

# Mechanical Behaviour of Materials

---

## Chapter 12

### Creep

---

Dr.-Ing. 郭瑞昭

# What is Creep?

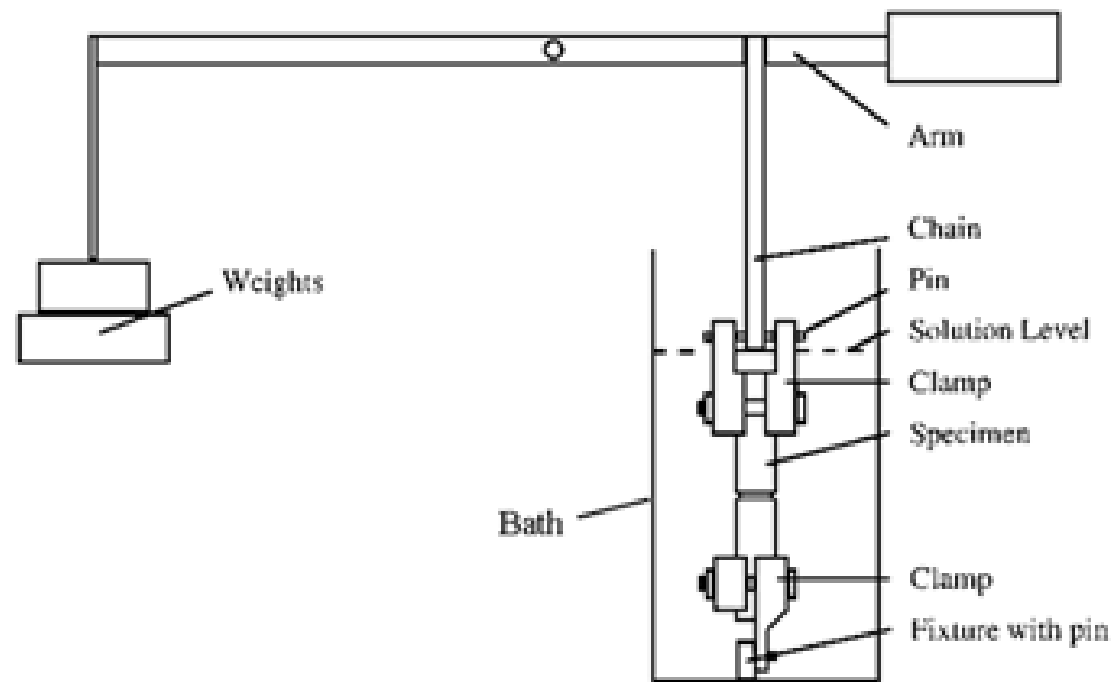
Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly  $0.5 T_m$ , where  $T_m$  is the absolute melting temperature.

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.

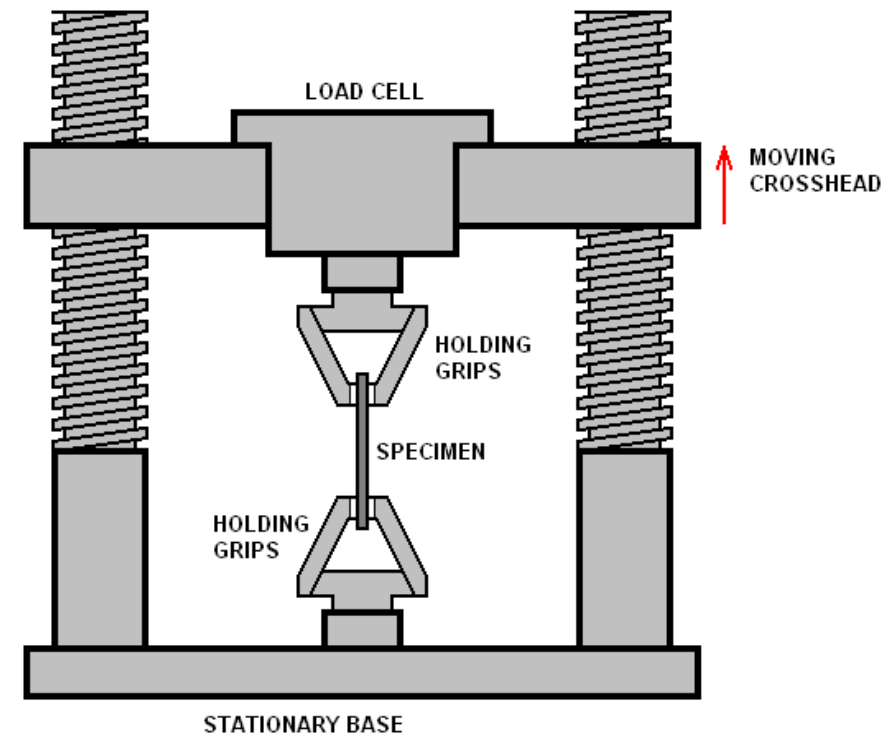
# Creep versus Tension test

**Creep:** A time-dependent plasticity when subjected to a constant load at a high temperature ( $> 0.4 T_m$ ).

Examples: turbine blades, steam generators.

