An Extension of the Omega Method to Primary and Tertiary Creep of Lead-Free Solders

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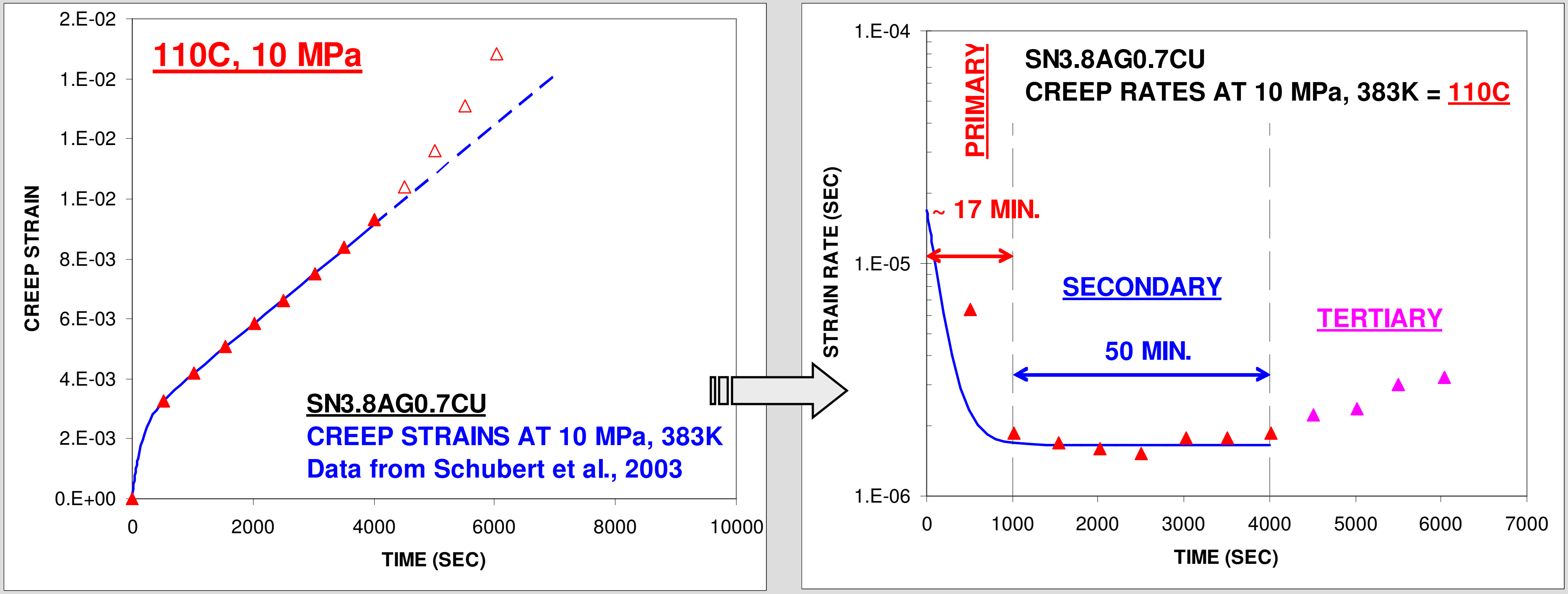
Objective

- **Reliable constitutive models are needed:**
  - For solder joint stress/strain analysis
  - To develop acceleration factors and life prediction models

- **This study investigates the importance of primary and tertiary creep for lead-free solders**

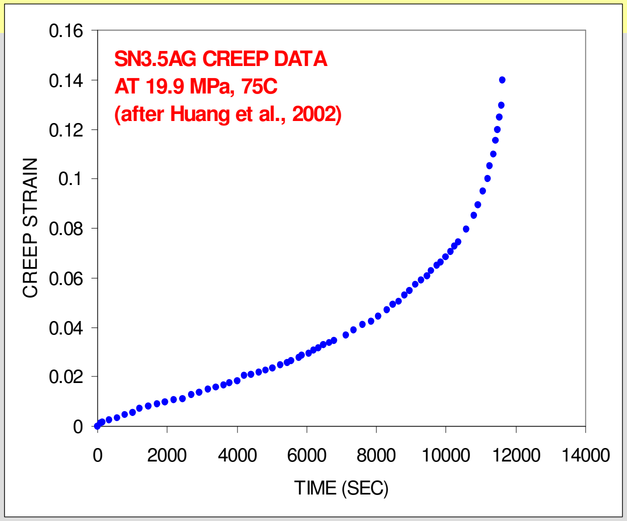
Classical Analysis of Creep Curves: Example: Creep of Sn3.8Ag0.7Cu at 110˚C

