FS 2025/26

MSE-422 – Advanced Metallurgy

2.2 - Reminder: Mechanical Properties & Strengthening Mechanisms

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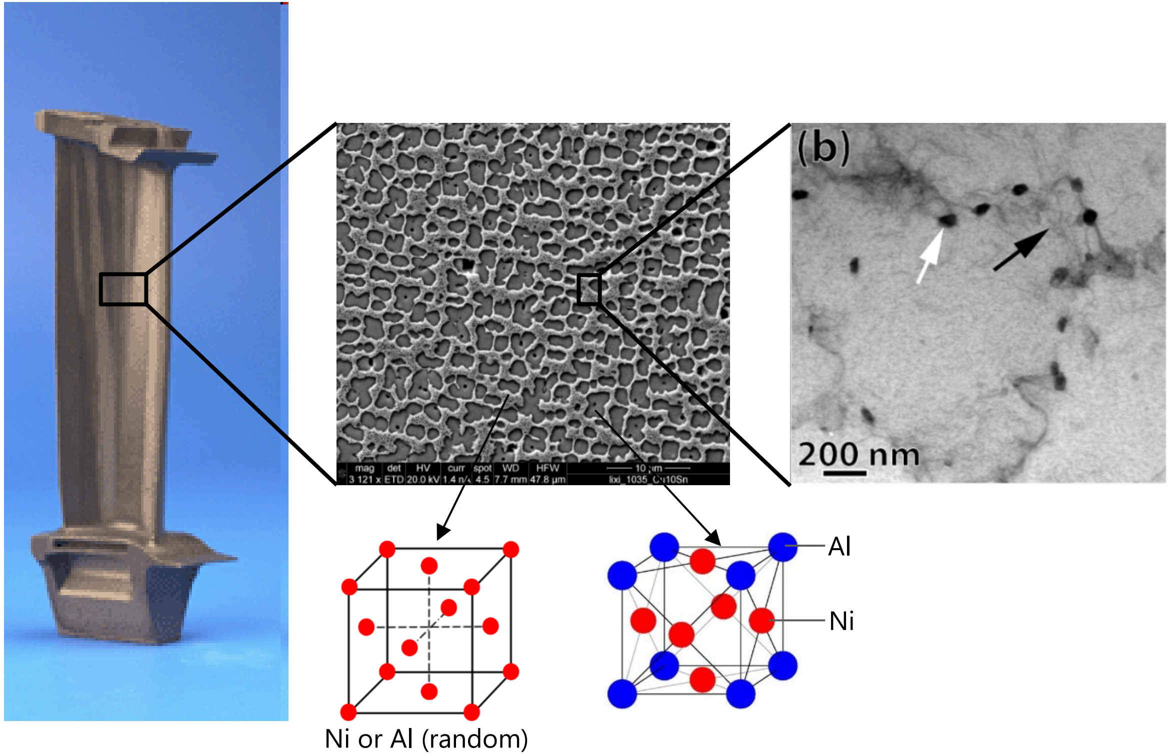
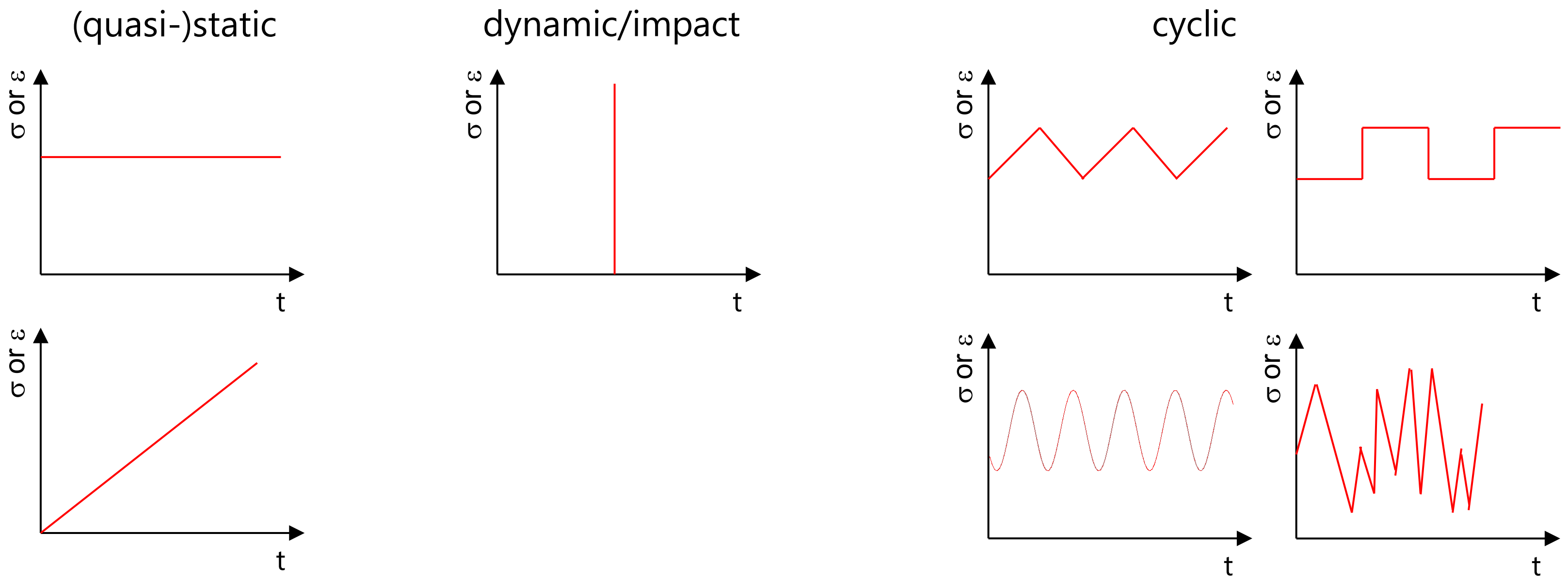
Alloy performance under thermo-mechanical loads

