Mechanical Behaviour of Materials

Chapter 08

Creep

Dr.-Ing. 郭 瑞 昭

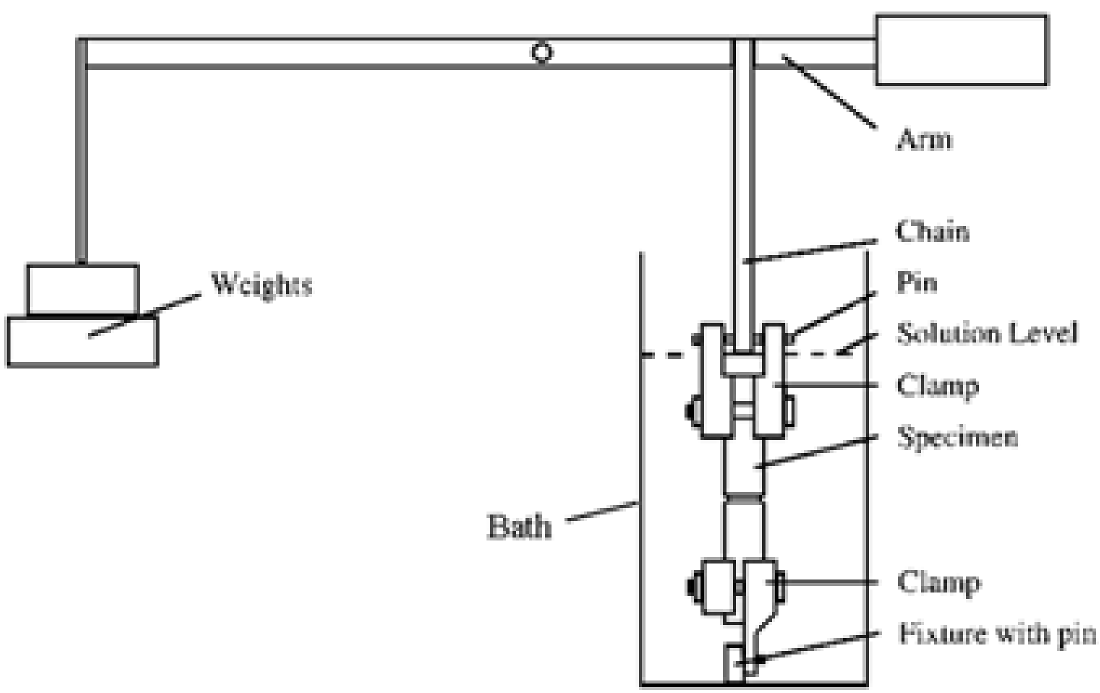
What is Creep?

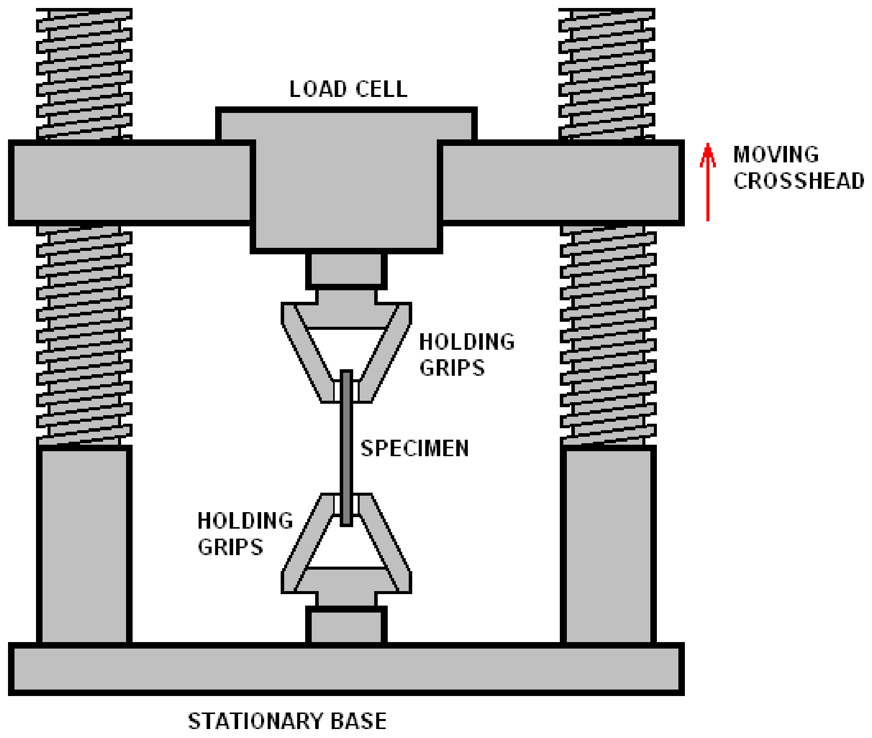
Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly 0.5 T_m, where Tm is the absolute melting temperature.

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.

