

FS 2024/25

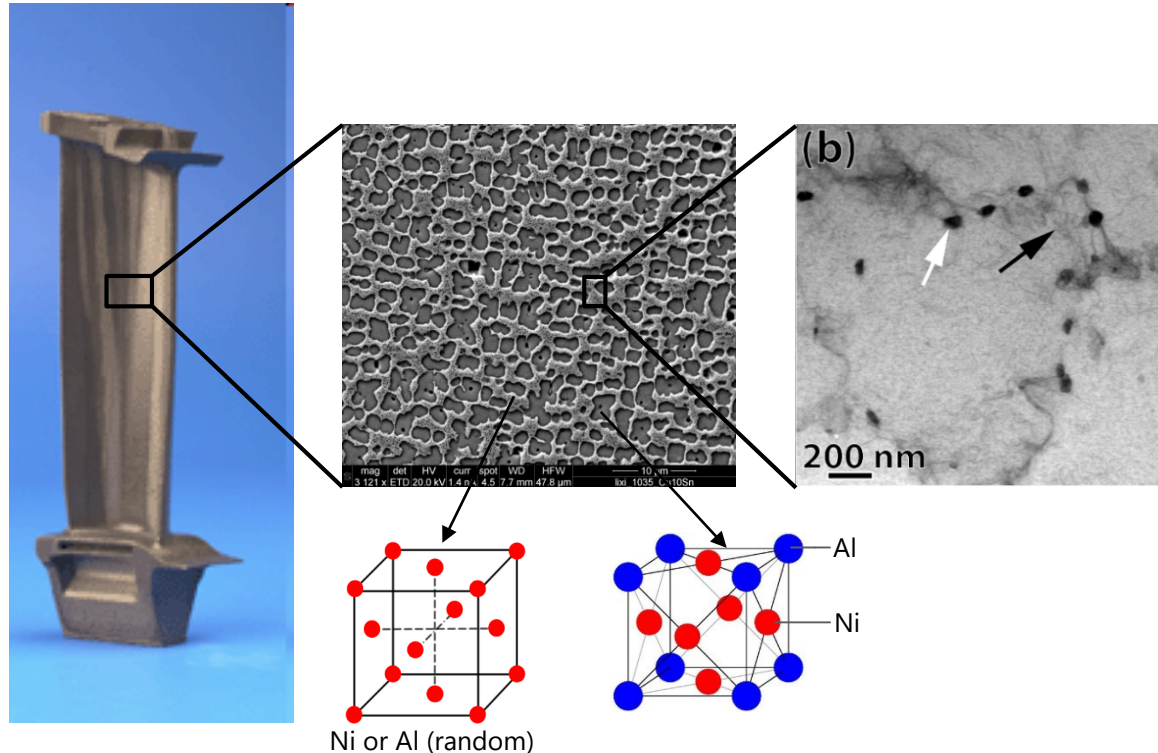
MSE-422 – Advanced Metallurgy

2.2 - Reminder: Mechanical Properties & Strengthening Mechanisms

Christian Leinenbach

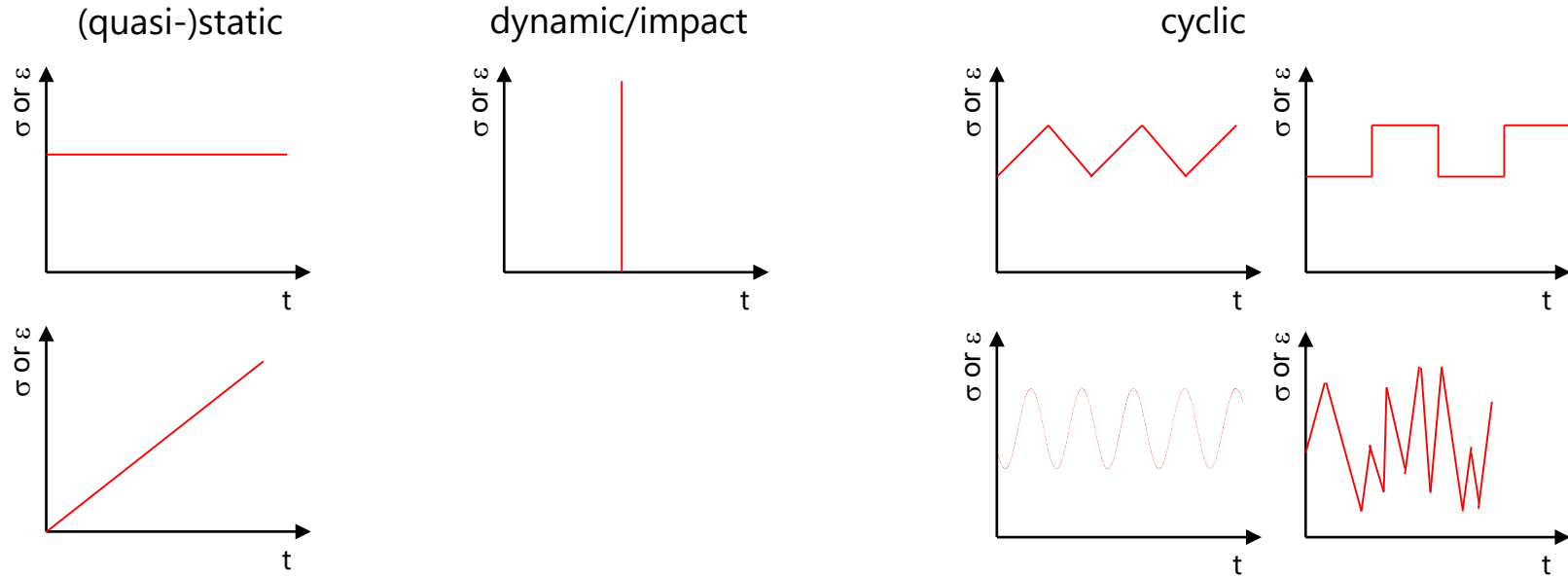
Alloy performance under thermo-mechanical loads

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



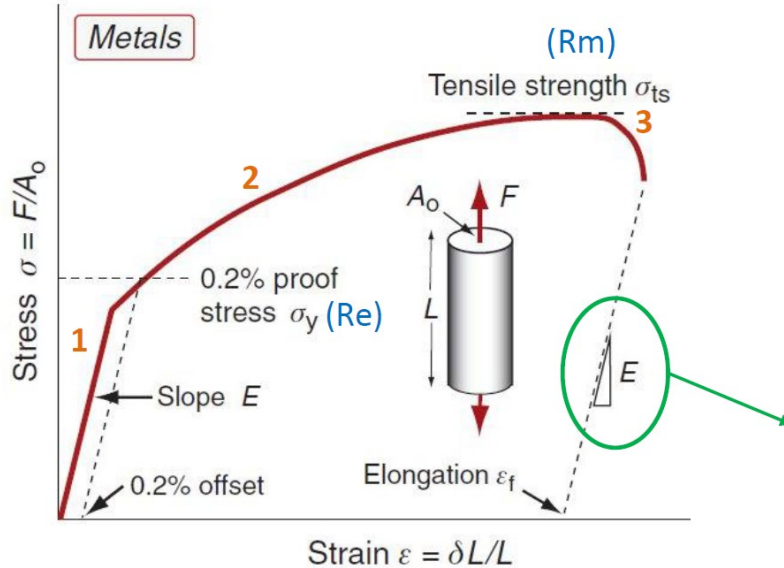
- What mechanical loads does the turbine blade experience?
