Introduction to Fracture and Fatigue Behavior of Materials

Introduction to Risk-based Inspection - Advanced Mechanical Systems Maintenance Engineering

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Outline

Unwanted failure...



- Improper design / specifications ?
- Wrong material ?
- Process defects ?
- Accidental overloading ?
- ...

Controlled fracture

Source : *https://youtu.be/ekv0kprA3AY*

- Can opening,
- Food packaging,
- Aircraft engines: shear-bolts as safeguards,
- ...

Motivations and objectives

Objectives

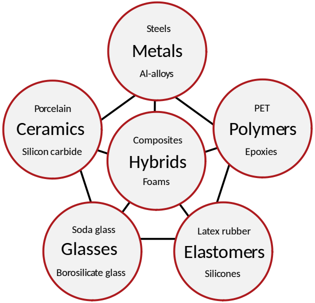
- Understand the link between materials processes, microstructures and defects.
- Understand the fundamentals of fracture in the presence of defects.
- Fundamentals of fatigue behavior.

Suggested reading

- Ashby, Shercliff, Cebon. *Materials: engineering, science, processing and design*, Ed. Butterworth-Heinemann, 2007
- Ashby, Jones. *Engineering materials 1: an introduction to properties, applications, and design*, Ed. Butterworth-Heinemann, 2012
- Ashby, Jones. *Engineering materials 2: an introduction to microstructures and processing*, Ed. Butterworth-Heinemann, 2013

Outline

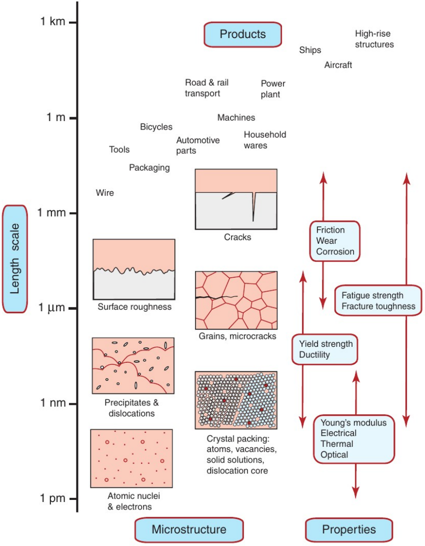
Families of materials



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Similar properties,
- Similar transformation processes,
- Often similar applications.

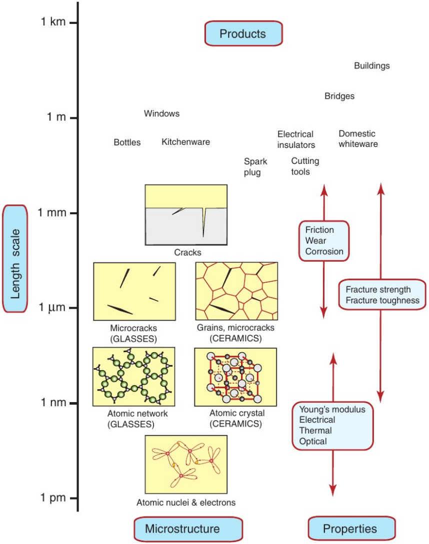
Length scales in metallic materials



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Atoms, crystal packing: Young's modulus E.
- Dislocations and microstructure obstacles: strength, toughness.
- Grains, surface roughness and cracks: fatigue behavior, friction, wear.

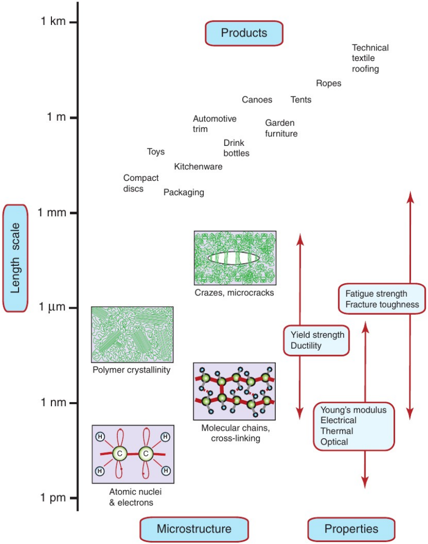
Length scales in ceramics and glasses



Source : *Materials – Engineering, Science, Processing and Design*, M. Ashby, H. Shercliff, D. Cebon

- Ceramics: mostly crystalline.
- Glasses: amorphous.
- Stiff atomic bonds and high lattice friction: high Young's modulus and hardness.
- Failure dominated by cracks and surface finish.

Length scales in polymers and elastomers

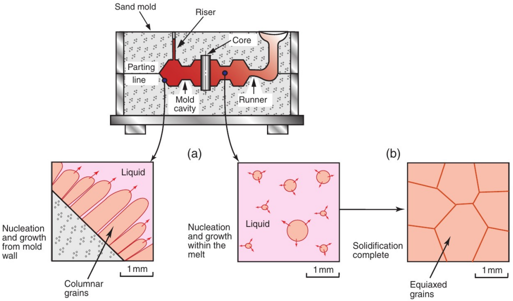


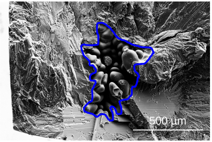
Source : *Materials – Engineering, Science, Processing and Design*, *M. Ashby, H. Shercliff, D. Cebon*

- Microstructure: (macro-) molecular rather than atomic
- Diverse arrangements: amorphous, crystalline, cross-linked, ...
- Foams, composites: additional length scale $\rightarrow$ architecture.

