Compression Deformation Response of 95.5Sn-3.9Ag-0.6Cu Solder*

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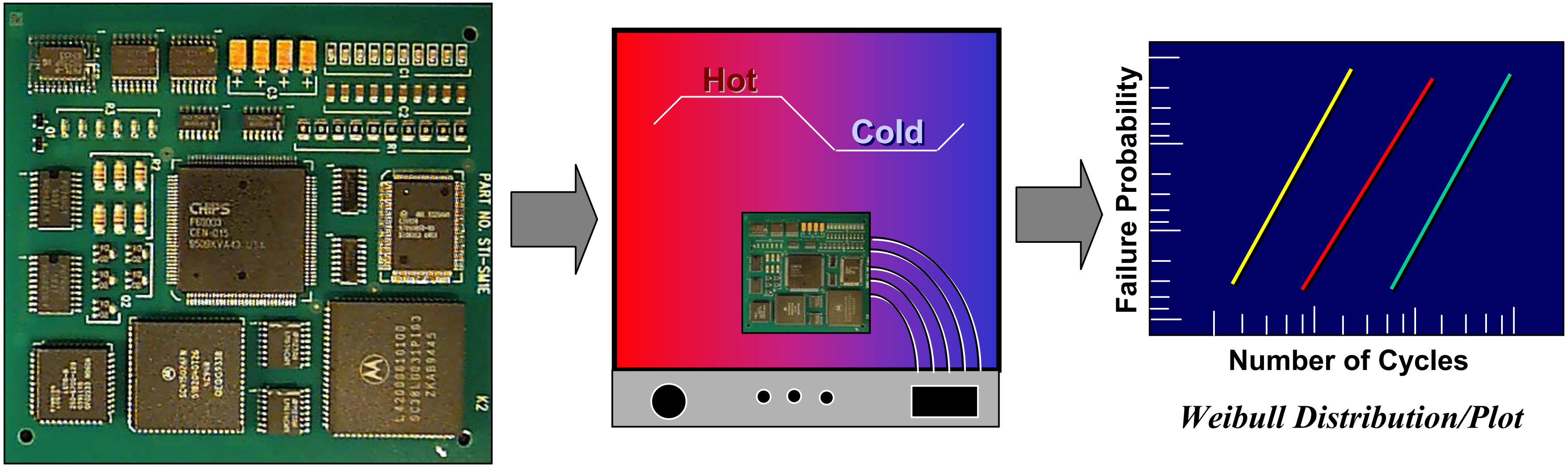
Empirical, accelerated aging programs are fast becoming impractical for developing long-term reliability databases



Weibull Distribution/Plot

- **A vast array of currently-used electronic packages**

- **Rapid development of new electronic packaging technologies**

- **Shift from OEM "circuit board technology" …**
  … to CMS "circuit board assembly"

- ***...and now -- Pb-free solders***

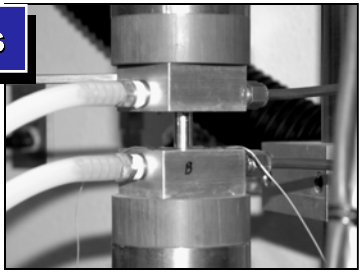
Computational modeling will be heavily relied upon to predict the reliability of Pb-free solder interconnects

Compile **materials properties** data for model input parameters.

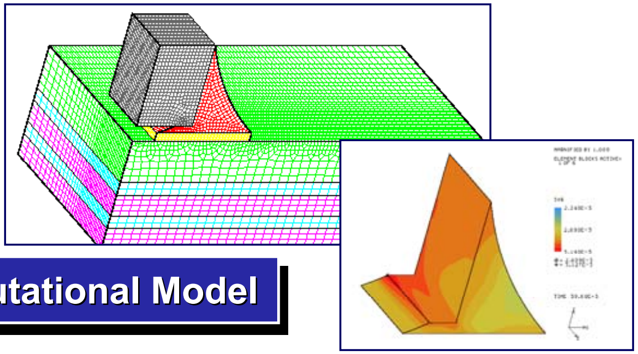
Develop the **computational model**:

- *Constitutive equation*
- *Finite element code (mesh)*
- *Optimization routines*

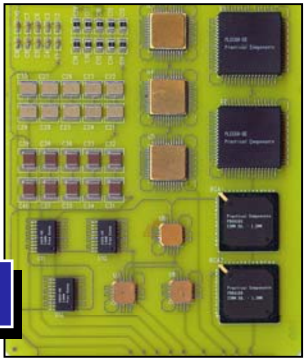
Model validation using *limited* accelerated aging experiments.



Material Properties



Computational Model



Model Validation

A Unified Creep-Plasticity (UCP) constitutive equation provides the basis for a computational model

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

"A Visoplastic Theory for Braze Alloys," … Neilsen, Burchett, Stone, and Stephens (1996)

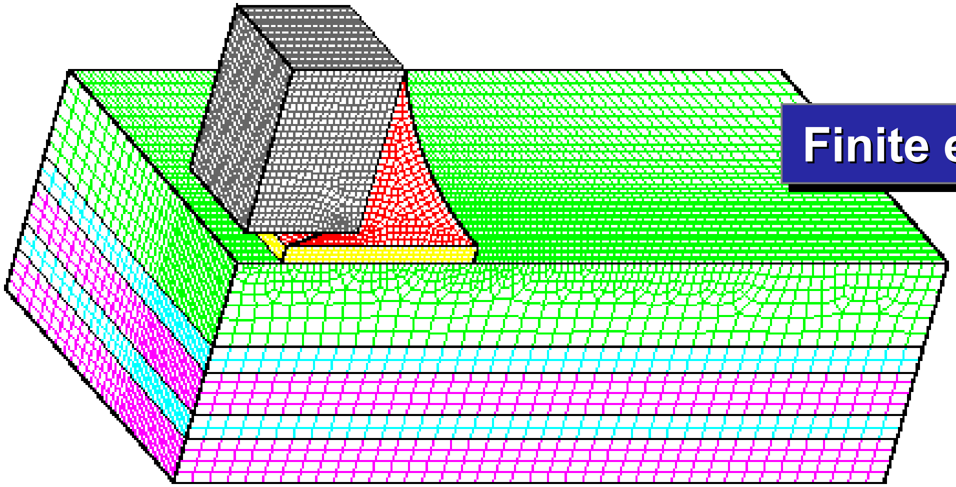
$d\varepsilon_{11}/dt$ ….. the inelastic strain rate *(creep + plasticity)*

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

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

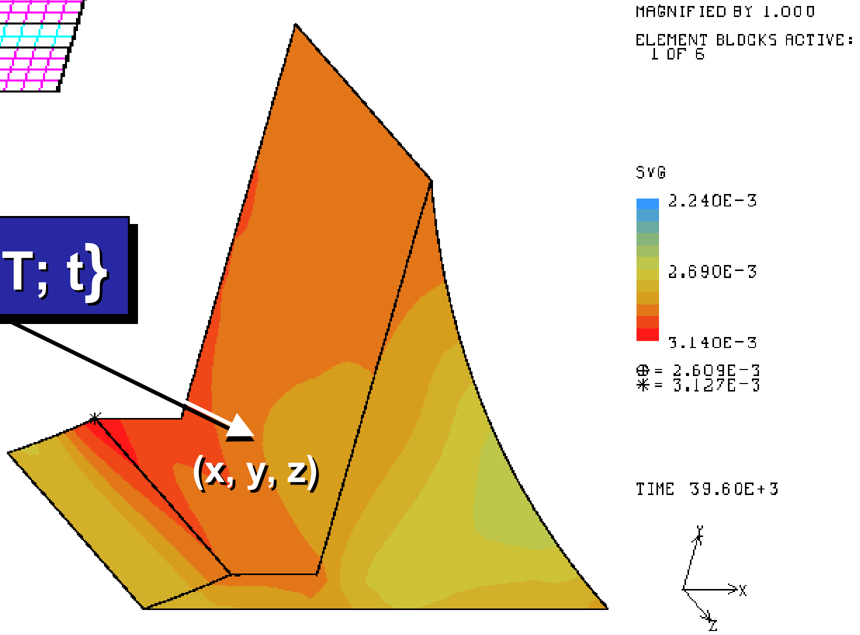
f_o …………. constant *(creep)*
Q …………. apparent activation energy *(creep)*
p …………. "sinh law" exponent *(creep)*

Finite element analysis provides the spatial "locator" of stress and strain rate within the solder joint geometry



Finite element mesh (x, y, z)

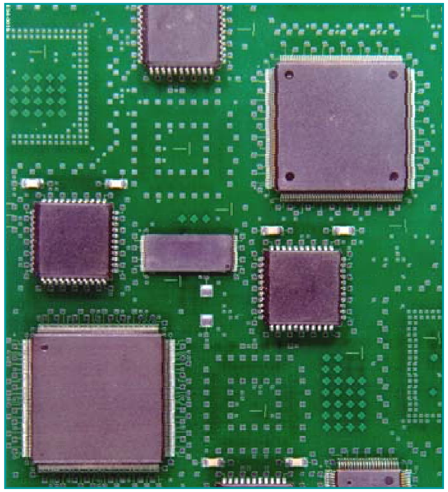
$d\varepsilon_{11}/dt = f\,\{\sigma(x, y, z); T; t\}$



Objective

Develop a unified creep-plasticity constitutive model to predict the reliability of 95.5Sn-3.9Ag-0.6Cu soldered interconnects.