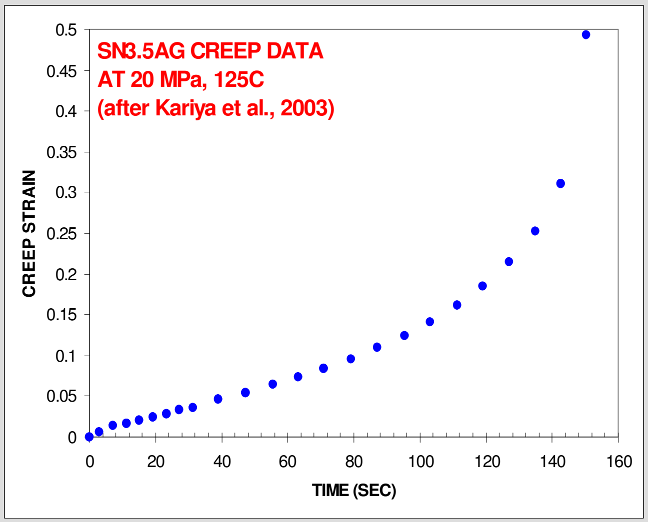


- **Primary creep at 110˚C: ~ 17 MINUTES**
  - In accelerated testing, primary creep may dominate
- **Secondary creep at 110˚C: ~ 50 MINUTES**
  - Could also say 0 minute if using the very lowest creep rate

<u>Log-Linear</u> Plots of Strain Rates vs. Strain

RAW DATA (CREEP CURVES)





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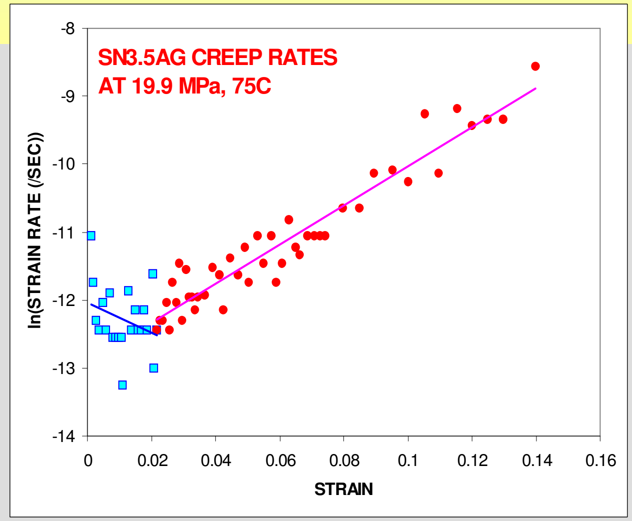
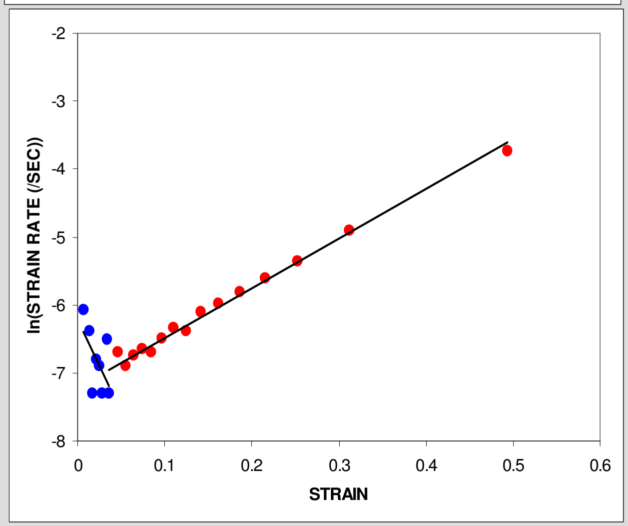
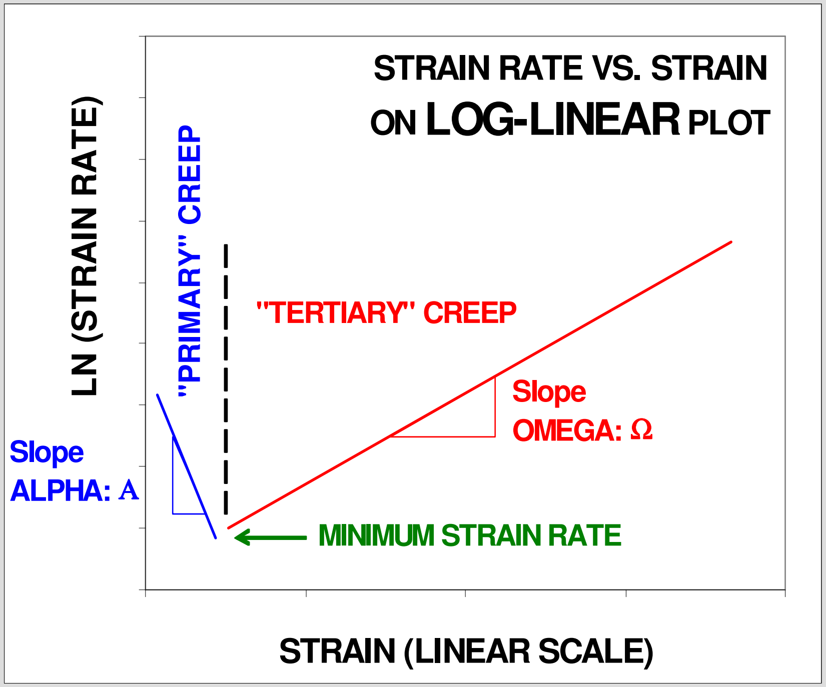




- <u>LOG-LINEAR</u> plots of STRAIN RATES VS. STRAIN highlight regions of decreasing and increasing rates