Outline

Metal casting and solidification



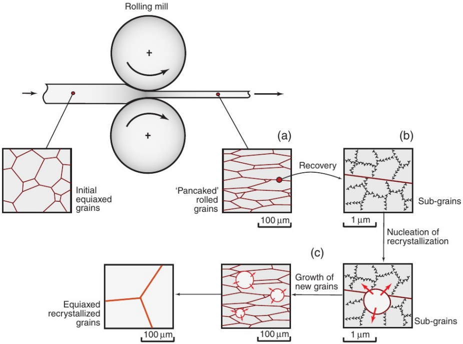


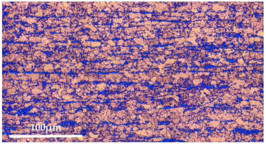
Sub surface micro-shrinkage in a A357 cast aluminum alloy. Source : *Serrano Munoz 2014, PhD thesis*

Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Low production cost, complex shapes, massive use in car industry.
- Control of grain size: (i) inoculant (stimulate nucleation) and (ii) cooling rate.
- Casting defects: shrinkages, gas pores, oxides and impurities due to segregation. $\Longrightarrow$ limited fatigue properties.

Deformation processing of metals and alloys



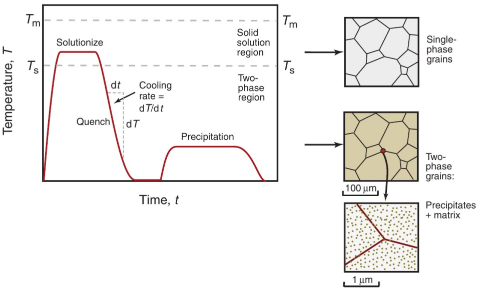


Microstructure of a DP600 steel.
Source: *Huin 2017, PhD thesis*.

Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Deformation processing (*e.g.* rolling) strongly affects microstructure: grain size/shape, distribution of 2nd phase particles or impurities, dislocation density
- Microstructural transformations often occur: recovery/recrystallization, phase transformations, ...

Heat treatment of metallic alloys



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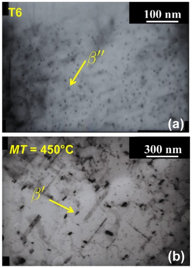
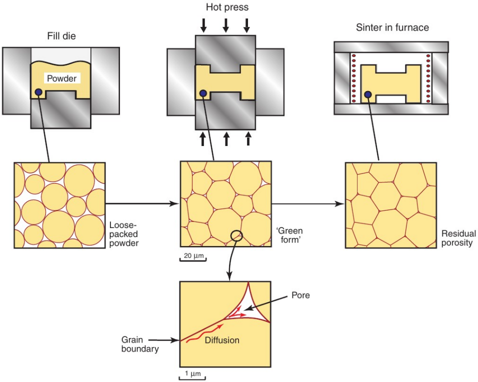


Nanosize precipitates in an 6061 aluminum alloy. *Bardel et al. Acta Mat. 2015*

- Metal alloys: usually heat treated for optimized strength.
- Precipitates and 2nd phase particles: some useful for hardening, others detrimental for toughness (*e.g.* crack initiation sites).

Powder processing



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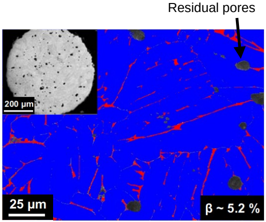
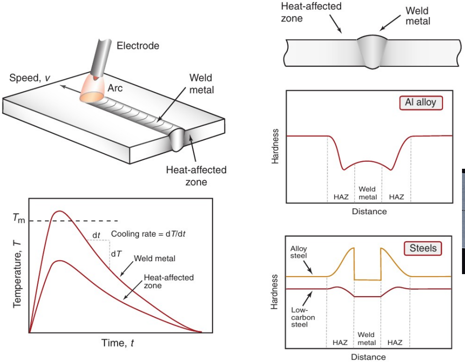


Sintered sample, Ti alloy. *Coffigniez 2021, PhD thesis*.

- Common process for high performance ceramics and many metals, complex shapes achievable.
- Residual porosity remains even after optimized compaction and sintering. Defect size critical!

Welding



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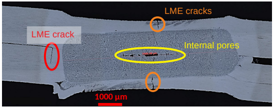
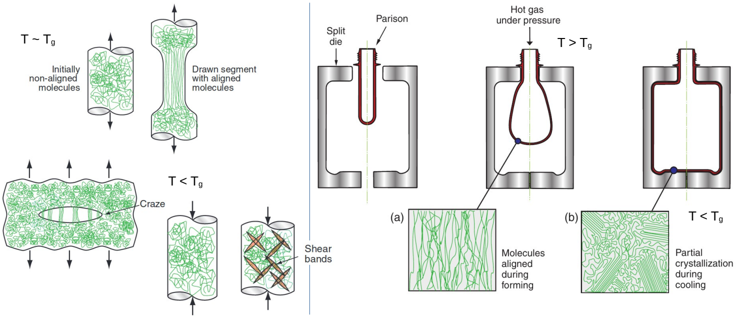


Different defects in a steel resistance spot weld. *Siar et al., Mat. Char. 2022*

- Welding severely alters the local microstructure in the joint.
- Welding defects (shrinkage pores, cracks, gaz bubbles, ...) often present. Harmfulness to be checked.

Thermoplastic polymer molding



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Glass transition temperature T_g: strong impact on deformation mechanism and arrangement of macromolecules.
- Different types of defects depending on process/service temperature *wrt* T_g: crazes, micro cracks, shear bands etc...