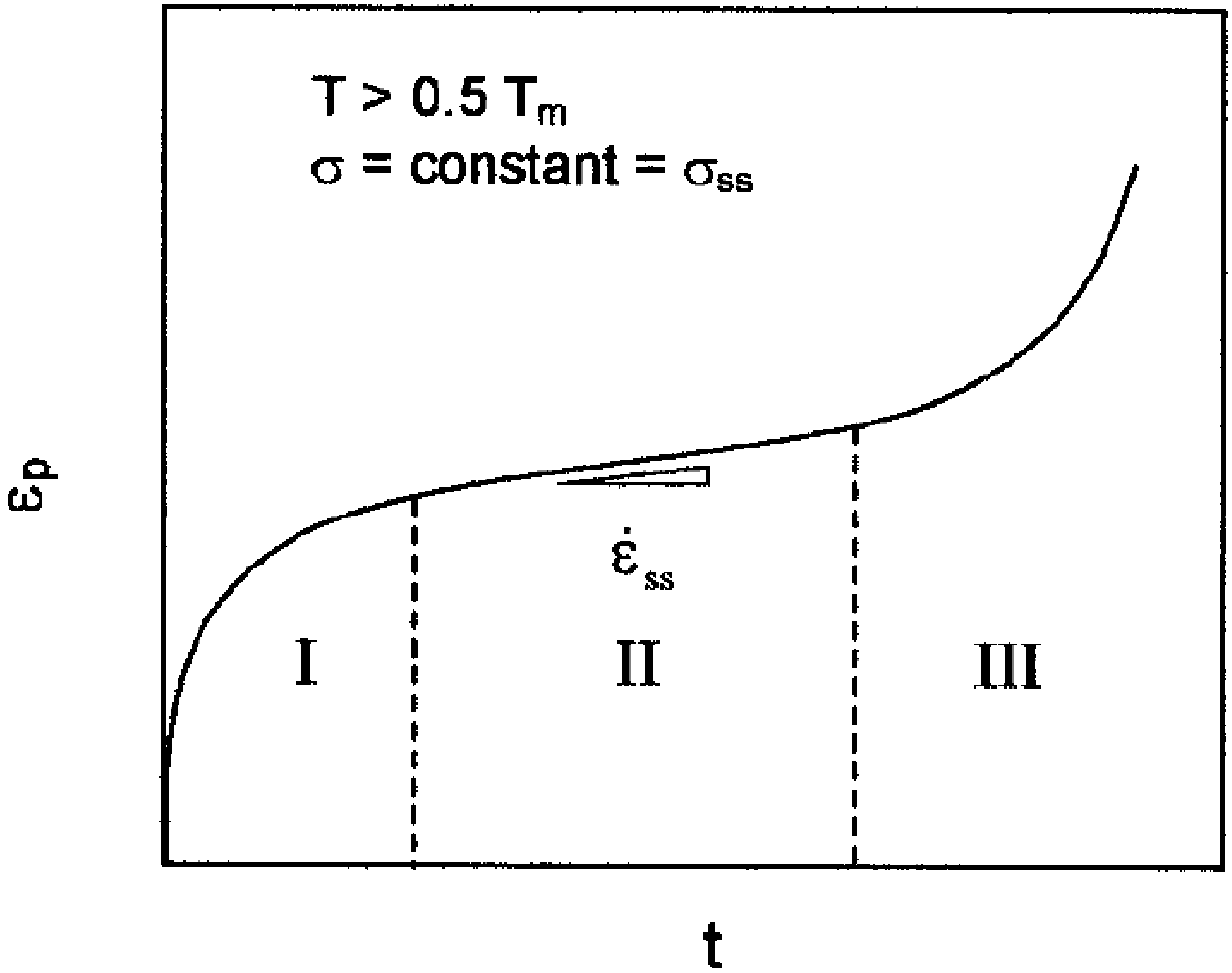




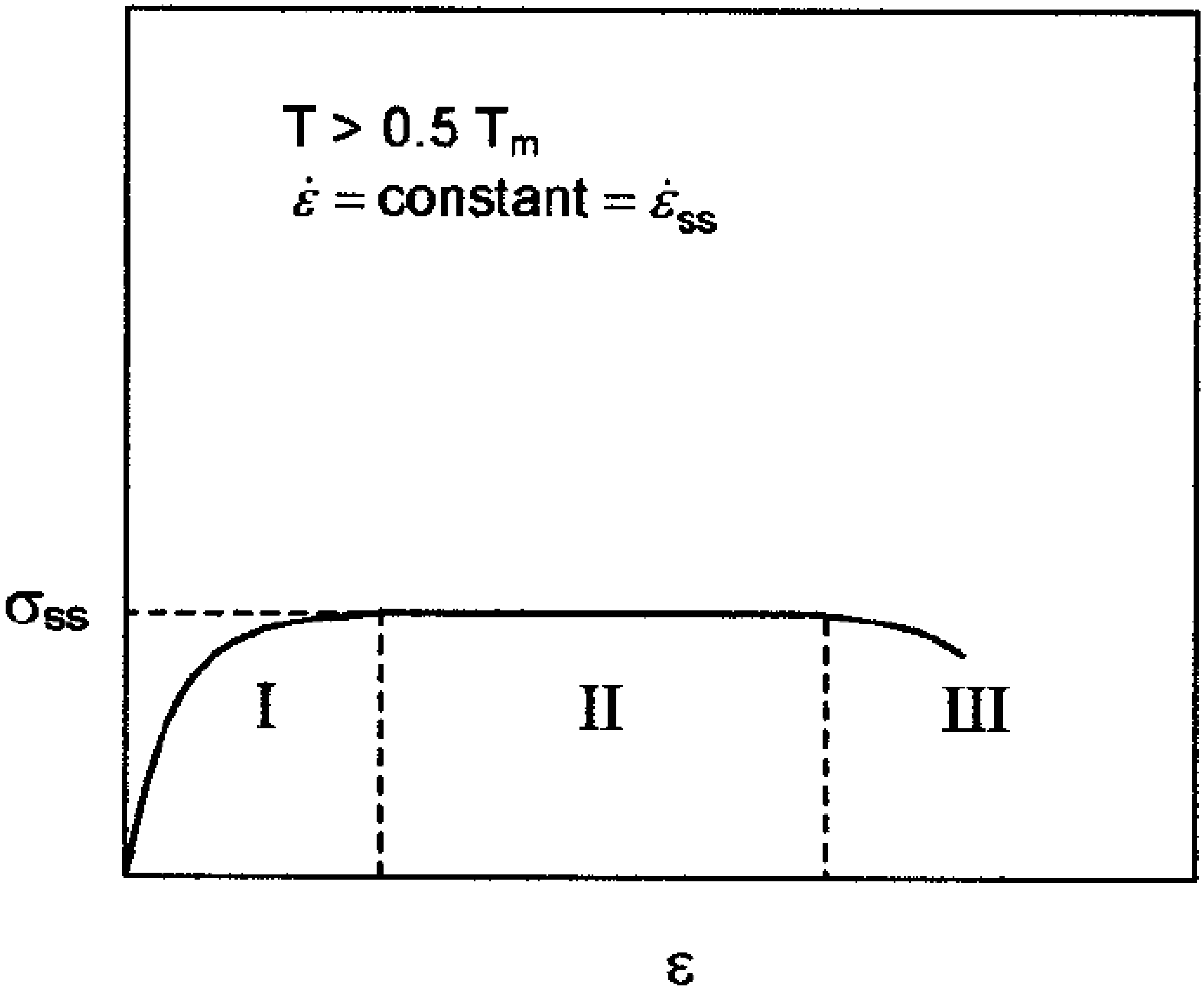
Creep test: constant Load