The Extended Ω Method



- **"Primary" stage:** $\ln(\overset{\circ}{\varepsilon}) = -\mathrm{A} \cdot \varepsilon + C_1$

$$\overset{\circ}{\varepsilon} = a \cdot e^{-\mathrm{A} \cdot \varepsilon}$$

- **"Tertiary" stage:** $\ln(\overset{\circ}{\varepsilon}) = \Omega \cdot \varepsilon + C_3$

$$\overset{\circ}{\varepsilon} = b \cdot e^{\Omega \cdot \varepsilon}$$: Ω method

(Prager, 2000)

- **Combined creep rate:**

HARDENING **SOFTENING**

$$\overset{\circ}{\varepsilon} = a \cdot e^{-\mathrm{A} \cdot \varepsilon} + b \cdot e^{\Omega \cdot \varepsilon}$$

Some Properties Of The $\mathrm{A}-\Omega$ Model: Primary Creep Region

- **In the early stages of creep, "primary" creep dominates, and for small strains, the model reduces to:**

$$\overset{\circ}{\varepsilon} \approx a \cdot e^{-\mathrm{A} \cdot \varepsilon} \approx a \cdot (1 - \mathrm{A} \cdot \varepsilon)$$

  - "a" is the initial strain rate at time t = 0
  - The integration of the approximate equation gives:

$$\varepsilon = \frac{1}{\mathrm{A}}\left[1 - e^{-(\mathrm{A} \cdot a)t}\right] \qquad \varepsilon_{SAT} = 1/\mathrm{A}$$

  which is the Pao-Marin (1957) primary creep model

    - **The primary creep saturation strain is the inverse of ALPHA**

Some Properties Of The A–Ω Model: Tertiary Creep Region

- **When "tertiary" creep dominates:** $\overset{\circ}{\varepsilon} \approx b \cdot e^{\Omega \cdot \varepsilon}$

  - The extended Ω model reduces to the OMEGA method (Prager, 2000)

  - The above equation is easily integrated (Prager, 2000)

$$e^{-\Omega \cdot \varepsilon} - e^{-\Omega \cdot \varepsilon_f} = \Omega \overset{\circ}{\varepsilon}_0 \cdot (t_r - t)$$

where t_r is the creep rupture time and ε_f is the creep ductility

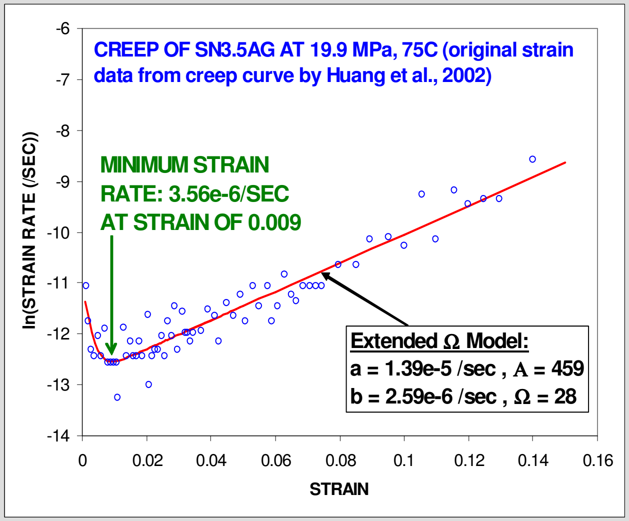
  - When $t << t_r$, ε is small (ε -> 0), and if ε_f is large, the above solution leads to the Monkman-Grant relationship for creep rupture times:

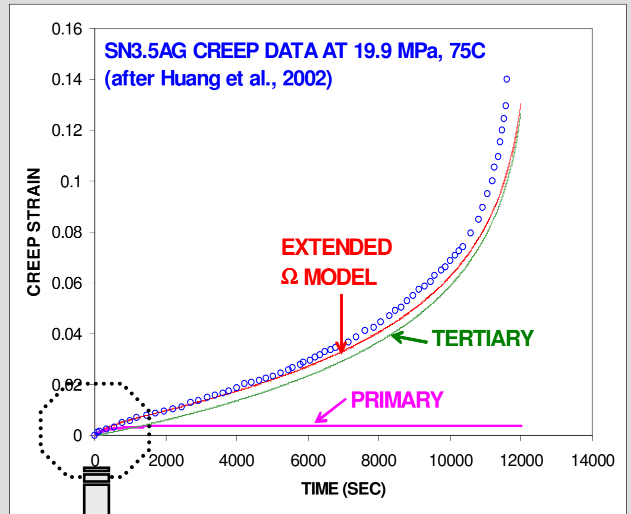
$$t_r \cdot \overset{\circ}{\varepsilon}_{MIN} \approx 1/\Omega$$

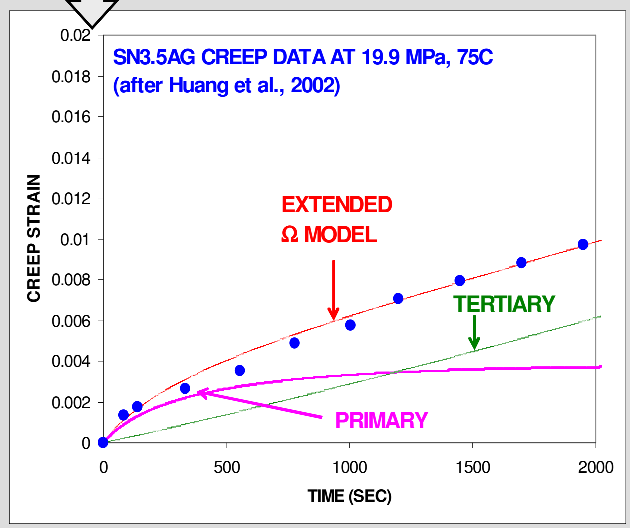
Ω is a damage parameter since it predicts rupture times

