Mechanical Behaviour of Materials

Chapter 04-1

Creep

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Alloys for high temperature applications

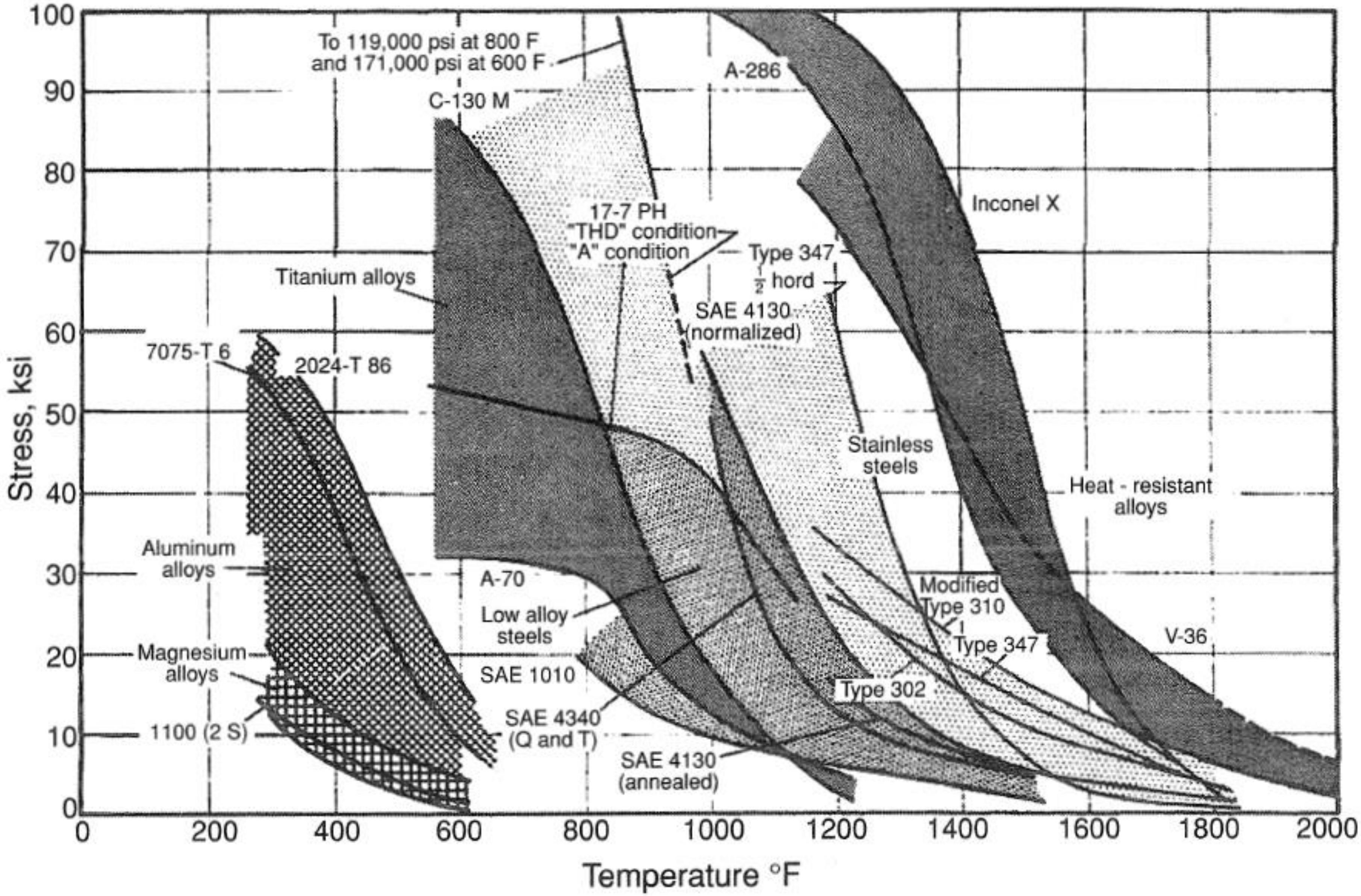


Figure 16.17. Strength of various alloys at high temperatures. From J. A. van Echo, *Short-Time High Temperature Testing*, ASM International (1958).

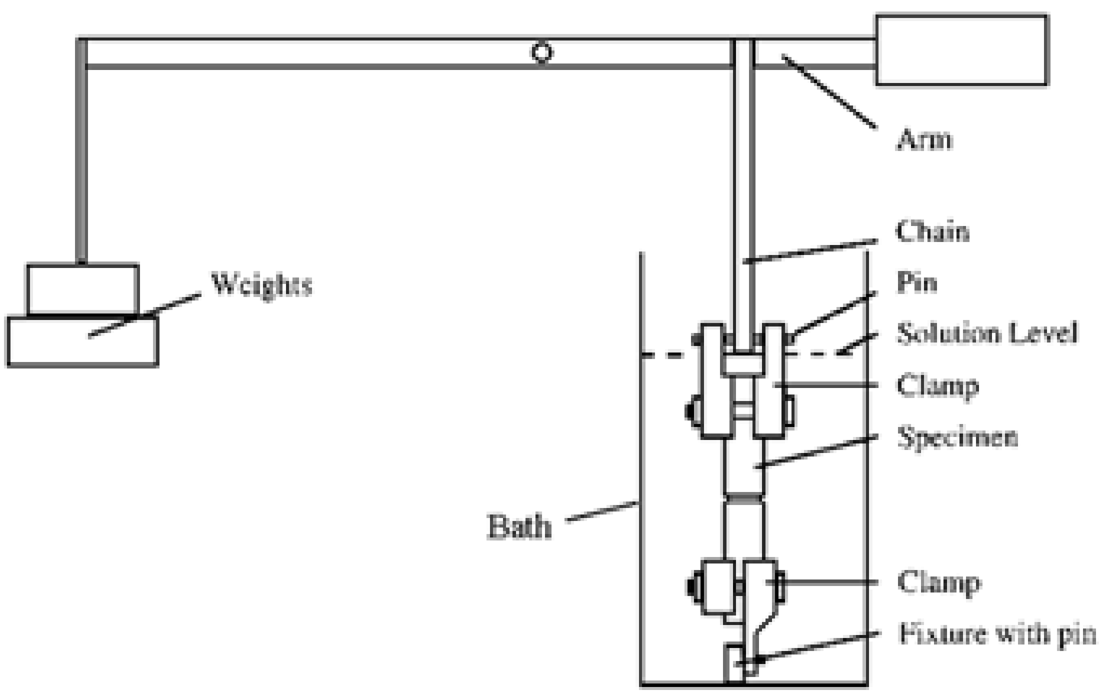
What is Creep?

