Creep and Stress Rupture :

Ch. 13 : 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15(optional)

- **Definition of Creep and Creep Curve :** (13-3)
- def. *Creep is the time-dependent plastic strain at constant stress and temperature*

  Creep curve : Fig. 13-4

  • steady-state creep-rate ($\dot{\varepsilon}_s$ or simply $\dot{\varepsilon}$) : Temperature and Stress Dependencies
  - Fig. 13-6 Fig. 13-8

  - total creep curve : $\varepsilon = \varepsilon_o + \varepsilon_p + \varepsilon_s$

  ε_o = instantaneous strain at loading (elastic, anelastic and plastic)

  ε_s = steady-state creep strain (constant-rate *viscous creep*) = $\dot{\varepsilon}_s t$

  ε_p = primary or transient creep : Andrade-β flow (or 1/3 rd law) : $\beta t^{1/3}$

primary or transient creep :

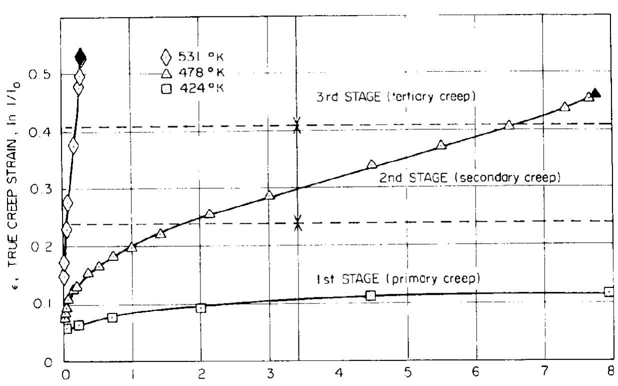
- Andrade-β flow (or 1/3 rd law) : $\varepsilon_p = \beta t^{1/3}$ ⇔ problem as $t \to 0$
- Garofalo / Dorn Equation : $\varepsilon_p = \varepsilon_t (1 - e^{-rt})$, r is related to $\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_s}$ (~1-20)

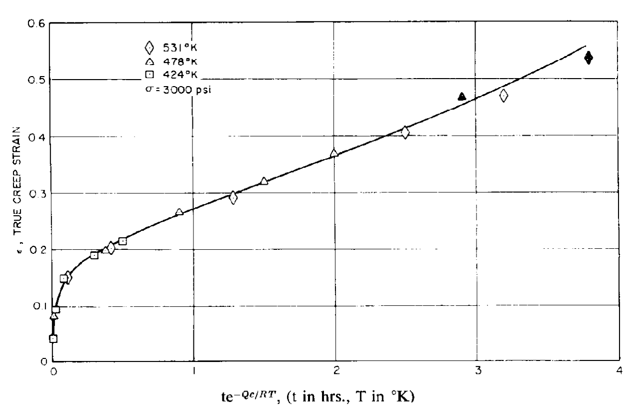
Dorn ⇒ Both primary and steady-state follow similar kinetics

- temperature compensated time ($\theta = t\, e^{-Q_c/RT}$)
- single universal curve with t replaced by θ or $\dot{\varepsilon}_s t$

Or, creep strain $\varepsilon - \varepsilon_o = \varepsilon_t (1 - e^{-\dot{\varepsilon}_s t}) + \dot{\varepsilon}_s t$ ⇔ see Sherby-Dorn (Al), Murty (Zr)

