AML 883 Properties and selection of engineering materials

LECTURE 13. Fatigue and fracture

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Announcement

Problem sheet 4 (Strengthening mechanisms) is up. One more will also be up in a couple of days – For Minor I, all the five problem sheets are included in the syllabus.

Initiation-controlled fatigue: S-N curve and some empirical laws

High-cycle fatigue: S-N curve

- Cyclically stress a component
- Mean value σ_m and amplitude of stress $\Delta\sigma$ are the key parameters
- Measure number of cycles (N) to cause fracture Nf
- Plot $\Delta\sigma$ versus Nf (S-N) curve
- Most tests vary the stress sinusoidally
- Fatigue data typically reported in terms of R value (which is the ratio of the minimum to the minimum stress)

High-cycle fatigue: S-N curve

Image courtesy: Wiki

Fatigue on endurance limit

- The stress amplitude about zero mean stress, below which fracture does not occur at all, or occurs after a very large number of cycles: σ_e
- Fatigue-limited design: endurance limit plays the role that is equivalent to the yield strength in plastic design (strength—endurance limit materials property charts, for example)

Basquin's law

$$\Delta\sigma N_f^b = C_1$$

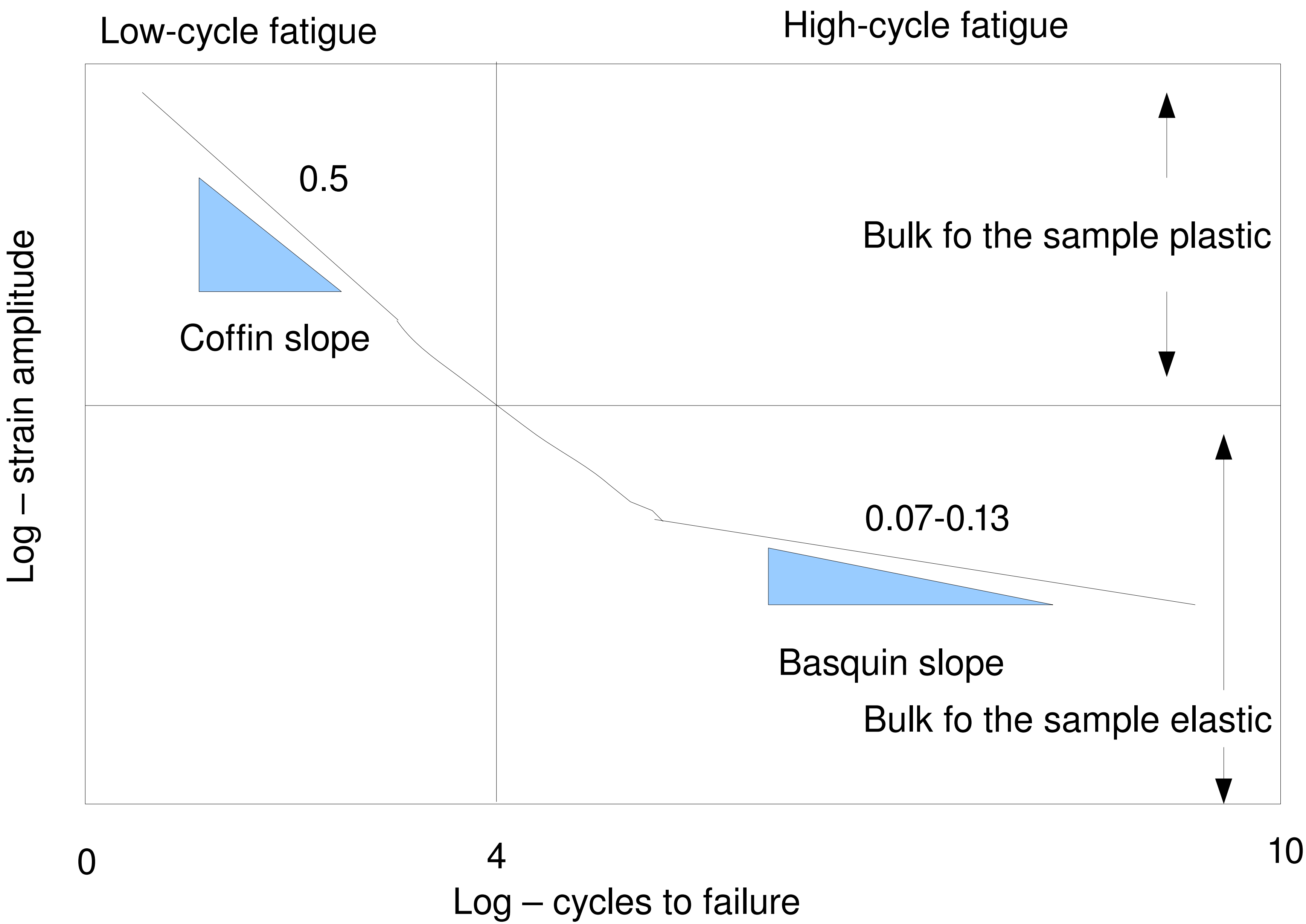
$$b, C_1 : constants$$

Coffin's law

$$\Delta \epsilon^{pl} = C_2 / N_f^c$$

$$c, C_2 : constants$$

Fatigue regimes



Goodman's and Miner's law

- Coffin and Basquin: fatigue failure of uncracked components cycled at constant amplitude about a mean stress zero
- Real loading!

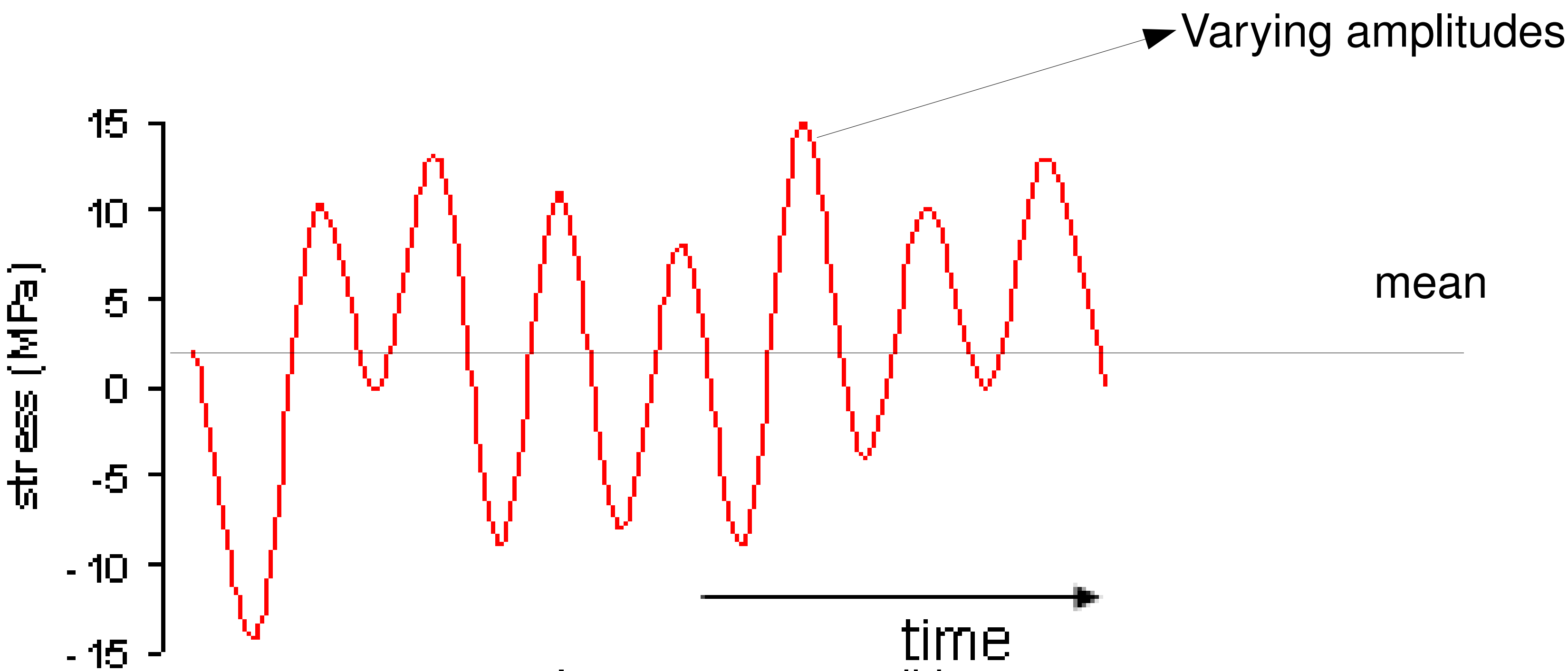


Image courtey: wiki

Goodman's and Miner's laws

[1] Releate the stress range for failure under a mean stress to that for failure at zero mean stress: Goodman