Tension: constant strain rate

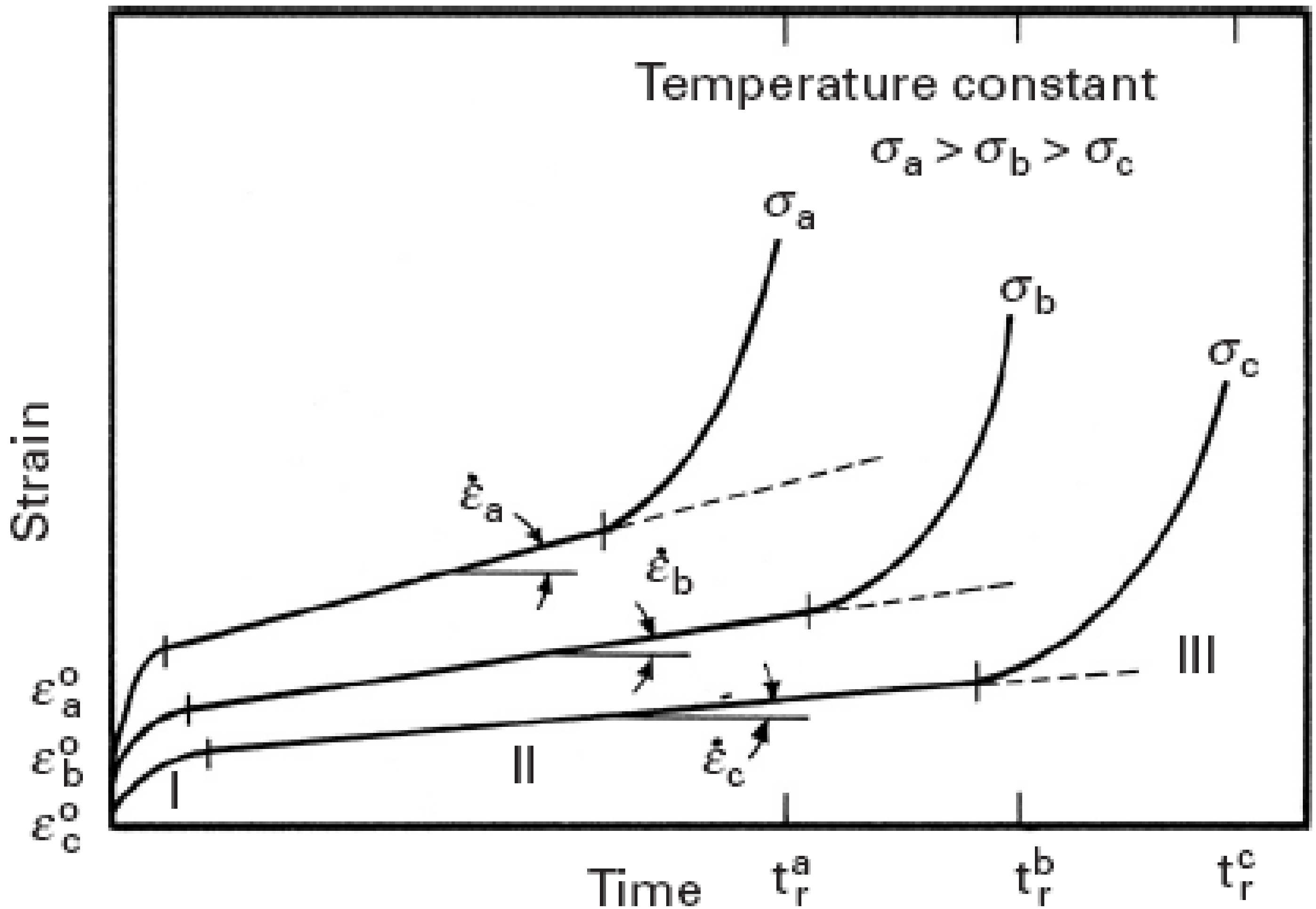
Phenomenological description:
creep curve at constant stress