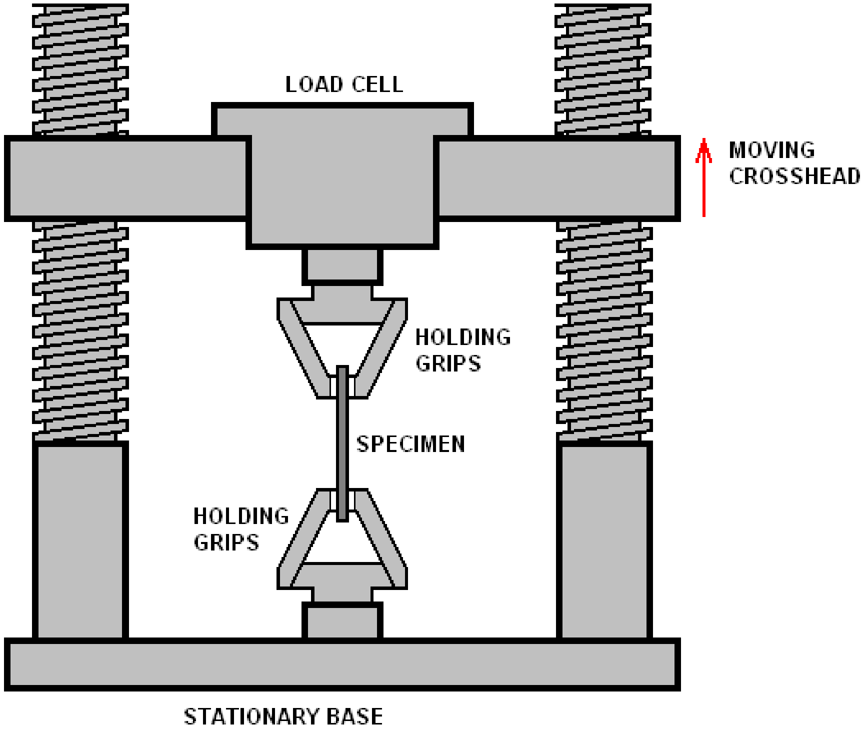
Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly 0.5 *Tm*, where Tm is the absolute melting temperature, that is, continuous plastic deformation under constant load or stress.

Creep occurs at some temperature and thus as being thermally activated is associated with diffusion. This may occur either by lattice diffusion or grain-boundary diffusion, or both may be involved.

Creep versus Tension test

<u>Creep</u>: A **time-dependent plasticity** when subjected to a constant load at a **high temperature** (> 0.4 Tm).
Examples: turbine blades, steam generators.

