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SPRING COLLEGE IN MATERIALS SCIENCE
ON
'CERAMICS AND COMPOSITE MATERIALS'
(17 April - 26 May 1989)

CREEP AND DEFORMATION
(Overheads)

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Estimated Schedule ↓

Outline of Lecture Series

O. Overview

A. Fundamentals of Creep and Deformation — L1 + Dislocations · Plastic deformation and Strengthening
   - Deformation at low and high temperature
   - Experimental techniques
   - Experimental results and data presentation

B. Mechanistics of Creep Deformation — L2
   - Diffusional Creep
   - Dislocation Based Creep
   - Class I Solid Solutions
   - Grain Boundary Sliding
   - Dispersion strengthened materials
   - The Big Picture -- Maps and the Dorn Equation — L3

C. Creep in Specific Systems
   - Comparison between metallic and ceramic creep
   - Superplasticity
     - basic principles
     - zirconia — L4

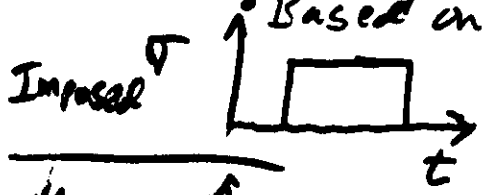
D. High Temperature Cavitation and Crack Growth
   - Types of Damage
   - Multiaxial Stress States
   - Crack Growth at elevated Temperature

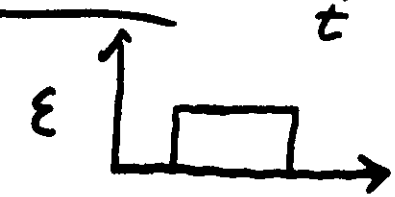
E. Effects of Internal Stresses - And Creep of Composites
   - Experimental Observations
   - Phase changes
   - Changing Temperature — L5
     - Whisker reinforced composites
     - Fiber reinforced composites

F. Creep Resistant Materials

Basic Modes of Deformation

1) Elastic
   - Reversible
   - Not time dependent
   - Based on bond Stretching
2) Anelastic
   - Reversible
   - time dependent
   - Based on reversible dislocation Motion or GB.
3) Plastic
   - Irreversible
   - Usually time dependent
   - Based on Motion of dislocations or diffusional flow





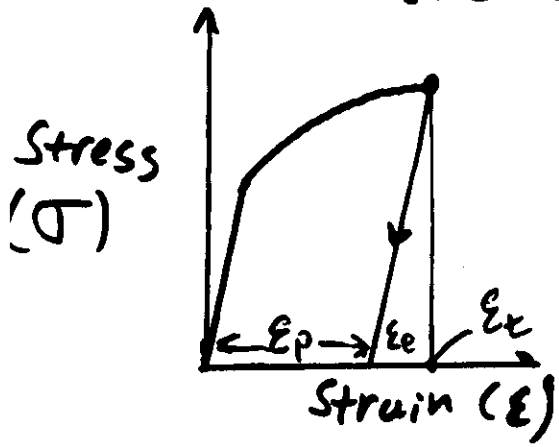
Elastic

Anelastic

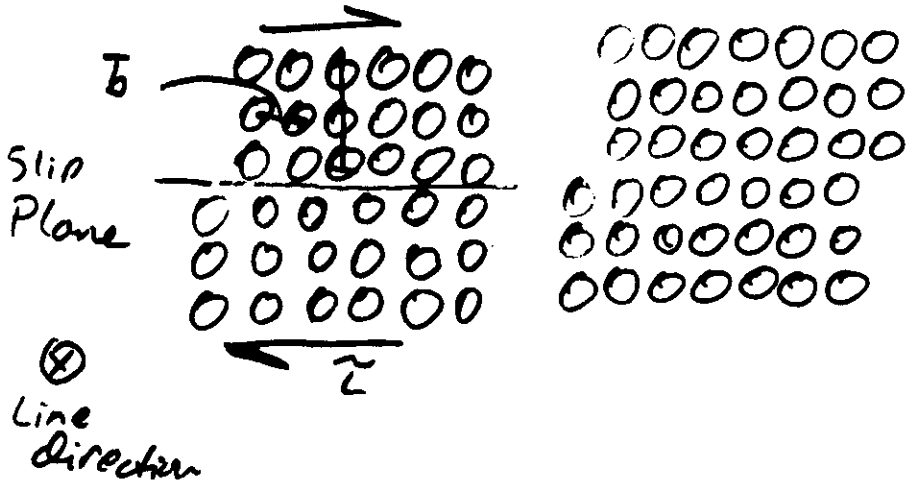
↕ Sometimes hard to distinguish

Plastic

Another way to see Elastic & Plastic Deformation



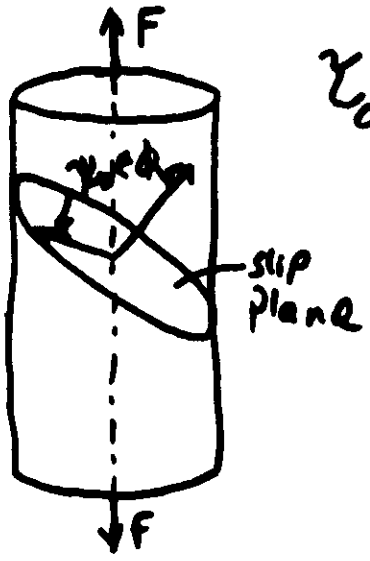
Plastic deformation is the result of Dislocation Motion



Mechanism of Plastic Deformation

Single Crystals

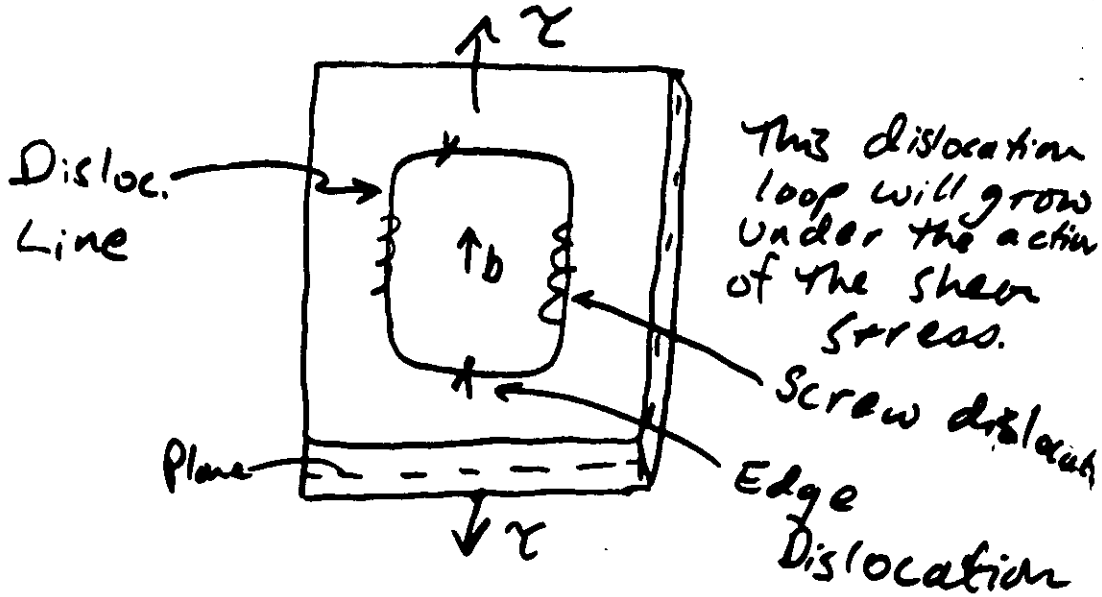
Experimentally found that flow occurs on specific Planes, in specific Directions in response to a Shear Stress, τ



$$\tau_{crit} = \frac{F}{A}\cos\phi\cos\psi$$

- Note: Plastic deformation responds to Shear Stresses only!

Note that the dislocation Line is the boundary between slipped and un-slipped regions.



