AN OBSTACLE-CONTROLLED CREEP MODEL FOR SN-PB AND SN-BASED LEAD-FREE SOLDERS

by Jean-Paul Clech, EPSI Inc.
Montclair, NJ, USA

http://jpclech.com

Presented at

SMTA International Conference
Chicago, Illinois, September 30, 2004

Addendum

- **Missing reference in paper:**
  - Shi, X. Q., Wang, Z. P., Zhou, W., Pang, H. L. J. and Yang, Q. J., "A new creep constitutive model for eutectic solder alloy", *ASME Trans., J. of Electronic Packaging*, June 2002, pp. 85-90
- **References for additional examples in presentation**
  - Lu, W-Y., Lim, T. J., Boyce, B. L., Grazier, J. M., and Fang, H. E., "Small scale multiaxial deformation experiments on solder for high-fidelity model development", Sandia National Laboratories, SAND Report, SAND2002-8592, December 2002
  - Kim, K. S., Huh, S. H. and Suganuma, K., "Effects of cooling speed on microstructure and tensile properties of Sn-Ag-Cu alloys", Materials Science and Engineering A, Elsevier Science, 2001
- **In the paper, "steady-state" refers to "minimum creep rates"**

CONTEXT

- **Reliability assessment requires a reasonably accurate description of the thermo-mechanical behavior of lead-free solders.**
- **If we don't understand how solder responds to external loads (thermal or mechanical), how can we interpret or extrapolate accelerated testing results?**
  - At best, thermal cycling profiles are not optimal and lack in efficiency
  - At worse, accelerated testing is equivalent to shooting in the dark.
- **Reliable constitutive models are needed:**
  - For solder joint stress/strain analysis
  - To develop acceleration factors and life prediction models

ABOUT CLASSICAL APPROACHES TO CREEP OF LEAD-FREE SOLDERS

- **Emphasis has been on “steady state” creep**
- **Primary creep rate models for solders include a time variable (not a recommended practice in constitutive modeling)**
- **Secondary creep stage: its duration is not well defined in test**
  - Reliability models assume that steady state creep can last for ever
- **Tertiary creep has received little attention**

- **THIS PRESENTATION FOCUSES ON THE STRESS AND TEMPERATURE DEPENDENCE OF MINIMUM CREEP RATES**

ABOUT MINIMUM CREEP RATES

- **The application of classical “steady-state” creep models to lead-free solders shows major anomalies.**
  - Power-law creep models give different temperature-dependent stress exponents in low and high stress regions (e.g., Song et al., 2002)
  - Hyperbolic sine creep models have led to widely different activation energies for a given alloy, depending on stress levels and the covered temperature range
- **Recurring theme: parameters of classical “steady-state” creep models are stress- and temperature-dependent**
  - “Something” is not captured in classical steady-state creep models
  - Use them with caution

What The Experts Say

- ***"DESPITE BEING WIDELY ADOPTED FOR OVER 50 YEARS, POWER-LAW CONCEPTS HAVE NOT LED TO THEORIES WITH VERIFIED PREDICTIVE CAPABILITIES…IT IS, THEREFORE PROPOSED THAT POWER-LAW REPRESENTATION OF STEADY STATE CREEP RATES SHOULD BE ABANDONED…"***

  Wilshire, 2002

- ***"LACKING ANY PHYSICAL MODEL, IT MUST BE CONSIDERED FORTUITOUS THAT ANY SET OF n' AND α', CAN CORRECTLY DESCRIBE THE BEHAVIOR OVER A WIDE RANGE OF STRESSES"***

  Frost and Ashby, 1982

  - In reference to the "sinh" model constants n' (exponent) and α' ("breakdown stress factor")

Alternative: Obstacle-Controlled Creep Models

- **One-cell model:**

$$\mathring{\varepsilon} = A\sigma^{m} \cdot \exp\left[-\frac{Q_a}{kT}\left(1-\frac{\sigma}{\sigma_0}\right)\right]$$

  - **A first-principle, material-based plasticity model (Ashby & Frost, 1982)**

    σ_0 " athermal flow strength = maximum flow strength at 0 K.

  - **The true activation energy: $Q = Q_a - V . \sigma$ (V = constant) is stress-dependent**
    - **Creep is a thermally-activated, stress-aided rate process**

- **Two-cell model:**

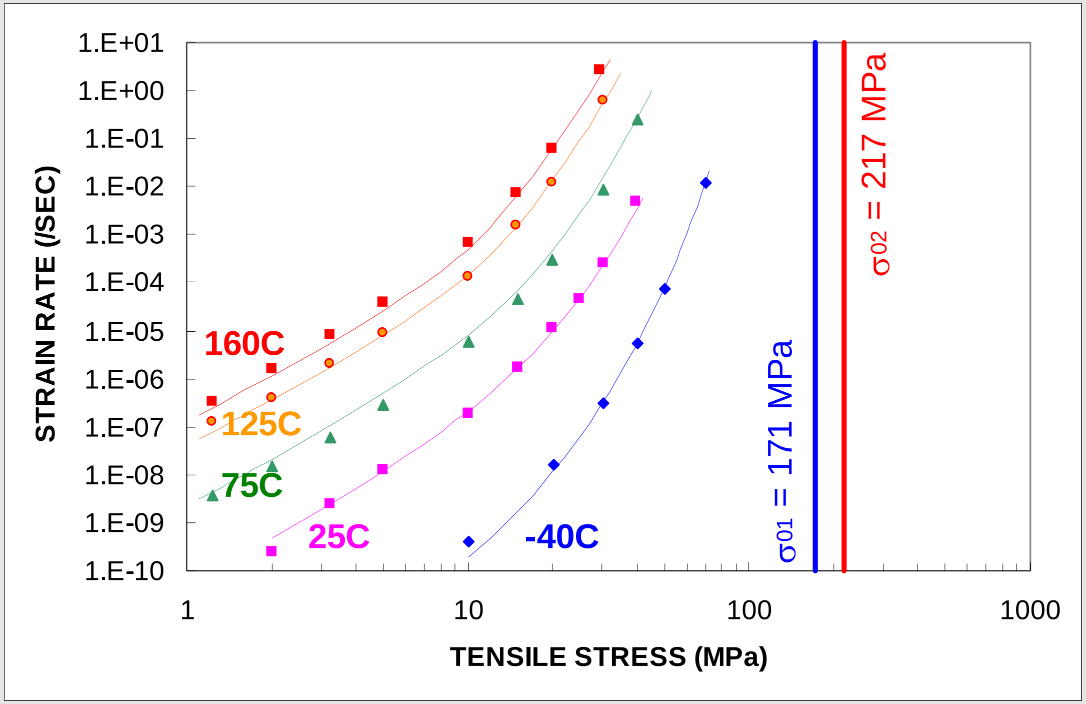
$$\mathring{\varepsilon} = A_1\sigma^{m_1} \cdot \exp\left[-\frac{Q_{a1}}{kT}\left(1-\frac{\sigma}{\sigma_{01}}\right)\right] + A_2\sigma^{m_2} \cdot \exp\left[-\frac{Q_{a2}}{kT}\left(1-\frac{\sigma}{\sigma_{02}}\right)\right]$$

when two creep mechanisms have been identified

Alternative: Obstacle-Controlled Creep Models (cont'd)

- **Paper presents the application of such models to:**
  - **Near-eutectic SnPb**
  - **Seven lead-free solders in the SnAg, SnAgCu, SnBi, SnCu families.**
- **Testing of models against independent data and over a wide range of circumstances is a must (for this or other type of model) before models can be applied to real joints.**