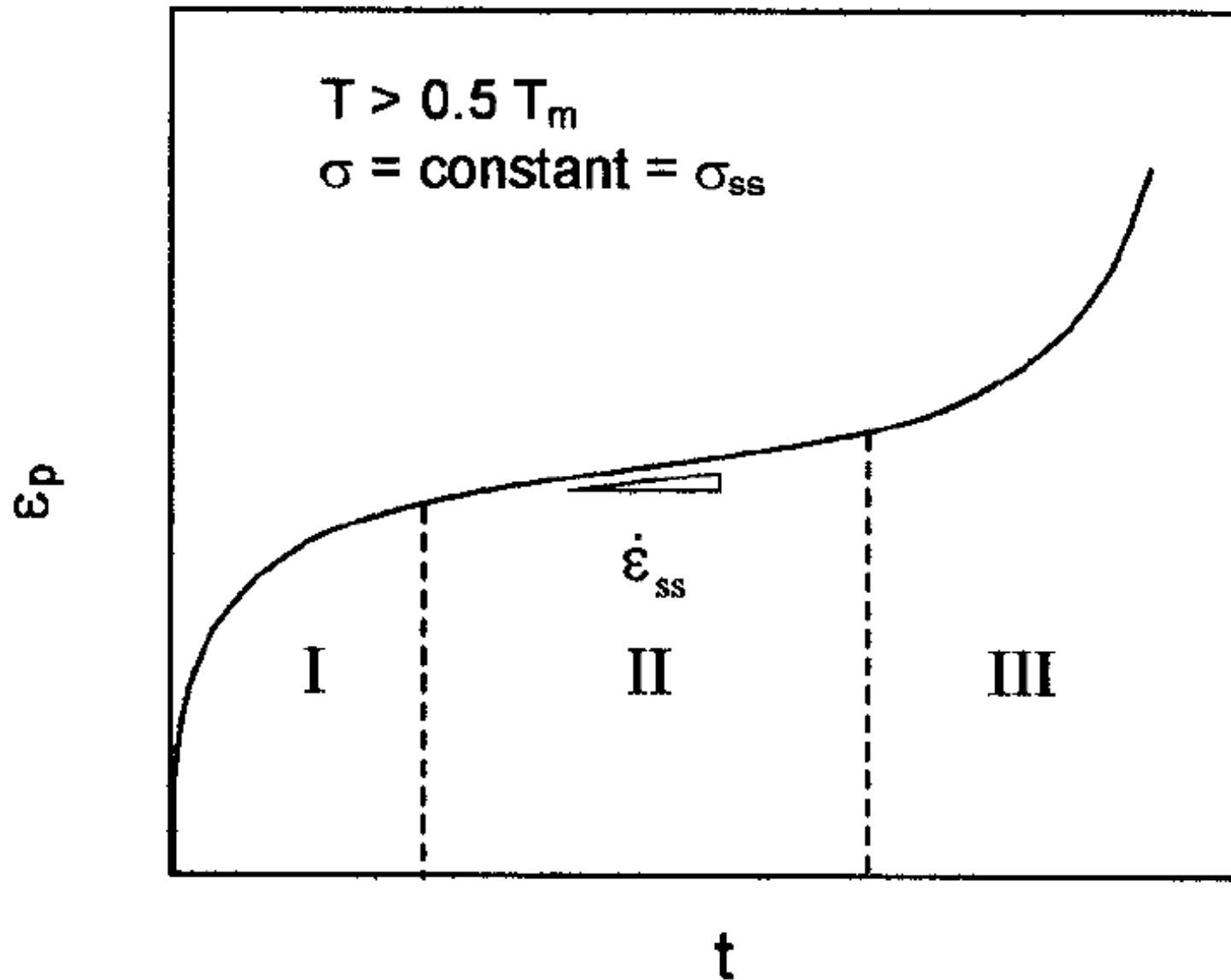


Creep test: constant Load

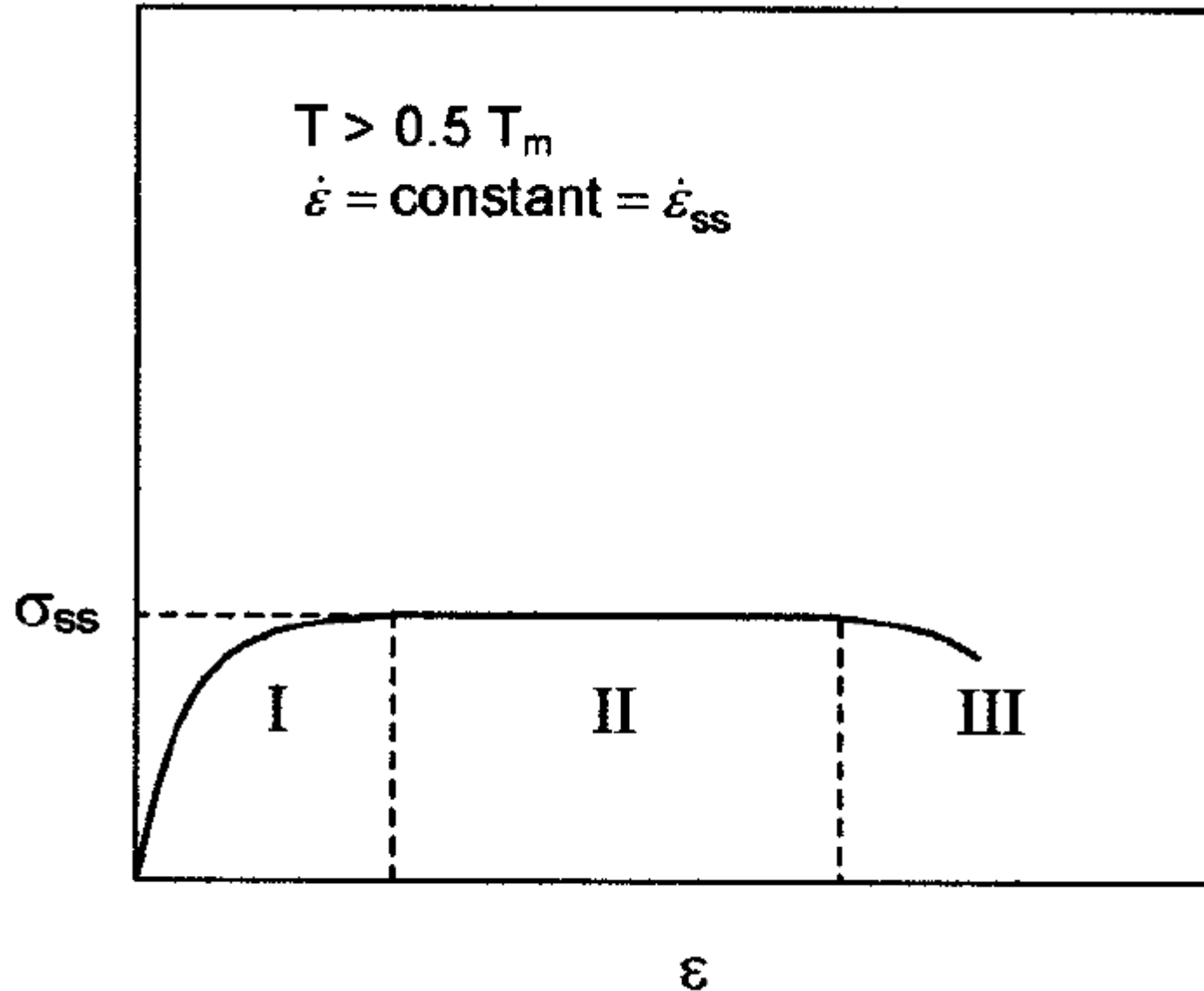


