

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

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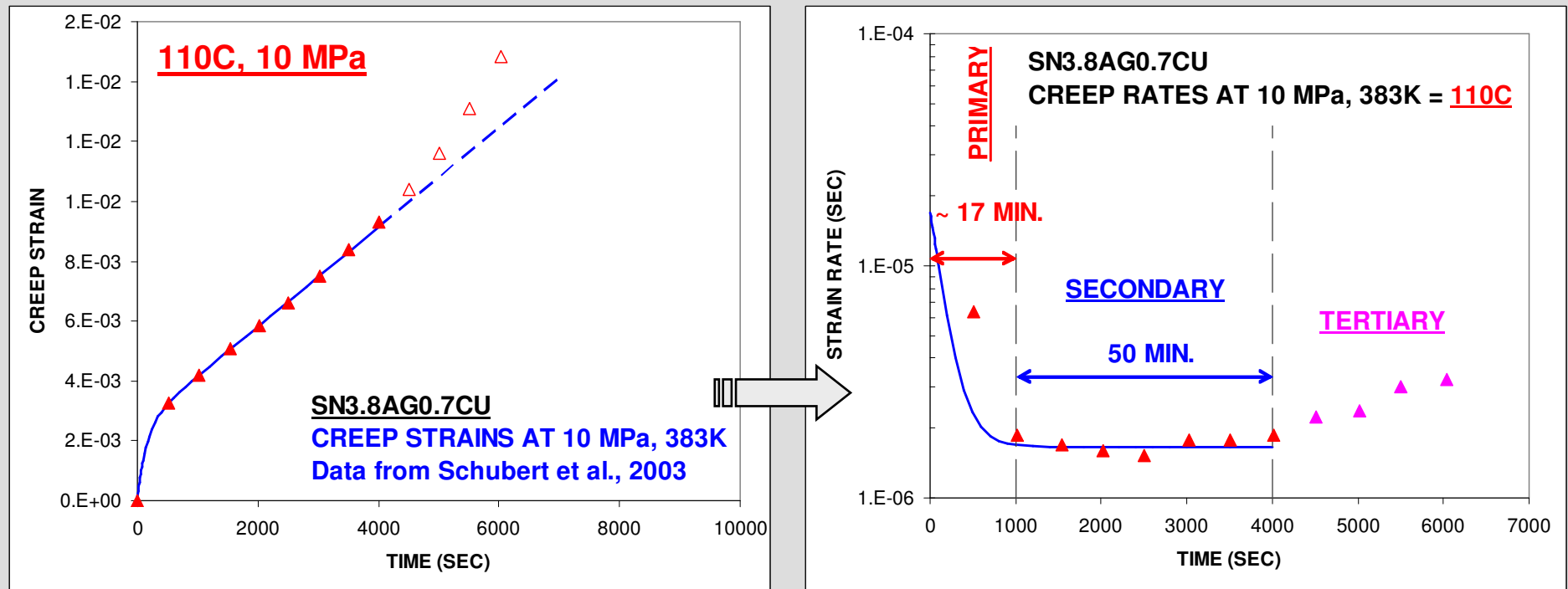
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Objective

- **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**

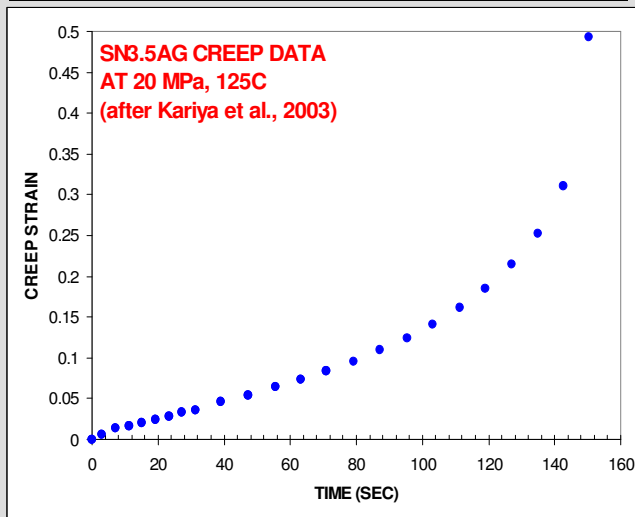
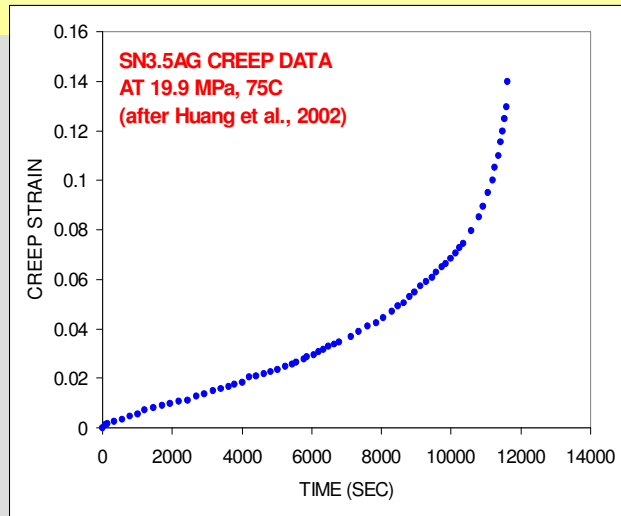
Classical Analysis of Creep Curves: Example: Creep of Sn3.8Ag0.7Cu at 110°C