- At what temperatures is the turbine blade operated? For how long?
- Are there further environmental influences that need to be considered?
- Why is Ni the material of choice for such service conditions?
- What is the (mechanical) reason for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

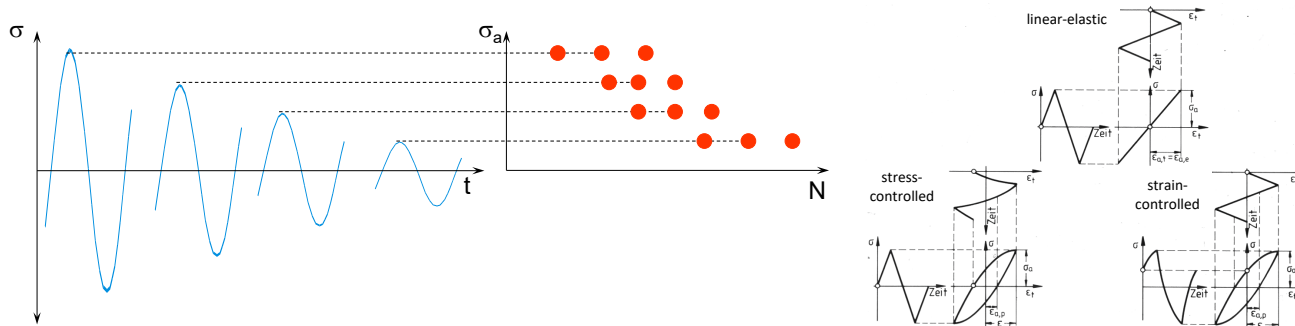
Static loading – the stress-strain curve