Tension: constant strain rate

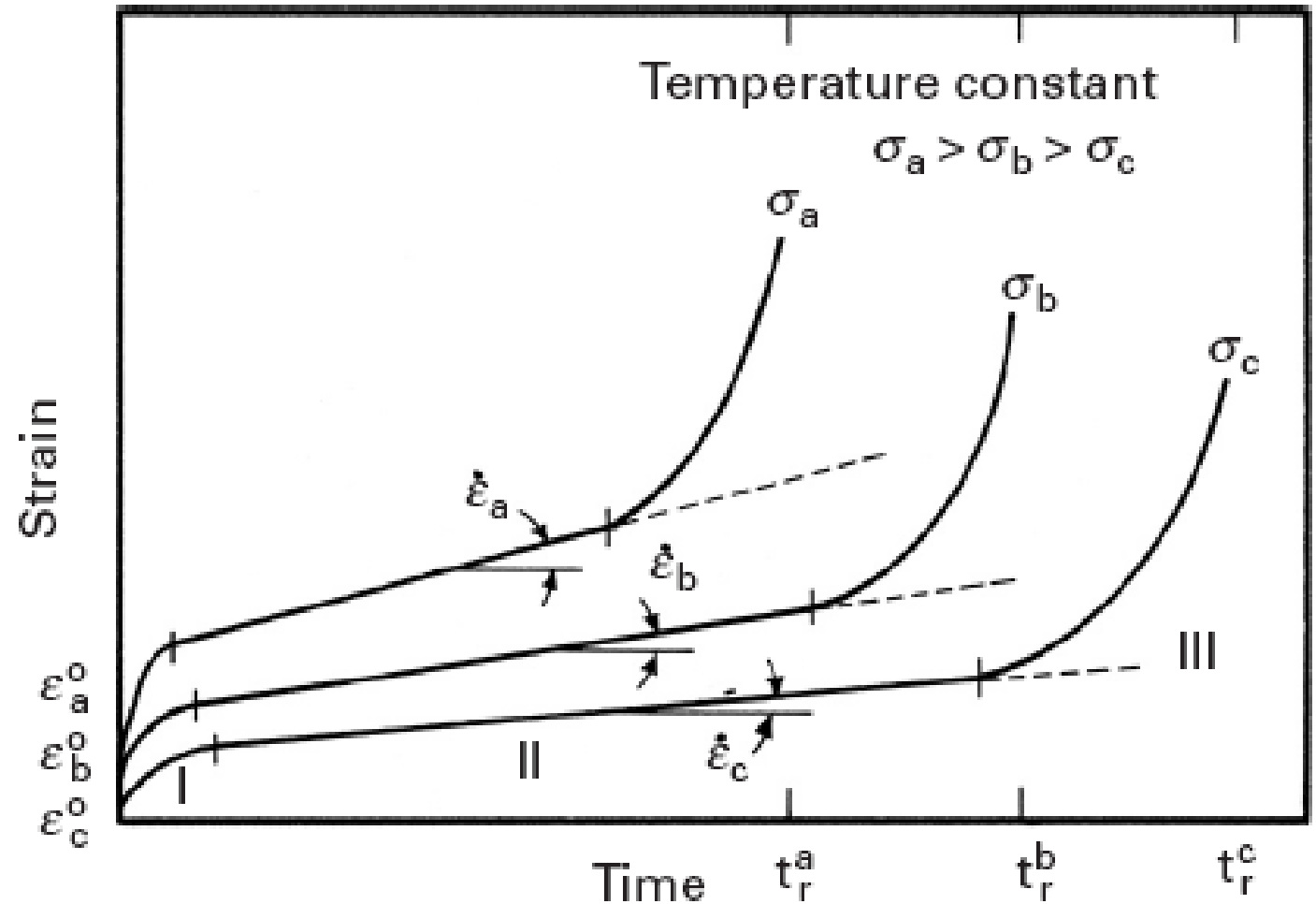
# Phenomenological description: creep curve at constant stress



