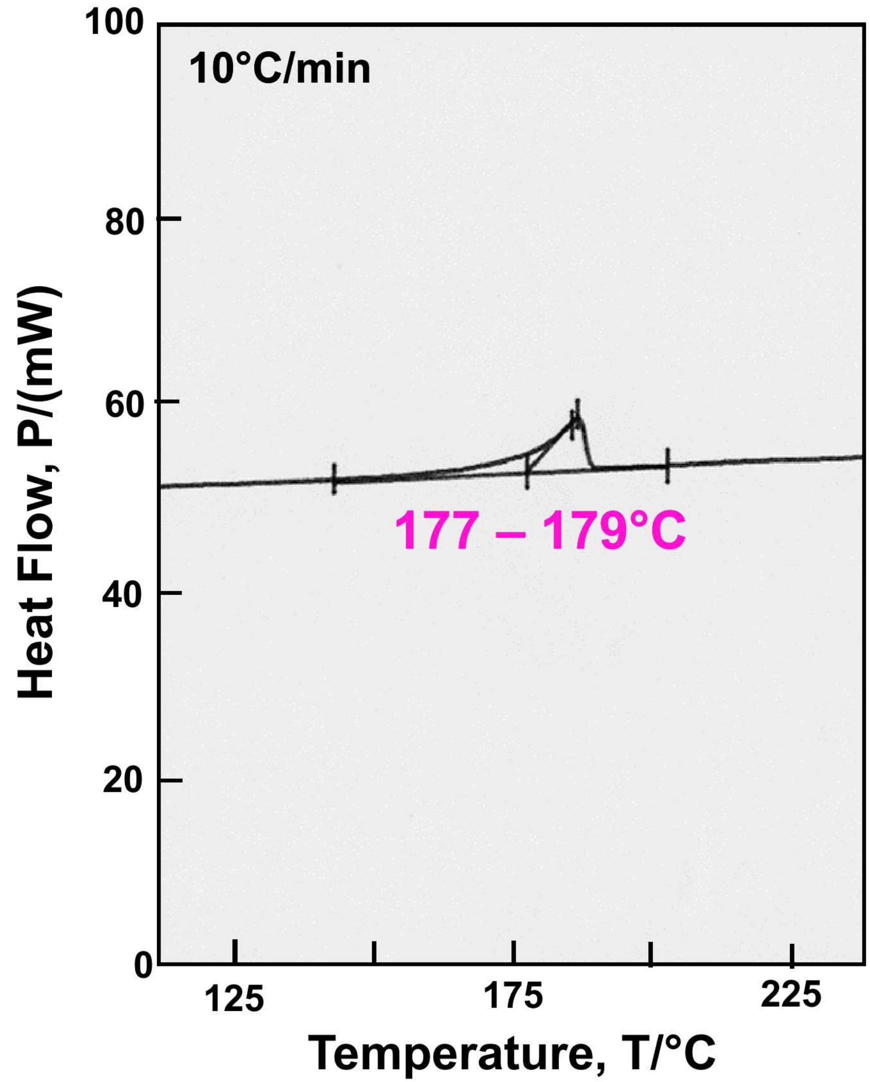


Novel Low Temperature Solders

- 66Sn-5.0Ag-10Bi-5Au-10In-4.0Cu had a solidus temperature that was in the range of 177-179°C and ΔH = 31 J/g.