Outline

Materials microstructures and defects
- Materials length scales
- Processes, microstructures and defects

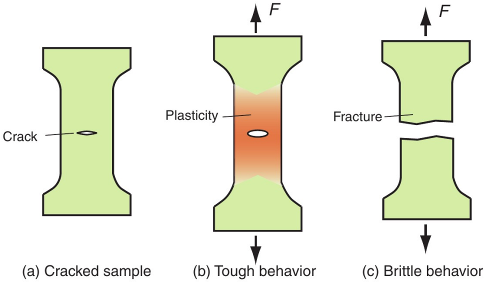
Fracture mechanics
- The mechanics of fracture ahead of a crack
- The mechanisms of fracture

Cyclic loading behavior: fatigue
- Cyclic loading
- Fatigue crack initiation and propagation

Summary

Further details
- Energetic approach to fracture
- Playing with the endurance limit
- Typical materials behaviors and properties

Strength vs Fracture toughness

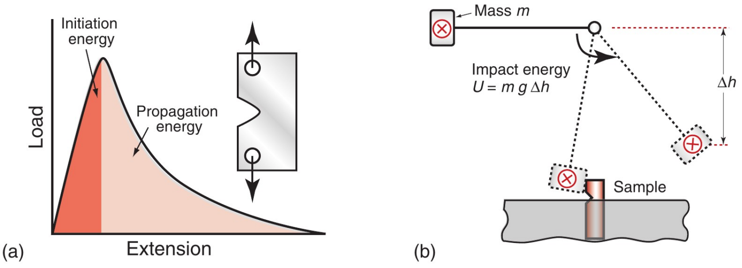


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Strength $\neq$ Toughness.
- Strength: resistance to plastic flow (yield stress σ_Y).
- Toughness: resistance to crack propagation (fracture toughness K_{Ic}).
- Facing a crack/defect, 2 extreme behaviors:
  - Ductile behavior (low σ_Y, high K_{Ic}),
  - Brittle behavior (high σ_Y, low K_{Ic}).

Macroscopic tests

Quickly assessing the type of fracture behavior



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Ex: tear test (a), impact test (b).
- Quick assessment of either ductile or brittle behavior $\Longrightarrow$ quality control, ranking.
- Not a true material property measurement (sample dependent).

Ductile to Brittle transition

Transition from ductile to brittle behavior at low temperature

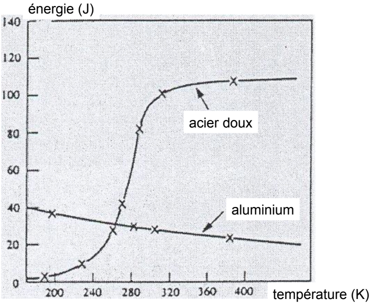
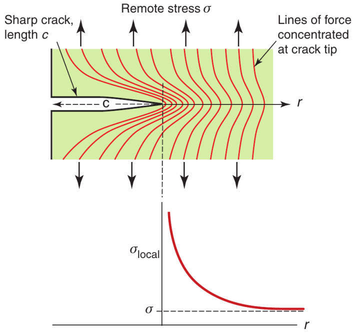


Figure: Charpy impact test, V notch

- HC and BCC material behavior changes at low T (not FCC materials).
- Ductile to Brittle transition temperature.
- ⚠ Test conditions greatly influence the results.

Singularity of the stress field at the crack tip

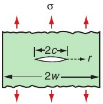


Source : *Materials – Engineering, Science, Processing and Design*, *M. Ashby, H. Shercliff, D. Cebon*

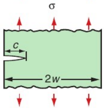
- $\sigma_{local} = \sigma \left(1 + Y\sqrt{\frac{\pi c}{2\pi r}}\right)$ with $Y \sim 1$. (geometry)
- $\sigma_{local} \approx \sigma Y \sqrt{\frac{\pi c}{2\pi r}}$ close to the crack tip.
- $K_I = Y\sigma\sqrt{\pi c}$: stress intensity factor (mode I: opening direction perpendicular to the crack plane).
- $\forall r, \sigma_{local} \propto K_I$

Stress Intensity Factor tables

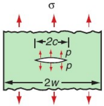
K_I is known for many standard situations



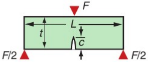
Continued through crack
$K_1 = \sigma\sqrt{\pi c}$ $(c \ll w)$



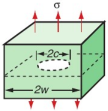
Single edge notch
$K_1 = 1.1\sigma\sqrt{\pi c}$ $(c \ll w)$



Through crack with pressure p
$K_1 = p\sqrt{\pi c}$ $(c \ll w)$



Cracked beam with central load F; b = thickness
$K_1 = 3\dfrac{FL}{bw^2}\sqrt{\pi c}$ $(c \ll w)$

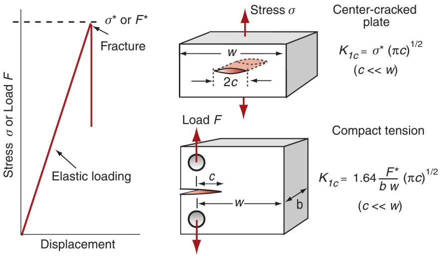


Contained, penny-shaped crack
$K_1 = 0.7\sigma\sqrt{\pi c}$ $(c \ll w)$

Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

Measuring fracture toughness

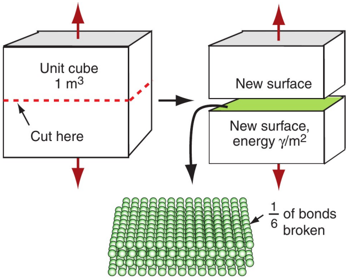
Linear elastic fracture mechanics



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Standardized samples, tracking crack propagation.
- Infinitely sharp initial crack.
- K_I evolution is known (unit: MPa$\sqrt{\text{m}}$).
- K_{Ic} (plain-strain fracture toughness):
  critical value of K_I for F^*, c^*
  (material property: sample independent)