Sherby-Dorn θ-parameter

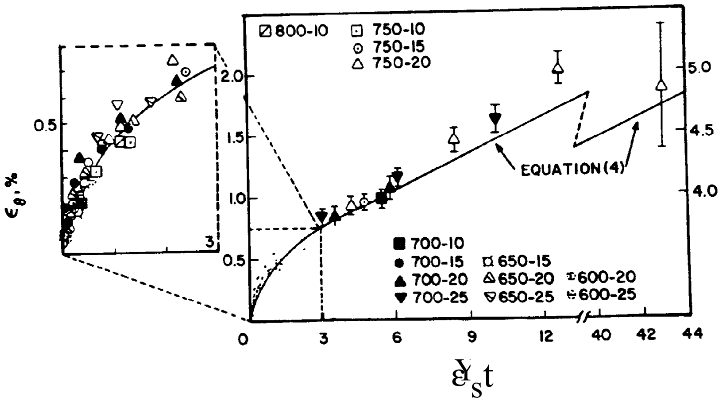




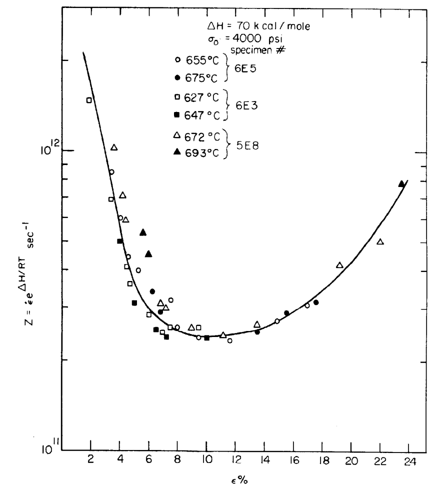
Creep curves for Al at (3,000 psi) and at three different temperatures

Sherby & Dorn (1956)

A single curve demonstrating the validity of θ-parameter



Creep data in Zircaloy at varied temperatures (˚F) and stresses (ksi) fall into a single curve demonstrating the validity of Dorn equation (Murty et al 1976)



(K. L. Murty, M.S. Thesis, 1967)

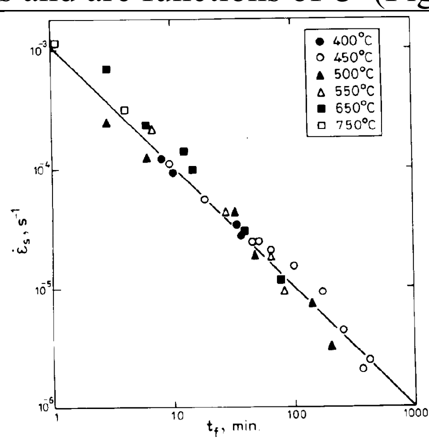
- Zener-Holloman : $Z = \dot{\varepsilon} e^{Q/RT}$

- **Stress Rupture Test** : (13-4) σ vs t_r
  - **Representation of engineering creep / rupture data** (13-12, 13-13) - Figs. 13-17, 13-18
    - Sherby-Dorn Parameter : $P_{S\text{-}D} = t\, e^{-Q/RT}$
    - Larson-Miller Parameter : $P_{L\text{-}M} = T(\log t + C)$ Fig. 13-19-21
    - Manson-Haferd Parameter : $P_{M\text{-}H} = \dfrac{T - T_a}{\log t - \log t_a}$

--- these parameters are for a given stress and are functions of σ (Fig. 13-20) ---

- Monkman-Grant : $\dot{\varepsilon}_s t_r = K$

  Eq. 13-24



Demonstration of Monkman-Grant Relationship in Cu (Feltham and Meakin 1959)

Creep Under Multiaxial Loading

(text 14-14)

Use Levy-Mises Equations in plasticity

$$\sigma_{eff} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}$$

and $$d\varepsilon_1 = \frac{d\varepsilon_{eff}}{\sigma_{eff}}\left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right],$$

since creep is plastic deformation 1/2 appears as in plasticity.

Similarly, $d\varepsilon_2$ and $d\varepsilon_3$.

Dividing by dt, get the corresponding creep-rates,

$$\dot{\varepsilon}_1 = \frac{\dot{\varepsilon}_{eff}}{\sigma_{eff}}\left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right], \text{ etc.}$$

One first determines the uniaxial creep-rate equation,

$$\dot{\varepsilon}_s = A\,\sigma^n\,e^{-Q/RT}$$

and assume the same for effective strain-rate : $\dot{\varepsilon}_{eff} = A\,\sigma_{eff}^{n}\,e^{-Q/RT}$

so that $$\boxed{\dot{\varepsilon}_1 = A\,\sigma_{eff}^{n-1}\,e^{-Q/RT}\left[\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)\right]}$$ etc.

Stress Relaxation

As noted in section 8-11, the stress relaxation occurs when the deformation is held constant such as in bolt in flange where the constraint is that **the total length of the system is fixed**.

