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Compression Creep of the 95.5Sn - (4.3, 3.9, 3.8)Ag - (0.2, 0.6, 0.7)Cu Solders*

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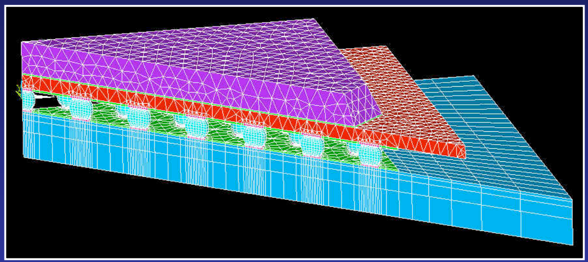
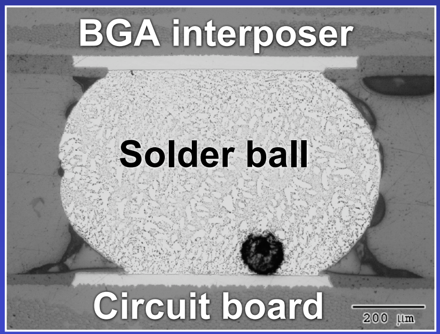
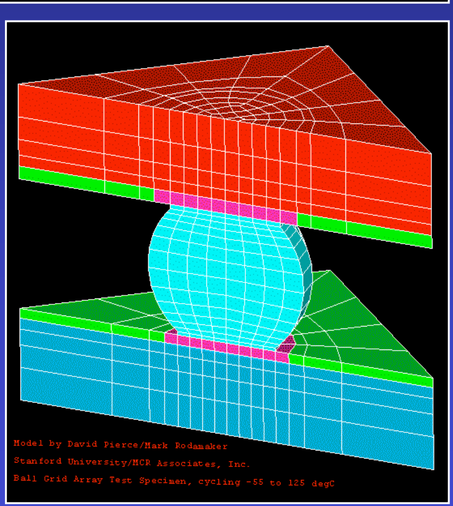
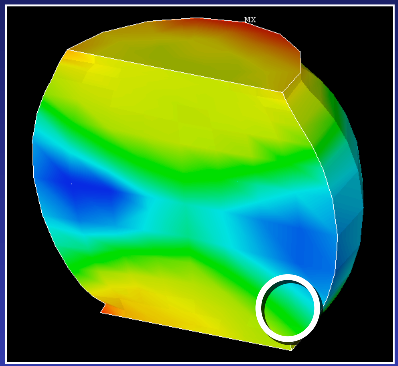
Introduction

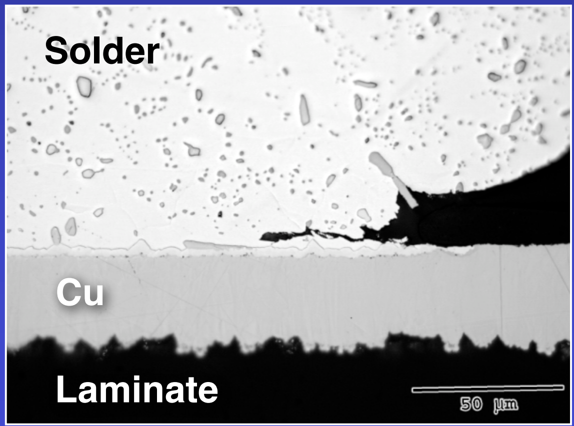
Computational modeling will be used to an increased extent for predicting the reliability of soldered interconnections.











Finite element mesh

Model prediction

Introduction

Computational models require accurate materials property data for the underlying constitutive equation.

$$d\varepsilon_{11}/dt = f_o \exp(-Q/RT) \sinh^p \left[\frac{|\sigma_{11} - B_{11}|}{\beta D} \right] \mathrm{sgn}(\sigma_{11} - B_{11})$$

$d\varepsilon_{11}/dt$ ….. the inelastic strain rate *(creep + plasticity)*

σ_{11} ………… applied stress
T …………. temperature
B_{11} ……….. back stress

D …………. isotropic strength *(plasticity)*
β …………. constant *(plasticity)*

f_o …………. constant *(creep)*
Q …………. apparent activation energy *(creep)*
p …………. "sinh law" exponent *(creep)*

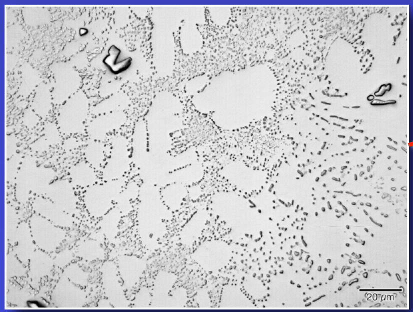
Introduction

The mechanical properties of the Pb-free solders, including the Sn-Ag-Cu alloys, are sensitive to small composition differences.

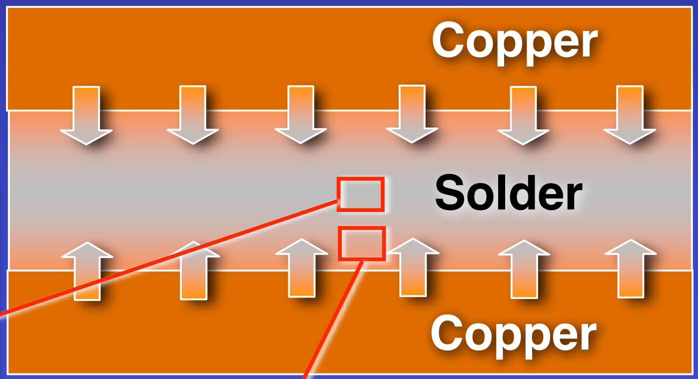
- **The solder composition may vary *intentionally*, by the selection the particular alloy for the application.**

  SAC105, SAC305, SAC387, SAC396, SAC405, etc.

- **The Cu content of the solder may vary *inadvertently* due to the dissolution of Cu substrate material during soldering.**



Sn-4.3Ag-0.2Cu



? ***Microstructure & mechanical properties***

Objective

- Understand the effects of small differences of **Ag** and **Cu** concentrations on the time-independent and time-dependent mechanical properties of the **Sn-Ag-Cu** solders by evaluating the following three alloys:

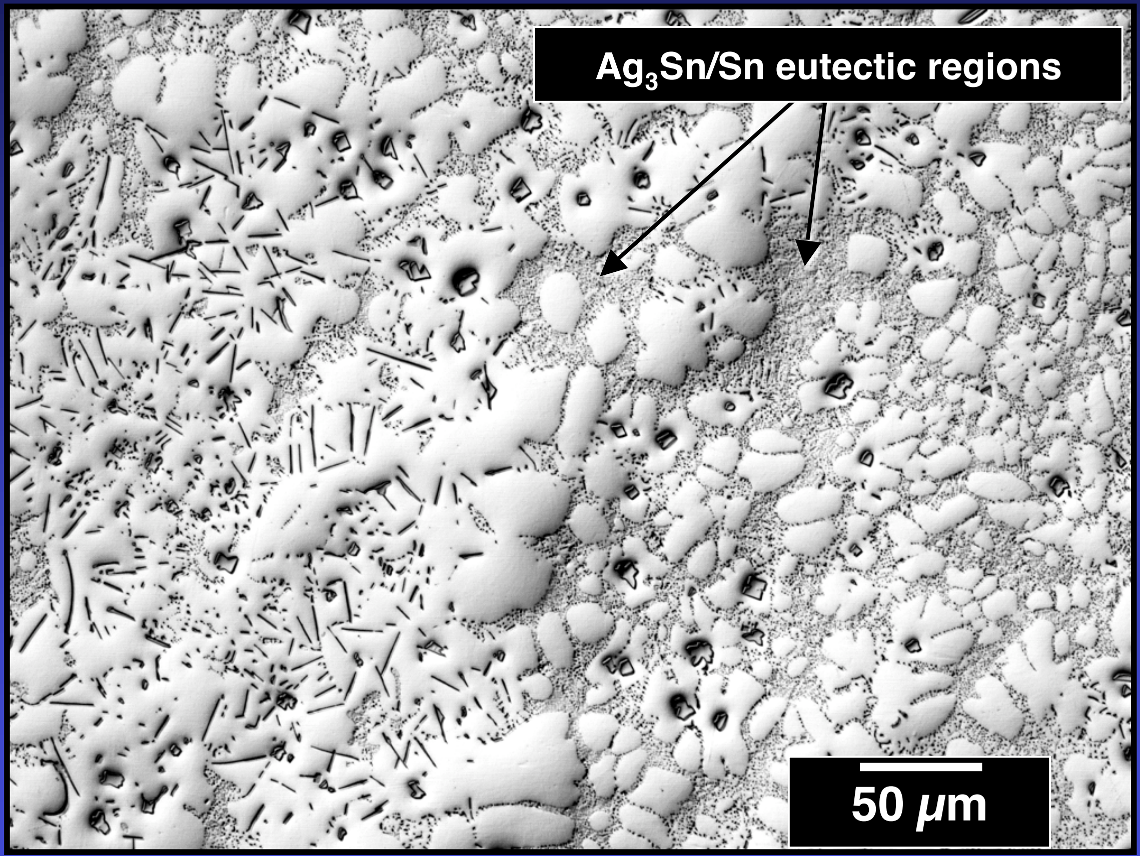
  - 95.5Sn - 4.3Ag - 0.2Cu
  - 95.5Sn - 3.9Ag - 0.6Cu*
  - 95.5Sn - 3.8Ag - 0.7Cu

- The study of the time-independent (stress-strain) properties was completed. Those results are briefly discussed .....