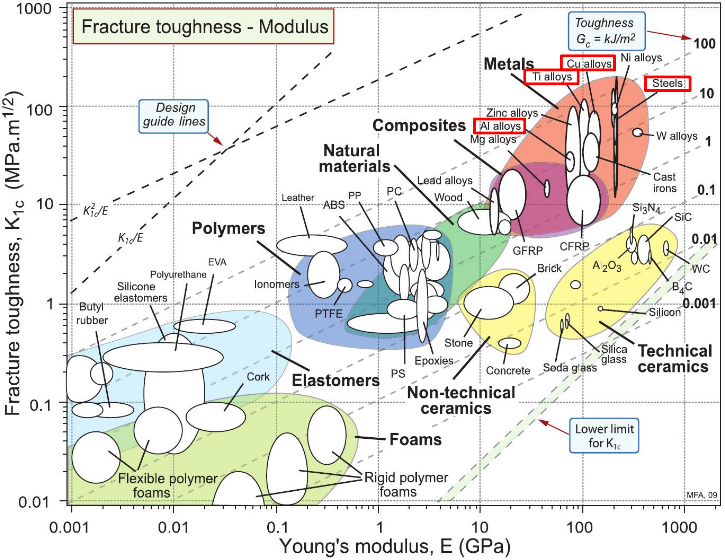
Energetic approach



Source : *Materials – Engineering, Science, Processing and Design*, M. Ashby, H. Shercliff, D. Cebon

- Crack: 2 new surfaces, energy γ (J/m^2).
  $\gamma \sim 1$ J/m^2 typically
- Necessary condition for a crack surface extension $\mathrm{d}A$:
  - $G\mathrm{d}A \geq 2\gamma\mathrm{d}A$
  - G: energy release rate (J/m^2).
- Real life: $G_c \gg 2\gamma$ (local plasticity).
- G_{Ic} (J/m^2): mode I toughness, or critical energy release rate.
- K_{Ic} proportional to G_{Ic}:
  $K_{Ic} = \sqrt{EG_{Ic}}$ (cf. demo, Appendix)

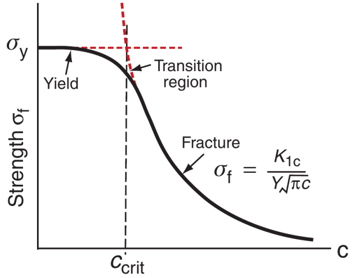
Fracture toughness – Young's modulus chart



Source : *www.grantadesign.com/education/resources*

Critical crack size

Transition from yield to fracture



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- $K_{Ic} = Y\sigma_f\sqrt{\pi c}$
- σ_f : failure stress for a given c value.
  $\sigma_f = K_{Ic}/(Y\sqrt{\pi c})$
- If $\sigma_f > \sigma_y$:
  global yielding before failure.
- c_{crit} defined by $\sigma_f = \sigma_y$:
  $c_{crit} = {K_{Ic}}^2/(Y^2\pi{\sigma_y}^2)$ with $Y \sim 1$
- Damage tolerance:
  - Metals (high K_{Ic}): still yield in a predictable, ductile, manner even with large cracks.
  - Ceramics (low K_{Ic}): fail in a brittle manner at stresses far below σ_y because of small cracks.

Critical crack size

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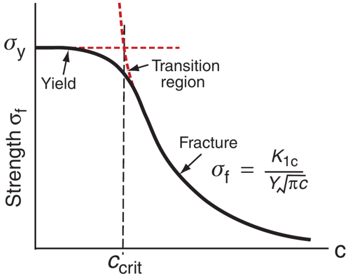

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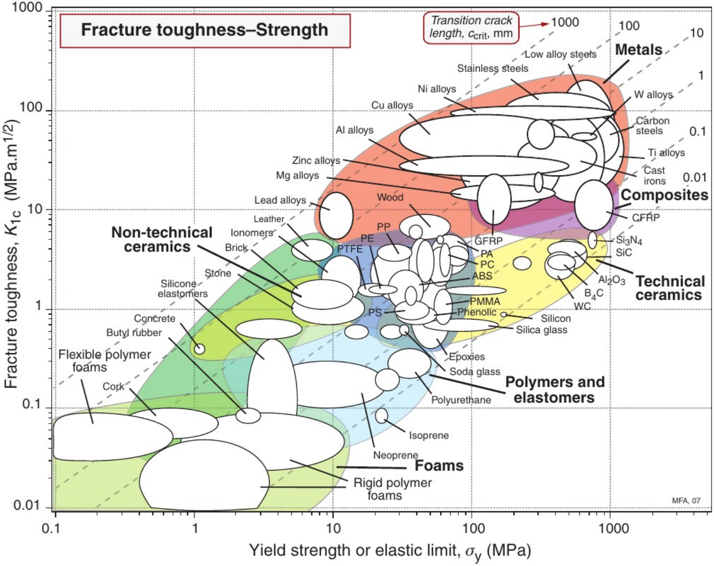
Fracture toughness – strength chart



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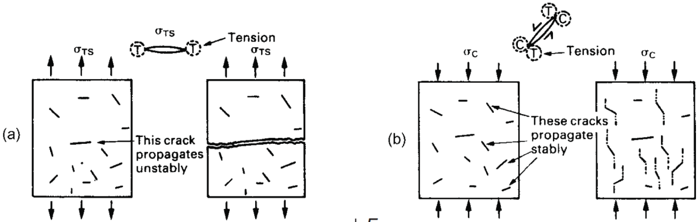
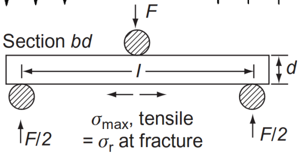
Mechanical tests for brittle materials



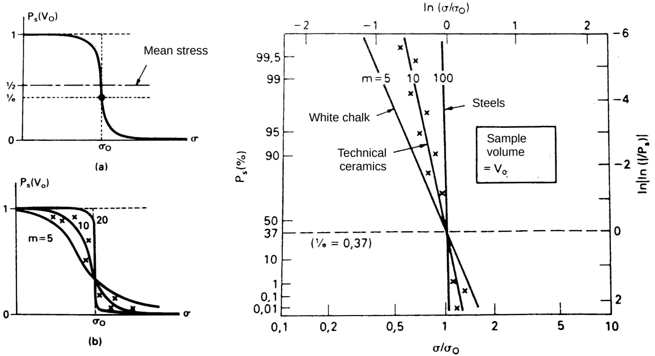


Source : *Engineering materials 2: an introduction to microstructures and processing, M. Ashby, D. Jones*