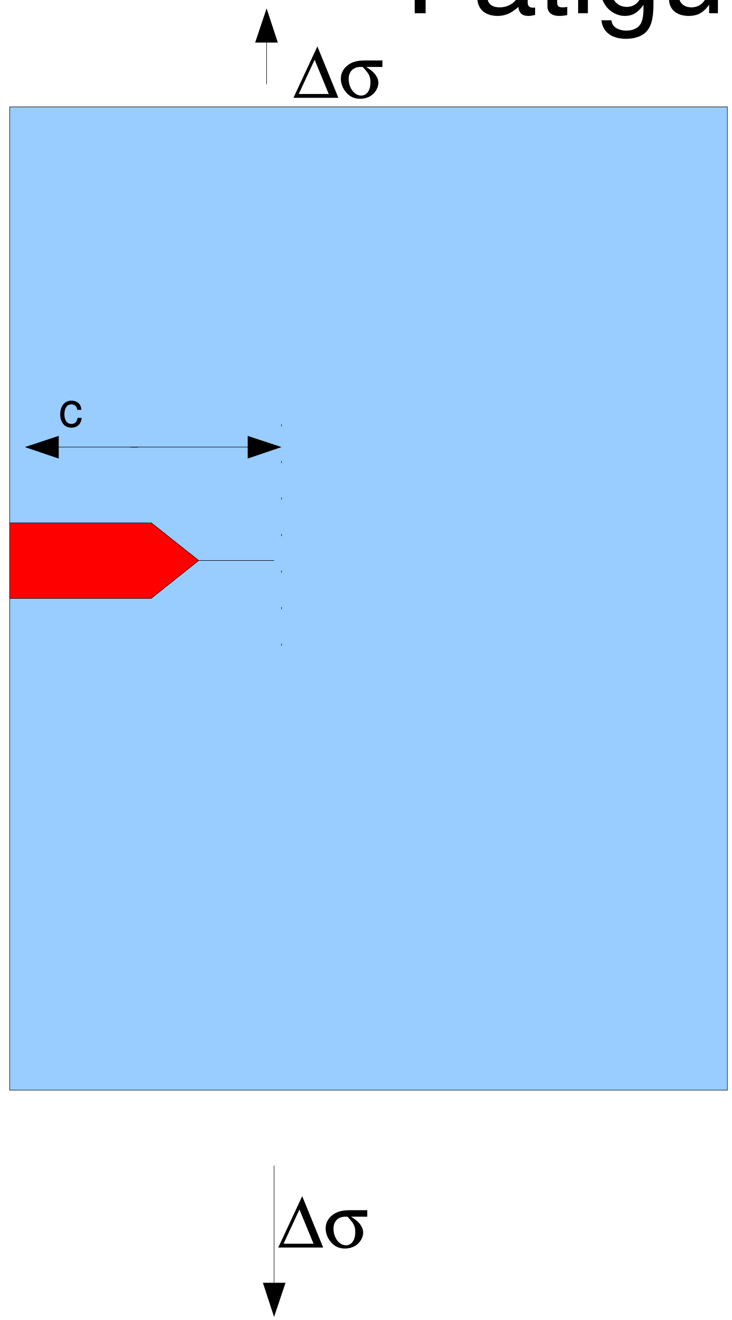
[2] Relate the numbers of cycles at various amplitudes to the life: Miner