* A computational model has been developed that predicts thermal mechanical fatigue (TMF) damage in 95.5Sn-3.9Ag-0.6Cu solder interconnections (Stanford U. and Sandia).

Background

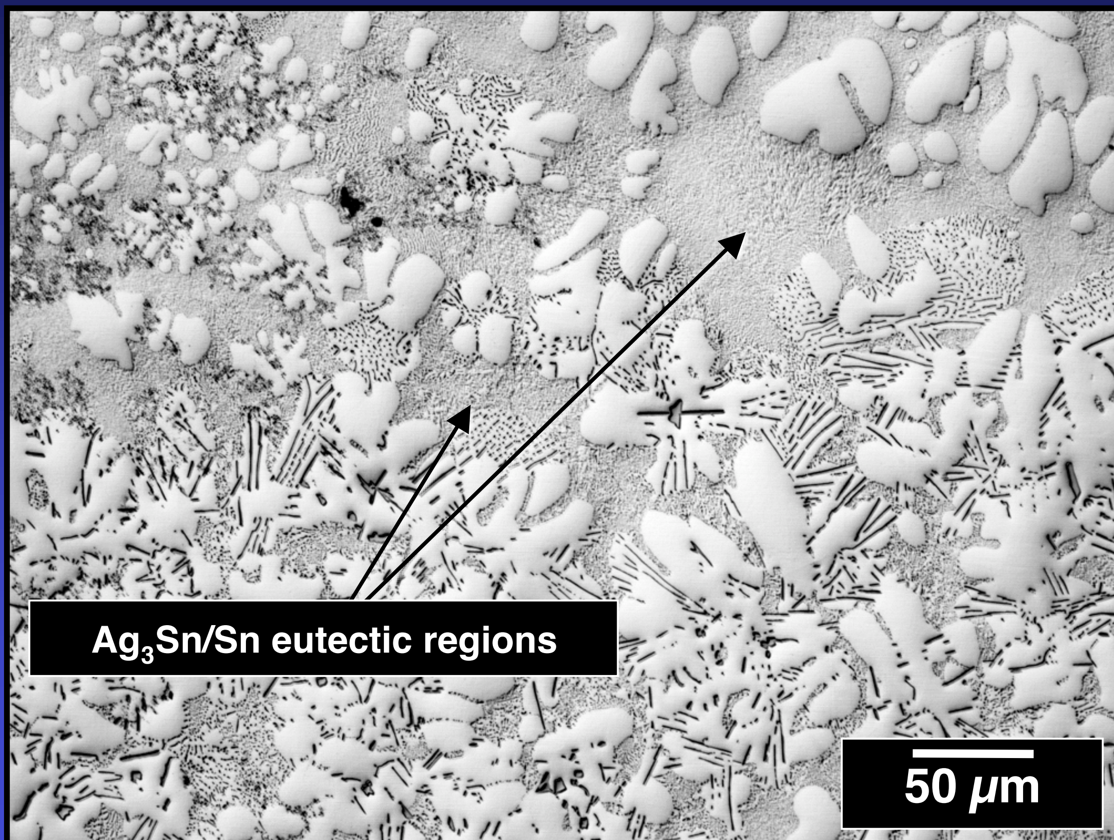
The microstructural feature of note in the Sn-Ag-0.2Cu alloy was the small, widely dispersed Ag_3Sn/Sn eutectic regions.



95.5Sn - 4.3Ag - 0.2Cu

Background

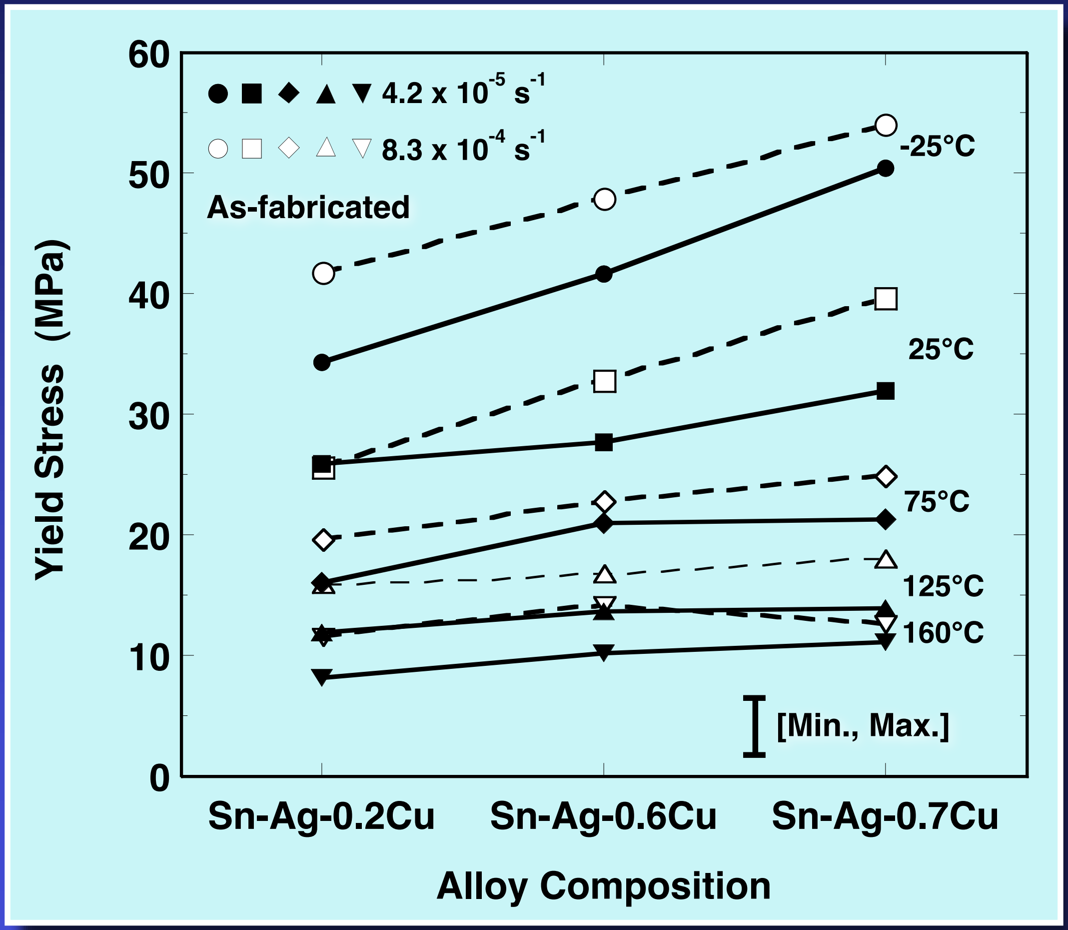
In Sn-Ag-0.6 and Sn-Ag-0.7Cu alloys, there were both small and larger Ag_3Sn/Sn eutectic regions within their microstructures.



