Chapter 7

Materials Mechanical Failures

Dr. Zhe Cheng

Mechanical Failure

<u>Statics</u>	Rigid body	No deformation	No failure

There are NO rigid bodies!

<u>Mechanics of Solids</u> (or MECH331, CIVE360)	Practical engineering materials	w/ <u>deformation</u> (elastic/reversible or plastic/irreversible	Can (often) <u>fail</u> (Fracture, Fatigue, Creep)

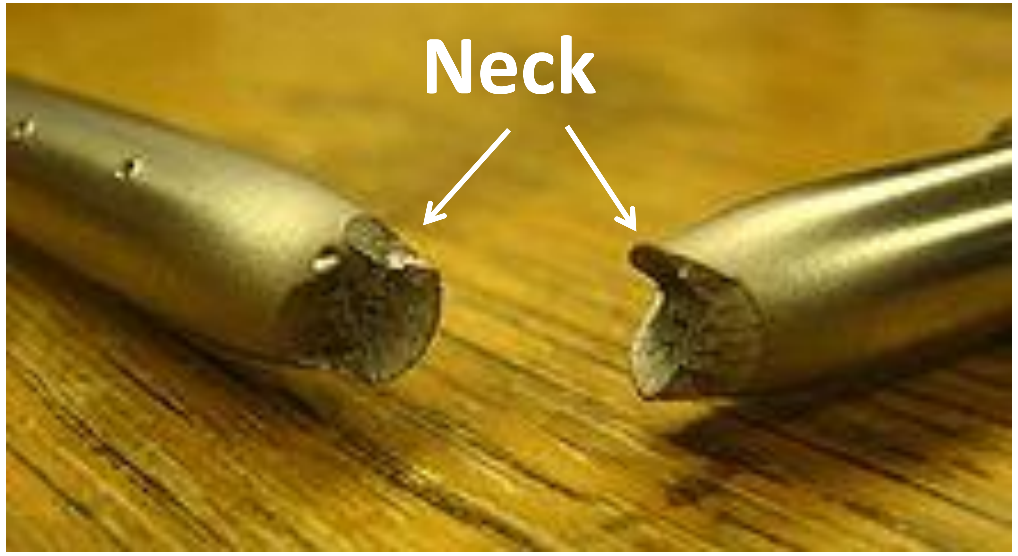
A 1st Means of Mechanical Failure - Fracture

- **Definition**

  A type of mechanical failure for materials, characterized by complete separation of a material into pieces and loss of mechanical integrity

- **Brittle** fracture
  - Little or **no plastic deformation**
  - Often sudden & catastrophic
  - Ceramics, glass, & some metals & polymers

- **Ductile** fracture
  - Accompanied by **significant plastic deformation**
  - More predictable
  - Most metals & polymers, and, under special conditions (e.g., high T), ceramics/glass



Material's (Tensile) Fracture Strength << Theoretical Value

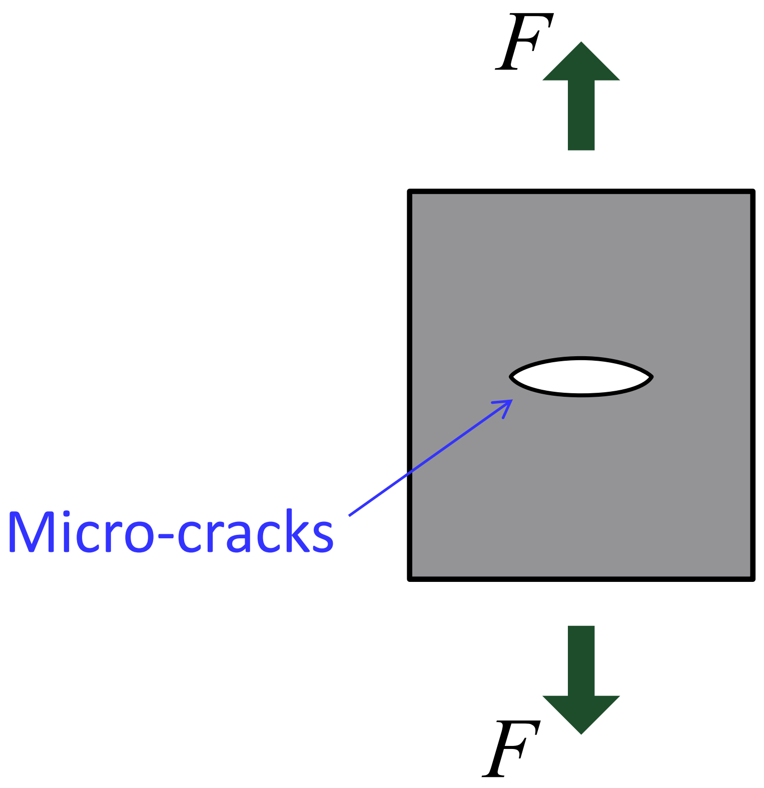
- Material ideal tensile strength, based on breaking all bonds simultaneously, is $\sim E/10$

  Reference: https://en.wikipedia.org/wiki/Theoretical_strength_of_a_solid

- Practical materials' tensile strength much lower than ideal - by ~10-100 times!

