Lecture 32

Failure in materials- Creep

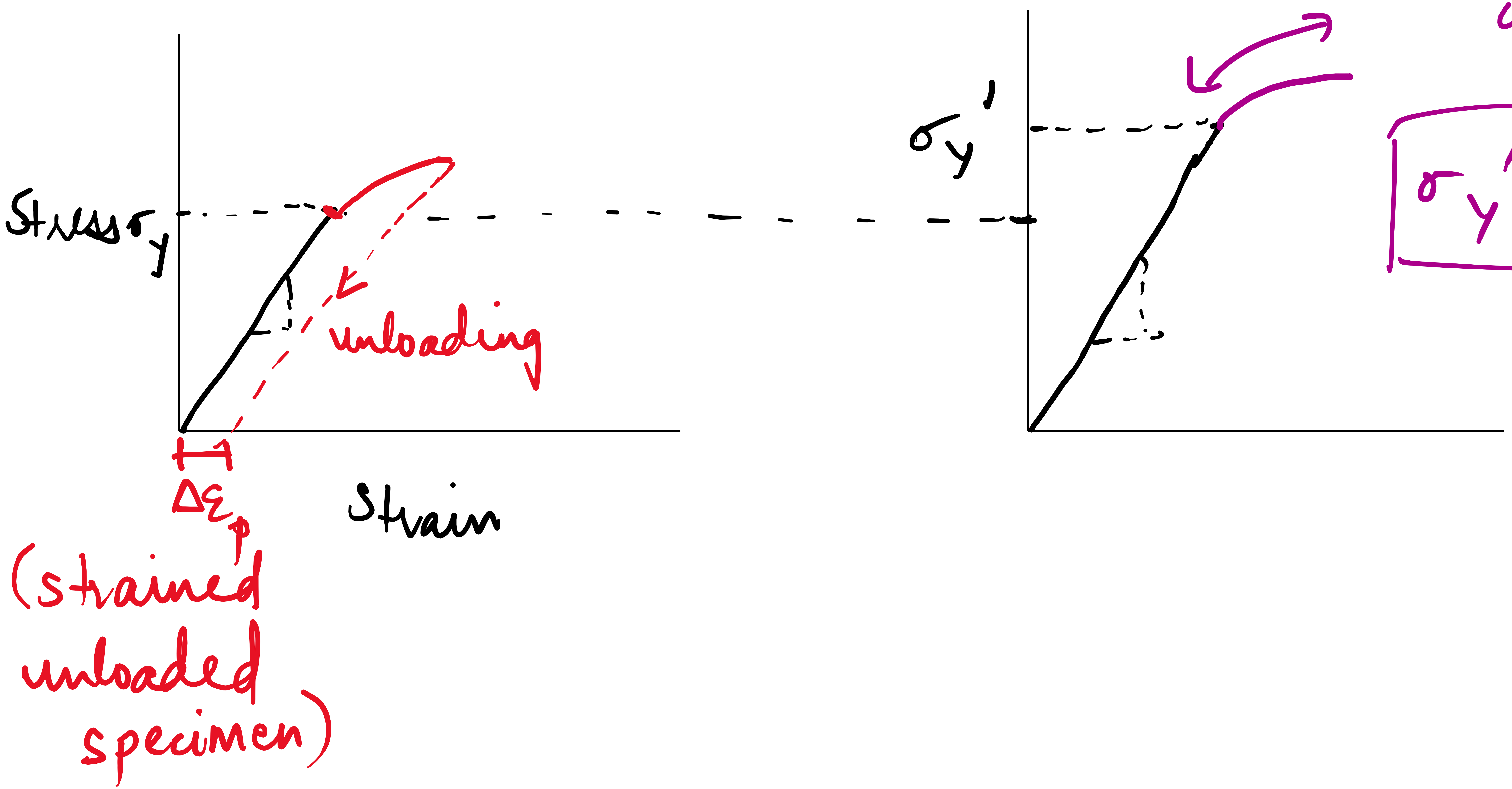
Prof. Divya Nayar
Department of Materials Science and Engineering
divyanayar@mse.iitd.ac.in

Recap…

- Surface defects: free surface, grain boundaries, stacking faults, twin boundary
- Lattice strains
- Strengthening mechanisms: grain size reduction

Strain hardening

Work hardening or cold working



$\sigma_y' = K\varepsilon^n$

n → strain hardening exponent

K → characteristic const. of metal

$$\boxed{\sigma_y' > \sigma_y}$$

Strain hardening

Dislocation-dislocation interactions

- **Strain hardening**: A ductile metal becomes harder and stronger as it is plastically deformed.
- The temperature at which deformation takes place is "cold" relative to the absolute melting temperature of the metal, **cold working.**
- Most metals strain harden at room temperature.

The dislocation density in a metal increases with deformation

↓

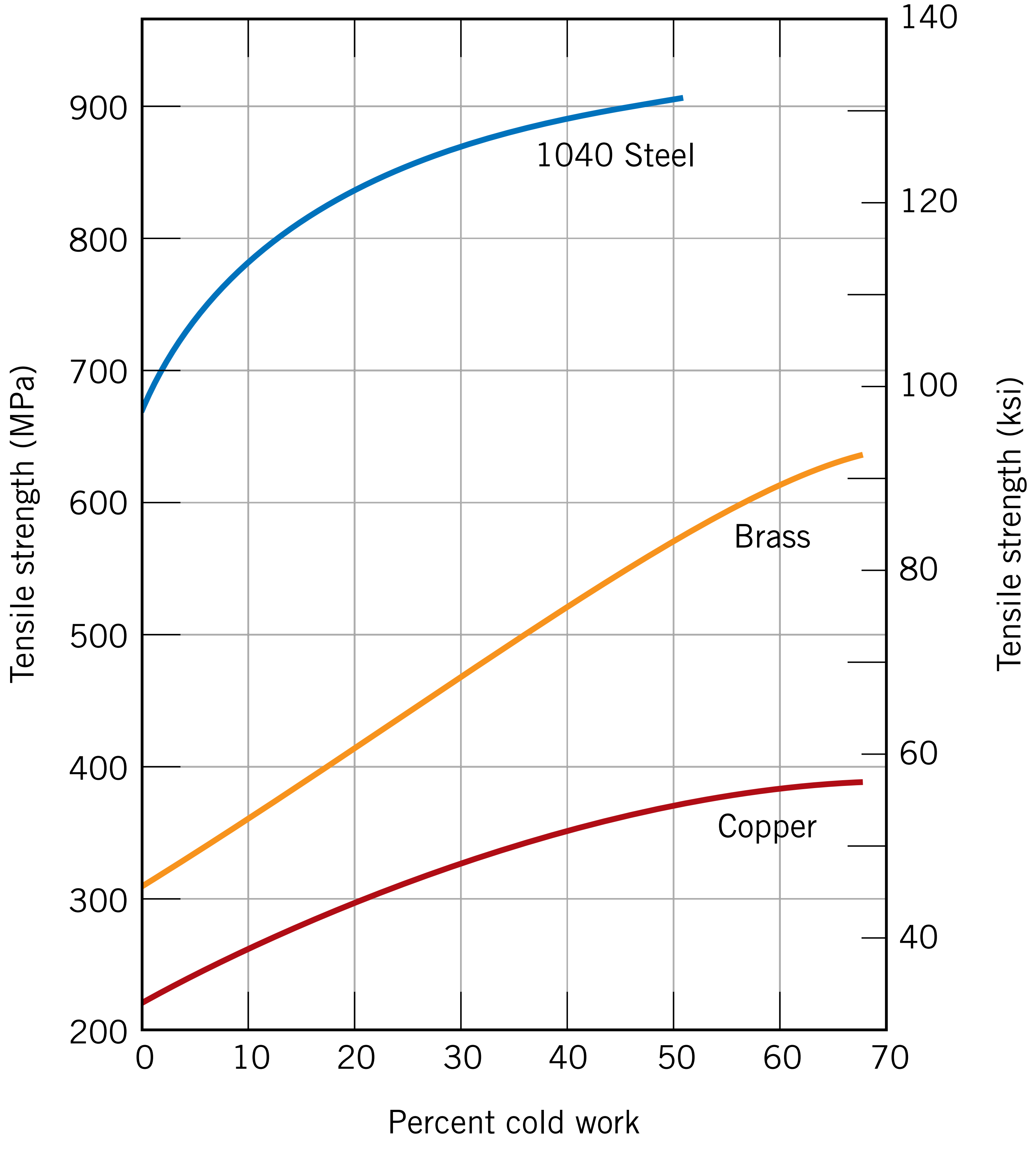
The average distance of separation between dislocations decreases