95.5Sn - 3.8Ag - 0.7Cu

Background

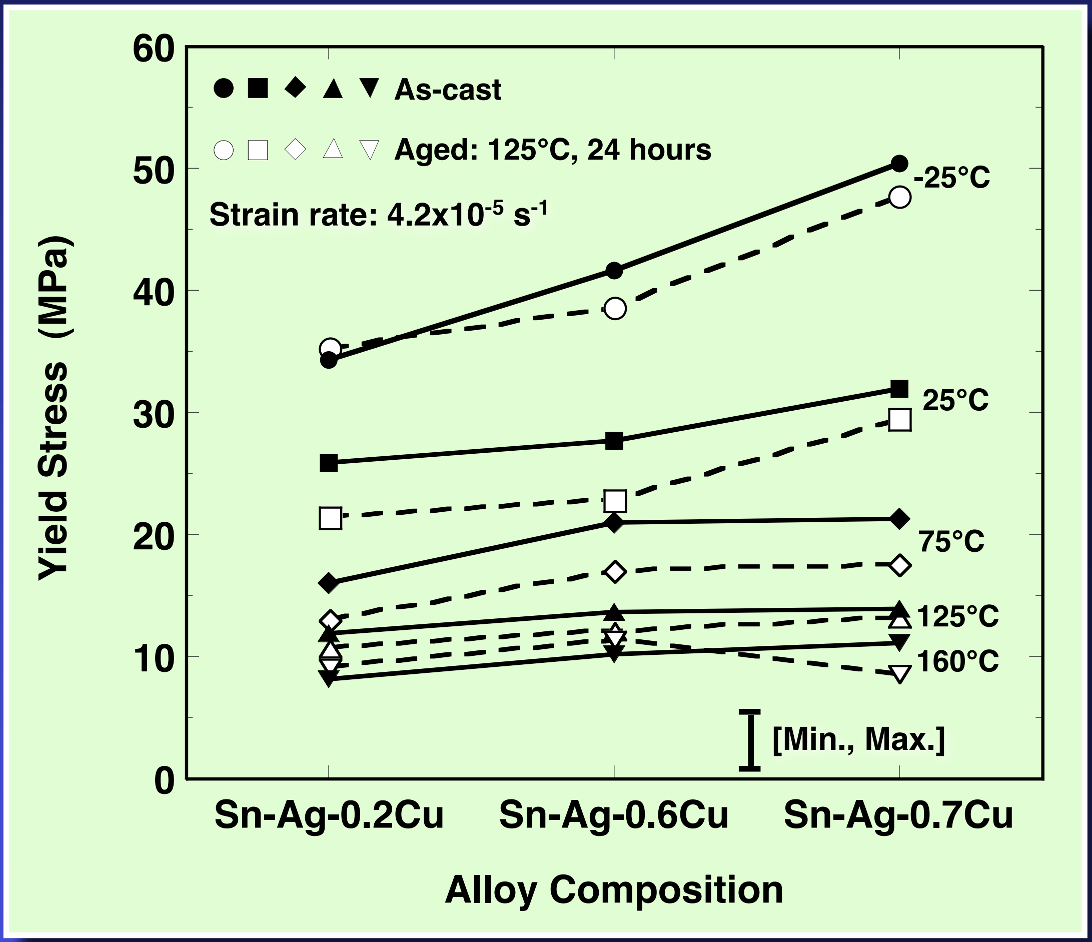
The yield stress was sensitive to solder composition, more so at the lower test temperatures and the slower strain rates.



P. Vianco, et al., J. of Metals (2003)

Background

The **125°C, 24 hours** aging treatment decreased the yield stress.
But, the decrease was sensitive to temperature and alloy composition.



P. Vianco, et al., J. of Metals (2003)

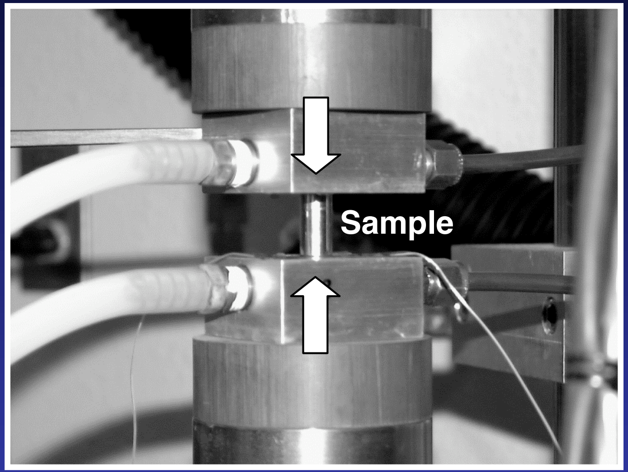
Experimental procedures

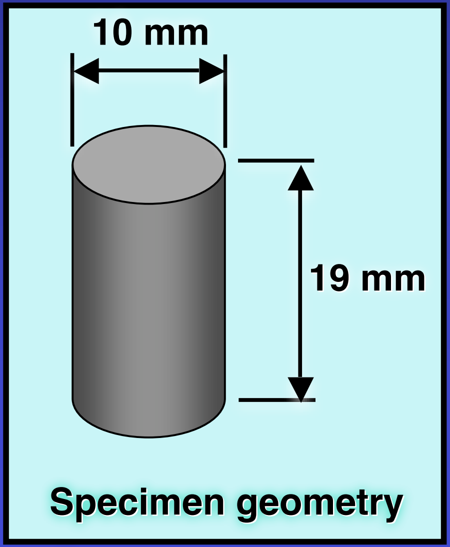
- **Test temperatures:**

  -25°C, 25°C, 75°C, 125°C, 160°C

- **Applied stress:**
  - 20, 40, 60, and 80% of $\sigma_{yield}(T)$
  - Stress range: 2 - 45 MPa

- **Samples test conditions:**
  - As-fabricated
  - Aged: 125°C, 24 hour (air)
  - *Duplicate tests per condition*





Compression testing per (ASTM E9-89A)

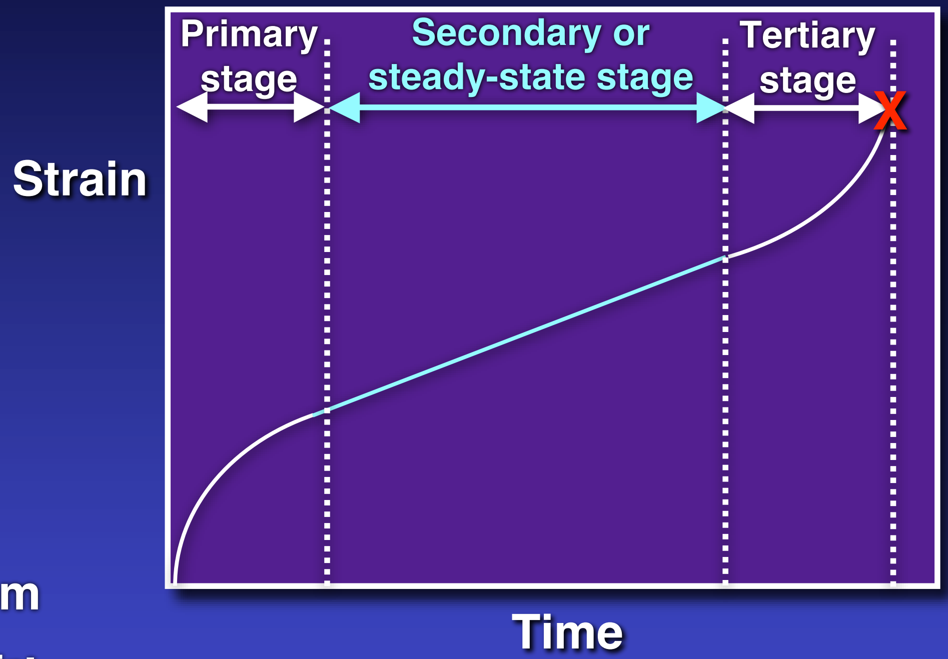
P. Vianco, et al., J. of Elect. Mater. (2003 and 2004)

Experimental procedures

- **Qualitative analysis:**

  Document the contributions to creep deformation from the three stages:

  - Primary
  - Secondary or steady-state
  - Tertiary



- **Quantitative analysis:**

  Rate kinetics as determined from the minimum strain rate, $d\varepsilon/dt_{min}$, in the secondary stage:

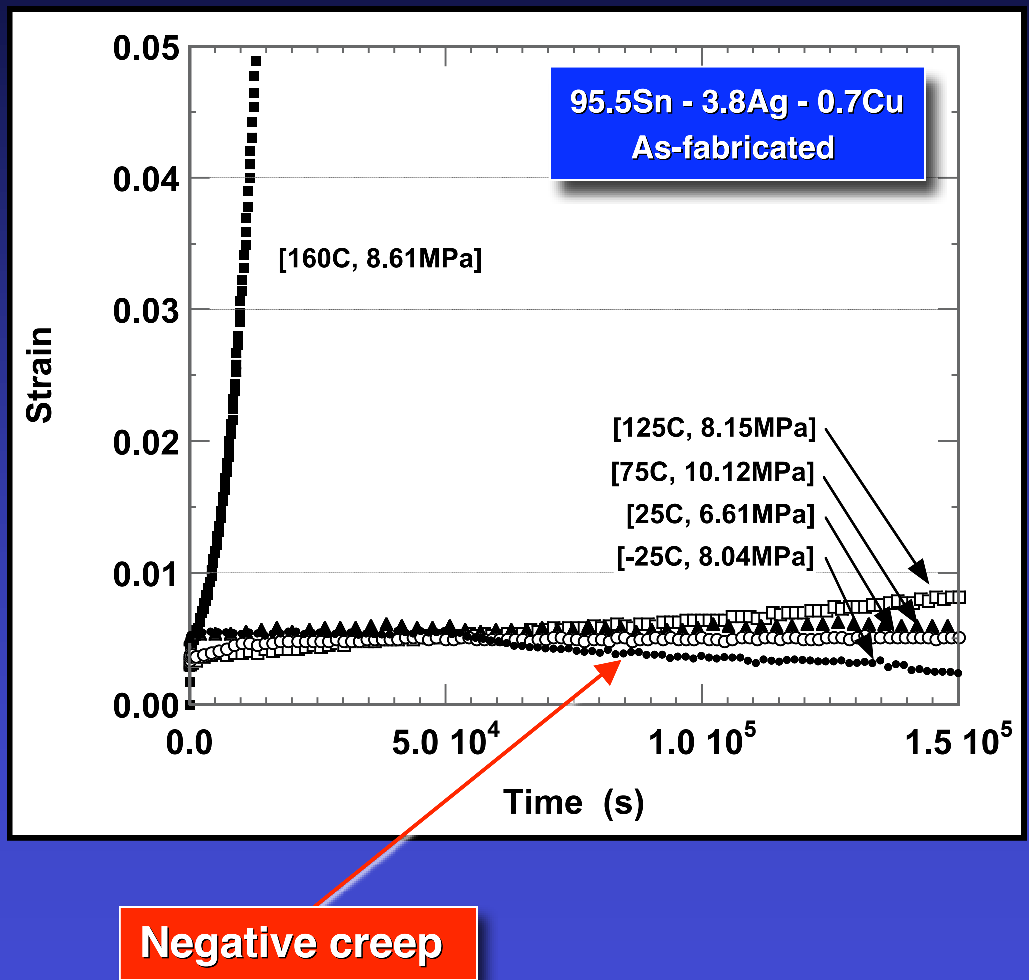
$$d\varepsilon/dt_{min} = A \sinh^{n}(\alpha\sigma) \exp[-\Delta H/RT]$$

T … temperature (K)	A … constant (s^{-1})
t … time (s)	ΔH … apparent activation energy (J/mol)
σ … stress (MPa)	n … sinh term exponent
α … constant (MPa^{-1})	R … universal gas constant (8.314 J/mol-K)

Results and Discussion

Strain-time curves:

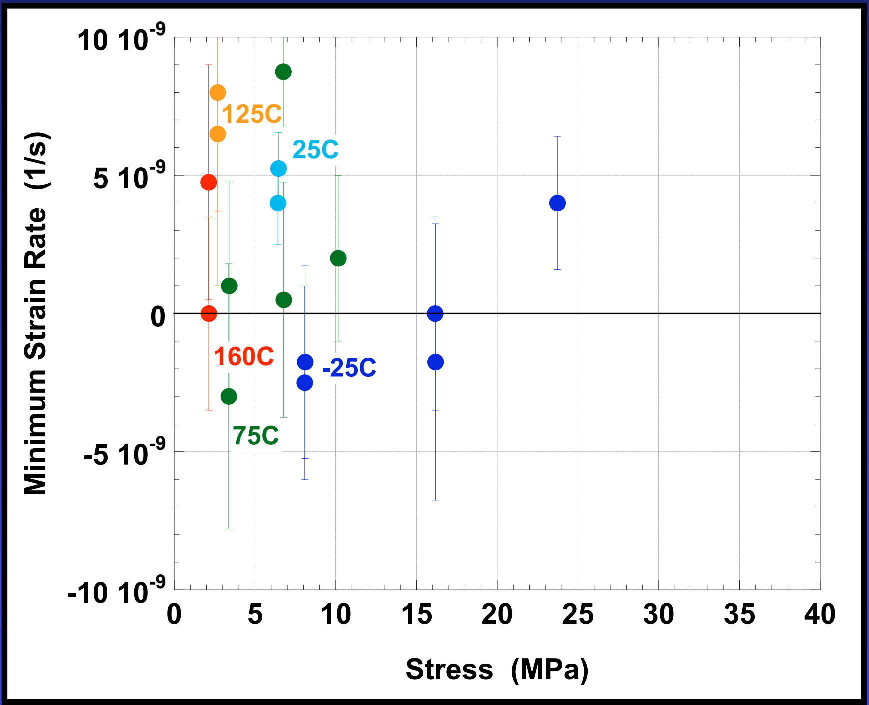
- Primary creep stage leading into the secondary or steady-state creep ($d\varepsilon/dt_{min}$).
- The tertiary creep stage was observed in several tests, particularly those performed at the higher stresses.
- Negative creep was noted that was synergistically dependent upon:
    - Alloy composition
    - Test conditions
    - Sample conditions



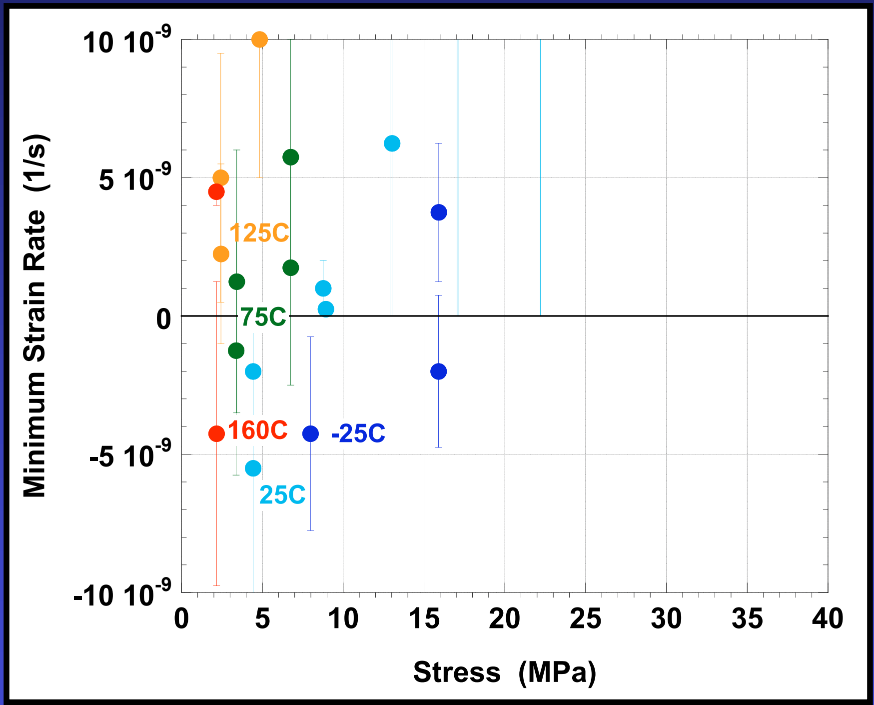
Results and Discussion

Strain-time curves:

The appearance and magnitude of the negative strain rate was a function of stress, temperature, alloy, and sample condition.