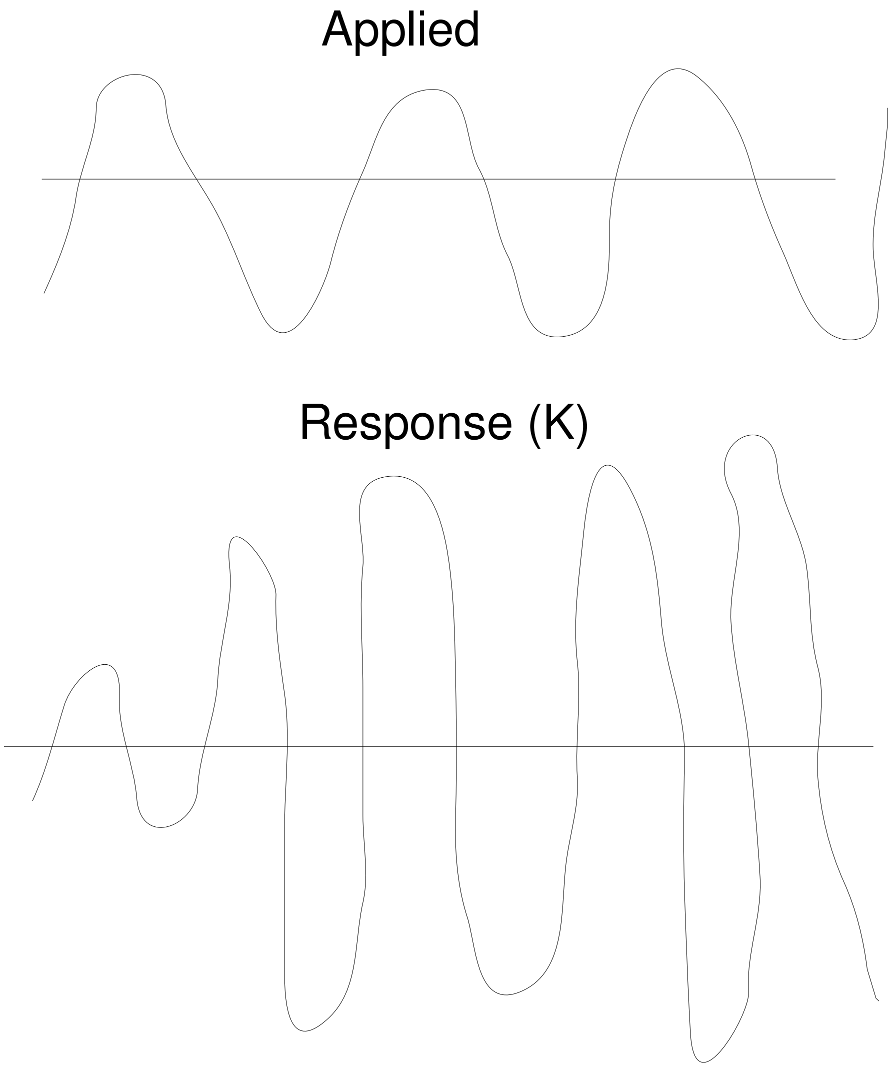
Propagation controlled fatigue

Cracks and ascertaining their presence

- Cracks – due to welding, casting, rolling, ...
- Non-destructive testing: detection of cracks is limited by the resolution achievable
- Thus, all you know is that, if the cracks are present, they are of less than some size, namely, the resolution limit
- Assume that such cracks exist, and desing accordingly!