↓

Resistance to dislocation motion by other dislocations becomes more pronounced.

↓

The imposed stress necessary to deform a metal increases with increasing cold work



Degree of plastic deformation as "percent cold work" (%CW)

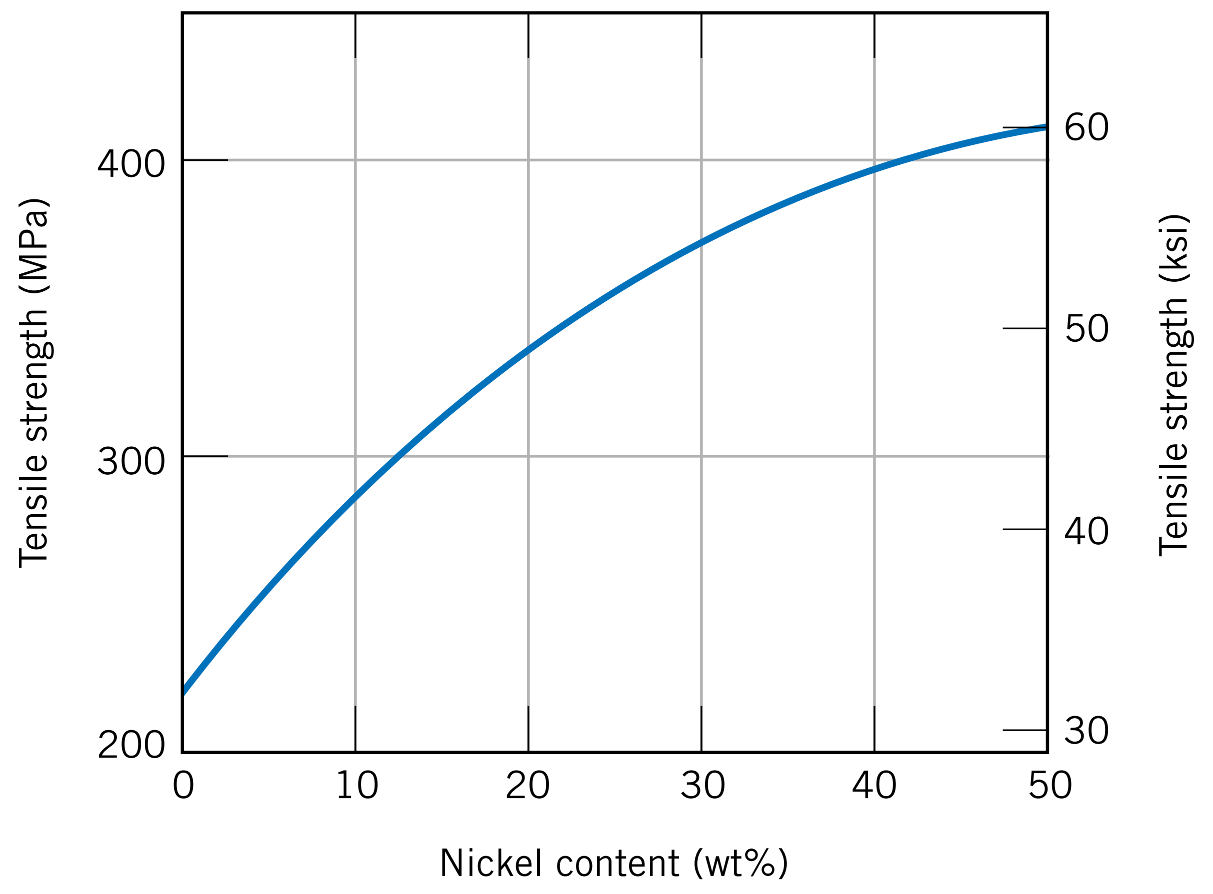
$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