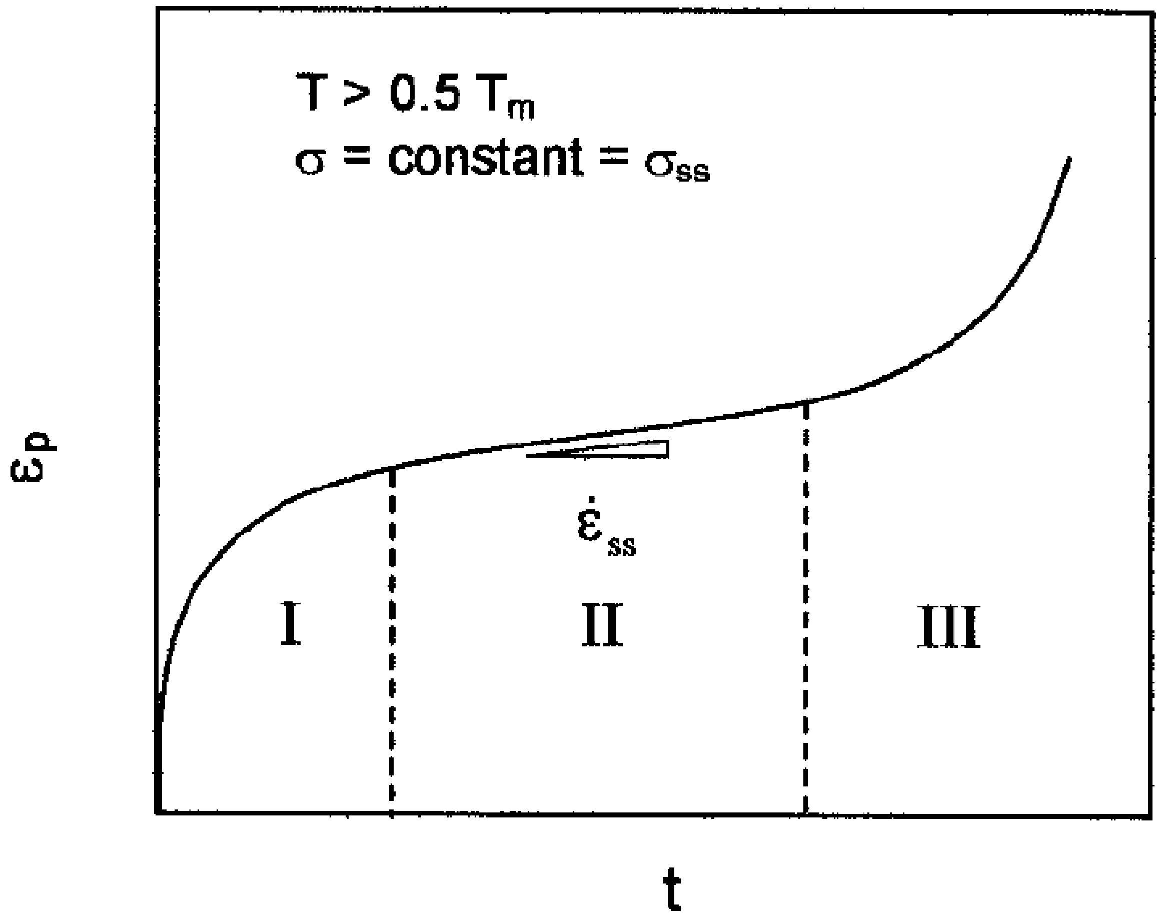




Creep test: constant Load

Tension: constant strain rate

Phenomenological description: creep curve at constant stress

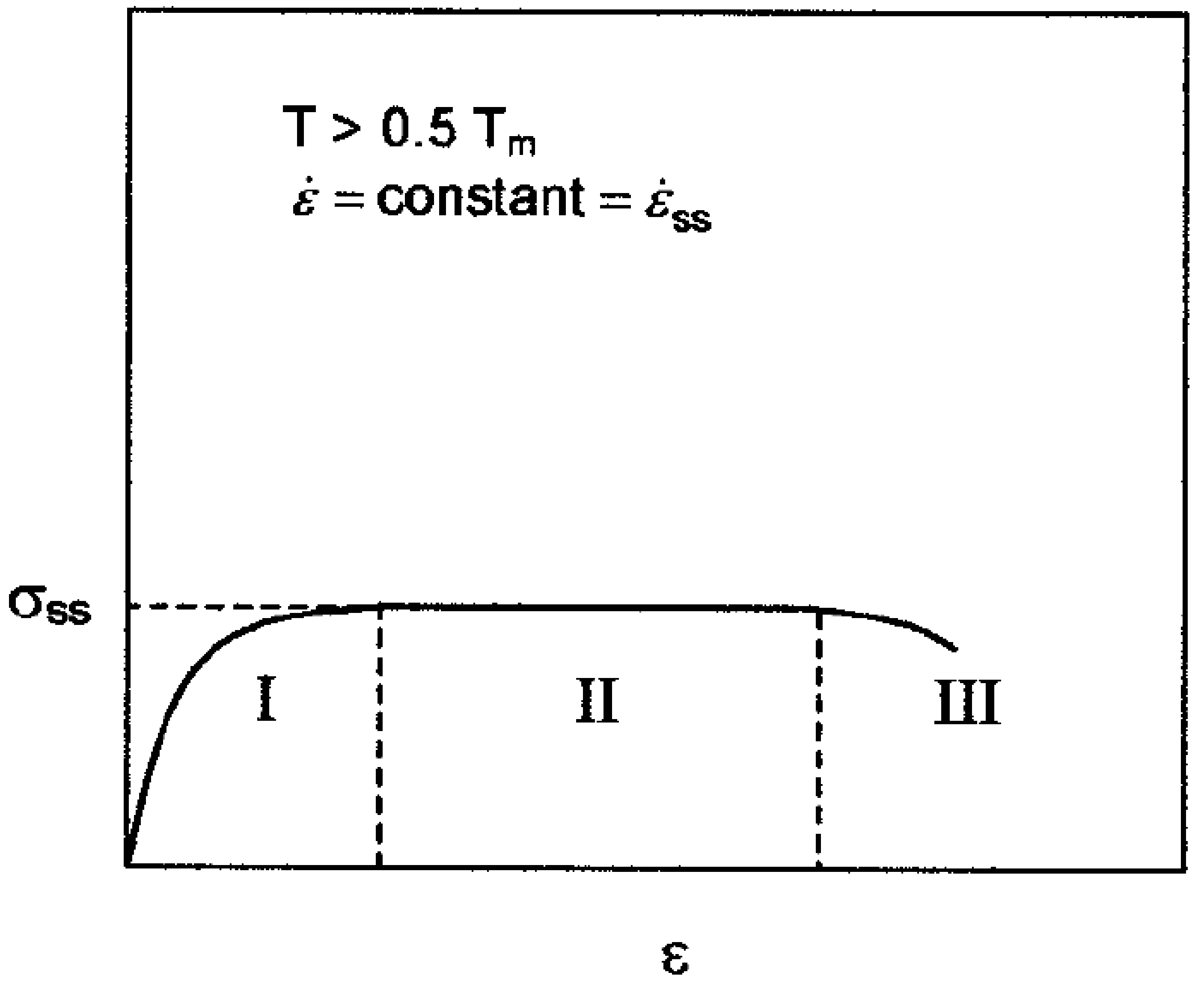


Primary/transient creep: slope of strain vs. time decreases with time (work-hardening)

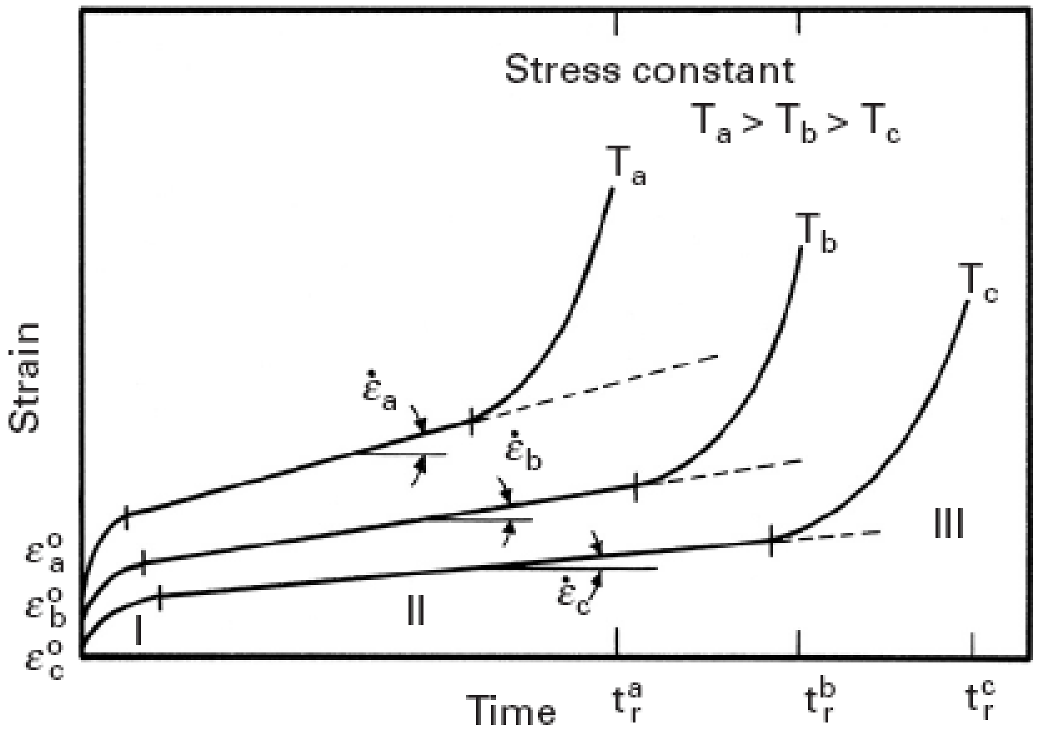
Secondary/steady-state creep: rate of straining is constant (balance of work-hardening and recovery)

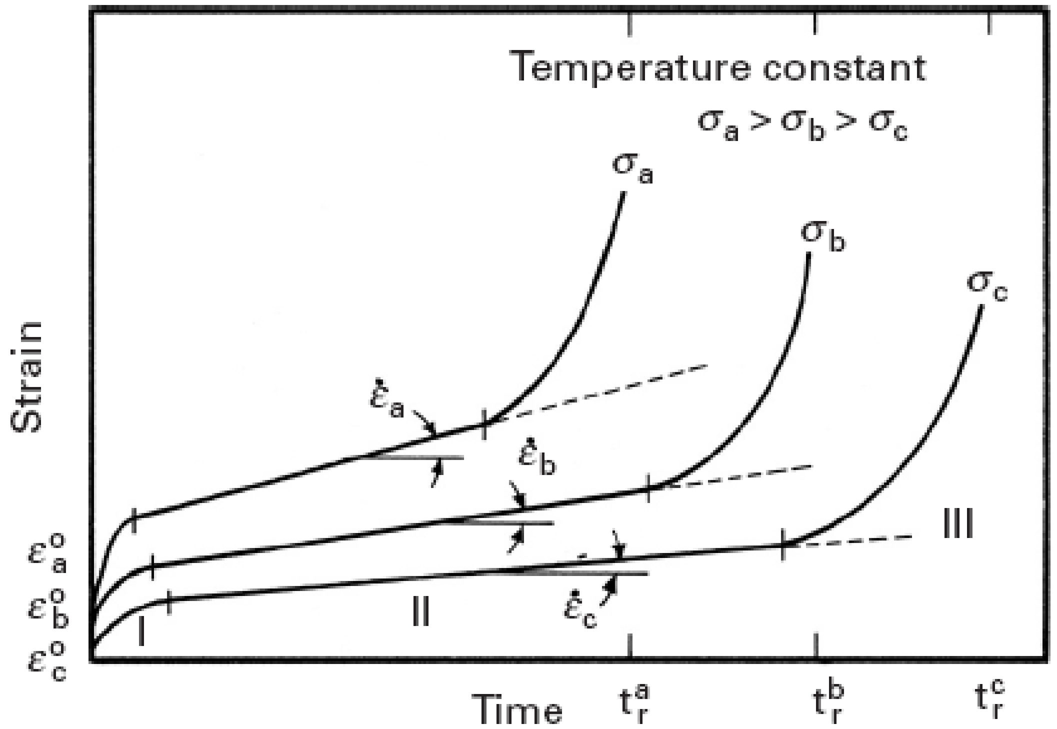
Tertiary: rapidly accelerating strain rate up to failure: formation of internal cracks, voids, grain boundary separation, necking, etc.

