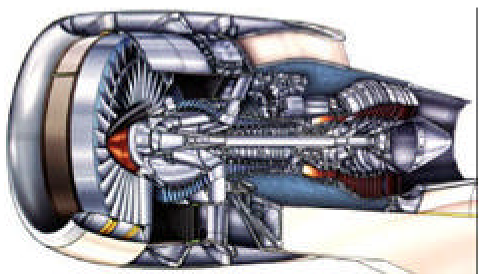
Lecture 21: Superalloys

MMat 380



Topics

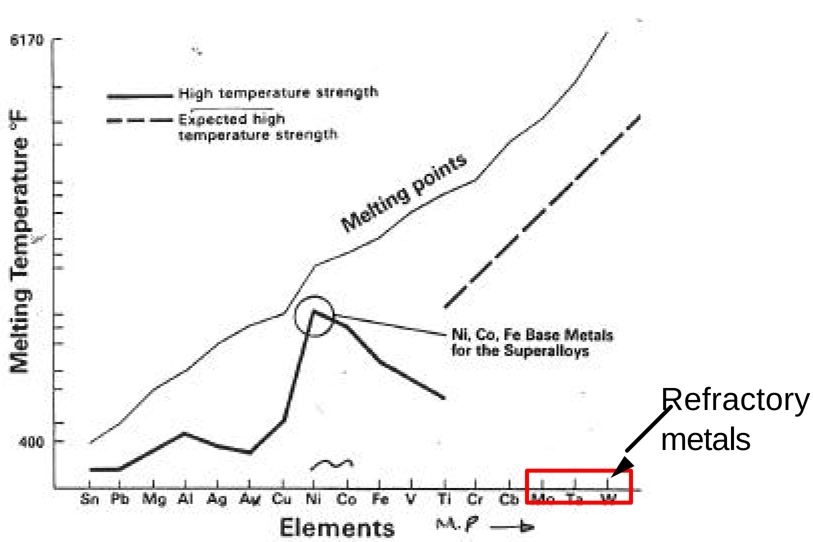
- Properties of metals at high temperatures
- Creep
- Deformation behaviour at high temperature
- Requirements for creep resistance

High temperature strength*

- Aluminum (FCC) 200°C
- Steel (BCC) 480°C
- 403 stainless steel (**ferritic BCC**) 650°C
- 316 stainless (**austenitic FCC**) 815°C
- Nickel-based superalloy 980°C

*Temperature at which strength is 275 MPa

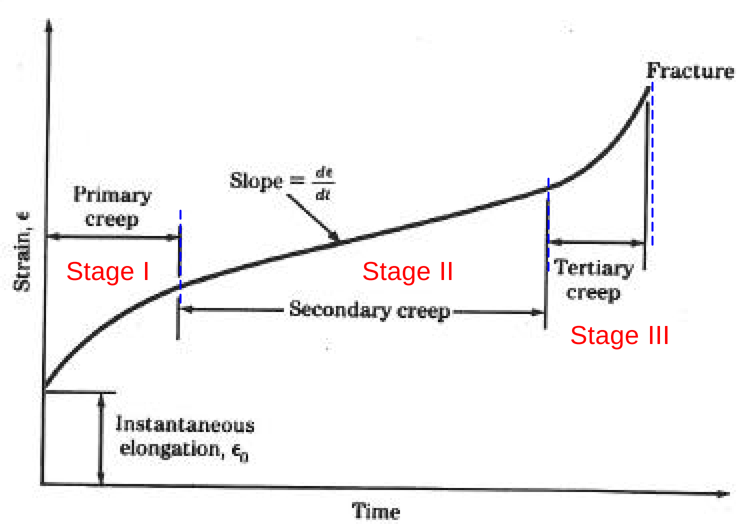
High temperature strength



Creep

- Measure strain (ε) as a function of time under constant load (stress)
- Typical creep curve with three stages of behaviour
  - Stage I – Primary creep
    - strain rate decreases as strain increases
  - Stage II – Secondary (steady state) creep
    - strain rate minimum and constant
  - Stage III – Tertiary creep
    - increasing strain rate