# Phenomenological description: creep curve at constant strain-rate

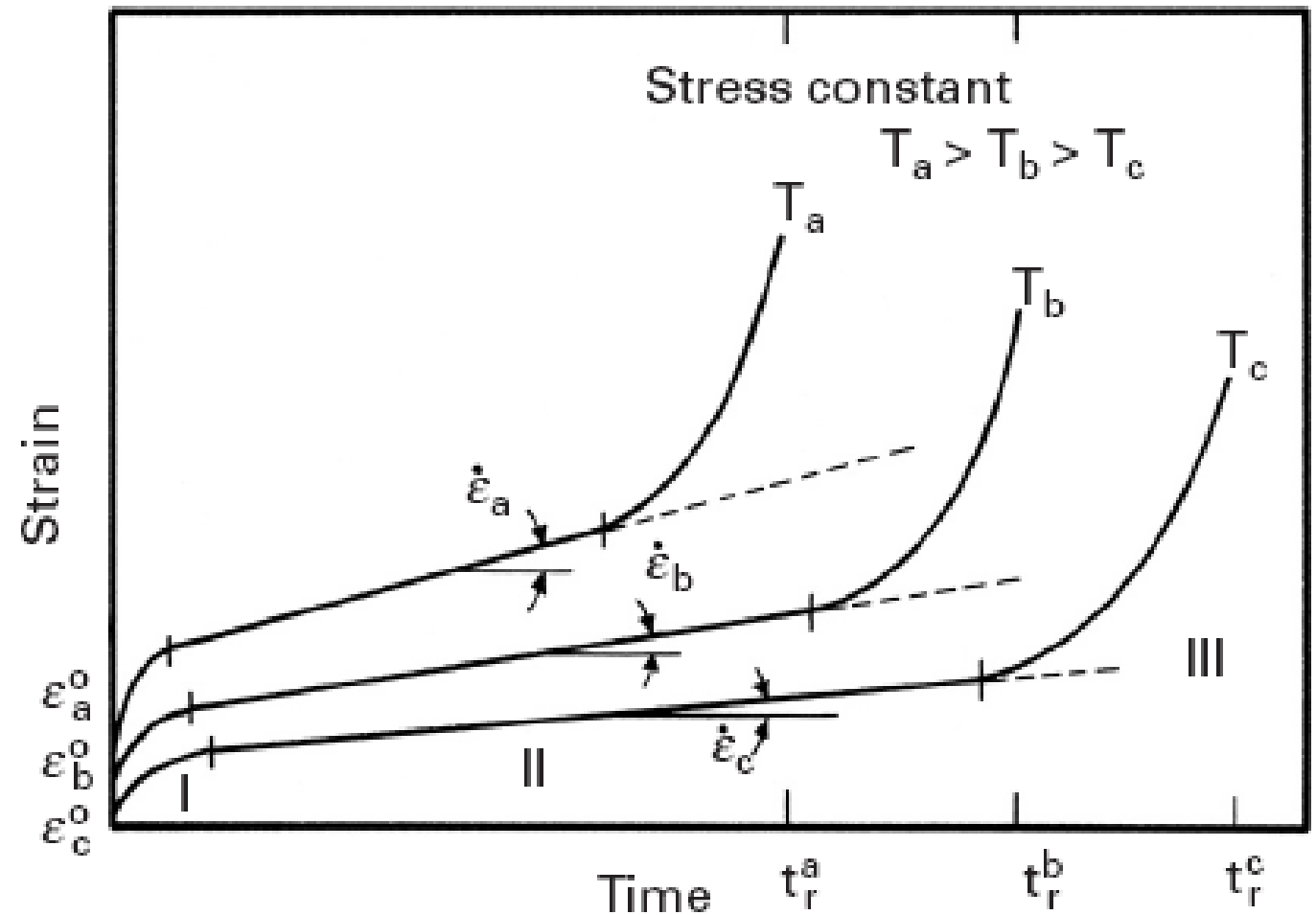


# Effects of Stress on Creep



- 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

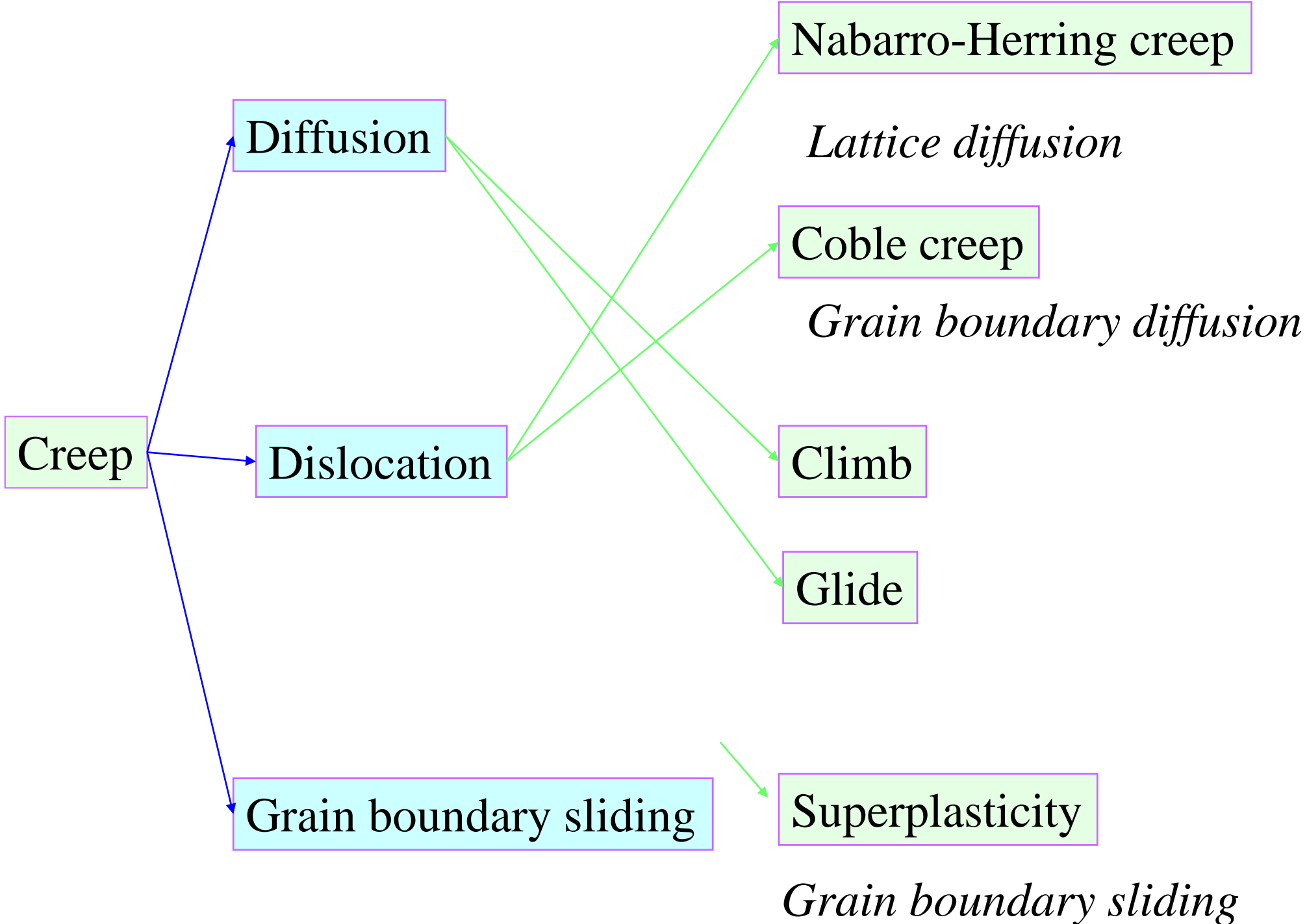
(e) Coble creep, involving grain-boundary diffusion