Let’s have a look into a turbine blade made from a Ni superalloy



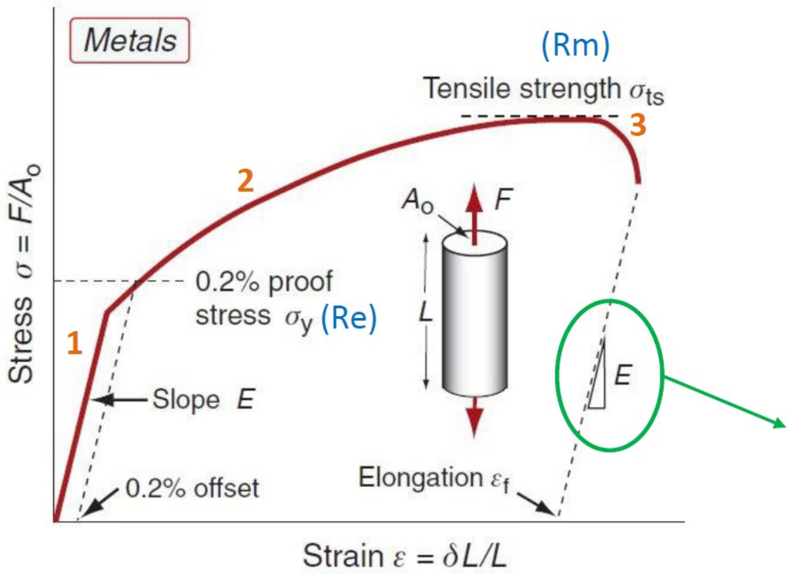
- What mechanical loads does the turbine blade experience?
- At what temperatures is the turbine blade operated? For how long?
- Are there further environmental influences that need to be considered?
- Why is Ni the material of choice for such service conditions?
- What is the (mechanical) reason for this particular microstructure

Mechanical loading of alloys



- In many applications, a superposition of the loads occurs (e.g. static + cyclic)
- These loading conditions can occur at low ($T<0.4T_s$ [K]) or at high ($T>0.4T_s$ [K]) temperatures

Static loading – the stress-strain curve



Phase 1: elastic (reversible) deformation

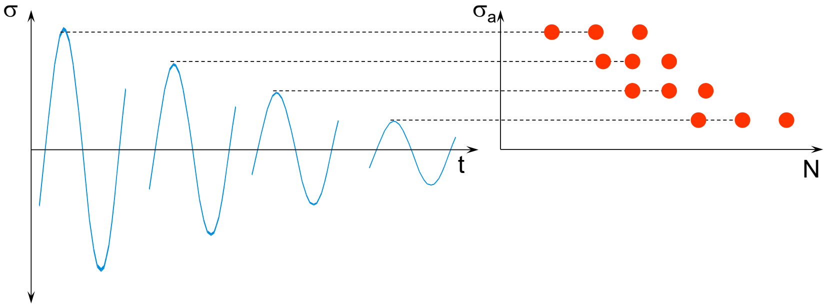
Phase 2: homogeneous plastic deformation (irreversible)

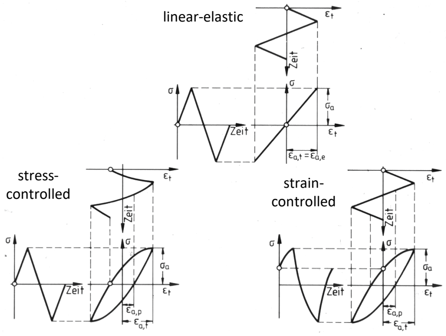
Phase 3: strain localisation, necking and final rupture