- Ceramics: low $K_{Ic} \Longrightarrow$ defect-sensitive materials.
- Tension: $\sigma_f = K_{Ic}/\sqrt{\pi c_{max}} = \sigma_{TS}$ (critical crack)
- Compression: $\sigma_C \simeq 15\sigma_{TS}$ (average crack)
- 3-point bending: $\sigma_r = MOR = 3Fl/(2bd^2) \simeq 1.7\sigma_{TS}$

Statistical variation in strength: Weibull

Brittle materials: dispersion of strength rather than a unique value



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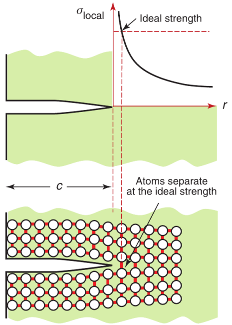
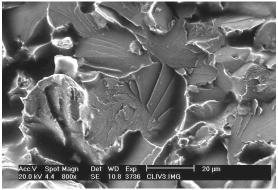
- Survival probability P_s, n samples of volume V_0:
  $P_s(V_0) = \exp[-(\sigma/\sigma_0)^m]$ $\quad \sigma_0$, m constants.
- σ_0: stress for 37% of survival,
- m: Weibull modulus (m small $\Rightarrow$ high deviation).

Outline

The origins of toughness

Brittle ‘cleavage’ fracture





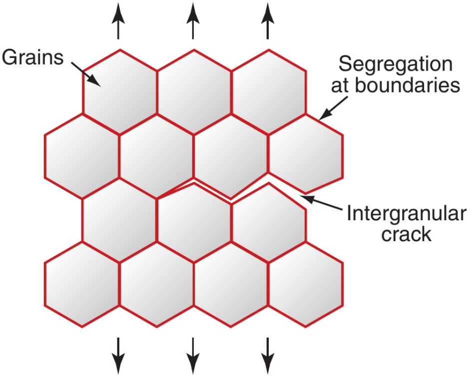
Cleavage of atomic planes

Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Hard and brittle materials: no way to release the crack tip stresses by plastic flow.
- σ_{local} about $E/15$ (ideal strength).
- atomic bonds fracture (cleavage): crack propagation and acceleration.
- NB: FCC materials not affected (many slip systems).

The origins of toughness

Brittle intergranular fracture

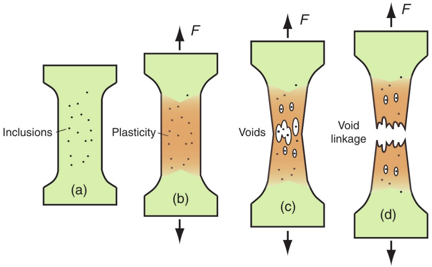


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Grain boundary segregation (impurities in the alloy, ex: during solidification):
  network of low-toughness paths through the material.
- Possible intergranular cracking.

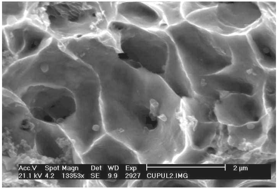
The origins of toughness

Ductile fracture



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

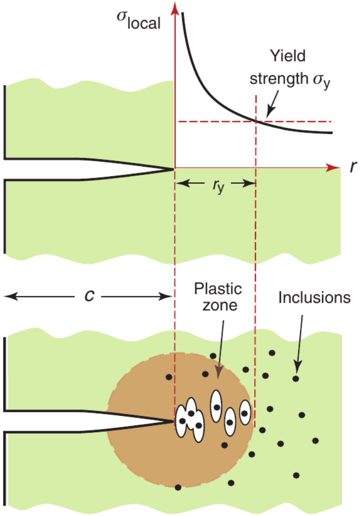
Deformed dimples and the inclusions leading to decohesion



- Inclusions act as stress concentration sites.
- Nucleation, growth and coalescence of cavities.

The origins of toughness

Cracks in ductile materials

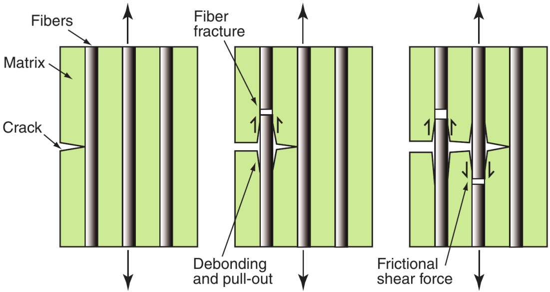


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Voids nucleate, grow and coalesce at the crack tip.
- Crack tip is blunted ($\Longrightarrow \sigma_{local}$ decreases).
- Plastic work at the crack tip dissipates (a lot of) energy: the work of fracture G_{Ic} is high, so is K_{Ic}.
- ($K_{Ic} = \sqrt{EG_{Ic}}$, see Further details)

Manipulating toughness

Composite/architectured materials: additional energy dissipation mechanisms can improve toughness



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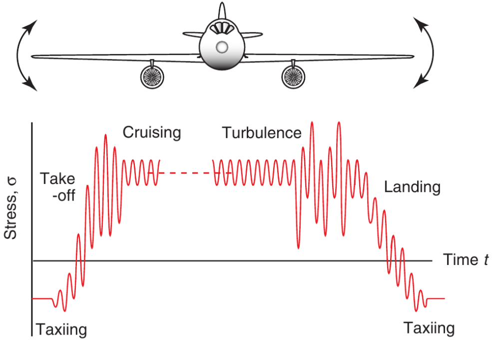
- Polymer matrix: $K_{Ic} = 3$ MPa$\sqrt{m}$
- Glass fiber: $K_{Ic} = 0.8$ MPa$\sqrt{m}$
- Composite (matrix+fibers): up to $K_{Ic} = 10$ MPa$\sqrt{m}$
- Multiple cracking, fiber debonding/pullout, friction: crack propagation delayed, energy dissipated.