  Steel: σ_{th} ~ 20 GPa vs. σ_U ~ 0.5-2 GPa

- Much lower fracture strength for practical materials due to **<u>flaws</u>**, especially **<u>microcracks</u>**



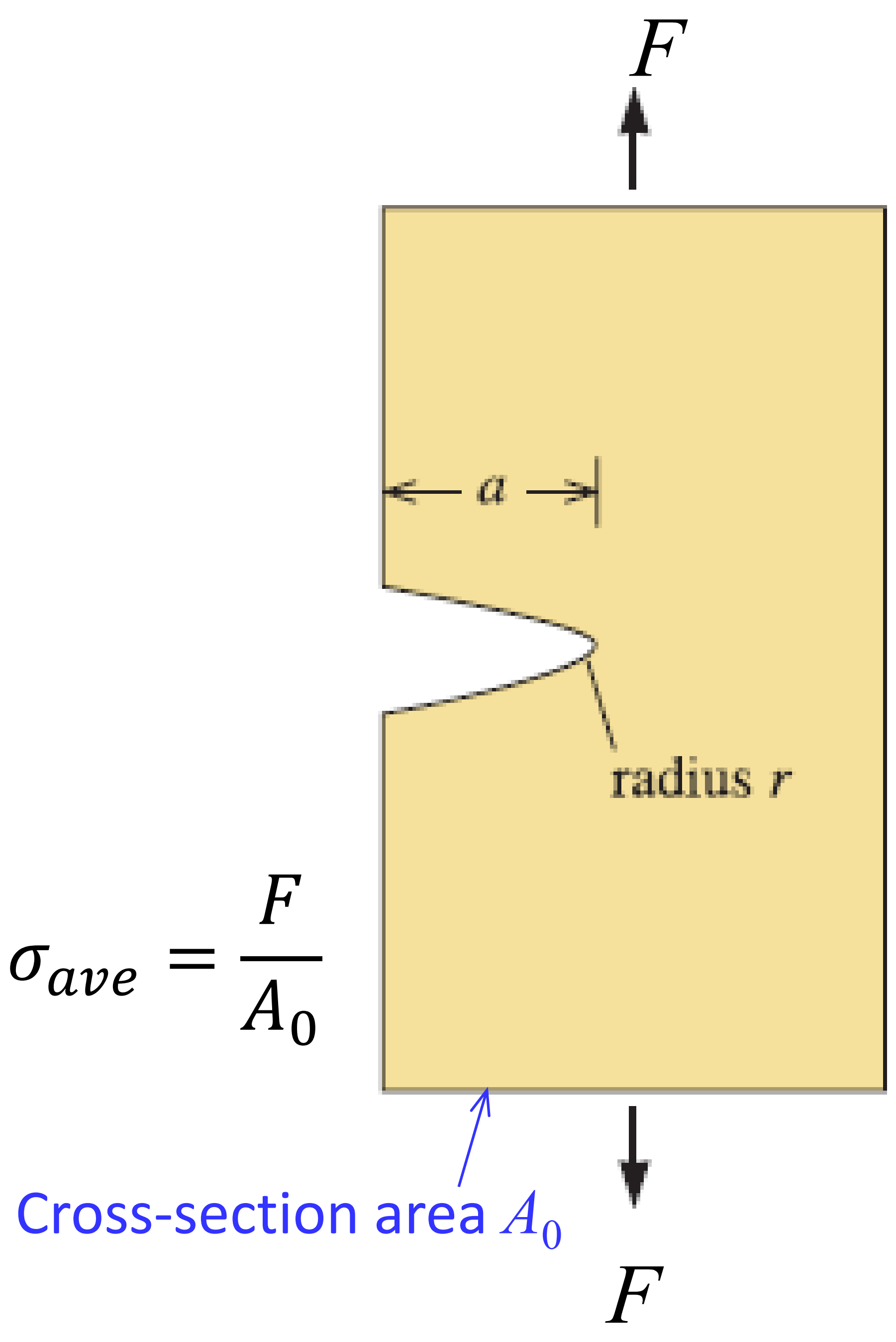
Micro-cracks as Stress Concentrator

- **Stress concentration**:
  Local (max) stress, at the **tip** of a flaw or microcrack, is much higher than average stress:

$$\sigma_{\max\, local} \approx 2\sigma_{ave}\sqrt{\frac{a}{r}} \gg \sigma_{ave}$$

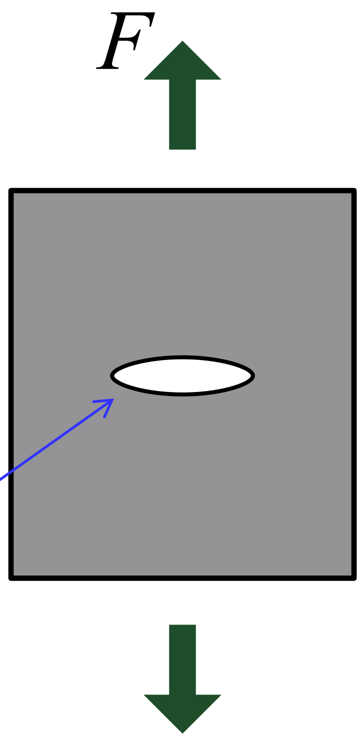
- Higher a/r ratio (i.e., longer crack or sharper tip) → greater crack-tip stress "concentration"

- When max local stress exceeds critical stress (i.e., when local bonds start to break significantly, e.g., $\sqrt{\frac{2E\gamma_S}{\pi a}}$ for brittle fracture), crack "propagate" or grow and materials fracture/fail