- ***Step 1 … Materials properties database***



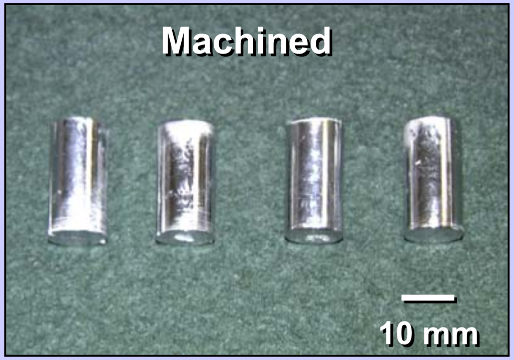
Experimental procedures

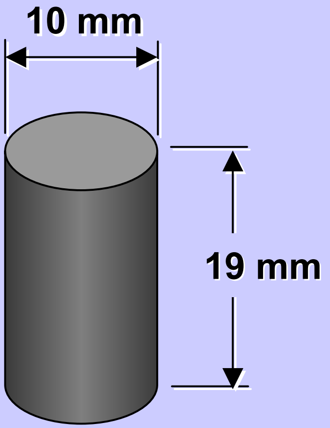
Compression testing (ASTM E9-89A):

95.5Sn-3.9Ag-0.6Cu

Chill-cast

(modified bullet mold)





Specimen geometry

Experimental procedures

- **Test Temperatures:**

  -25°C, 25°C, 75°C, 125°C, 160°C

- **Strain rates** *(stress-strain)*:

  4.2×10^{-5} s^{-1}, 8.3×10^{-4} s^{-1}

- **Creep stress** *(percent of σ_y)*:

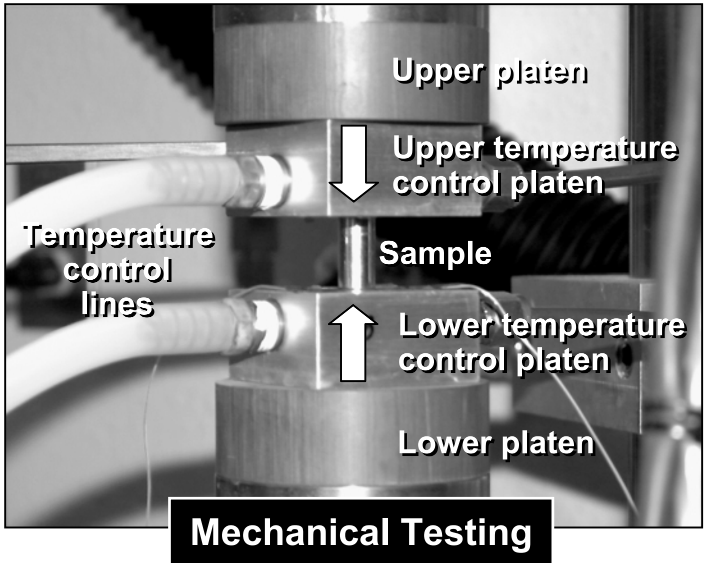
  20%, 40%, 60%, 80%

  (2.7 - 35 MPa)

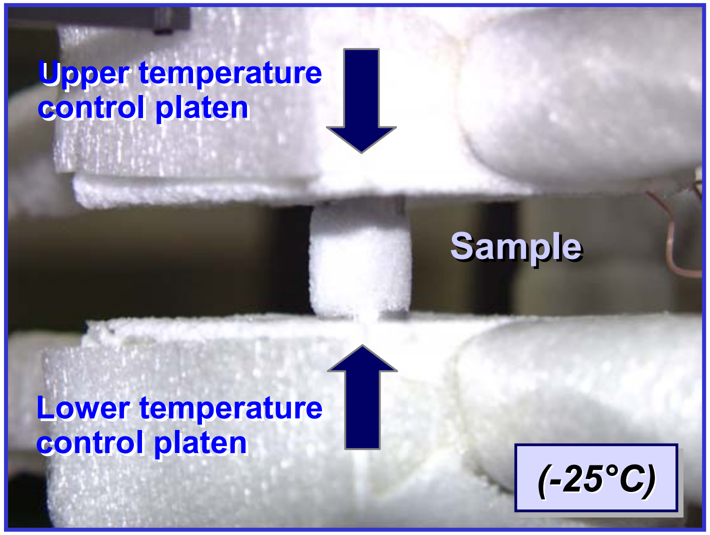
- **Samples test conditions:**

  •as-fabricated

  •post - 125°C, 24 hour heat treat



Mechanical Testing



Experimental procedures

•Dynamic elastic modulus meausurements:

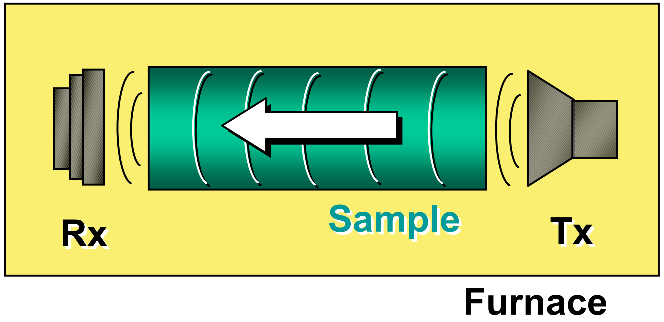
- -50°C to 200°C
- Temperature dependence of density, ρ:

25°C

$- 4.0 \times 10^{-4}$ g/cm^3-C°

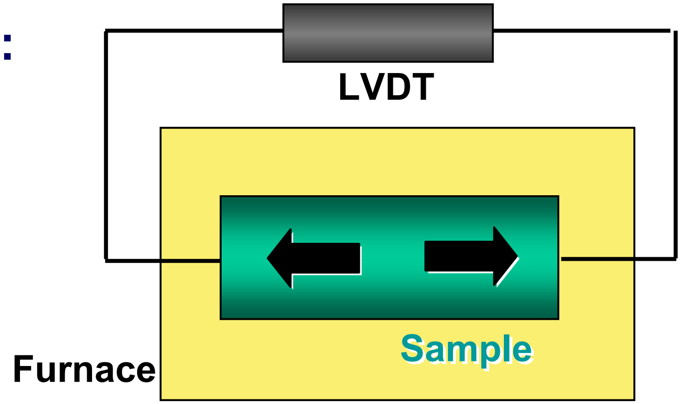
$+ 4.0 \times 10^{-4}$ g/cm^3-C°

7.30 g/cm^3



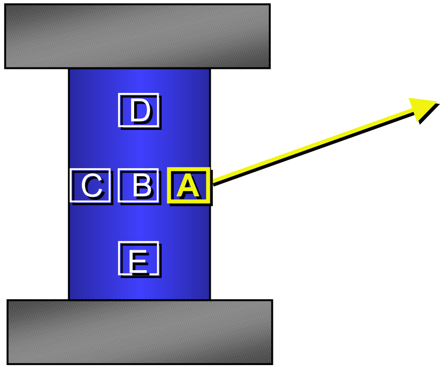
•Thermal expansion coefficient measurements:

- -50°C to 200°C
- Convert the expansion data to a coefficent of thermal expansion (CTE).

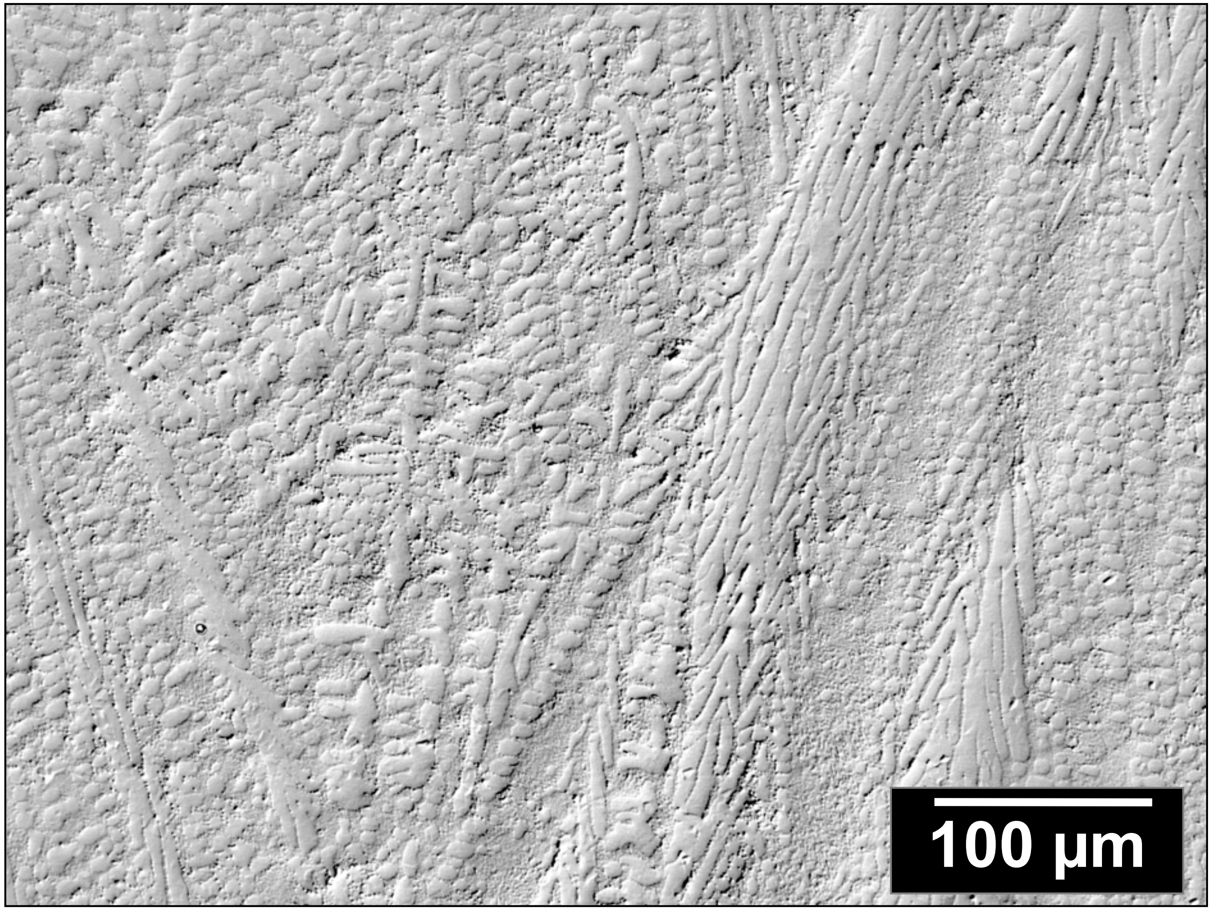


Microstructure of the as-cast Sn-Ag-Cu solder

Dendritic microstructure was prevalent near the cylinder walls.