Use of the A–Ω Creep Model: Ex. # 1
Sn3.5Ag at 19.9 MPa, 75˚C

- **Curve-fit strain-rate & strain data**







- **From constitutive model parameters, predict rupture time!**

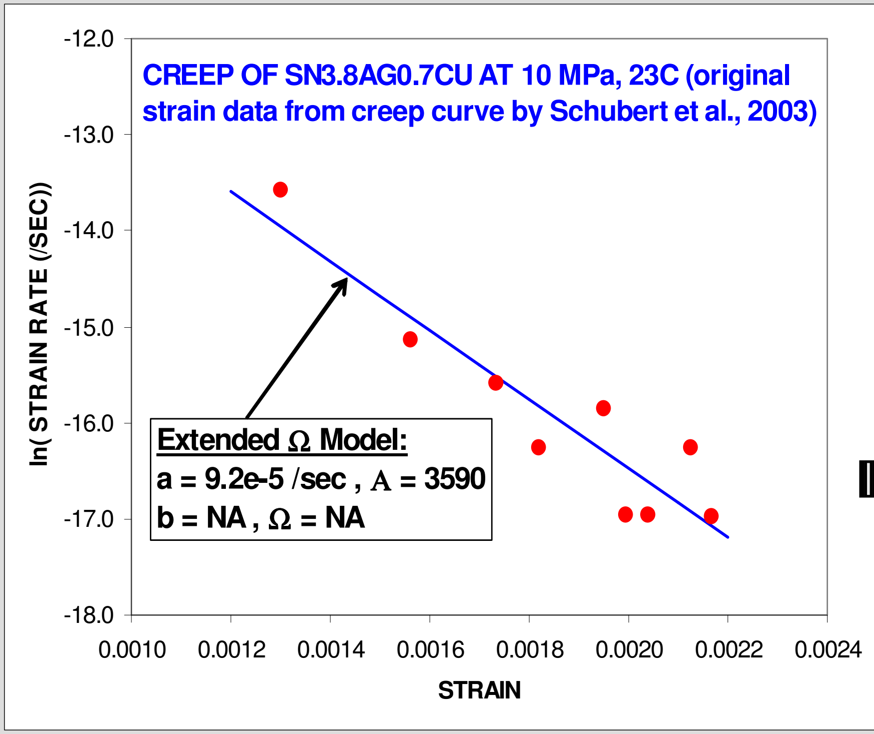
$$t_r \cdot \overset{\circ}{\varepsilon}_{MIN} \approx 1/\Omega$$

$$t_r \cdot (3.56\times10^{-6}) = 1/28 \Rightarrow t_r = 10{,}032$$

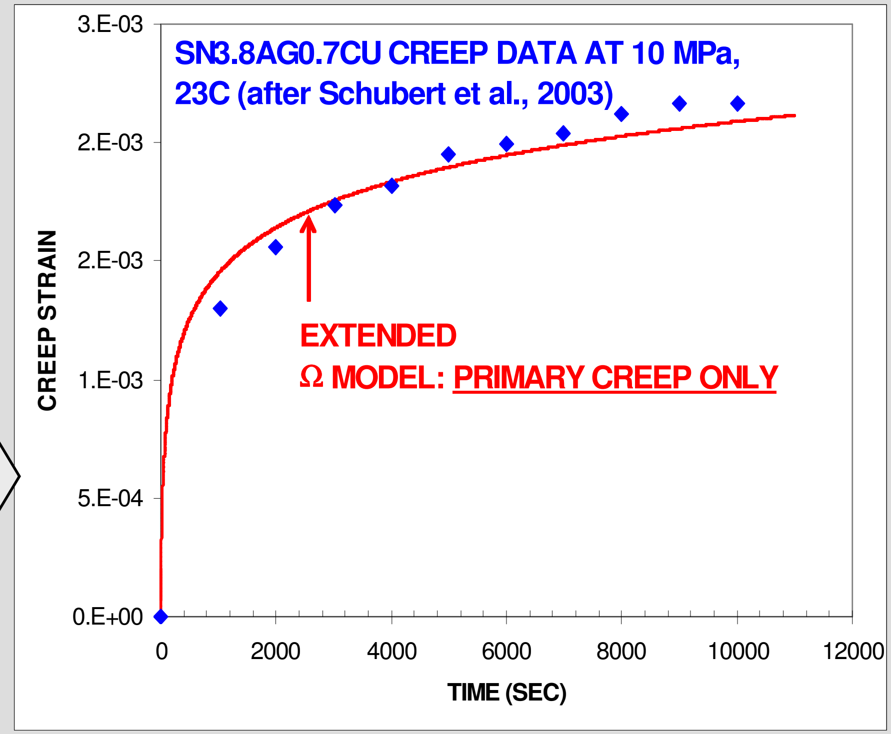
  - 14% less than t_r ~ 11607 seconds from actual creep curve