Phenomenological description: creep curve at constant strain-rate



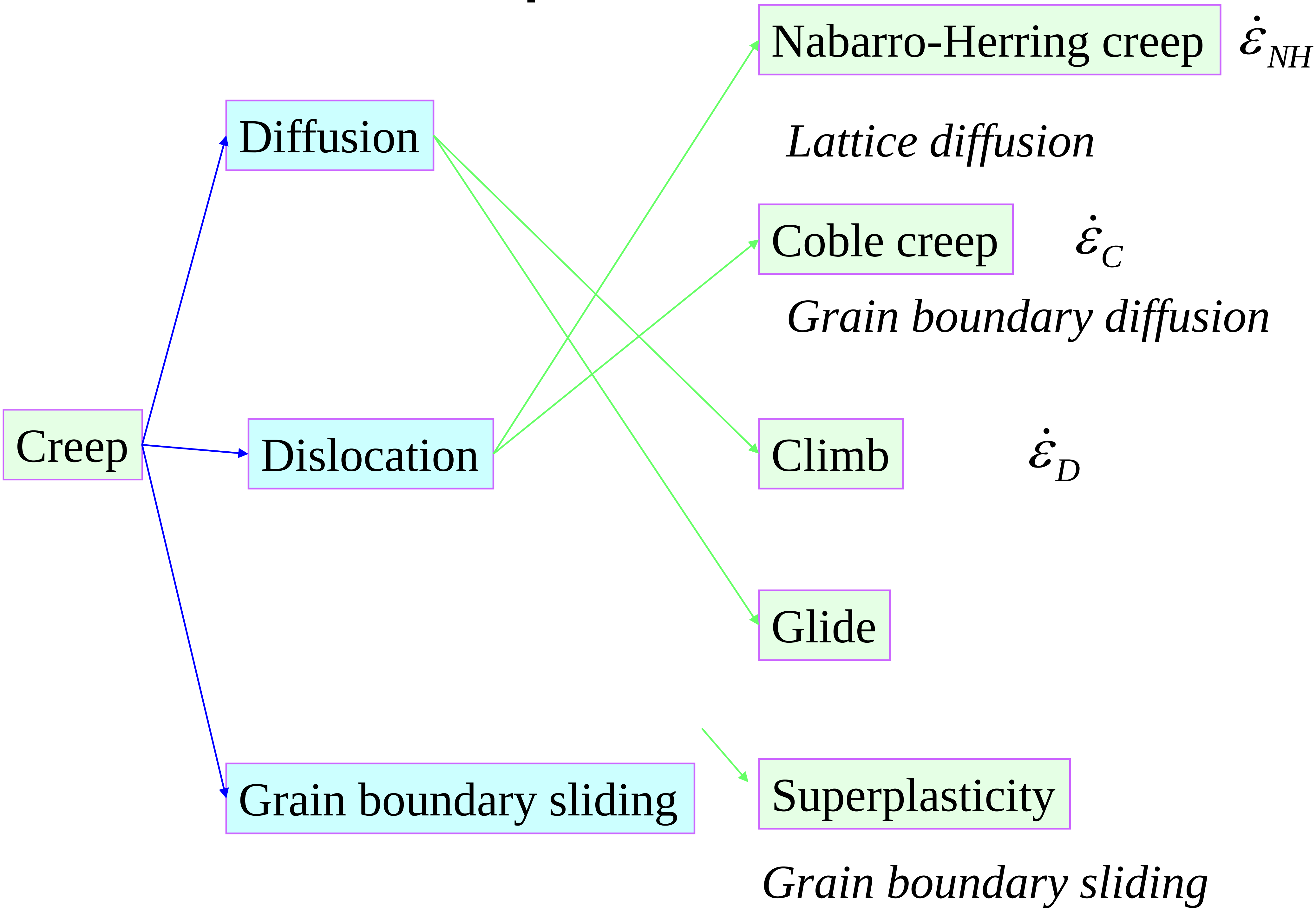
Effects of Stress and Temperature on Creep





- The instantaneous strain increases
- The steady-state creep rate increases
- The time to rupture decreases

Mechanisms of Creep



Creep mechanisms

(a) Nabarro-Herring creep

(b) climb, in which the strain is actually obtained by climb

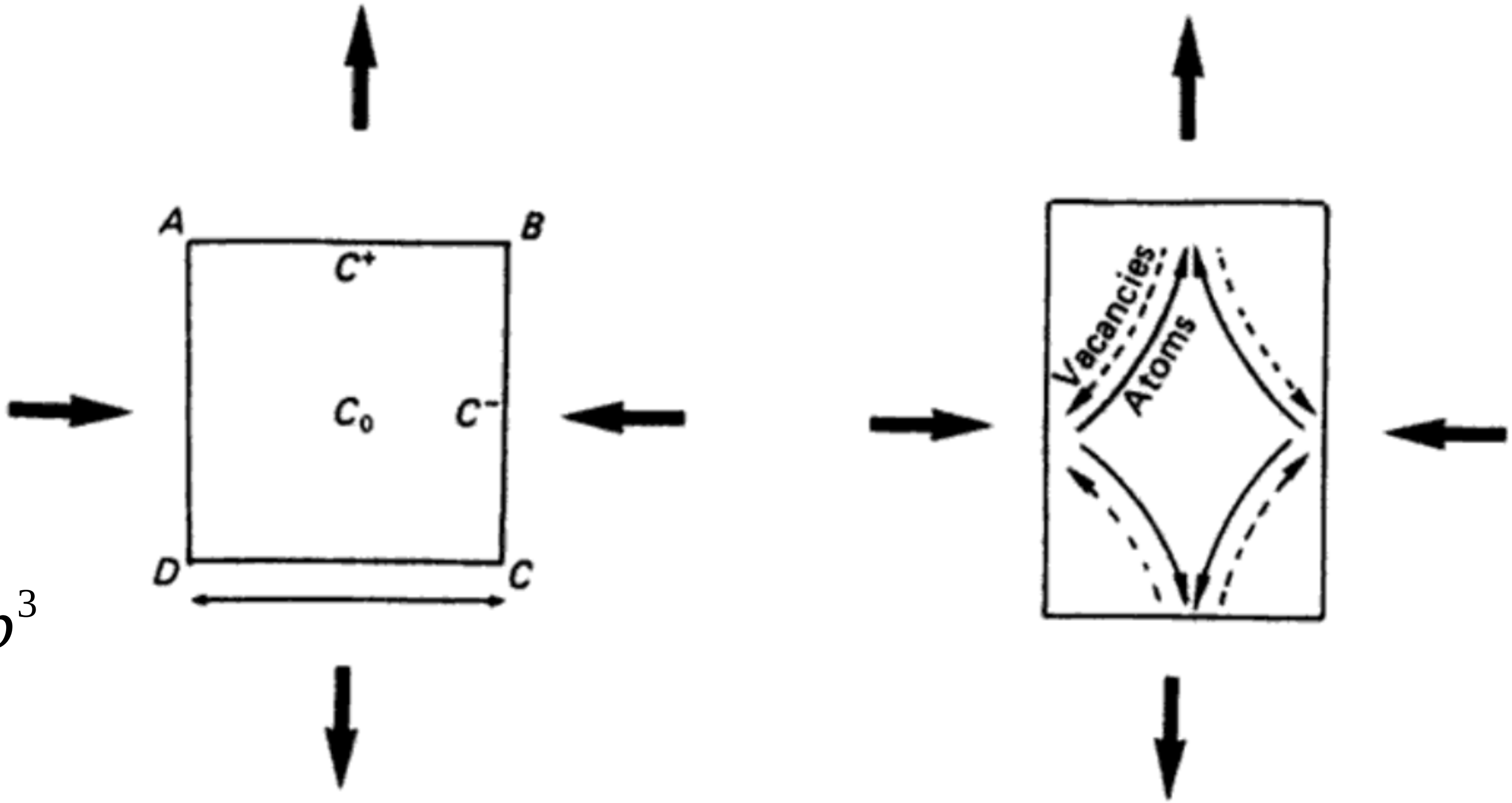
(c) climb-assisted glide, in which climb is a mechanism allowing dislocations to bypass obstacles

(d) thermally activated glide via cross-slip

(e) Coble creep, involving grain-boundary diffusion

Bulk-diffusion-assisted creep: (a)–(d)
Grain-boundary diffusion: (e)

(I) Schematics of Nabarro-Herring (N-H) creep $\dot{\varepsilon}_{NH}$



$$\Omega = b^3$$

At a given temperature T, the thermal equilibrium concentration of vacancies in the crystal is C_0, where N_v is the equilibrium atomic fraction and b^3 is the atomic volume. The concentration at faces in tension C is higher than that at faces in compression. Vacancies flow from faces in tension to faces in compression and matter flows in the opposite sense.