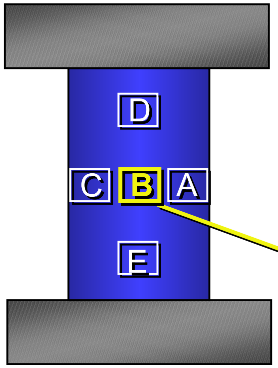


Untested

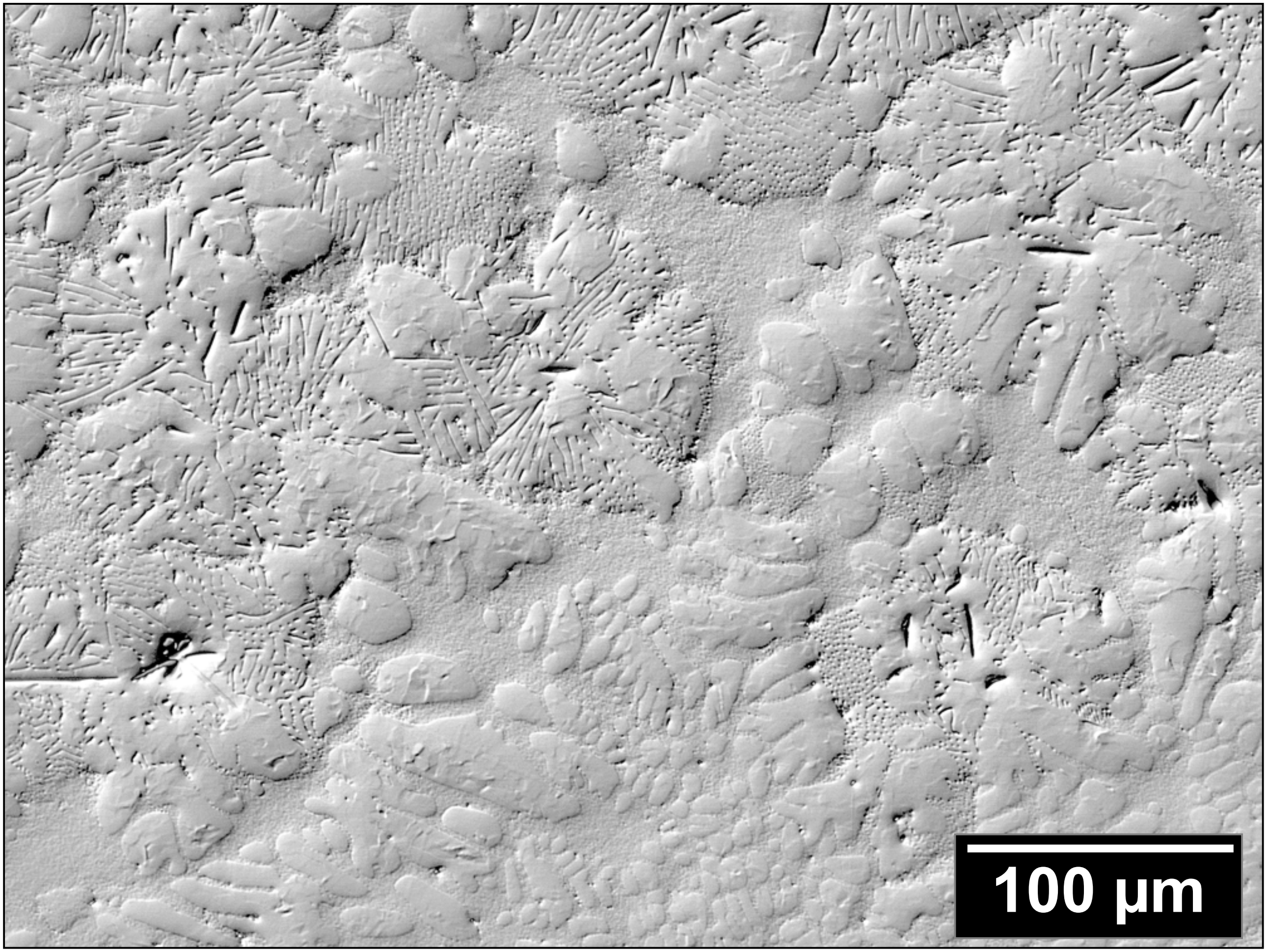


Microstructure of the as-cast Sn-Ag-Cu solder

Equiaxed microstructure was observed near the cylinder interior.



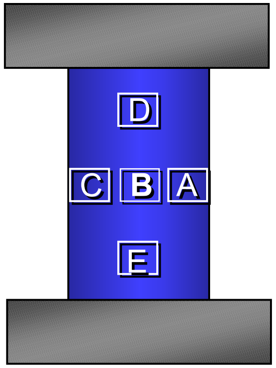
Untested



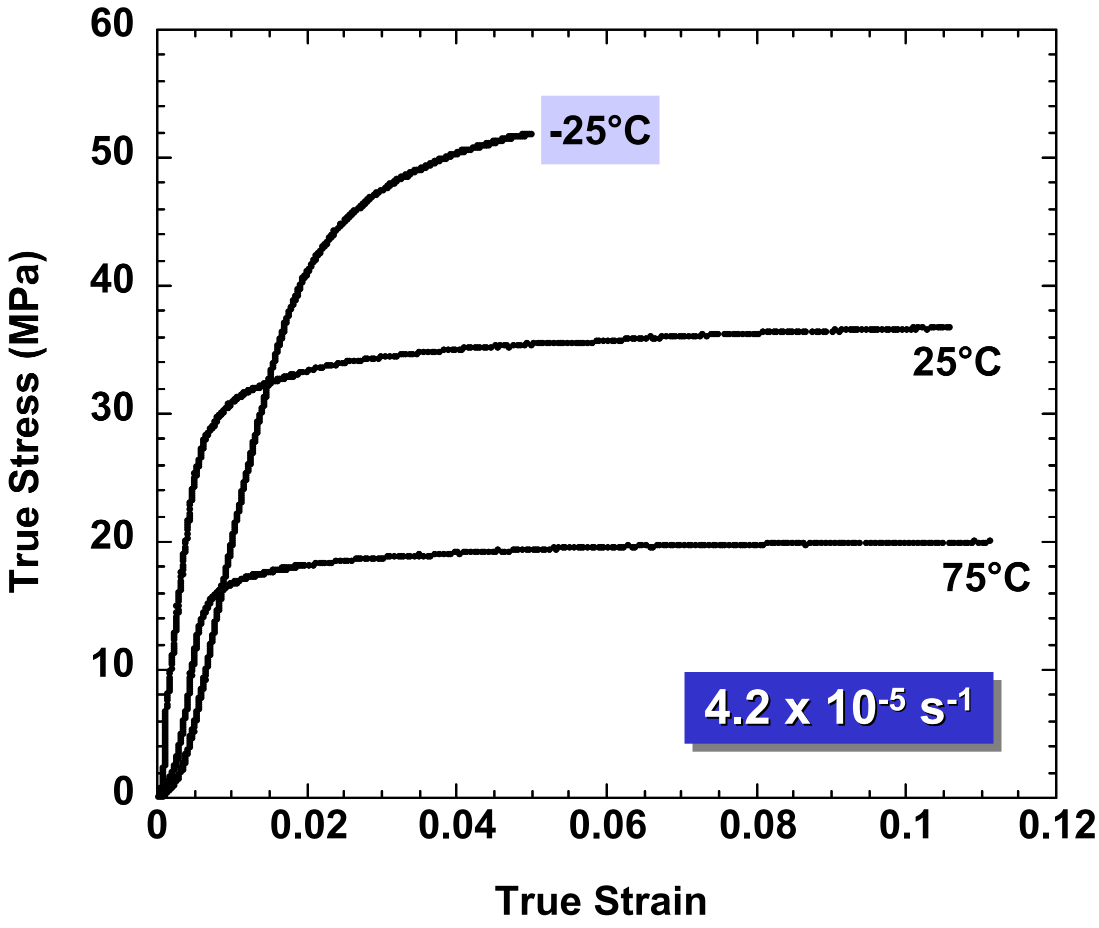
Microstructure of the as-cast Sn-Ag-Cu solder

Effect of the 125°C, 24 hour aging treatment on the Sn-Ag-Cu solder microstructure:

- **The dendritic morphology near the cyclinder walls became slightly more equiaxed in appearance.**
- **There was no noticeable change to the microstructure that was interior to the cylinder sample geometry.**