Fatigue crack growth





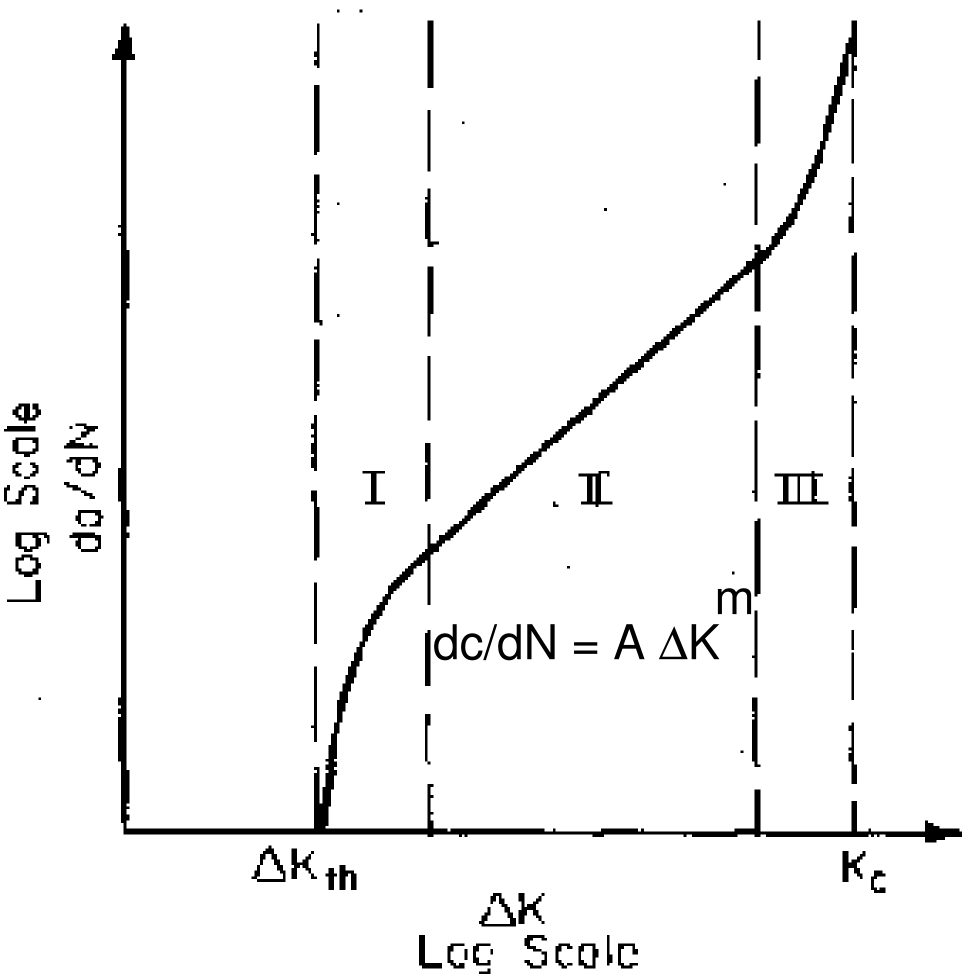
Fatigue crack growth

- Load a specimen of given crack length
- Define cyclic stress intensity range:

$$\Delta K = \Delta \sigma (\pi c)^{1/2}$$

- The range increses with time under constant cyclic stress
- This increase is related to the growth of the crack per cycle

Fatigue loading of cracked components



- Below threshold – growth rate is zero
- Steady-state regime: Paris law (A, m: constants)
- Accelerated growth rate: finally, loading once is sufficient

Image courtesy: Key to steel homepage

Material indices for fracture-safe design

- Fracture toughness: material property
- Manipulate geometry and loads (See Figure 10.2 for the effect of geometry and loading on stress intensity factor)
- Make sure that there are no cracks beyond a given size
- Choose materials with a given fracture toughness

Fracture-safe design

- Rule of thumb: avoid materials with fracture toughness less than 15 M Pa per sq. root metre