- Phase 1: elastic (reversible) deformation
- Phase 2: homogeneous plastic deformation (irreversible)
- Phase 3: strain localisation, necking and final rupture

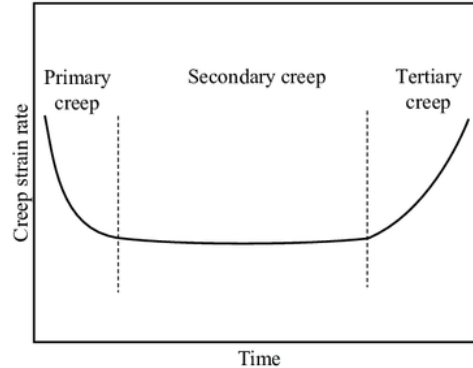
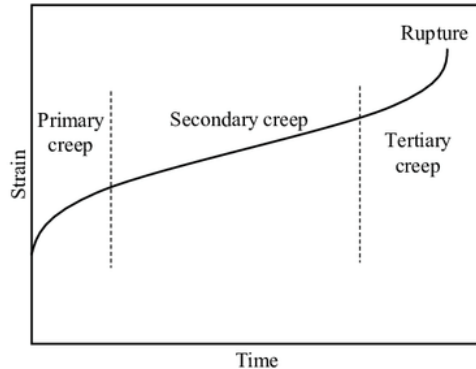
Cyclic deformation and fatigue

- 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 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



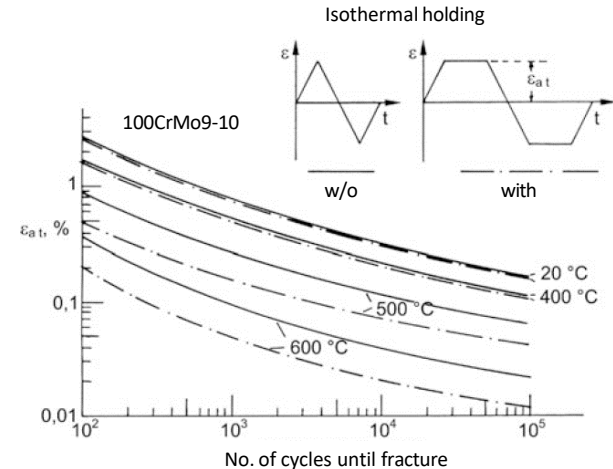
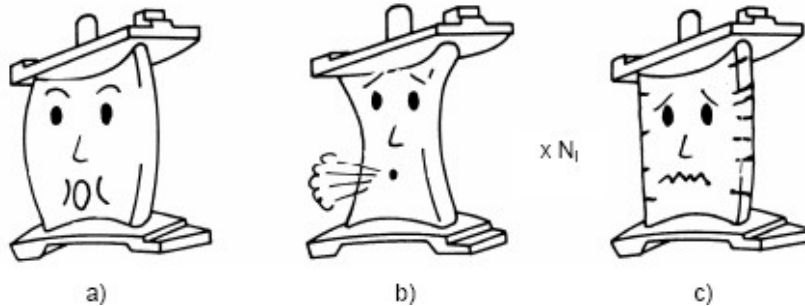
(b) 500°C



(c) 600°C

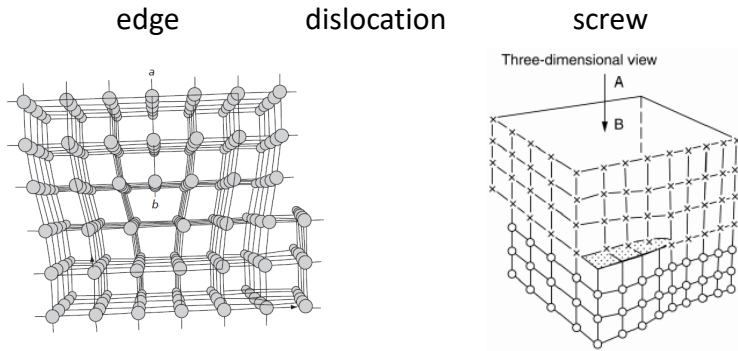
Thermo-mechanical fatigue – creep fatigue