95.5Sn - 4.3Ag - 0.2Cu
As-fabricated

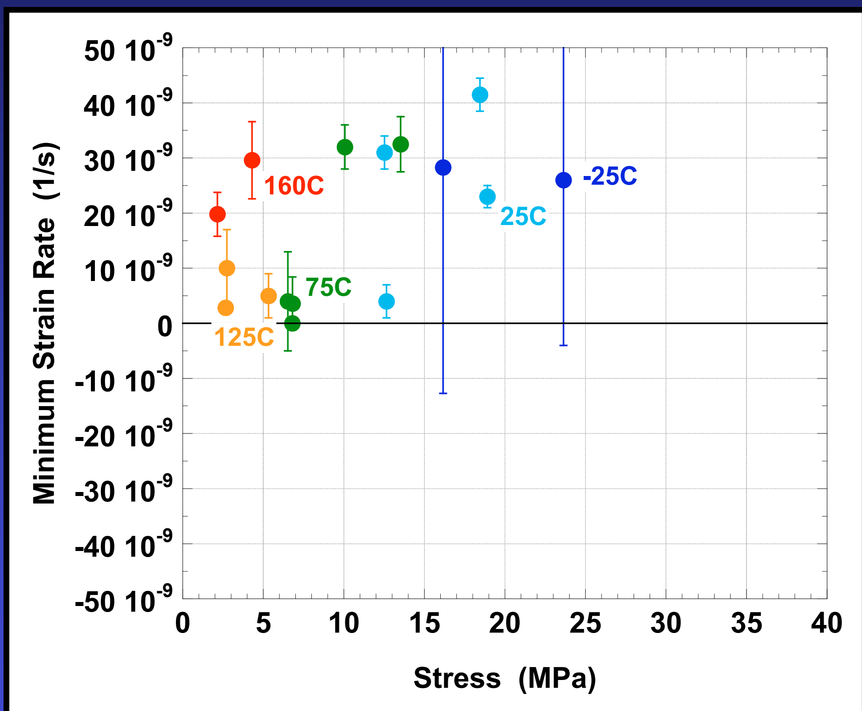


95.5Sn - 4.3Ag - 0.2Cu
Aged: 125C, 24 hours

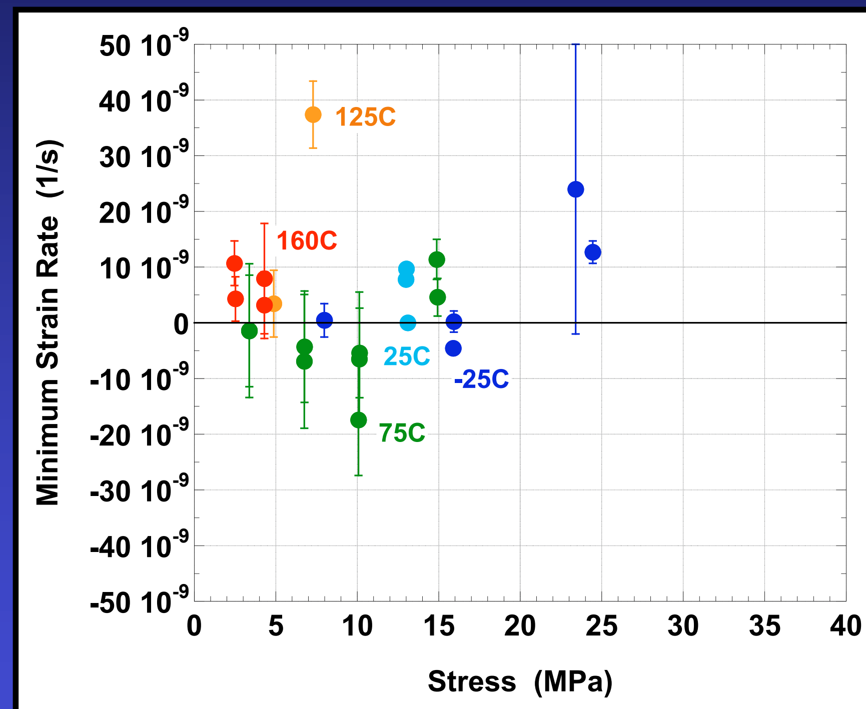
Results and Discussion

Strain-time curves:

The dependence of negative strain rate on aging treatment was particularly significant for the Sn-Ag-0.6Cu alloy.



95.5Sn - 3.9Ag - 0.6Cu
As-fabricated

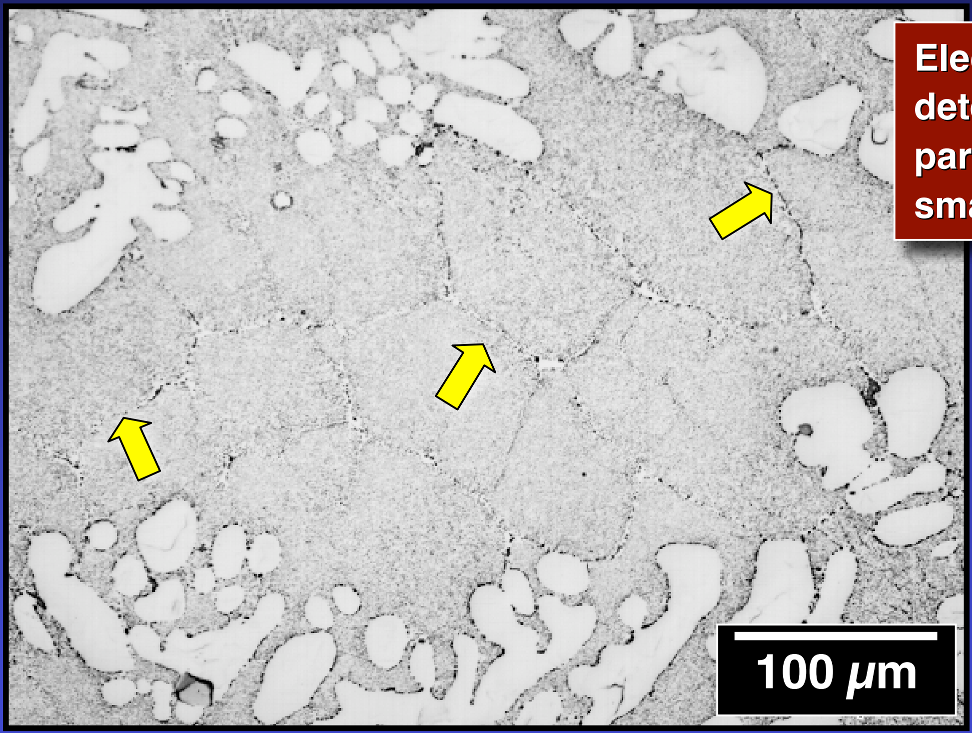


95.5Sn - 3.9Ag - 0.6Cu
Aged: 125C, 24 hours

Results and Discussion

Microstructures:

The phenomenon of particular interest was the formation of the **coarsened-particle boundaries** in the Ag_3Sn/Sn eutectic regions.



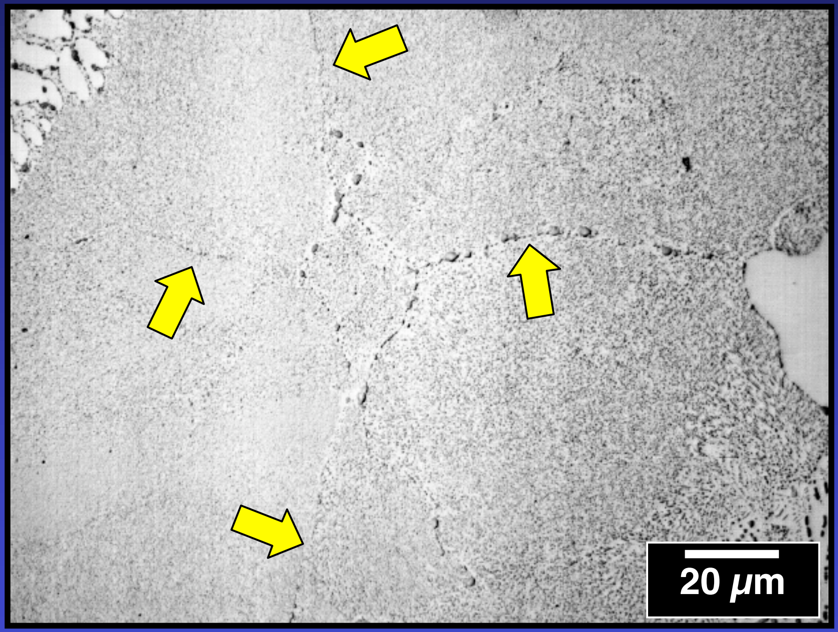
Electron probe microanalysis (EPMA) determined the composition of the particles to be primarily Cu_6Sn_5 and a small contribution of Ag_3Sn particles.

95.5Sn - 3.8Ag - 0.7Cu … As-cast, 160°C, 8.61 MPa,
Strain = 0.114, $d\varepsilon/dt_{min} = 1.4 \times 10^{-6}\ s^{-1}$

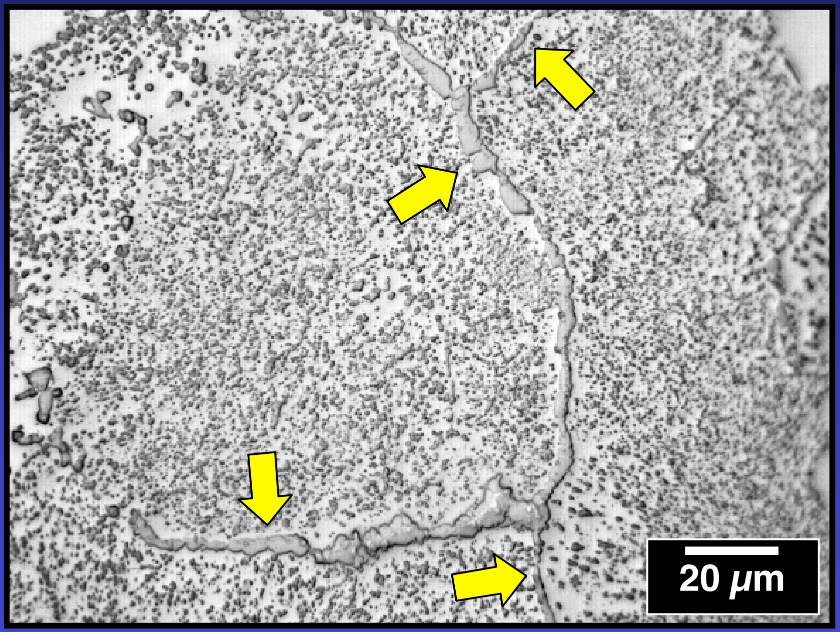
Results and Discussion

Microstructures:

The degree of particle coarsening within the boundaries increased from low to high test temperatures.