Strength-toughness chart

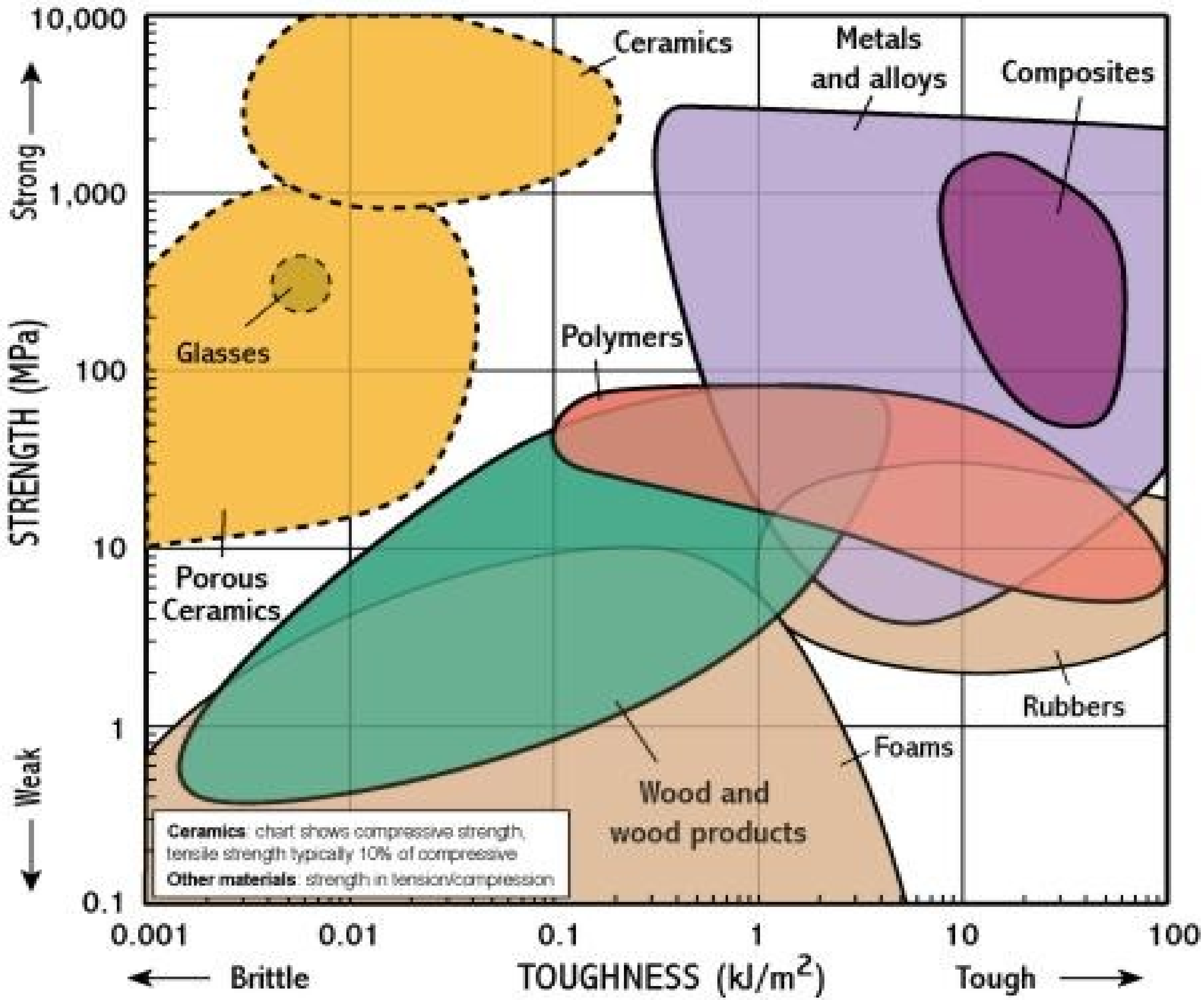


Image courtesy: Cambridge University site

Fracture-safe design

- Most metals and alloys pass (except few like cast iron)
- Ceramics don't
- How about polymers?
- What is happening?

Design limitations

- Load limited design: structural member will fail if stress exceeds a specific value: K1c is the key
- Energy limited design: Gc (“toughness”, or critical strain energy release rate) is the key (metals, polymers, and many composites pass – ceramics don't)
- Displacement limited design: (K1c/E) is they key (polymers are the best!)

Testing for toughness

- Tear test
- Impact test (Charpy and Izod)

Surface energy

- Surfaces in solids cost energy
- Bond breaking model works
- Cohesive energy is a good indicator of surface energies
- Surface energies are of the order of 1 J per square metre
- Typical materials Gc is larger than twice this value – reason is the plasticity