Force on dislocation, $F = \tau \cdot b$

Stress fields associated w/ dislocations

$$\sigma \propto \frac{\mu b}{r}$$

μ = Shear Modulus
b = Burgers vector
r = distance

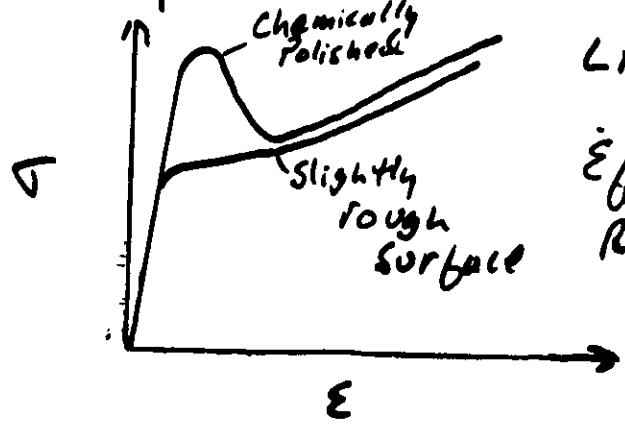
Also, There is a line tension

$$E \propto \mu b^2$$

Now we may use this to understand deformation.

1) Single Crystals

Typical Ceramic σ-ε curves



LiF

$\dot{\varepsilon}$ fixed

Room Temp

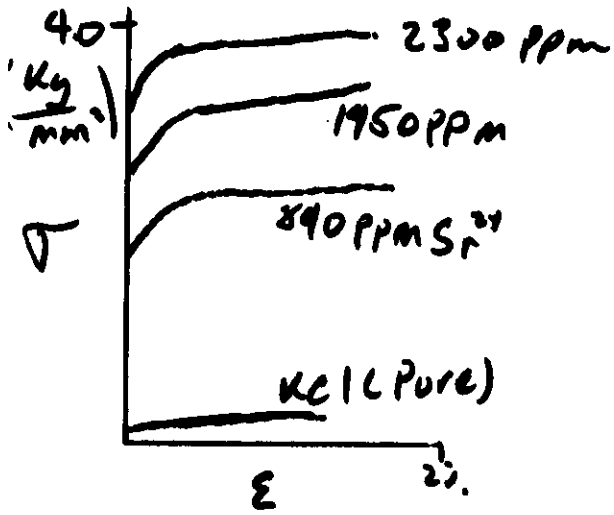
$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} = \rho v b$$

if ρ very low high σ needed for flow.
dislocations multiply and interact
increasing ρ and σ with strain

Interactions with point defects

Consider addition of $SrCl_2$ to KCl

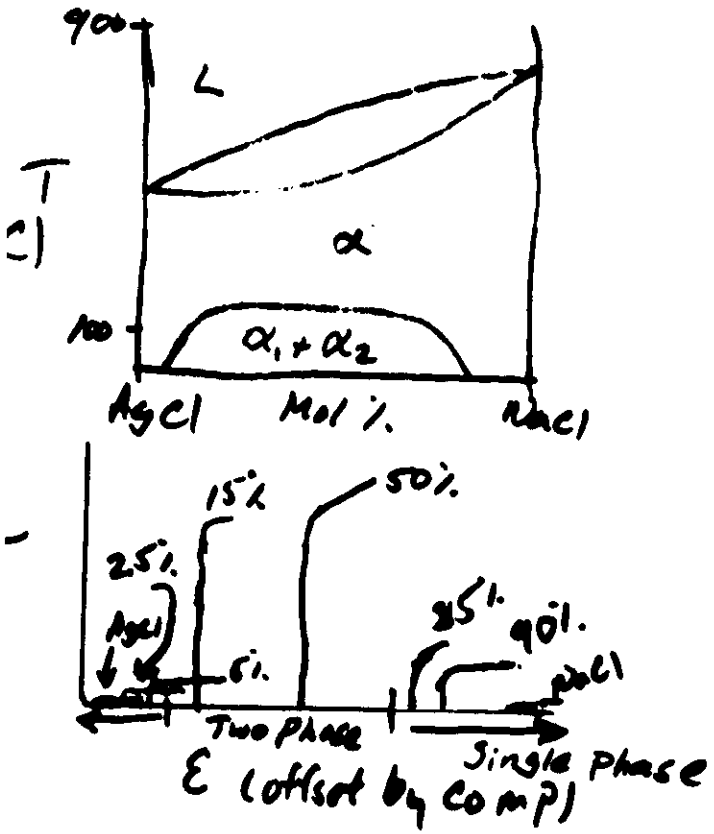
K Vacancies form and produce dipoles w/ Sr ions



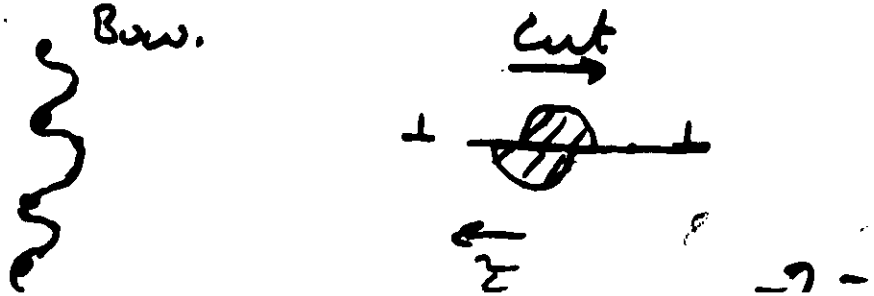
Two Effects
1) Strain field interaction
2) breaking of dipoles

Usually $\sigma_y \propto C^t$

Effect of Precipitates & Solutes



for Small dispersed precipitates, dislocations must cut or bow around the precipitates



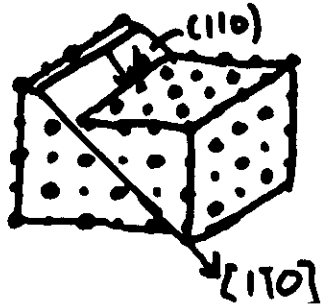
Deformation of Polycrystaline Solids

- 5 independent slip systems are required for general deformation by slip.
  - this condition is only found at elevated temperature by Ceramic materials.

- It is difficult to propagate slip through grain boundaries. Thus at low T small grains strengthen a solid against slip deformation (Hall-Petch)

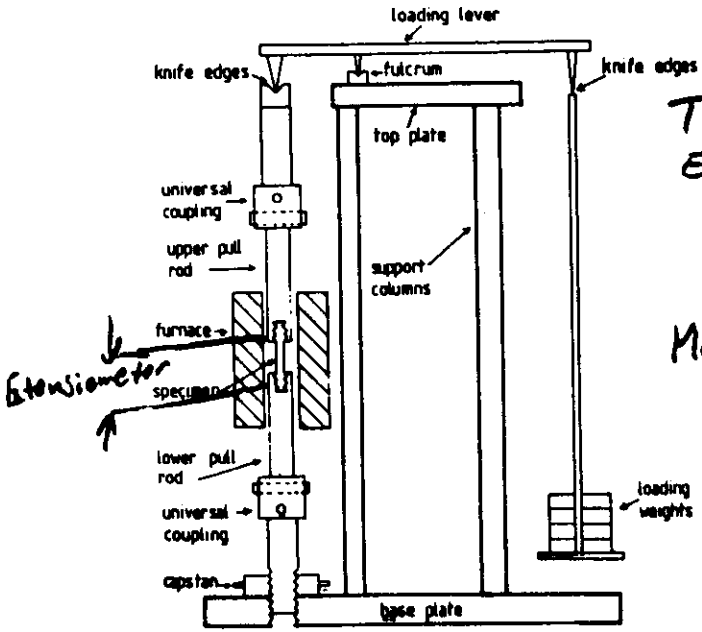
$$\sigma = \sigma_0 + C d^{-\frac{1}{2}}$$

Consider NaCl structure at low temp only {110} ⟨1T0⟩ System is available.



Note: Ions with same charge never become nearest neighbors.