- 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

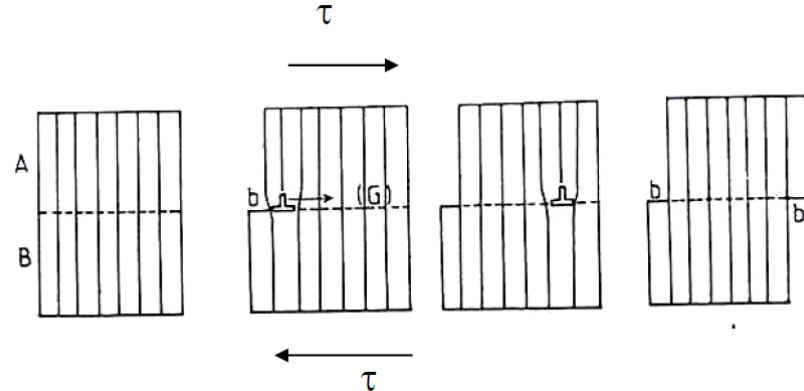


Plastic deformation – dislocations

- 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

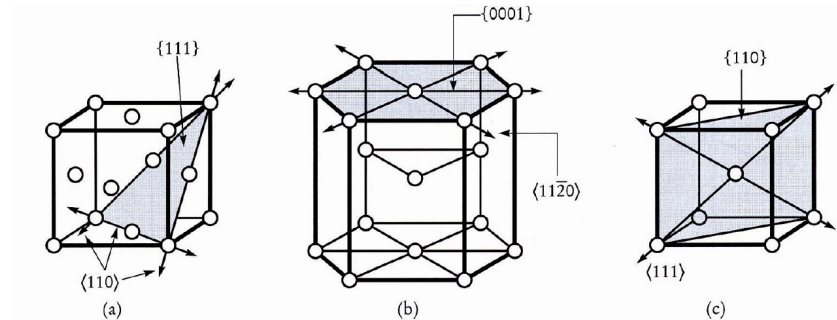


/Ashby & Jones, Engineering Materials 1/



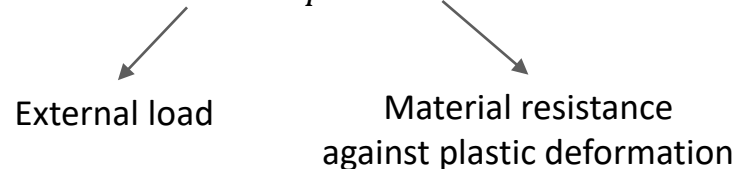
Plastic deformation – slip systems

- 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: $\{111\} \langle 110 \rangle$; hcp: $\{0001\} \langle 11\bar{2}0 \rangle$; bcc: $\{110\} \langle 111 \rangle$
- 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 $\{111\}\langle 110 \rangle$ and bcc materials with slip systems $\{110\}\langle 111 \rangle$ the values for M_i 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: $\sigma = M_T \tau = R$



- 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

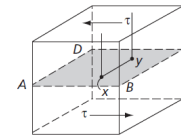
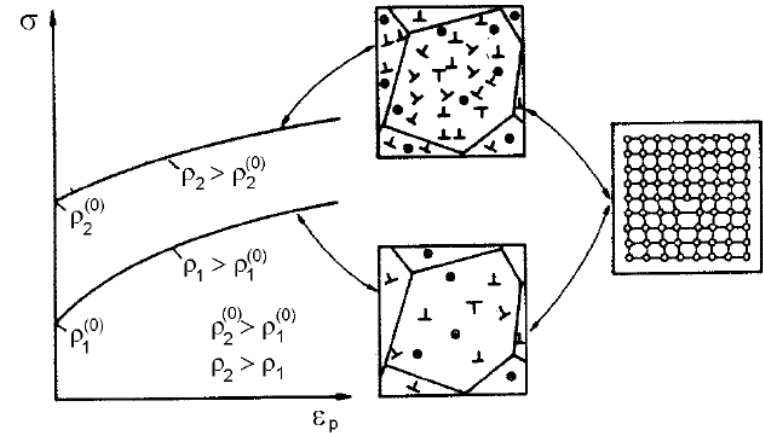