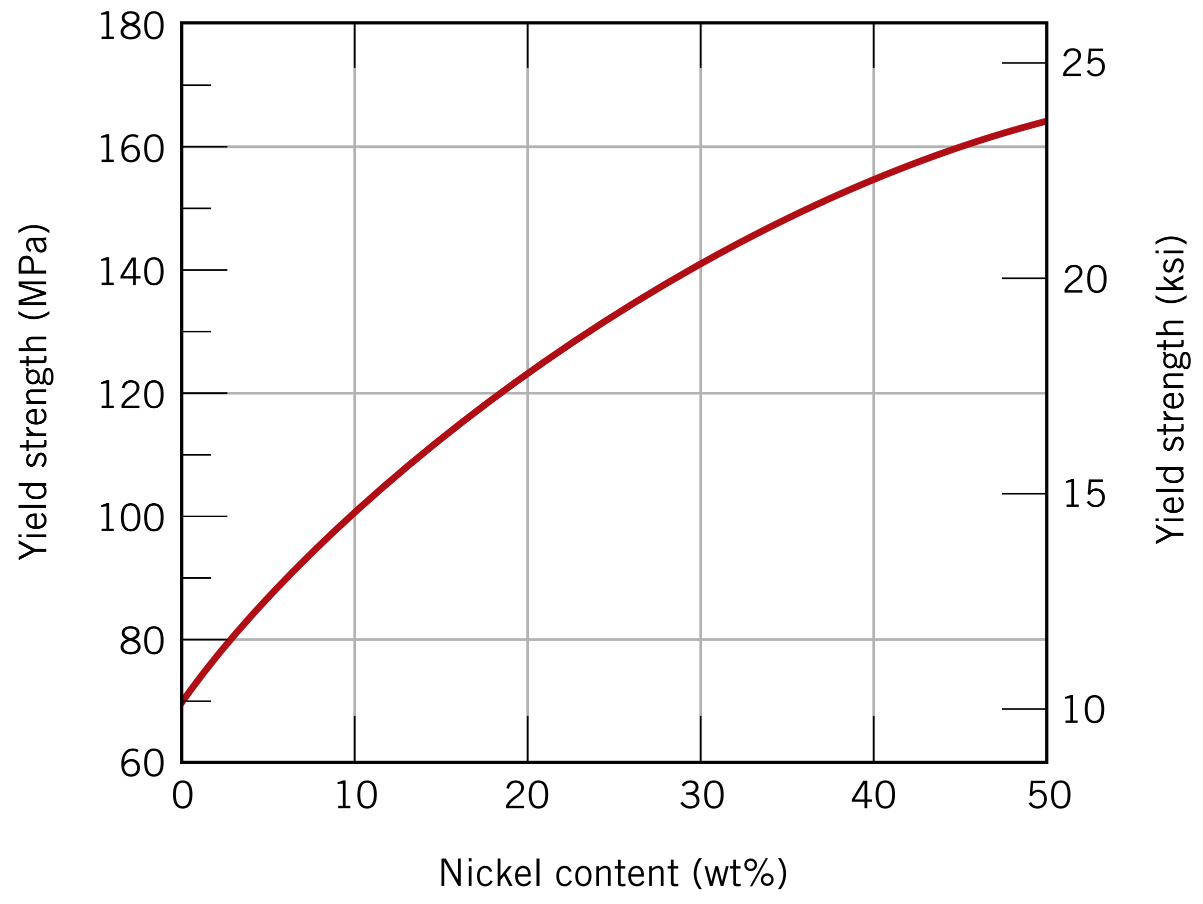
where, A_0 : original cross-section area

A_d : area after deformation

Solid solution hardening

Strengthen the metals by alloying with impurity atoms that go into either substitutional or interstitial solid solution



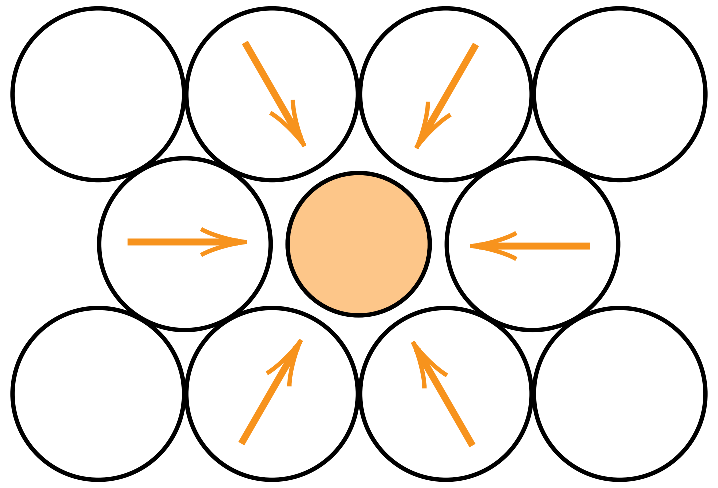


Alloys are stronger than the pure metals

-Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.

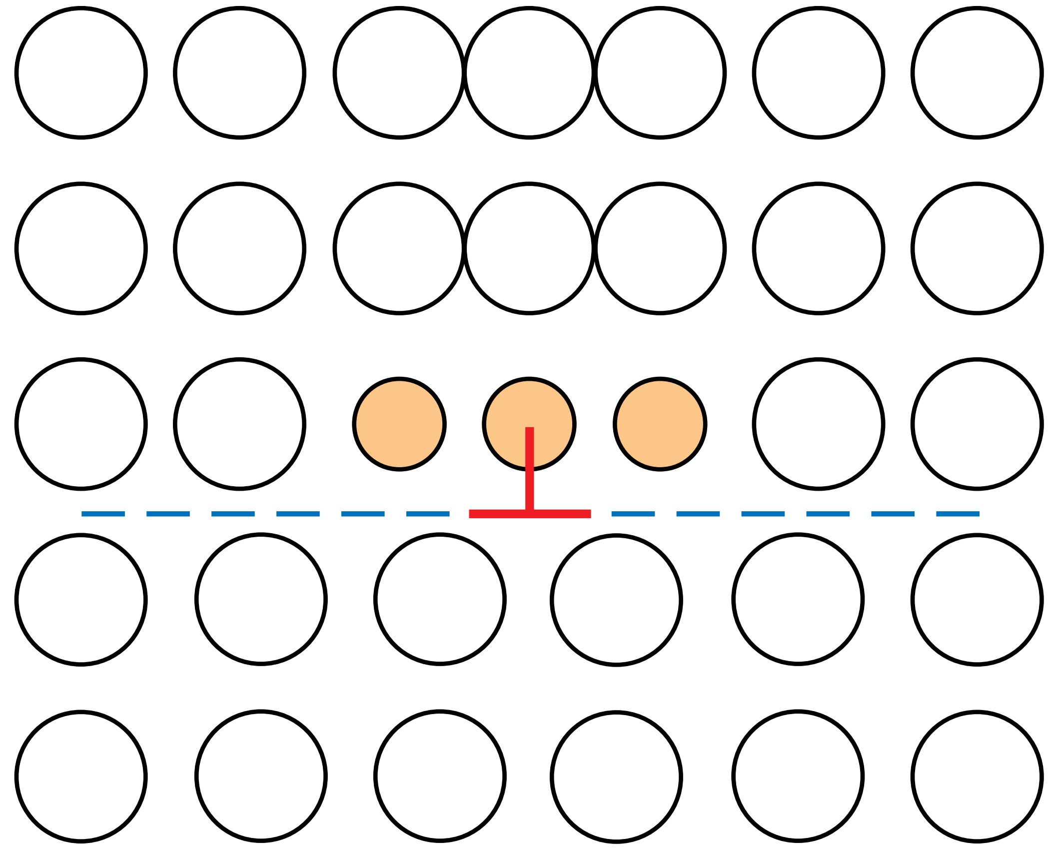
- Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted.