Use of the A–Ω Creep Model: Ex. # 2 Sn3.8Ag0.7Cu at 10 MPa, 23˚C

- **Curve-fit strain-rate & strain data**



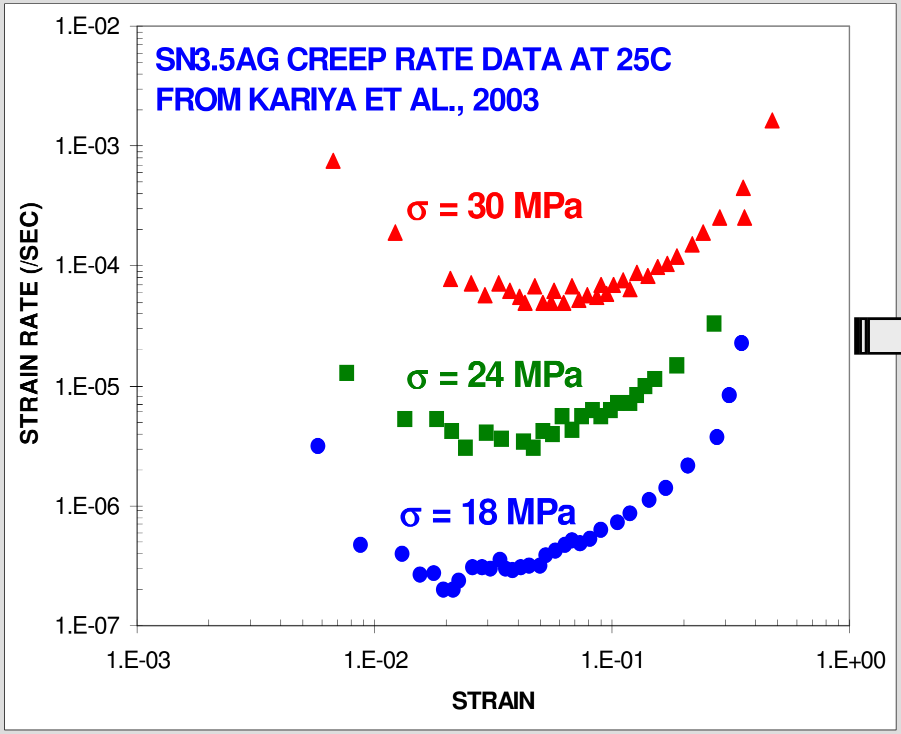
- **Creep Curve Predictions**

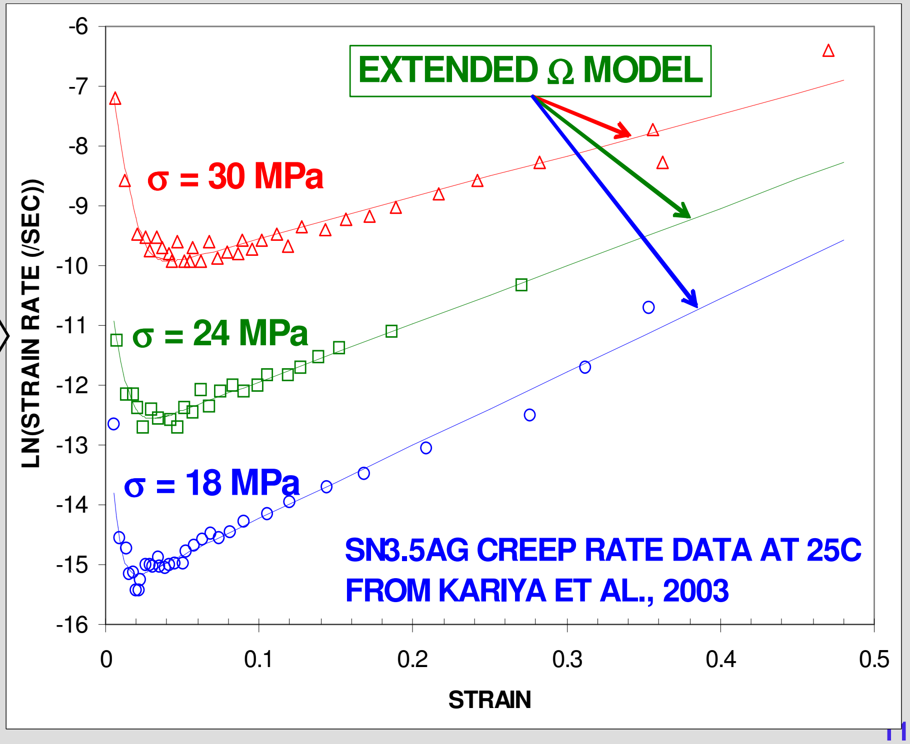


- **In this example, log-linear plot of strain rate vs. strain data only shows primary creep**