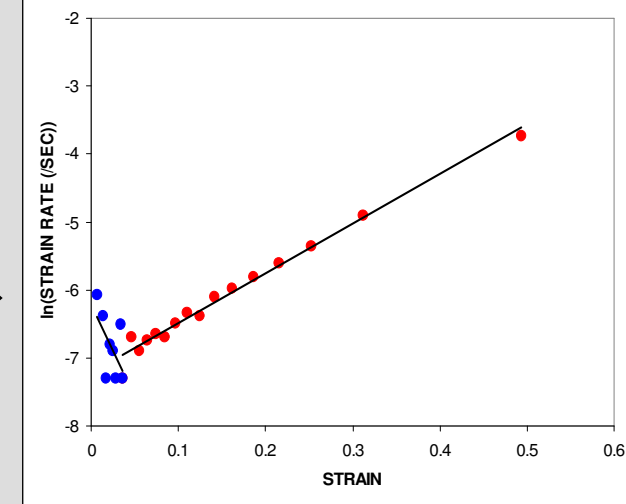
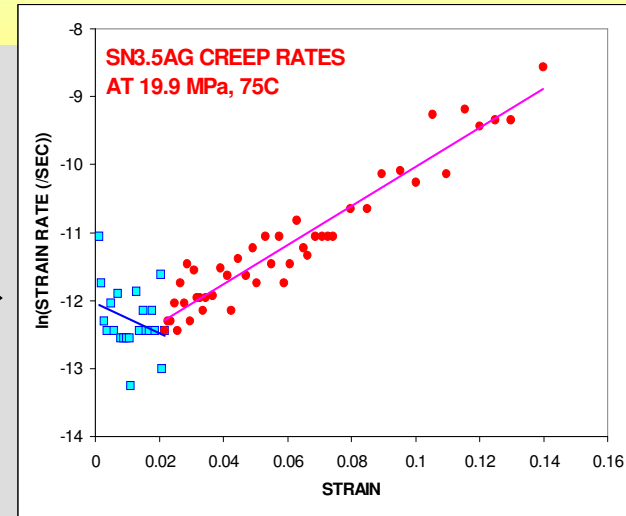
- **Primary creep at 110°C: ~ 17 MINUTES**
 - In accelerated testing, primary creep may dominate
- **Secondary creep at 110°C: ~ 50 MINUTES**
 - Could also say 0 minute if using the very lowest creep rate

Log-Linear Plots of Strain Rates vs. Strain

RAW DATA (CREEP CURVES)

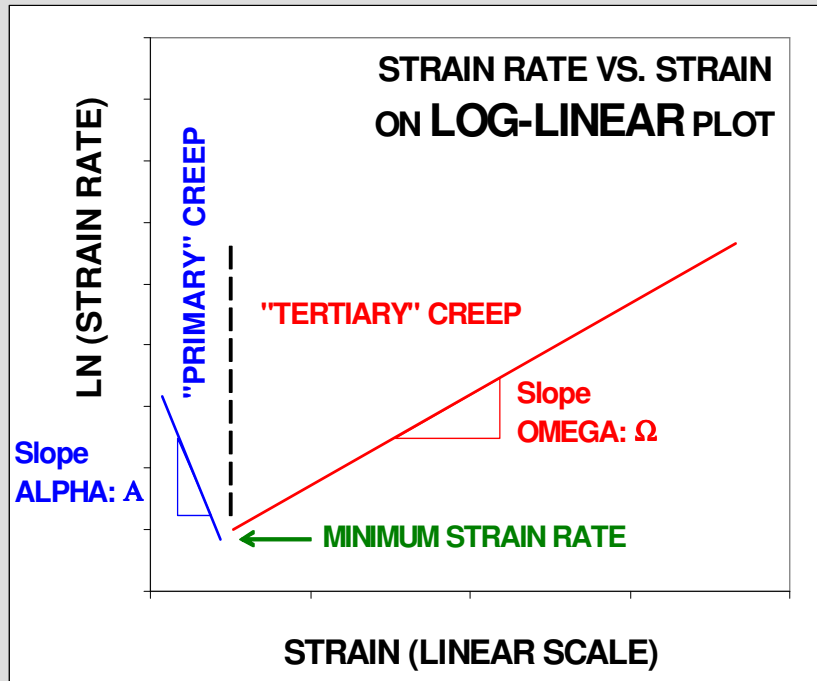


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- LOG-LINEAR plots of STRAIN RATES VS. STRAIN highlight regions of decreasing and increasing rates