Small-sized impurity



(a)

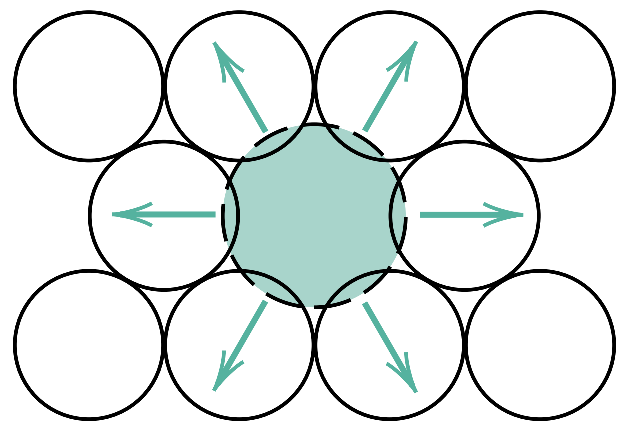
tensile lattice strains imposed on host atoms

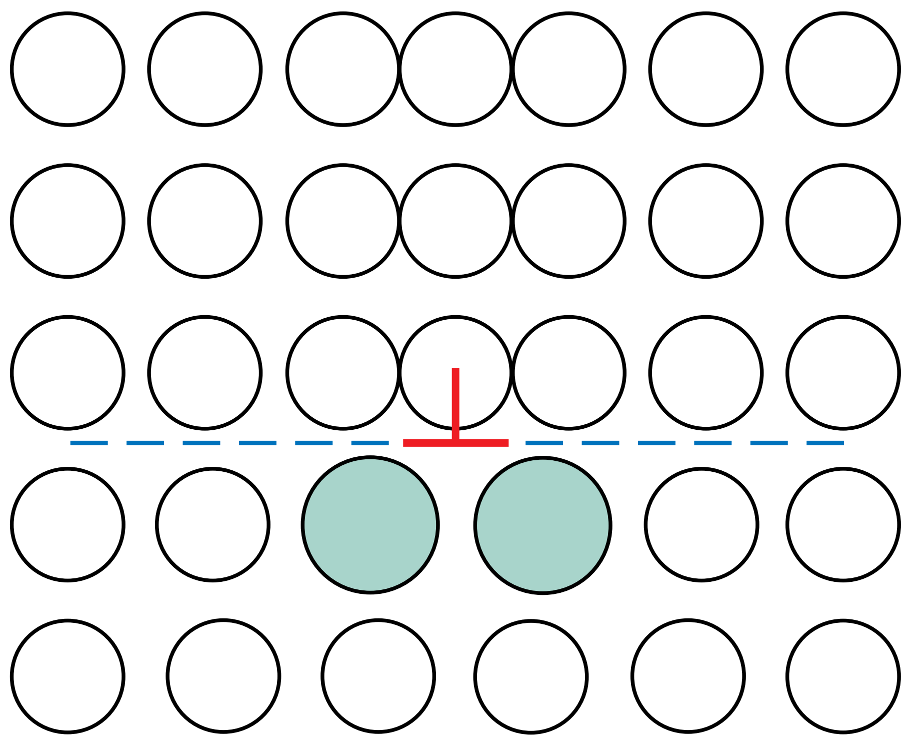


Possible locations of smaller impurity atoms relative to an edge dislocation: cancellation of lattice strains

Large-sized impurity

Compressive lattice strains





Failure in materials

- Creep
- Fracture
- Fatigue

Strengthening mechanism

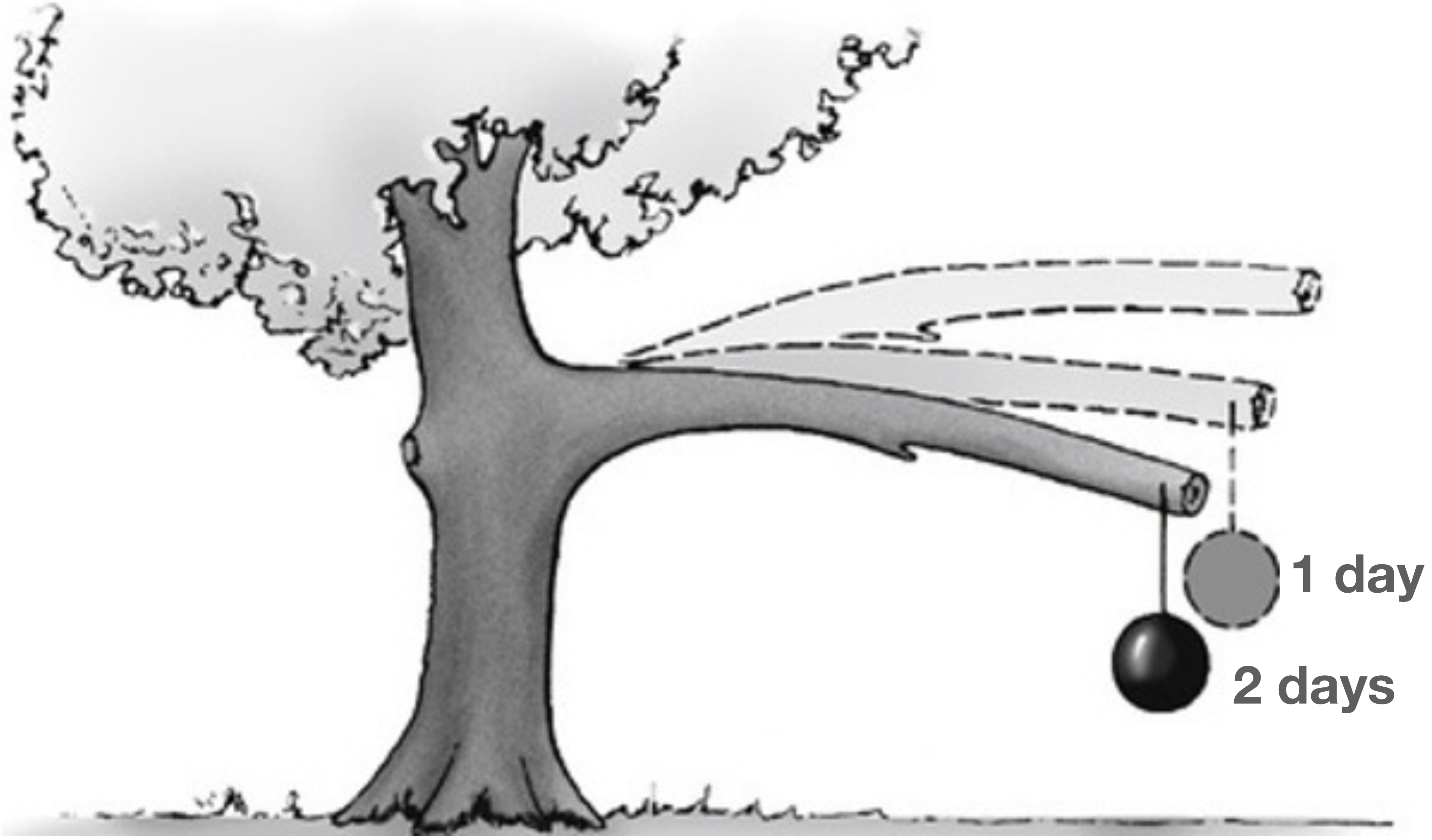
- Grain size reduction
- Strain hardening
- Solid sol^n hardening
- Precipitation hardening

Food for thought…

Wood bends by weight of fruit but steel bridges do not

Young's modulus of timber : 150-200 GPa

Young's modulus of steel: 200 GPa



Similar Young's modulus!