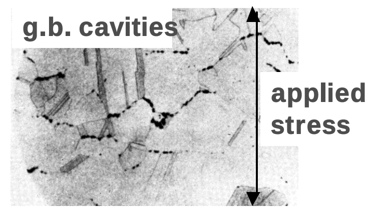
Typical creep curve



Component design based on creep considerations

Failure Criterion

- Shape Change:
  - Stage II: components designed for longevity
- Rupture:
  - Stage III: intergranular void formation, creep rupture; shape change tolerated
- e.g. Design parameters based on stage II



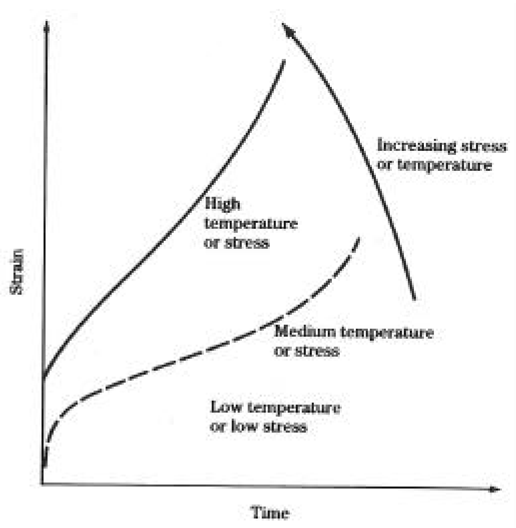
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

Application of criteria for design

Shape change: typical for hot stage turbine in gas turbine engines (aircraft)

Rupture: typical for steam turbine design for power generation

Effect of load/temperature on creep



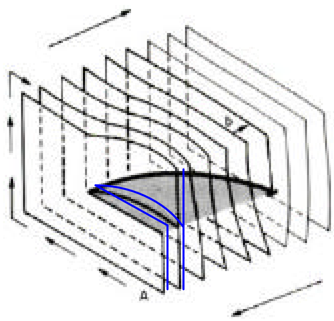
Deformation behaviour at high temperature

- Deformation processes are **thermally activated**;
  - movement of dislocations become easier at high T

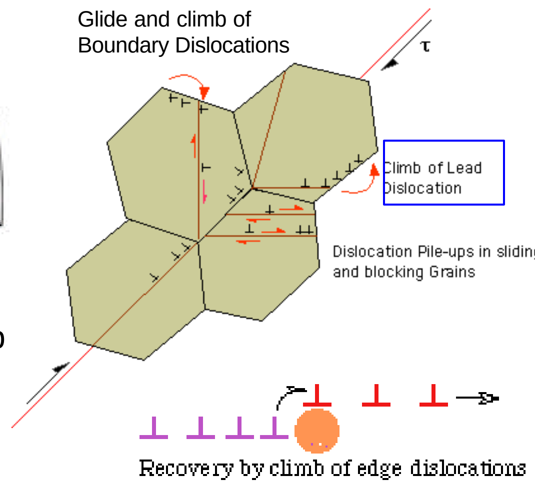
Dislocation behaviour as T↑

1. Cross-slip becomes easier
   - dislocations cross-slip around barriers more easily (e.g. around 2nd phase particles)
2. Dislocation climb processes occur more easily (climb controlled by movement of vacancies; **diffusion controlled** process) $Rate \propto \exp\left(Q/RT\right)$

Dislocation cross-slip and climb



Illustrating cross slip

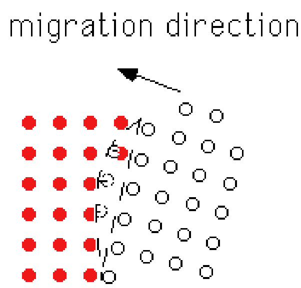


Deformation behaviour at high temperature

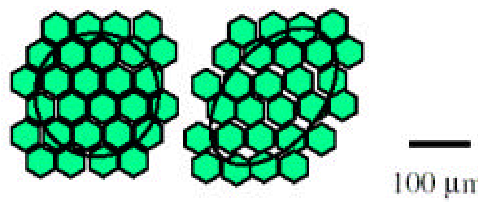
<u>Grain boundary behaviour</u>

1. Grain boundary migration (controlled by diffusion)
   - Grain boundary moves into and through regions of high strain energy (high dislocation density area) – leaving a strain free grain in its wake
2. At higher T (> 0.42 T_m) grain boundary sliding
   - shearing at grain boundaries produces plastic deformation
   - grain boundaries become a source of weakness at - T
   - grain boundaries are a source of strength at ¯ T