Brittle 'cleavage' fracture

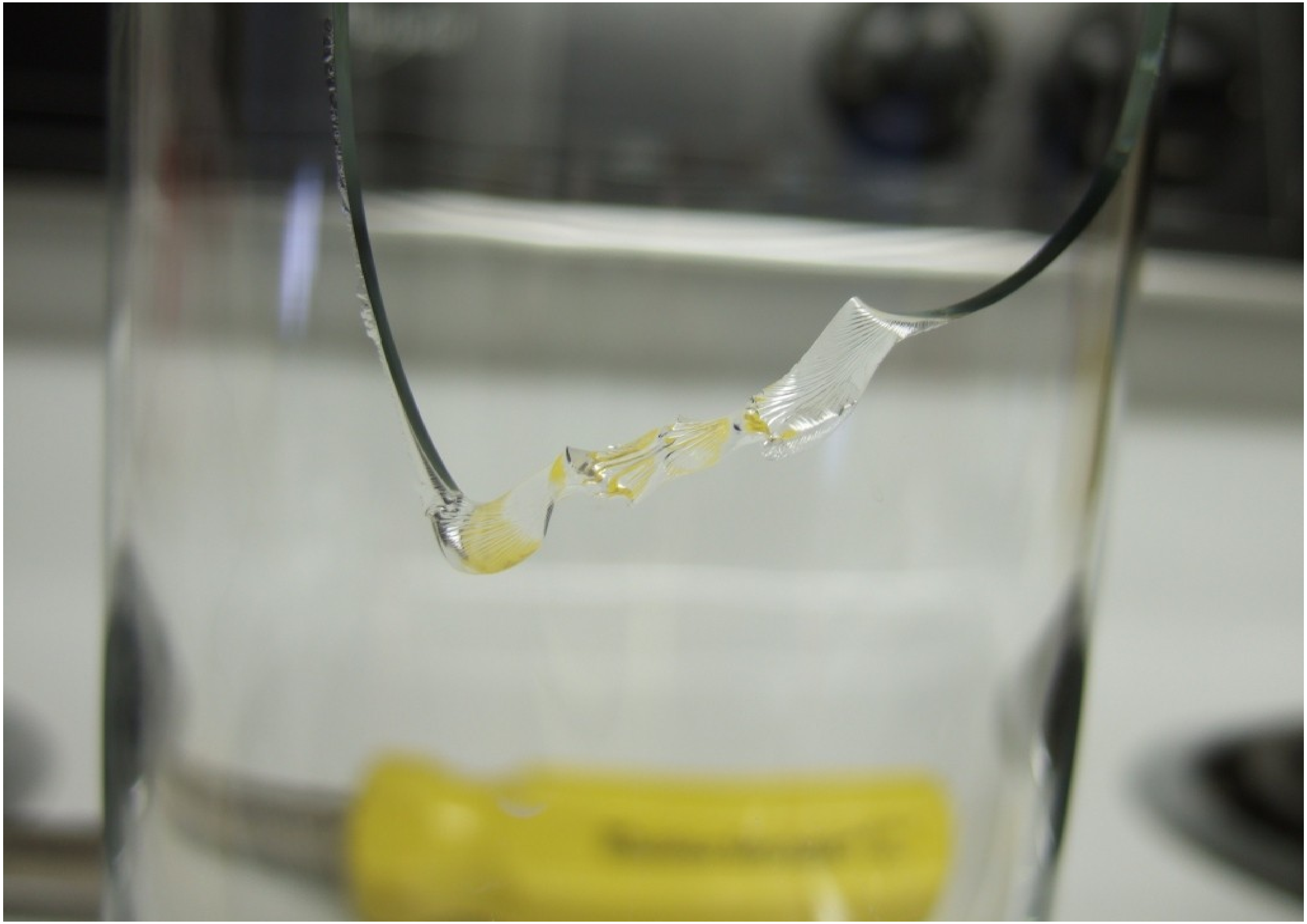


Image courtesy: http://ctho.ath.cx/pics/new/2007-03-28/

Brittle fracture

- Glasses and ceramics
- Yield strength is very high
- No relief of stresses at the crack tip
- Near the tip stress reaches the ideal strength
- Atomic bonds are torn
- Crack propagates at the velocity of sound in the medium
- Brittle materials – fail with a bang but with little notice!