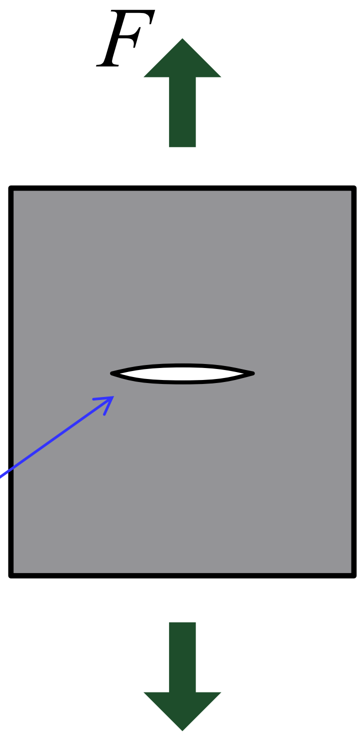
Crack Propagation/Growth

- Cracks w/ sharp tips grow faster than blunt tip



Blunt crack tip
w/ <u>larger</u> radius of
curvature *r*

$$\sigma_{\max local} \approx 2\sigma_{ave}\sqrt{\frac{a}{r}}$$



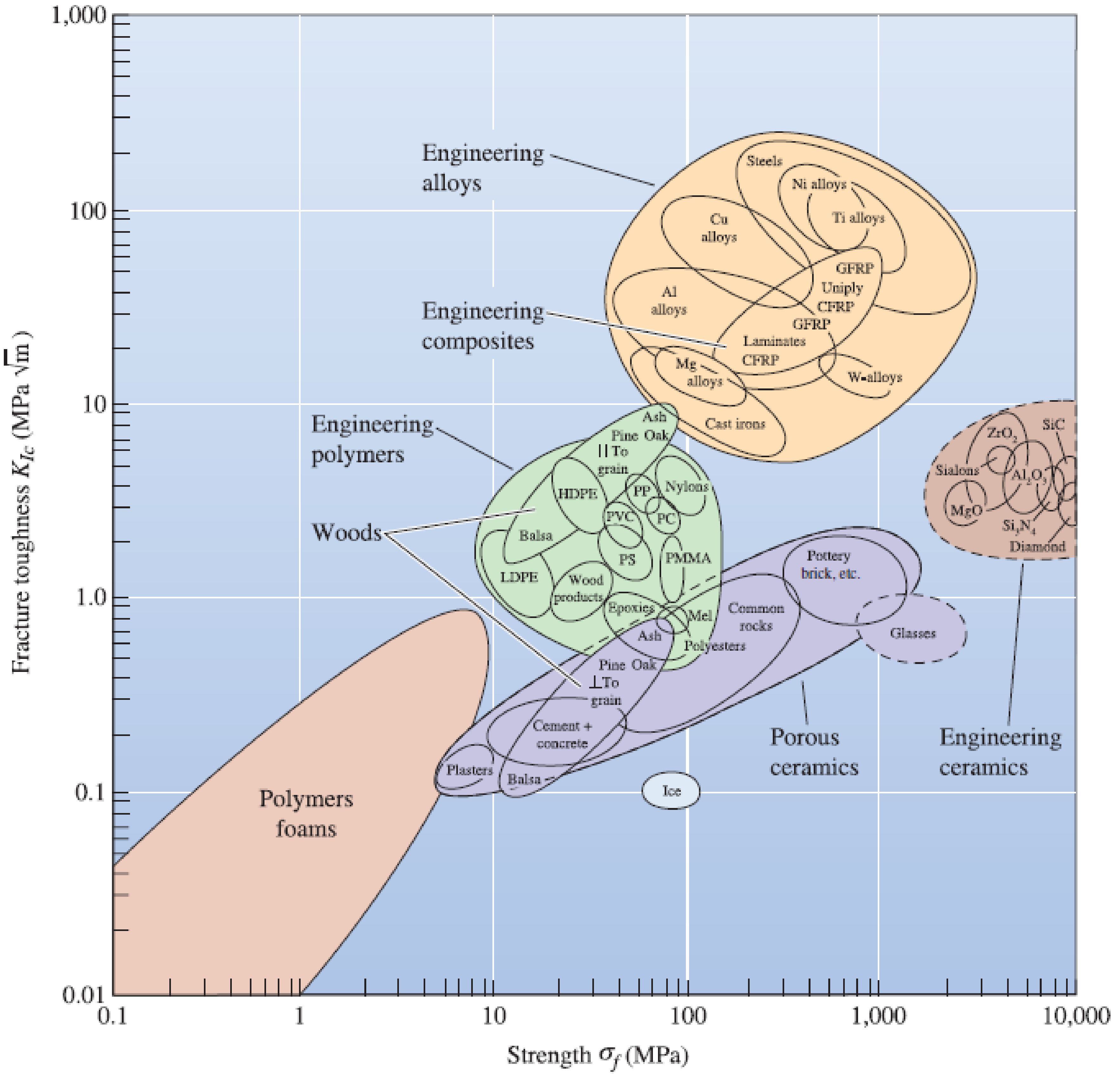
Sharp crack tip
w/ <u>smaller</u> radius
of curvature *r*

- Ductile material plastically deform at crack-tip, absorbing much more energy before crack can grow/propagate than brittle material

Brittle　　Ductile

(Plane Strain) Fracture Toughness K_{1c}

- A parameter to represent a material's practical capability to resist fracture
- Unit **MPa • m$^{0.5}$**
- Often a range for a given material, due to difference in processing/flaws
- High for metals, especially **steel**
- Low for ceramics and common polymers