Definitions of N-H creep

C_0	the total number of available atomic sites per unit volume
Q_f	the formation energy of vacancies
k	the Boltzmann constant
T	the absolute temperature
d	grain size
Q_m	the activation energy for vacancy migration

Definitions of N-H creep-conti.

$\Omega = b^3$ the volume of vacancy

b^2 the cross-section area exposed to the stress

$\sigma b^2 \cdot b$ the work done by the stress due to removing an atom

C^+ the vacancy concentration at the tensile stress

C^- the vacancy concentration at the compression stress

b the average jump distance of vacancy

Excess concentration of vacancies

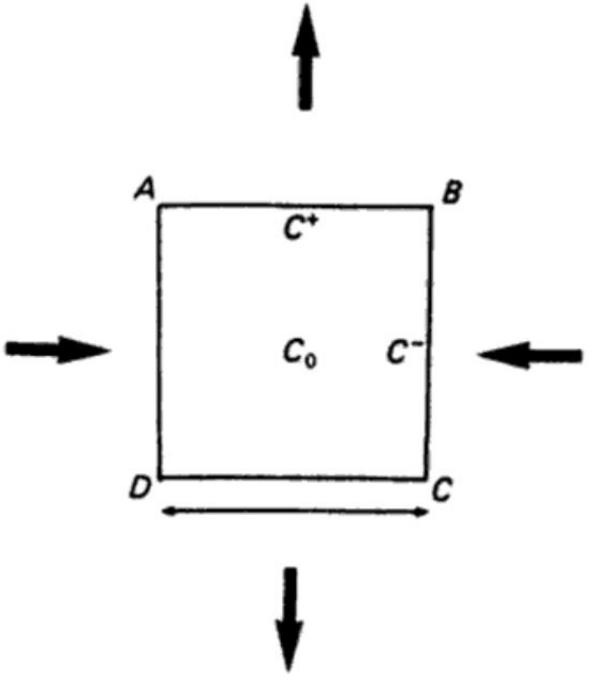
The thermal equilibrium concentration of vacancies C_0, and the activation energy are expressed from the unstressed values by

$$C_0 = e^{-Q_f / kT}$$

The thermal equilibrium concentration of vacancies at faces AB and BC is respectively by

$$C^+ = e^{-(Q_f - \sigma b^3) / kT}$$

$$C^- = e^{-(Q_f + \sigma b^3) / kT}$$



Fick's first law

The flux of vacancies is given by Fick's equation:

$$J_V = -D_V \nabla C_V = D_V \frac{\Delta C}{\Delta x} \qquad D_V = D_0 e^{-Q_m / kT}$$

where the distance over which the diffusion occurs is approximated by the grain diameter $\Delta x = d$

$$\Delta C_V = C^+ - C^- = C_0 \left(e^{\frac{\sigma\Omega}{kT}} - e^{\frac{-\sigma\Omega}{kT}} \right) \approx C_0 \cdot \frac{2\sigma \cdot \Omega}{kT}$$

$$\Delta x = d$$

$$D_V \frac{\Delta C_V}{\Delta x} = D_0 e^{-(Q_f + Q_m) / kT} \cdot \frac{2\sigma \cdot \Omega}{d \cdot kT} = D_S \cdot \frac{2\sigma \cdot \Omega}{d \cdot kT}$$

Creep strain rate

$$Q_s = Q_f + Q_m$$

the area of a grain boundary facet *A* is approximated by d^2 and Q_S is the activation energy for self-diffusion

$$\dot{\varepsilon}_{NH} = \frac{\Delta d}{d} \cdot \frac{1}{\Delta t} = \frac{1}{d^3} \cdot \frac{\Delta d \cdot d^2}{\Delta t} = \frac{1}{d^3} \cdot \frac{\Delta V}{\Delta t}$$

$$\dot{\varepsilon}_{NH} = \frac{1}{d^3} \cdot J_v \cdot d^2$$

$$J_V \cdot \mathrm{A} = \frac{\Delta V}{\Delta t}$$

$$= D_S \cdot \frac{2\sigma \cdot \Omega}{d^2 \cdot kT}$$

$$J_V = D_S \cdot \frac{2\sigma \cdot \Omega}{d \cdot kT}$$

Summary of N-H creep

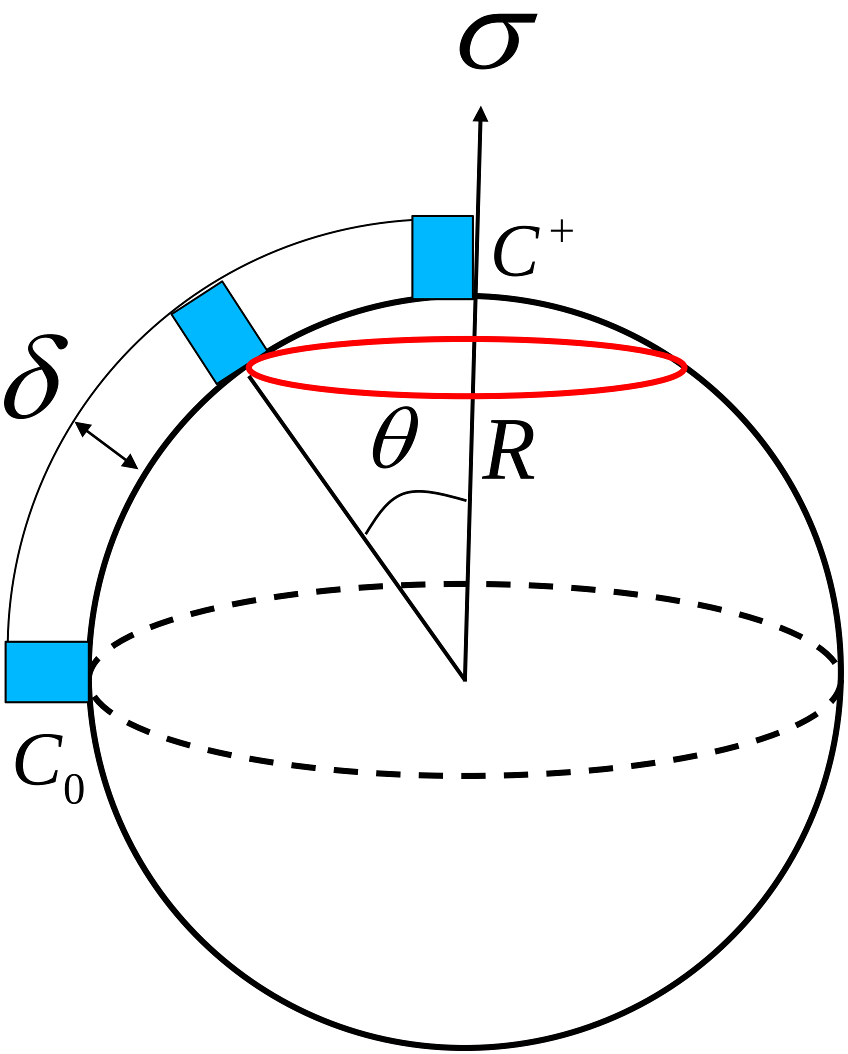
Thus, the strain rate is the rate of change of strain:

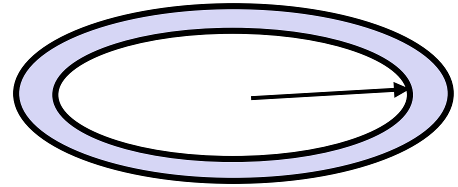
$$\dot{\varepsilon}_{NH} = \frac{2D_s}{d^2} \cdot \frac{\sigma\Omega}{kT}$$

$$\dot{\varepsilon}_{NH} = A_{NH} \cdot \frac{D_s}{d^2} \cdot \frac{\sigma\Omega}{kT}$$

Note the grain size dependence!