Sn37Pb Creep Model

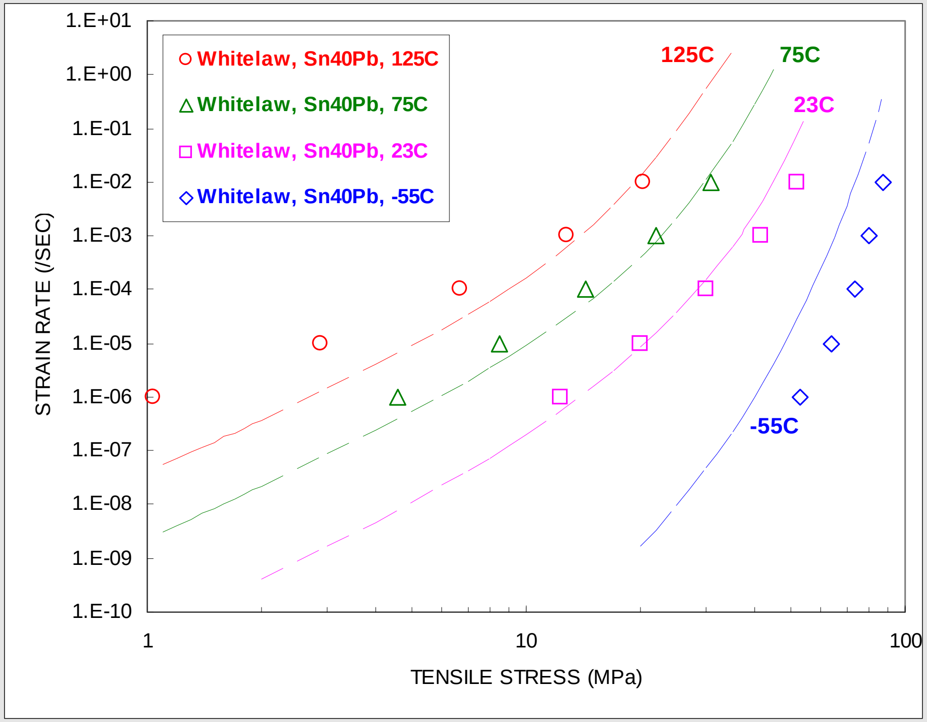


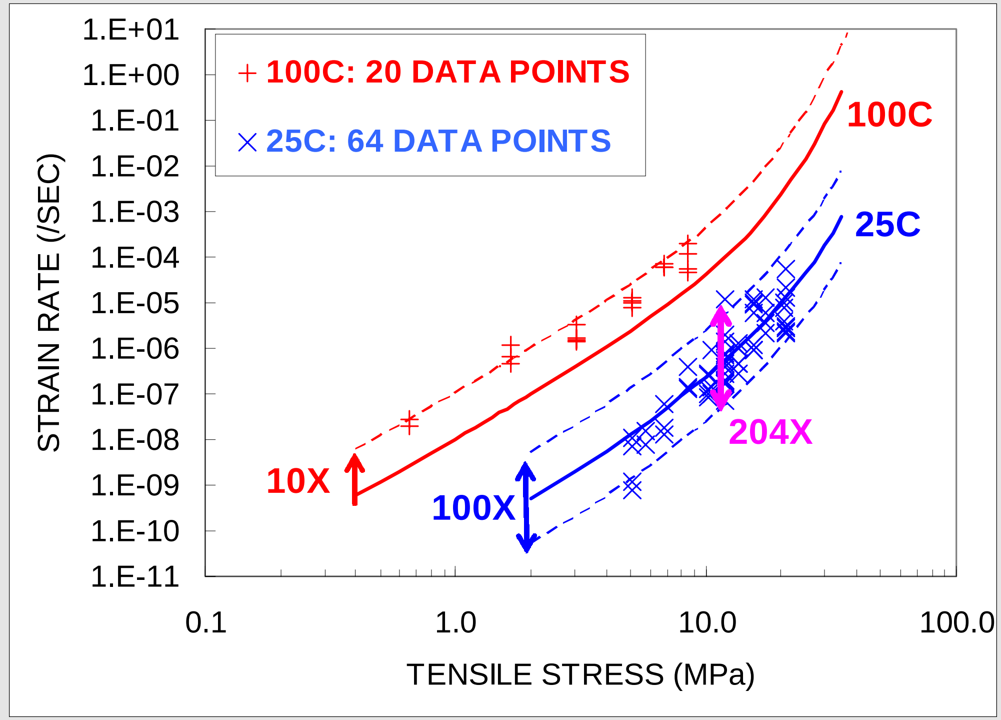
- **Two-cell model for two creep mechanisms**
  - **Grain boundary sliding**
  - **Matrix creep**
- **Six test cases**
  - Tensile creep
  - Tensile strength
  - Compressive stress relaxation
  - Thermal cycling hysteresis loop

- **Model after Sn37Pb tensile creep data**
  - Data from Shi et al., June 2002, *J. of Electronic Packaging*

$$\mathring{\varepsilon}(/\sec) = 17.4\sigma^{3.07}\cdot\exp\left[-\frac{7988}{T(K)}\left(1-\frac{\sigma}{171}\right)\right] + 5112\sigma^{5.89}\cdot\exp\left[-\frac{13516}{T(K)}\left(1-\frac{\sigma}{217}\right)\right]$$

SnPb Model Test # 1 & 2: Tensile Creep

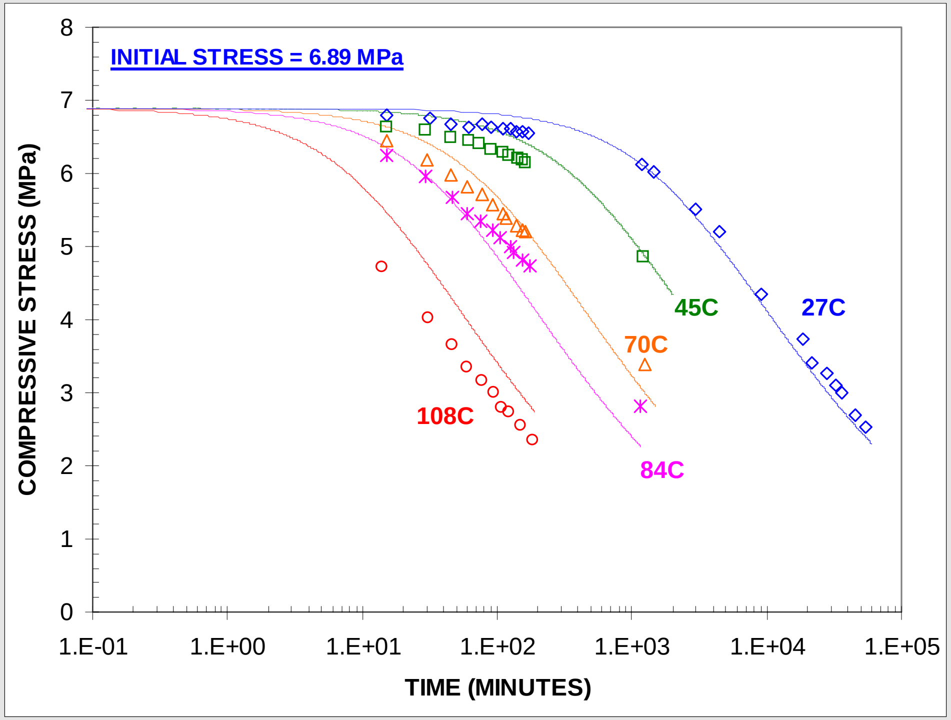


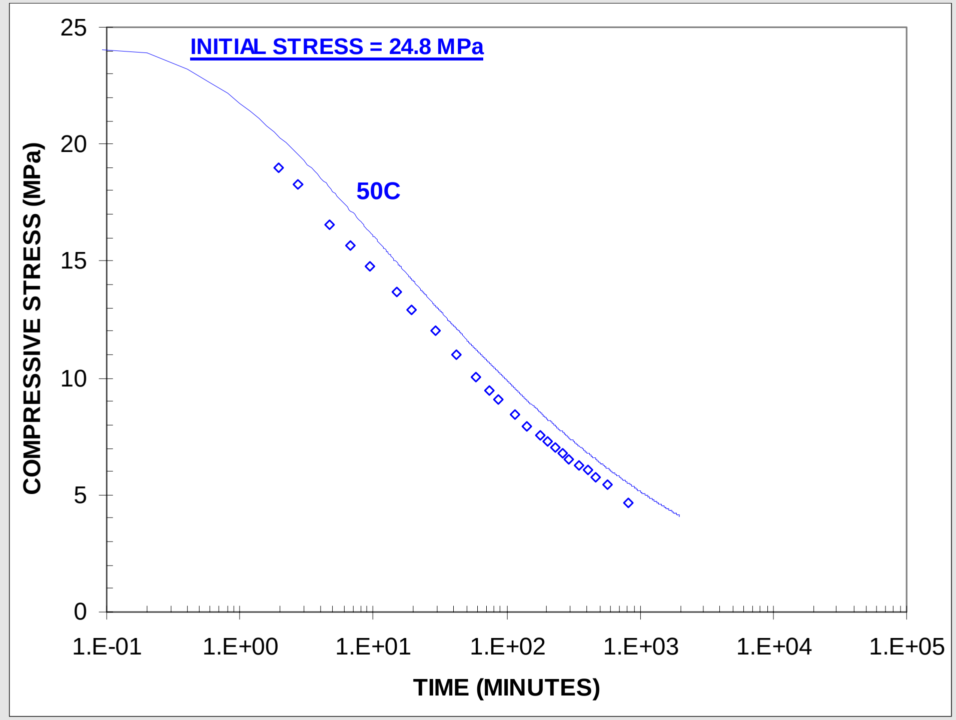


- **Sn40Pb tensile data**
  - From Whitelaw et al., 1999
- **Sn37Pb tensile data**
  - From Lu et al., 2002, SAND2000-8592 report (Sandia National Laboratories)
  - This example is not in the paper
  - Model is represented by solid lines