Phenomenological description: creep curve at constant strain-rate

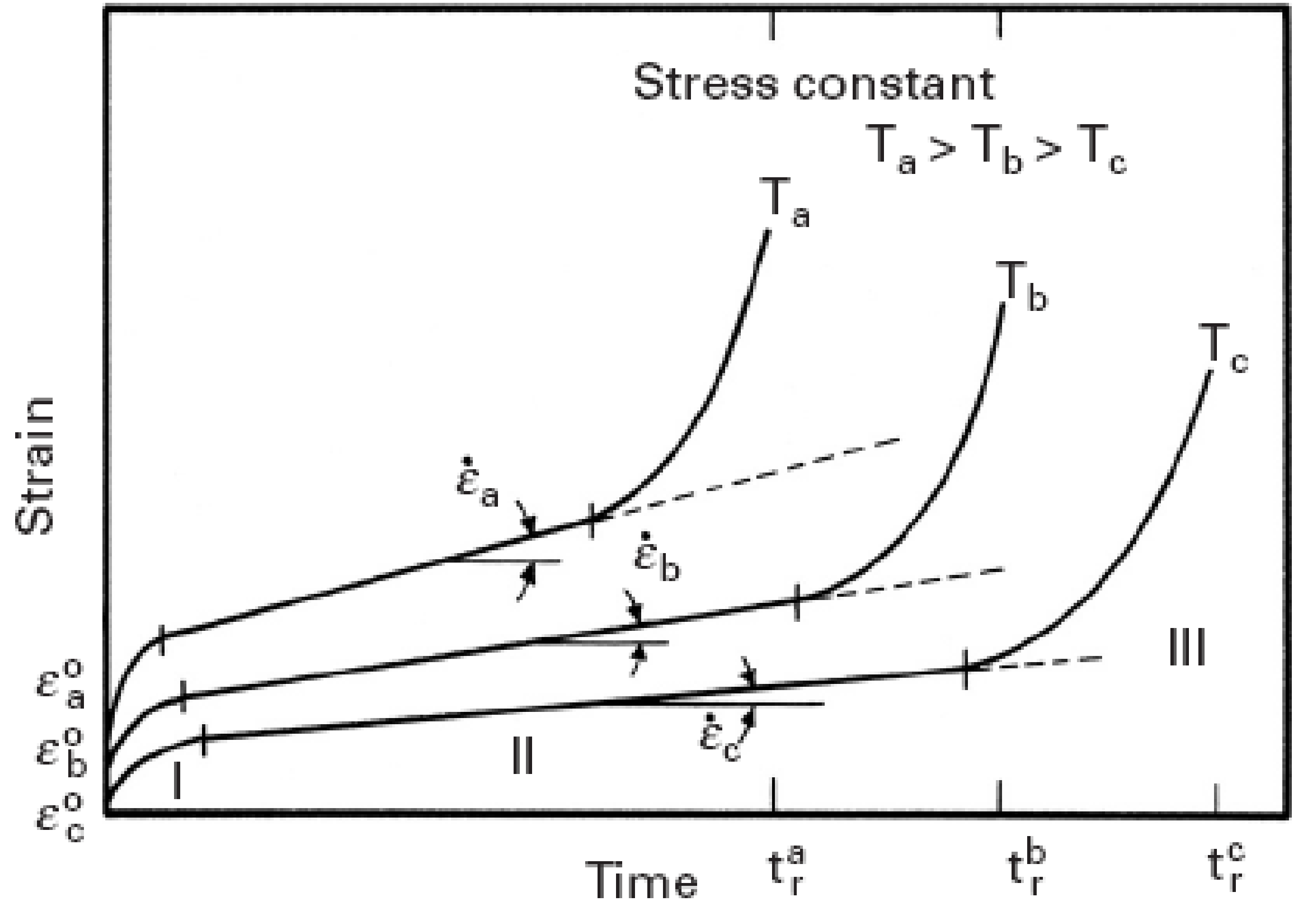


Effects of Stress on Creep



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

Effects of Temperature on Creep



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

Creep mechanisms

(a) Nabarro-Herring creep

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

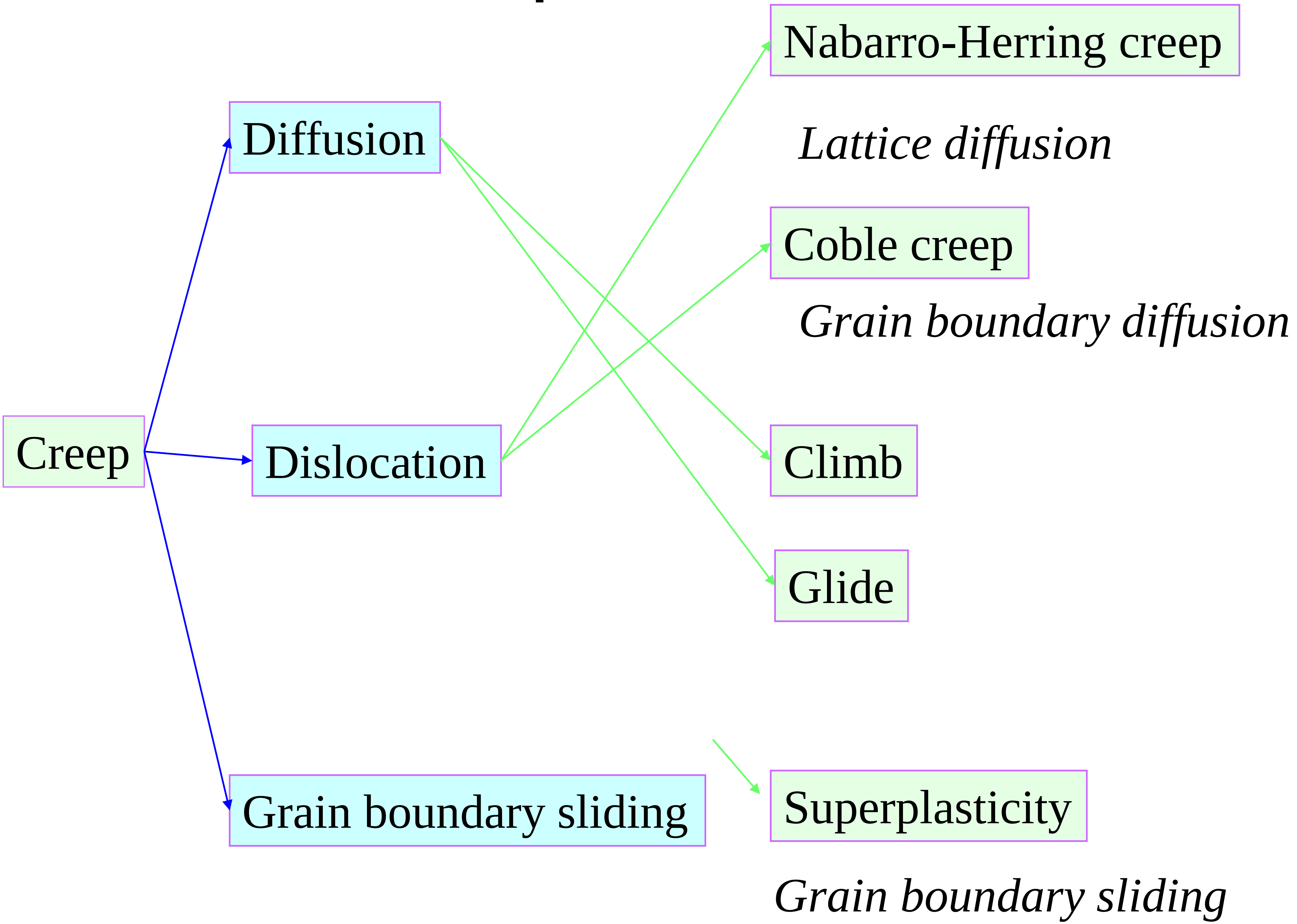
(c) climb-assisted glide, in which climb is a mechanism allowing dislocations to bypass obstacles