Stress-dependence Of Parameters Α & Ω
Ex. # 1: Sn3.5Ag

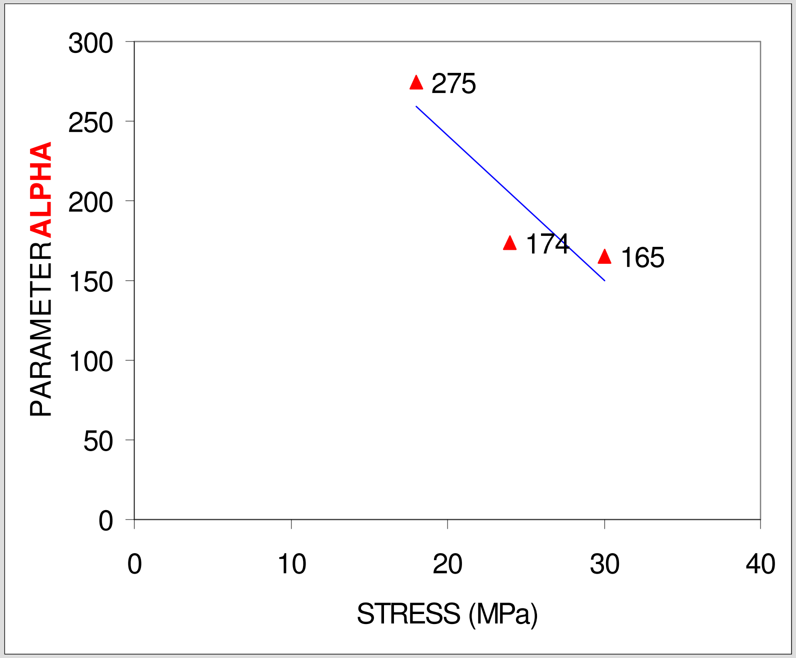
- **Original strain rate vs. strain data on log-log plot**
  - Start and end of secondary creep stage are not well-defined
- **Strain rate vs. strain data on log-linear plot, and fit of extended Ω model**
  - Shows a sharper transition from hardening to softening

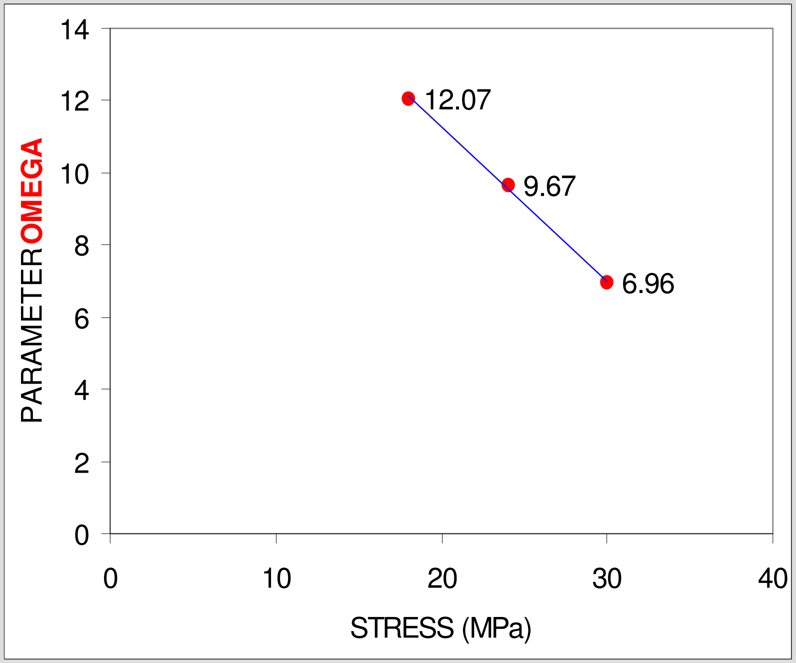




Stress-dependence Of Parameters Α & Ω
Ex. # 1: Sn3.5Ag (cont'd)

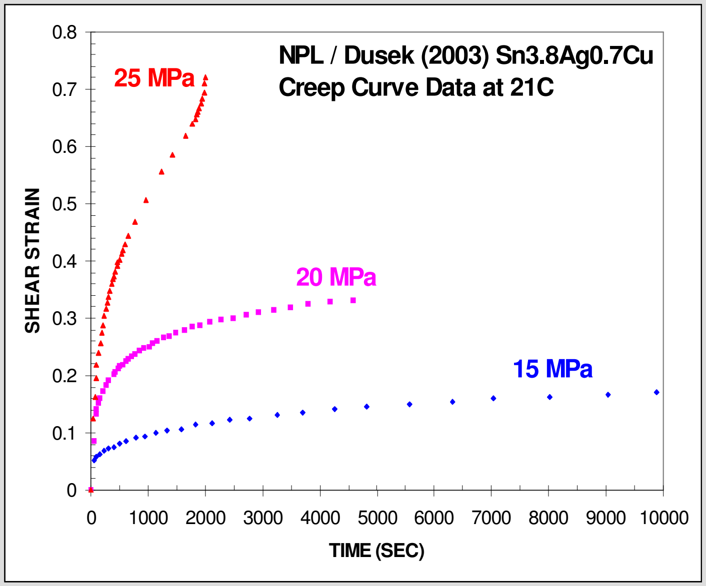
- **Stress-dependence of ALPHA (Α) and OMEGA (Ω) for Sn3.5Ag at 25˚C (from fitting of extended Ω model to Kariya's data on previous slide)**