- **Creep rate model with no calibration factor**

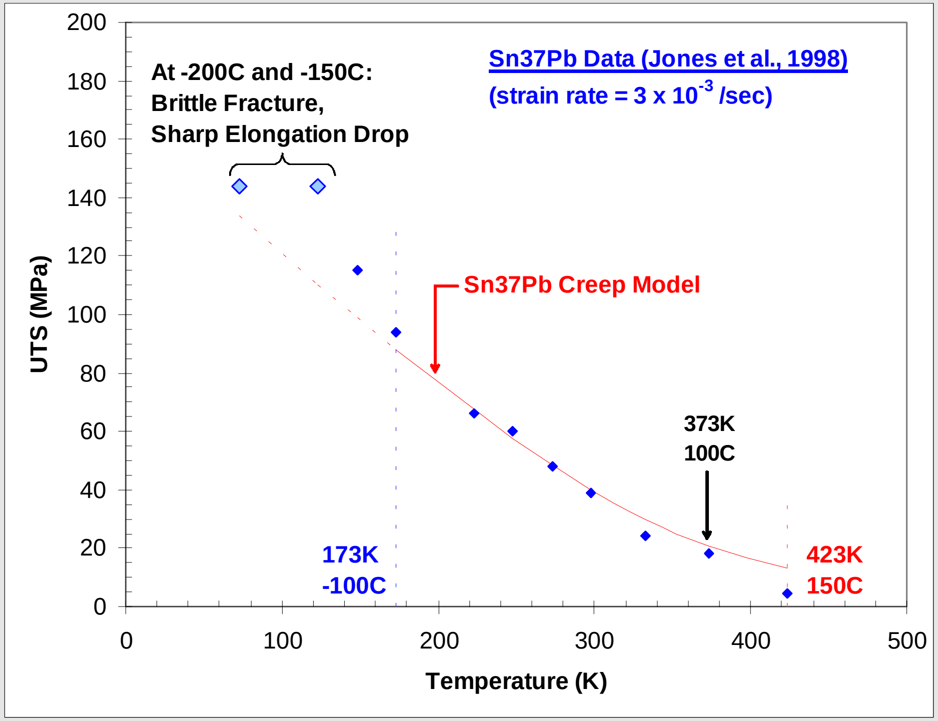
SnPb Model Test # 3: Stress Relaxation Data

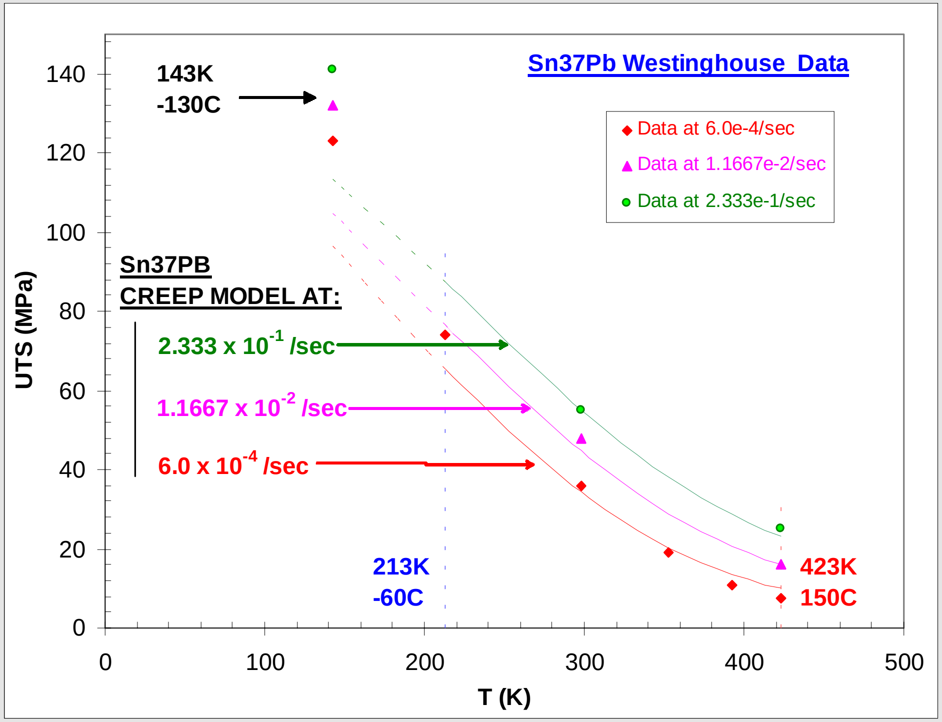




- **Sn40Pb data**
  - From Baker et al., 1973
    - Temperature: 27℃ to 108℃
    - Intitial stress: 6.89 MPa or 24.8 MPa
- **Creep rate model with calibration factor: C = 9 x 10^{-3} ~ 1/100**