(II) Schematics of Coble creep





$$A = 2\pi R\sin\theta \cdot \delta$$

If the top spherical cap surrounding the pole generates vacancies, then the lower annular section surrounding by the equator supplies an equal number of atoms at $\theta=60^o$.

$$\Delta C_V = C^+ - C_0 \approx C_0 \cdot \frac{\sigma \cdot \Omega}{kT}$$

$$A_{top} = A_{top} = \pi R^2$$

Fick's first law

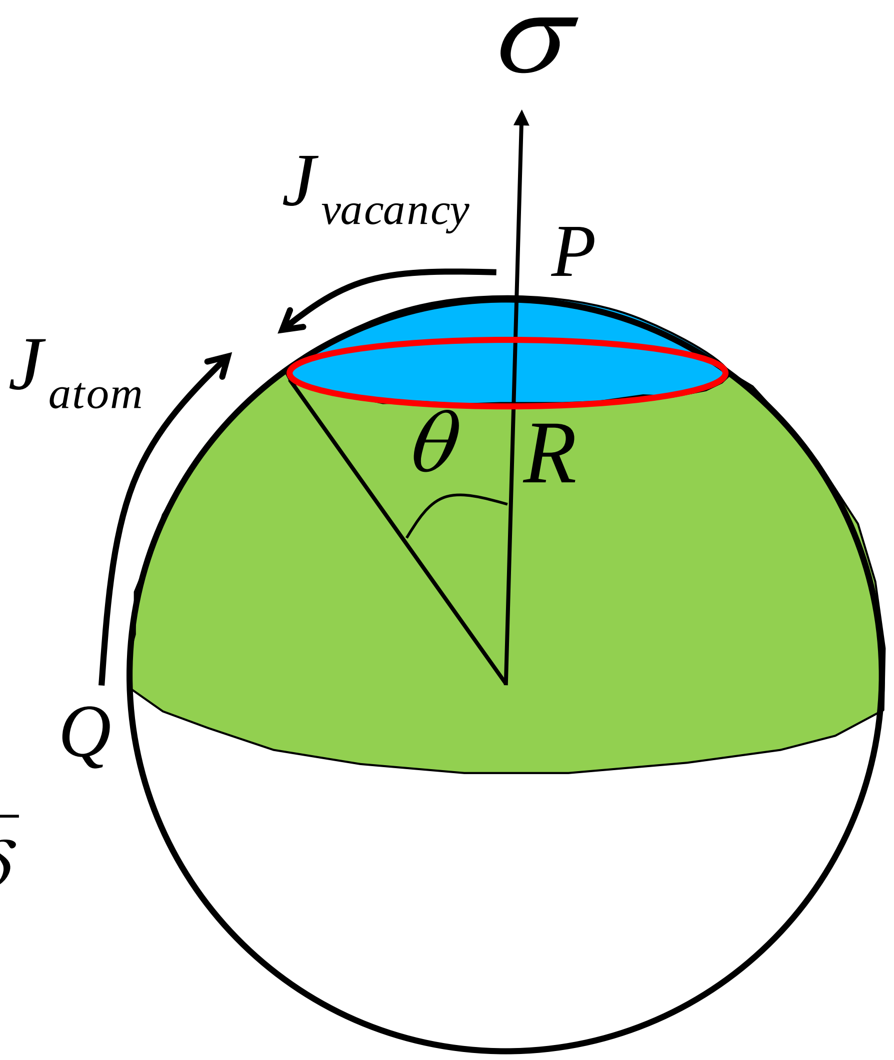
The average concentration gradient along the path PQ is

$$\frac{\Delta C_V}{\pi R/2} = \frac{0.432}{\pi/2} \cdot \frac{BR}{D_V \delta} = 0.275 \frac{BR}{D_V \delta}$$

The maximum concentration gradient at θ=60°. boundary is

$$\left(\frac{dC_V}{R d\theta}\right)_{\theta=60^o} = \cot 60^o \cdot \frac{BR}{D_V \delta} = 0.577 \frac{BR}{D_V \delta}$$

$$N = \left(\frac{dC_V}{R d\theta}\right)_{\theta=60^o} \Bigg/ \frac{\Delta C_V}{\pi R/2} = 2.1$$



$$A_{top} = 2\pi R^2 \cdot (1 - \cos\theta)$$

$$A_{low} = 2\pi R^2 \cdot \cos\theta$$

Maximum flux

The maximum flux at θ=60^o boundary is

$$J(vac/s) = \mathrm{D_V}\left(\frac{dC_V}{Rd\theta}\right)_{\theta=60^o} \cdot 2\pi \mathrm{R}\delta \sin 60^o$$

$$= \mathrm{D_V} N \frac{\Delta C_V}{\pi R/2} \cdot 2\pi \mathrm{R}\delta \sin 60^o = 7.3\mathrm{D_V}\delta \cdot \Delta C_V$$

$$\dot{\varepsilon}_{Coble} = \frac{\Delta R}{R} \cdot \frac{1}{\Delta t} = \frac{1}{\pi R^3} \cdot \frac{\pi R^2 \cdot \Delta R}{\Delta t} = \frac{1}{\pi R^3} \cdot \frac{\Delta V}{\Delta t}$$

$$\dot{\varepsilon}_{Coble} = \frac{1}{\pi R^3} \cdot \left(7.3\mathrm{D_V}\delta \cdot \Delta C_V\right)\Omega$$

$$J \cdot \Omega = \frac{\Delta V}{\Delta t}$$

Coble creep rate

$$\dot{\varepsilon}_{Coble} = \frac{1}{\pi R^3} \cdot \left(7.3 \mathrm{D_V} \delta \cdot \Delta C_V\right)\Omega$$

$$= 7.3 \frac{\mathrm{D_V}\delta}{\pi R^3} \cdot \left(C_o \frac{\sigma\Omega}{kT} \right) \cdot \Omega$$

$$= 7.3 \frac{\mathrm{D_{gb}}\delta}{\pi R^3} \cdot \frac{\sigma\Omega}{kT} = 18.6 \mathrm{D_{gb}} \frac{\delta}{d^3} \cdot \frac{\sigma\Omega}{kT}$$

the effective grain boundary diffusion coefficient: $\mathrm{D_{gb}} = \mathrm{D_V} C_o \Omega$

the grain size: $d = 2R$

the vacancy concentration: $\Delta C_V = C_0 \cdot \frac{\sigma \cdot \Omega}{kT}$