?

Creep

Cold flow

Failure of Turbine rotors in jet engines

Creep in concrete bridges

High temperatures, static mechanical stresses

Creep

Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses

- The stress in elastic deformation is time-independent.
- Creep is the time-dependent and permanent plastic deformation of materials when subjected to a constant load or stress.
- Amorphous polymers, which include plastics and rubbers, are especially sensitive to creep deformation
- **Creep test** consists of subjecting a specimen to a *constant load or stress* while maintaining the temperature constant; deformation or strain is measured and plotted as a function of elapsed time.
- Thermally activated process.

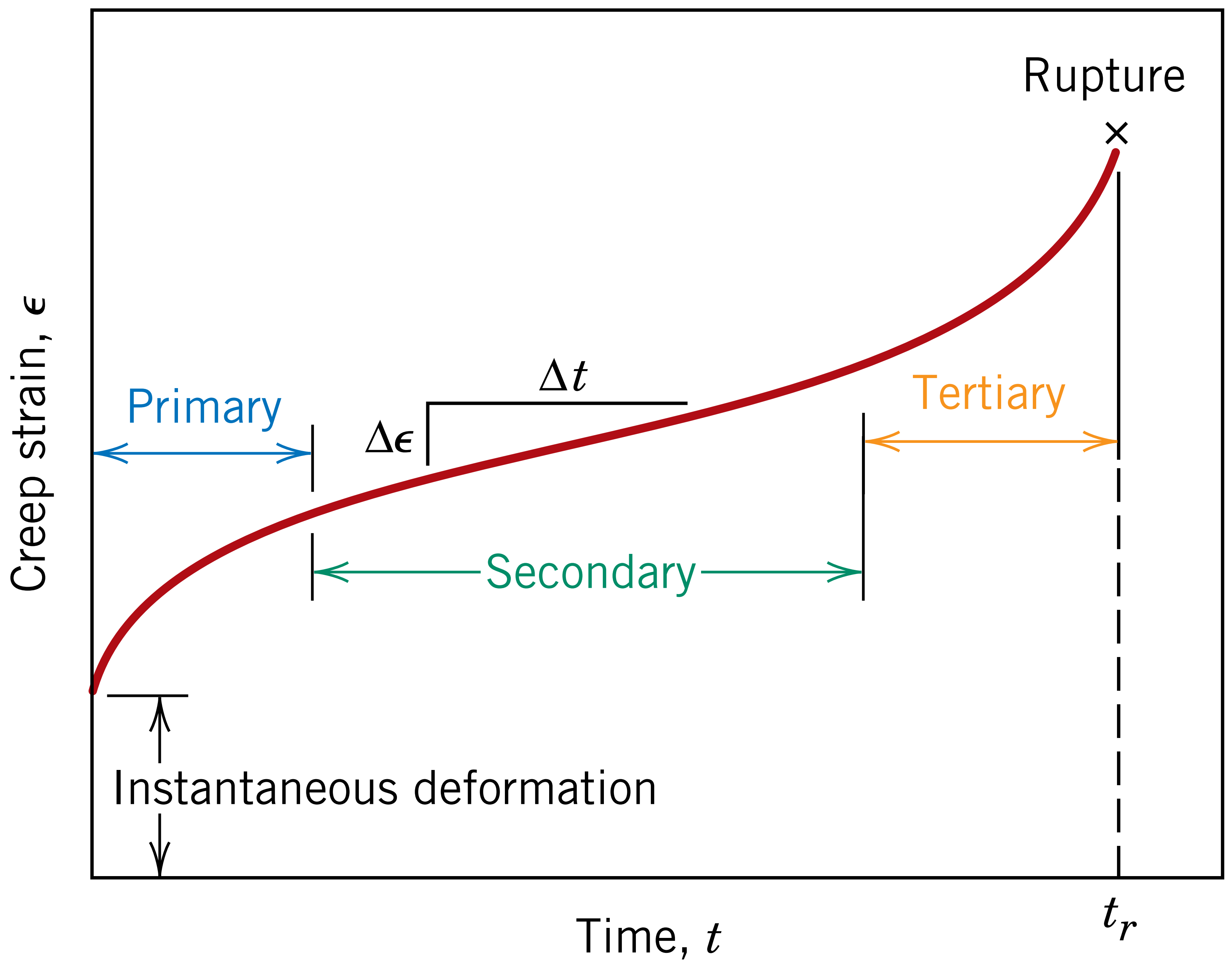
Creep is observed only at $T > 0.4T_m$
(T_m = melting point)

Find $\frac{T}{T_m}$ and check!

eg: Room T for Fe is $0.16T_m$, Cu is $0.22T_m$: No creep at room T
Room T for Pb is $0.5T_m$: Creep observed at room T.

Creep Test

Creep strain vs. time: conducted in uniaxial tension using a specimen having the same geometry as for tensile tests



Three stages:
1. Primary
2. Secondary
3. Tertiary

Minimum creep rate: $\dot{\varepsilon}_{ss} = \frac{d\varepsilon}{dt}$ (slope) [Also, called steady-state creep rate]