SnPb Model Test # 4 & 5: Strength Data



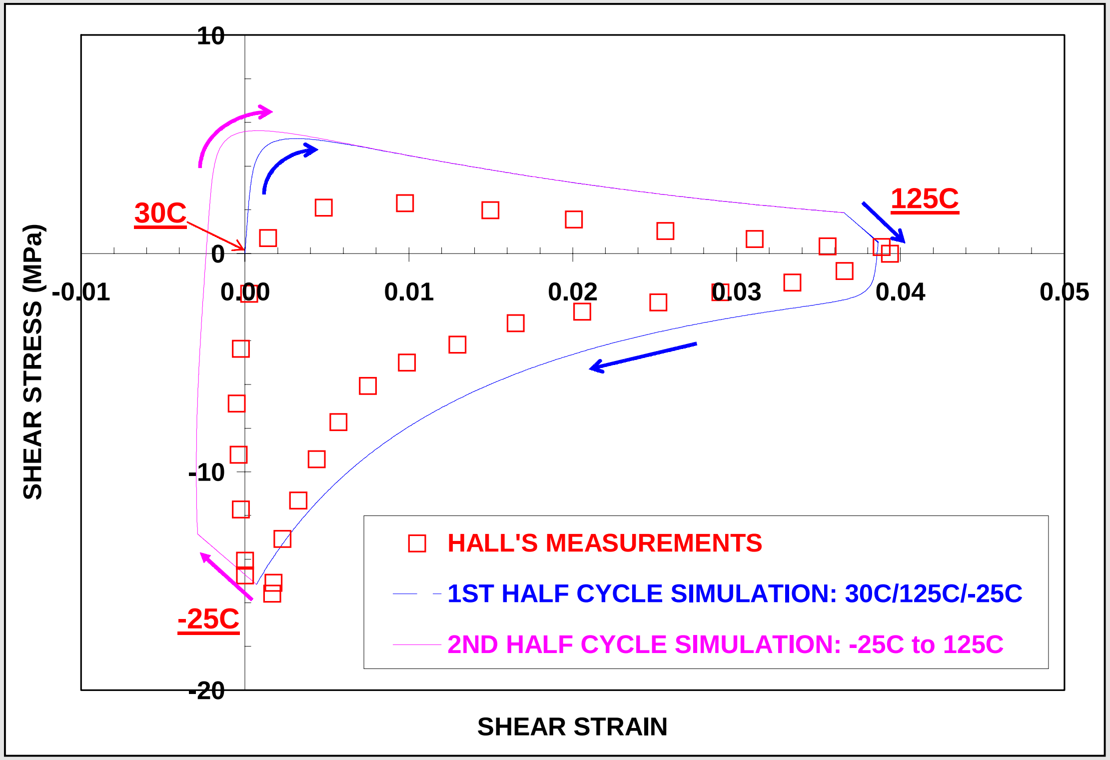


- **1 strain rate**
  - Temperature: -200℃ to 150℃

- **3 strain rates**
  - Temperature: -130℃ to 150℃

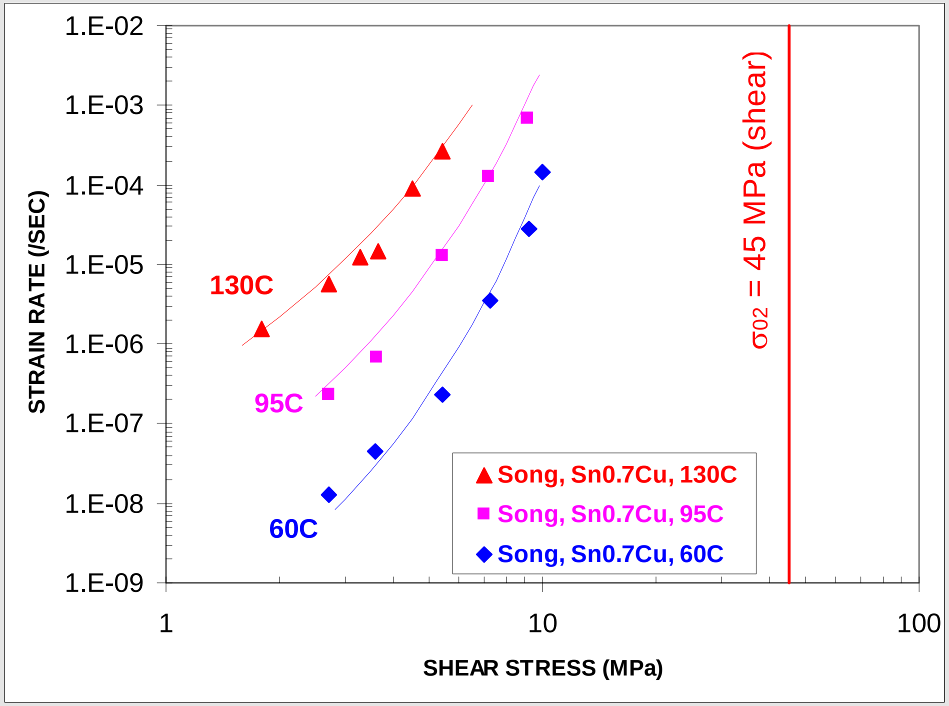
- **Strength (UTS) from creep rate model with no calibration factor**

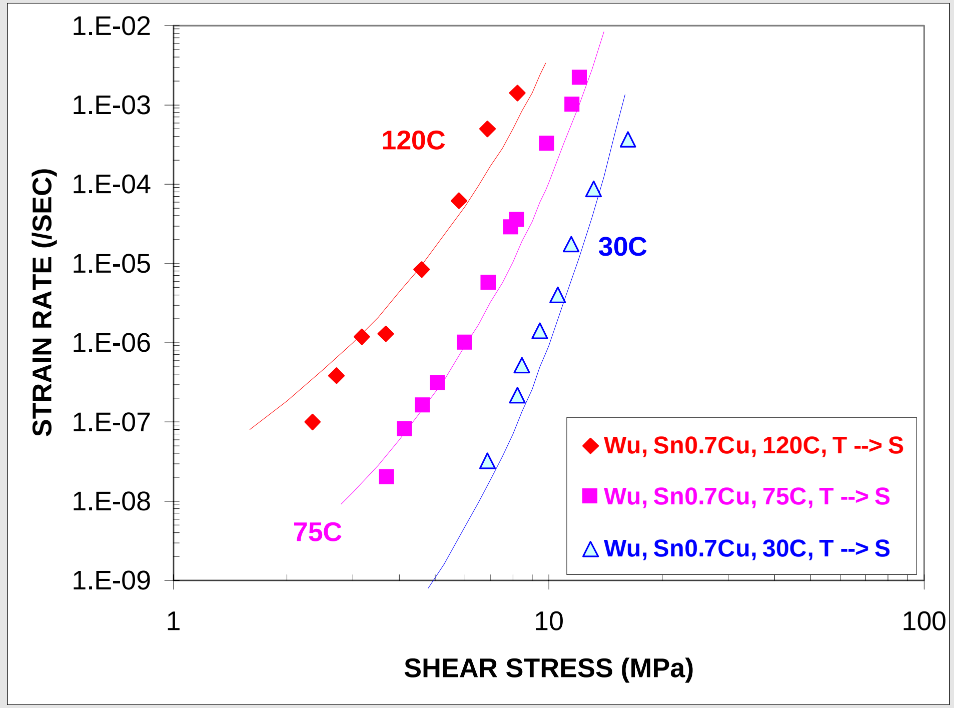
SnPb Model Test # 6: Thermal Cycling Hysteresis Loop



- **Sn40Pb data**
  - From Hall, 1984: -25℃ to 125℃ Thermal Cycling (5 hour ramps, 2 hour dwells)
- **Model lines: elastic deformation + steady-state creep only**
- **Used creep rate model with no calibration factor**

Sn0.7Cu: One-Cell Creep Model & Model Testing



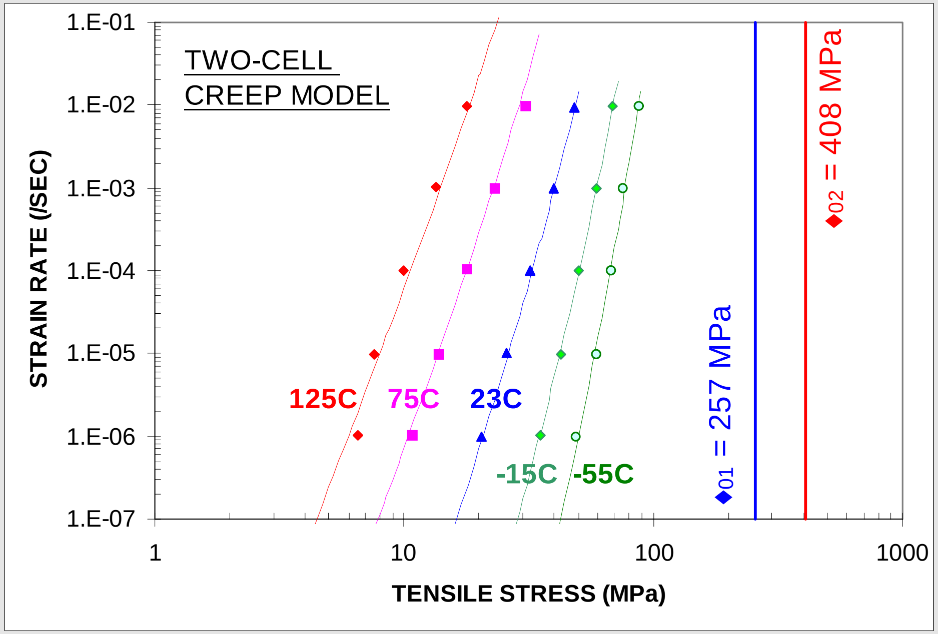


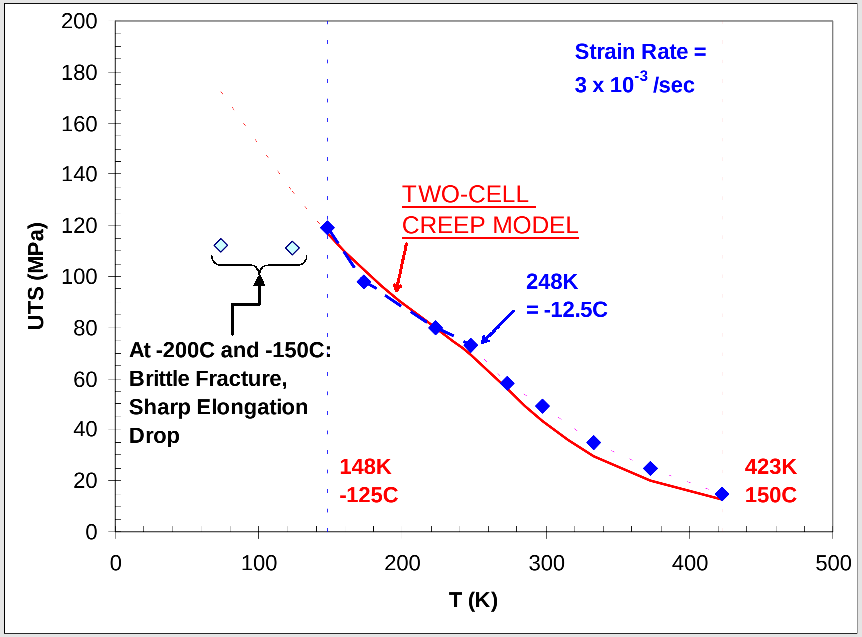
- **Model after Sn0.7Cu <u>shear creep</u> data**
  - From Song et al., 2002a
  - One-cell model:

$$\overset{\circ}{\gamma}(/\sec) = 2.23 \cdot 10^{8} \cdot \tau^{2.23} \cdot \exp\left[-\frac{14235}{T(K)}\left(1-\frac{\tau}{45.2}\right)\right]$$

- **Sn0.7Cu <u>tensile creep</u> data**
  - From Wu et al., 2002
  - Converted to shear (Von Mises)
- **Creep rate model with calibration factor C = 0.2**