- **Stress-dependence of Α and Ω is linear in given stress range**

Stress-dependence Of Parameters Α & Ω
Ex. # 2: Sn3.8Ag0.7Cu in Shear



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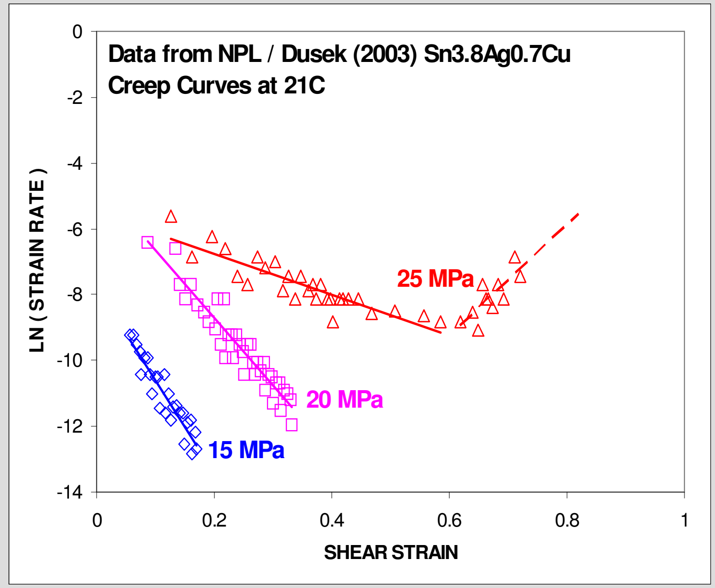

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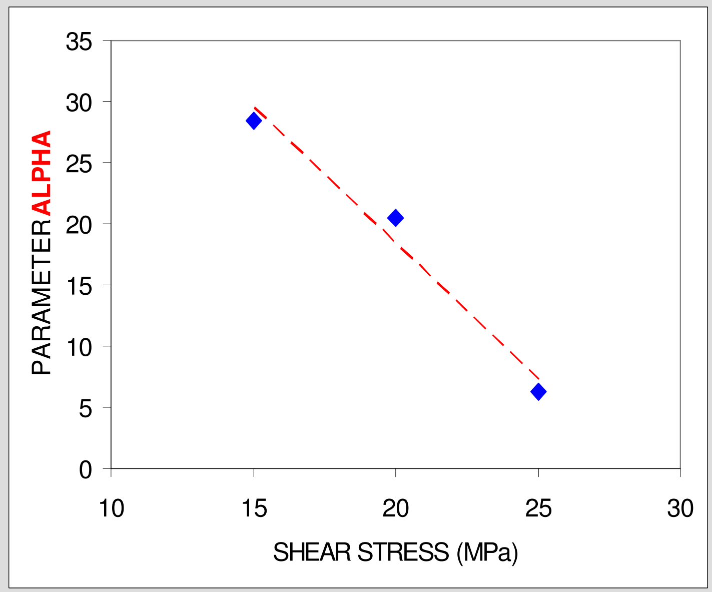
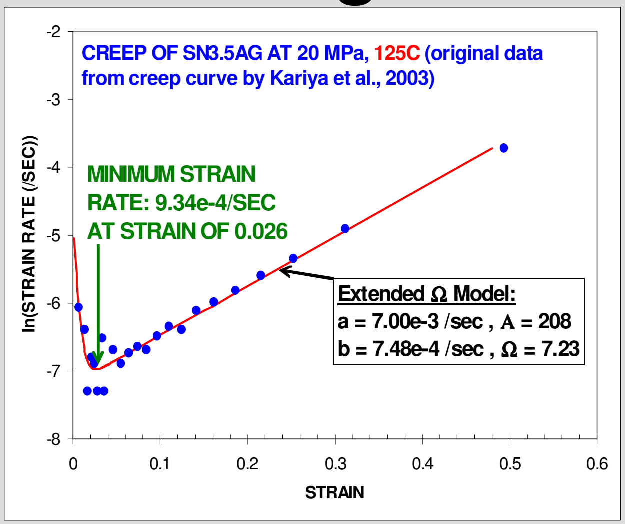
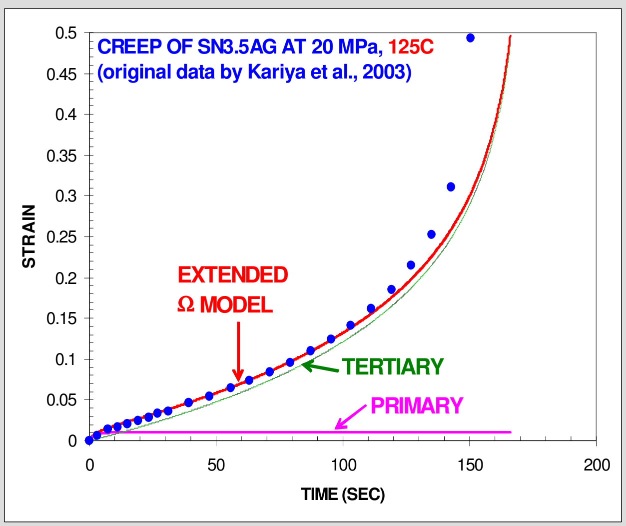