/Ashby & Jones, Engineering Materials 1/

Cyclic deformation and fatigue

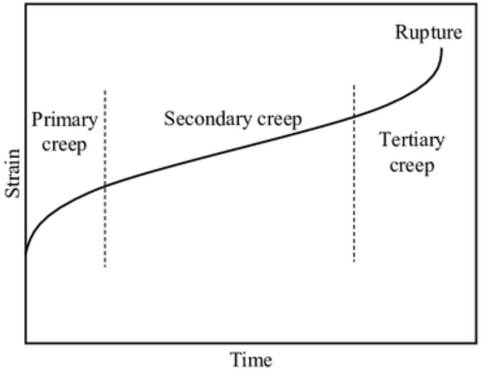
- The fatigue performance of an alloy is characterized by S,N- or Wöhler-curves
- The origin of fatigue failure is the localized and accumulated micro-plastic deformation
- Fatigue is failure under applied cyclic stress
  - Responsible for 90% of mechanical engineering failures
  - Possible failure of components for $\sigma_{max} < \sigma_y$
  - Brittle fracture w/o pronounced macroscopic deformation also for ductile materials (no warning)

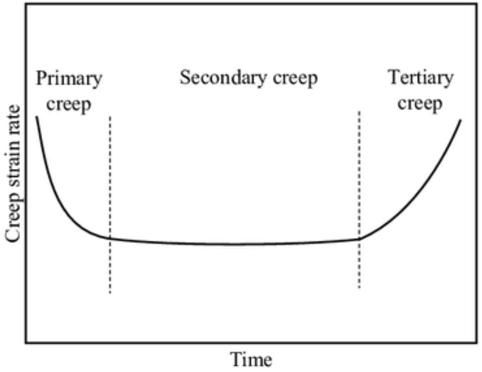




Creep

- Creep is the time-dependent plastic deformation under a constant stress at elevated temperatures, which can result in sudden catastrophic failure
- Creep can occur at even at very low mechanical loads significantly below the static yield stress (e.g. dead weight of the component, centrifugal forces in rotating parts)





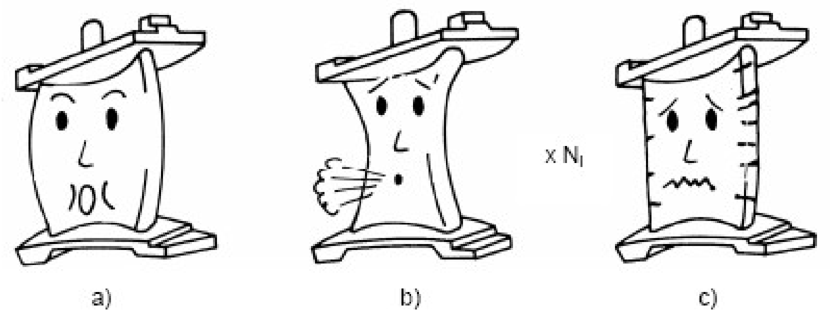
(a) 400°C

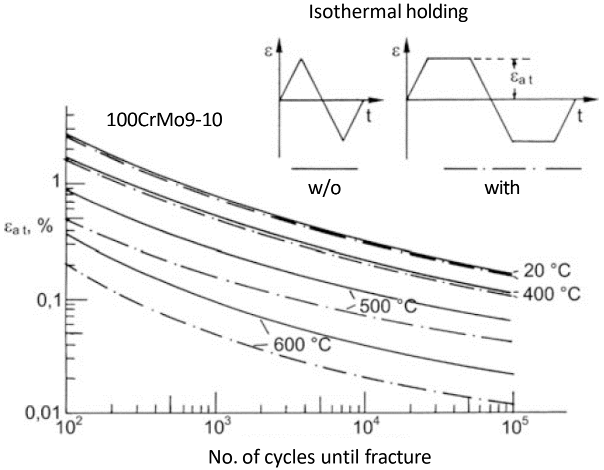
(b) 500°C

(c) 600°C

Thermo-mechanical fatigue – creep fatigue

- Cyclic heating/cooling of a part leads to cyclic expansion/contractions, which can lead to part failure
- Superposed thermal and cyclic loading leads to accelerated damage of the part

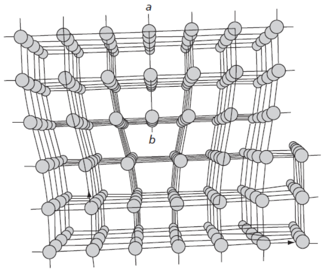


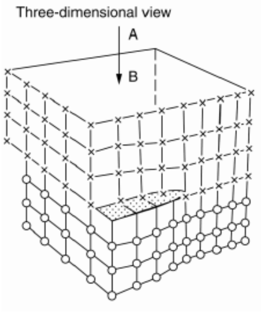


Plastic deformation – dislocations

- Plastic deformation in metals and alloys occurs by dislocation movement
- The dislocation will move if the shear stress acting on the dislocation is larger than the intrinsic stress of the crystal lattice, the so-called Peierls-Nabarro stress