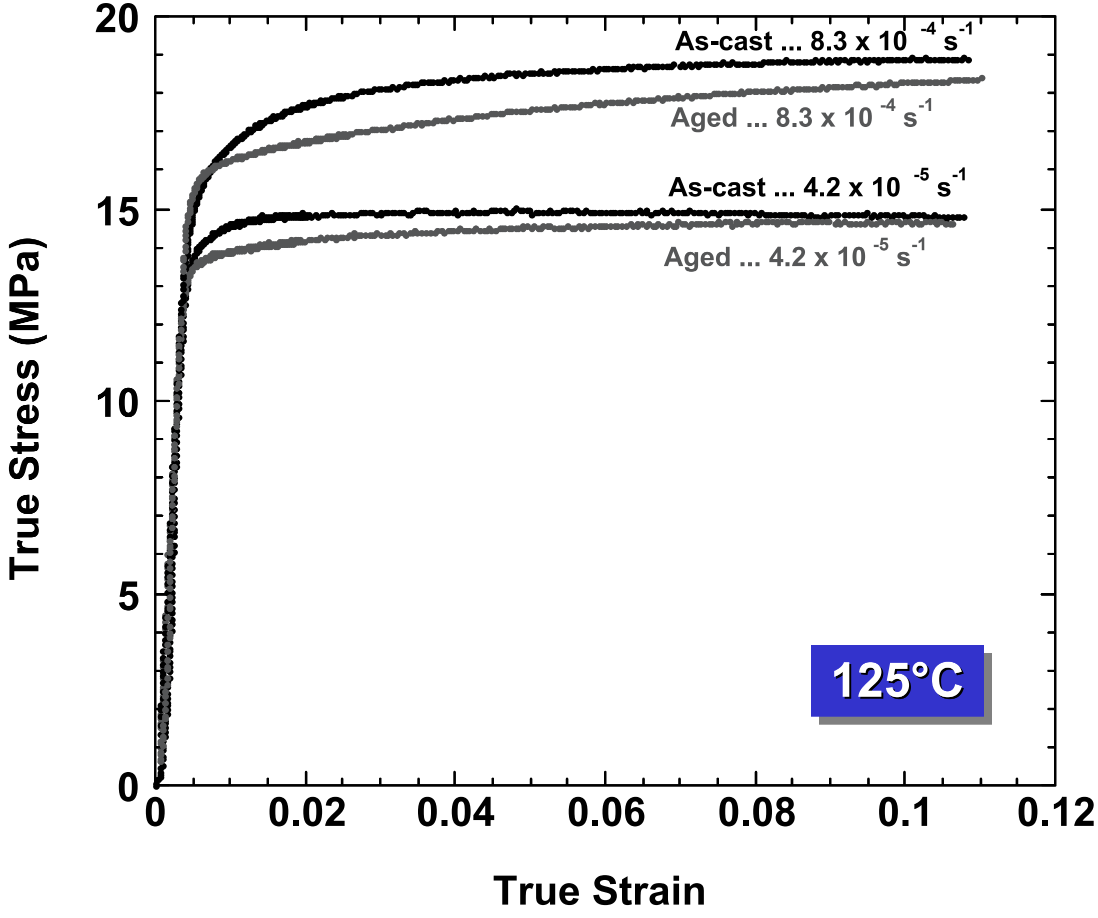


Stress/strain response of the Sn-Ag-Cu solder



- “Roll-up” to linear-elastic deformation for tests at -25°C and 75°C.
- Transition from linear-elastic to plastic deformation for tests at 25°C.

Stress/strain response of the Sn-Ag-Cu solder



Plastic deformation appears to reflect two simultaneous processes: work hardening ? dynamic recovery.

Stress/strain response of the Sn-Ag-Cu solder

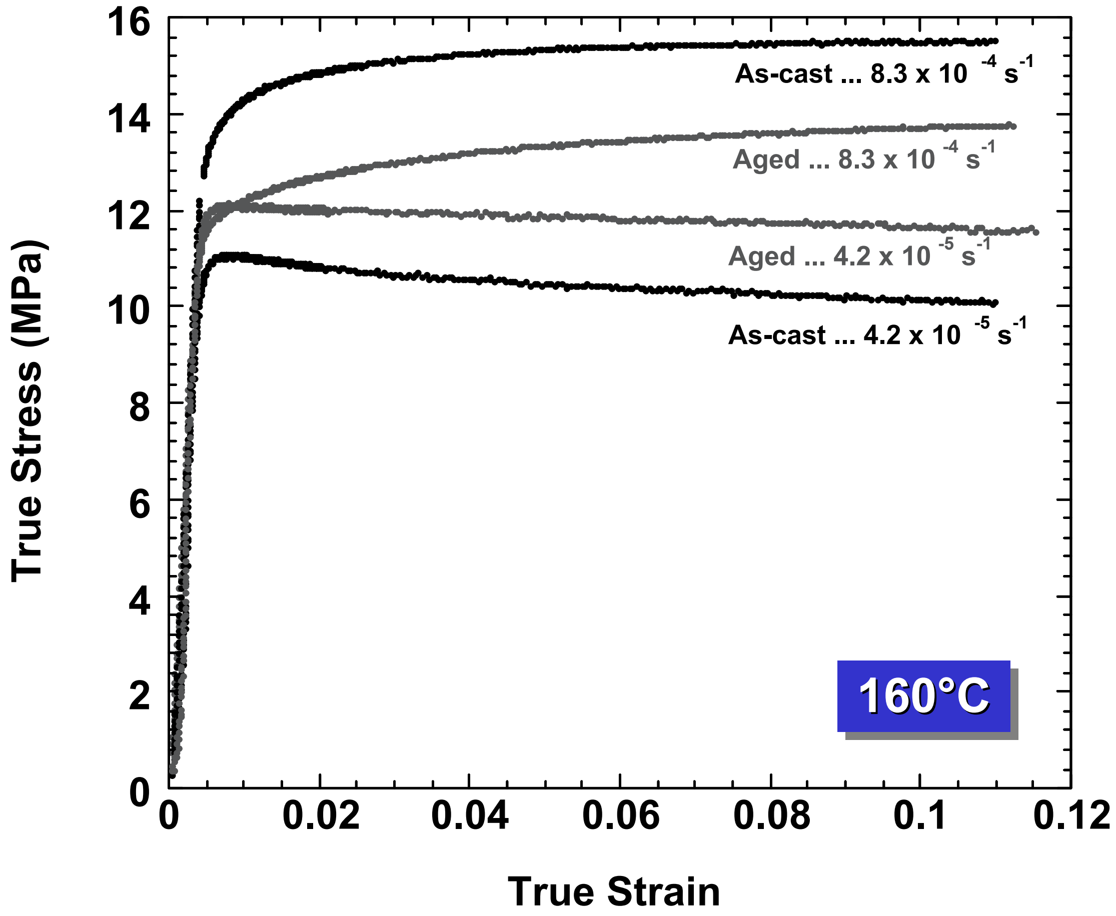
Plastic deformation at 125°C:

work hardening ? dynamic recovery

Thermal aging: **WORK HARDENING > dynamic recovery.**

Faster strain rate: **WORK HARDENING > dynamic recovery.**

Stress/strain response of the Sn-Ag-Cu solder



Plastic deformation appears to reflect two simultaneous processes:

work hardening ? dynamic recrystallization

Stress/strain response of the Sn-Ag-Cu solder

Plastic deformation at 160°C:

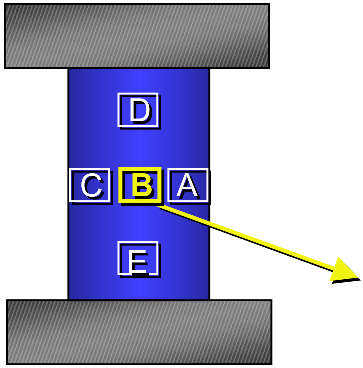
work hardening ? dynamic recrystallization

Thermal aging: **WORK HARDENING > dynamic recrystallization.**

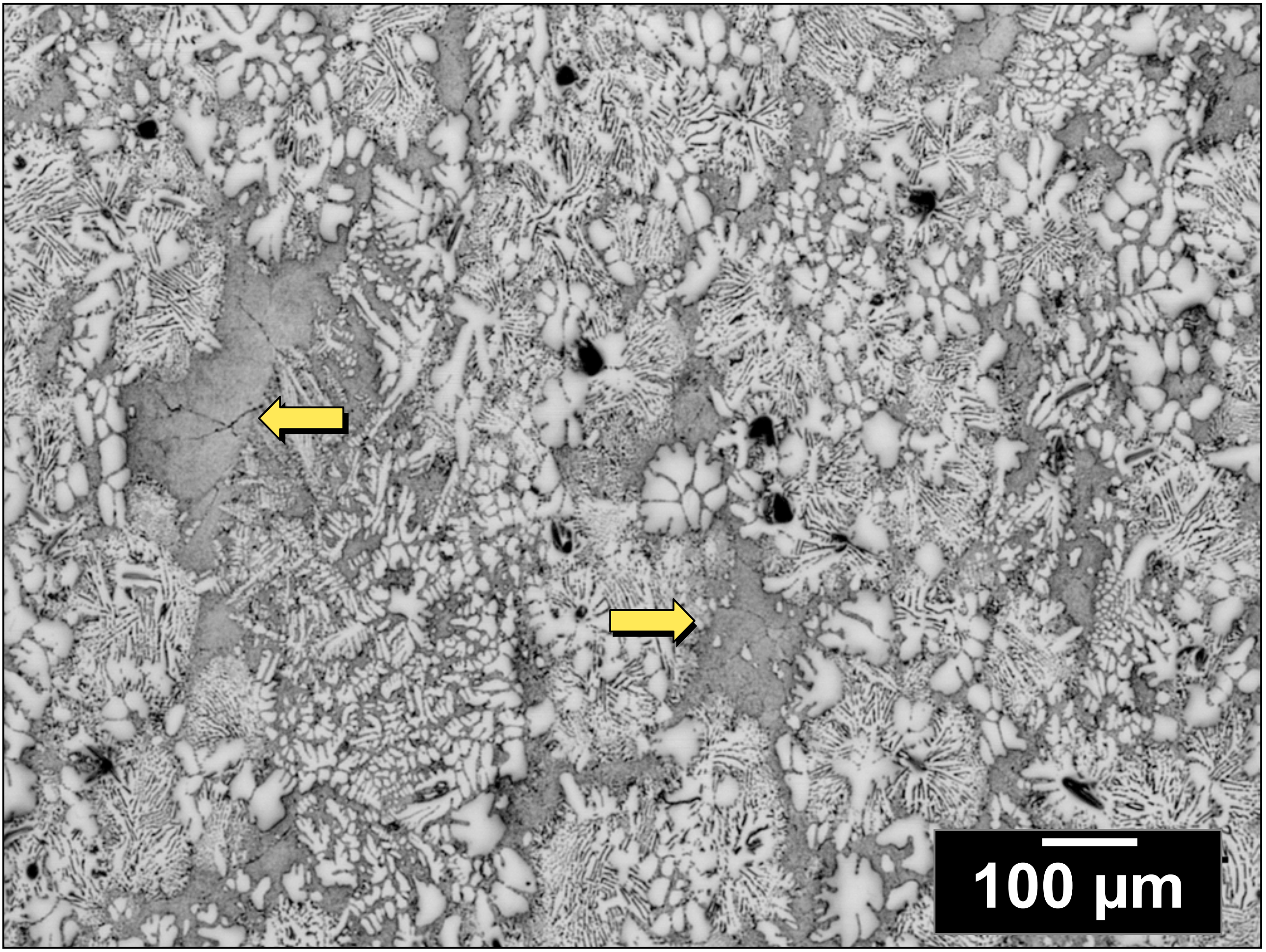
Faster strain rate: **WORK HARDENING > dynamic recrystallization.**

Work hardening, dynamic recovery and dynamic recrystallization are not adequately understood to develop quantitative state variables.

