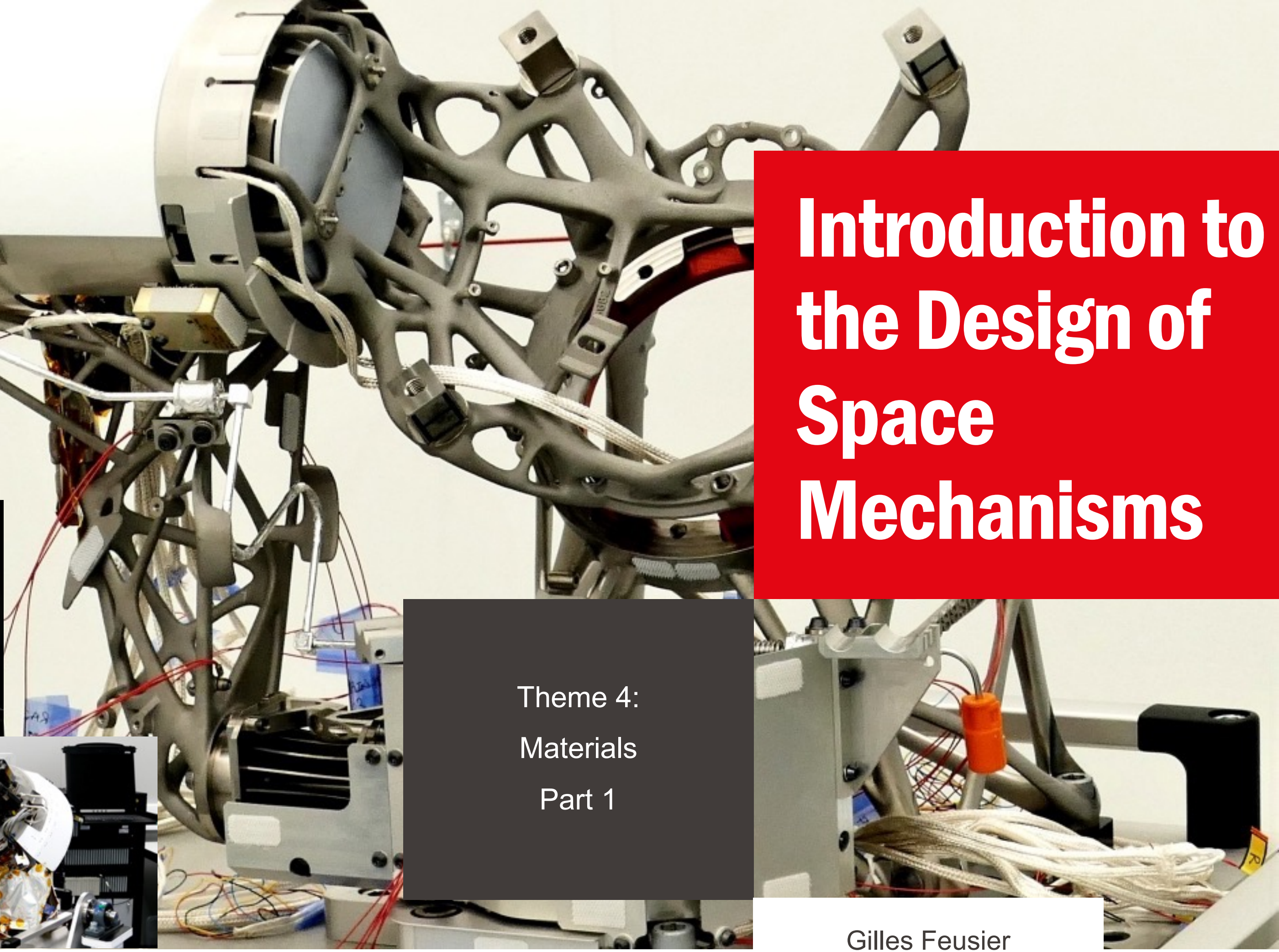

Introduction to the Design of Space Mechanisms

Theme 4:

Materials

Part 1

Gilles Feusier

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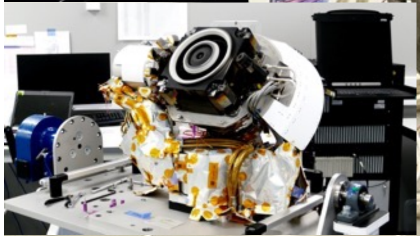


© Thales Alenia Space

Material Properties

- Fundamental properties
  - Physical
  - Mechanical
  - Thermal
  - Electrical
  - Magnetic
  - Optical
- Necessary Verifications and Qualifications
  - ECSS-Q-ST-70C Rev.2 [4.1]
    Space Product Assurance - Materials, mechanical parts and processes
- Selection
  - ECSS-Q-ST-70-71C Rev.1 [4.2]
    Space Product Assurance - Materials, processes and their data selection
  - Note: European Space Materials Database (ESMDB) available at ESA.

Material Properties

- Physical properties
  - Specific weight
  - Metallurgical states
    - Highly dependent on the phase
      - Strength, elasticity, toughness, resilience, wear, …
      - Magnetic susceptibility, remanent magnetization
      - Heat capacity, linear thermal expansion, melting, vaporization
  - Chemical
    - Outgassing
      - Vapor pressure
      - Absorption, adsorption
    - Electrochemical potential
      - Corrosion, stress-corrosion cracking
    - Aging
    - Biocompatibility, toxicity
    - Flammability
  - Environmental
    - Resistance against radiations
    - Water absorption
    - Resistance to biological agents (fungus, bacteria, …)

Mechanical Properties

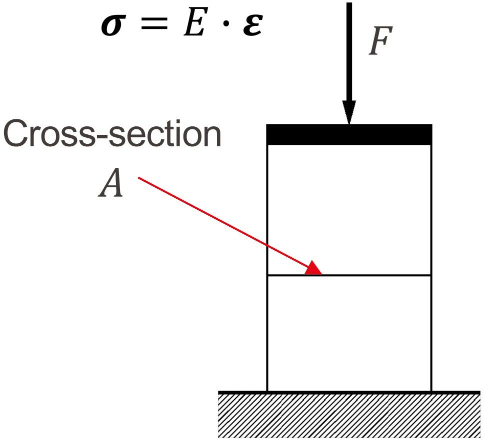
- Strength (tensile, bending, compression)
  - Ultimate Tensile Strength (UTS) [MPa]
  - Yield Strength (Hooke's law) [MPa]
- Fatigue strength
  - Cyclic loading
  - Crack growth related to the number of cycles, until fracture
- Shock Resistance (toughness)
  - Energy of mechanical deformation to fracture
  - Effects of notches
  - Dynamic effects (impact)
- Wear resistance
  - Hertz pressure
  - Materials in contact
- Other properties
  - Hardness, ductility, creep, friction coefficient

Mechanical Properties (reminder)

- **Stress (σ), strain (ε), stiffness (k)**, Hooke's law, Young's modulus (E)

$$\boldsymbol{\sigma} = \frac{F}{A} \qquad \boldsymbol{\varepsilon} = \frac{\Delta L}{L}$$