edge dislocation screw





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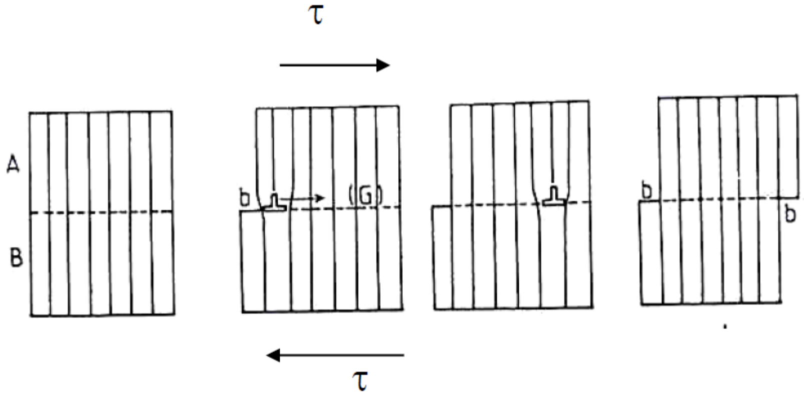
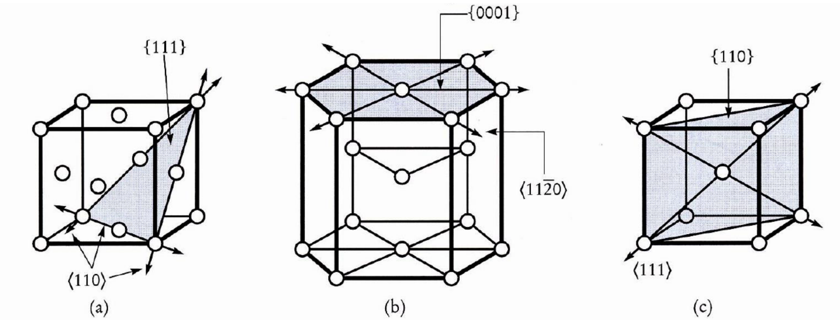


Plastic deformation – slip systems

- Dislocation movement occurs on crystallographic planes with highest packing density (slip planes) along the direction with highest packing density (slip direction)
- Slip plane + slip direction = slip system
- The main (primary) slip systems in metals are

  fcc: $\{111\} < 110 >$; hcp: $\{0001\} < 11\bar{2}0 >$; bcc: $\{110\} < 111 >$
- Slip systems with almost densest packing densities might be also activated (secondary slip systems)



Plastic deformation – polycrystals

- In the case of plastic deformation of a polycrystal to any arbitrary shape, at least 5 different slip systems need to be activated per grain (von-Mises criterion)
- The relationship between the externally applied normal stress σ and the average shear stress τ is: $\sigma = M_i \tau$
- Depending on the grain orientation in fcc materials with slip systems {111}<110> and bcc materials with slip systems {110}<111> the values for Mi are $2.27 < M_i < 3.67$
- The average value $M_T = \overline{M_i} = 3.06$ is the Taylor factor
- For a polycrystal with random grain orientation: $\sigma = M_T \tau = R$

External load

Material resistance
against plastic deformation

Strengthening mechanisms in metals and alloys

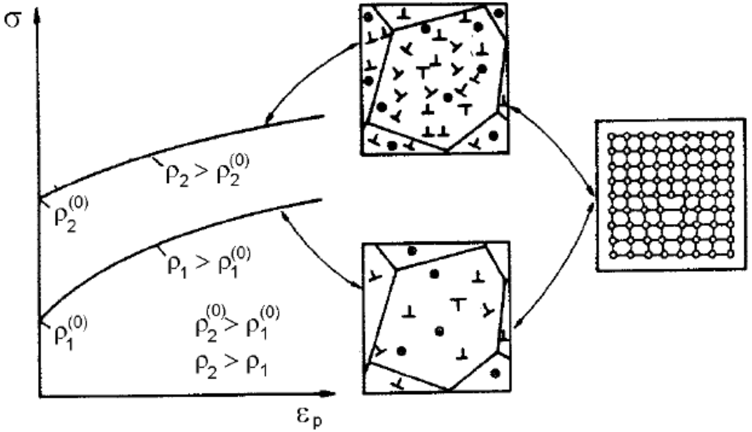
- Structural alloys have to withstand high loads without plastic deformation, i.e. the movement of dislocations must be hindered
- This can be achieved by activating one or more of the following strengthening mechanisms
  - Dislocation hardening/strengthening
  - Solid solution strengthening
  - Grain boundary strengthening
  - Particle strengthening (precipitation/dispersoid strengthening)
  - Grain orientation (texture) strengthening

Dislocation strengthening

- Moving dislocations have to overcome the residual stress field of other dislocations
- This leads to a material resistance

$$R_{dis} = \alpha_1 G b \sqrt{\rho_{tot}}$$

α_1: constant
G: shear module
b: contribution of the Burger’s vector of a dislocation
ρ_{tot}: total dislocation density



- Dislocation hardening can be achieved in all metals by cold working (e.g. cold rolling, drawing, hammering etc.)
- During plastic deformation, new dislocations are generated according to the Frank-Read mechanism

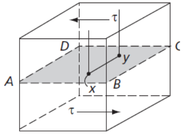


FIG. 5.1 Frank-Read source. The dislocation segment *xy* may move in plane *ABCD* under the applied stress. Its ends, *x* and *y*, however, are fixed