Outline

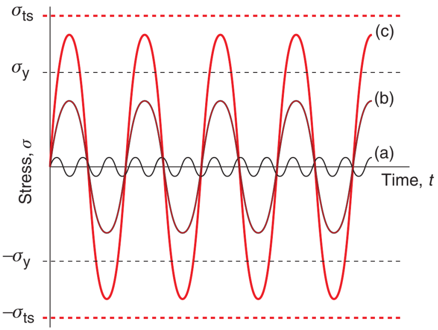
Cyclic loading



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Cyclic loadings are legion: waves on off-shore platforms, gas tank under cyclic pressure, axles of coaches, etc...
- Materials grow tired if repeatedly stressed, leading to failure.
- Failure can happen even if $\sigma < \sigma_y$.

Different types of fatigue

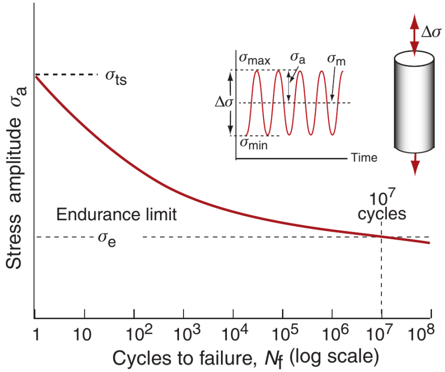


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- (a): acoustic vibration ($\sigma \ll \sigma_y$),
- (b): high-cycle fatigue ($\sigma < \sigma_y$),
- (c): low cycle fatigue ($\sigma_y < \sigma < \sigma_R$).

Wöhler curve - the endurance limit

S-N or Wöhler curve: number of cycles to fracture as a function of stress

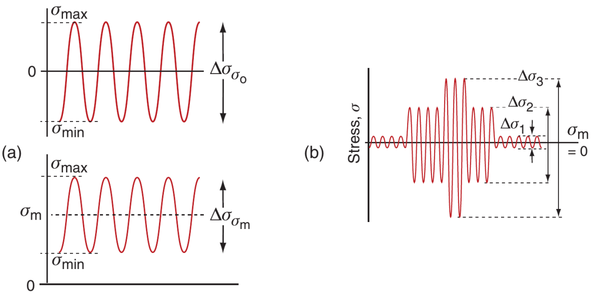


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- $\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$, $\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$, $R = \frac{\sigma_{min}}{\sigma_{max}}$.
- Lifetime $N_f = f(\sigma_a)$ (cycles to failure).
- Endurance limit σ_e for 10^7 cycles, with $\sigma_m = 0$.

Real-life fatigue

When the applied stress is not constant

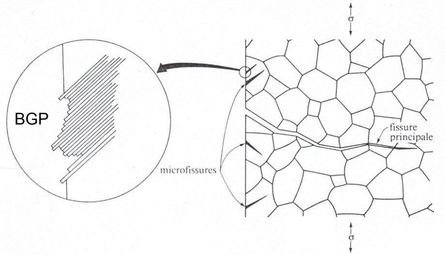


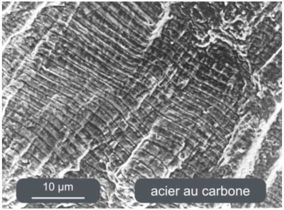
Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- If $\sigma_m \neq 0$, Goodman's law: look for $\Delta\sigma_{\sigma_0}$ such that
  $\Delta\sigma_{\sigma_m} = \Delta\sigma_{\sigma_0}\left(1 - \frac{\sigma_m}{\sigma_R}\right)$
  $(\sigma_a = \frac{\Delta\sigma_{\sigma_0}}{2}$ on Wöhler curve)
- If σ_a changes, Miner's cumulative damage rule:
  $\sum_{i=1}^{n} \frac{N_i}{N_{f,i}} = 1$ (failure: sum = 1)

Outline

Crack growth during cyclic loading

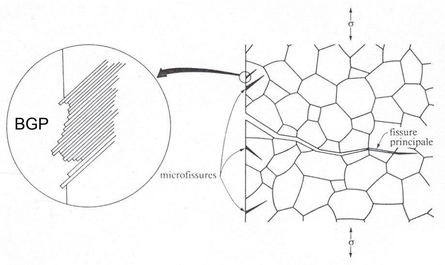


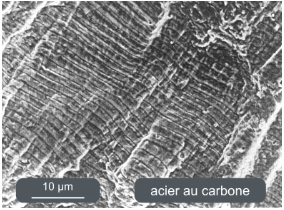


Source : *http://nte.mines-albi.fr/SciMat/co/SM6uc3-3.html*

- 3 main stages for fatigue failure:
  - Stage I: crack initiation,
  - Stage II: crack growth,
  - Stage III: fast fracture.
- Stage I in crystalline ductile materials: microcracks initiation in Persistant Gliding Bands.
- Stage II: main crack grows along a plane almost perpendicular to the applied stresses.
- Fracture surface: micro-roughness $\Longrightarrow$ fatigue striations.