$$\boldsymbol{\sigma} = E \cdot \boldsymbol{\varepsilon}$$

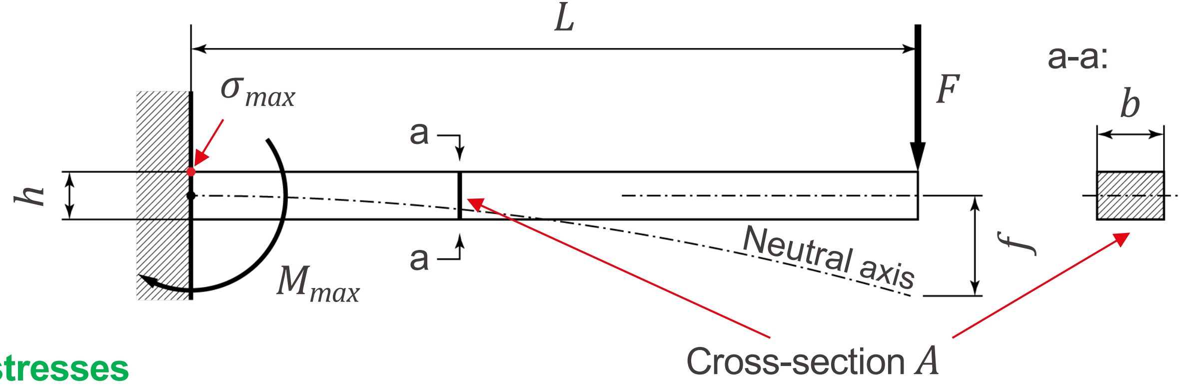


Example: ***cantilever beam****, rectangular cross-section*

Stiffness: $k = \frac{F}{f}$ Deflection: $f = \frac{F \cdot L^3}{3 \cdot E \cdot I}$ with $I = \frac{b \cdot h^3}{12}$

I: area moment of inertia (second moment of area)

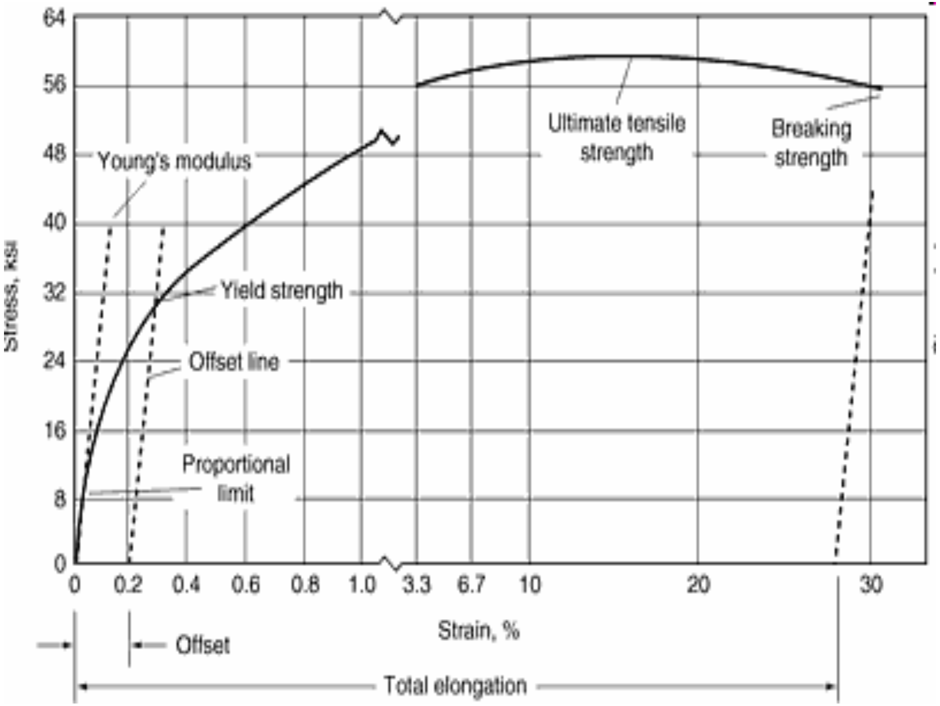
Maximum stress: $\sigma_{max} = \frac{M_{max}}{2 \cdot I} h$