The Extended Ω Method



- “Primary” stage: $\ln(\dot{\epsilon}) = -A \cdot \epsilon + C_1$
 $\dot{\epsilon} = a \cdot e^{-A \cdot \epsilon}$
- “Tertiary” stage: $\ln(\dot{\epsilon}) = \Omega \cdot \epsilon + C_3$
 $\dot{\epsilon} = b \cdot e^{\Omega \cdot \epsilon}$: Ω method
 (Prager, 2000)
- Combined creep rate:

HARDENING **SOFTENING**

$$\dot{\epsilon} = a \cdot e^{-A \cdot \epsilon} + b \cdot e^{\Omega \cdot \epsilon}$$

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

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

$$\dot{\epsilon} \approx a \cdot e^{-A \cdot \epsilon} \approx a \cdot (1 - A \cdot \epsilon)$$

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

$$\epsilon = \frac{1}{A} \left[1 - e^{-(A \cdot a)t} \right]$$

$$\epsilon_{SAT} = 1/A$$

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

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

Some Properties Of The $A-\Omega$ Model: Tertiary Creep Region

- When “tertiary” creep dominates:

$$\dot{\varepsilon} \approx b \cdot e^{\Omega \cdot \varepsilon}$$

- The extended Ω model reduces to the OMEGA method (Prager, 2000)
- The above equation is easily integrated (Prager, 2000)

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

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

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

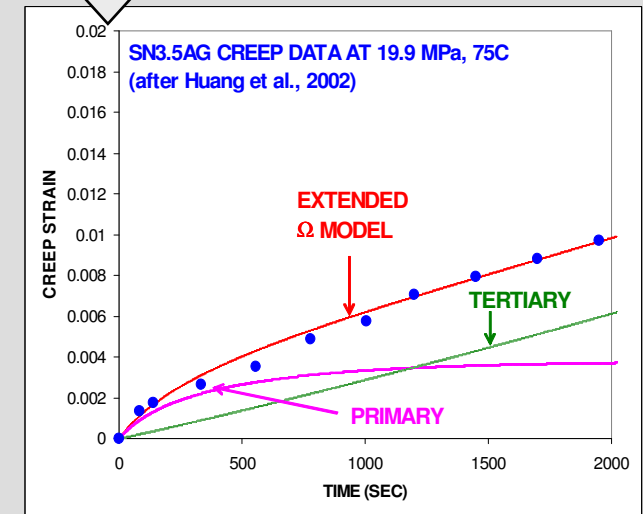
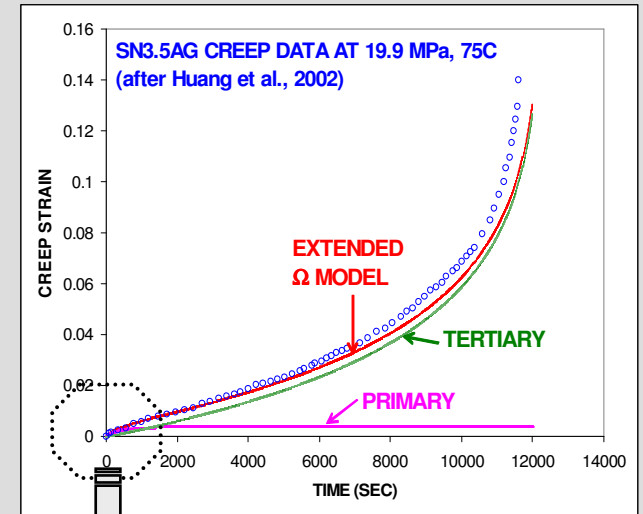
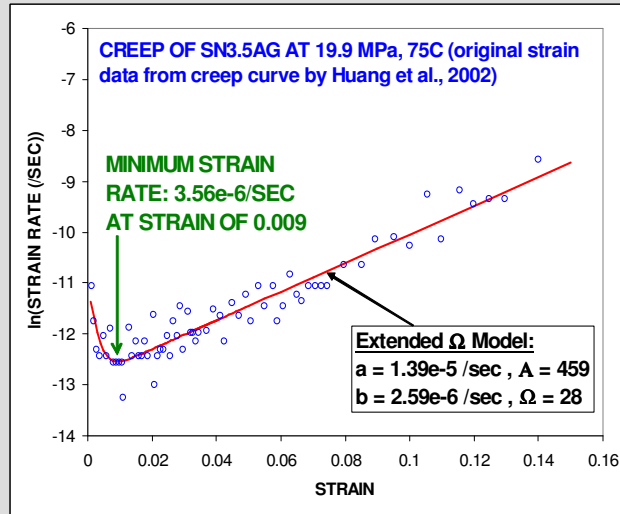
$$t_r \cdot \dot{\varepsilon}_{MIN} \approx 1/\Omega$$