Bulk-diffusion-assisted creep: (a)–(d)

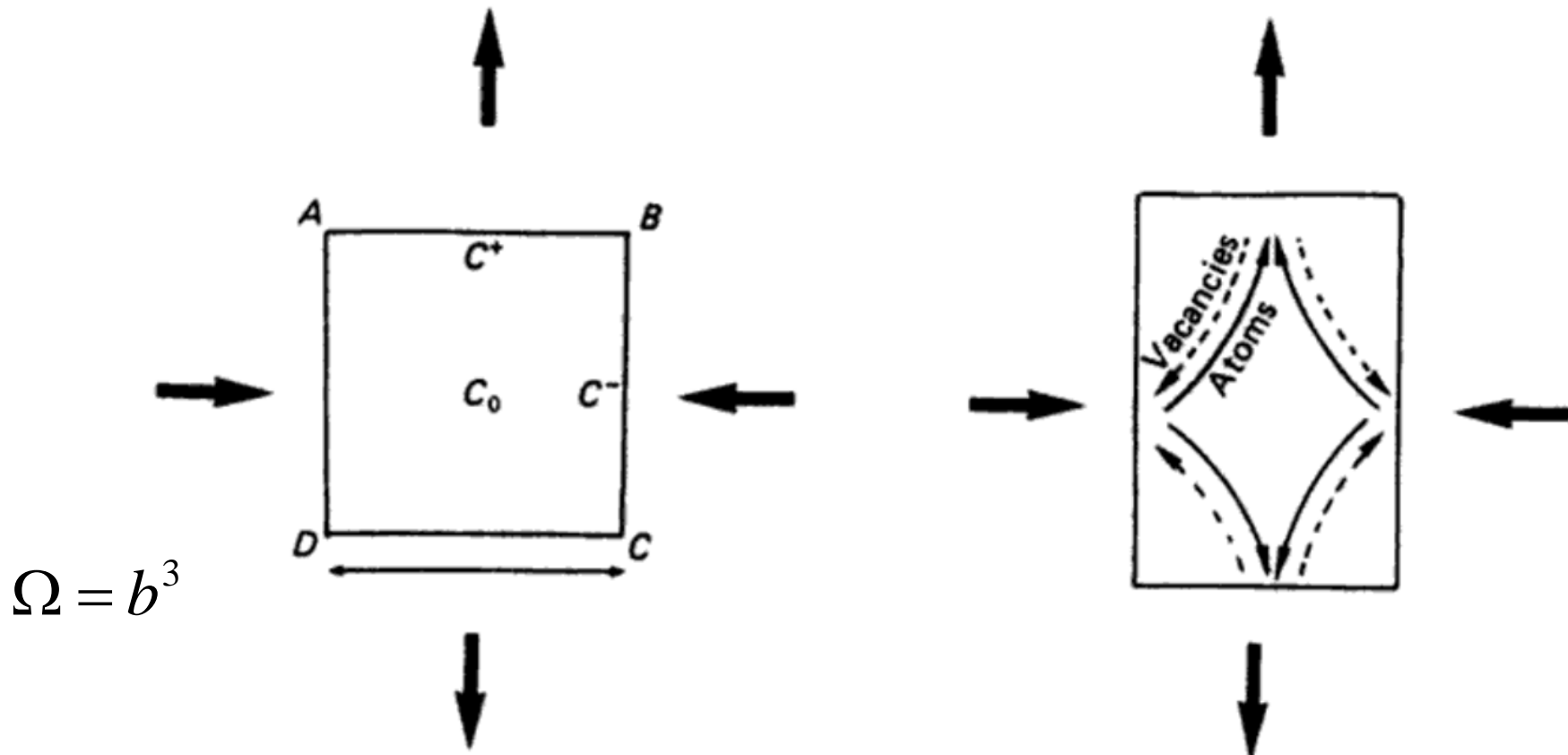
Grain-boundary diffusion: (e)



# Mechanisms of Creep



# Principle of Nabarro-Herring creep



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

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

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

# 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

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

$$\dot{\epsilon}_{NH} = \frac{1}{d^3} \cdot J_v \cdot d^2 \quad J_v \cdot A = \frac{\Delta V}{\Delta t}$$