FIG. 5.1 Frank-Read source. The dislocation segment xy may move in plane $ABCD$ under the applied stress. Its ends, x and y , however, are fixed

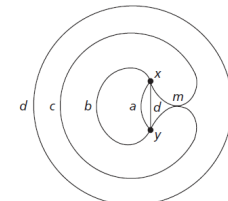
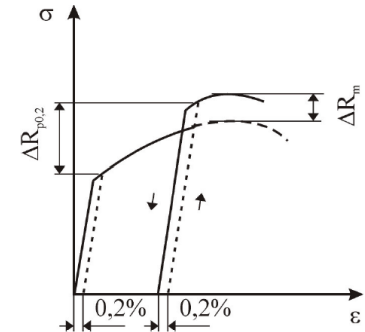
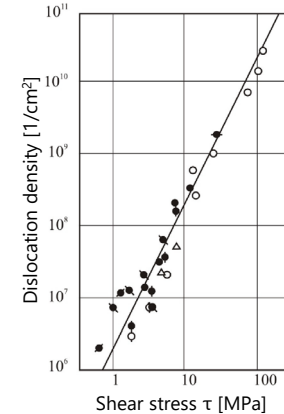


FIG. 5.2 Various stages in the generation of a dislocation loop at a Frank-Read source

Dislocation strengthening

- The dislocation density can be increased to $\sim 10^{12} \text{ 1/cm}^2$
- 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: $R_m = 1400 \dots 2200 \text{ MPa}$
 - Piano strings: $R_m = 3600 \text{ MPa}$



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

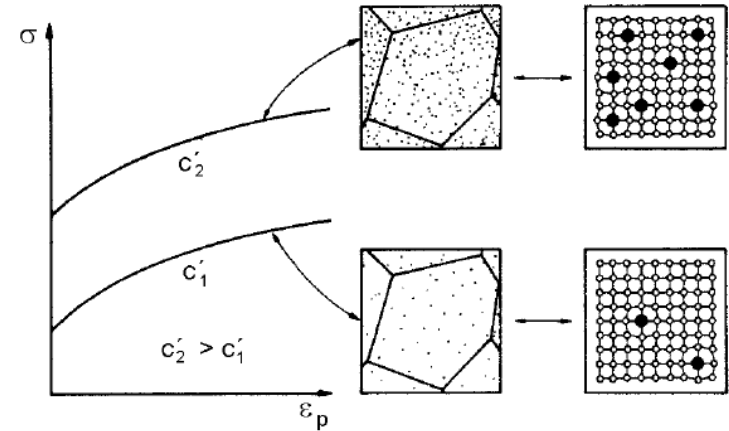
$$R_{ss} = \alpha_2 G (c')^n$$

α_2 : constant

G : shear module

n : strengthening exponent ($0.5 < n < 1$)