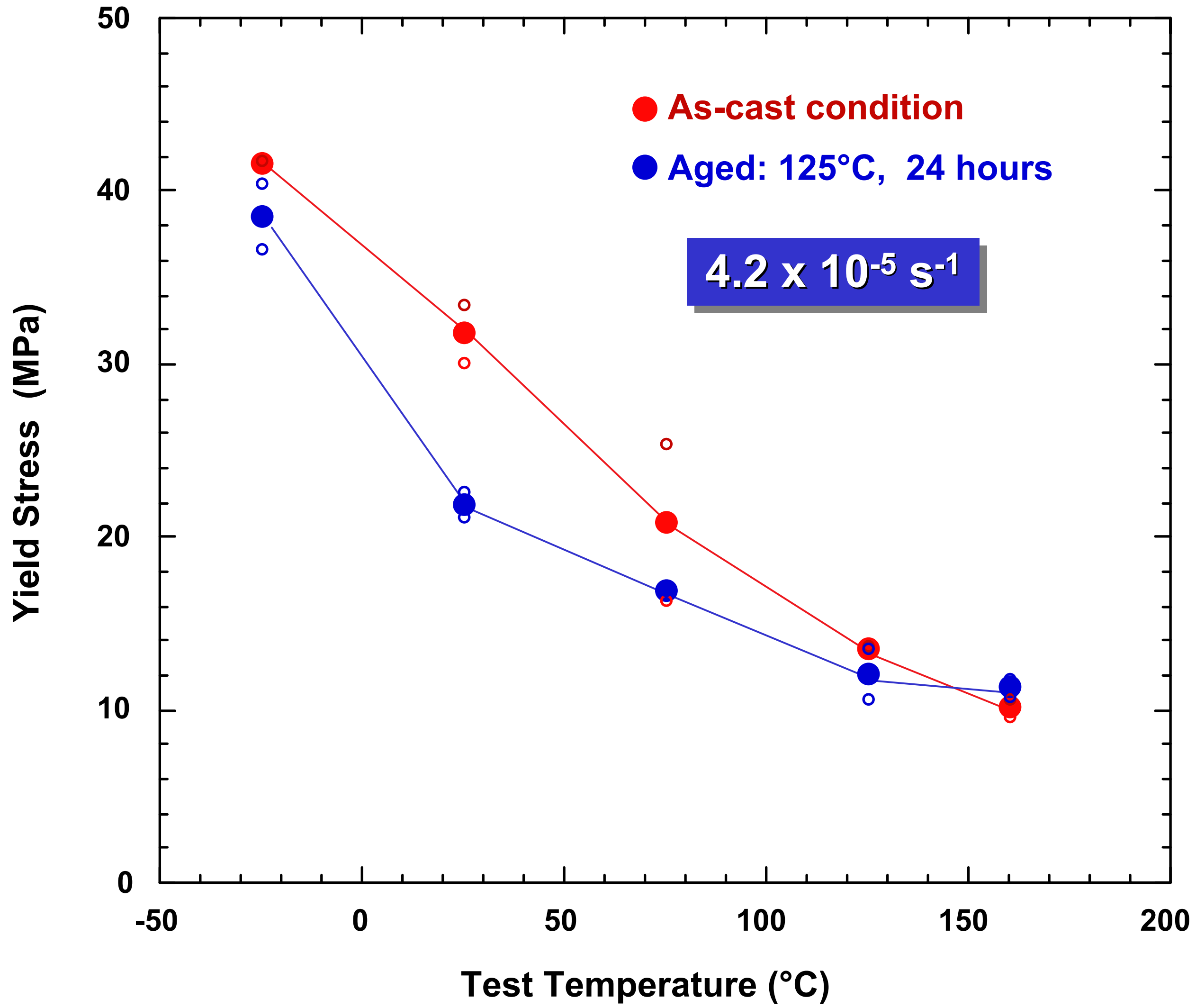
Deformation microstructure of Sn-Ag-Cu solder