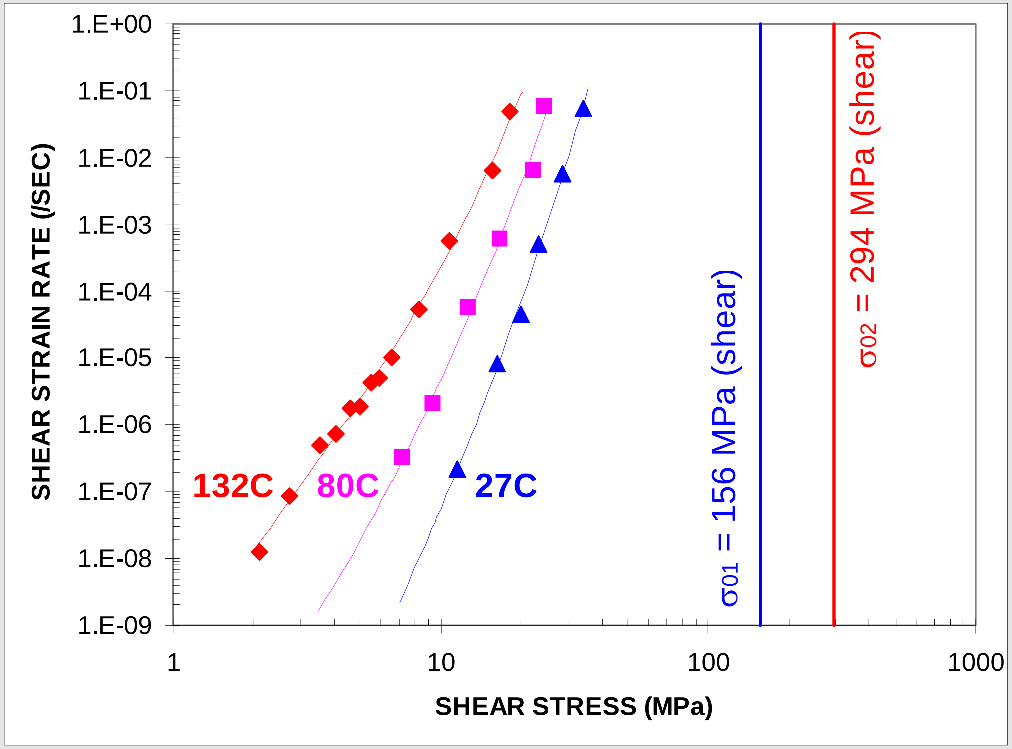
Sn4.0Ag: Two-Cell Creep Model & Model Testing





- Model after Sn4Ag **tensile strain-rate jump creep** data
  - From Neu et al., 2001
- Sn4Ag **strength** data
  - From Jones et al., 1998
- Predicted strength using creep rate model with no calibration factor

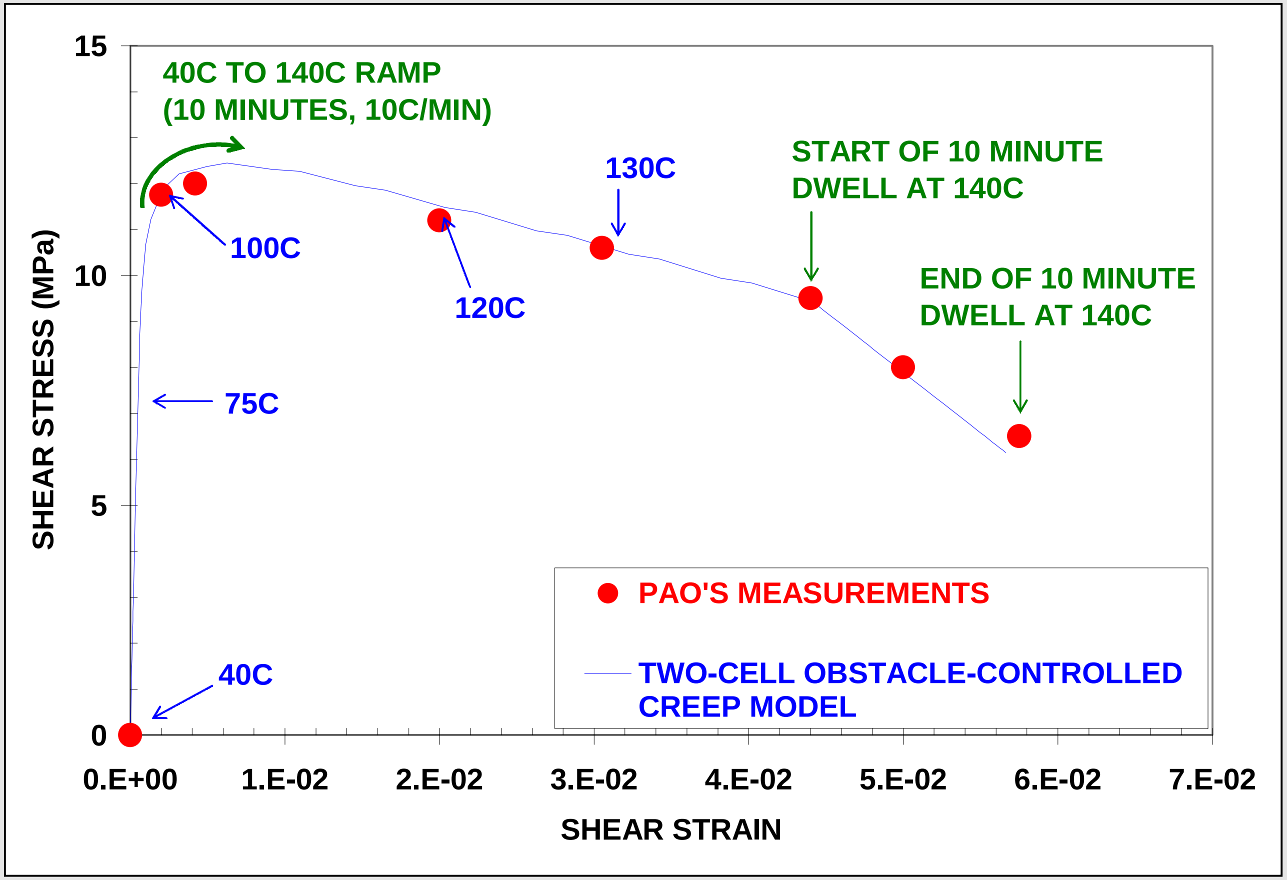
Sn3.5Ag Creep Model



- **Model after Sn3.5Ag <u>shear creep</u> data from shear testing of chip carrier solder joints**
  - From Darveaux et al., 1992

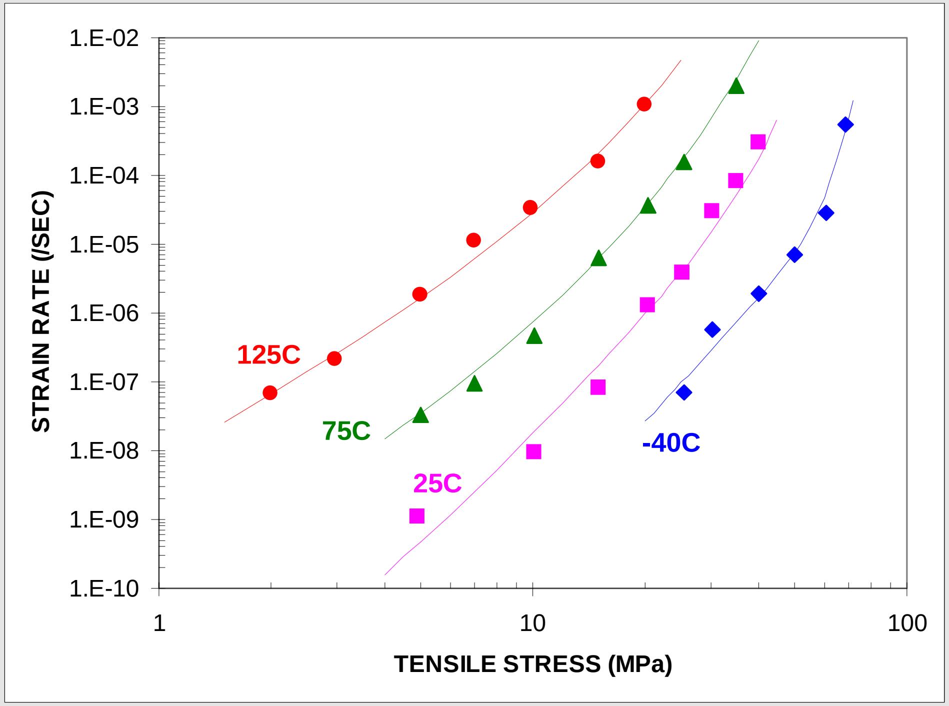
- **Two-cell model based on limited data: 27-132℃**
- **Nine test cases**
  - Tensile creep
  - Tensile strength
  - Compression creep
  - Shear creep (lap joint)
  - Shear creep of flip-chip joints
  - Shear strength
  - Thermal cycling stress/strain cycle
- **Need creep rate calibration factor for 4 test cases**