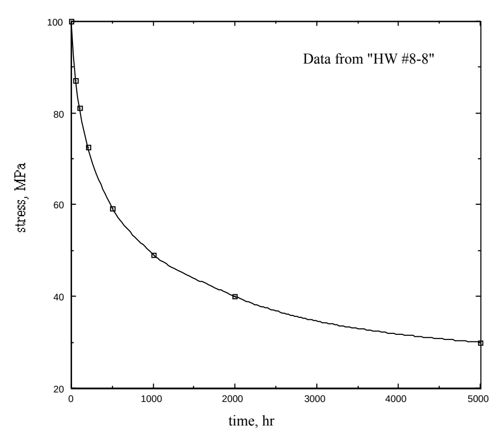
$\varepsilon_t = \varepsilon_E + \varepsilon_{creep} = \text{const.}$ Here, $\varepsilon_E = \frac{\sigma}{E}$.

Thus $\frac{d\varepsilon_t}{dt} = 0 = \frac{1}{E}\frac{d\sigma}{dt} + \dot{\varepsilon}_s$ Or, $\frac{d\sigma}{dt} = -E\,\dot{\varepsilon}_s = -E\,A\,\sigma^n$ @ fixed T

Integration from o to t gives,

$$\int_{\sigma_i}^{\sigma_f} \frac{d\sigma}{\sigma^n} = -E\,A\int_o^t dt = -E\,A\,t$$

$$\sigma_{final} \text{ or } \sigma(t) = \frac{\sigma_o}{[1 + AE(n-1)\sigma_o^{n-1}t]^{1/(n-1)}}$$



- **Deformation / Creep Mechanisms :**
  - Introduction - structural changes (13-5)
  - Slip (difficult to observe slip lines / folds etc are usually noted)
    Subgrains
    GBS
  - excess (deformation induced) vacancies

- Two important relationships :

  Orowan equation : $\dot{\varepsilon} = \rho b v$ and Taylor equation : $\boxed{\rho = \dfrac{\sigma^2}{\alpha^2 G^2 b^2}}$

- **Thermally Activated Dislocation Glide** (at low T and/or high strain-rates)

$\dot{\varepsilon} = A\, e^{B\sigma}\, e^{-Q_i/RT}$ where Q_i is the activation energy for the underlying mechanisms

Peierls mechanism (bcc metals) Intersection mechanism (fcc and hcp metals)

- **Dislocation creep** - (lattice) diffusion controlled glide and climb

- **Diffusion creep** - (viscous creep mechanisms mainly due to point defects) - at low stresses and high temperatures

- **Grain-Boundary Sliding** - (GBS) - intermediate stresses in small grained materials and ceramics (where matrix deformation is difficult)

  - Many different mechanisms may contribute and the total strain-rate :

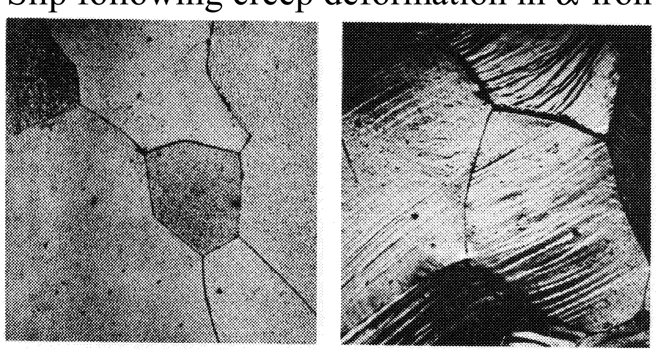
parallel mechanism
(fastest controls / dominates)

$$\dot{\varepsilon} = \sum_i \dot{\varepsilon}_i$$

series mechanisms
(slower controls / dominates)

$$\dot{\varepsilon} = \sum \left(\frac{1}{\dot{\varepsilon}_i}\right)^{-1}$$

Slip following creep deformation in α-iron



Uncrept specimen Crept at 5500 psi to 21.5% strain
(K.L. Murty, MS thesis, Cornell University, 1967)

- **Dislocation Creep :**

• Pure Metals / Class-M alloys: Experiments : $\dot{\varepsilon} = A\,\sigma^n\, e^{-Q_c/RT}$, $n \approx 5$, $Q_c \approx Q_L$ (Q_D)