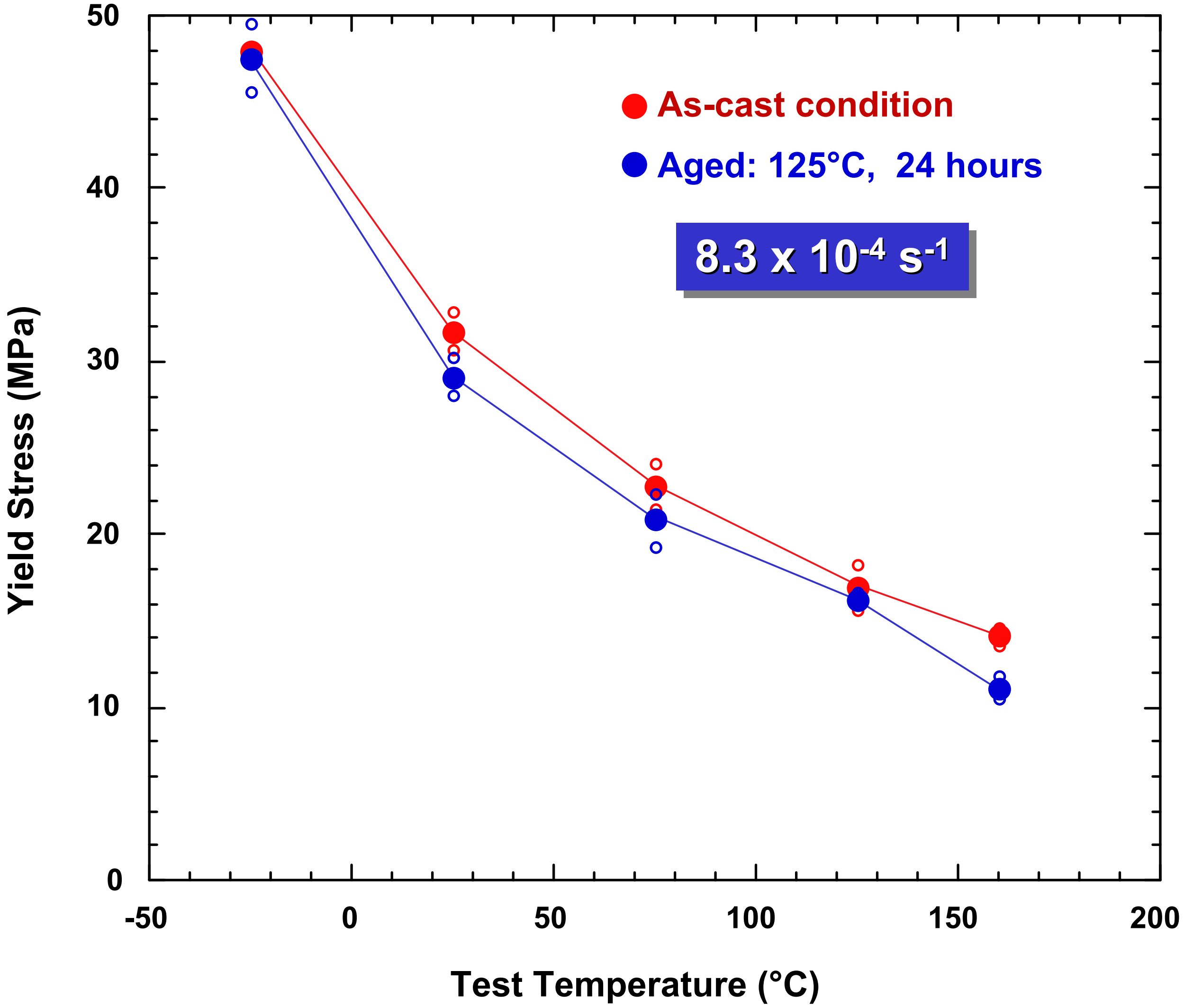
As-cast
160°C
8.3×10^{-4} s^{-1}



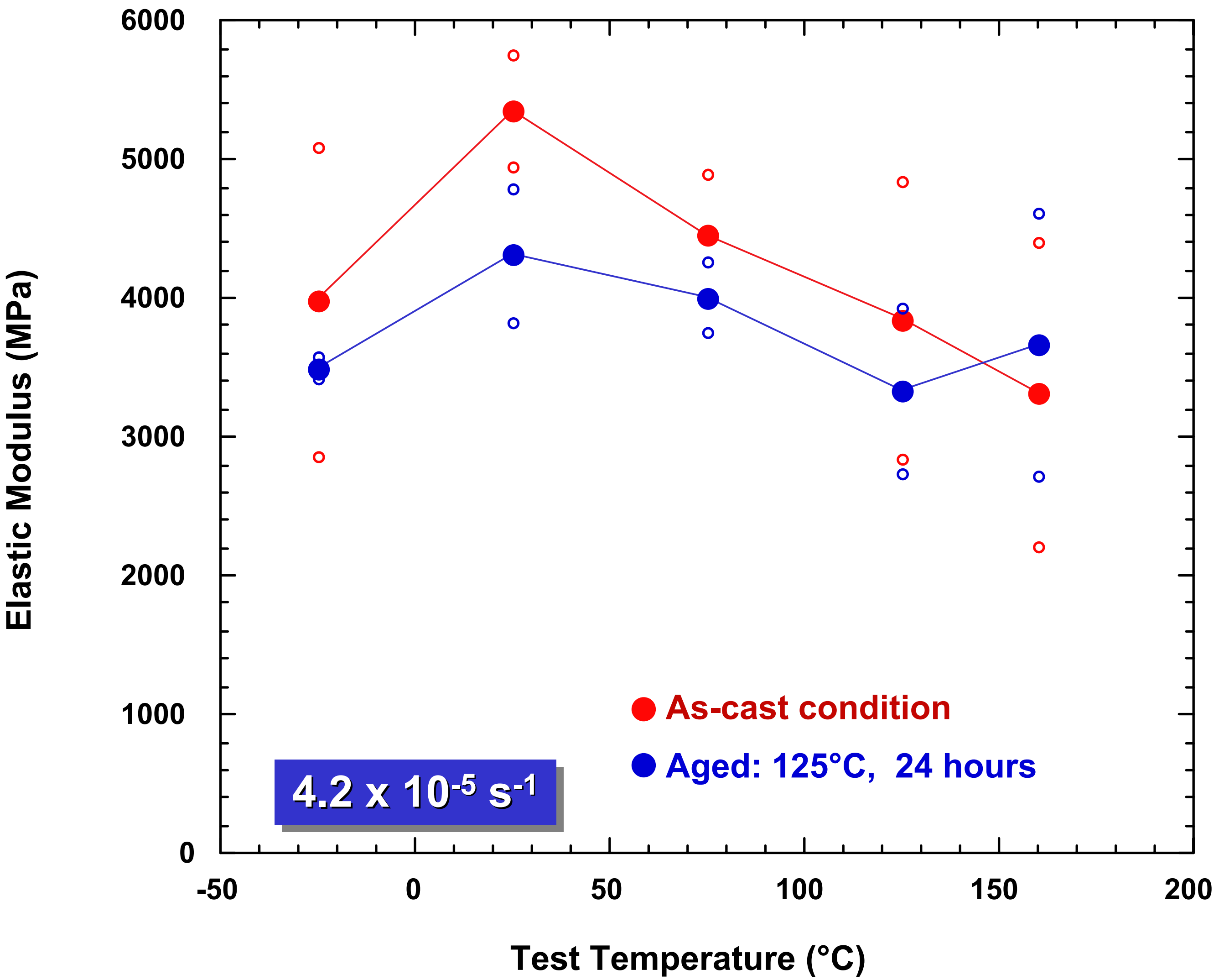
Yield stress versus temperature (ASTM E9-89)



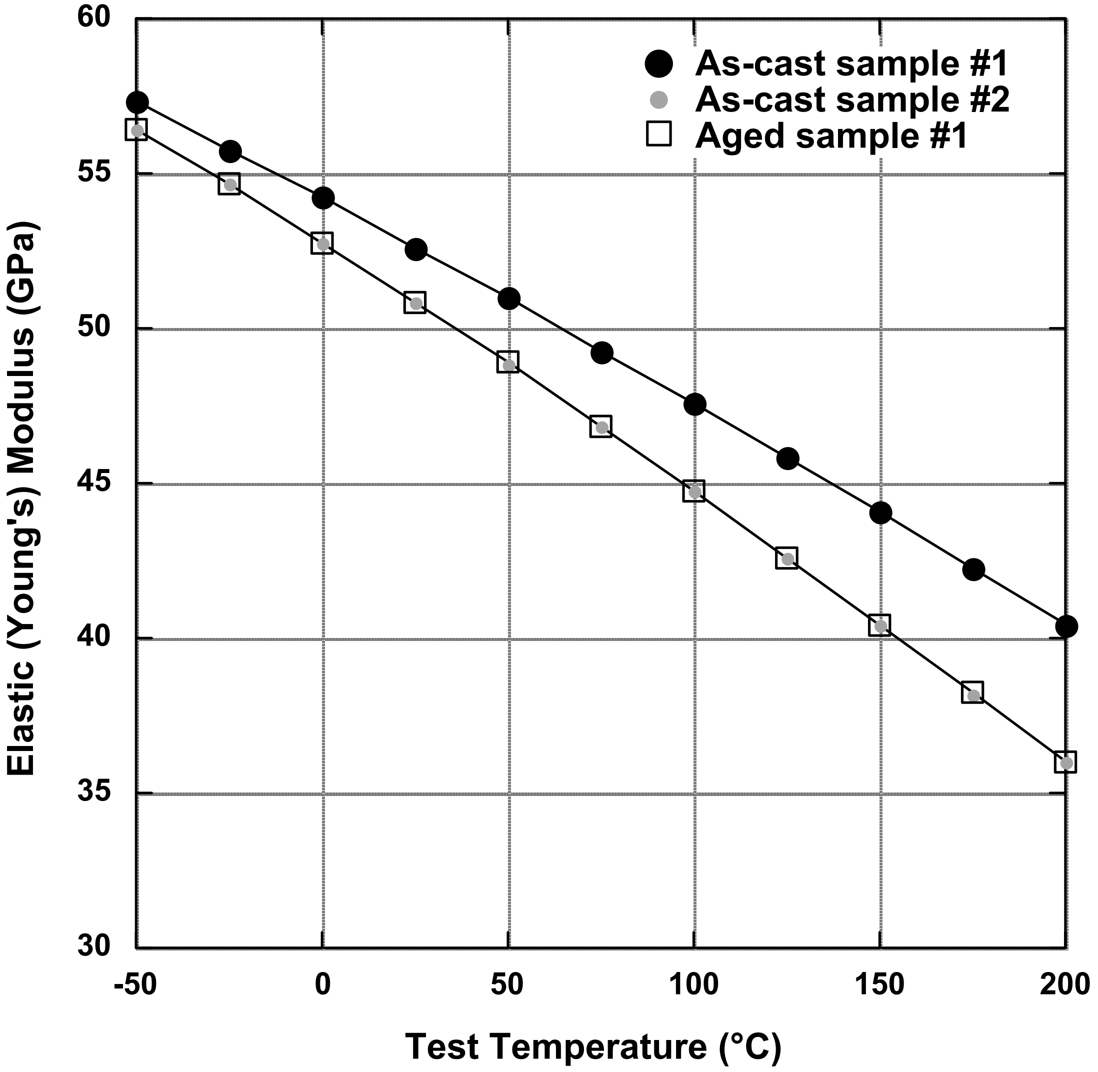
Yield stress versus temperature (ASTM E9-89)



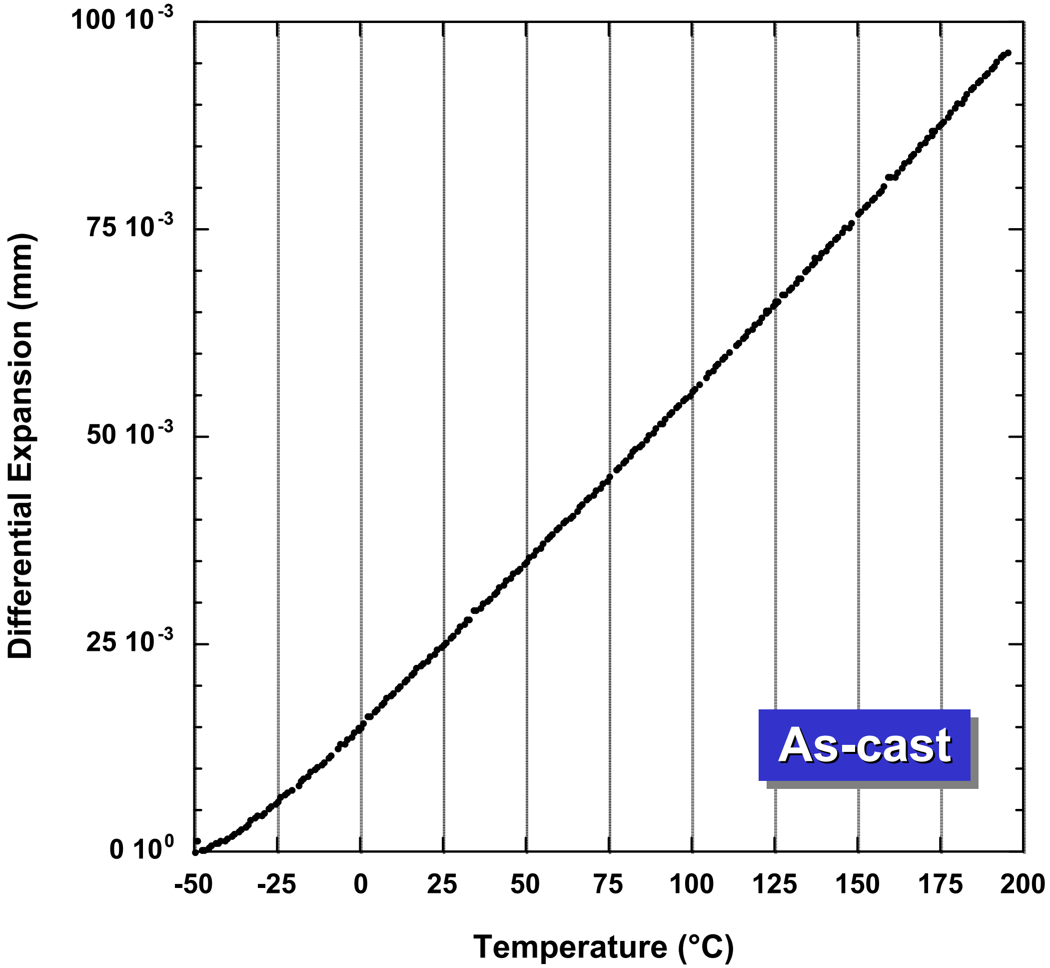
Static elastic modulus versus temperature (ASTM E111-82)