Crack growth during cyclic loading





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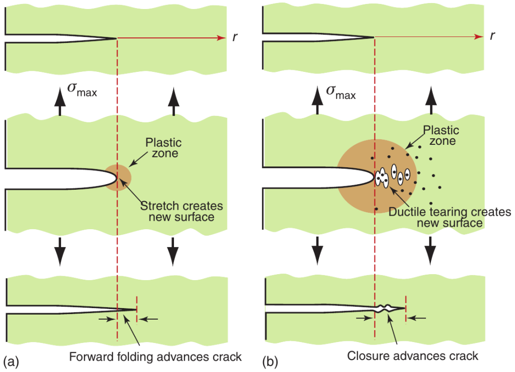
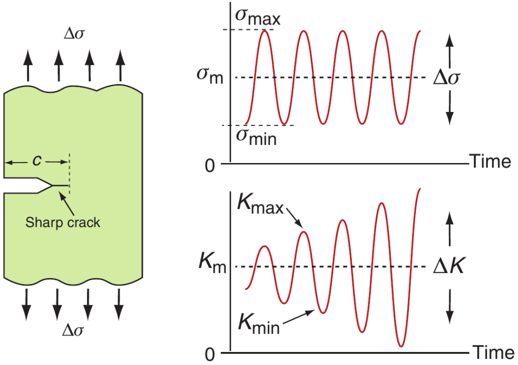
Fatigue crack propagation mechanism



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- High-cycle fatigue (a): small plastic zone and crack advance.
- Low-cycle fatigue (b): large plastic zone and crack advance

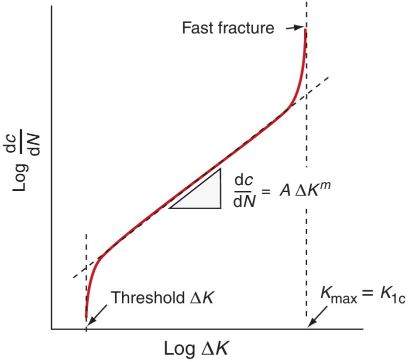
Fatigue loading of cracked components



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Pre-cracks / defects (impossible to avoid in large structure)
- $\Delta K = K_{max} - K_{min} = Y \Delta\sigma \sqrt{\pi c}$
- c increases (propagation) $\Longrightarrow$ ΔK increases.

Propagation - Paris law



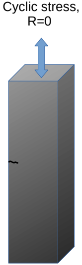
Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

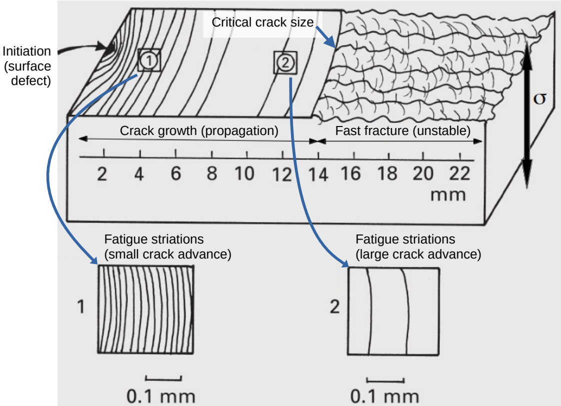
- Paris law: $dc/dN = A(\Delta K)^m$ A & m constants.

1. No propagation below a critical threshold ΔK_{th}.
2. Growth rate increases (Paris law)
3. Failure when $K_{max} = K_{Ic}$.

Fracture surface

Sketch of a typical fracture surface, tensile cyclic loading





- Details of fracture surface:
  $\Longrightarrow$ A lot can be learned on the material and fatigue crack propagation mechanism.

Summary

Fracture

- All materials: microstructure and/or process defects.
- Ductile behavior *v.s.* Brittle behavior .
- Transition with temperature for many metals.
- Macroscopic tests (ex. impact test) do NOT measure true (sample independent) properties.
- K_I - K_{Ic} (or G_I - G_{Ic}) to describe sudden fracture.

Fatigue

- Fatigue: cyclic loading propagates small cracks in materials.
- Paris law to describe propagation.
- Wöhler curve to assess lifetime under given stress amplitude.

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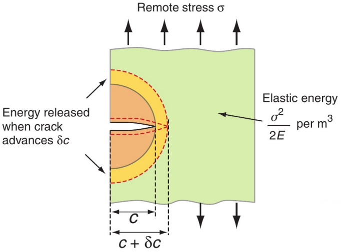
Outline

$K_{Ic} = f\left(G_{Ic}\right)$
simplified demonstration

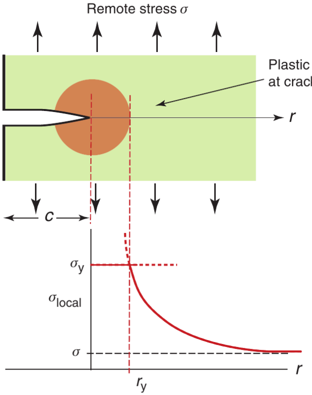


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- sample, thickness b.
- stored elastic energy (J/m^3) : $U^v = \frac{1}{2}\sigma\varepsilon = \frac{1}{2}\sigma^2/E$
- Crack, length c. Approximately:
  - σ relaxed in a $\frac{1}{2}$ cylinder, radius c.
  - released energy: $U(c) \approx \frac{\sigma^2}{2E} \times \frac{\pi}{2} c^2 b$

- $\partial U(c)/\partial c = \frac{\sigma^2 \pi b}{2E} \times c$
- $\delta U = \frac{\sigma^2 \pi c}{2E} \times b\delta c$ with $K_I^2 = \sigma^2 \pi c$ $(Y \sim 1)$
- Failure condition: $\delta U = G_{Ic} \times b\delta c$
- $G_{Ic} = K_{Ic}^2/(2E)$ ou $K_{Ic} = \sqrt{2EG_{Ic}}$
- More accurate analysis $\Longrightarrow K_{Ic} = \sqrt{EG_{Ic}}$

Plastic zone at the crack tip



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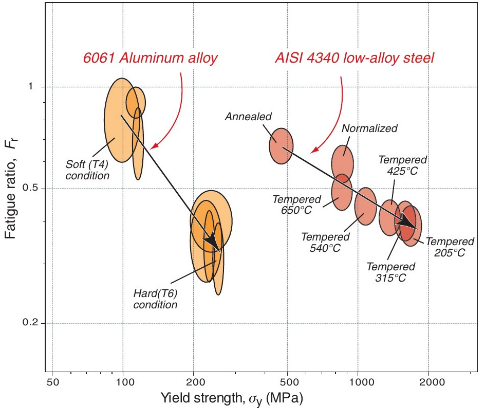
- Crack tip: σ_{local} very high. Consequences :
  - plasticity in ductile materials,
  - micro-cracks in ceramics,
  - decohesion in composites.
- $G_c \gg 2\gamma$ (necessary work of fracture higher than the sole surface creation).