(edge ⊥) glide - climb model *Weertman-Climb model* (Weertman Pill-Box Model)

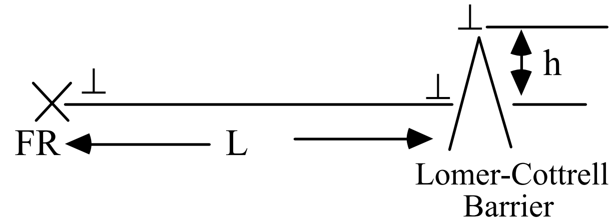
• *sequential processes*

L = average distance a dislocation glides

t_g = time for glide motion

h = average distance a dislocation climbs

t_c = time for climb



$\Delta\gamma$ = strain during glide-climb event = $\Delta\gamma_g + \Delta\gamma_c \approx \Delta\gamma_g = \rho\, b\, L$

t = time of glide-climb event = $t_g + t_c \approx t_c = \dfrac{h}{v_c}$, v_c = climb velocity

$$\therefore\ \dot{\gamma} = \frac{\Delta\gamma}{t} = \frac{\rho\, b\, L}{h/v_c} = \rho\, b\, \left(\frac{L}{h}\right) v_c$$

where $v_c \propto \Delta C_v\, e^{-E_m/kT}$, E_m = activation energy for vacancy migration

$$\text{Here, } \Delta C_v = C_v^+ - C_v^- = C_v^o\, e^{\sigma V/kT} - C_v^o\, e^{-\sigma V/kT} = C_v^o\ 2\,\mathrm{Sinh}\left(\frac{\sigma V}{kT}\right)$$

$$\therefore\ \dot{\varepsilon} = \alpha\,\rho\, b\left(\frac{L}{h}\right) v_c = \alpha\,\rho\, b\left(\frac{L}{h}\right) C_v^o\ e^{-E_m/kT}\, 2\,\mathrm{Sinh}\left(\frac{\sigma V}{kT}\right)$$

At low stresses, $\mathrm{Sinh}(\xi) \approx \xi$ so that

$$\dot{\varepsilon} = A_1\,\rho\, b\left(\frac{L}{h}\right) C_v^o\ e^{-E_m/kT}\ \frac{\sigma V}{kT}$$

$$\dot{\varepsilon} = A_1\,\rho\, b\left(\frac{L}{h}\right) D_L \frac{\sigma V}{kT} \approx A_2\,\rho\,\sigma\left(\frac{L}{h}\right) D_L$$

Or $\dot{\varepsilon} = A\sigma^3 D$ ⇔ *natural creep-law*

Weertman: $\dfrac{L}{h} \propto \sigma^{1.5}$, $\dot{\varepsilon} = A\,\sigma^{4.5}\,D$ as experimentally observed in Al

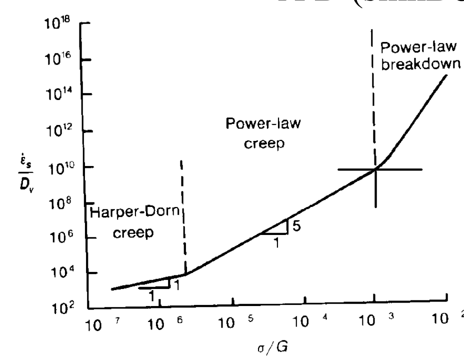
In general $\dot{\varepsilon} = A(T)\,\sigma^n$ Power-law

- n is the stress exponent

{f(xal structure, Γ)}

Garofalo Eqn.