Dynamic *(acoustic)* elastic modulus versus temperature

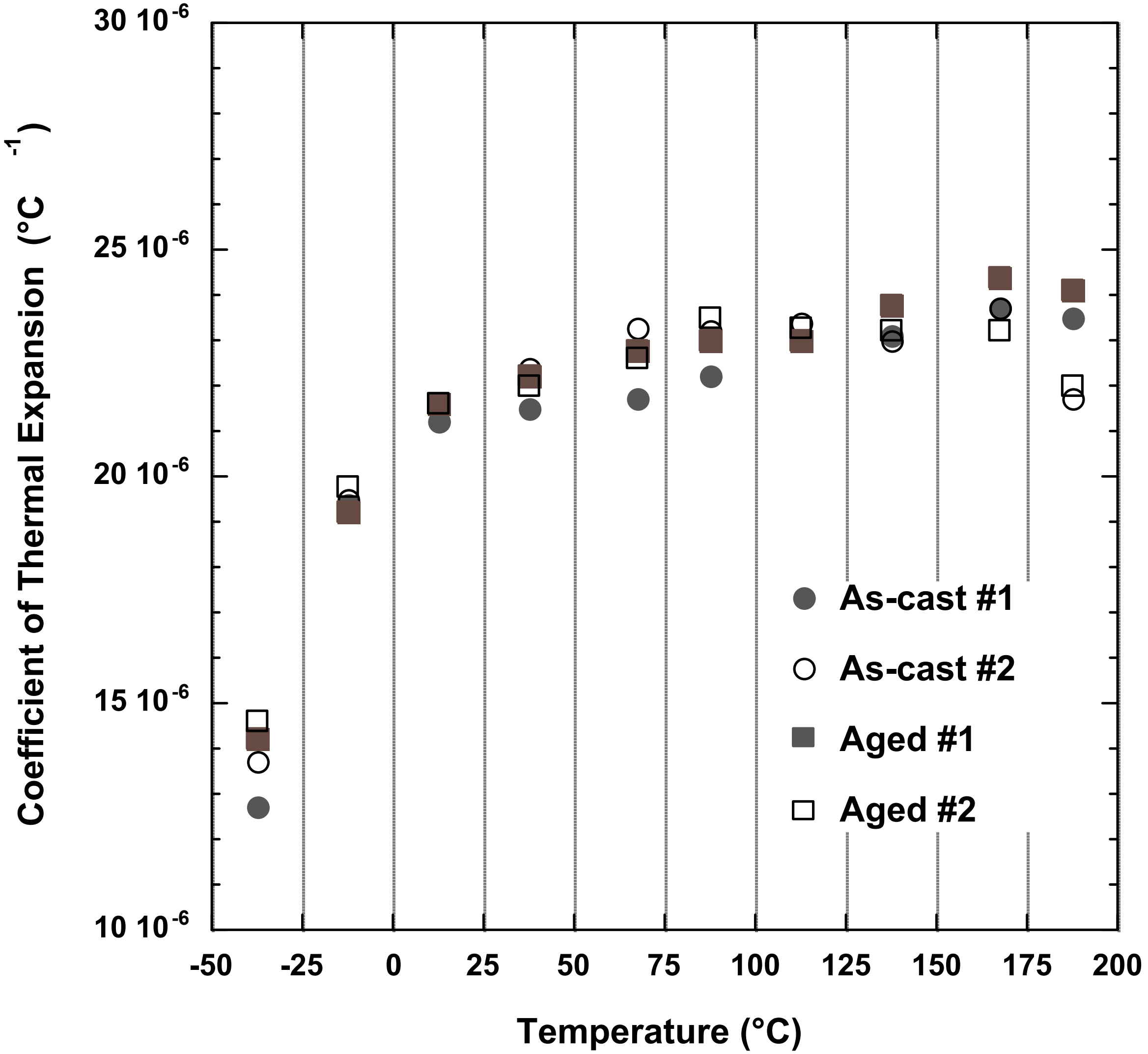


Differential expansion versus temperature



There was no indication of solid-state phase transitions.

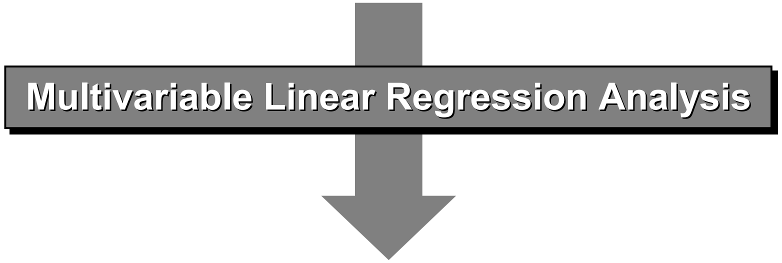
Coefficient of thermal expansion versus temperature



Analysis of the creep test data

$$d\varepsilon/dt_{min} = f_o \exp(-Q/RT) \sinh^p(\alpha\sigma)$$

Hyperbolic Sine Creep Law



Multivariable Linear Regression Analysis

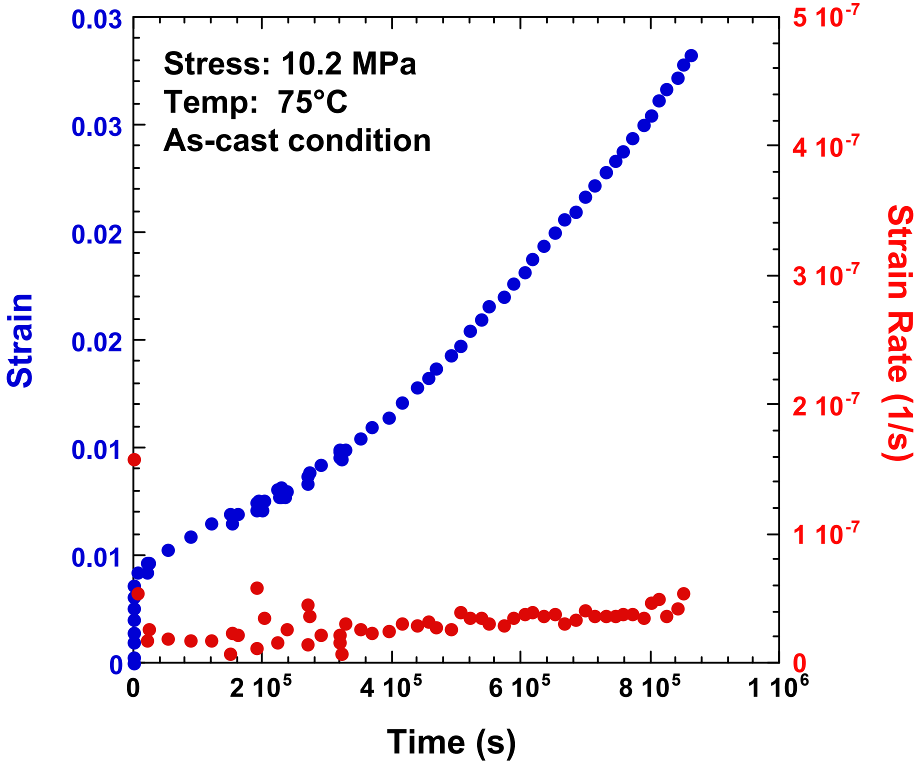
Independent variables:

- $\ln(d\varepsilon/dt_{min})$,
- $(1/T)$,
- $\ln[\sinh(\alpha\sigma)]$

Independent parameter

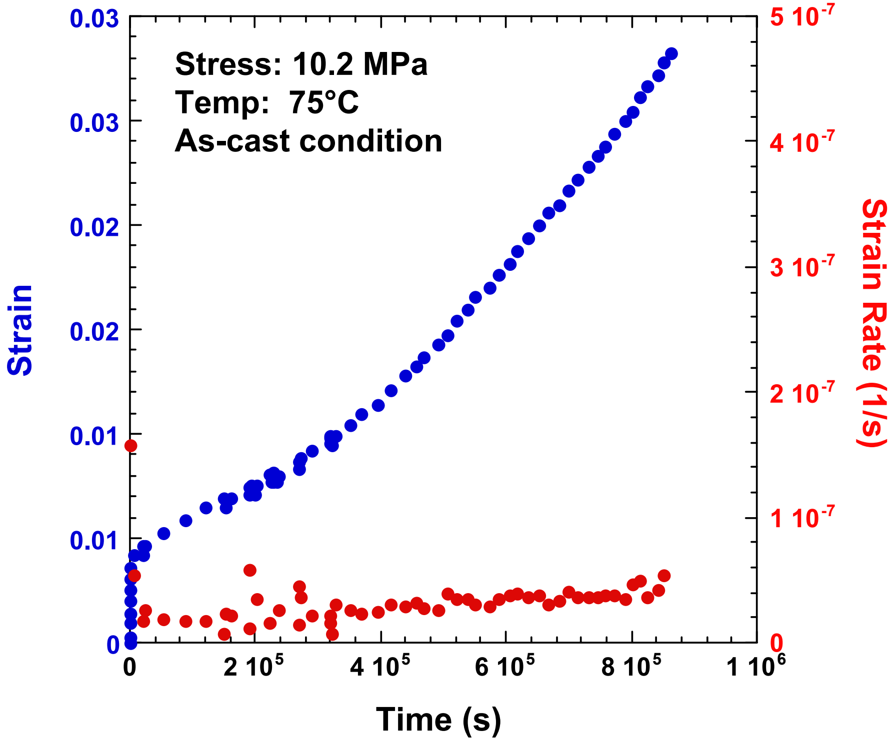
Coefficients:

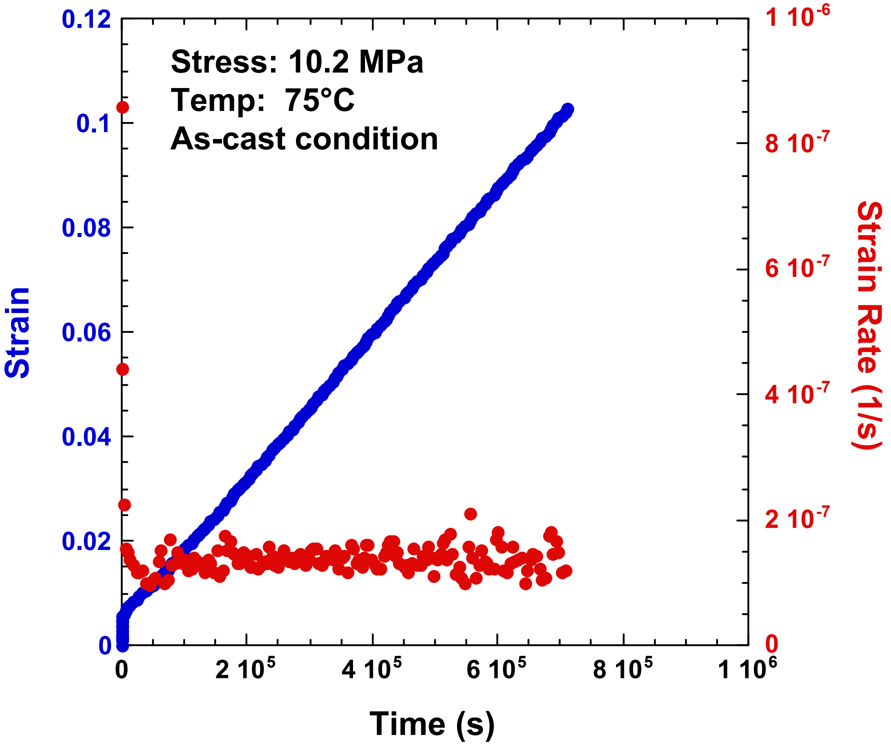
- $\ln(f_o)$,
- $-Q/R$,
- p



Reported data will be for the AS-CAST condition.