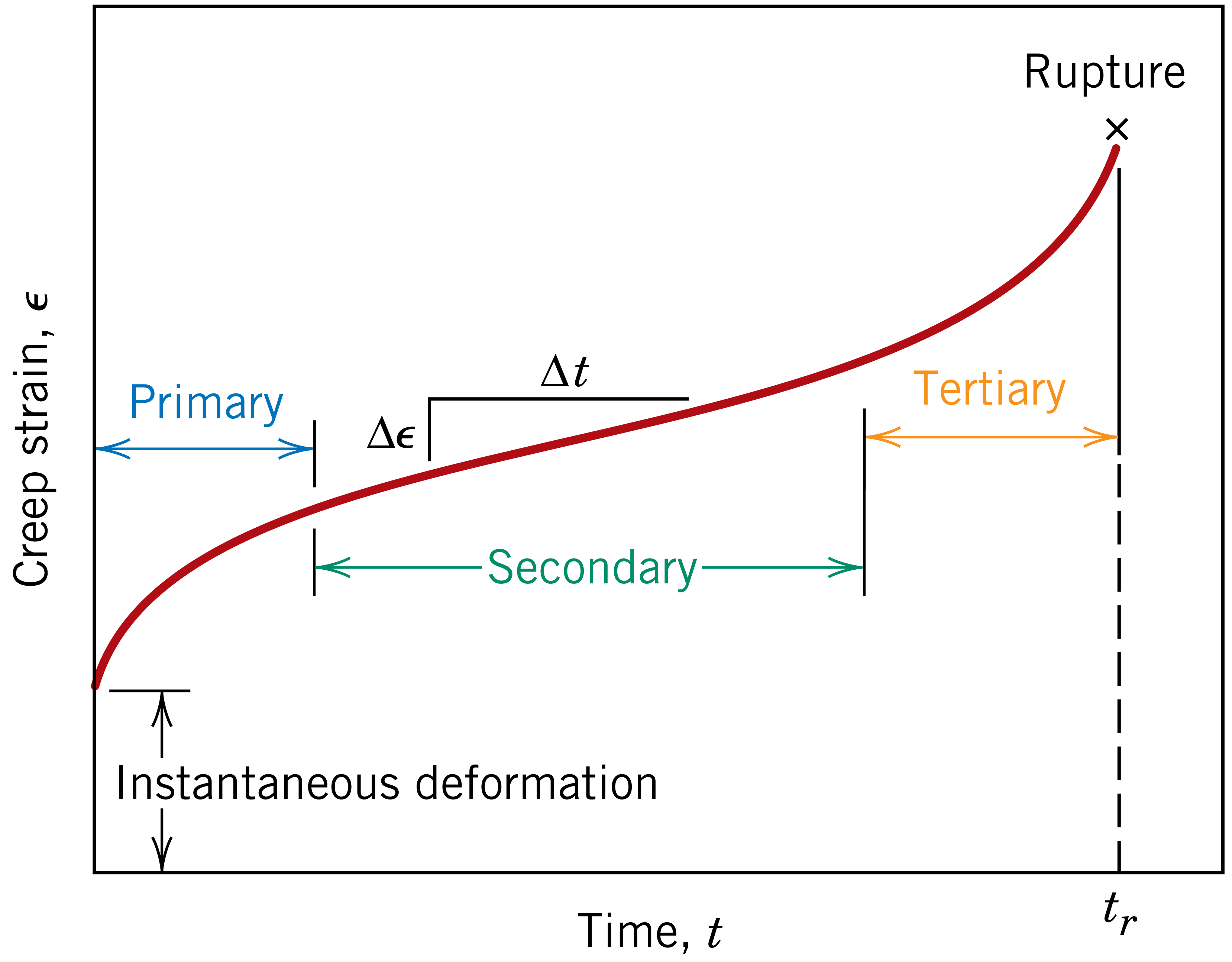
Rupture lifetime, t_r : total time to rupture

Creep Test

1. **Primary or transient creep:** The creep rate continuously decreases i.e. the slope of the curve diminishes with time. Increase in creep resistance or strain hardening.

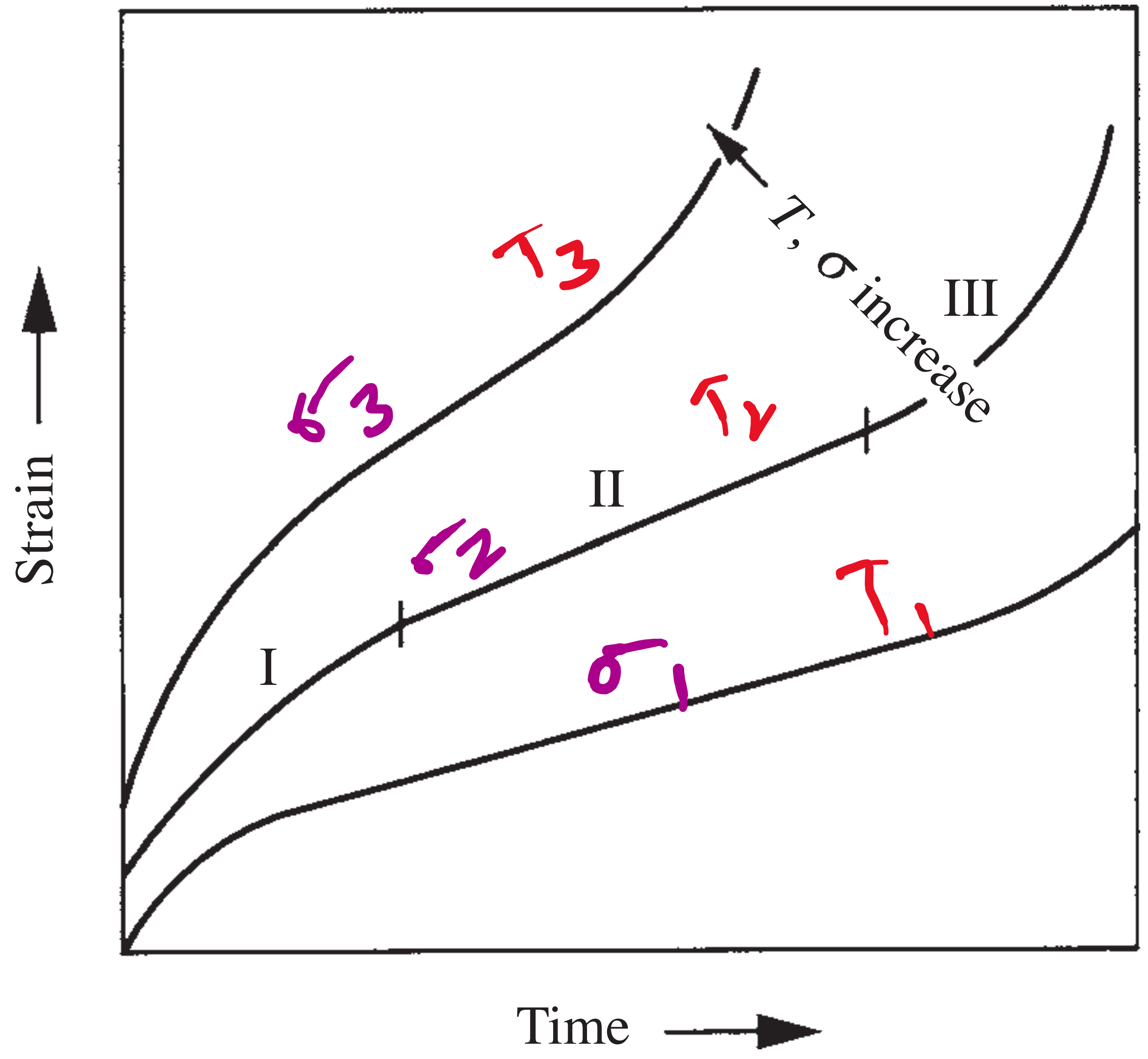
2. **Secondary creep or steady-state creep:** the rate is constant; the plot becomes linear. This is often the stage of creep that is of the longest duration. Balance between the competing processes of strain hardening and recovery. ***Recovery*** is the process whereby a material becomes softer and retains its ability to experience deformation.