# Derivation of N-H creep- conti.

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

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

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

*Note the grain size dependence!*

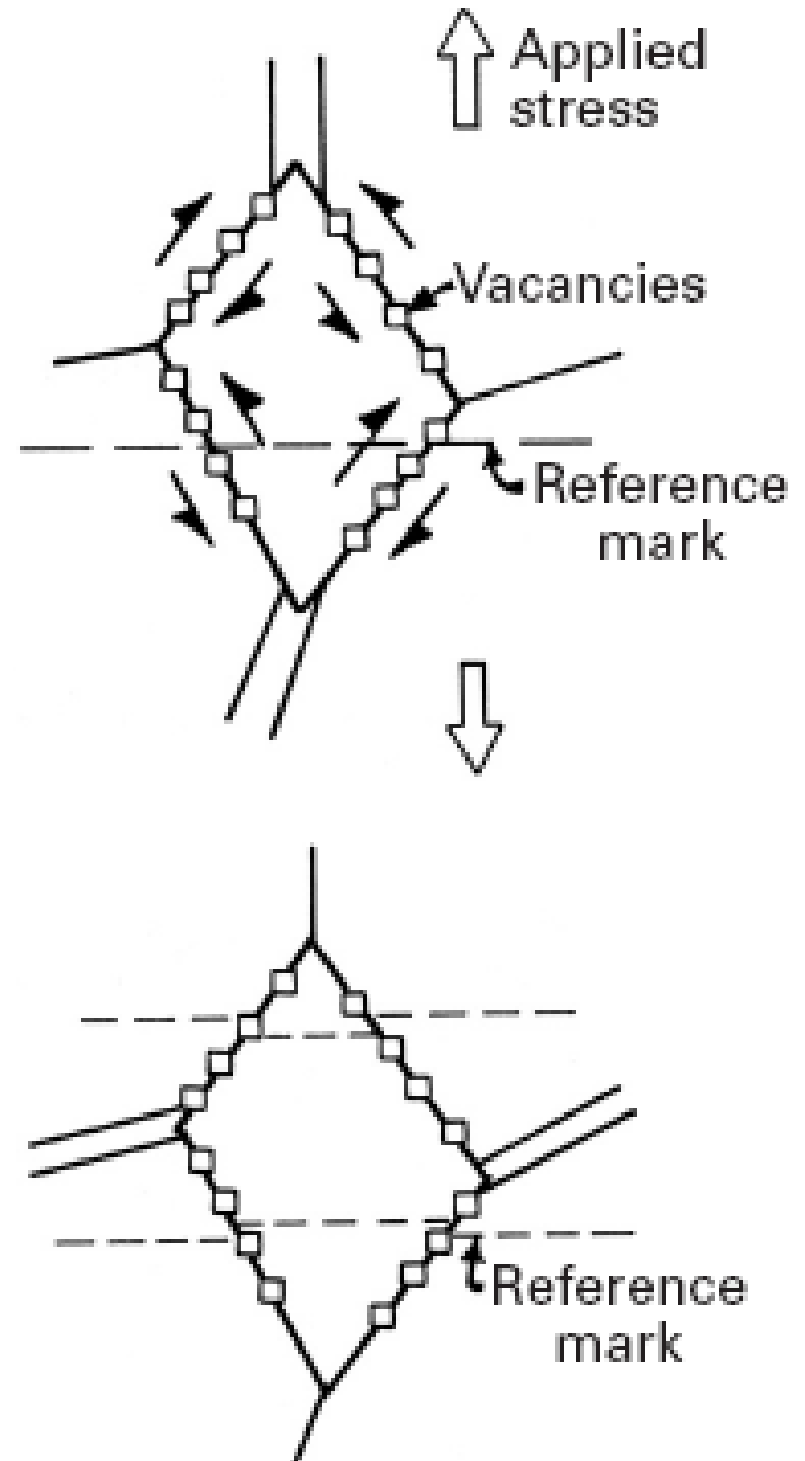
# Coble creep

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

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

$\delta$  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.

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

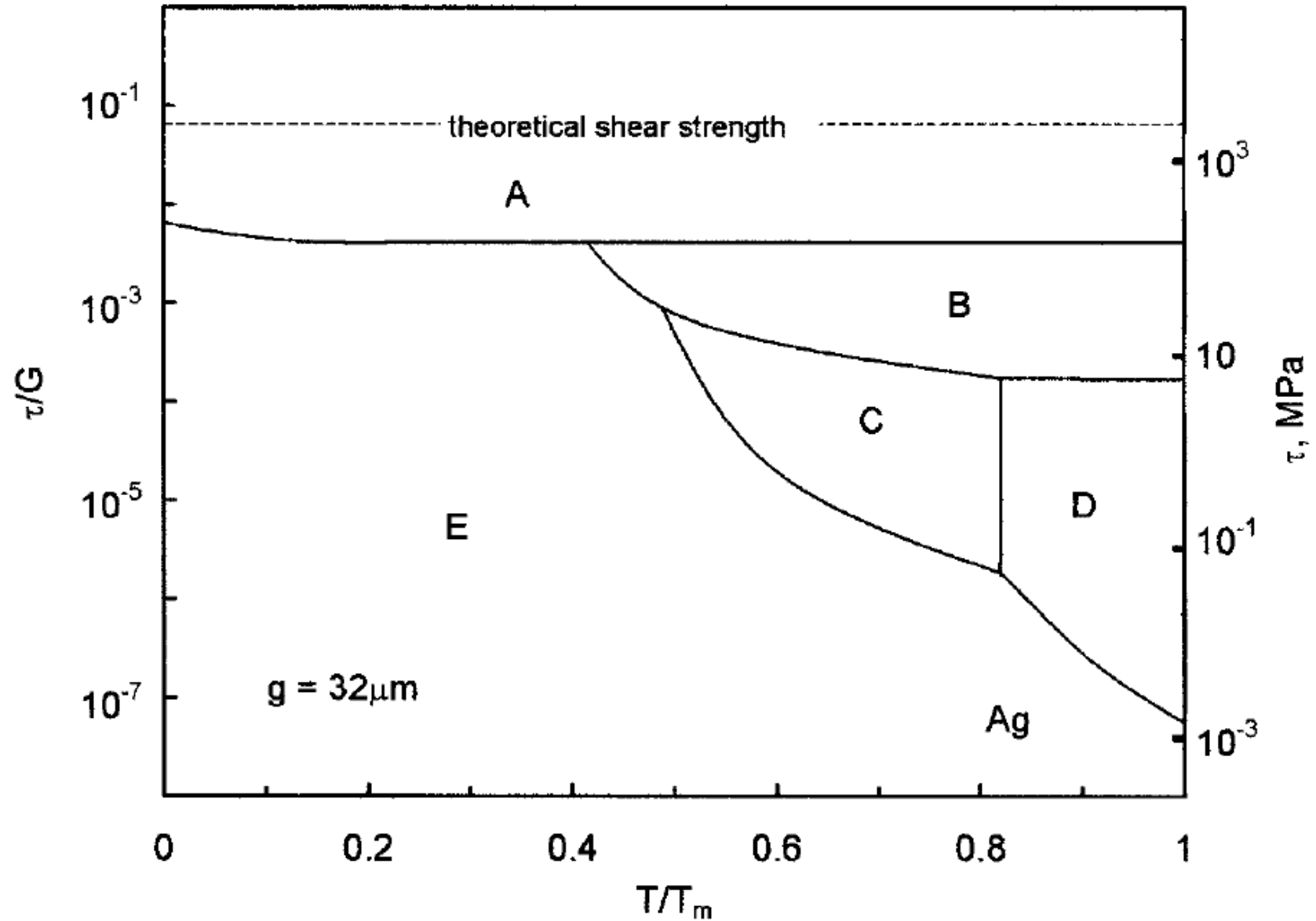
$$v_D = B \cdot F = \frac{D_V}{kT} \cdot \sigma b \quad \rho = \left( \frac{\sigma}{\alpha G b} \right)^2$$