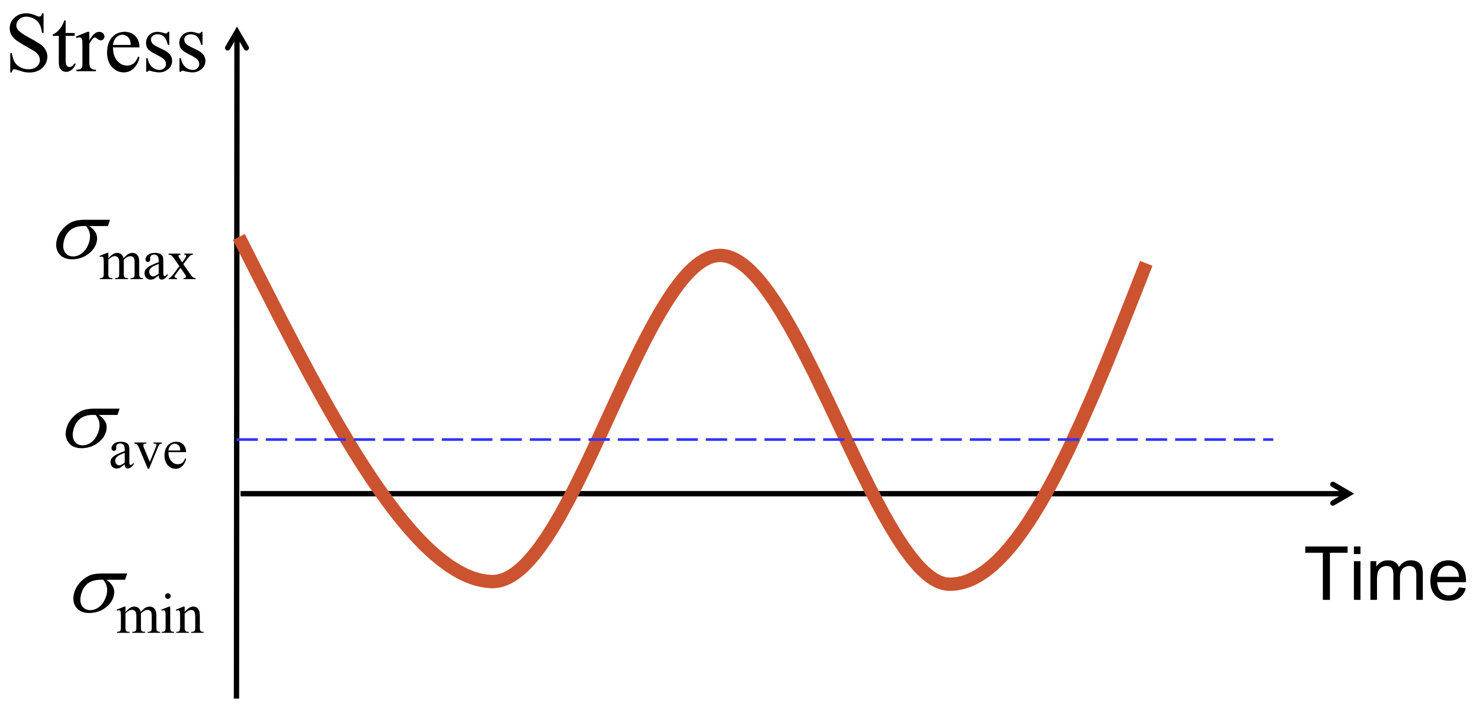


A 2nd Means of Mechanical Failure - Fatigue

Fatigue

Failure under repeated applied or cyclic stress (or load), **often below yield strength or tensile strength**.

- Lead to failure, even though $\sigma_{max} << \sigma_y$
- ~ 90% of mechanical failures



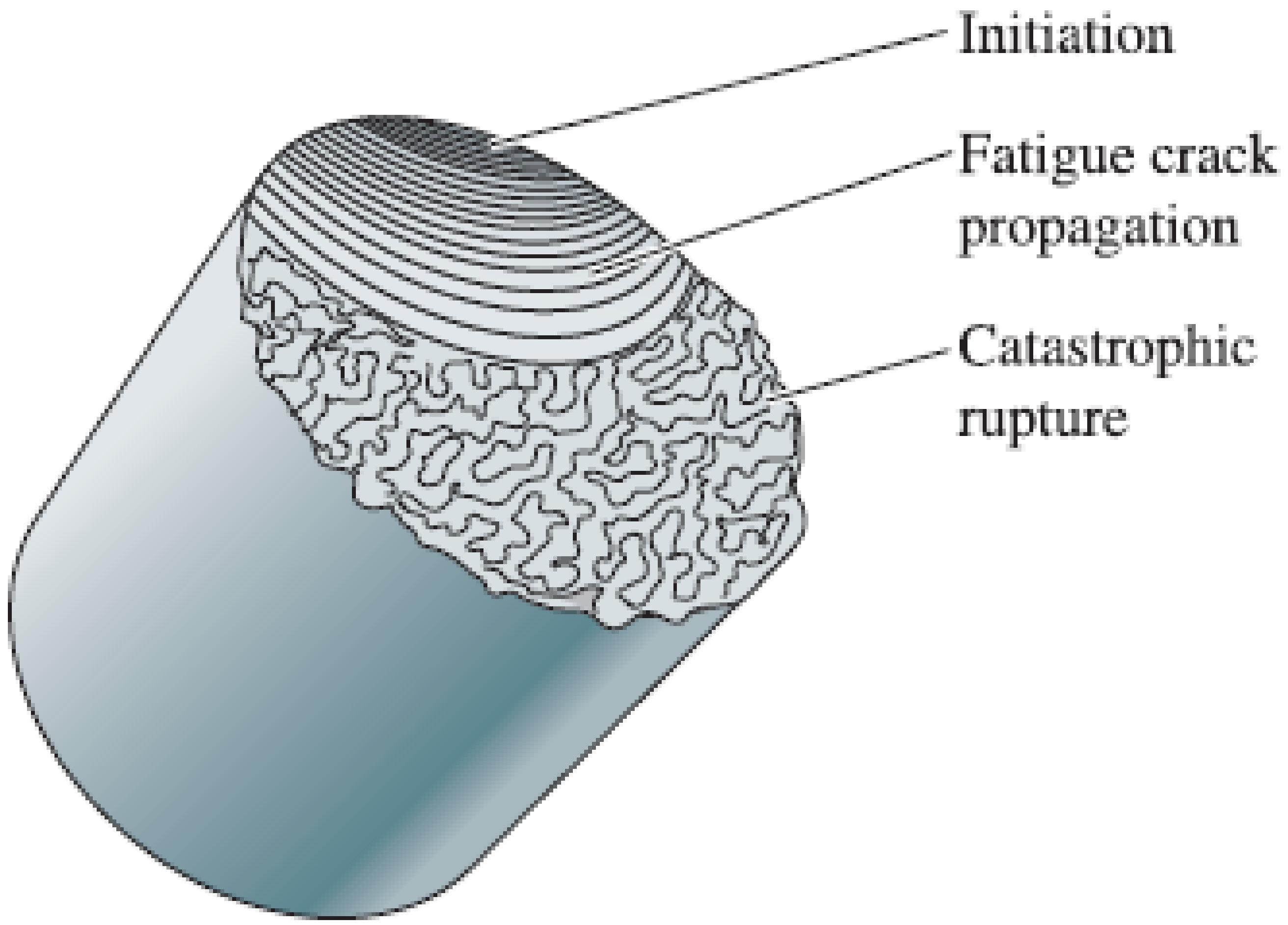
Key parameters of cyclic stress:

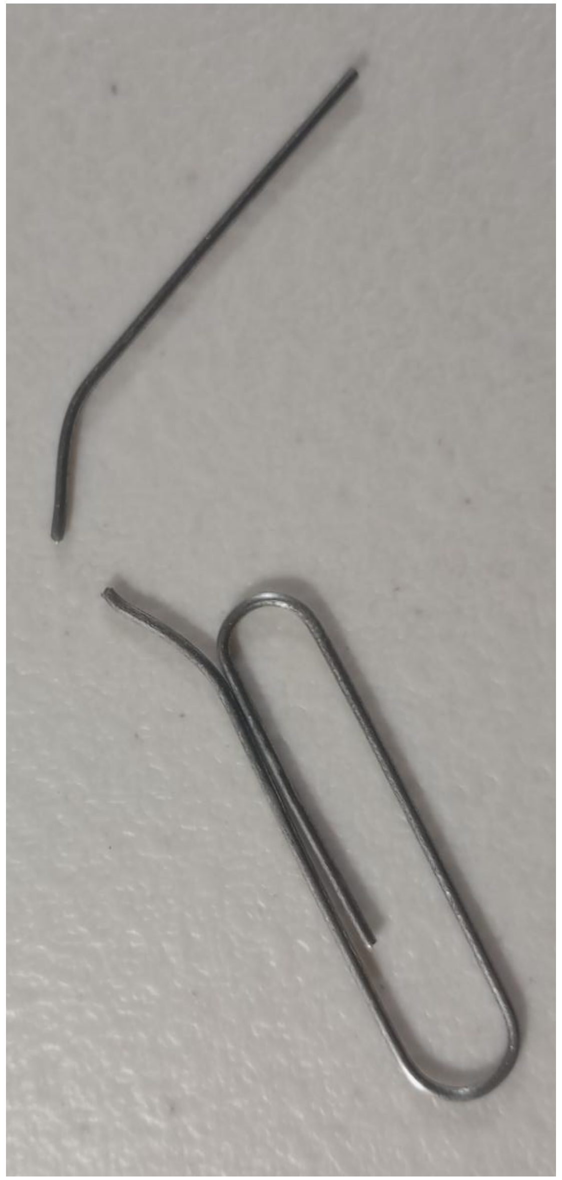
- Max and Min stress: σ_{max} and σ_{min}
- Average stress σ_{ave}
- Amplitude s
- Cycle frequency f or period T

Higher frequency, higher stress (average, amplitude, or max), temperature → faster/earlier failure

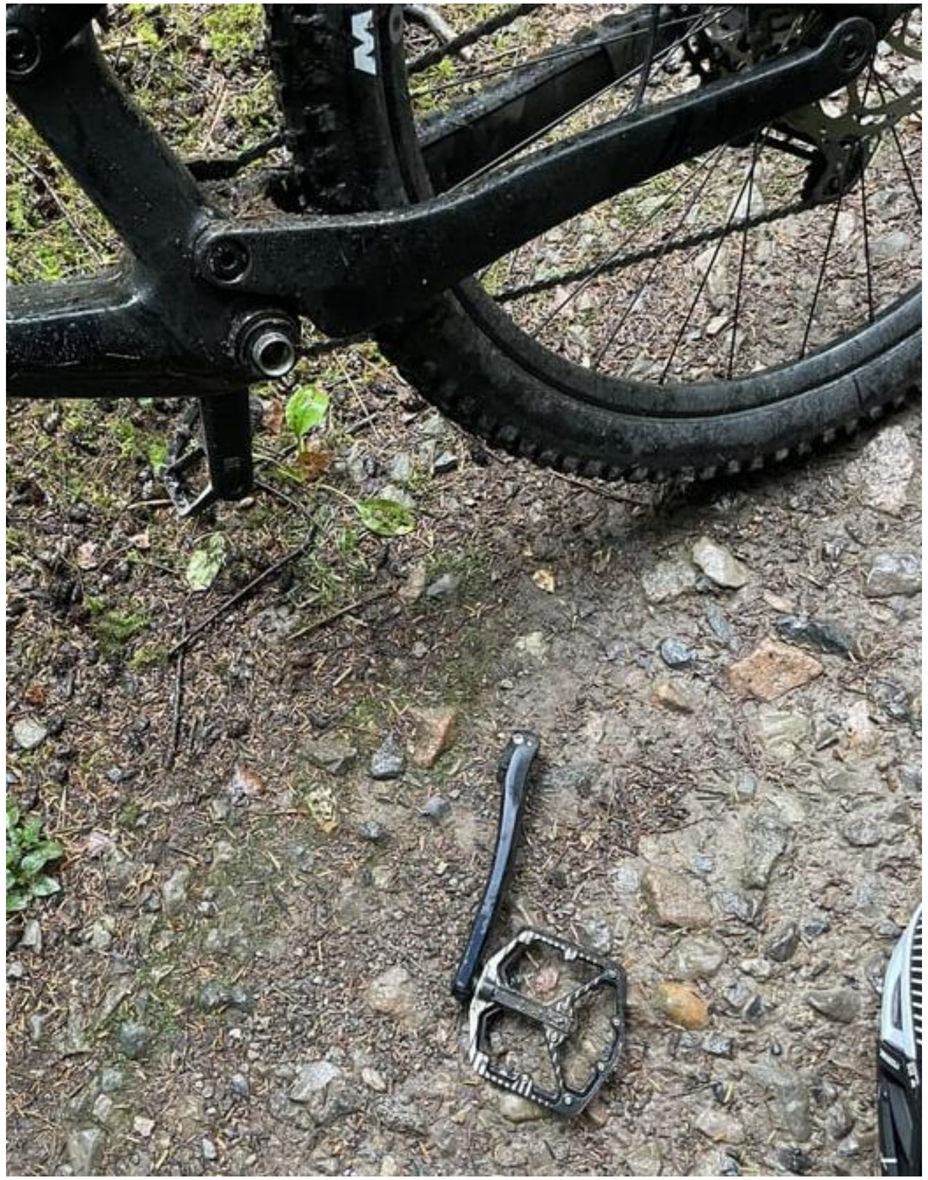
Microcrack Growth Leading to Fatigue Failure