c' : concentration of solute atoms



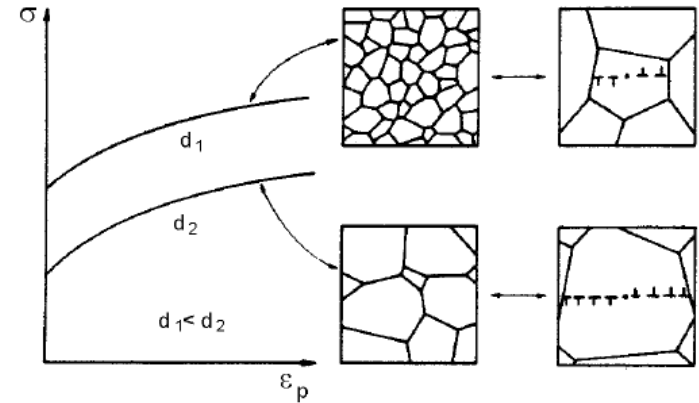
Grain boundary strengthening

- 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

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

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

$\alpha_{3,4}$: constants

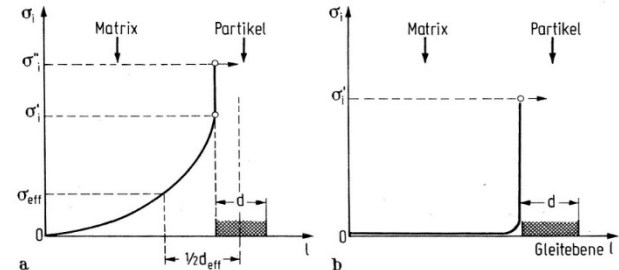
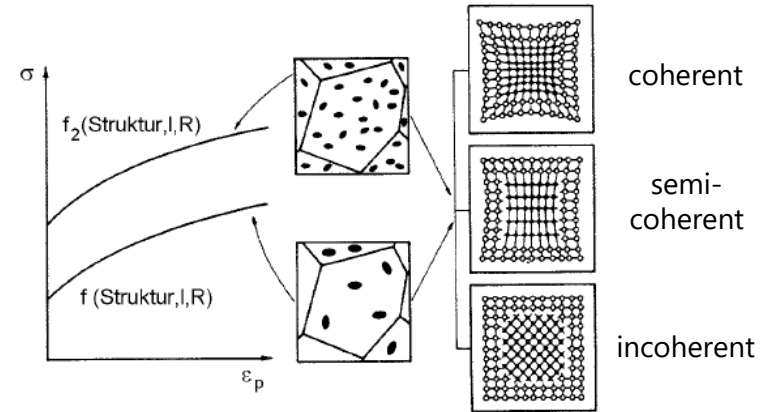
G: shear module

B: contribution from Burger's vector

l: average particle spacing

r: average particle radius

γ_{if} : interfacial energy



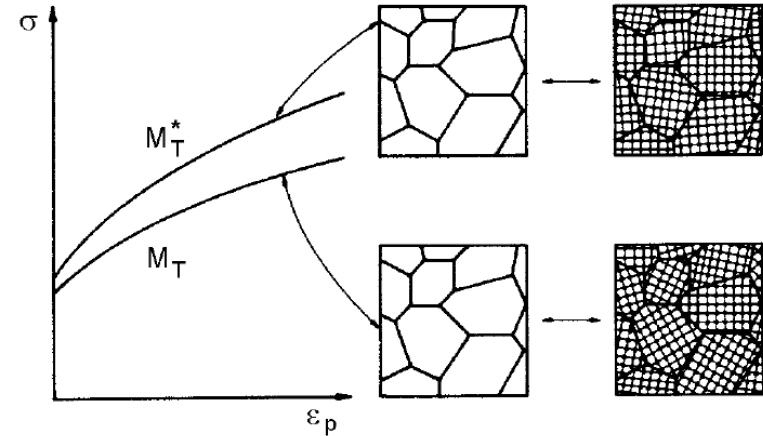
Grain orientation strengthening

- 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



Additivity 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

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

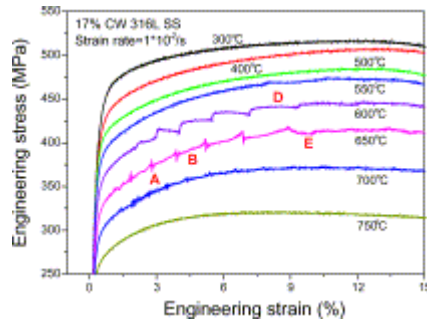
- At temperatures above $0.4 T_s$ [K], a transition from time-independent to time dependent plastic deformation occurs
- Dislocations are thermally activated and are continuously moving
- Mechanical stresses consist of a thermal part σ_{therm} , which can be thermally activated and an intrinsic athermal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

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

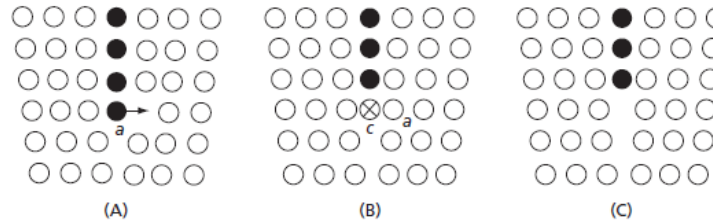
- The thermal part σ_{therm} includes
 - The Peierls stress
 - Cutting stress
 - Cross slip stress
- The athermal part σ_i includes
 - Residual stresses induced by the dislocation
- Recovery through annihilation of dislocations, recrystallization and grain growth can significantly alter the microstructure