(d) thermally activated glide via cross-slip

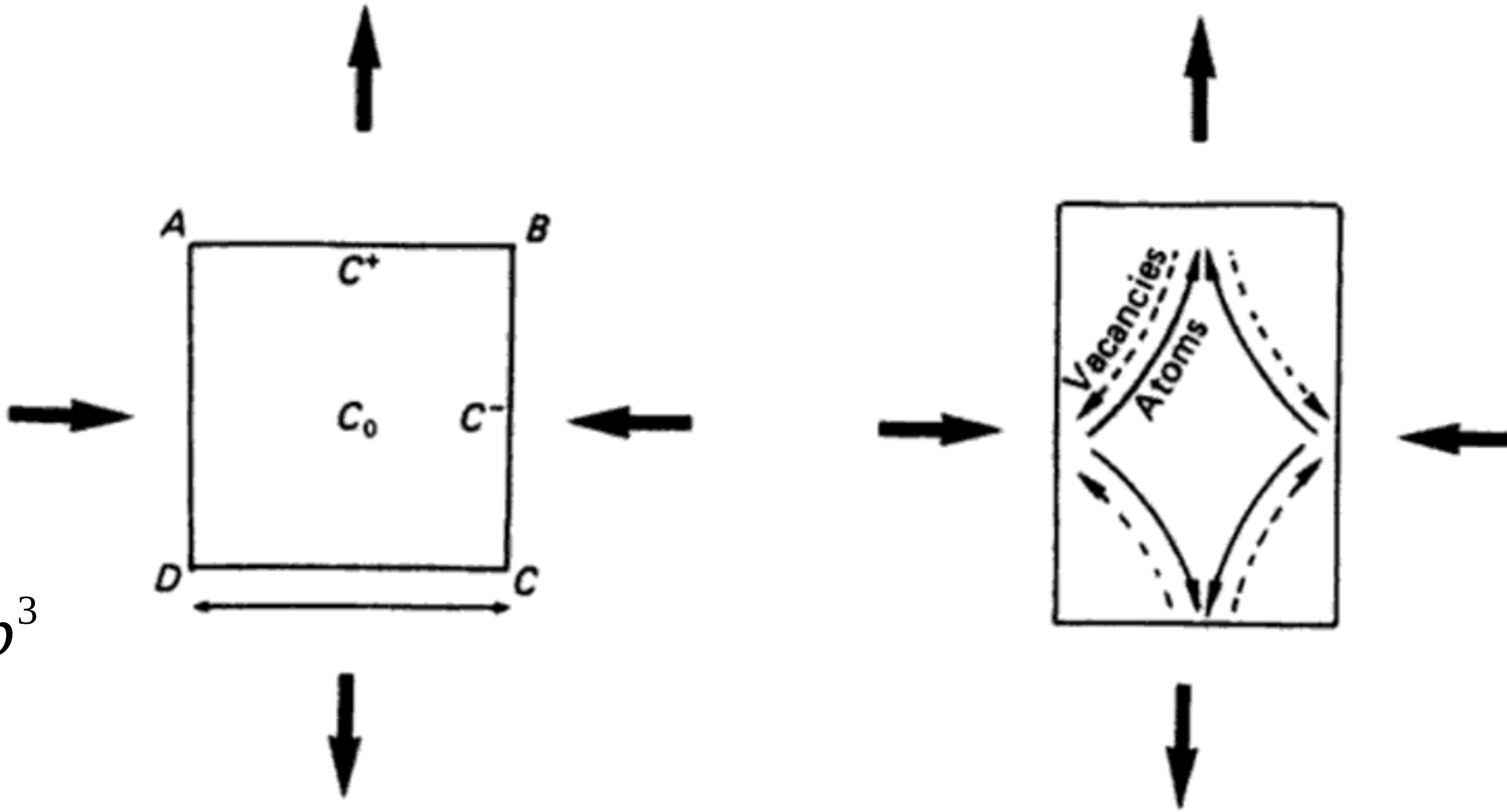
(e) Coble creep, involving grain-boundary diffusion

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

Mechanisms of Creep



Principle of Nabarro-Herring creep



$$\Omega = b^3$$

At a given temperature T, the thermal equilibrium concentration of vacancies in the crystal is $C_0 = N_v/b^3$, 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.