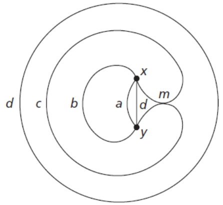
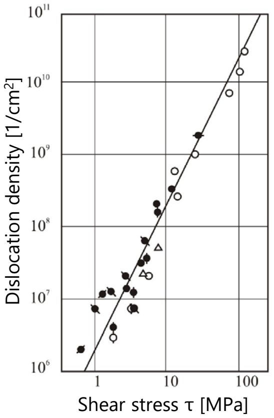
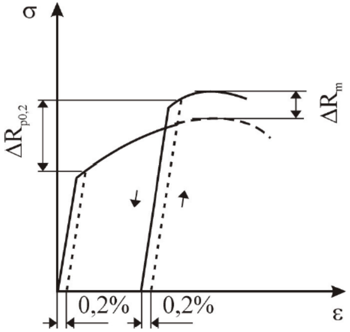


FIG. 5.2 Various stages in the generation of a dislocation loop at a Frank-Read source

Dislocation strengthening

- The dislocation density can be increased to ~10^{12} 1/cm^2
- The residual stress fields of glide dislocations are interacting with the residual stress fields of other dislocations
- This leads to an increase of the strength and a decrease of the ductility
- The strengthening effect depends on
  - The strain hardening performance
  - The range of uniform deformation
- fcc metals (e.g. austenitic steel) exhibit in general a more pronounced dislocation hardening than bcc (ferritic steel) or hex metals
- Cold working/dislocation strengthening is only useful if the service temperature is below the recrystallization temperature
- Examples:
  - Crane wires: R_m = 1400…2200 MPa
  - Piano strings: R_m = 3600 MPa



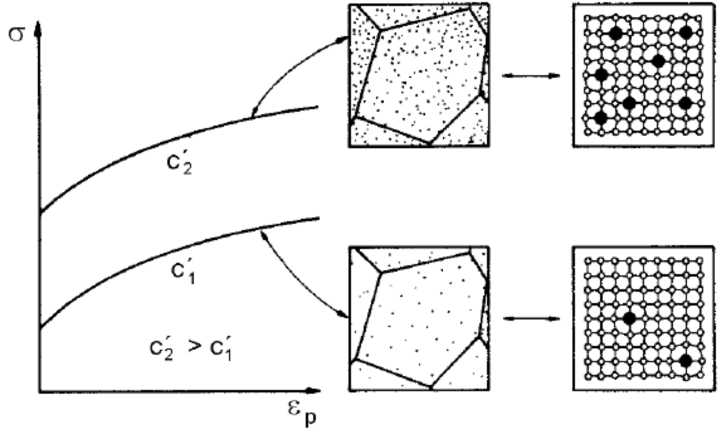


Solid solution strengthening

- Moving dislocations have to overcome the residual stress field of solute atoms on the slip plane
- This leads to a material resistance

$$R_{ss} = \alpha_2 G(c')^n$$

α_2: constant
G: shear module
n: strengthening exponent (0.5<n<1)
c': concentration of solute atoms

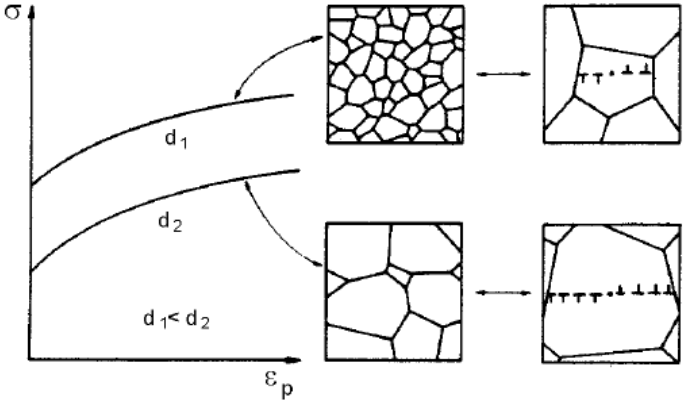


Grain boundary strengthening

- Moving dislocations pile up at grain boundaries
- The stress fields of these dislocations
  - interact with other gliding dislocations
  - induce slip activities in neighbouring grains
- This leads to a material resistance

$$R_{gb} = \frac{k}{\sqrt{d}}$$

k: material and temperature dependent parameter
(Hall-Petch-parameter)
d: average grain diameter