High temperature plasticity

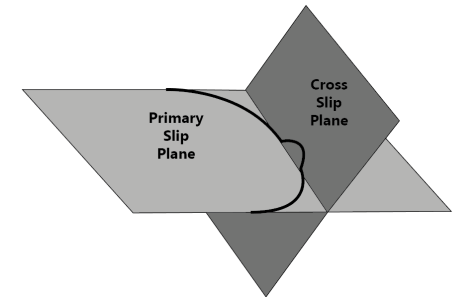
- The yield stress decreases with increasing $T \rightarrow$ the resistance against plastic deformation (i.e. dislocation movement) is decreased
- The following dislocation movement mechanisms are active
 - Dislocation glide is facilitated because of a decreased Peierls stress at high T
 - Dislocations 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



Edge dislocation climb

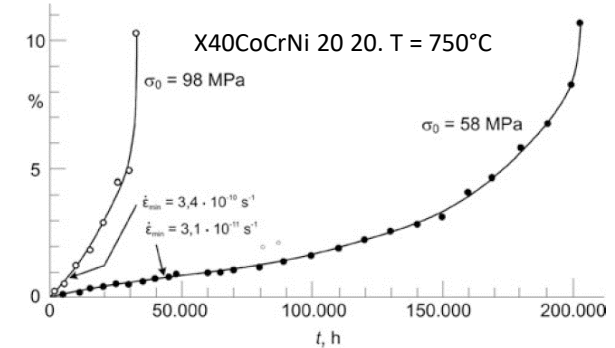
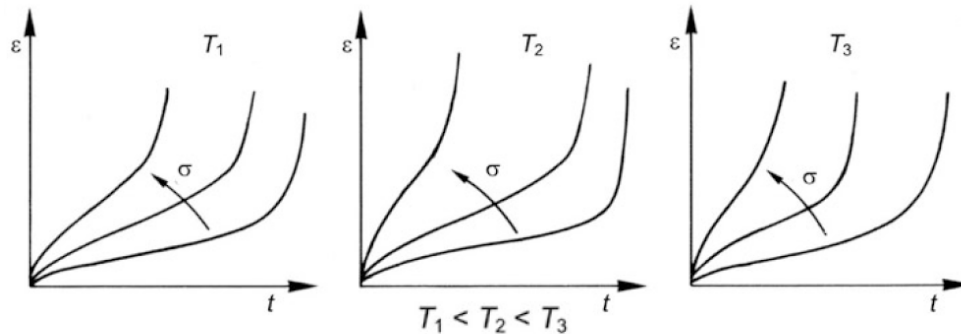


Cross slip



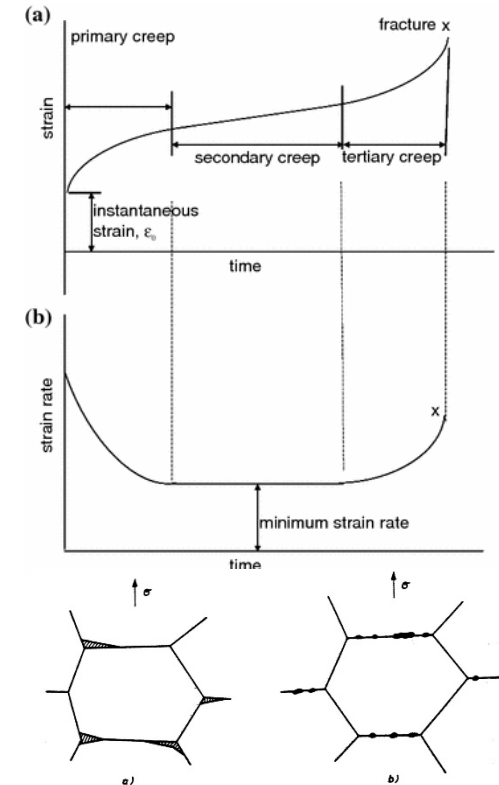
Time dependent plasticity - creep

- Creep is the time-dependent plastic deformation under a constant stress at elevated temperatures, which can result in sudden catastrophic failure
- Creep can occur 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