Properties at Elevated Temperature



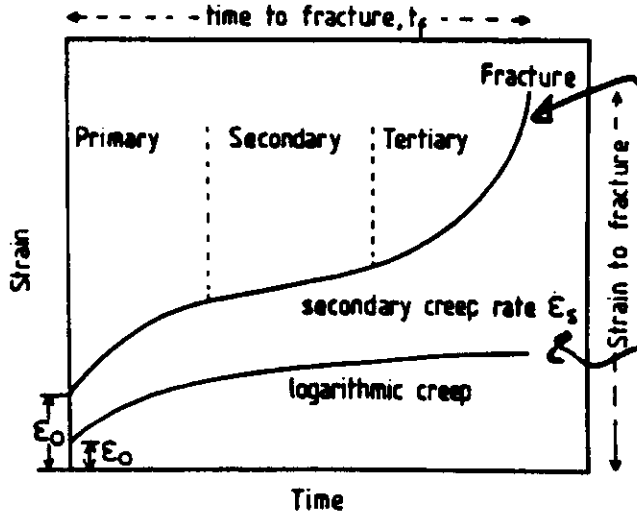
Typical Creep Experiment

Measure Δl with t

$e = \frac{\Delta l}{l_o}$

$\varepsilon = \ln(1+e)$

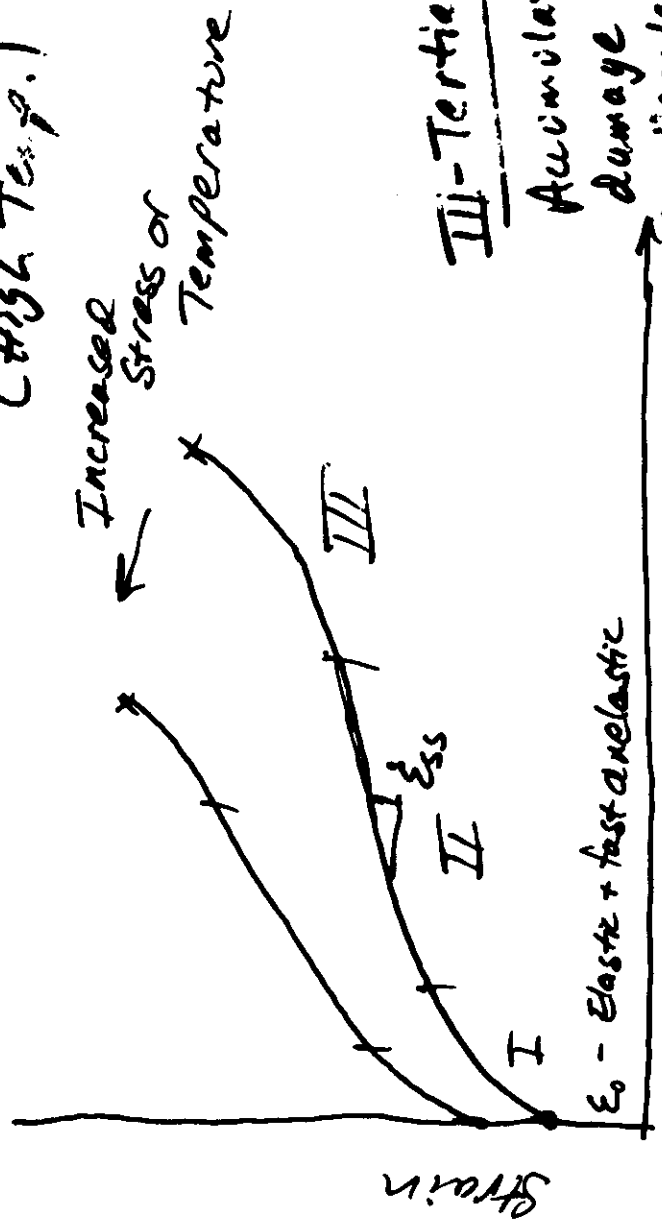
$\sigma = F/A$



Typical for elevated T

Typical at low T

Interpretation of Creep Curves (High Temp.)



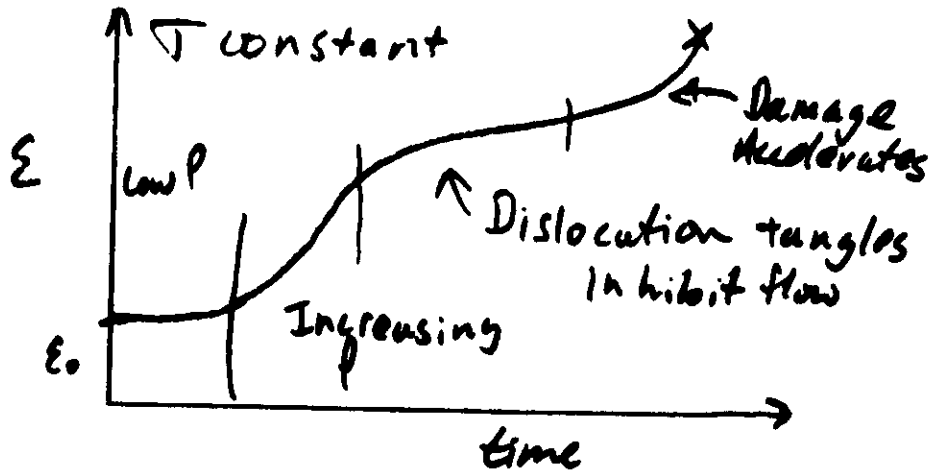
III - Tertiary
Accumulation of damage accelerates the creep rate (not seen in compression)

II - Steady State
Structure reasonably constant, rate also.

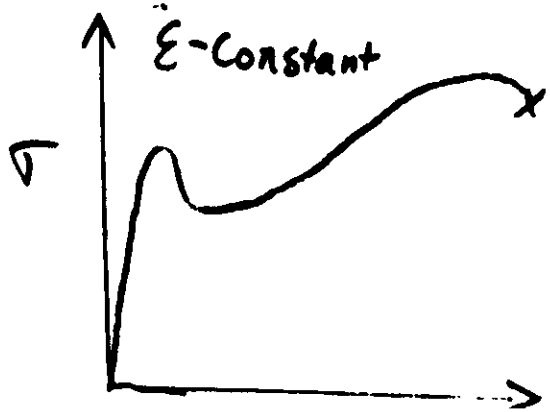
I - Primary - can be evaluated w/ strain hardening (not always

Creep Curves with other shapes can also be understood...

Single xtals w/ low P_o:



Corresponding Stress Strain Curve



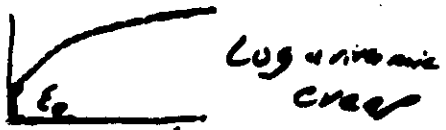
Complementary Information

Deformation at Low & high Temp.

Low ($< 0.35\ T_m$) — Note: seldom accessible w/ Polycrystalline Ceramics

Analyses of deformation based on Strain hardening alone work well. Weak time-dependancy

Cells:



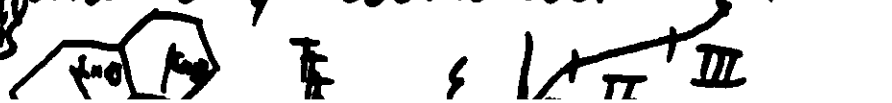
Intermediate ($0.35\ T_m$ to $0.6\ T_m$)

- Significant time dependancy
- Structure will change w/ Strain
- Diffusion & hardening should be considered

high ($> 0.6\ T_m$)

- Large time dependancy
- Structure almost simple function of Stress only
- Diffusion-only accounts work well

Subgrains



TEST Methods

Tensile

Constant load -or- Constant Stress

Creep -or- Instron

Uniaxial Stress σ

$\dot{x}$ or $\dot{\varepsilon}$ fixed

$\dot{x}$ Final

Comparable data is obtained either way.

Other loading Geometries Available, [illegible]

Compression

Uniaxial σ

Torsion

τ or $\sigma_1 = -\sigma_2$

Bending

Complicated State of [illegible]

Notched Tensile

σ_a and σ_t

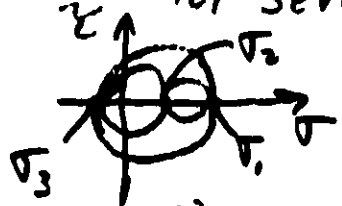
Biaxial Tension

Pressure under diaphragm

Complicated State of [illegible]

Despite differences, data from all loading conditions can be correlated, assuming The Material is isotropic

1) Find Principal Stresses (rotate axes for zero shear)



$\Rightarrow \sigma_1, \sigma_2, \sigma_3$

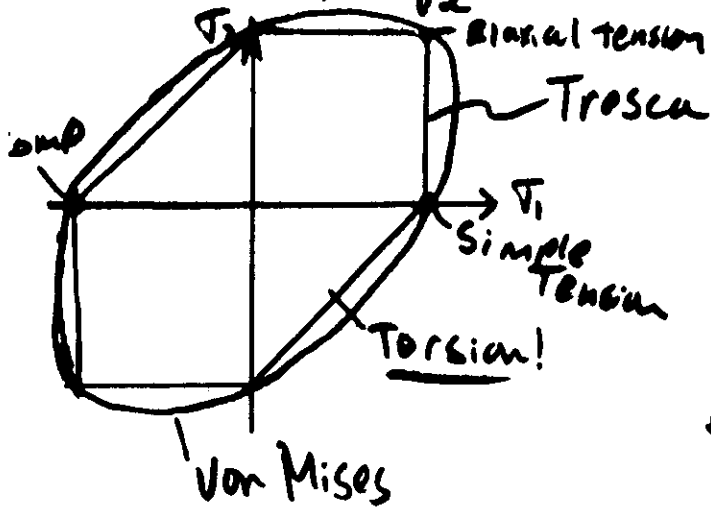
2) Need a flow law:

Tresca

$$\tau_{max} = \tau_{crit} = \frac{\sigma_1 - \sigma_3}{2} \Rightarrow \text{Flow}$$

Von Mises

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



This is all OK for yielding but we need a different formulation for Creep... →

Effective Stress and Strain

Based on previous criteria

Effective Stress, $\bar{\sigma}$

Tresca $\bar{\sigma} = 2\tau_{max} = \sigma_1 - \sigma_2$

Von Mises $\bar{\sigma} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_3)^2+(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2\right]^{\frac{1}{2}}$

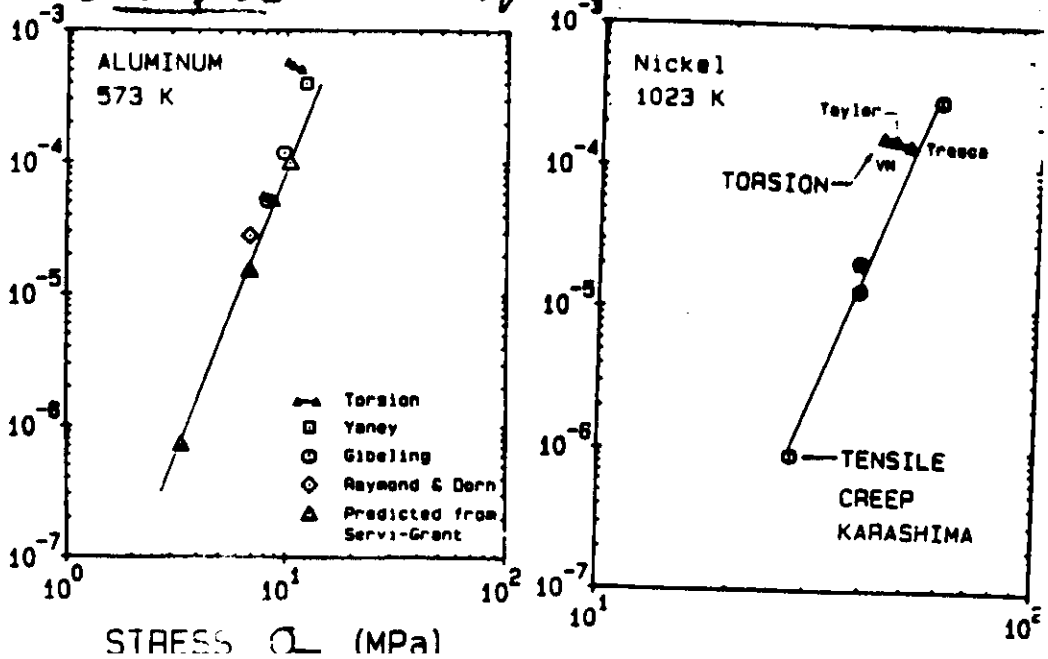
By work arguments, Effective Strain $\bar{\varepsilon}$

Tresca $\bar{\varepsilon} = \gamma/2$

Von Mises $\bar{\varepsilon} = \left[\frac{2}{3}(\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2)\right]^{\frac{1}{2}}$ — (Proportional Strain Plastic)

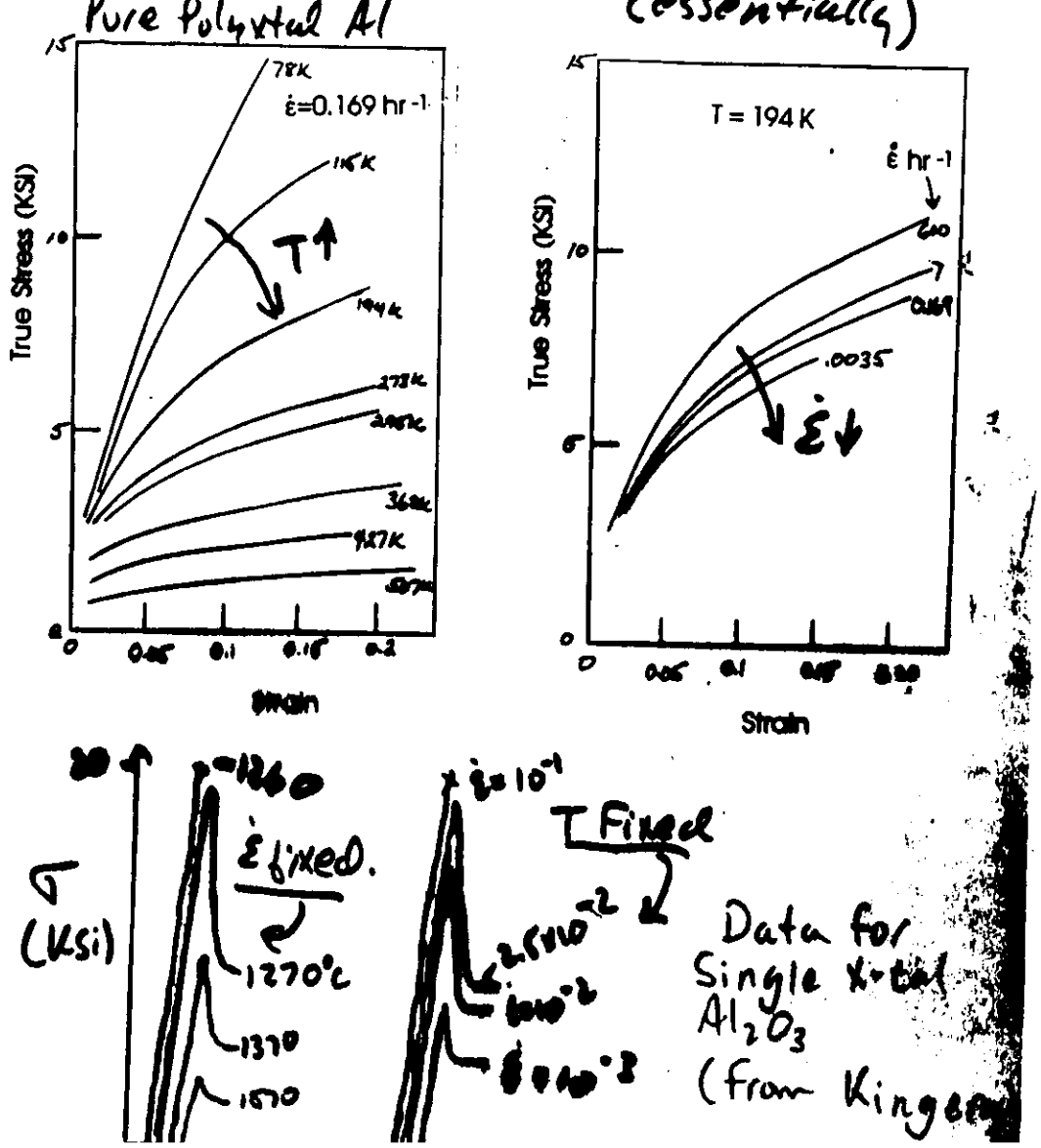
Note: This analysis applies to plastic def. **Only** flow via void formation requires a different analysis.

Examples



Effects of Temperature & $\dot{\varepsilon}$

$T\uparrow$ and $\dot{\varepsilon}\downarrow$ can be traded... (essentially)



Analysis

- Plastic deformation is a thermally activated process!