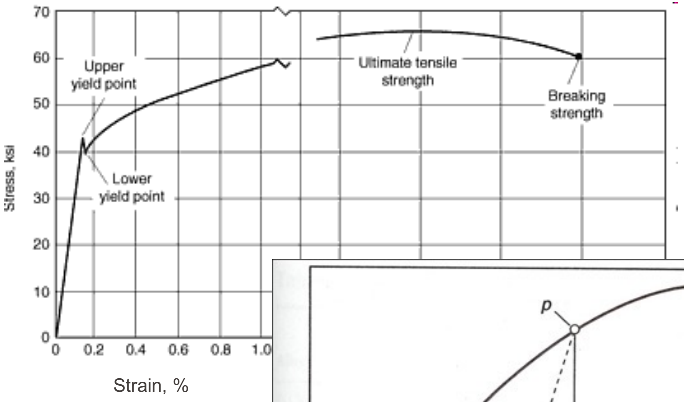


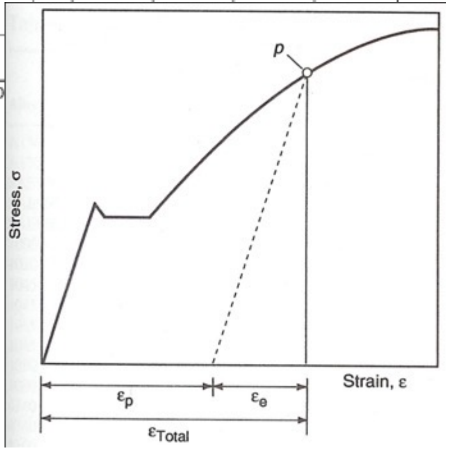
Exercise 4.1: Solar Array
Exercise 4.2: Stiffness and stresses

Mechanical Properties

- **Tensile test**
  - Stress-Strain curve (source: ASM Metals Handbook)







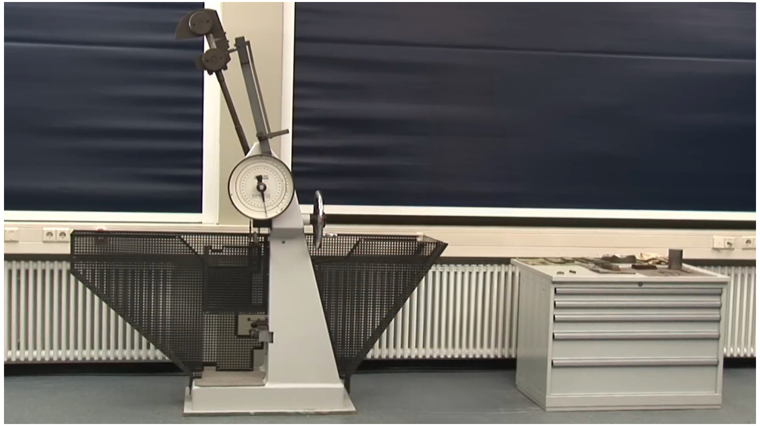
ε_p plastic strain

ε_e elastic strain

Mechanical Properties

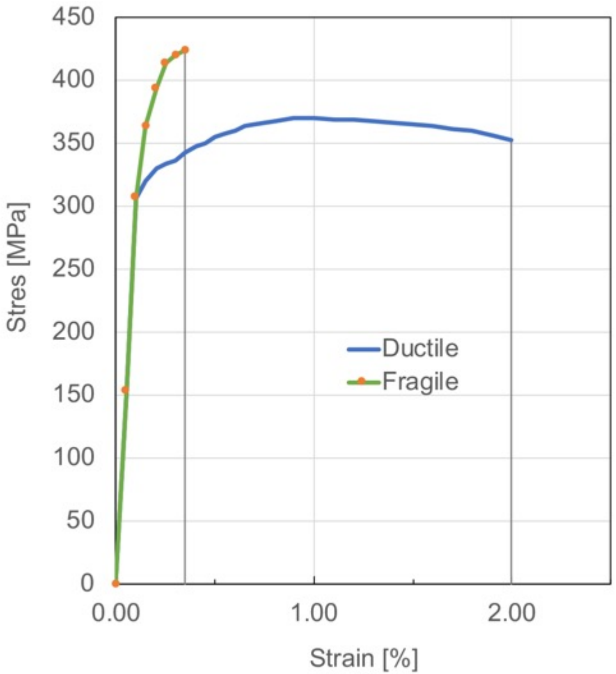
- **Toughness**
  - Ability to absorb energy before fracture

Impact Pendulum (Charpy Test)



Source: MaterialsScience2000/Youtube

Unit (SI): J/m^3



ECSS-Q-ST-70-71C Rev.1

4.2.21 Ceramics and other non-metallic materials

“Ceramics and glasses, except as fibres, shall not be used in a structural applications without the prior approval of the customer.“

What is the main cause of brittle fracture?