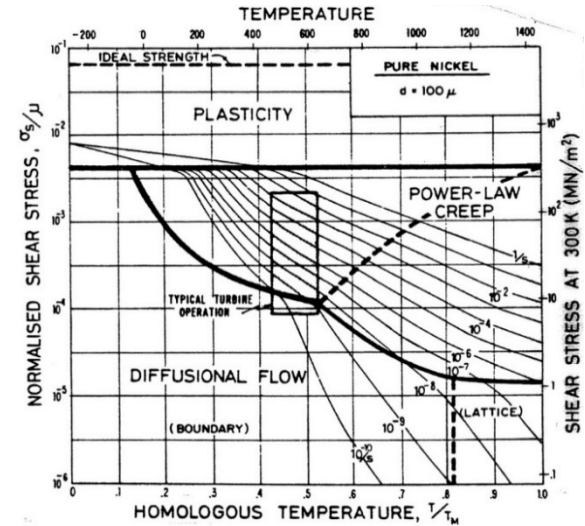
Creep curves

- Primary creep
 - decreasing creep rate $\dot{\epsilon}$, hardening because of increasing dislocation density
- Secondary creep
 - $\dot{\epsilon}$ 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 $\dot{\epsilon}$, pronounced material damage
 - Cracks at grain boundary triple points (high σ , short t)
 - Pores on grain boundaries $\perp$ loading direction (low σ , long t)



Creep deformation mechanisms

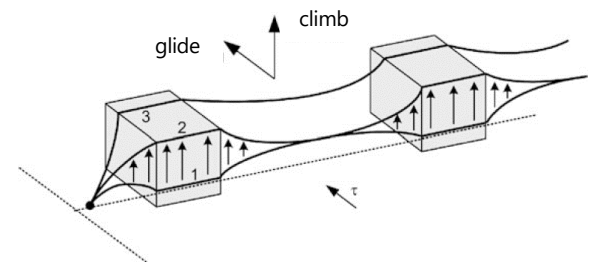
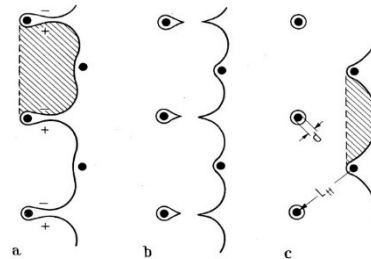
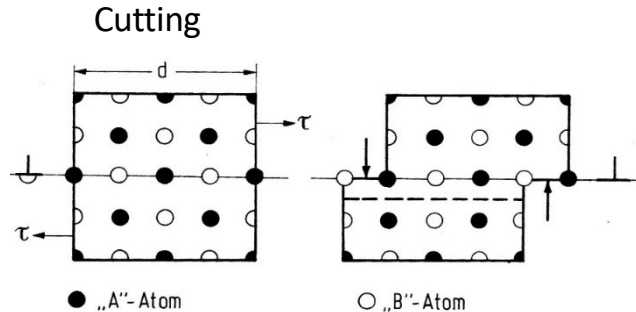
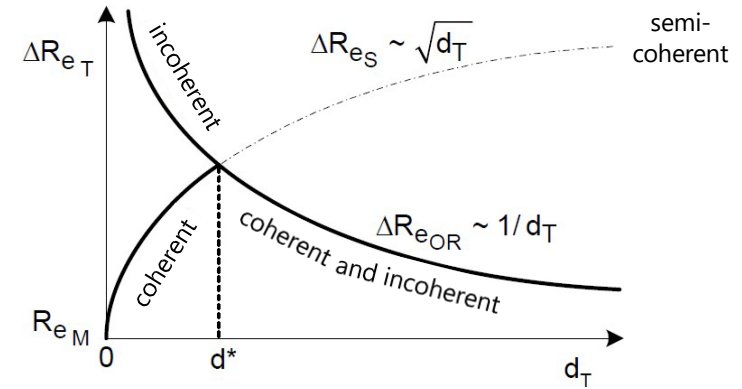
- At low/medium T and high σ (below YS)
 - Plastic deformation due to dislocation glide and twinning
- At low/medium T and medium σ (below YS)
 - Power law creep due to cross slip of screw dislocation and climb of edge dislocations $\dot{\epsilon} = A\sigma^n$ (Norton)
- At medium T and low/medium σ
 - 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 – T _s	Yes	No
Bowing/looping	0K – T _s	Yes	Yes
Climbing	>0.4 T _s	Yes	Yes



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