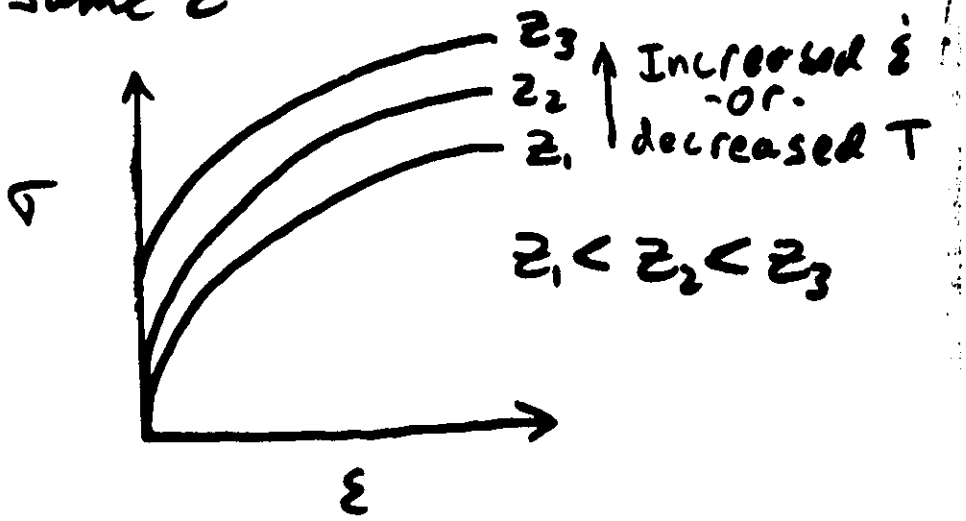
Zener-Holoman parameter, Z

$$\sigma = \Phi(\dot{\varepsilon}, Z)$$

$$Z = \dot{\varepsilon} \exp\left(\frac{\Delta H}{RT}\right)$$

← activation E. for plastic flow (also called Q)

Thus σ-ε curves will fall atop each other if performed at the same Z

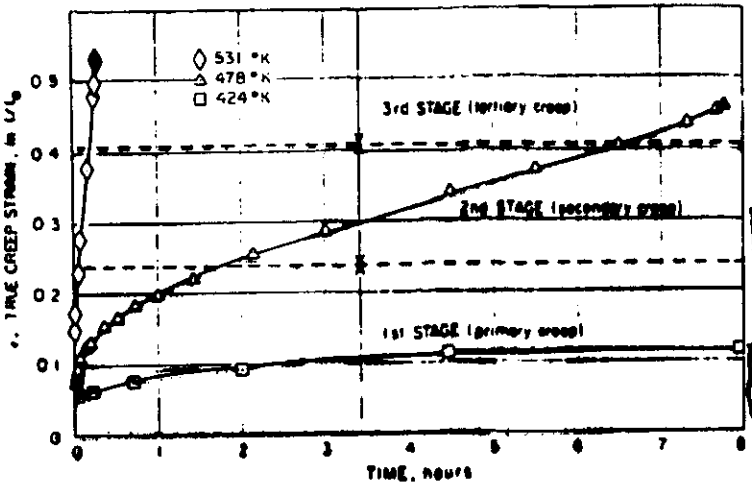


Reporting of yield stress is not meaningful

The Sherby-Orr-Dorn approach to Life Prediction.

Zener-Holoman in Creep!

Pure Polycrystalline Al at 3,000 psi

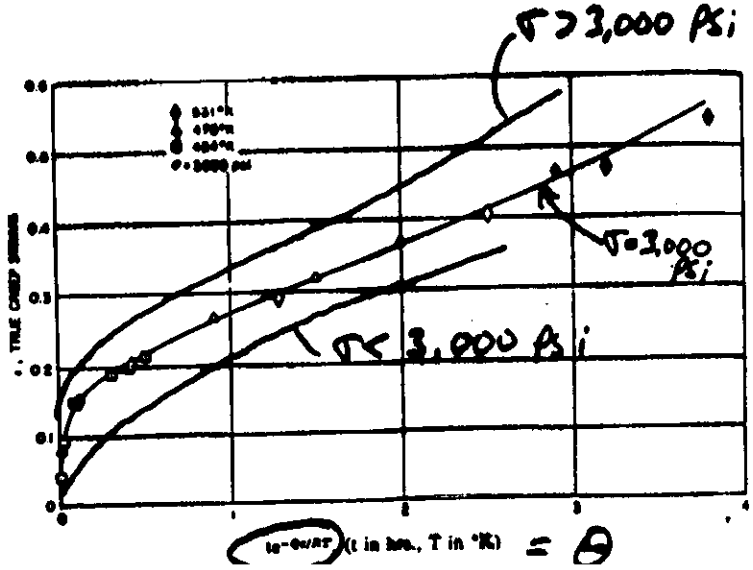


Here we say...

$$\dot{\varepsilon} = \Phi(\sigma, \theta)$$

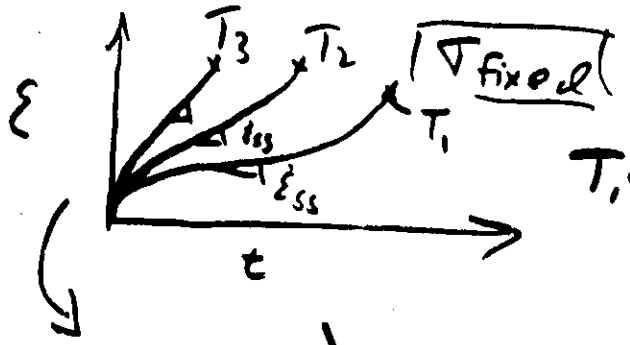
Where

$$\theta = t \exp\left(\frac{-Q_c}{RT}\right)$$

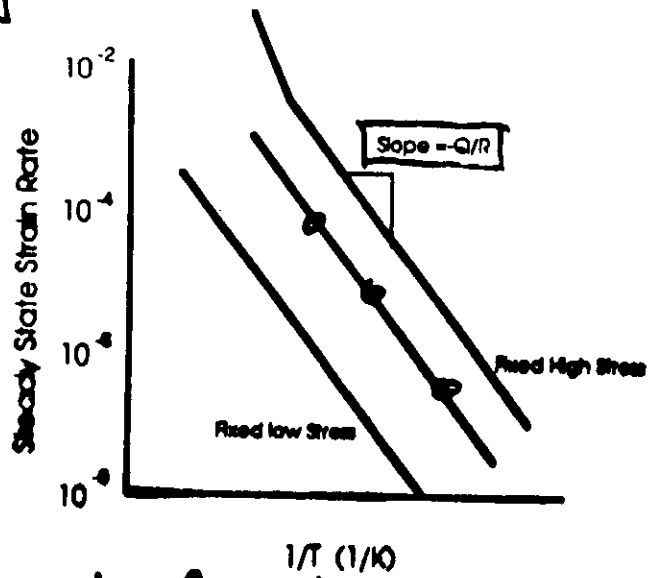


$Q_c \sim 35{,}000$ KJ/Mol

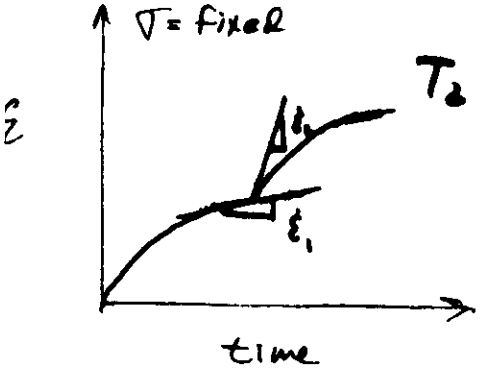
The usual way to determine Q_c



$T_1 < T_2 < T_3$



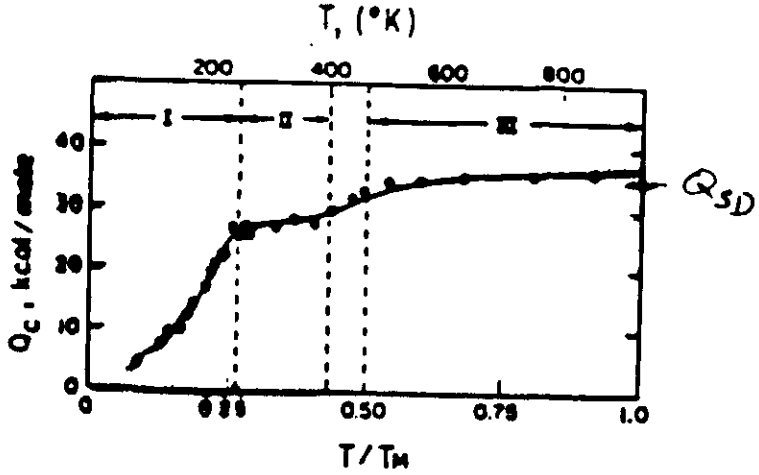
Or can be done by T change Expt's



$T_2 > T_1$

From this we find
1) $Q \neq f(\varepsilon)$ (usually)
2) $Q_c = Q_{SD}$
for $T > 0.6\,T_m$