Ω is a damage parameter since it predicts rupture times

Use of the $A-\Omega$ 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!**

$$t_r \cdot \dot{\epsilon}_{MIN} \approx \frac{1}{\Omega}$$

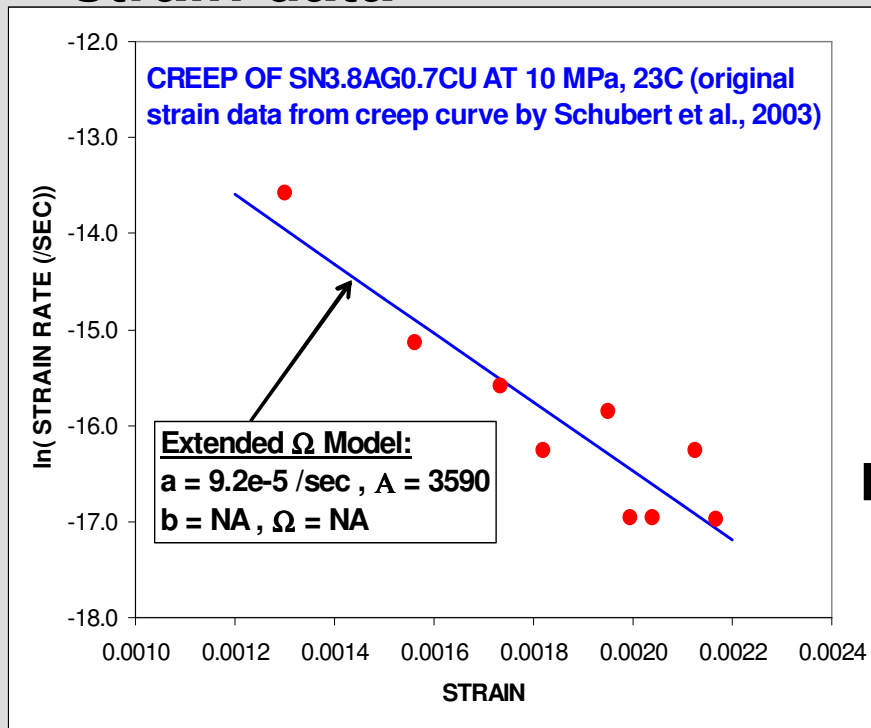
$$t_r \cdot (3.56 \times 10^{-6}) = 1/28 \Rightarrow t_r = 10,032$$

- 14% less than $t_r \sim 11607$ seconds from actual creep curve

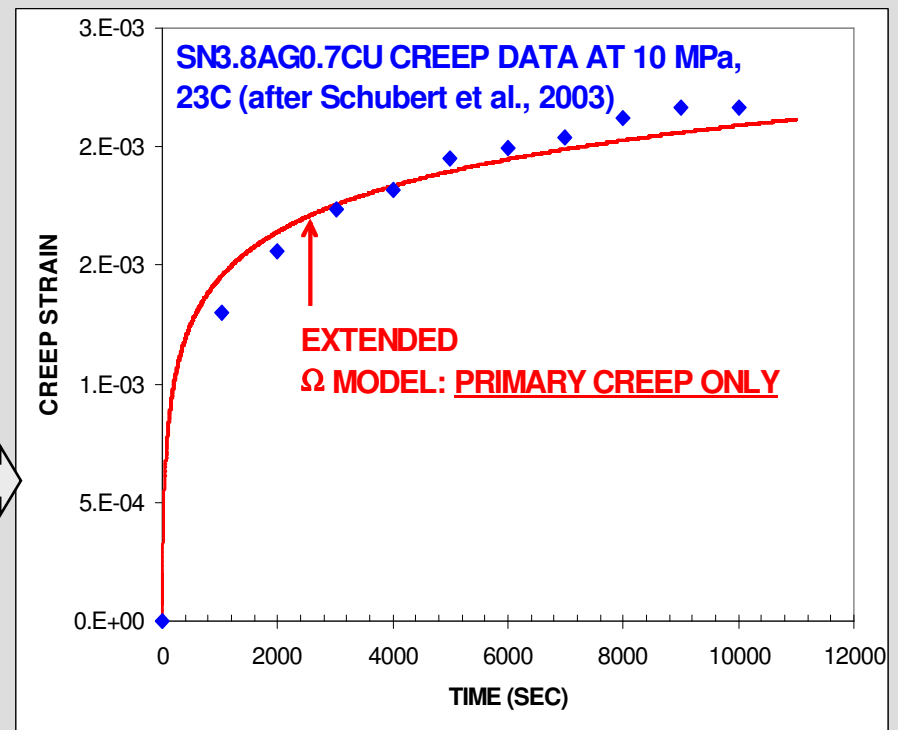
Use of the $A-\Omega$ Creep Model: Ex. # 2