Derivation of N-H creep

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

$$C_V = \exp\left(\frac{-G_f}{kT}\right) = C_0 \exp\left(\frac{-H_V}{kT}\right)$$

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

$$C_V^{+} = C_0 \exp - \left(\frac{H_V - \sigma\Omega}{kT}\right) = C_{\mathrm{V}} \cdot \exp\left(\frac{\sigma\Omega}{kT}\right)$$

$$C_V^{-} = C_0 \exp - \left(\frac{H_V + \sigma\Omega}{kT}\right) = C_{\mathrm{V}} \cdot \exp\left(\frac{-\sigma\Omega}{kT}\right)$$

Derivation of N-H creep- conti.

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

$$J_V = -D_V \nabla C_V = D_V \frac{\Delta C_V}{\Delta x} = D_V \frac{\Delta C_V}{d}$$

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

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

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

Derivation of N-H creep- conti.

the area of a grain boundary facet A is approximated by d^2 and H_m is the activation energy for vacancy motion

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

$$\dot{\varepsilon}_{NH} = \frac{1}{d^3} \cdot J_v \cdot d^2 \qquad J_V \cdot \mathrm{A} = \frac{\Delta V}{\Delta t}$$

Derivation of N-H creep- conti.

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

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

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

Note the grain size dependence!

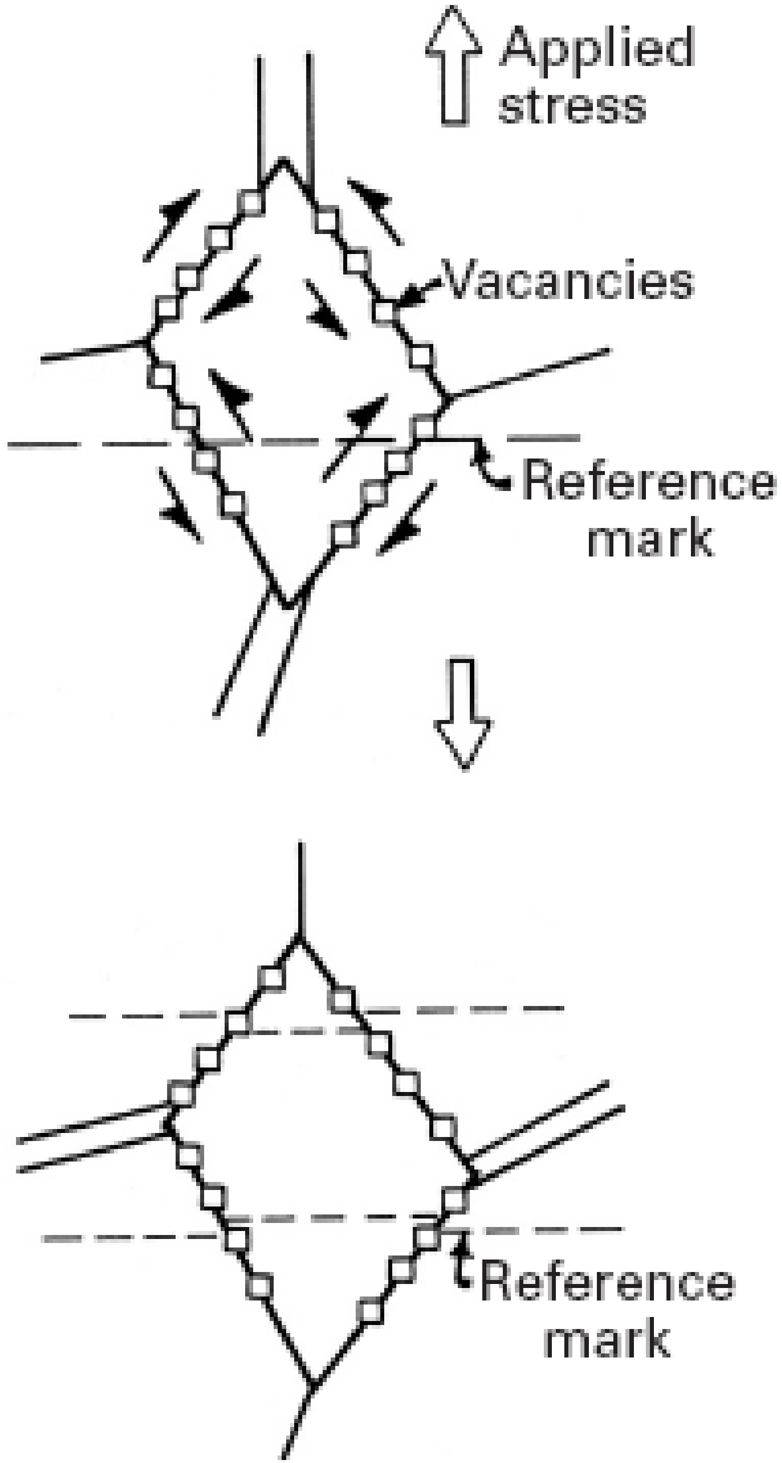
Coble creep

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

$$\dot{\varepsilon}_C = A_C \cdot \frac{D_{GB}\delta \cdot \sigma\Omega}{d^3 \cdot kT}$$

δ the effective grain boundary thickness for mass transport

D_{GB} the effective grain boundary diffusivity



Power law creep (PLC): dislocation climb

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.