- Microcracks grow (out of flaws), slowly, eventually leading to catastrophic rupture or fracture





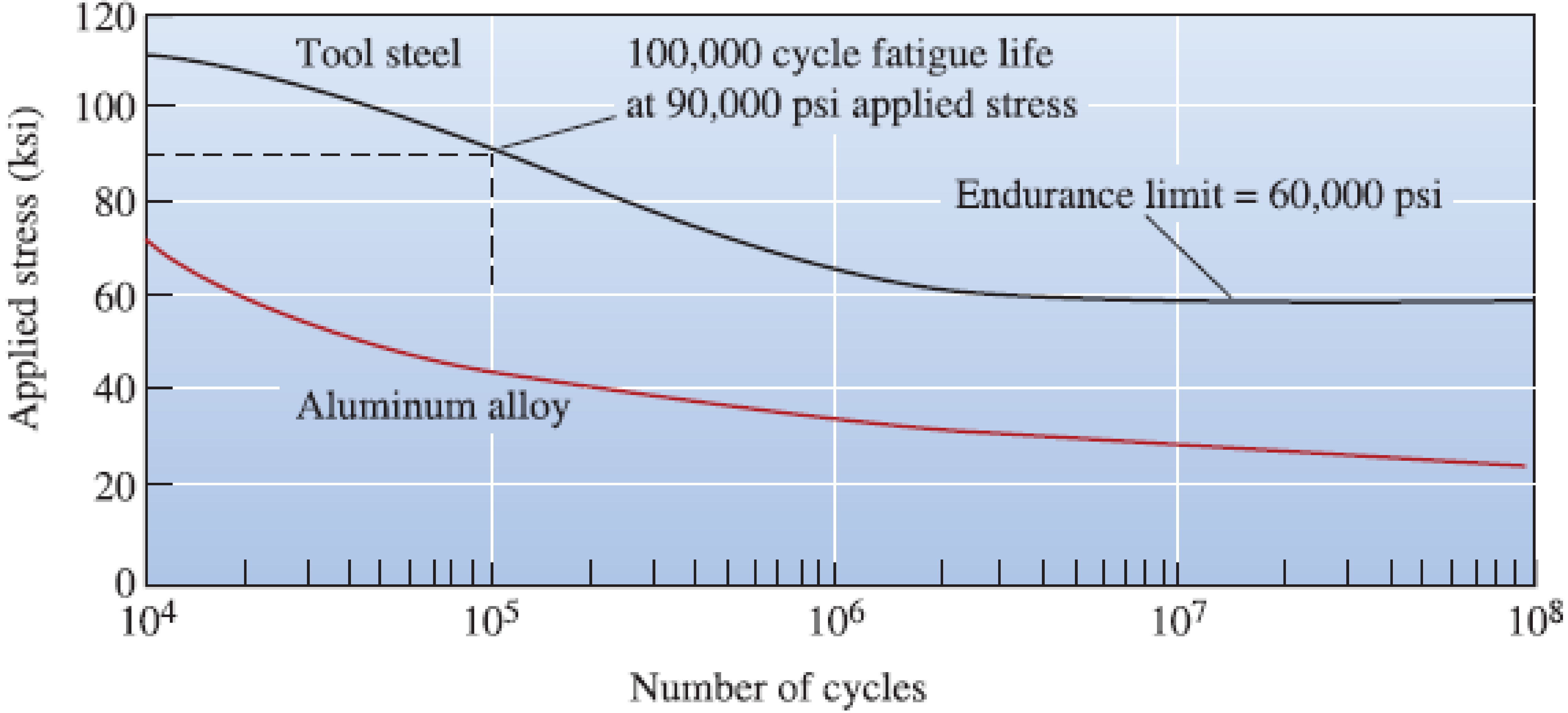
Ruptured paper clip due to fatigue



Ruptured bicycle pedal due to fatigue

Endurance Limit for Fatigue

- As cycle number increases, critical stress (e.g., the stress amplitude) tends to drop
- Critical stress may **stabilize** at some values, called **endurance limit**, for some metals like **steel**, but may **continue to drop** with no lower boundary for some other metal like **aluminum alloy**