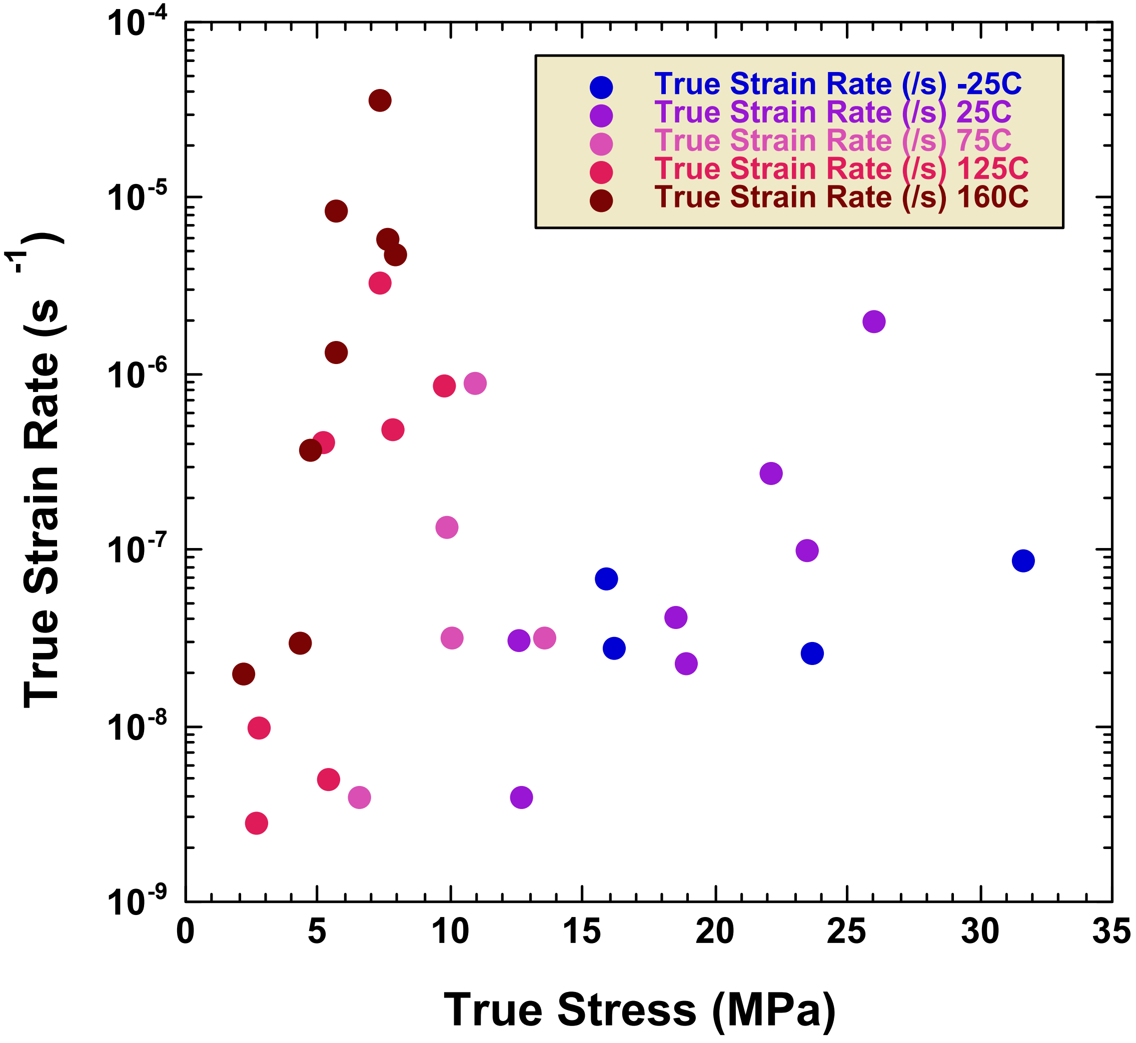
Analysis of the creep test data



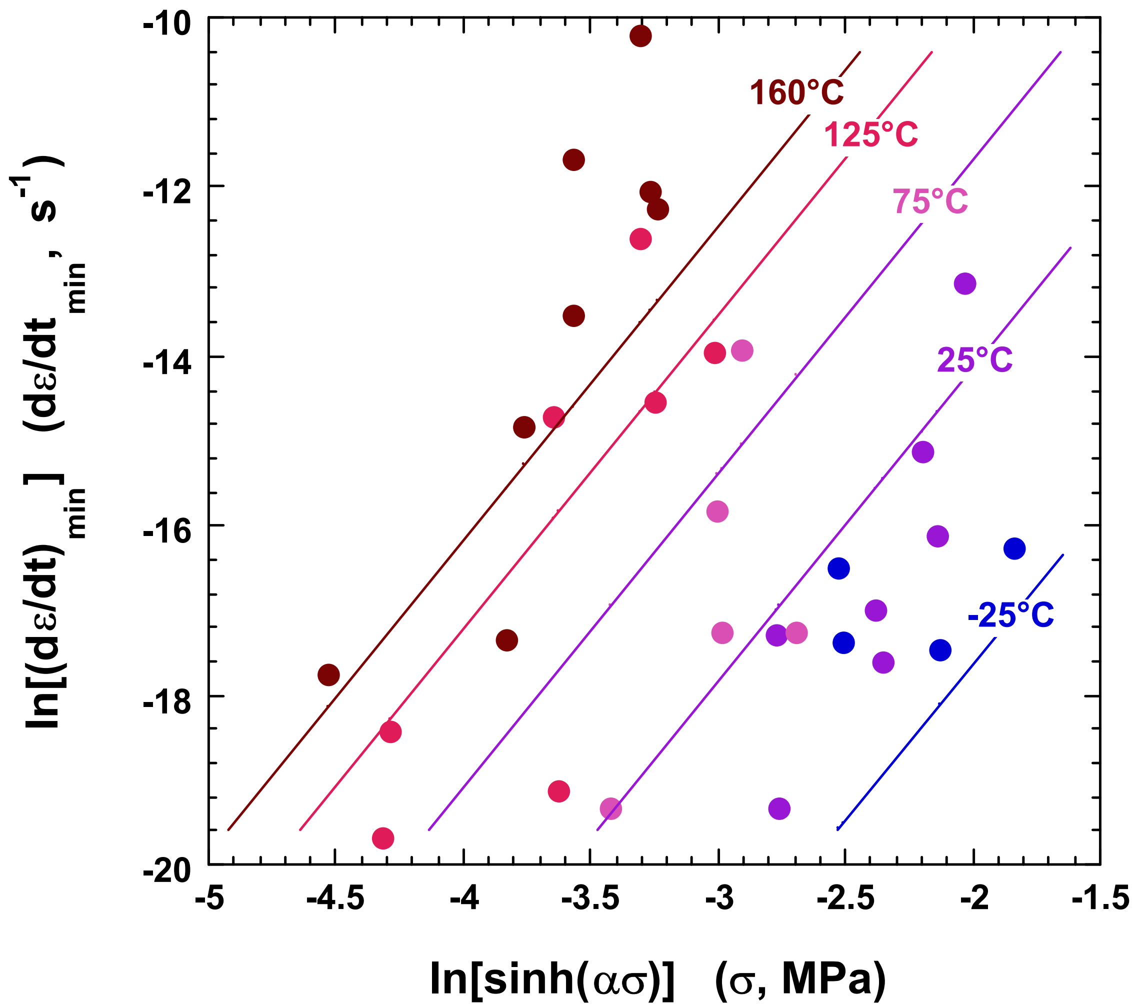


A large degree of sample-to-sample variability was observed for specimens tested in the as-cast condition.

Analysis of the creep test data



Analysis of the creep test data



$$d\varepsilon/dt_{min} = 34856 \exp(-43?13\ (kJ/mol)/RT)\ \sinh^{4?3}(0.005\sigma)$$

Summary

1. A Unified Creep Plasticity (UCP) model is being developed to describe inelastic deformation in **95.5Sn-3.9Ag-0.6Cu (wt.%) solder**. for the conditions:

   As-fabricated
   Aged: 125°C … 24 hours

2. Yield stress, elastic (Young's) modulus, bulk modulus, Poisson's ratio, and coefficient of thermal expansion were determined for:

   -25°C to 160°C

3. The creep data as-cast samples were fit to a hyperbolic sine law:

$$d\varepsilon/dt_{min} = 34856 \exp(-43 ? 13\ (\mathrm{kJ/mol})/RT)\ \sinh^{4?3}\ (0.005\sigma)$$

A final note ….. the back stress, B_{11}

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

- **The impact of the back stress, B_{11}, or *Bauschinger effect*, on the fatigue response of solder is not well defined.**

A scenario in which $B_{11} = 0$ can be hypothesized when recovery processes occur very rapidly after load reversal

- **The back stress, B_{11}, is difficult to measure experimentally.**

Experimental techniques almost certainly require load reversal procedures.