95.5Sn - 3.8Ag - 0.7Cu … As-cast,
25°C, 39.5 MPa,
Strain = 0.122, $d\varepsilon/dt_{min} = 2.5 \times 10^{-5}\ s^{-1}$

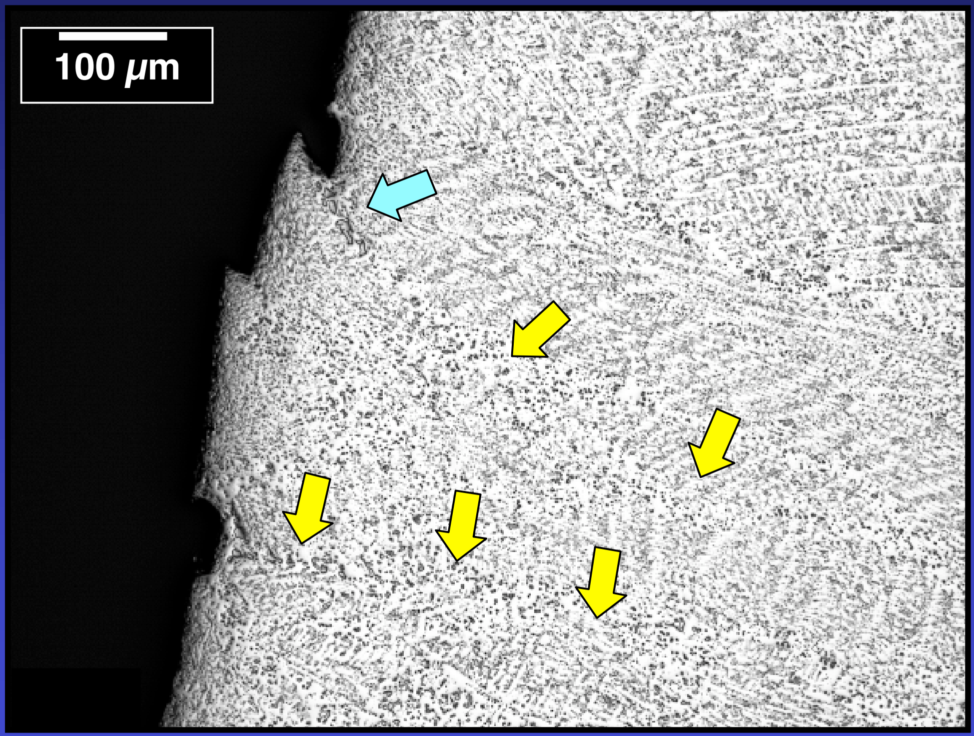


95.5Sn - 3.8Ag - 0.7Cu … As-cast,
125°C, 10.8 MPa,
Strain = 0.119, $d\varepsilon/dt_{min} = 2.1 \times 10^{-7}\ s^{-1}$

Results and Discussion

Microstructures:

Shear bands at the specimen edge indicated that **deformation** was the underlying source of the coarsened-particle boundaries.



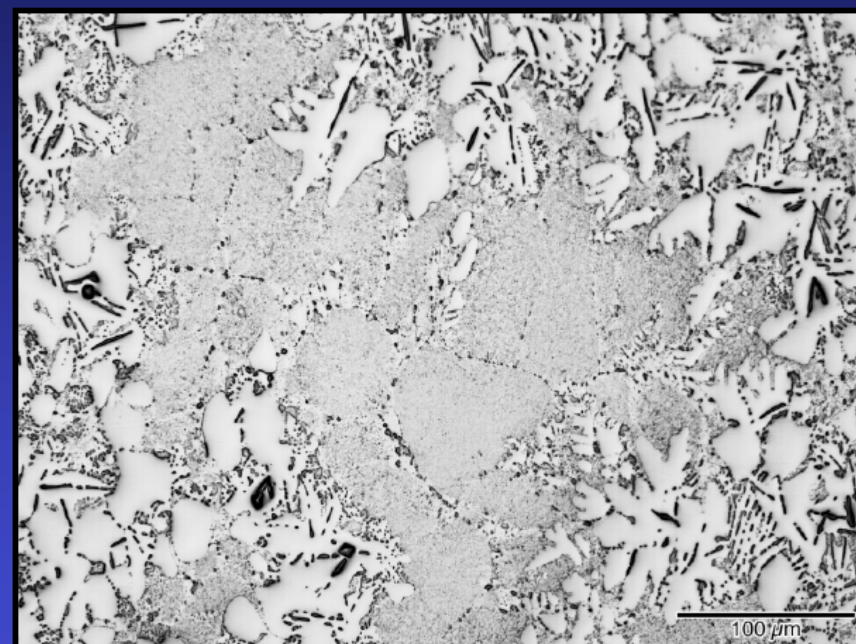
95.5Sn - 3.8Ag - 0.7Cu … As-cast, 160°C, 8.63 MPa,
Strain = 0.280 $d\varepsilon/dt_{min} = 9.3\text{x}10^{-7}\ s^{-1}$

Results and Discussion

Microstructures:

Dark-field microscopy confirmed that the coarsened-particle boundaries separated newly-formed **sub-grains** or **grains**.

95.5Sn - 3.8Ag - 0.7Cu … As-cast, -25°C, 41.4 MPa,
Strain = 0.069, $d\varepsilon/dt_{min} = 1.8\times10^{-7}\ s^{-1}$

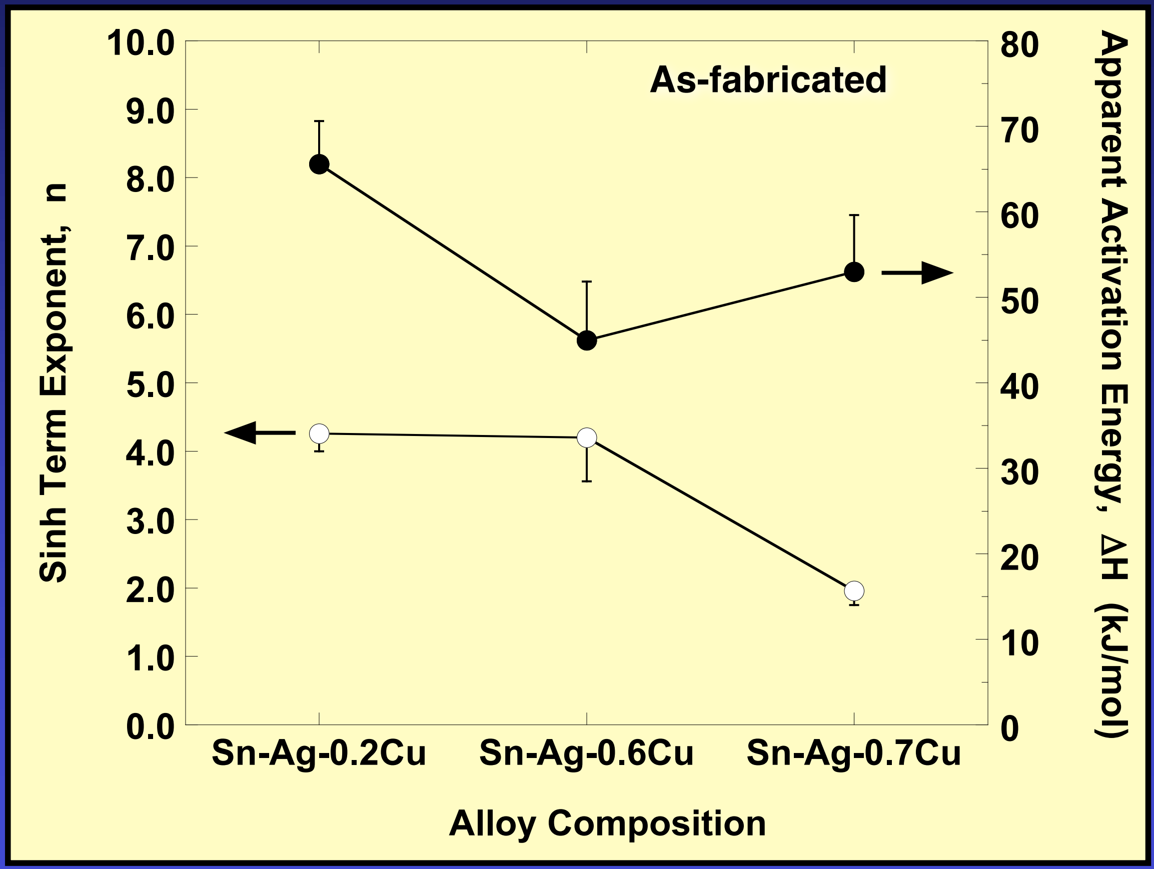


95.5Sn - 3.8Ag - 0.7Cu … As-cast, 25°C, 39.1 MPa,
Strain = 0.122, $d\varepsilon/dt_{min} = 6.1\times10^{-5}\ s^{-1}$