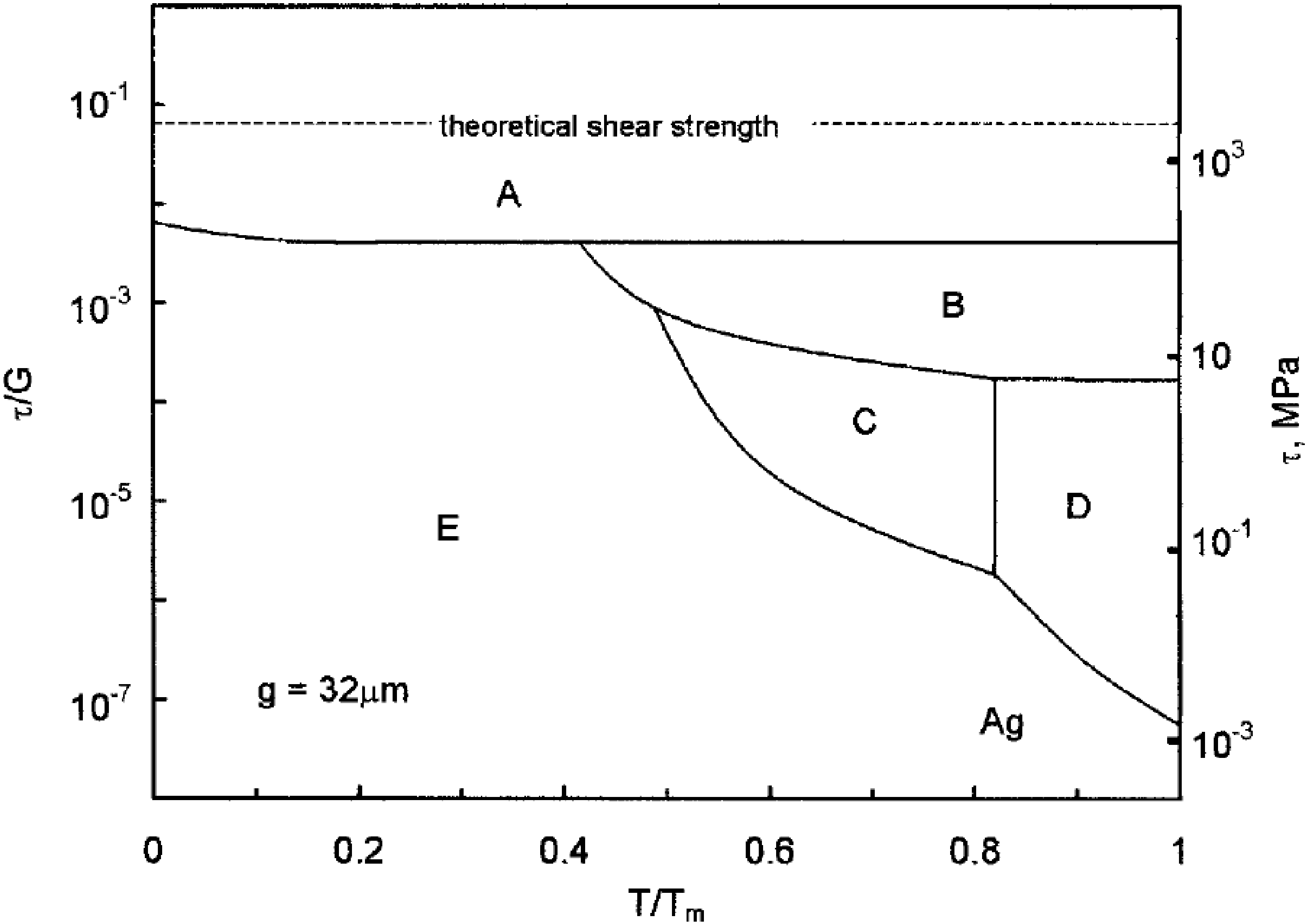
$$\dot{\varepsilon}_D = \rho \cdot b \cdot v_D$$

$$v_D = B \cdot F = \frac{D_V}{kT} \cdot \sigma b \qquad \rho = \left(\frac{\sigma}{\alpha G b} \right)^2$$

$$\dot{\varepsilon}_D = \rho \cdot b \cdot v_D = \left(\frac{\sigma}{\alpha G b} \right)^2 \cdot b \cdot \frac{D_V}{kT} \cdot \sigma b$$

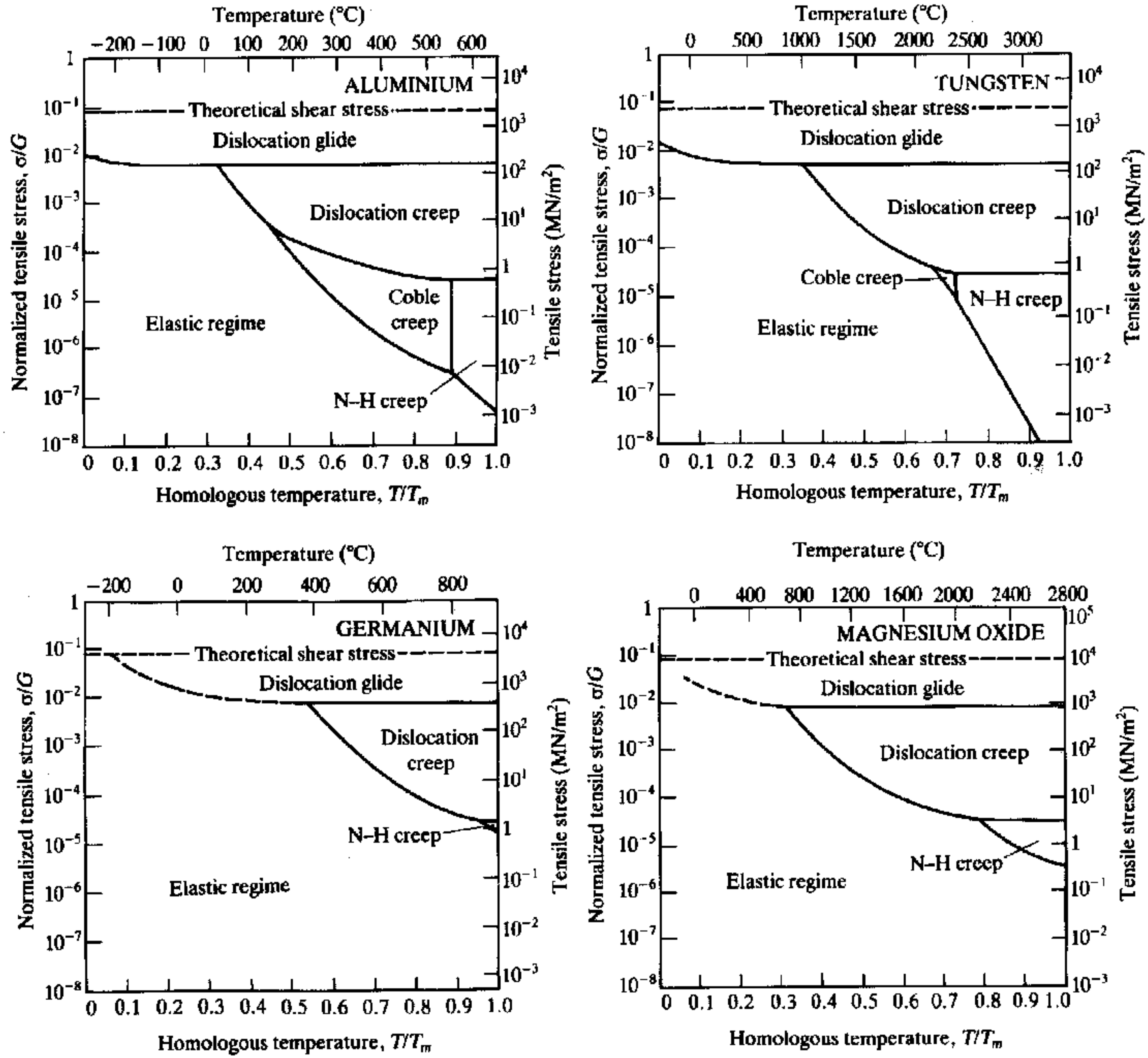
$$= A_D \left(\frac{D_V G b}{kT} \right) \left(\frac{\sigma}{G} \right)^3$$