Ductile fracture

Image courtey: wiki

Ductile fracture

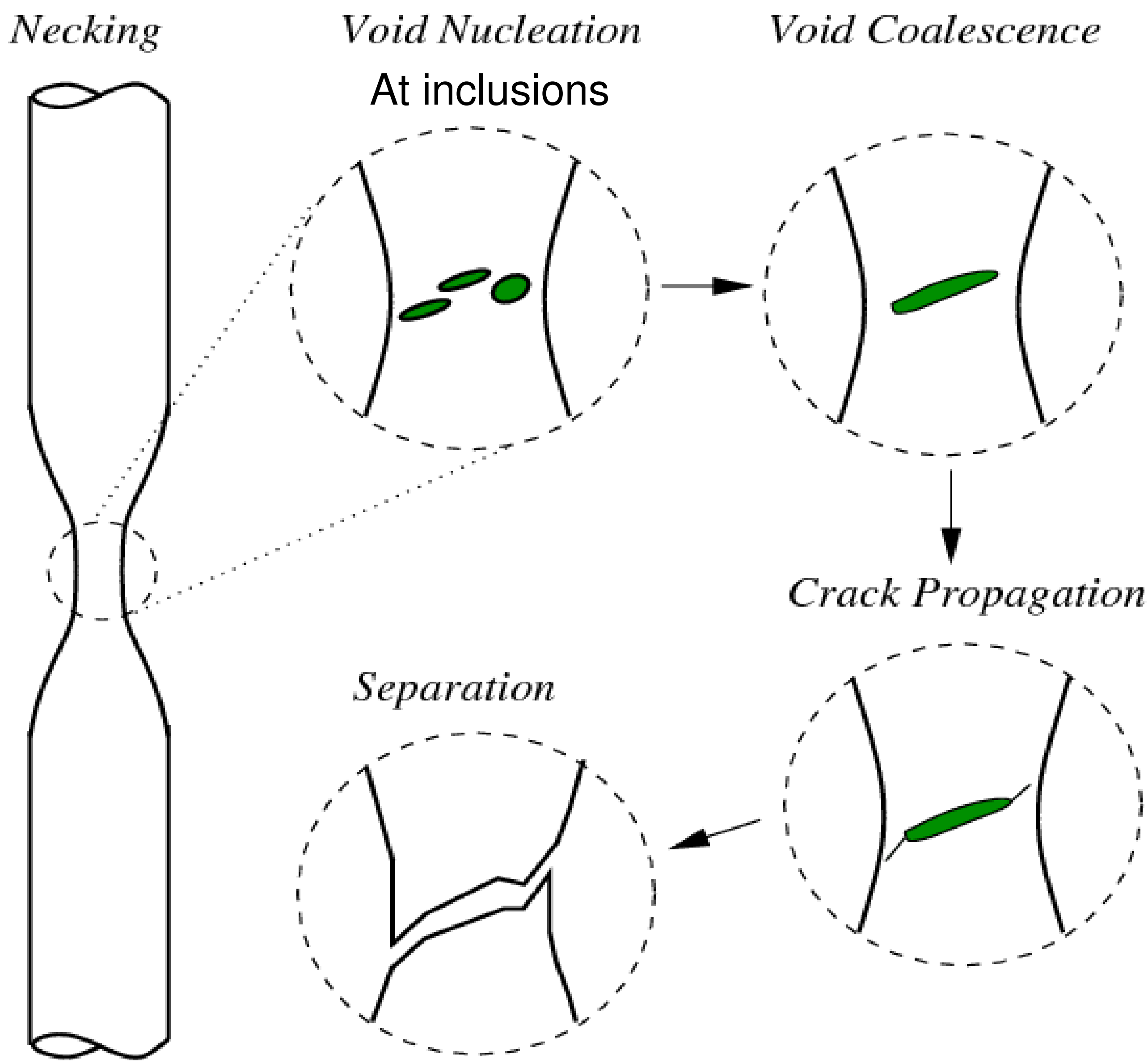


Image courtesy: wiki

Ductile fracture

- Polymers: crazing
- Crazes nucleate, grow and lead to failure
- Ductile fracture

A couple of disasters!

- Aluminium alloy – failed by ductile fracture leading to a cup and cone!
- Image courtesy: wiki

Challenger disaster

Images courtey: wiki

A Feynman quote

I took this stuff that I got out of your seal and I put it in ice water, and I discovered that when you put some pressure on it for a while and then undo it, it does not stretch back. It stays the same dimension. In other words, for a few seconds at least and more seconds than that, there is no resilience in this particular material when it is at a temperature of 32 degrees.

-- Richard Feynman