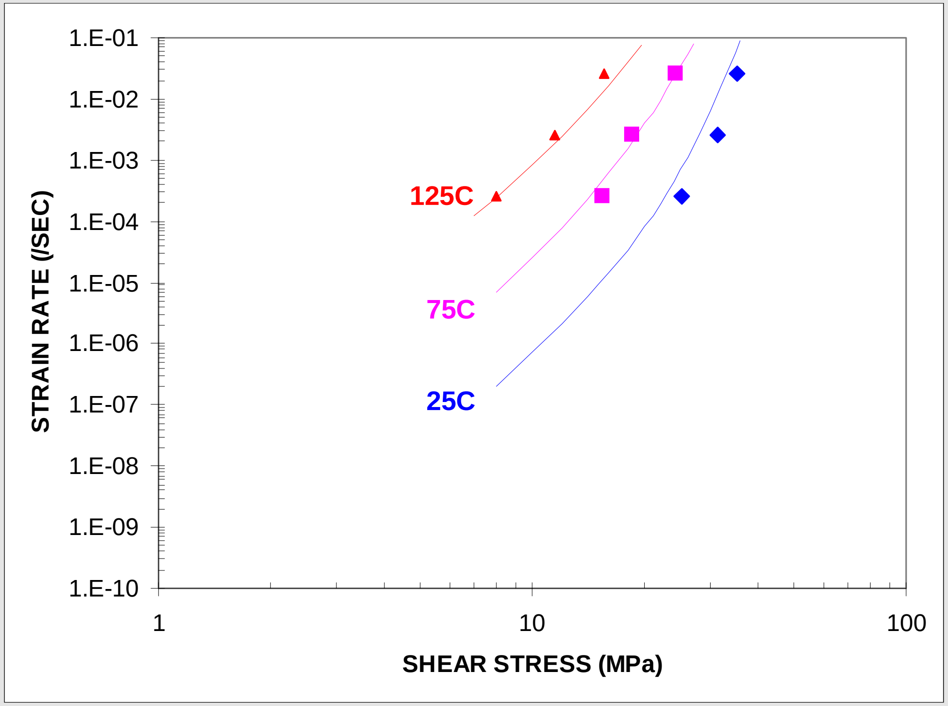
Sn3.5Ag Model Test: Thermal Cycling Data



- **Sn3.5Ag thermal cycling data**
  - From Pao, 1997
- **Creep rate model with calibration factor C = 22**

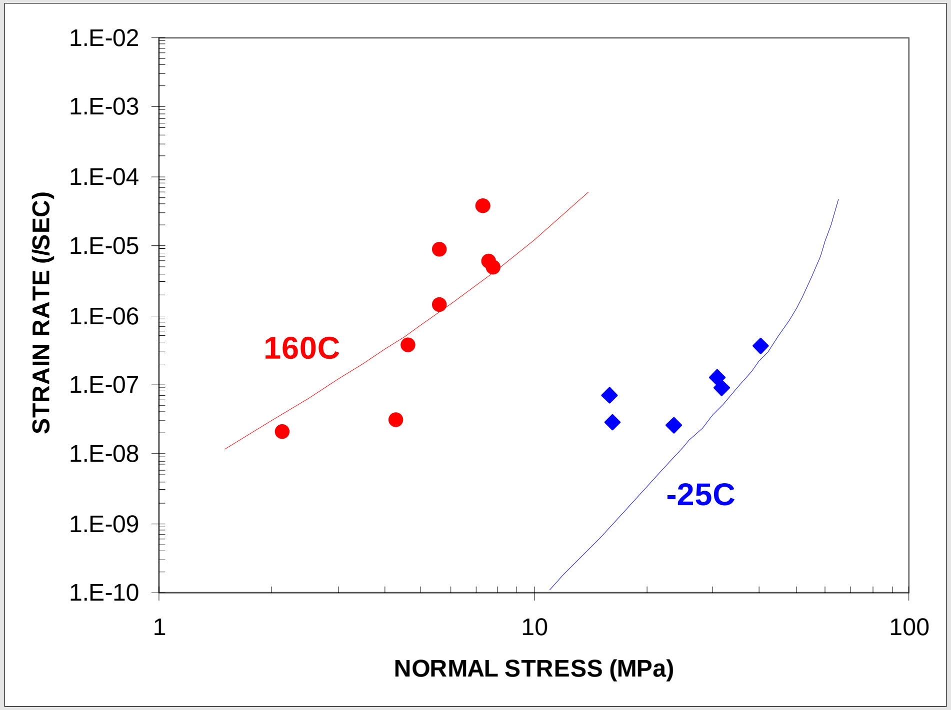
Sn3.8Ag0.7Cu Two-Cell Creep Model & Model Testing

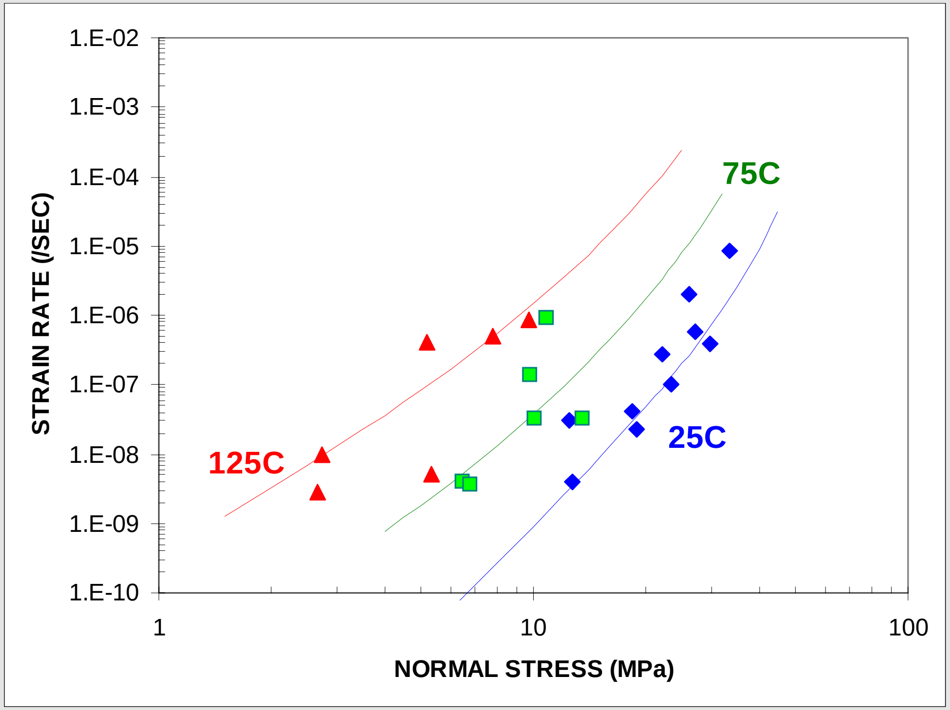




- **Model after Sn3.8Ag0.7Cu <u>tensile creep</u> data**
  - From Pang et al., 2004
- **Two-cell model**
  - 5 test cases
- **Sn3.8Ag0.7Cu <u>shear strength</u> data**
  - From Pang et al., 2003
- **From creep rate model with no calibration factor.**