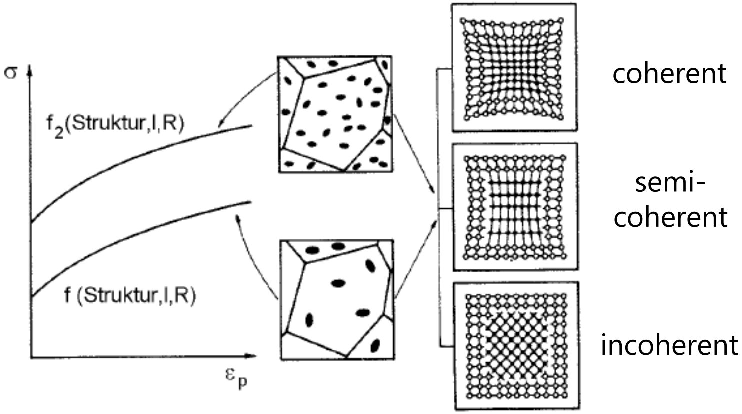
Particle strengthening

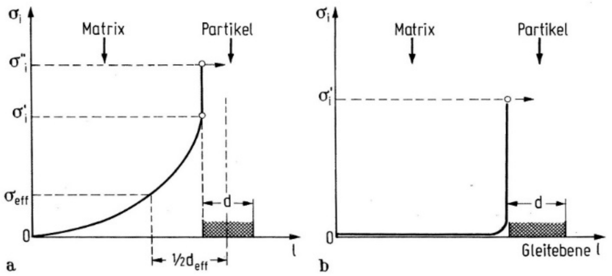
- Particles in the grains are obstacles for moving dislocations
- The dislocations must
  - cut through ptc. (coherent)
  - move around ptc. ((semi-)coherent/incoherent)
- This leads to a material resistance

$$R_{ptc}^{cut} = \alpha_3 f\left(2r, l, \gamma_{if}\right)$$

$$R_{ptc}^{circum} = \alpha_4 \frac{Gb}{l} f(r)$$

$\alpha_{3,4}$: constants
G: shear module
b: contribution from Burger's vector
l: average particle spacing
r: average particle radius
γ_{if}: interfacial energy



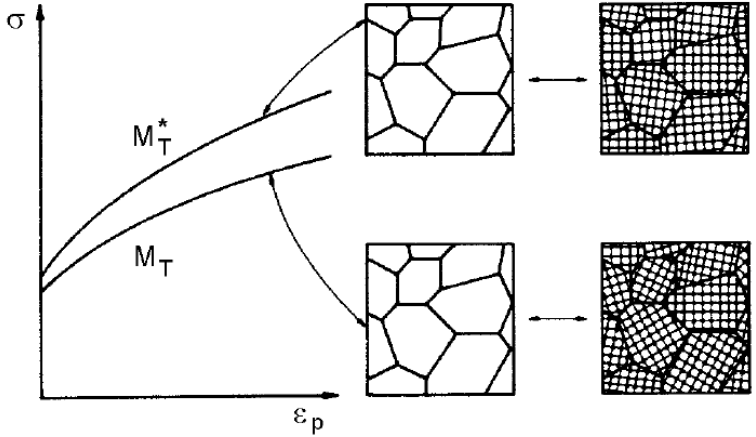


Grain orientation strengthening

- In a polycrystal, dislocation slip occurs only in grains for which the slip systems are oriented with regard to the main loading direction
- A preferred orientation of certain grain families (texture) results in softening/strengthening
- This leads to a material resistance

$$R_{orient} = \frac{M_{T*}}{M_T} R$$

M_{T*}: orientation dependent Taylor factor
M_T: Taylor factor



Additvity of strengthening mechanisms

- If several strengthening mechanisms are applied, then the overall material resistance against plastic deformation is the sum of all individual resistances

$$R_{total} = R_{dis} + R_{ss} + R_{gb} + R_{ptc}$$

and when considering the texture influence

$$R_{orient} = \frac{M_{T*}}{M_T}\left(R_{dis} + R_{ss} + R_{gb} + R_{ptc}\right)$$

High temperature plasticity

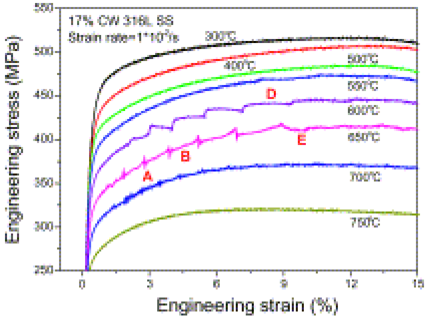
- At temperatures above 0.4 Ts [K], a transition from time-independent to time dependent plastic deformation occurs
- Dislocations are thermally activated and are continously moving
- Mechanical stresses consist of a thermal part σ_{therm}, which can be thermally activated and an intrinsic athermal part σ_i

$$\sigma_{mech} = \sigma_{therm} + \sigma_i \text{ with } \sigma_{therm} = f(T, \dot{\varepsilon}) \text{ and } \sigma_i \neq f(T, \dot{\varepsilon})$$

- The thermal part σ_{therm} includes
  - The Peierls stress
  - Cutting stress
  - Cross slip stress
- The athermal part σ_i includes
  - Residual stresses induced by the dislocation
- Recovery through annihilitaion of dislocations, recrystallization and grain growth can significantly alter the microstructure