Sn3.8Ag0.7Cu at 10 MPa, 23°C

- Curve-fit strain-rate & strain data



- Creep Curve Predictions

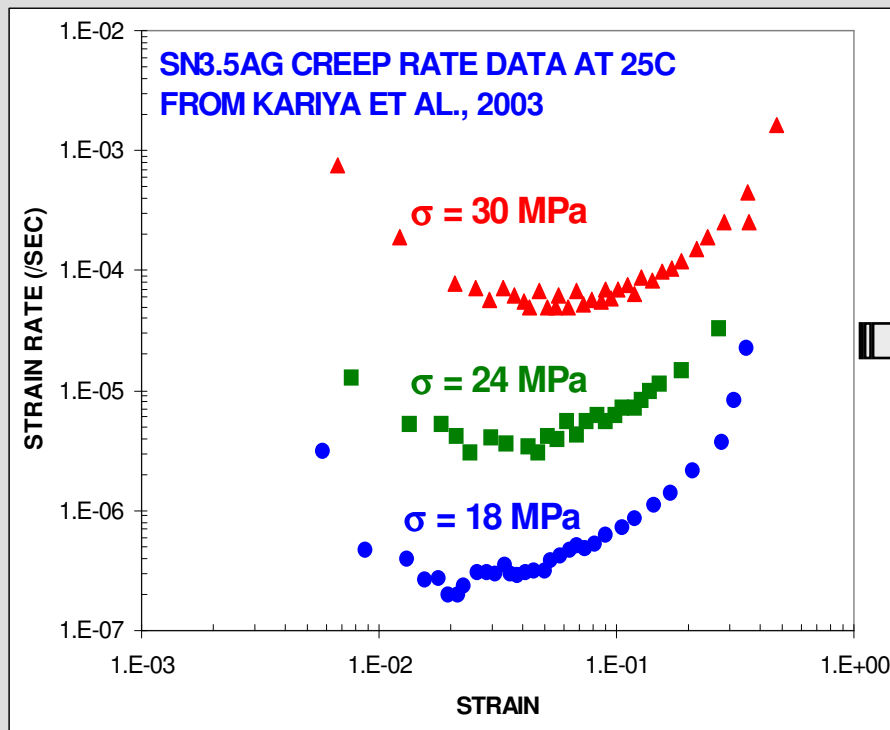


- In this example, log-linear plot of strain rate vs. strain data only shows primary creep