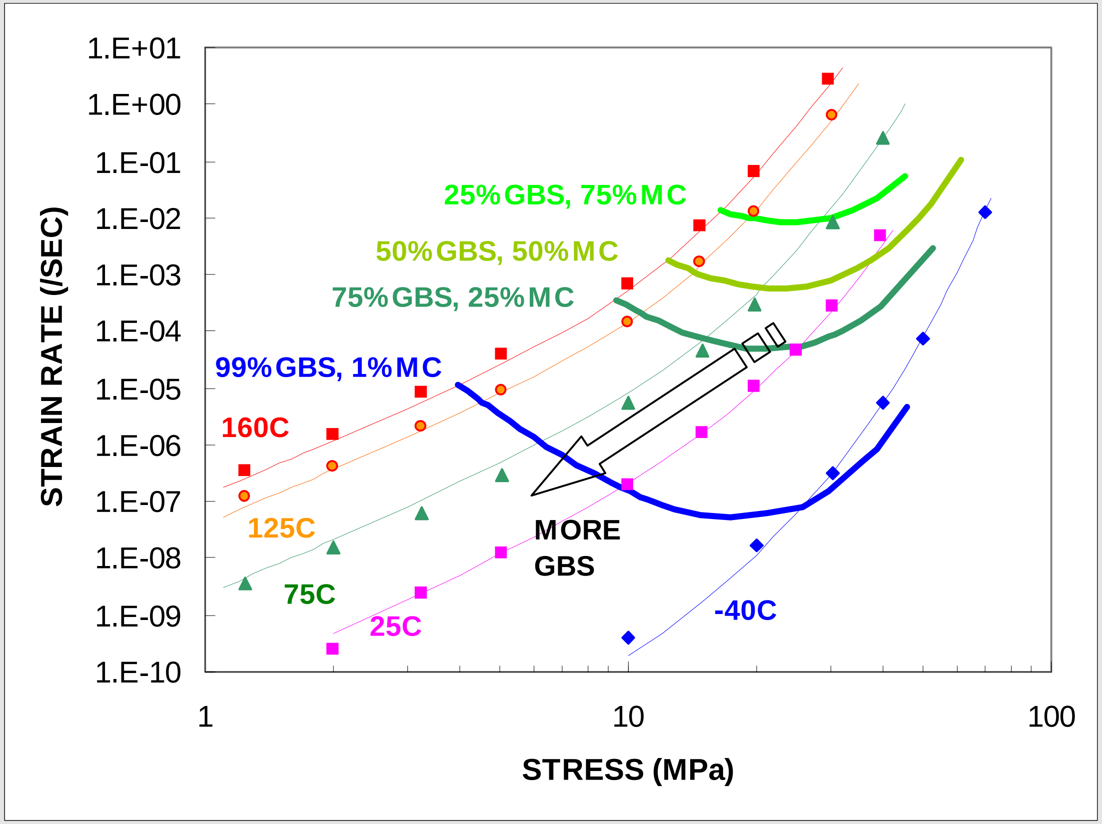
Sn3.8Ag0.7Cu Model Testing: Comparison to Sn3.9Ag0.6Cu Compression Creep Data





- **Sn3.9Ag0.6Cu compression creep data**
  - From Vianco, 2004
- **Comparison to Sn3.8Ag0.7Cu two-cell model**
  - **With model calibration factor C = 0.05**

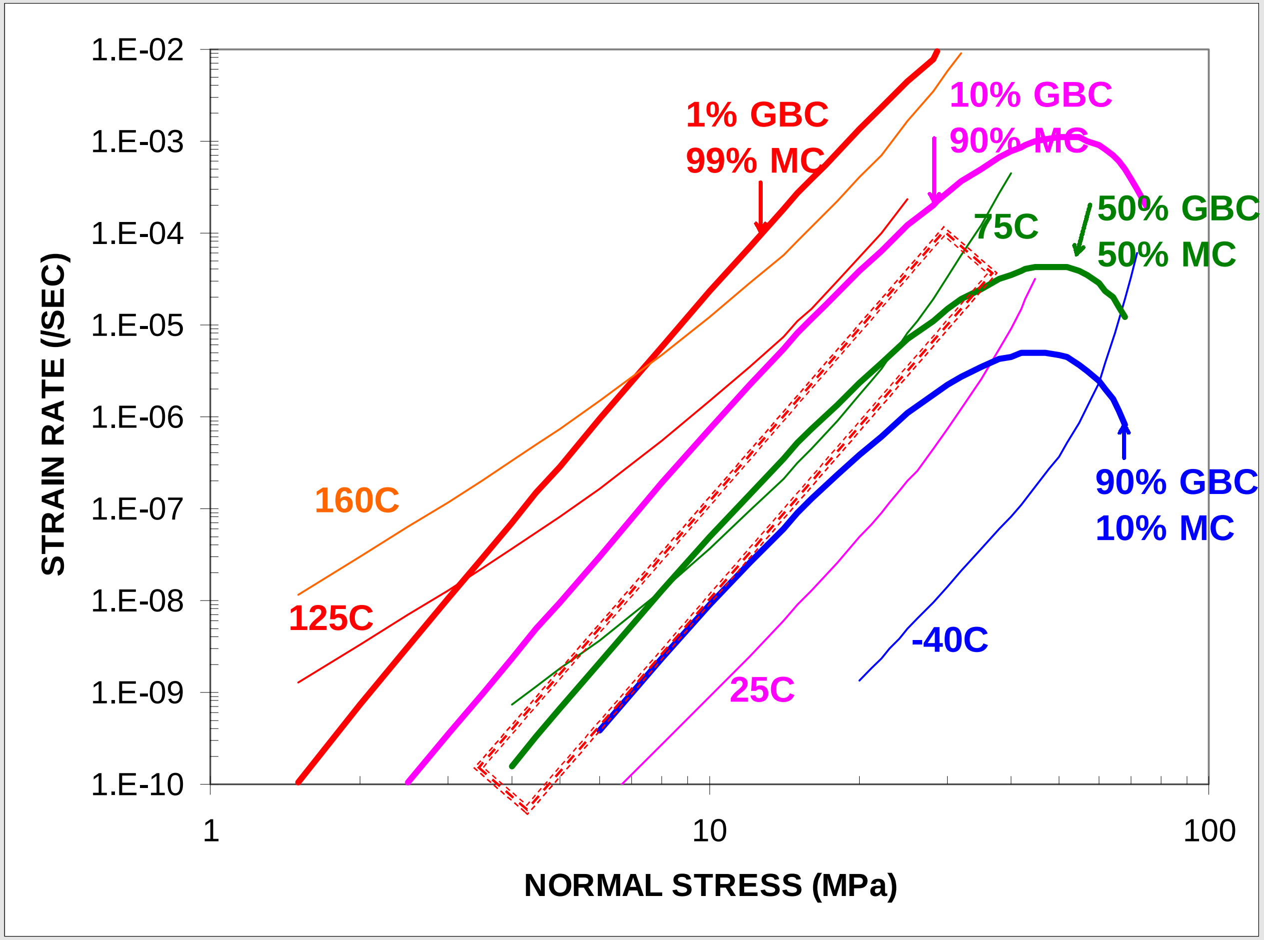
Sn37Pb Creep Mechanism Contours



- **Creep mechanism contour lines predict “75% GBS, 25% MC” transition at stresses < 10 MPa and temperatures from -40℃ to 160℃**
  - **GBS is dominant mechanism**
  - **Agrees with creep contour charts by Grossman, 2002**

- Isothermal creep rate lines as in Slide # 9
- GBS = Grain Boundary Sliding; MC = Matrix Creep

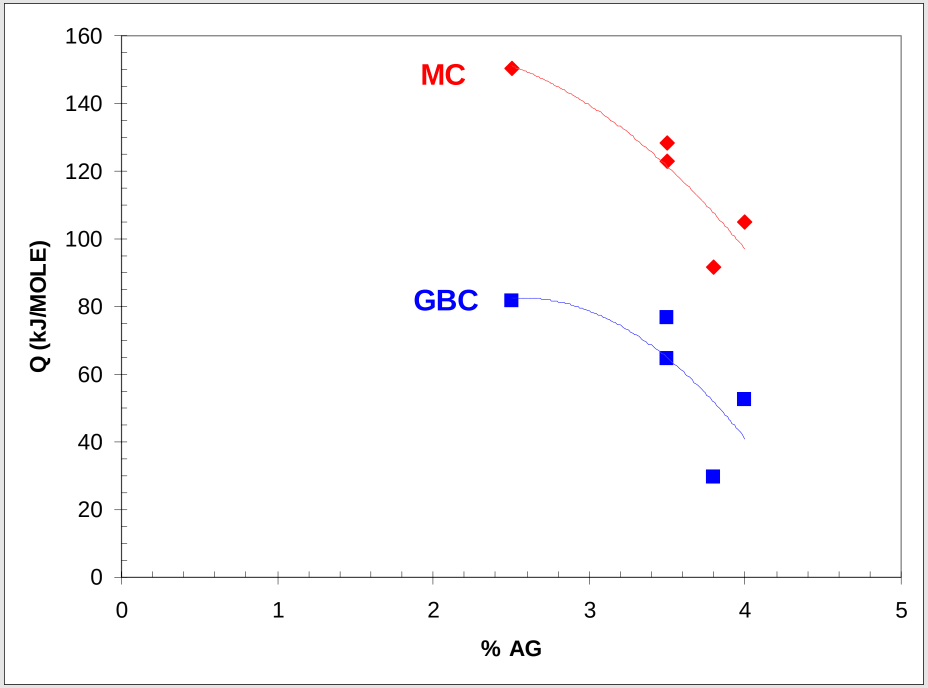
Sn3.9Ag0.6Cu Creep Mechanism Contours: A Very Different Pattern