- plastified area r_y such as $\sigma_{local}(r) = \sigma\sqrt{\frac{\pi c}{2\pi r}} \geq \sigma_y$.
- σ redistribution: factor 2 on resulting r_y.
- $r_y = 2 \times \frac{\sigma^2 \pi c}{2\pi {\sigma_y}^2} = \frac{{K_I}^2}{\pi {\sigma_y}^2}$

Outline

Effect of hardening heat treatments

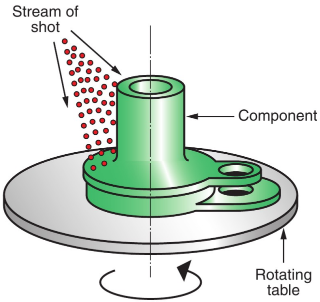


Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Fatigue ratio $F_r = \sigma_e/\sigma_y$.
- F_r decreases with hardening heat treatment, but σ_y strongly increases !

Enhancing resistance to fatigue

Playing with defects and surface



Source : *Materials – Engineering, Science, Processing and Design, M. Ashby, H. Shercliff, D. Cebon*

- Minimize defects, pre-cracks, porosity etc...
- Introduce compressive stresses at the surface:
  - cracks often start at the surface
    $\Longrightarrow$ compressive stresses tend to close the cracks.
  - Shot peening, sanding, but also carburizing, nitriding, etc...

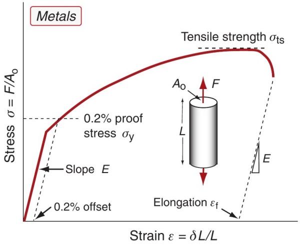
Outline

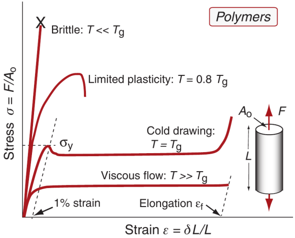
Typical behaviors

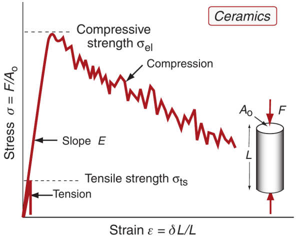
Uniaxial tension/compression

- Stiffness : E (elasticity)
- Strength :

  σ_y, $\sigma_{0.2\%}$, σ_{ts}
- Ductility : ε_f







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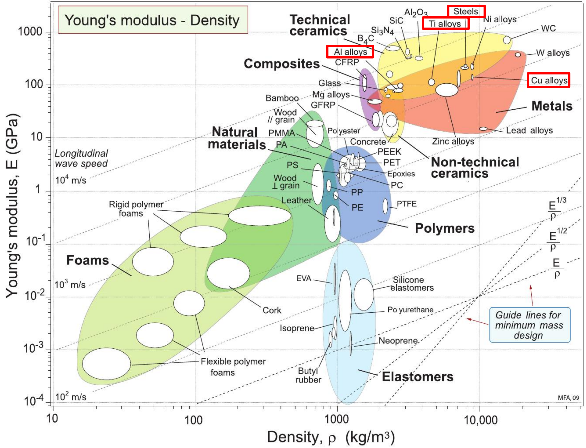
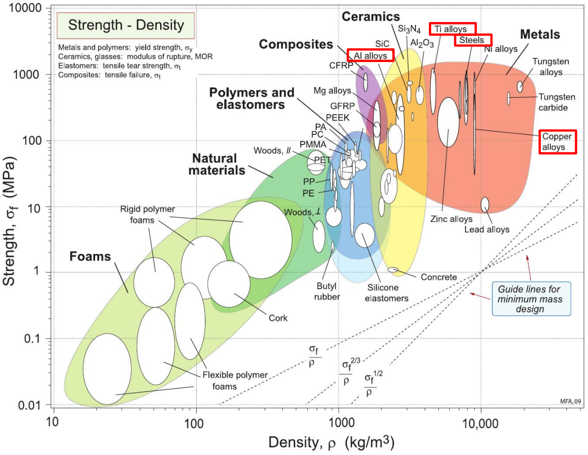
Stiffness



Source : *www.grantadesign.com/education/resources*

- Pure materials: atomic bounds and crystallography.
- Hybrids, composites, etc... : structure / architecture also.

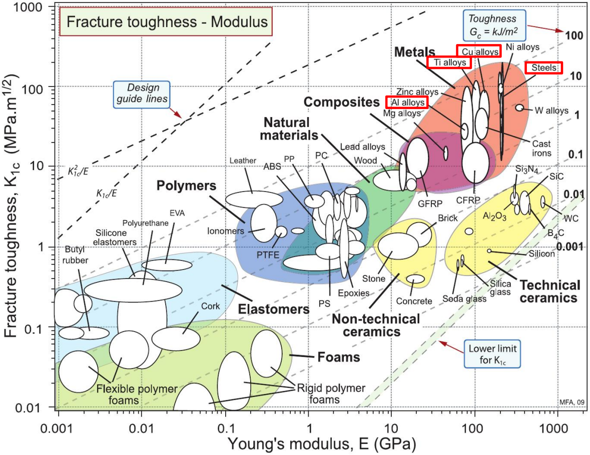
Strength



Source : *www.grantadesign.com/education/resources*

- Huge effect of microstructure and defects.
- Highly sensitive to composition and process.

Toughness



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