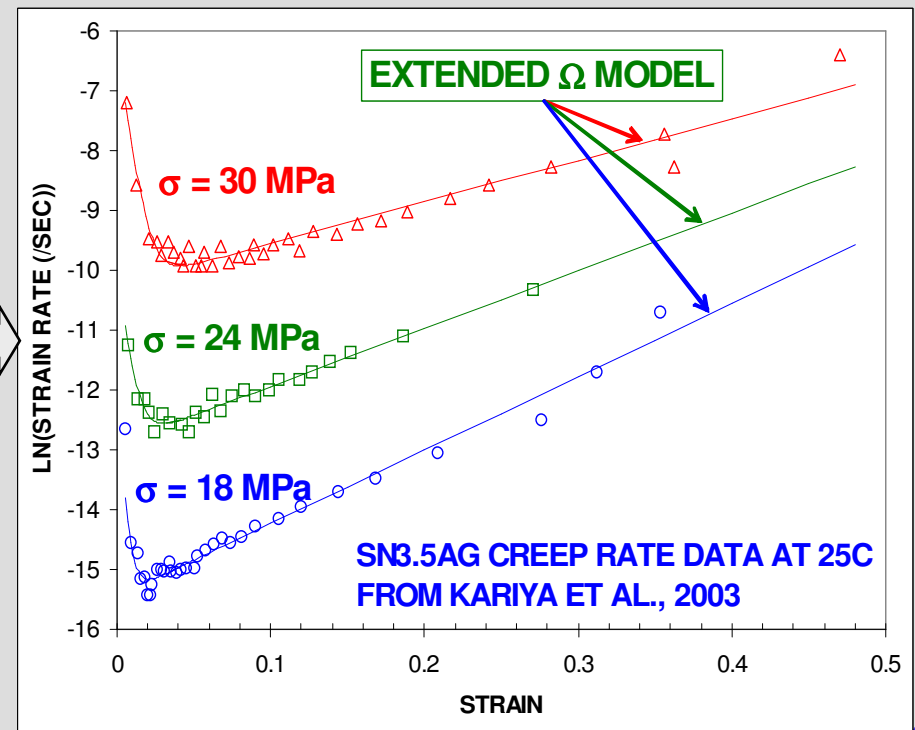
Stress-dependence Of Parameters A & Ω

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



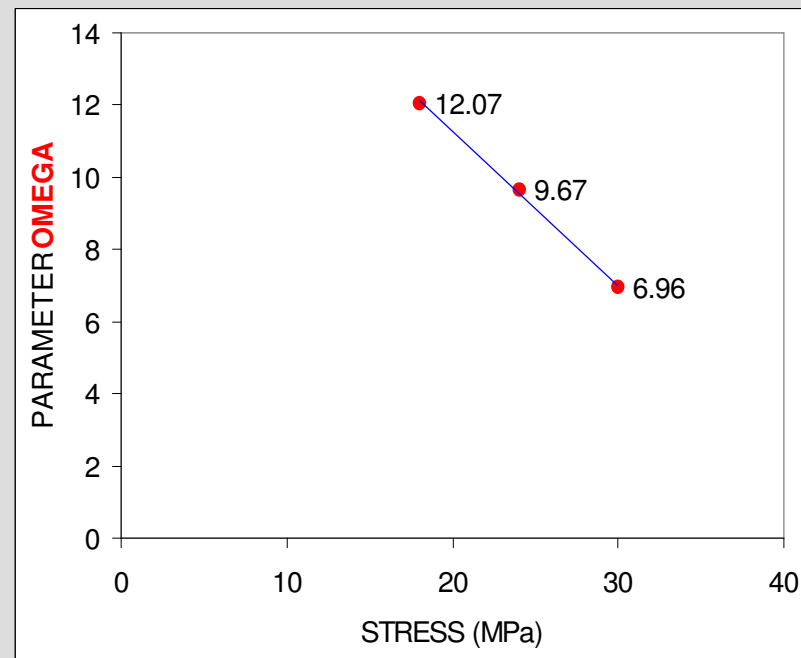
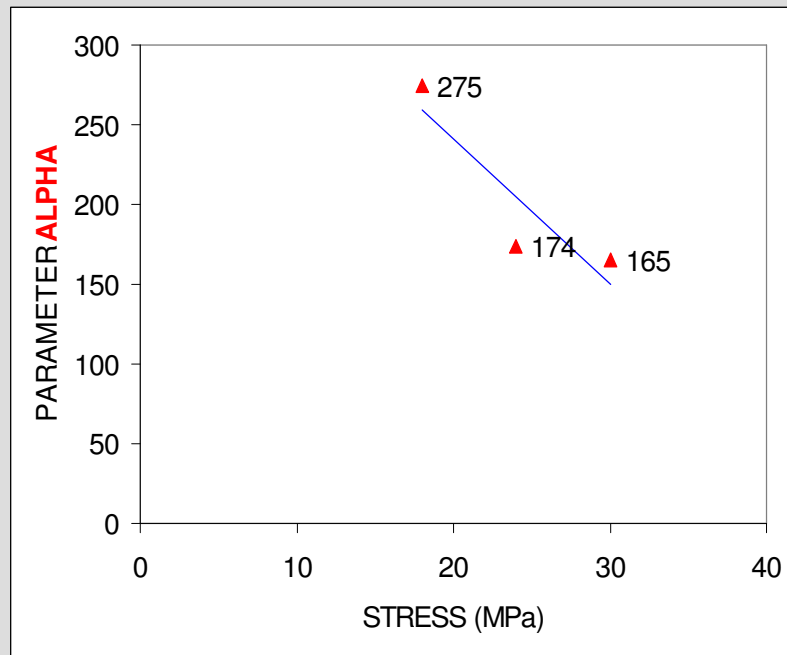
- Strain rate vs. strain data on **log-linear** plot, and fit of **extended Ω model**
 - Shows a sharper transition from hardening to softening



Stress-dependence Of Parameters Λ & Ω

Ex. # 1: Sn3.5Ag (cont'd)

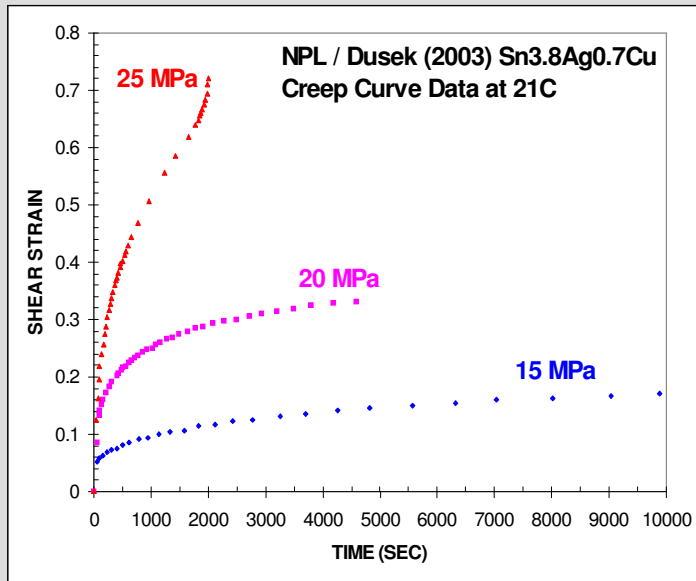
- Stress-dependence of **ALPHA** (Λ) and **OMEGA** (Ω) for Sn3.5Ag at **25°C** (from fitting of extended Ω model to Kariya's data on previous slide)