3. **Tertiary creep**: there is an acceleration of the rate and ultimate failure. This failure is frequently termed ***rupture*** and results from microstructural and/or metallurgical changes; for example, grain boundary separation, and the formation of internal cracks, cavities, and voids.



Stress and temperature dependence on Creep

$T_1 < T_2 < T_3$, $\sigma_1 < \sigma_2 < \sigma_3$



$$\dot{\varepsilon}_{ss}(T, \sigma) = C\sigma^{n} \exp\left(-\frac{Q}{RT}\right)$$

$\dot{\varepsilon}_{ss}$ = steady-state strain rate at T and σ

T = test temperature

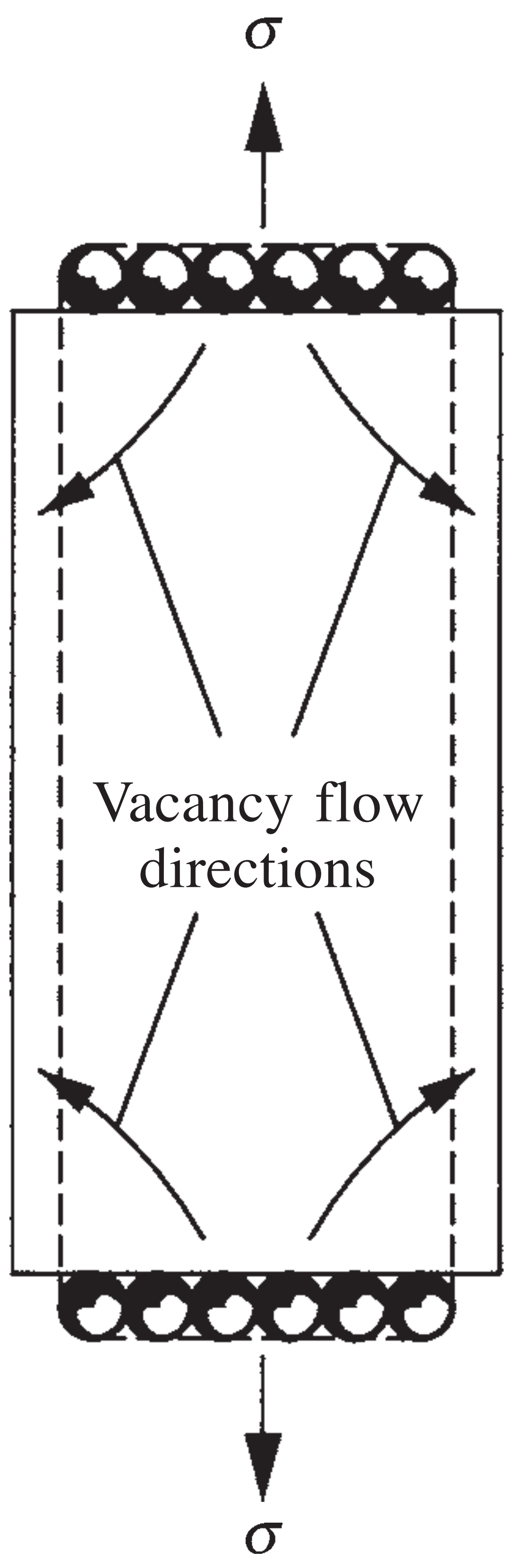
C = a constant

σ = test stress

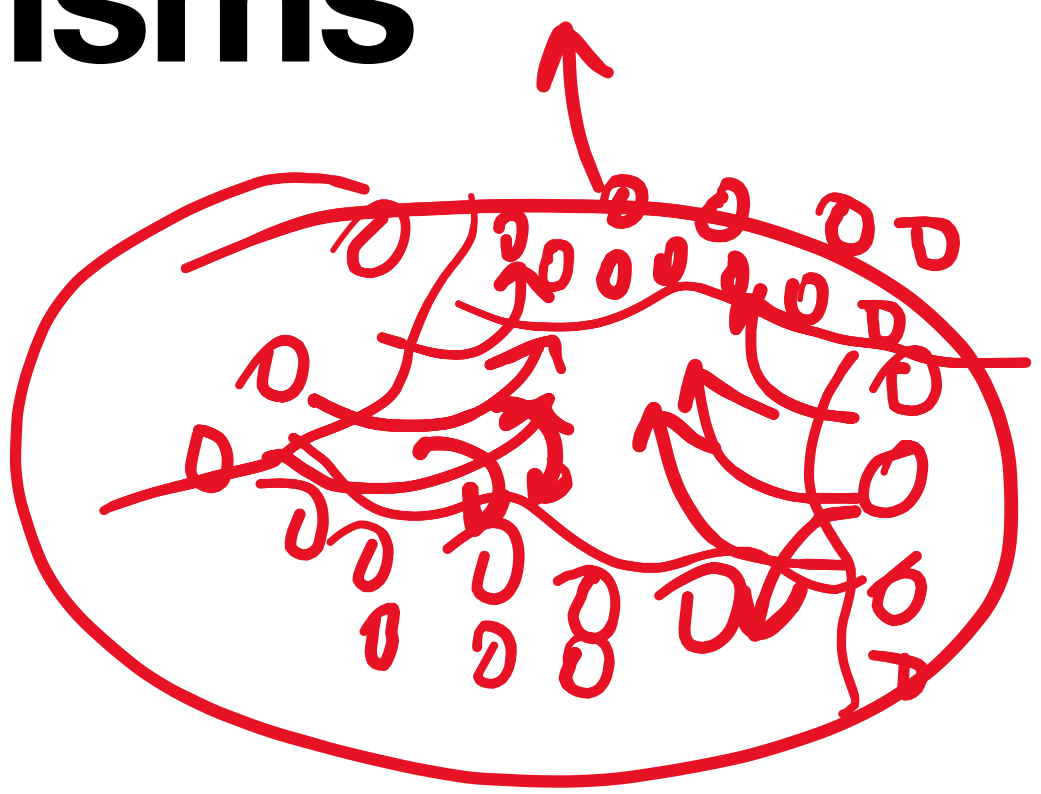
n = stress exponent ($n \sim 1$ to 8)