Results and Discussion

Minimum creep rate kinetics:

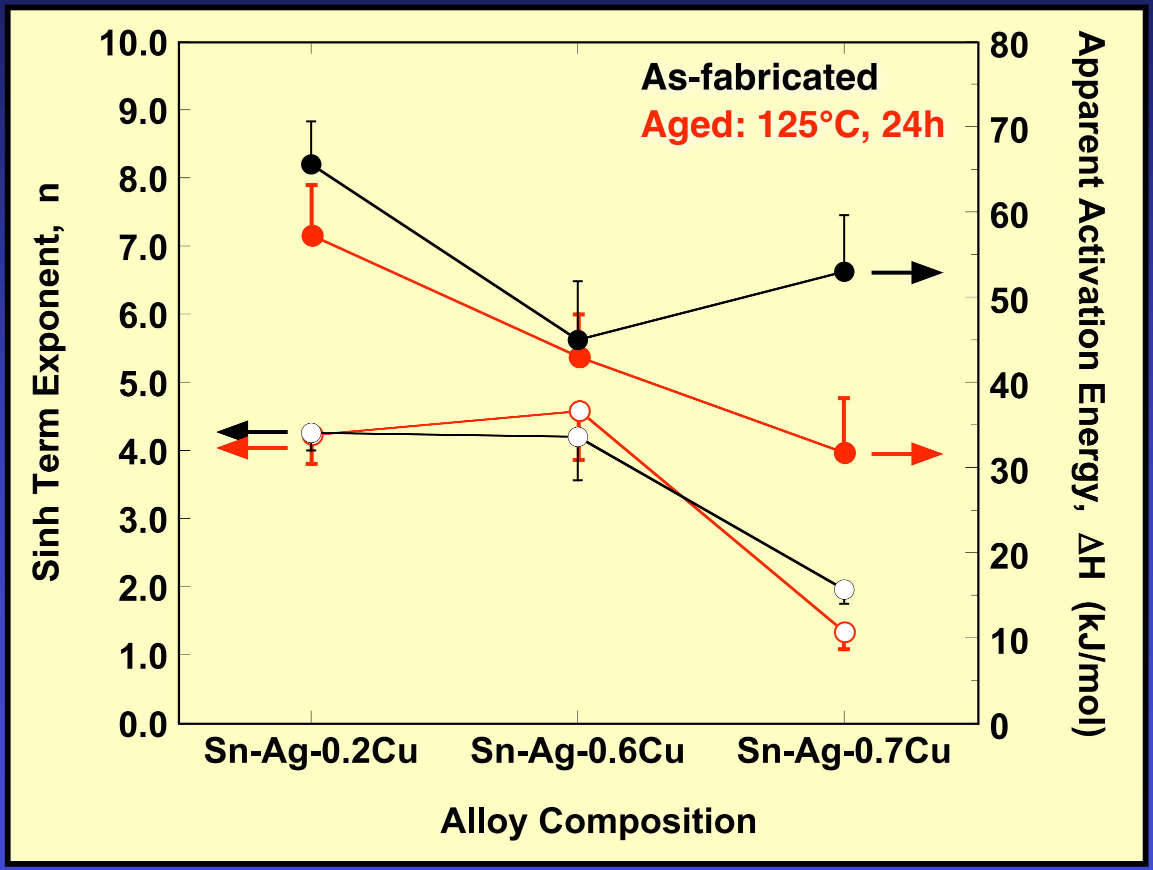
$$d\varepsilon/dt_{min} = A \sinh^{n}(\alpha\sigma) \exp[-\Delta H/RT]$$



Results and Discussion

Minimum creep rate kinetics:

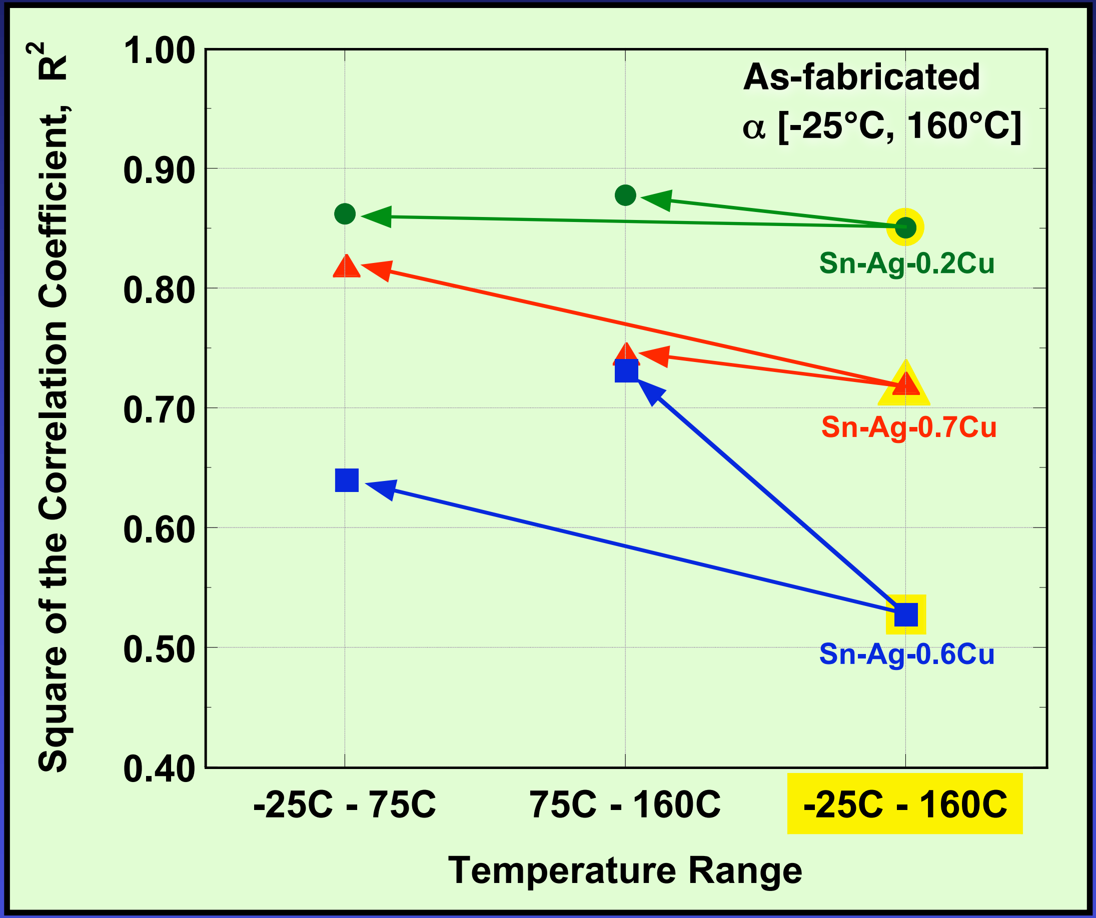
$$d\varepsilon/dt_{min} = A \sinh^n(\alpha\sigma) \exp[-\Delta H/RT]$$



Results and Discussion

Minimum creep rate kinetics:

Low R^2 values indicated the need to look for different deformation mechanisms that controlled creep as a function of test temperature.