Grain boundary deformation



Grain boundary
migration



Grain boundary slide

Microstructural changes after deformation

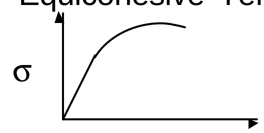
Grain boundary migration and growth

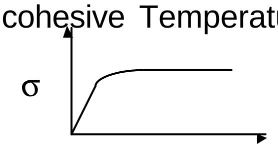
Grain boundary sliding

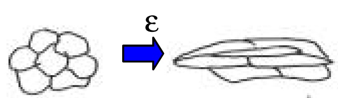
Grain growth

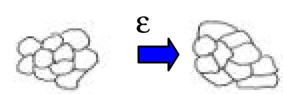
Equicohesive transition

Below Equicohesive Temperature	Above Equicohesive Temperature

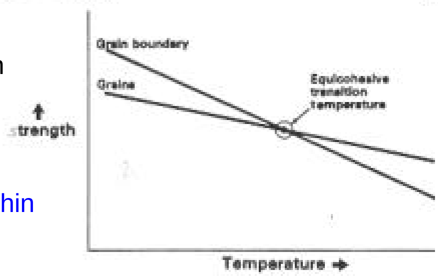






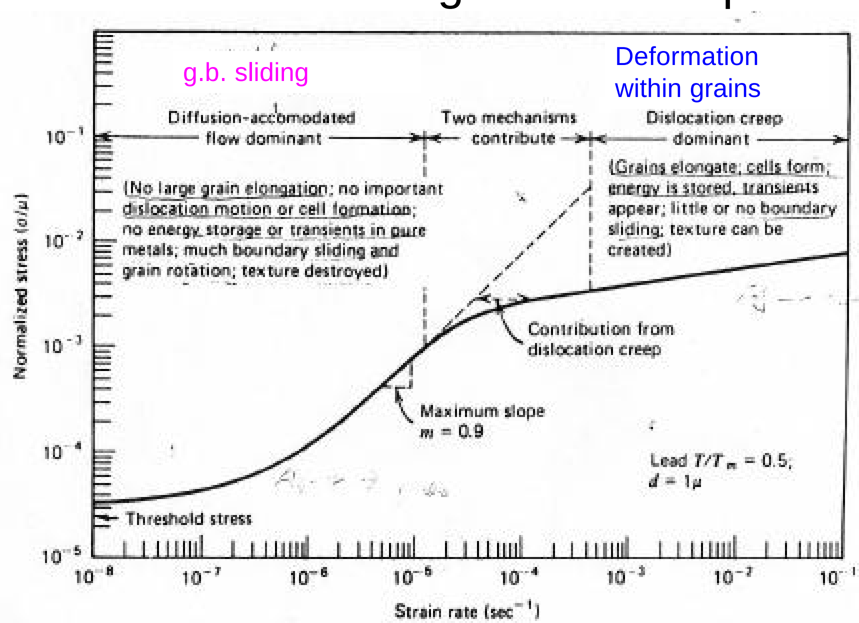


- grain elongation
- ↑ in dislocation density
- work hardening
- Deformation within grains
- No g.b. sliding



- No grain elongation
- No ↑ in dislocation density
- No work hardening
- Deformation by g.b. sliding
- Grain rotation

Mechanism regimes in creep



Deformation behaviour at high temperature

2nd phase particles

- required to impede dislocation motion
- also impede grain boundary sliding
- as T - fine dispersion of 2nd phase particles:
  - redissolve if temperature is very high
  - coarsen
- diffusion controlled processes

Requirements for a creep resistant alloy

1. Alloy with a low diffusion rate i.e. FCC matrix and high melting point
2. Stable second phase particles
   - Particles within the grain (impede dislocation glide)
   - Particles on the grain boundaries (such as carbides) will impede grain boundary sliding

Requirements for a creep resistant alloy

3. Addition of solutes (small concentration) segregate to the grain boundaries and impede grain boundary migration.
4. Minimize grain boundary area to minimize grain boundary sliding
   – increase grain size
   – single crystal if possible