Activation Energy as a f(T) for Pure Polycrystalline Aluminum

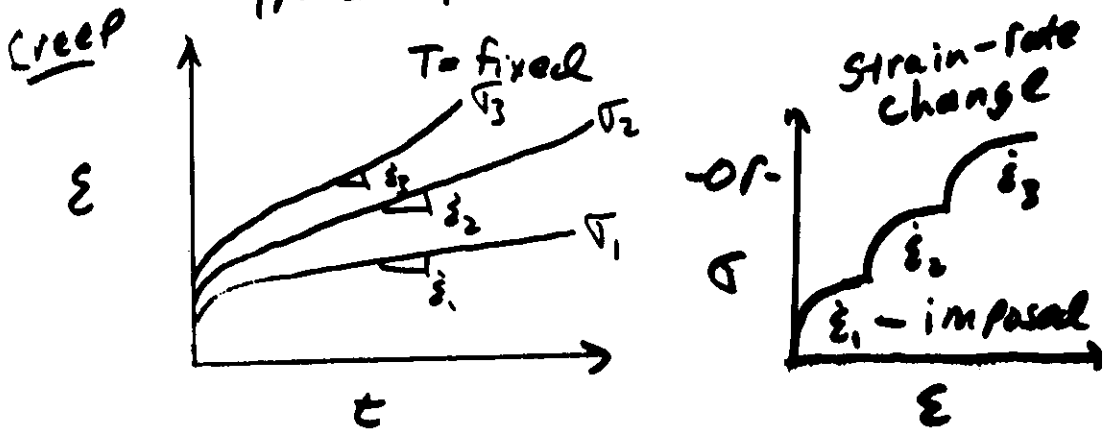


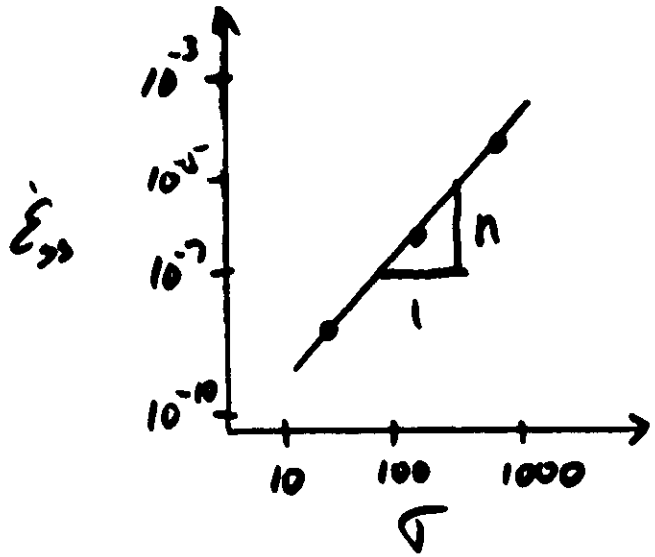
$Q_{SD} \approx 35\ KJ/mol$

from Tracer Experiments

The Stress Dependence of Creep

Typical Procedures





$$n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma}$$

$$m = \frac{1}{n} = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}$$

n is typically between 1 and 10

* Procedures for finding n & Q can influence Measurements

By the results presented, it is suggested that creep (each mechanism) can be described By

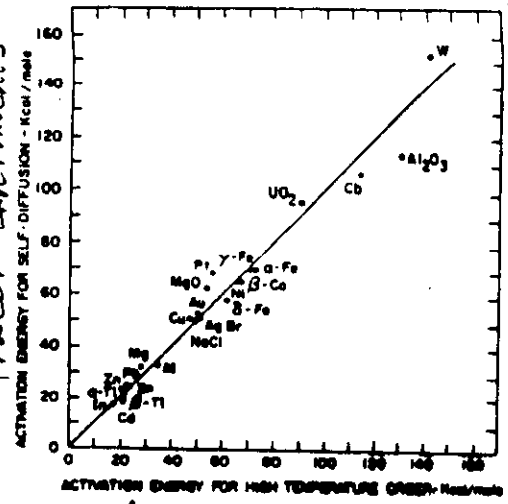
$$\dot{\varepsilon} = A \sigma^n \exp\left(\frac{-Q_c}{RT}\right)$$ (usually)

Further:
- n
- Q_c
- Transient Behavior
- Structure (grains, subgrains & dislocs)

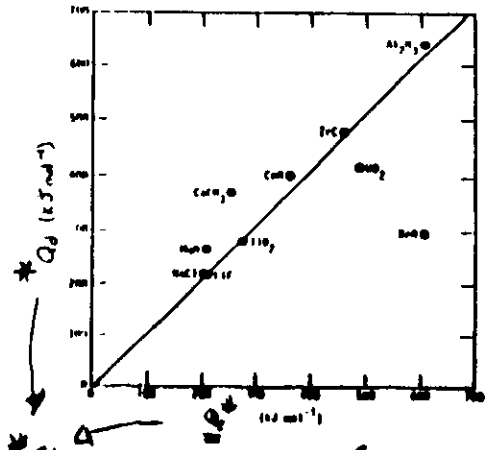
can be used to gain fundamental insight to creep deformation.

Evidence For Diffusional Control In Creep

Tracer Experiments



Creep Experiments

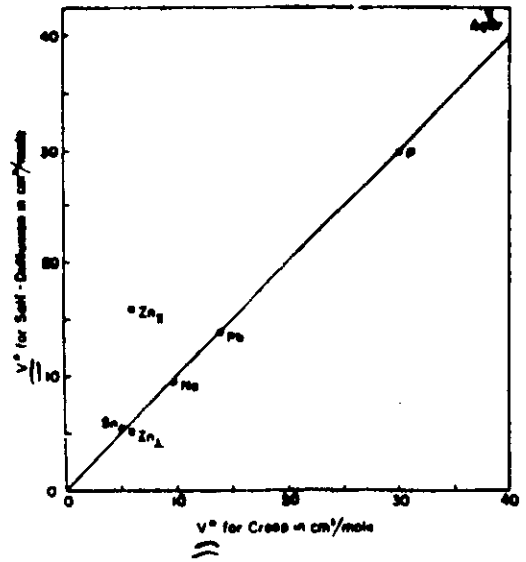


*Slowest species, on fastest Path.

1) Activation Energy ↗

2) Activation Volume ↘

[Above 0.5 T_m Creep (Even if by slip) is controlled by self-Diffusion]

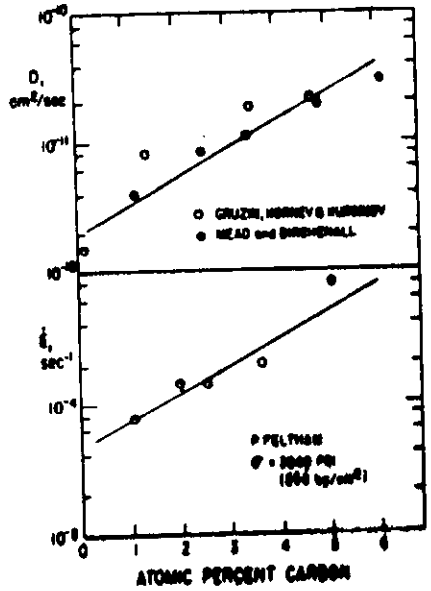


Activation Volumes

$$V_D^* = -RT \frac{\partial \ln D}{\partial P}$$

$$V_c^* = -RT \frac{\partial \ln \dot{\varepsilon}_s}{\partial P}$$

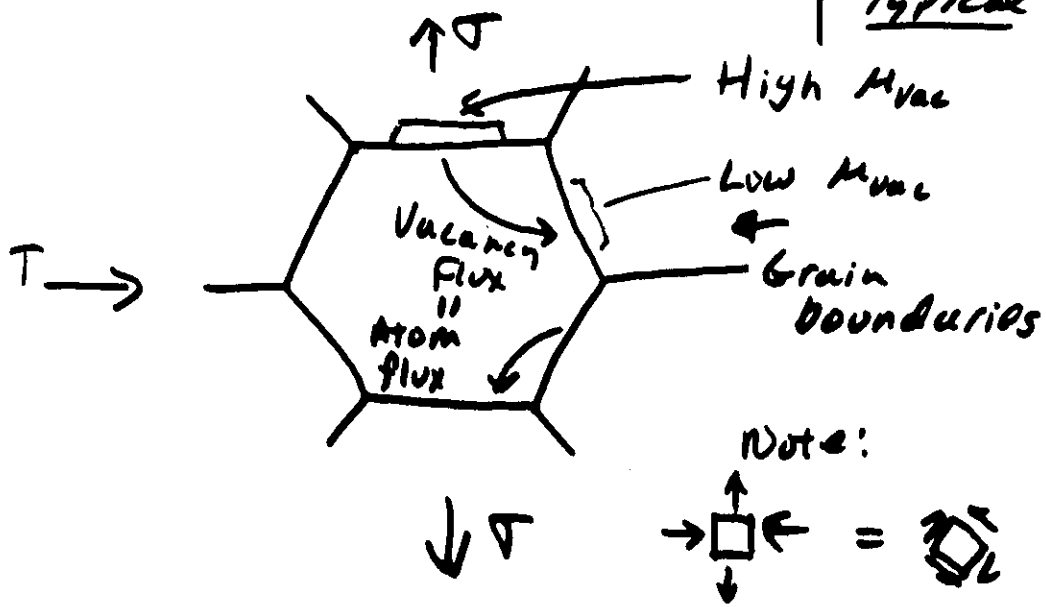
3) Effects of Solutes often have same effect on creep and self-Diffusion!