Q = activation energy

Creep mechanisms



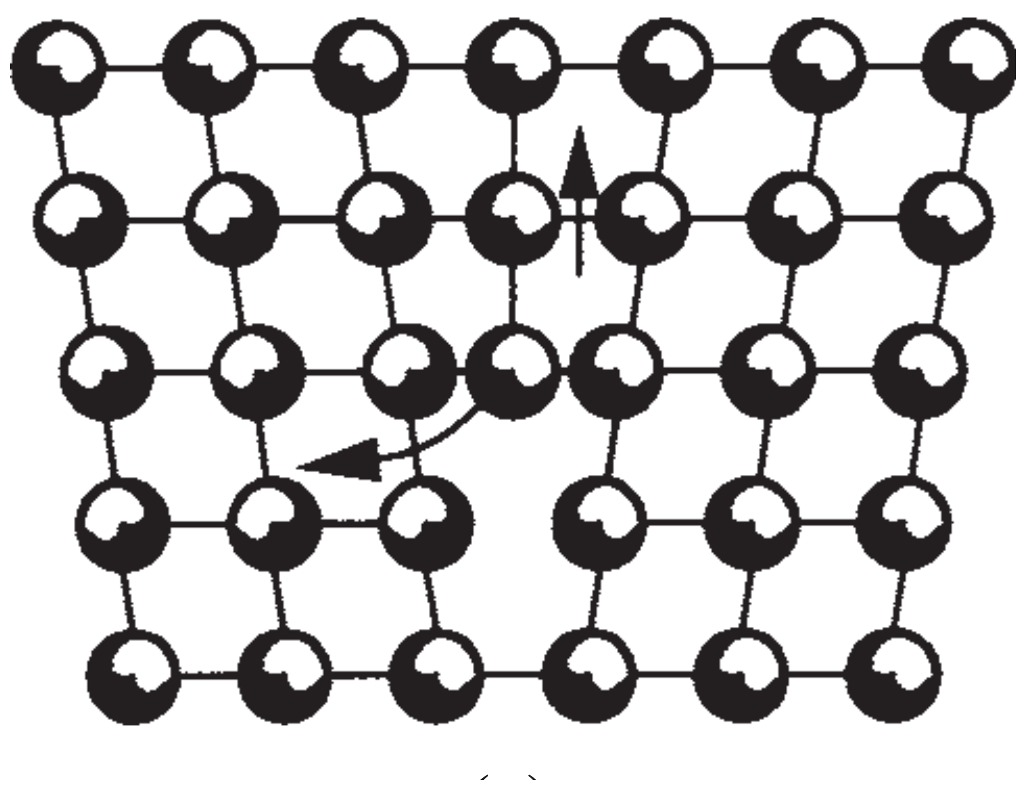
ε



Stress-assisted vacancy Diffusion

σ

reduction of cross-section



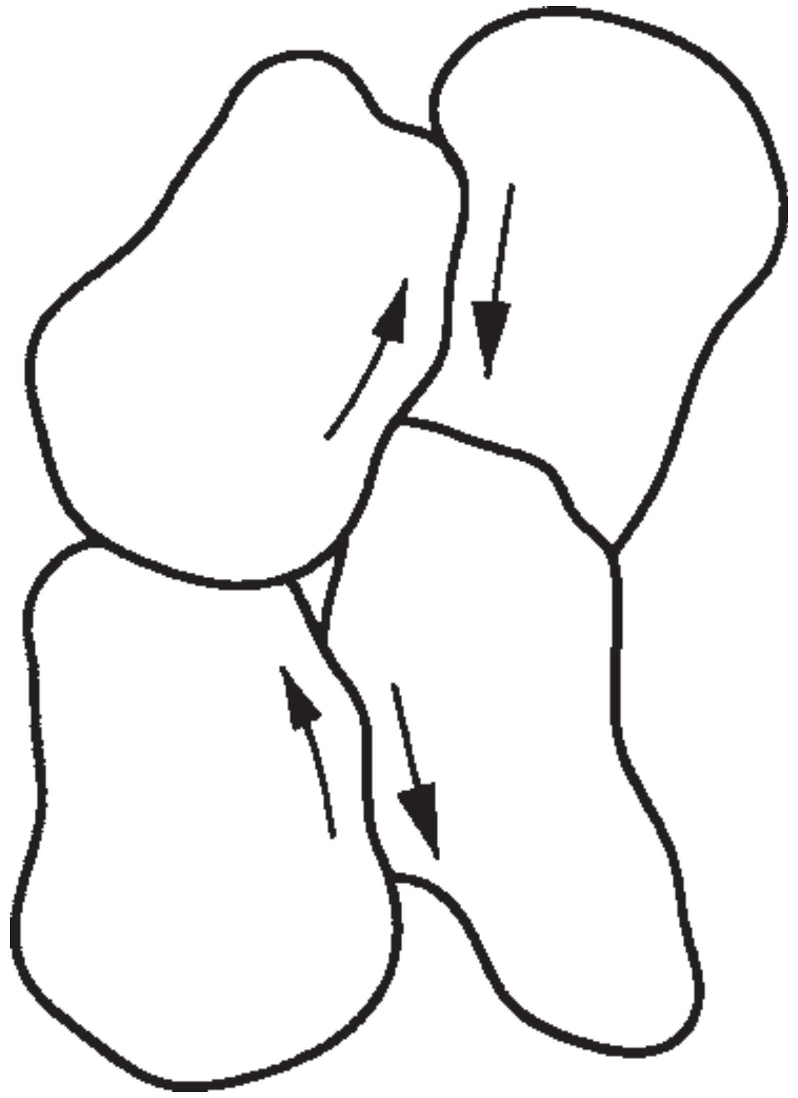
Dislocation Climb

σ

- Thus edge dislocations piled up against an immobile dislocation can move to other parallel slip planes by climb and continue their motion in response to the stress.
- *The rate controlling step in the climb process is the diffusion of vacancies*.
- The measured activation energy for creep agrees with the activation energy for self-diffusion by the vacancy mechanism in a number of materials.

- Vacancies move in response to the applied stress from surfaces of the specimenperpendicular to the stress axis to the surfaces that are parallel to the stress axis.
- Over a period of time, this movement would elongate the specimen in the direction of the stress axis and contract it in the transverse direction resulting in creep.

Creep mechanisms



Grain boundary sliding

- Grain boundaries lose their strength at a lower temperature than the grains themselves.
- At temperatures above 0.5 *Tm*, the viscosity of the grain boundaries is small enough for them to behave like a very viscous liquid separating the neighbouring grains and allowing them to slide against each other.
- At high temperatures, the grain boundaries facilitate the deformation process by sliding, whereas at low temperatures, they increase the yield strength by stopping the dislocations.

Creep resistant materials:

- *Cold working or strain hardening cannot be used* for creep resistance. At temperatures above $0.4T_m$, recrystallization will occur quite readily and the cold-worked strength will be lost on recrystallization. *Recrystallization* is the process of nucleation and growth of new, strain-free crystals, which replace all the deformed crystals of the worked material. It starts on heating to temperatures in the range of 0.3–0.5*Tm*, which is above the recovery range.
- *Solid solution hardening can be used* for better creep resistance.
- *Fine-grained materials should be avoided* at high T as grain boundary sliding can add to creep deformation.
- Minimizing grain boundary sliding.
- Using high melting point material.