$\dot{\varepsilon} = A\,D\,(\sinh B\sigma)^n$



also known as Norton's Equation (n is Norton index)

At high stresses ($\sigma \geq 10^{-3}$ E), $\mathrm{Sinh}(x) \approx e^x$, $\dot{\varepsilon} = A_H\, e^{B\sigma}\, D$ (Power-law breakdown)

Experimental Observations - Dislocation Creep

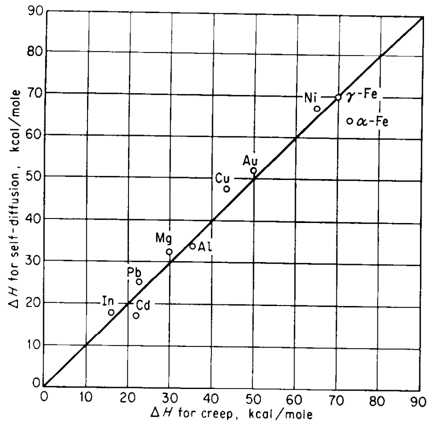
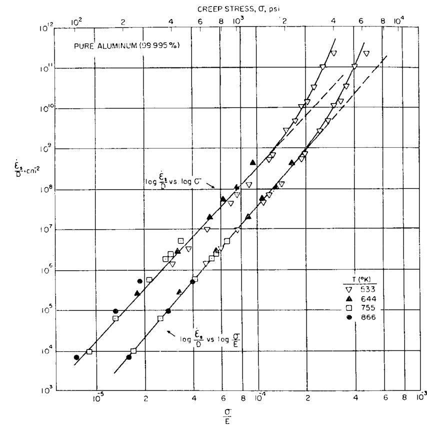


Fig. 13-13 (Dieter)



(Sherby)

What happens if we keep decreasing the stress, say to a level at and below the τ_{FR}?

As σ is decreased $\Rightarrow$ reach a point when $\sigma \leq \sigma_{FR}$,

dislocation density would become constant (independent of σ): $\dot{\varepsilon} \propto \sigma$

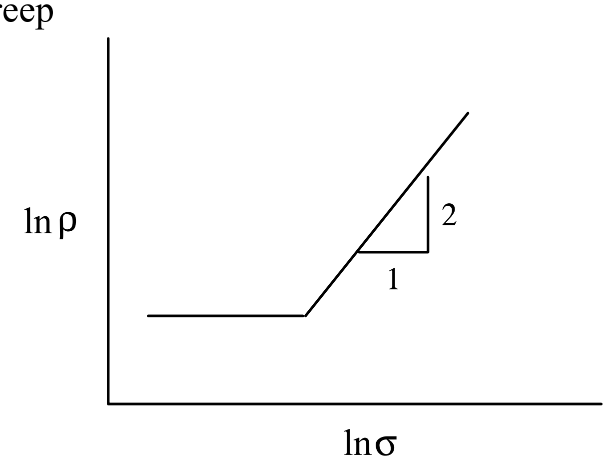
- viscous creep known as Harper-Dorn creep

Harper-Dorn creep occurs at

$$\frac{\sigma}{E} \leq b\sqrt{\rho_o} \approx 10^{-5}\,, \quad \rho_o \approx 10^6 \text{cm}^{-2}$$

- H-D creep is observed in **large** grained materials (metals, ceramics, etc.)

$$\dot{\varepsilon}_{HD} = A_{HD}\, D_L \sigma$$



Characteristics of Climb Creep (Class-M) :

- large primary creep regions
- subgrain formation ($\delta \propto \frac{1}{\sigma}$)
- dislocation density $\propto \sigma^2$
- independent of grain size

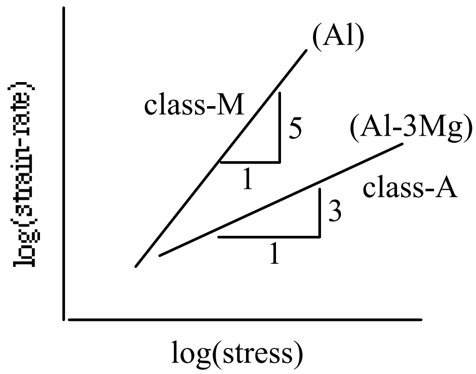
- **Effects of Alloying : (class-A)**

- Solid-solution - decreases rate of glide ┌ glide controlled creep although annihilation due to climb still occurs *(micro-creep / viscous glide creep)*

  viscous glide controlled creep : (decreased creep-rates)

  $\dot{\varepsilon}_g = A_g D_s \sigma^3$, D_s is solute diffusion

  - little or no primary creep
  - **no** subgrain formation
  - $\rho \propto \sigma^2$
  - grain-size independent



- At low stresses (for large grain sizes), Harper-Dorn creep dominates
  ⇒ what happens as grain size becomes small ⇐