- **For Sn3.8Ag0.7Cu in shear at 21˚C, ALPHA (Α) has a linear stress-dependence in given stress range**

Temperature Dependence OF A & Ω

- **Sn3.5Ag at 125˚C**



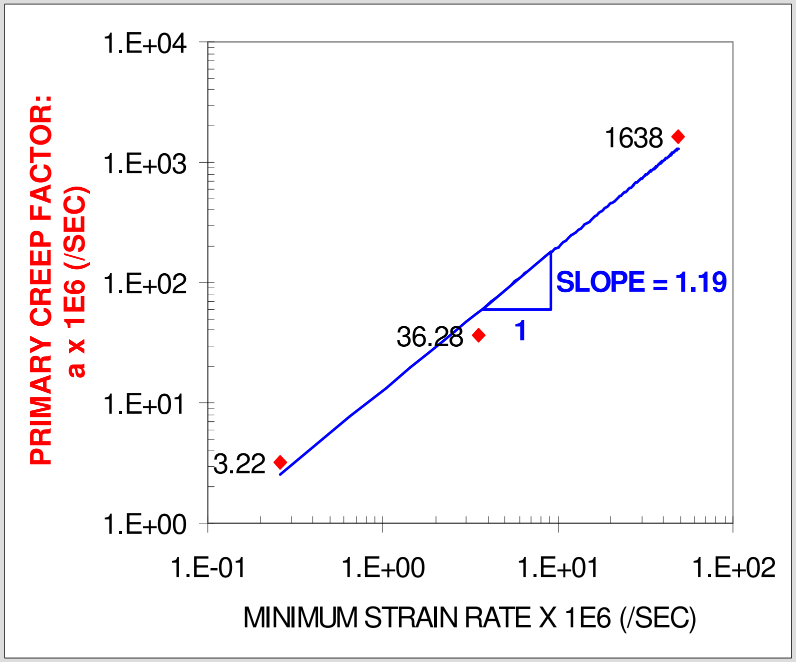


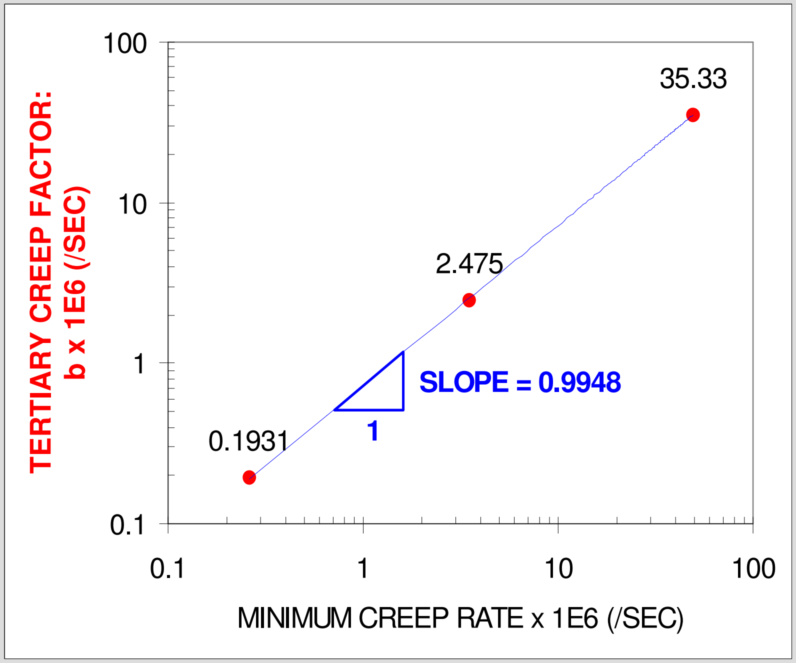
Sn3.5Ag (Kariya, 2003):

- At 25˚C & 20 MPa:
  - **A ~ 241, Ω ~ 11**
- At 125˚C & 20 MPa:
  - **A = 208, Ω = 7.23**
- **A and Ω have weak temperature-dependence (compared to the effect of temperature on minimum creep rates)**

Creep Rate Factors a and b vs. Minimum Strain Rate

- Creep rate factors a and b vs. minimum strain rate for Sn3.5Ag at 25˚C (from fitting of extended Ω model to strain rate vs. strain data)





- **As expected:**
  - a has an almost linear dependence on minimum creep rates
  - b has a linear dependence on minimum creep rates

The A–Ω Creep Model: Summary

- **For Sn-based solders:** $\overset{\circ}{\varepsilon} = a \cdot e^{-A \cdot \varepsilon} + b \cdot e^{\Omega \cdot \varepsilon}$

  - a and b $\propto \overset{\circ}{\varepsilon}_{MIN}$
  - The minimum creep rate, determined by "steady-state" creep models, is a strong function of stress and temperature
  - A = A(σ, T) and Ω = Ω(σ, T) have a weak dependence on stress, σ, and temperature, T
    - "WEAK" is in comparison to the much larger effect of stress and temperature on minimum creep rates
    - A and Ω decrease with increasing stress and/or temperature

Conclusions

- Primary and tertiary creep of lead-free solders are important
- Extended Ω model captures both and allows for prediction of entire creep curves

THANK YOU FOR YOUR ATTENTION