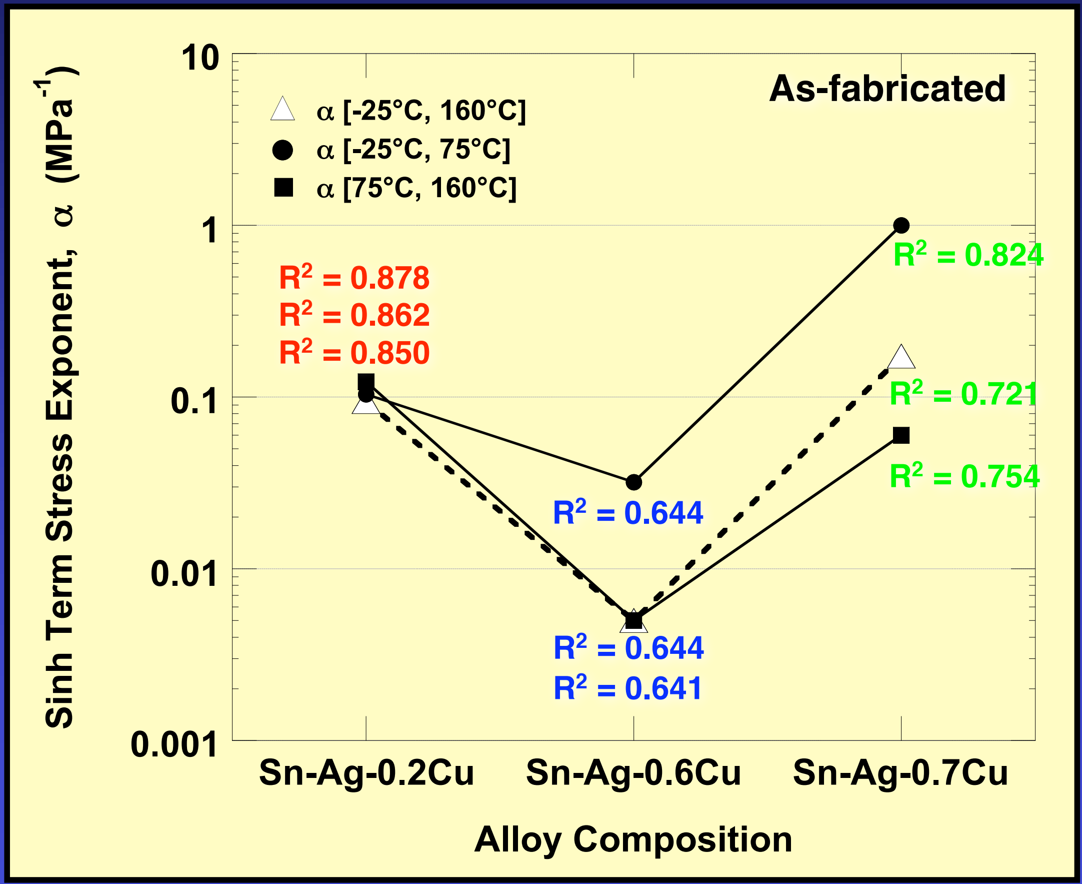


Results and Discussion

Minimum creep rate kinetics:

The α values were re-optimized for each temperature regime:

$$d\varepsilon/dt_{min} = A \sinh^n(\alpha\sigma) \exp[-\Delta H/RT]$$



Results and Discussion

Minimum creep rate kinetics:

$$d\varepsilon/dt_{min} = A \sinh^n(\alpha\sigma) \exp[-\Delta H/RT]$$

The following trends were observed for ΔH:

1. The values of ΔH were relatively insensitive to the α parameter.

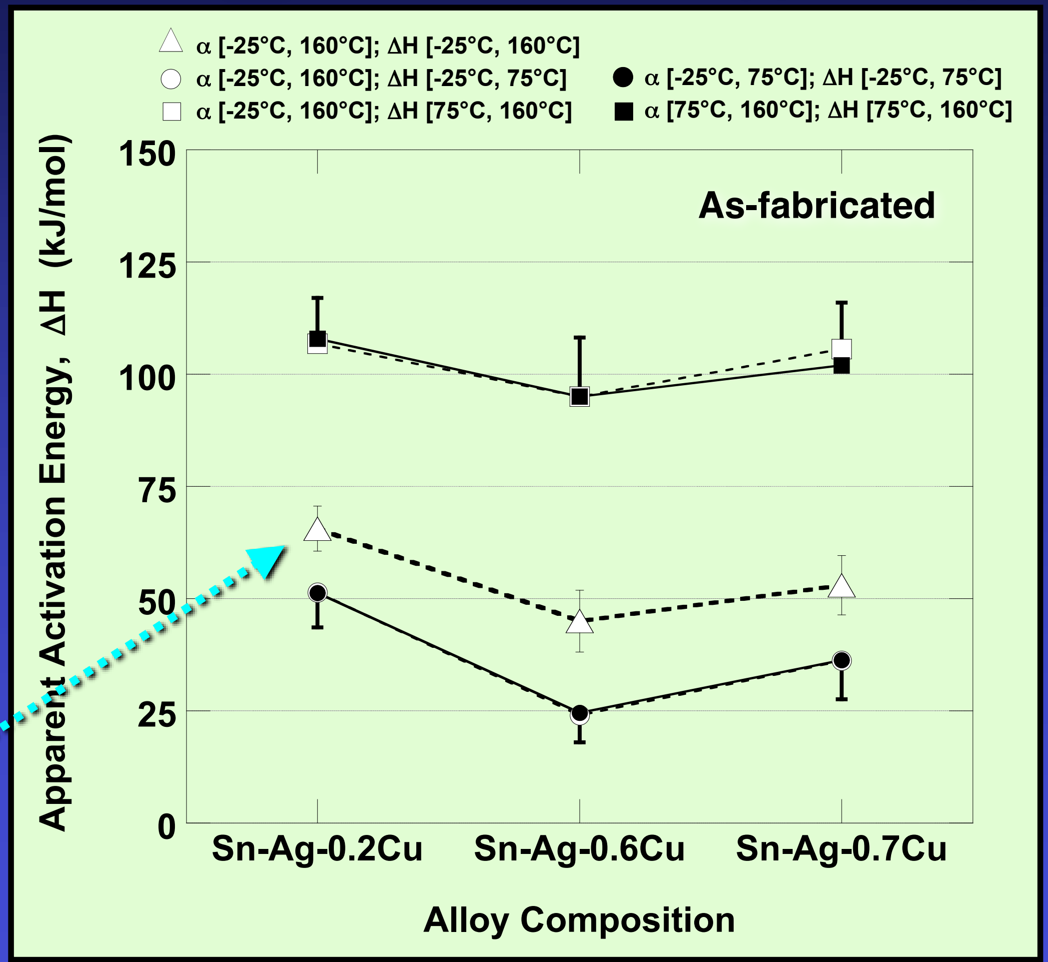
2. Different mechanisms controlled creep in the low and high temperature regimes:

Low-temp. [-25°C, 75°C]:
25 < ΔH (kJ/mol) < 50

Fast or short circuit diffusion

High-temp. [-25°C, 75°C]:
100 < ΔH (kJ/mol) < 110

Bulk or self-diffusion



Summary

1. A study examined the effects of composition variations on the time-dependent (creep) deformation properties of three Sn-Ag-Cu solders:
   - 95.5Sn - 4.3Ag - 0.2Cu
   - 95.5Sn - 3.9Ag - 0.6Cu
   - 95.5Sn - 3.8Ag - 0.7Cu

2. The stresses are 2 - 45 MPa and temperatures: -25°C, 25°C, 75°C, 125°C, and 160°C. Sample conditions: as-fabricated or aged: 125°C, 24 hours.

3. Negative creep was observed, which was sensitive alloy composition, sample condition, test temperature, and applied stress.

4. The microstructural artifact of creep deformation was the development of coarsened-particle boundaries in the Ag_3Sn/Sn eutectic regions. These boundaries delineated sub-grain formation.

(con't)

Summary *(con't)*

5. The minimum creep rate kinetics were evaluated with the sinh law:

$$d\varepsilon/dt_{min} = A \sinh^{n}(\alpha\sigma) \exp[-\Delta H/RT]$$

6. The sinh term exponent values [-25°C, 160°C]:

   n = 4 – 6 ……….. Sn-Ag-0.2Cu and Sn-Ag-0.6Cu solders

   n = 1 – 2 ……….. Sn-Ag-0.7Cu solder.

   The apparent activation energy values [-25°C, 160°C]:

   ΔH = 30 – 70 kJ/mol ……. *all alloys* ⇨ short-circuit or fast-diffusion

   The aging treatment did *not* consistently alter n or ΔH.

7. The minimum creep rate data was separated into low-temperature and high-temperature regimes:

   - Low temperatures [-25°C, 75°C]: ΔH ⇨ ⇨ short-circuit diffusion
     ⇨ composition sensitive
   - High temperatures [75°C, 160°C]: ΔH ⇨ ⇨ bulk diffusion
     ⇨ composition insensitive