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



Alloys for high temperature applications

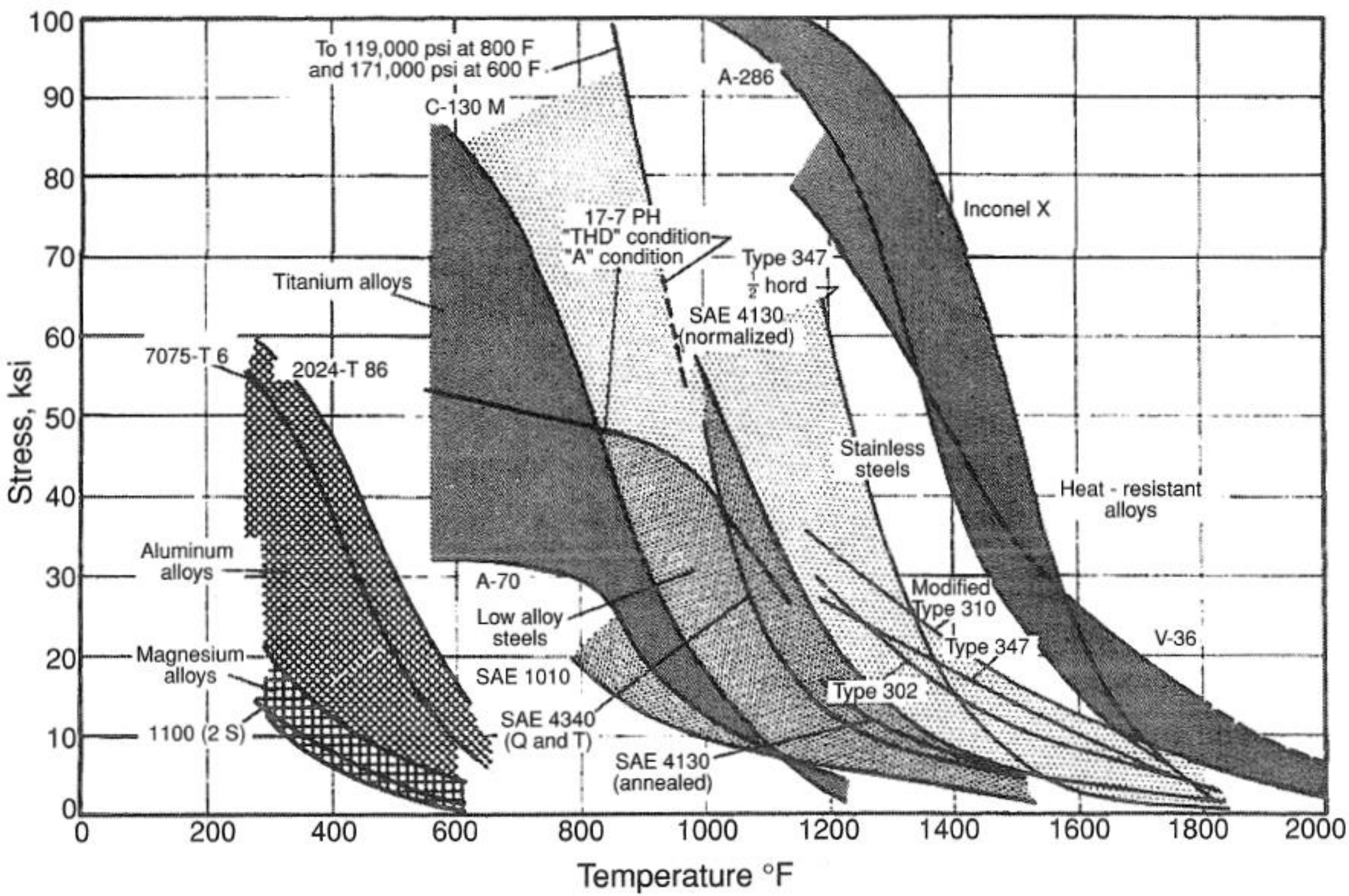


Figure 16.17. Strength of various alloys at high temperatures. From J. A. van Echo, *Short-Time High Temperature Testing*, ASM International (1958).