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

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

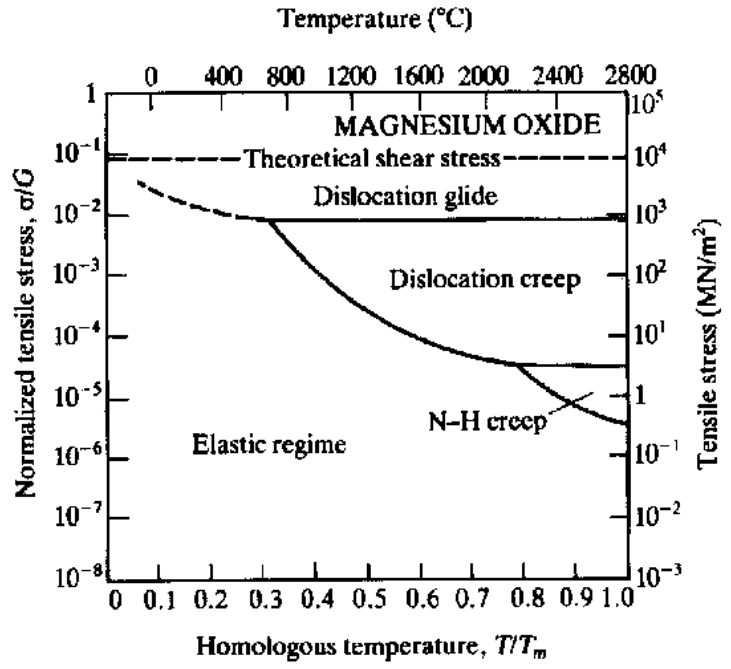
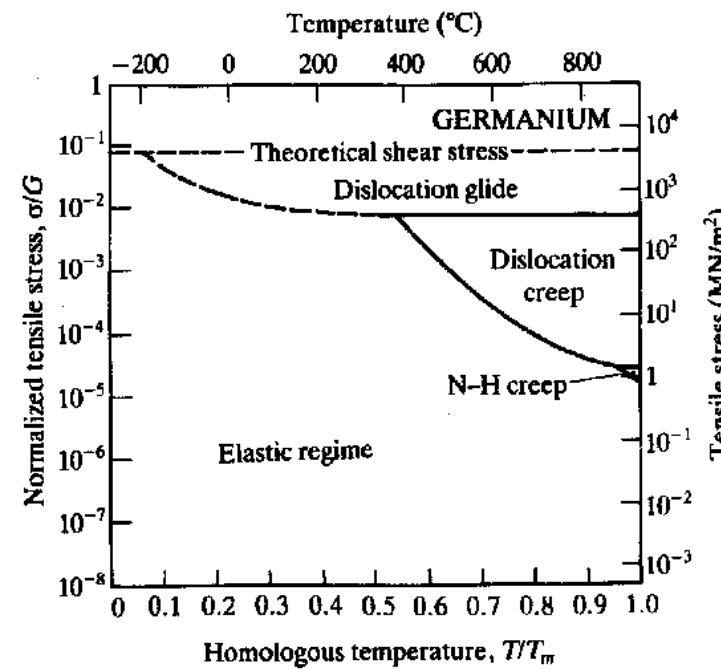
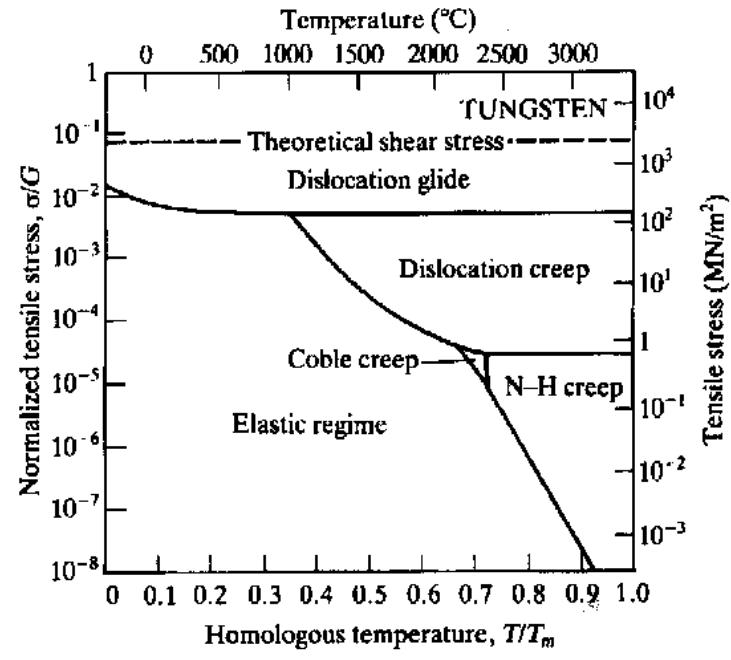
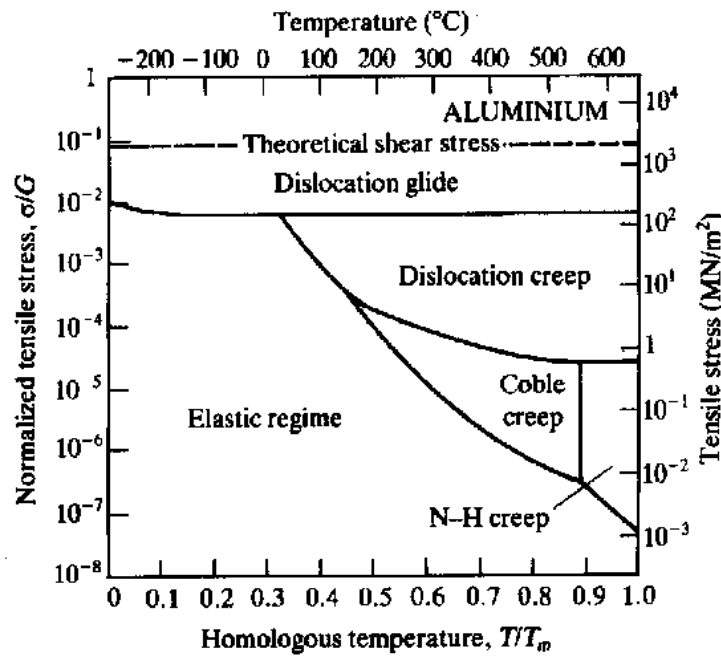