As grain-size **decreases** (and at low stresses) diffusion creep due to point defects becomes important : (due to migration of vacancies from tensile boundaries to compressive boundaries)

- Nabarro-Herring Creep (diffusion through the lattice) : $\dot{\varepsilon}_{NH} = A_{NH} D_L \frac{\sigma}{d^2}$

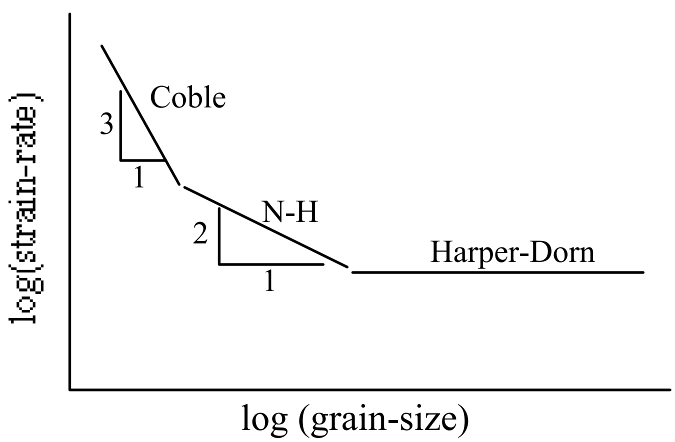
- Coble Creep (diffusion through grain-boundaries) : $\dot{\varepsilon}_{Co} = A_{Co} D_b \frac{\sigma}{d^3}$

Nabarro-Herring Creep vs Coble Creep :

Coble creep for small grain sizes and at low temperature

NH creep for larger grain sizes and at high temperatures

- at very large grain sizes, Harper-Dorn creep dominates



At small grain-sizes, GBS dominates at intermediate stresses and temperatures :

- $\dot{\varepsilon}_{GBS} = A_{GBS} D_b \frac{\sigma^2}{d^2}$ ⇔   *superplasticity*

- Effect of dispersoids : Dispersion Strengthening / Precipitate Hardening
  - recall Orowan Bowing
- at high temperatures, climb of dislocation loops around the precipitates controls creep ⇒ $\dot{\varepsilon}_{ppt} = A_{ppt}\, D\, \sigma^{8\,-\,20}$

Rules for Increasing Creep Resistance

- Large Grain Size
  (directionally solidified superalloys)
- Low Stacking Fault Energy
  (Cu vs Cu-Al alloys)
- Solid Solution Alloying
  (Al vs Al-Mg alloys)
- Dispersion Strengthening
  (Ni vs TD-Ni)

Formability Improvement

- Small (stable) Equiaxed Grain Size
  (superplasticity)
- Strengthen Matrix
  (i.e., increase GBS - ceramics)
- Stoichiometry
  (especially Ceramics)

Summary of Creep Mechanisms: $\dot{\varepsilon}_t = \dot{\varepsilon}_{N\text{-}H} + \dot{\varepsilon}_{Coble} + \dot{\varepsilon}_{H\text{-}D} + \dot{\varepsilon}_{GBS} + \left(\frac{1}{\dot{\varepsilon}_c} + \frac{1}{\dot{\varepsilon}_g}\right)^{-1}$

Dorn Equation : $\frac{\dot{\varepsilon}kT}{DEb} = A\left(\frac{\sigma}{E}\right)^n$