Note:
Tool steel
$\sigma_y \sim 200$ ksi

Aluminum alloy
$\sigma_y \sim 70$ ksi
(e.g., for 7075)

A 3rd Means of Mechanical Failure - Creep

Creep

Sample deformation/strain increase over time, at a **constant stress** (or load)

Primary Creep/1st stage:

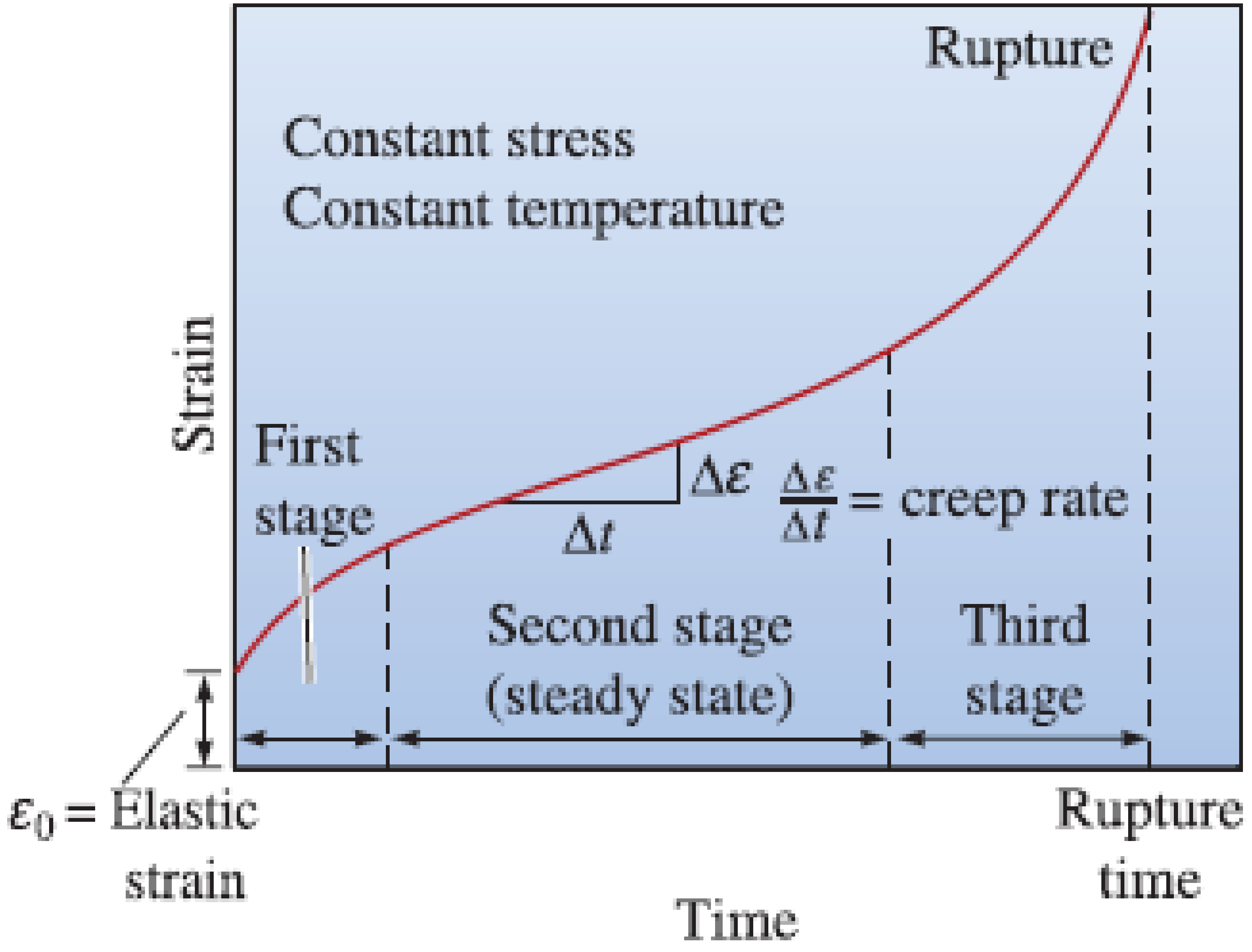
Slope (or creep rate, $\frac{d\epsilon}{dt}$) decreases with time

Secondary Creep/2nd stage:

Constant creep rate

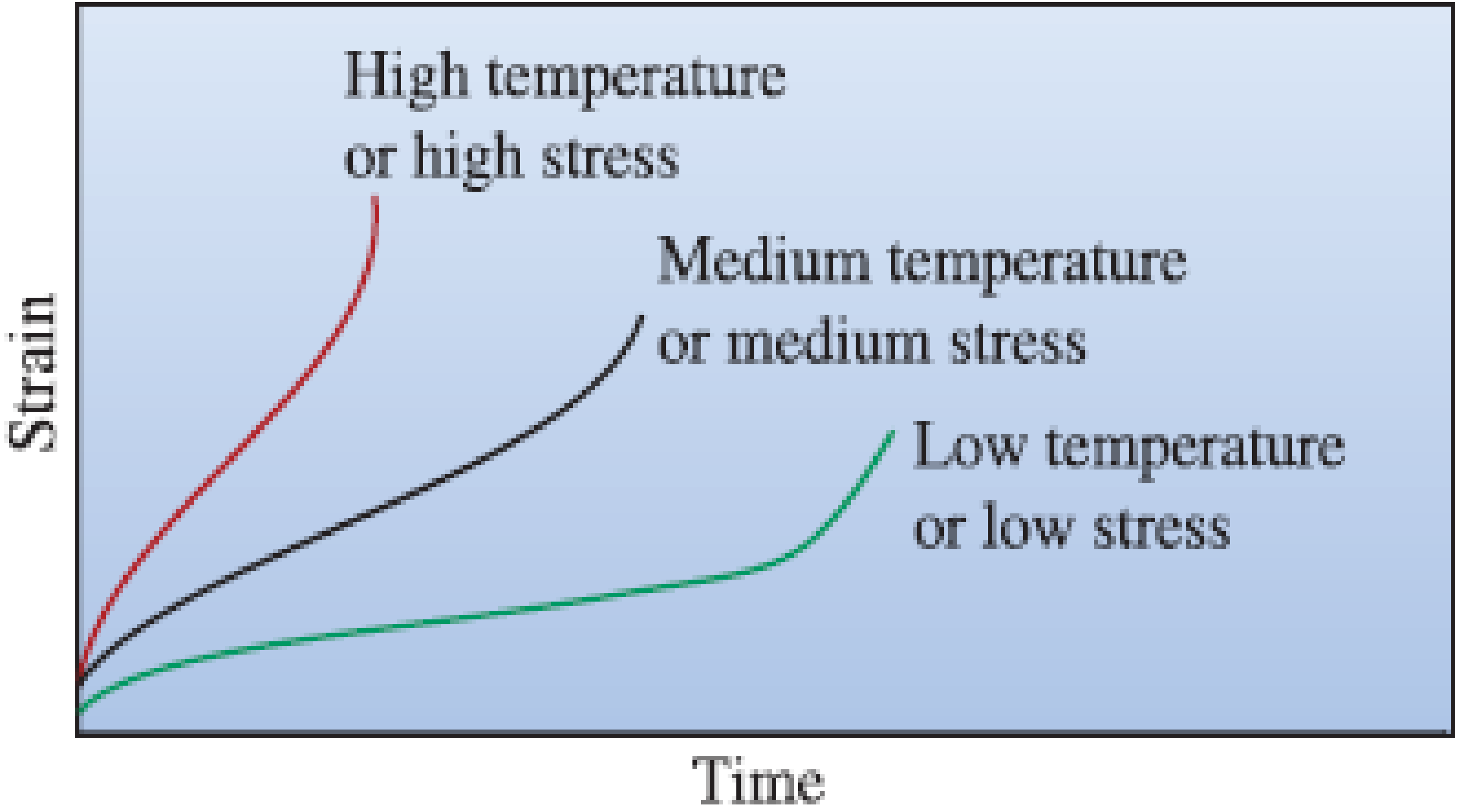
Tertiary Creep/3rd stage:

Creep rate increases with time



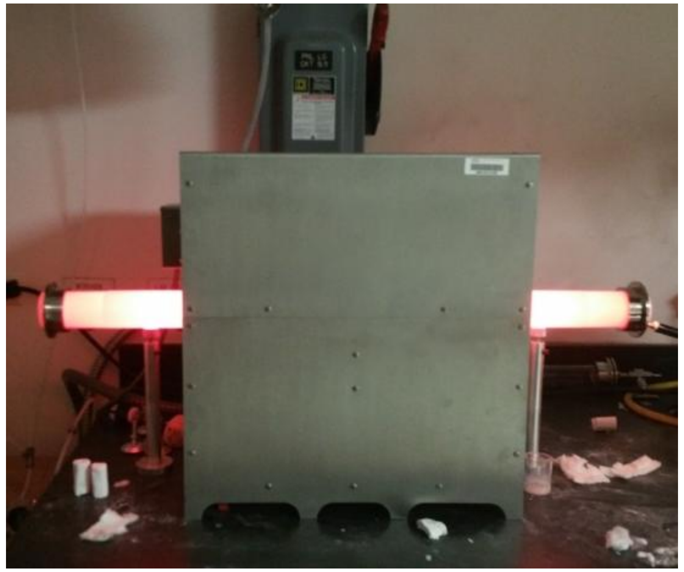
Temperature & Stress Effect on Creep

Above ~0.4 T_m (in K), higher temperature or higher stress leads to faster creep



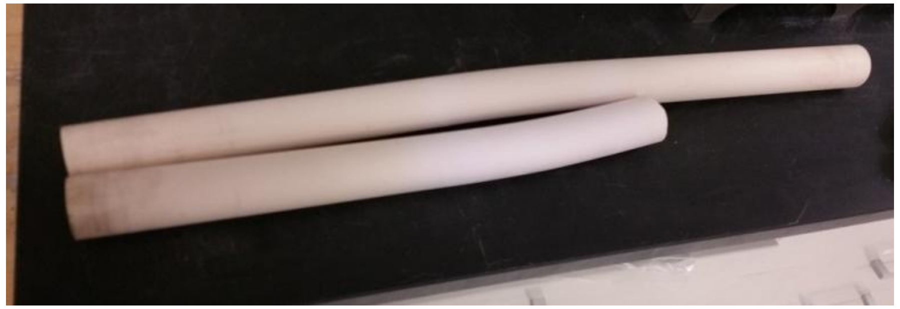
Example of Creep for Al_2O_3 Ceramics (Tm = 2025 ^oC)

As received Al_2O_3 tube



After running at >1400^{o}C for hours w/o proper mechanical support

Curved or **fractured** Al_2O_3 tube after creep



END

Homework 7.0

Carefully review chapter 7 lecture slides and, if time allows, read textbook sections of Askeland 7.1-7.4, 7.6, 7.9-7.10 (some numerical example problems such as 7-1 to 7-3, 7-10 could be omitted) and give an honor statement confirming the reading

Homework 7.1

- Please write down one question that you are not clear or feel interested about in this chapter (Chapter 7).
- Check for answers using any AI tool and give brief comments on **your challenge to or suspicion of** the answer given by the AI.