- Turn out to your neighbors (3-5 people teams)
- What is the main cause of brittle fractures?
- Do you have some examples, examples of failures? From your own experience?
- 5 minutes discussion
- Share your outcomes

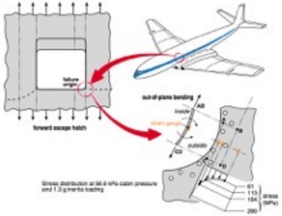
Mechanical Properties

▪ Fatigue

- Weakening caused by cyclic loads
  - Applied forces of variable amplitudes (oscillatory, unidirectional periodic, random, vibrations, ...)
  - Thermal cycles
- The fatigue depends on:
  - The material
    - Ductility, brittleness
    - Strength, intergranular cohesion, inclusions
  - Size of the structural defects (surface cracks or embedded cracks/voids)
  - Surface finish (initial crack size)
  - Geometry of the part (stress concentration)
  - Amplitude of the load cycles
  - Environment
    - Temperature
    - Chemical environment (corrosion, stress corrosion, hydrogen embrittlement, …)

Source: https://commons.wikimedia.org/wiki/File:TankerSchenectady.jpg

Source: BAE Systems



Source: https://aerospaceengineeringblog.com/dehavilland-comet-crash/

Crack growth

- **Fatigue**
  - **Critical value of K for crack growth K_c:**

    $K = f(\sigma, \sqrt{a}) \geq \boldsymbol{K_c}$ [MPa√m]

    K: stress intensity factor

    σ: applied stress

    a: characteristic size of the crack

  - **Crack growth (Paris equation)**

    $$\frac{da}{dN} = C \cdot (\Delta K)^n$$

    ΔK: stress intensity factor range

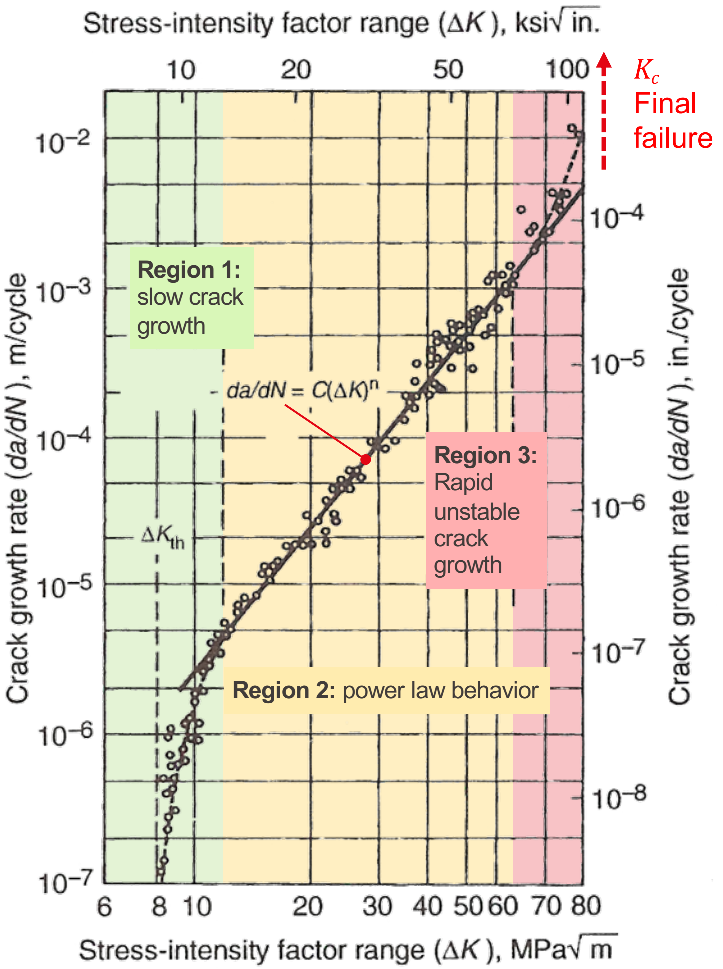
    $\Delta K = \Delta\sigma \cdot \sqrt{a \cdot f(g)}$ [MPa√m]