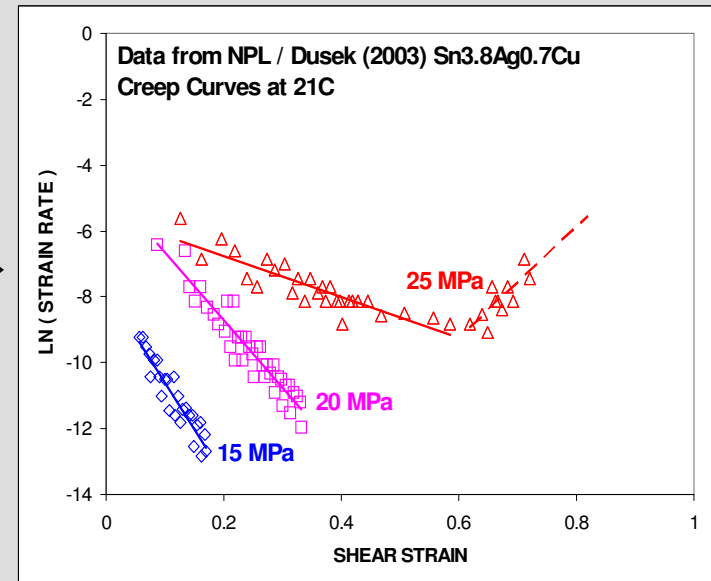
- Stress-dependence of **Λ** and **Ω** is linear in given stress range

Stress-dependence Of Parameters A & Ω

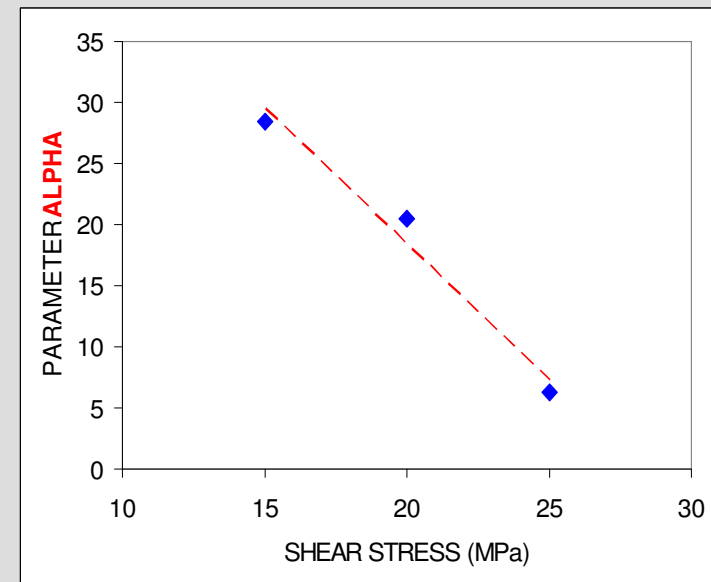
Ex. # 2: Sn3.8Ag0.7Cu in Shear



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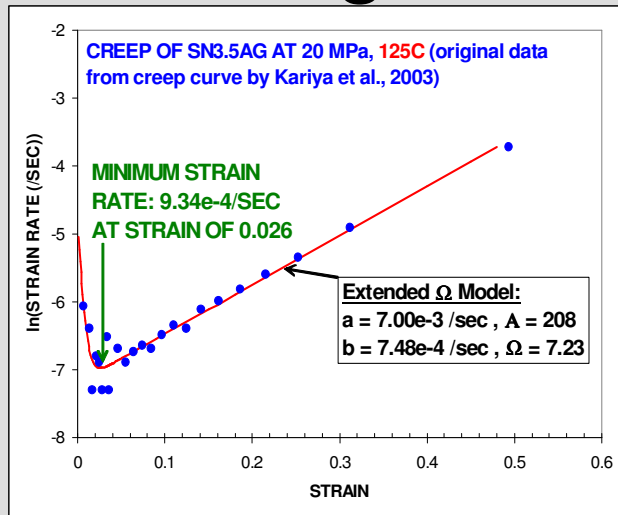
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- For Sn3.8Ag0.7Cu in shear at 21°C, ALPHA (A) has a linear stress-dependence in given stress range