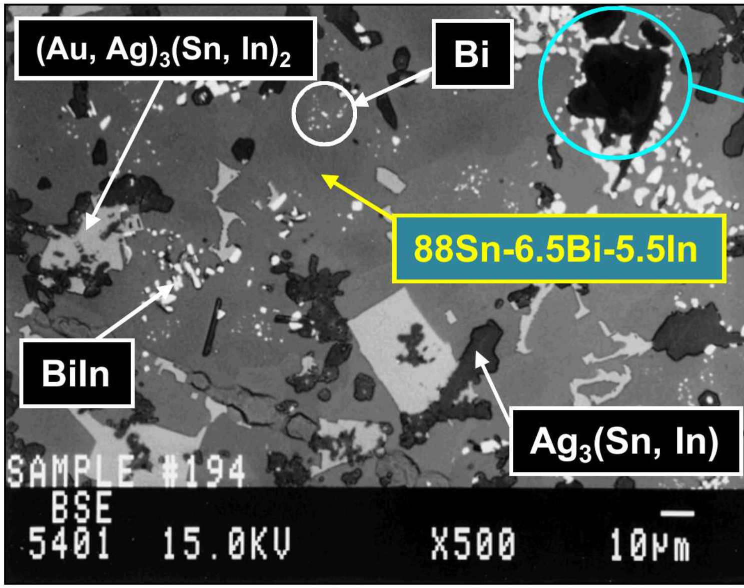
- Although complicated, the particle phases were uniformly distributed within the microstructure.

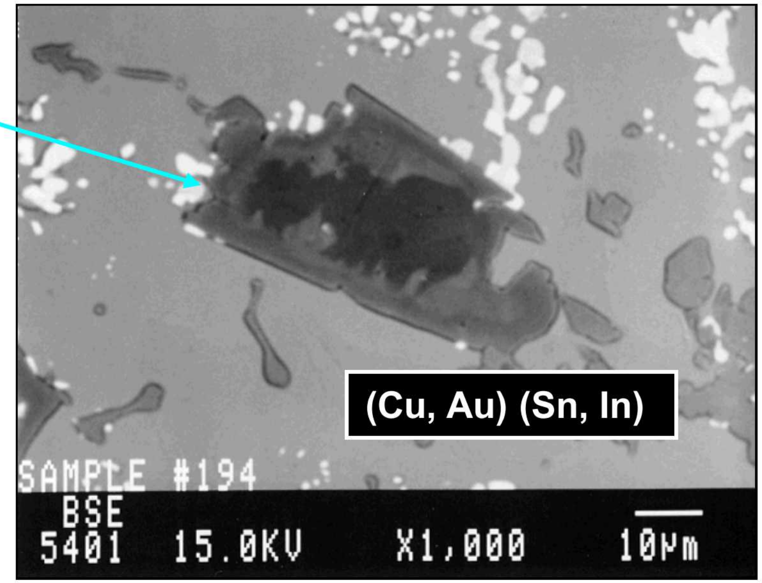




Novel Low Temperature Solders

- The 66Sn-5.0Ag-10Bi-5Au-10In-4.0Cu microstructure was comprised of several particles and a 88Sn-6.5Bi-5.5In matrix phase.





- Solderability:

"… pretty good"

Solder alloy (mass%)	Contact angle (°)	Solder-flux interfacial tension (dynes/cm)
66Sn-5.0Ag-10Bi-5.0Au 10In-4.0Cu	34.2±0.7	418±9
96.5Sn-3.5Ag	36±3	460±30
95.5Sn3.9Ag-0.6Cu	40±5	500±40
91.84Sn-3.33Ag-4.83Bi	31±5	420±30

250°C, RMA flux

Summary

- The current low temperature solders are based upon the 91.84Sn-3.33Ag-4.83Bi ternary composition.
    - An extensive database exists of the physical and mechanical properties of the material.
    - Semi-quantitative, thermal cycling studies were performed on older technologies (e.g., peripheral leaded packages).
    - "High-fidelity", temperature cycling reliability data (e.g., IPC-9701) are just now being accumulated for the Sn-Ag-Bi alloy.
    - Data is limited with respect to long-term interactions between this solder and current PCB surface finish technologies.

- Several novel compositions were developed that had melting temperatures in-line with that of the eutectic Sn-Pb alloy.
    - Although highly unlikely to achieve "mainstream status," they showcased *metallurgical methods to optimize alloy performance*.