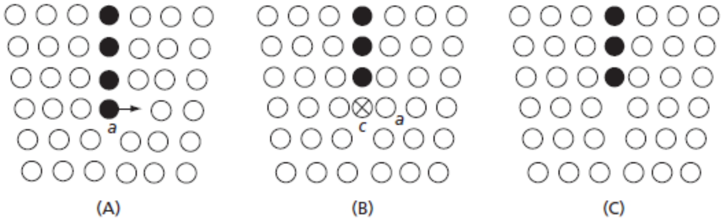
High temperature plasticity

- The yield stress decreases with increasing T → the resistance against plastic deformation (i.e. dislocation movement) is decreased
- The following dislocation movement mechanisms are active
  - Dislocation glide is facilitaed because of a decreased Peierls stress at high T
  - Dislocations can leave their primary slip plane and move on other slip planes due to thermally activated climbing of edge dislocations or cross slip of screw dislocations

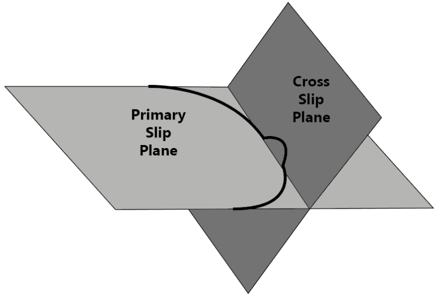


/S.G. Hong,, J. Nuclear Mater. 328(2-3) (2004) 232-242/

Edge dislocation climb

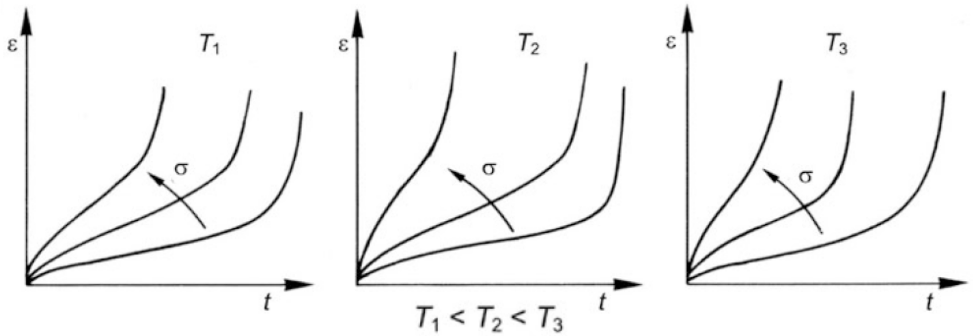


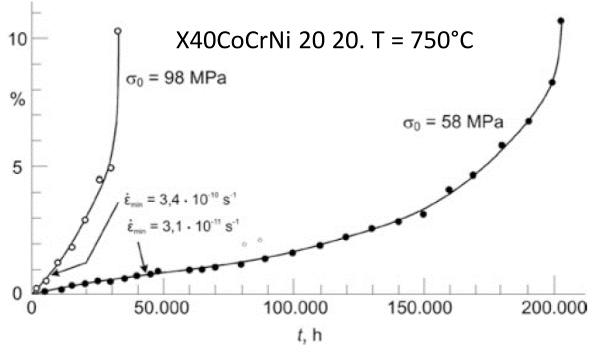
Cross slip



Time dependent plasticity - creep

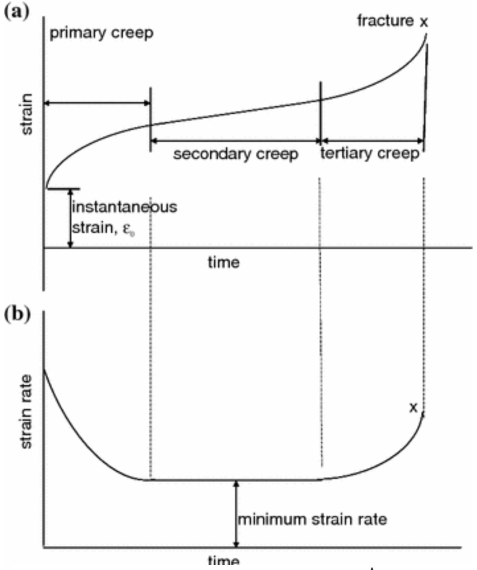
- Creep is the time-dependent plastic deformation under a constant stress at elevated temperatures, which can result in sudden catastrophic failure
- Creep can occur at even at very low mechanical loads significantly below the static yield stress (e.g. dead weight of the component, centrifugal forces in rotating parts)
- Creep is more pronounced with increasing loads and increasing temperature