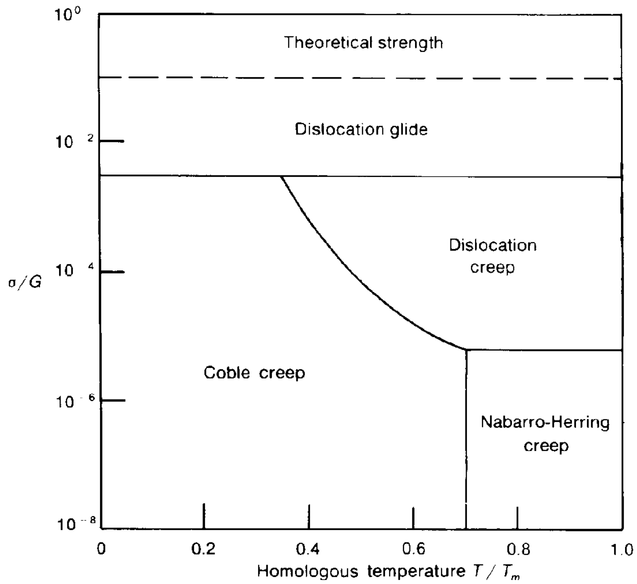
Mechanism	D	n	A
Climb of edge dislocations	D_L	5	$6x10^7$
(Pure Metals and class-M alloys)	(n function of Xal structure & Γ)*		
Low-temperature climb	$D_\perp$	7	$2x10^8$
Viscous glide (Class-I alloys - microcreep)	D_s	3	6
Nabarro-Herring	D_L	1	$14 (\frac{b}{d})^2$
Coble	D_b	1	$100 (\frac{b}{d})^3$
Harper-Dorn	D_L	1	$3x10^{-10}$
GBS (superplasticity)	D_b	2	$200 (\frac{b}{d})^2$

D_L = lattice diffusivity; D_s = solute diffusivity; $D_\perp$ = core diffusivity;
D_b = Grain-Boundary Diffusivity; b = Burgers vector; d = grain size;
δ = subgrain size = $10 \frac{Gb}{\tau}$ and $\rho = \frac{\sigma^2}{G^2b^2}$ where G is the shear modulus

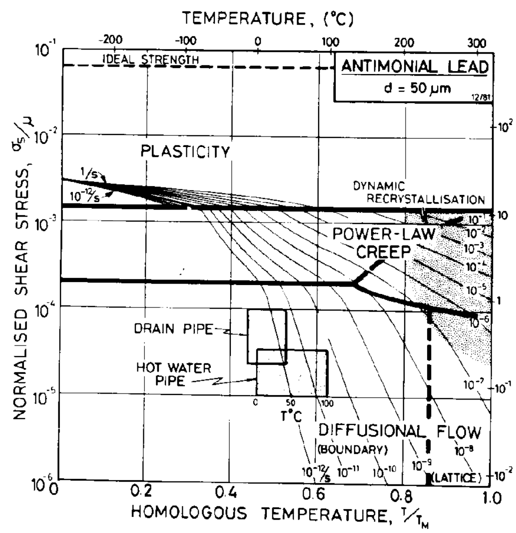
*n increases with decreasing Γ (stacking-fault energy)