Next let's consider what mechanistic Processes can give rise to the behavior illuded to . . .

Diffusional Creep
(no dislocation Motion)

$T > 0.9 T_m$
$\sigma/E < 10^{-5}$
Typical



Energy barrier to Vacancy formation

Tensile: $E = (Q_f - \sigma b^3)$ comp: $E = (Q_f + \sigma b^3$

Vacancy concentration gradient sets up a diffusional flux. Diffusion down Both grain boundaries and Through the Lattice.

* Analogous problem to Sintering, but different driving force.

If Bulk Diffusion controlls:

Nabarro-Herring Creep:

$$\dot{\varepsilon} = 0.7 B \frac{D_L b}{kT} \left(\frac{b}{G}\right)^2 \sigma^1$$

B = Constant (Geometry) 12-40*
G = Grain size ; b = Burgers vector

Note: $n=1$, $Q = Q_L$, G^{-2}

If Grain boundary diffusion Dominates:

Coble creep:

$$\dot{\varepsilon} = 33.4 \frac{D_{gb} b}{kT} \left(\frac{d_{gb}}{b}\right) \left(\frac{b}{G}\right)^3 \sigma^1$$

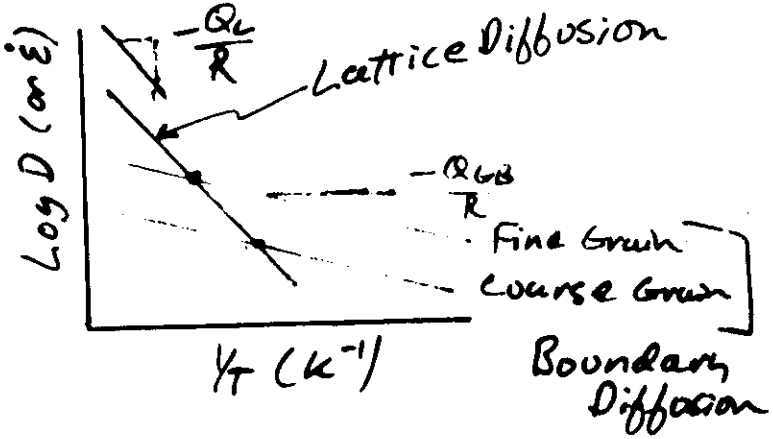
d_{gb} = boundary thickness

$n=1$, $Q = Q_{gb} \approx 0.6 Q_L$, G^{-3}

- Actually Both Are Active!

But one is usually Strongly favored...

* increasing Grain aspect ratio, in the direction of applied stress reduces creep rate (longer diffusion



The Plot shows Coble (Grain boundary) Creep is favored at:
+ Small grain sizes
+ Lower Temperatures.

- Grains are elongated by diffusional Creep
  - Boundary sliding is required to fill space
- Microstructural Evidence "Proves" diffusional creep

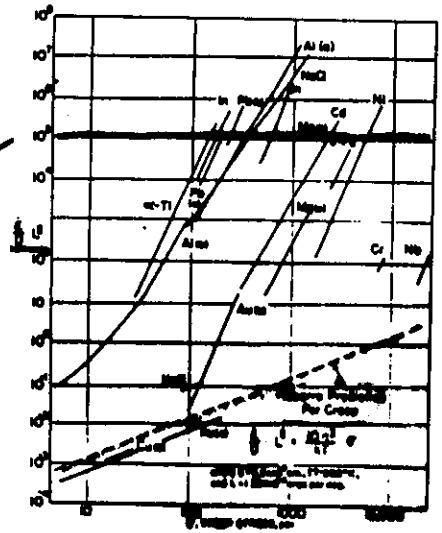
Oxide dispersion Strengthened Alloy
← Oxide-free Zones.

Diffusional flow in Ceramics

- Diffusion of Slowest species (usually anion) down the fastest path controls rate.
- If multi-component ceramic (e.g. Y_2O_3 stabilized ZrO_2) we may expect segregation of the faster component to the tops of the grains (not yet observed, however)
- There is a mechanism similar to Diffusional flow (in response), Harper-Dorn creep. Not understood. But,
  - $n = 1$
  - $Q_c = Q_L$
  - Based on motion of dislocations
  - $\dot{\varepsilon}$ is independent of G.
  - Also occurs @ $T > 0.9\,T_m$ and Low stress.

Consider flow @ higher stresses

Slip Creep



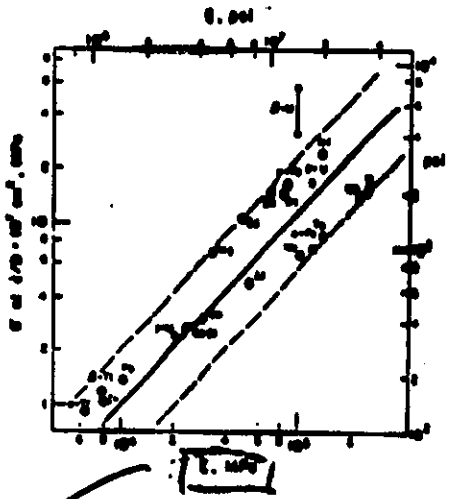
$\frac{\dot{\varepsilon}}{D_L}$

There is a trend in this range

$n \simeq 5$ for Slip Creep.

$$\sigma_{flow} \doteq \sqrt[5]{\frac{\dot{\varepsilon}}{D_L}}\ \underline{K(M)}$$

$K(M)$ ← Fn of Metal's Properties



Compare Location on Plot above W/ Modulus ...

Dynamic Darolewell Plastic

From this we see Creep resistance has a first-order correlation with Elastic Modulus.

This is expected since the stress field associated with a dislocation varied with E.

We can now Estimate Slip creep rate as

$$\dot{\varepsilon}_{ss} \doteq \frac{10^{n}}{b^{2}} D_L \left(\frac{\sigma}{E}\right)^{5}$$

Above 0.6 T_m This empirical relation predicts the creep rates of simple metals within a factor of ~10^{2-10} (or σ at $\dot{\varepsilon}$ fixed within a factor of ~3).

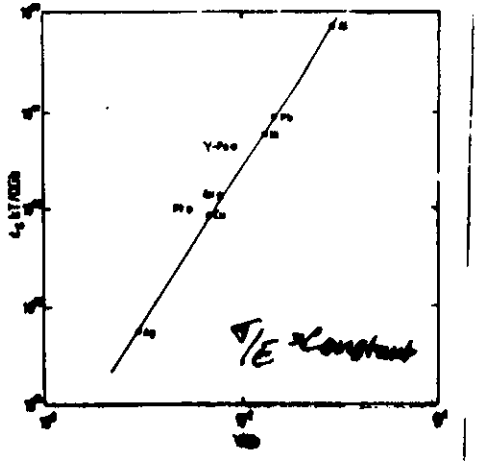
Also, to find Q_c in the above Eq'n we should hold (σ/E) – not σ – constant, and measure $\dot{\varepsilon}$ as $f(T)|_{\sigma}$.

If done at σ fixed Anomalously Large Q_c is found...

$$Q_c^{True} = Q_c^{App} + \frac{\Delta R I^2}{E}\left(\frac{dE}{dT}\right)$$

↑ ↑

The correlation can be further Enhanced by consideration of Stacking fault Energy.