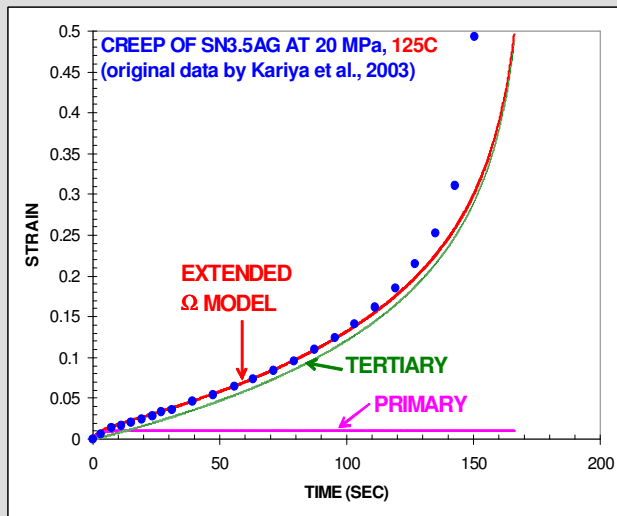
Temperature Dependence OF A & Ω

● Sn3.5Ag at 125°C



Sn3.5Ag (Kariya, 2003):

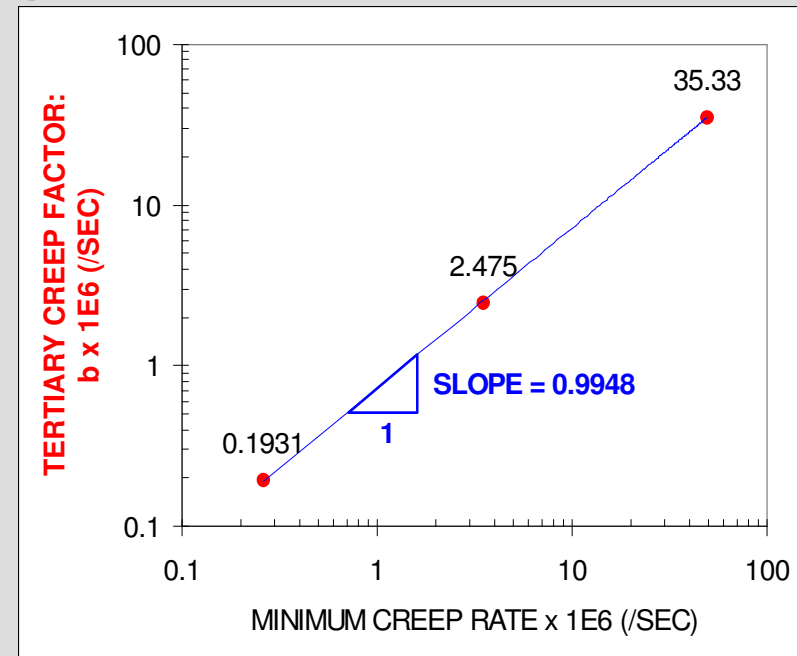
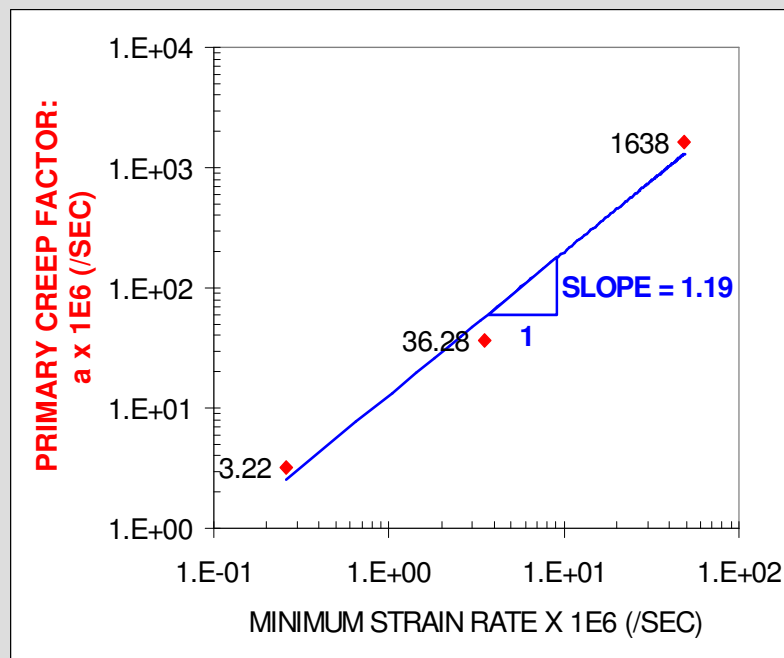
- At 25°C & 20 MPa:
 $A \sim 241, \Omega \sim 11$
- At 125°C & 20 MPa:
 $A = 208, \Omega = 7.23$



- 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:

$$\dot{\epsilon} = a \cdot e^{-A \cdot \epsilon} + b \cdot e^{\Omega \cdot \epsilon}$$

- a and b $\propto \dot{\epsilon}_{MIN}$

- The minimum creep rate, determined by “steady-state” creep models, is a strong function of stress and temperature
- $A = A(\sigma, T)$ and $\Omega = \Omega(\sigma, T)$ 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