    C and n: constants of the material

    $f(g)$: function of the specimen geometry, loading conditions, and the ratio of crack length to specimen width

    $\Delta\sigma = \sigma_{max} - \sigma_{min}$

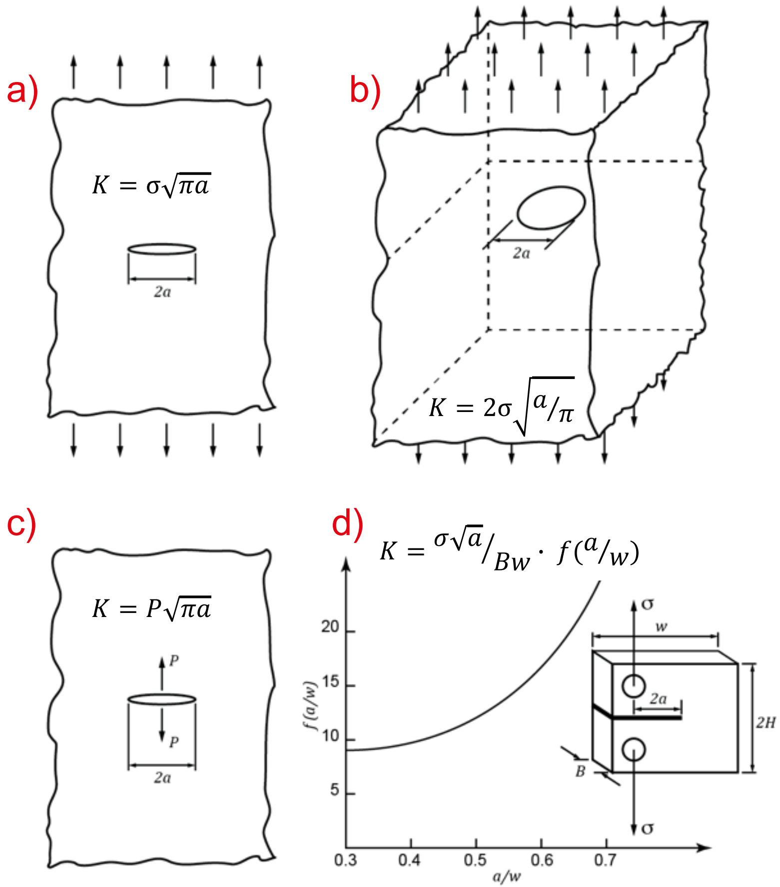
    $\sigma_{max}, \sigma_{min}$ max, resp. min nominal stress



Ref: R.M.N. Pelloux, Trans. ASM, Vol 62, 1969, p. 281-285

Crack growth

- Effect of the defect geometry the **stress-intensity factor *K***:
  a) Through crack
  b) Embedded crack
  c) Crack growth through internal pressure
  d) Off-center load



Note: Geometry function f :

$$\left(\frac{da}{dN}\right)_{R,\nu} = f(\text{geometry}, a, \Delta\sigma, \text{configuration})$$

Where R: load ratio $R = \frac{\sigma_{min}}{\sigma_{max}}$

ν: cyclic frequency

Crack growth

Fatigue fracture:

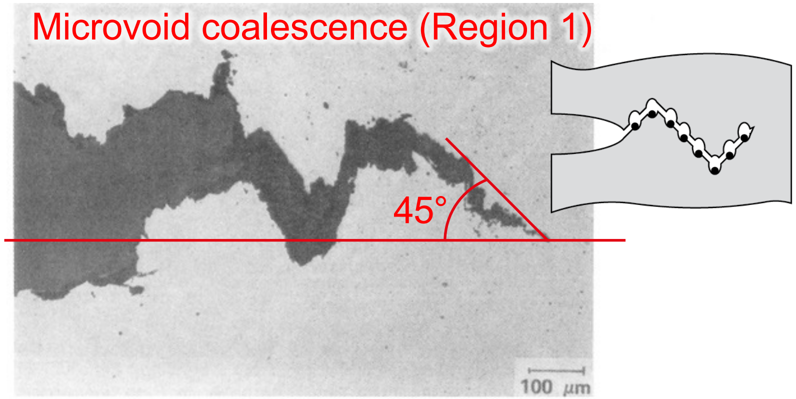
- Cyclic stresses
- Tensile stress
- Plastic deformation

Cyclic stress → Plastic deformation → Crack initiation

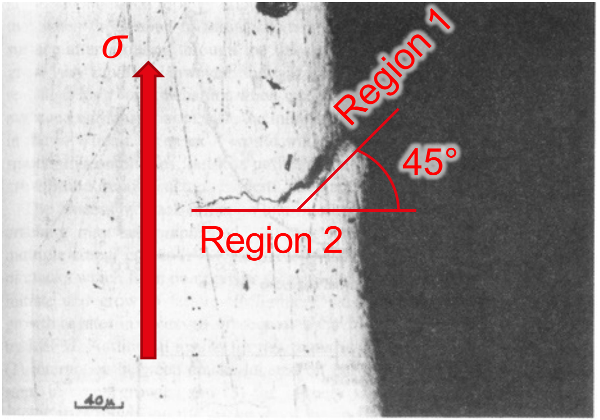
Tensile stress → Crack propagation

Crack growth

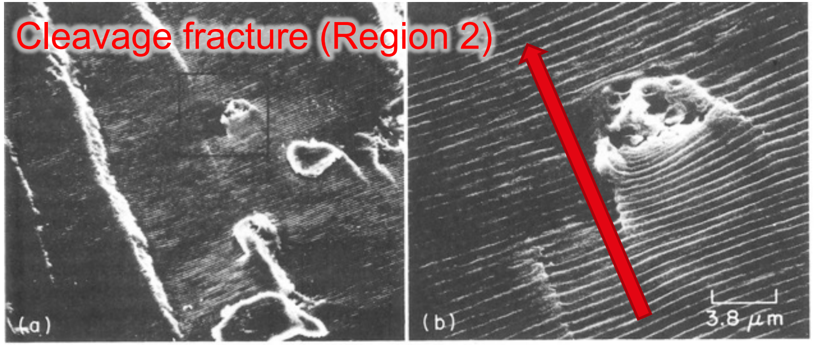
Crack growths: plastic flow and atomic plan cleavage



Ductile crack growth in a high-strength low-alloy steel (A 710). The zig-zag crack growth results from void initiation and growth on the plane of maximum strain



Cross section through a crack that initiates on the maximum shear plane and grows as a stage I fatigue crack until it rotates normal to the maximum tensile stress range and becomes a stage II fatigue crack