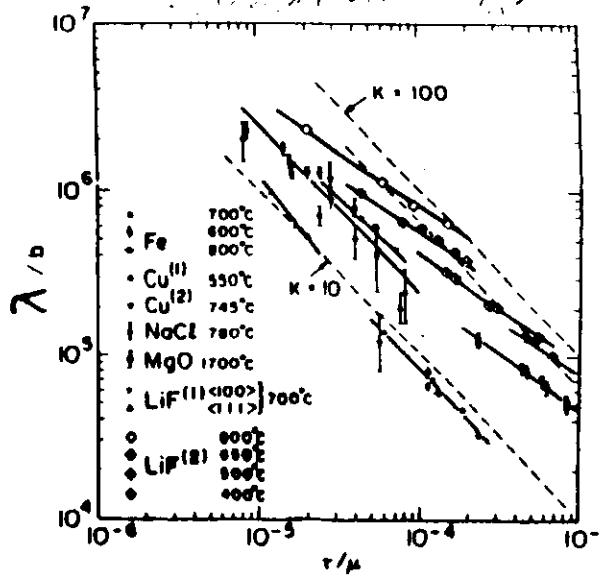


Using this information the empirical relation can be refined to:

$$\dot{\varepsilon}_{ss} = A D_L \left(\frac{\chi}{Gb}\right)^3 \left(\frac{\tau}{E}\right)^5$$

stopped

Dislocation Size Varies w/ Stress



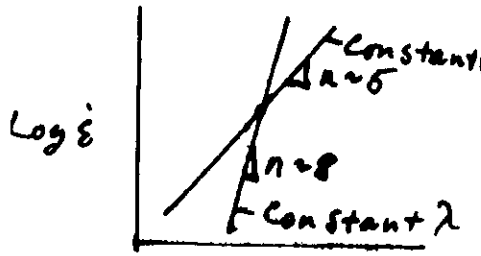
$$\frac{\lambda}{b} = K\left(\frac{\tau}{E}\right)^{-1}$$

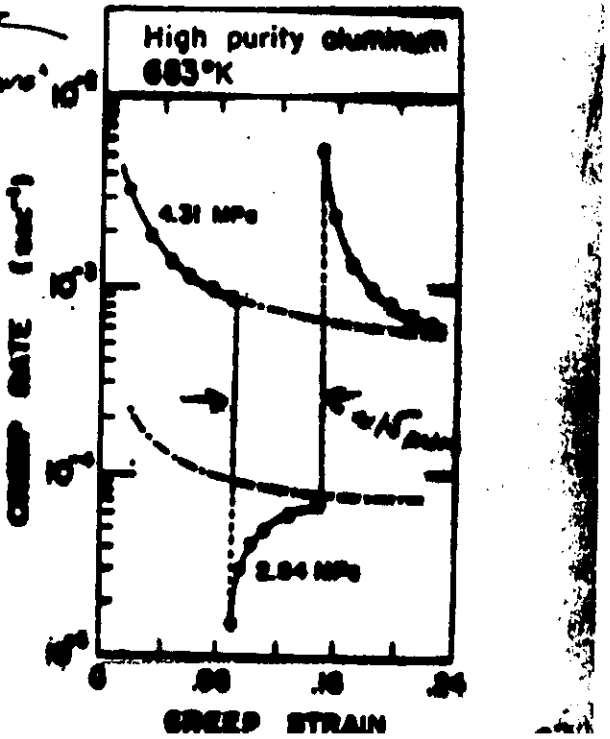
$K \sim 10$ for Metals
$\sim 25-100$ for Ceramics

Effect of fixing λ by Sudden σ change

$$\dot{\varepsilon} = A \frac{D_{eff}}{b^2}\left(\frac{\lambda}{b}\right)^3 \left(\frac{\tau}{E}\right)^8$$ ← "Constant Structure"

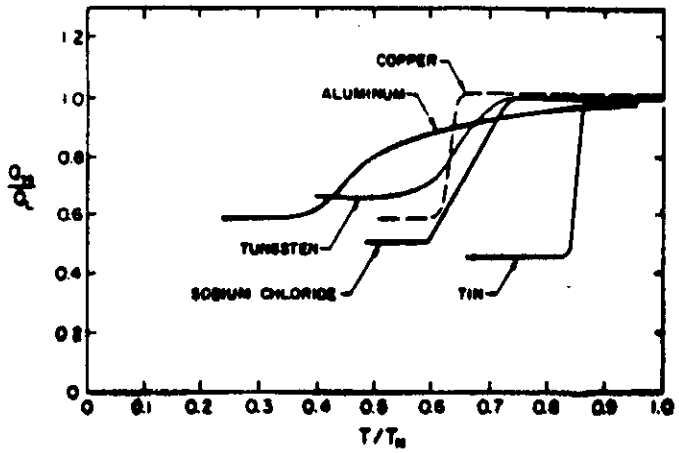
Note: There seems to be a higher Stress exponent if λ is fixed

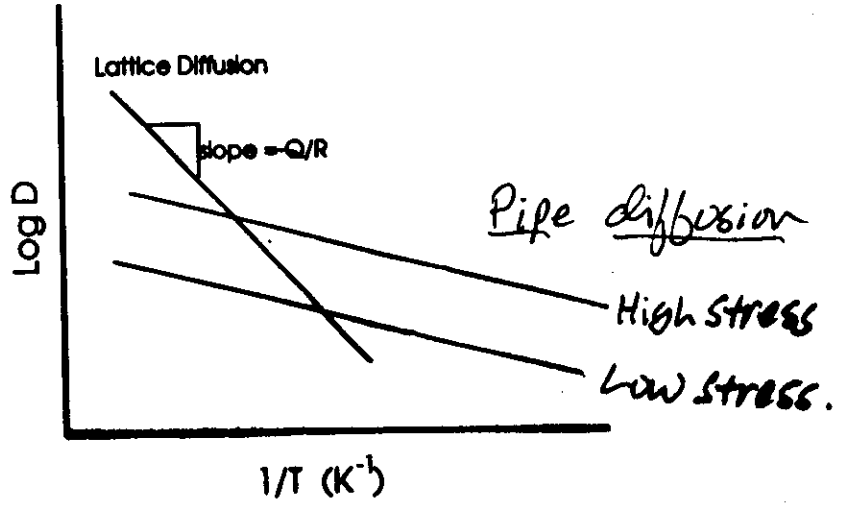




Support For Effective Diffusion Concept

Data Taken in Steady State.





We Expect a transition, which is affected by stress.

Low T → Pipe diffusion

then

$$\dot{\varepsilon} = A\, D_p \left(\frac{\sigma}{E}\right)^5$$

But $D_p \propto \sigma^2$

∴ Effective Stress Exponent

$= 5 + 2$

$= 7$ → This trend is seen.

Another refinement (slightly Controversial)

1) use "Effective" Diffusion coefficient

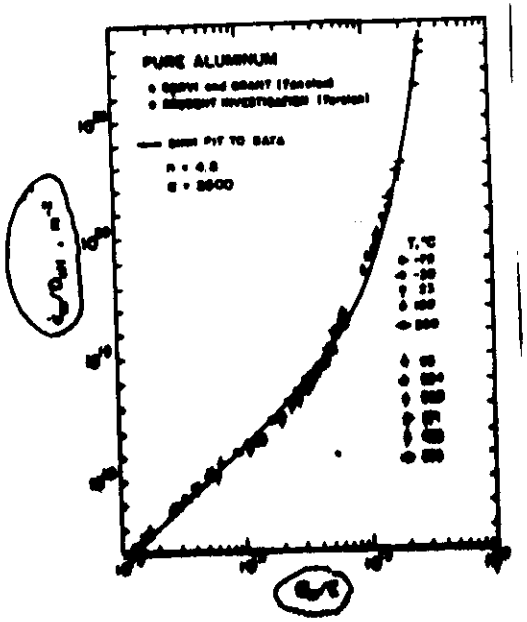
$$D_{eff} = f_c D_L + A\rho D_p + B\frac{1}{d} D_{gb}$$

-or-

$$D_{eff} = D_L + 100\left|\frac{\nabla}{E}\right|^2 D_p$$

2) Use $\dot{\varepsilon} = A D_{eff} (\sinh \sigma)^n$

TO fit high stress behavior



Note: Graph is not a f(T)!

With these refinements, Lothy Miller & Sherby were able to correlate Slip Creep data for Al over 21 orders of Magnitude