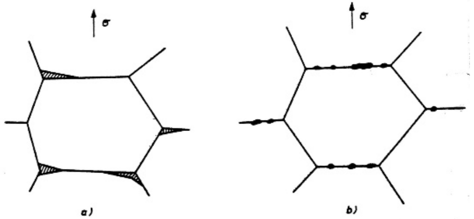



X40CoCrNi 20 20. T = 750°C

Creep curves

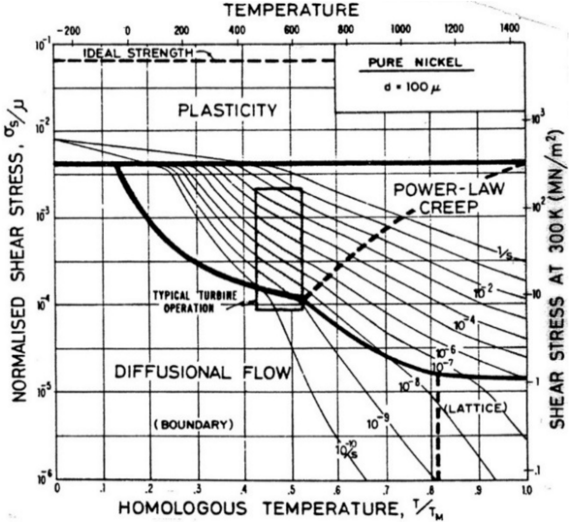
- Primary creep
  - Decreasing creep rate $\dot{\varepsilon}$, hardening because of increasing dislocation density
- Secondary creep
  - $\dot{\varepsilon}$ minimal and constant, softening because of recovery processes (dislocation annihilation)
  - Cross slip and climb are activated
  - Diffusion of vacancies
  - Overall, equilibrium between hardening (formation of dislocations) and softening processes
- Tertiary creep
  - Increasing $\dot{\varepsilon}$, pronounced material damage
  - Cracks at grain boundary triple points (high σ, short t)
  - Pores on grain boundaries ⊥ loading direction (low σ, long t)





Creep deformation mechanisms

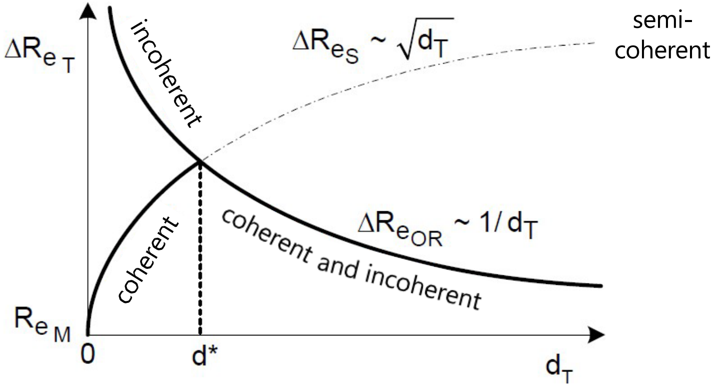
- At low/medium T and high σ (below YS)
  - Plastic deformation due to dislocation glide and twinning
- At low/medium T and medium σ (below YS)
  - Power law creep due to cross slip of screw dislocation and climb of edge dislocations $\dot{\varepsilon} = A\sigma^n$ (Norton)
- At medium T and low/medium σ
  - Diffusional creep, grain boundary diffusion (Coble)
- At high T and low/medium σ
  - Diffusional creep, bulk (lattice) diffusion (Nabarro-Herring)
  - Grain boundary sliding



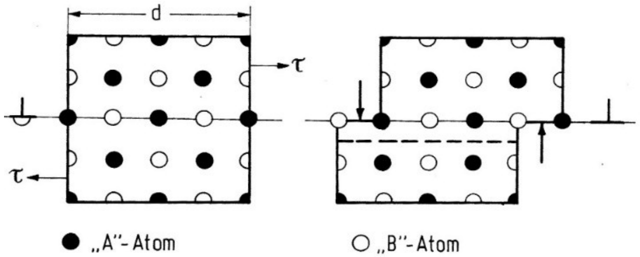
Particle strengthening at high T

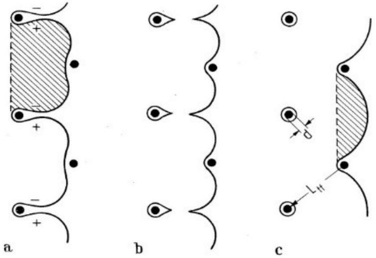
- Mechanisms for dislocations to pass precipitates/particles

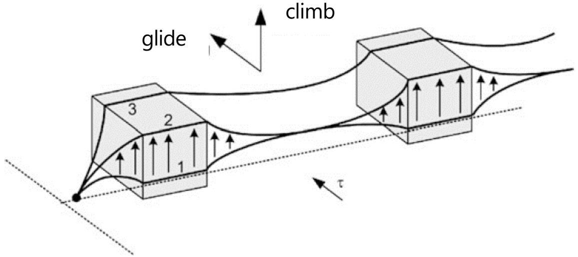
Mechanism	Temperature	(semi-) Coherent IF	Incoherent IF
Cutting	0K – Ts	Yes	No
Bowing/looping	0K – Ts	Yes	Yes
Climbing	>0.4 Ts	Yes	Yes



Cutting







High temperature deformation

- The RT strengthening mechanisms are only effective within limits
- Dislocation strengthening not efficient due to rapid recovery and re-crystallization
- GB strengthening
    - small grains → many GB's for diffusion
    - Large grains preferred
- Only ss and particle strengthening are efficient at elevated T

	Dislocation strengthening	**Grain boundary strengthening**	**Solid solution strengthening**	**Particle strengthening**
<0.4 Ts	strong	medium	medium/strong	medium/strong
>0.4 Ts	Only temporal strengthening; Can induce re-crystallization and grain refinement	Fine grains lead to decrease of strength	medium	medium/strong