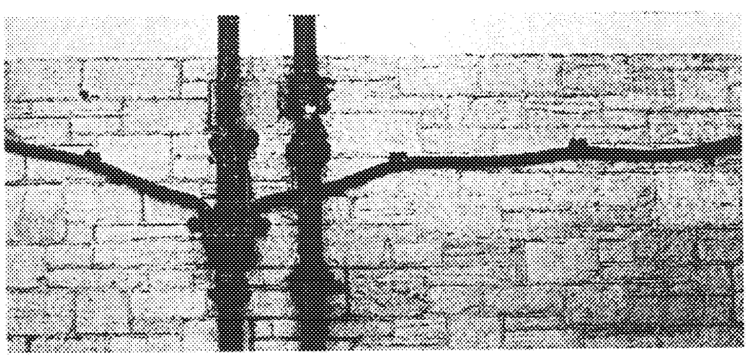
Deformation Mechanism Maps

- Visual picture of the domains (σ, T) where various mechanisms dominate

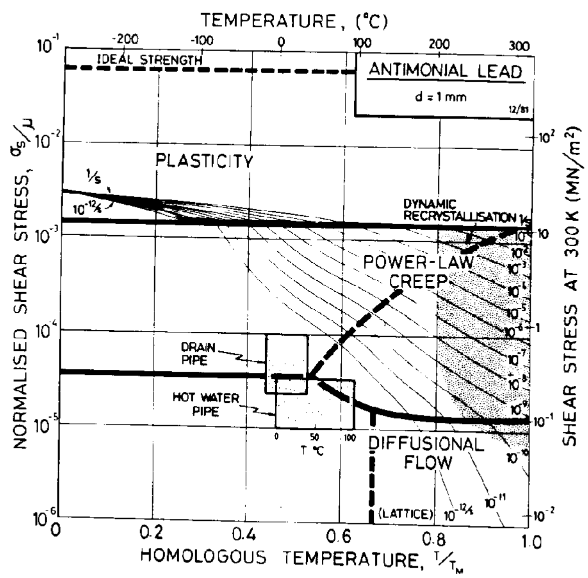


Ashby-Map





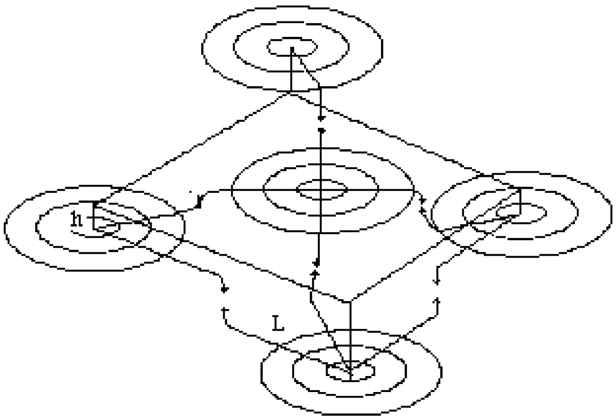
Lead pipes on a 75-year-old building in southern England
The creep-induced curvature of these pipes is typical
of Victorian lead water piping. (Frost and Ashby)



Other examples :

- W filament (light bulbs)
- turbind blade {Ni-based alloy DS by $Ni_3(Ti,Al)$}

WEERTMAN PILL-BOX MODEL



Pure Metals - Glide faster
Climb-controlled creep (n≈5)

$$\dot{\varepsilon}_t = \left(\frac{1}{\dot{\varepsilon}_c} + \frac{1}{\dot{\varepsilon}_g} \right)^{-1}$$

Alloys - Glide slower
Glide-controlled creep (n≈3)

Solid Solution Alloys

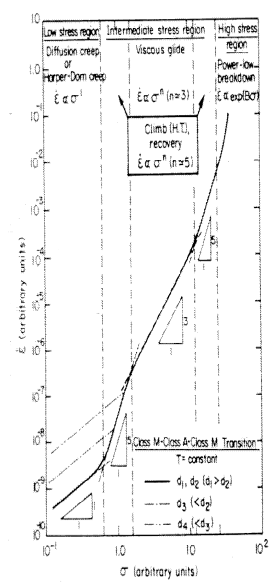


Fig. 9 Schematic illustration of logarithmic strain rate versus logarithmic stress for solid solution alloys.

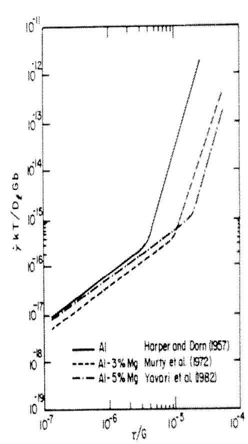
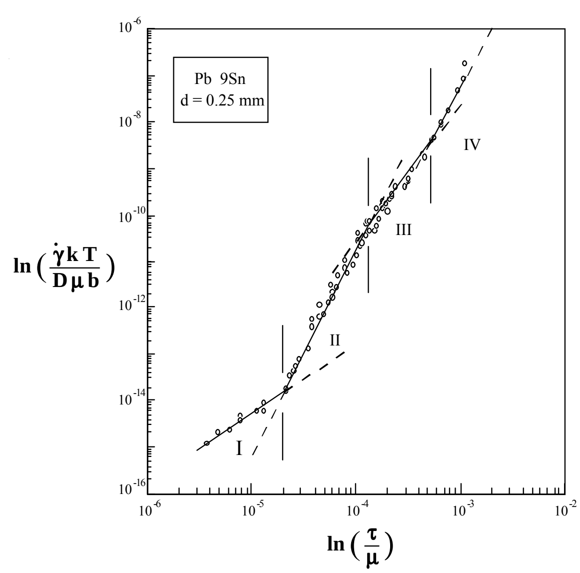


Fig. 10 Temperature compensated shear strain rate versus normalized shear stress for pure Al and two Al-Mg alloys.



Creep Transitions for Alloy Class

Murty and Turlik (1992)