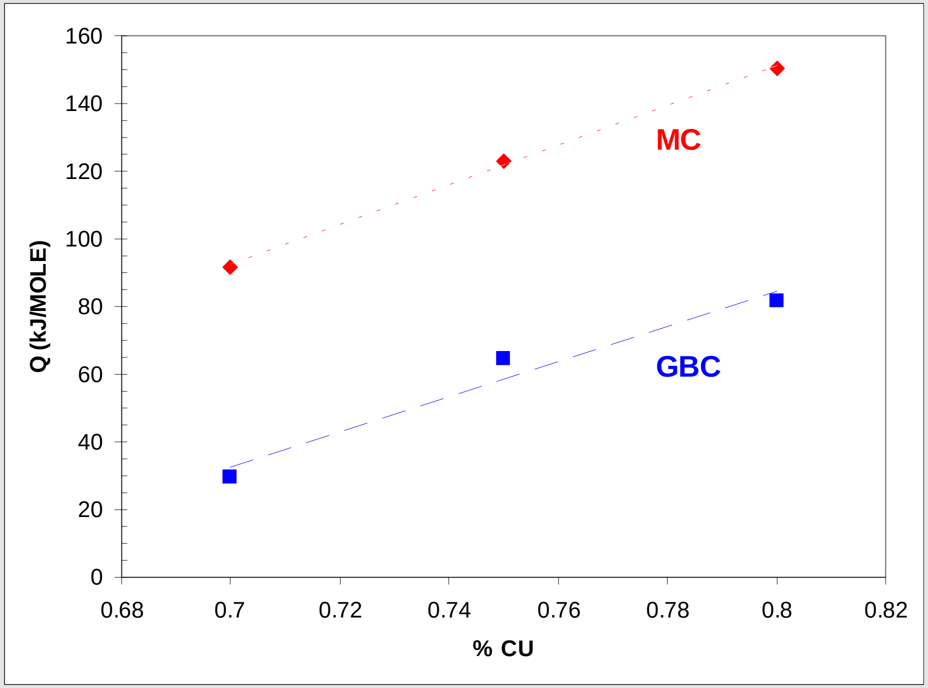


- **Creep mechanism contour lines predict "50% GBC, 50% MC" transition at about 75℃ (for stresses below 30 MPa)**
- **Agrees with creep rate and micro-structural analysis by Vianco, 2004**

- Isothermal creep rate lines with calibration factor (C = 0.05) to match Sn3.9Ag0.6Cu compression creep data as in slide # 19

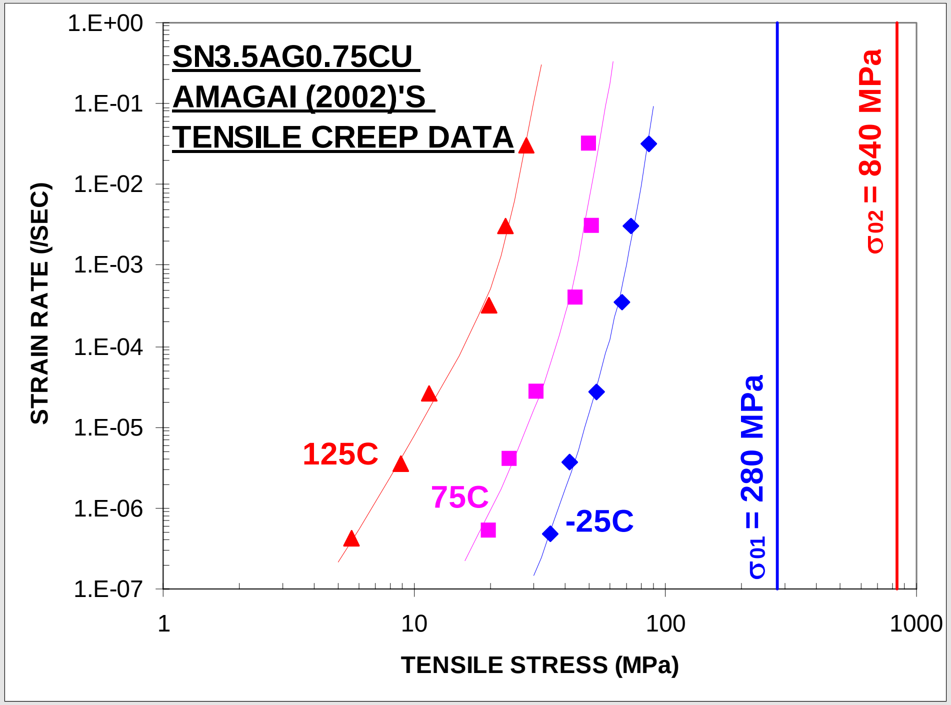
Effect of Alloy Composition on Creep Activation Energy

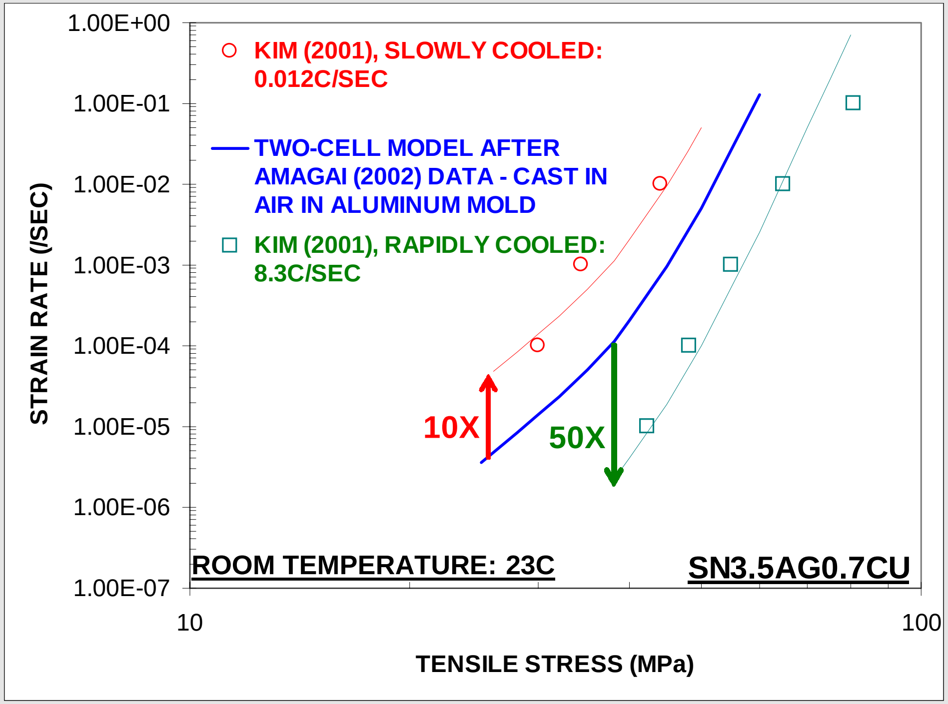




- **Effect of %wt. Ag (range 2.5-4.0%) on apparent creep activation energies of Sn-Ag and Sn-Ag-Cu alloys**
- **Effect of %wt. Cu (range 0.7-0.8%) on creep activation energies of Sn-Ag-Cu alloys**
  - There may be %wt. Ag confounding effects

What About Calibration Factors?





- **Sn3.5Ag0.7Cu creep model: data for ingot air-cooled in Aluminum mold**
- **Compare creep model to Sn3.5Ag0.75Cu strength data:**
  - C = 10 for slowly cooled samples
  - C = 1/50 for rapidly-cooled samples

- **Calibration Factors (CFs) depend on many factors: microstructure, specimen size ….**
  - Example to the right shows that CFs are dependent on cooling rate.

Conclusions

- **The application of classical creep models to lead-free solders has led to many anomalies**
- **The obstacle-based creep models offer a promising alternative to describe the stress and temperature dependence of minimum creep rates of lead-free solders**
  - Models should be fit to creep data covering the largest temperature range of interest (e.g. -55℃ to 160℃ for SnAgCu)
- **Whatever model is used, test it against many independent results**
  - Verify model applicability to real solder joints.
  - Calibration factors may be needed.
- **Primary and tertiary creep of lead-free solders deserve as much attention**

THANK YOU FOR YOUR ATTENTION

QUESTIONS OR COMMENTS?