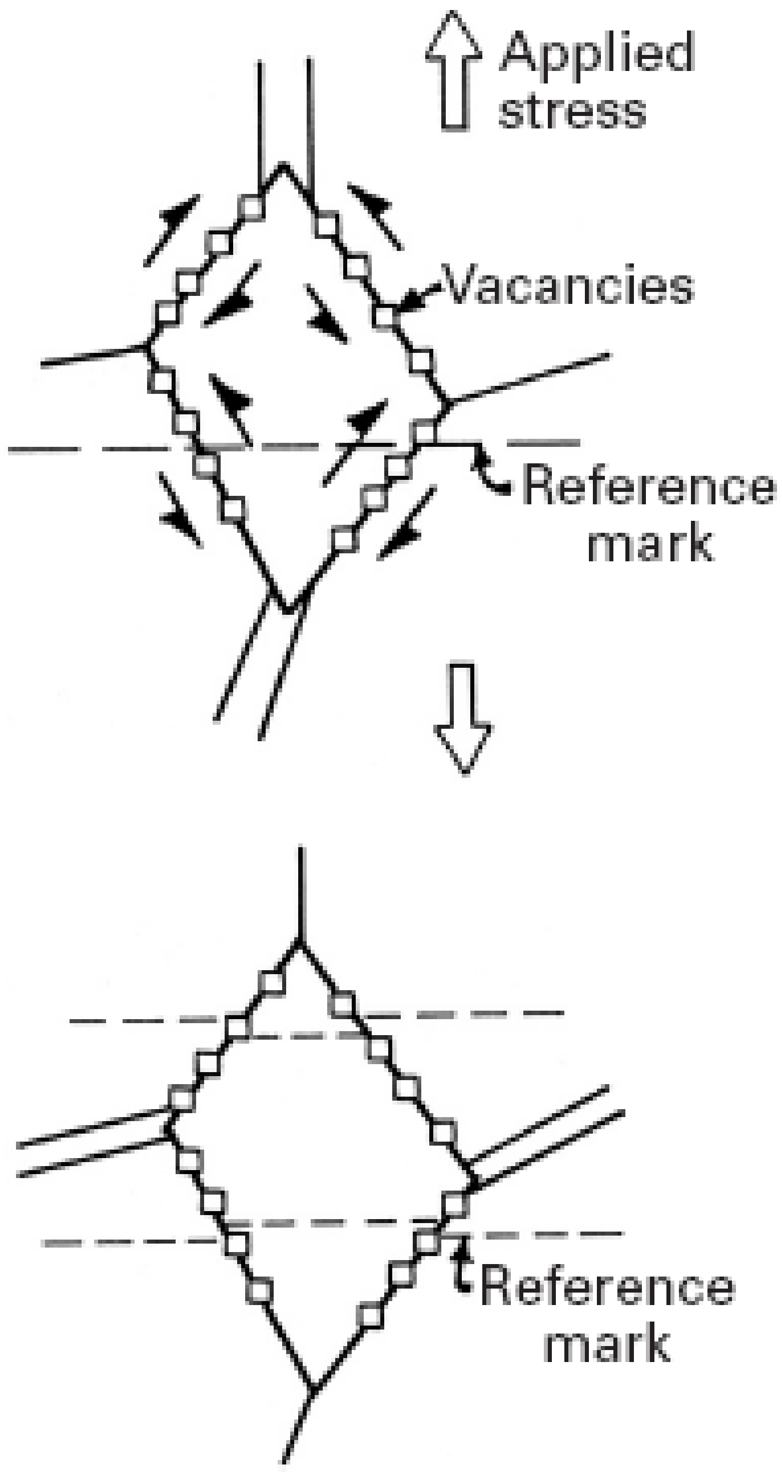
Summary of Coble creep $\dot{\varepsilon}_C$

In Coble creep mass transport occurs by diffusion along grain boundaries in a polycrystal.

$$\dot{\varepsilon}_{Coble} = A_{Coble} \cdot D_{gb} \cdot \frac{\delta}{d^3} \cdot \frac{\sigma\Omega}{kT}$$

δ the effective grain boundary thickness for mass transport

D_{gb} the effective grain boundary diffusivity



Definitions of Power law creep (PLC)

Ω the volume of vacancy

B the mobility of vacancy

F the force due to the potential gardient

v_D the drift velocity of vacancy

$\bar{l}$ the average spacing between intersection dislocations

ρ the average mobile dislocation density

(III) Power law creep (PLC) by dislocation climb $\dot{\varepsilon}_D$

At "moderate" stresses above about 0.6 T_m, over a wide range of stresses, power-law creep is observed that is widely believed to be dislocation climb-controlled, with the activation energy for creep to be close to that of vacancy diffusion.

$$\dot{\varepsilon}_D = \rho \cdot b \cdot v_D$$

$$v_D = B \cdot F = \frac{D_V}{kT} \cdot \frac{\sigma b^3}{\bar{l}} \qquad \rho = \left(\frac{\sigma}{Gb}\right)^2$$

$$\dot{\varepsilon}_D = \rho \cdot b \cdot v_D = \left(\frac{\tau}{Gb}\right)^2 \cdot b \cdot \frac{D_V}{kT} \cdot \frac{\tau b^3}{\mathrm{G}b/\tau}$$

$$= A_D \left(\frac{D_V G b}{kT}\right)\left(\frac{\tau}{G}\right)^4$$

$$\dot{\varepsilon}_D = \frac{A_D}{kT} \sigma^4 \cdot e^{-Q_D/kT}$$

Summary of three theories

$$\dot{\varepsilon}_{NH} = A_{NH} \cdot \frac{D_V}{d^2} \cdot \frac{\sigma \cdot \Omega}{kT}$$