# Ashby Deformation mechanism map of Ag



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

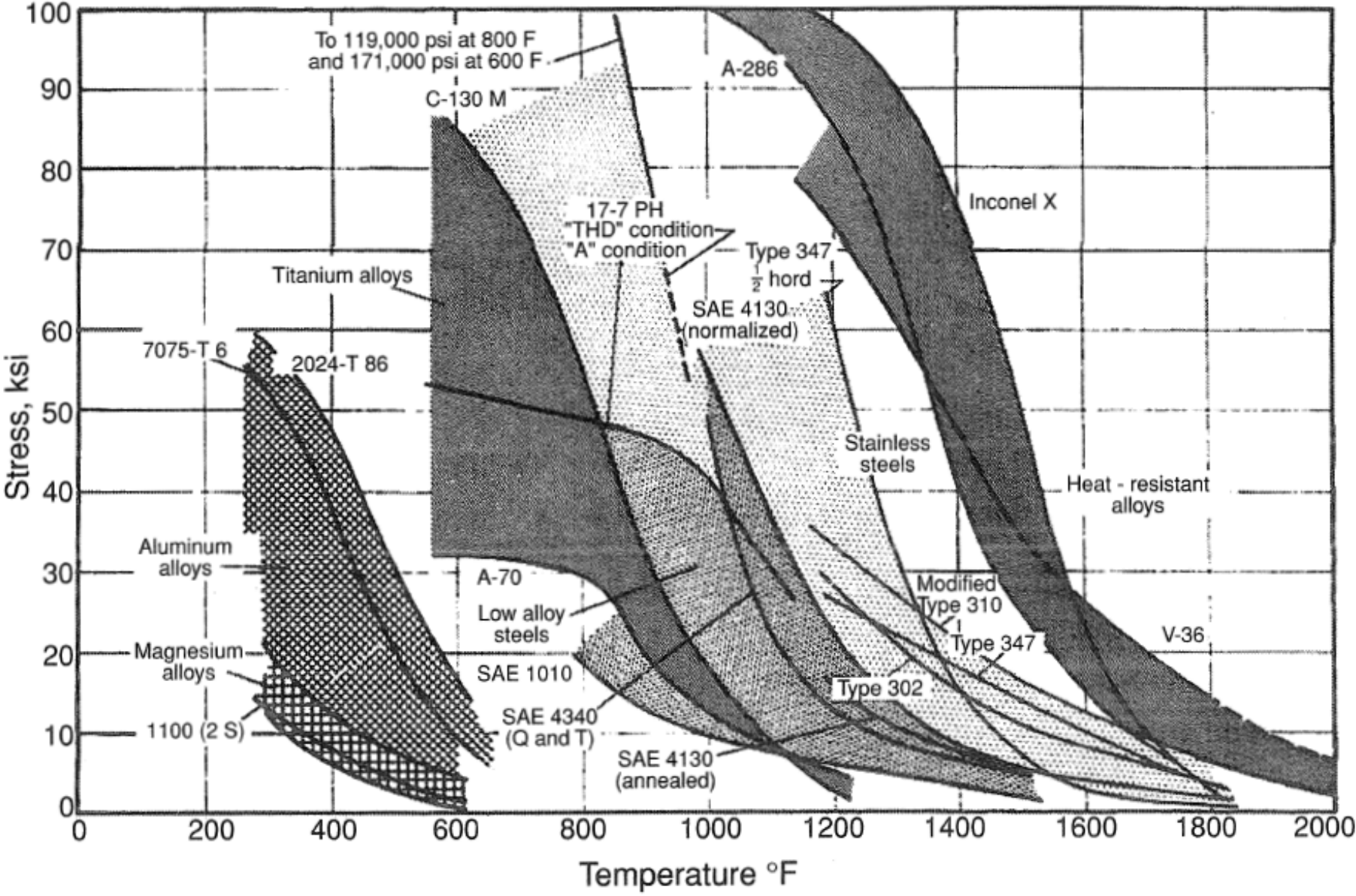


Figure 16.17. Strength of various alloys at high temperatures. From J. A. van Echo, *Short-Time High Temperature Testing*, ASM International (1958).