$n = 1$

Lattice diffusion controlling

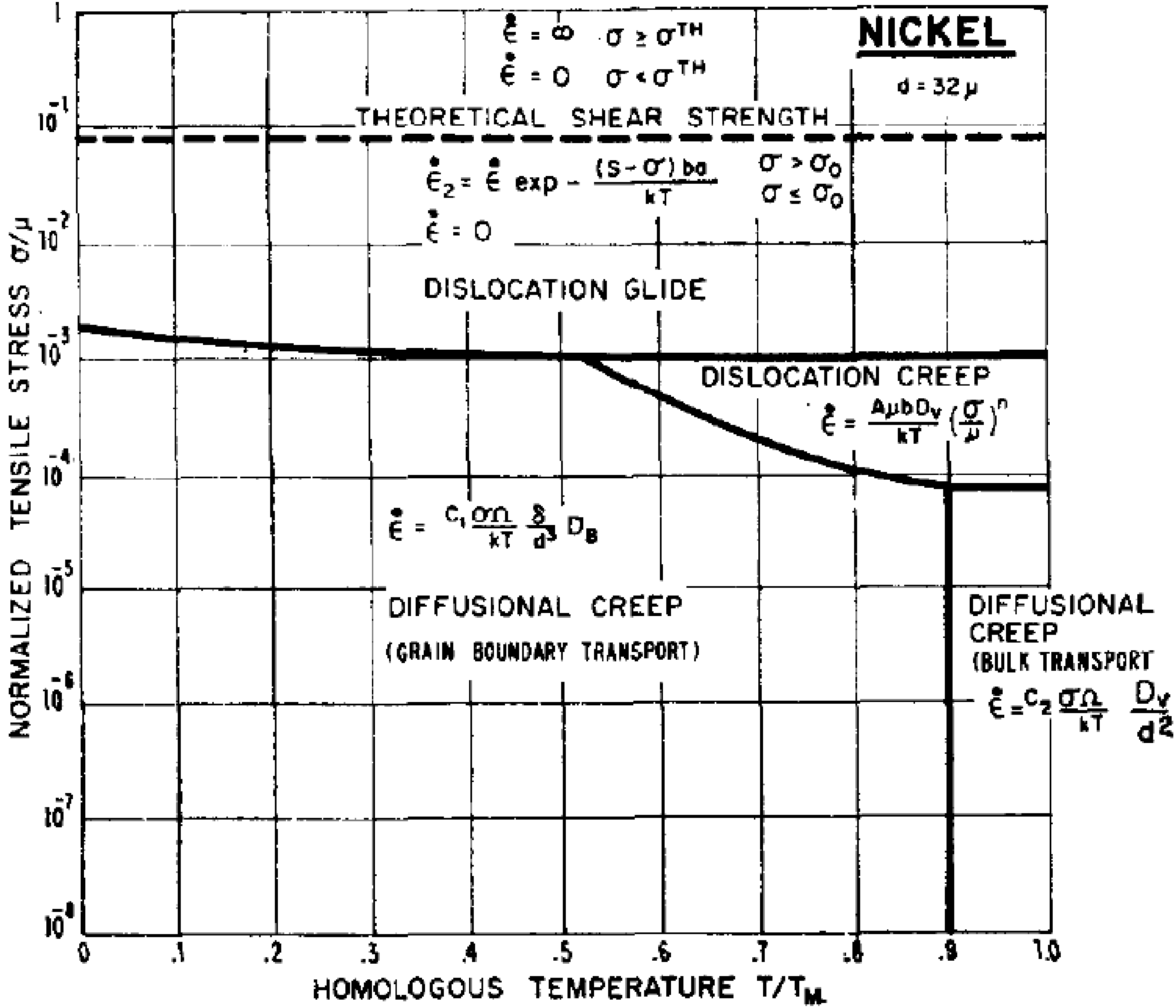
$$\dot{\varepsilon}_{Coble} = A_{Coble} \cdot D_{GB} \cdot \frac{\delta}{d^3} \cdot \frac{\sigma \cdot \Omega}{kT}$$

$n = 1$

Grain boundary diffusion controlling

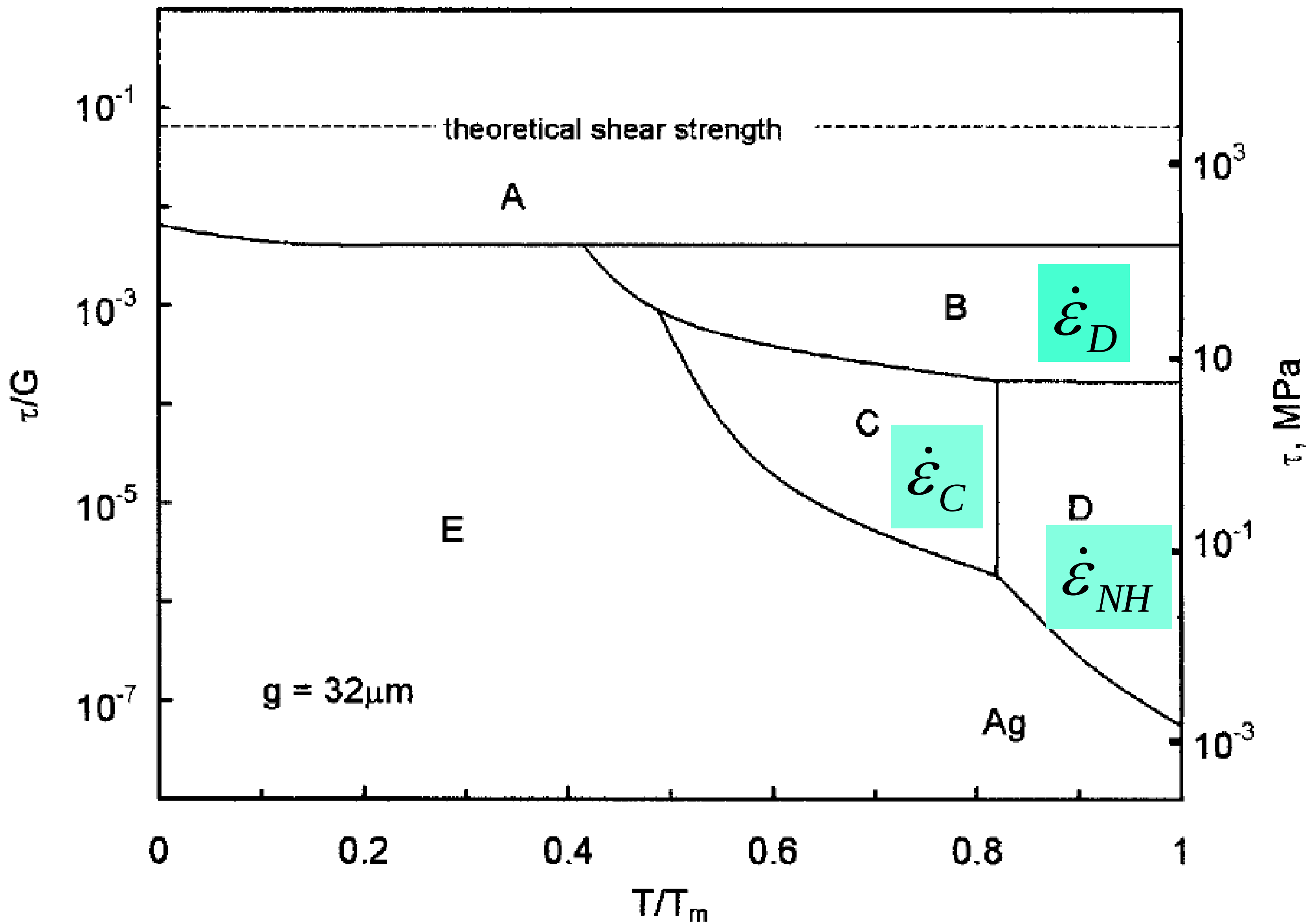
$$\dot{\varepsilon}_D = A_D \left(\frac{D_V G b}{kT} \right) \left(\frac{\sigma}{G} \right)^n$$

Dislocation climb controlling



NICKEL
d = 32 μ
$\dot{\epsilon} = \infty \quad \sigma \geq \sigma^{TH}$
$\dot{\epsilon} = 0 \quad \sigma < \sigma^{TH}$
THEORETICAL SHEAR STRENGTH
$\dot{\epsilon}_2 = \dot{\epsilon} \exp - \frac{(S-\sigma) ba}{kT} \quad \sigma > \sigma_0$
$\dot{\epsilon} = 0 \quad \sigma \leq \sigma_0$
DISLOCATION GLIDE
DISLOCATION CREEP
$\dot{\epsilon} = \frac{A \mu b D_v}{kT} \left(\frac{\sigma}{\mu}\right)^n$
$\dot{\epsilon} = \frac{C_1 \sigma \Omega}{kT} \frac{\delta}{d^3} D_B$
DIFFUSIONAL CREEP
(GRAIN BOUNDARY TRANSPORT)
DIFFUSIONAL CREEP
(BULK TRANSPORT
$\dot{\epsilon} = C_2 \frac{\sigma \Omega}{kT} \frac{D_v}{d^2}$
NORMALIZED TENSILE STRESS σ/μ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
HOMOLOGOUS TEMPERATURE T/T_M

Ashby Deformation mechanism map of Ag



A: dislocation glide, B: power law creep, C: Coble creep,
D: Nabarro-Herring creep and E: elastic deformation.

Deformation mechanism maps