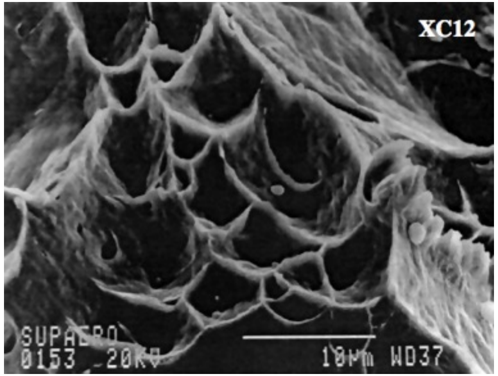


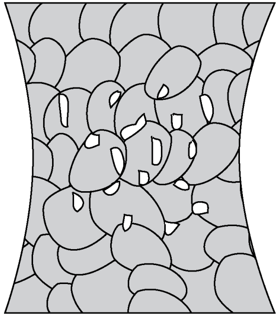
Uniformly distributed fatigue striations in an aluminum 2024-T3 alloy. (a) Tear ridge and inclusion (outlined by rectangle). (b) Higher-magnification view of the region outlined by the rectangle in (a), showing the continuity of the fracture path through and around the inclusion

Source: Fatigue and fractures, ASM Handbook Vol. 19, 1996, pp 42-60

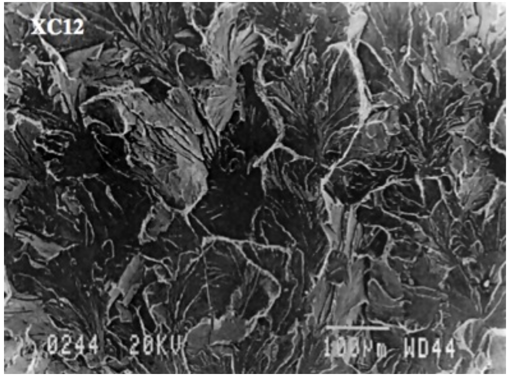
Types of fracture

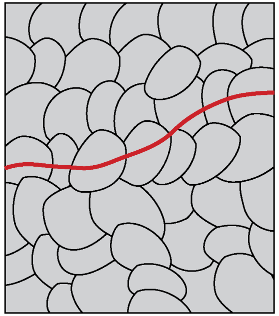
Ductile fracture
(by microvoid coalescence)



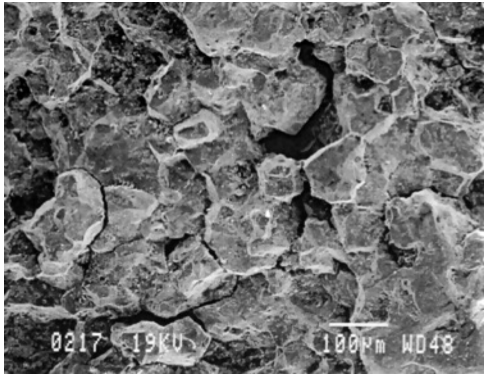


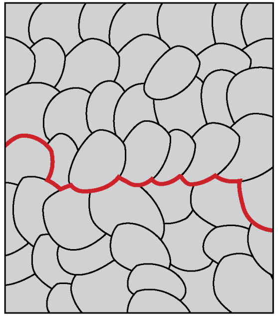
Cleavage fracture





Intergranular fracture





Source of photos: IMT, École des Mines d'Albi-Carmaux

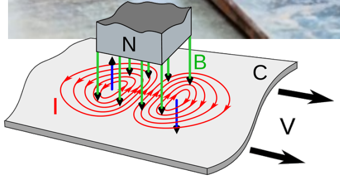
Mechanical Properties – Fracture Control

Space engineering - Fracture control
ECSS-E-ST-32-01C Rev. 1

- Non Destructive Testing Methods
  - **Magnetic Particle Testing (MT)**
  - **Liquid Penetrant Testing (PT)**
  - **Radiographic Testing (RT)**
  - **Ultrasonic Testing (UT)**
  - **Electromagnetic Testing (ET)**
  - **Visual Testing (VT)**
  - Acoustic Emission Testing (AE)
  - Laser Testing Methods (LM)
  - Leak Testing (LT)
  - Magnetic Flux Leakage (MFL)
  - Neutron Radiographic Testing (NR)
  - Thermal/Infrared Testing (IR)
  - Vibration Analysis (VA)

Source: Superior Joining Technologies, Inc.

Source: N_Sakarin/Shutterstock.com



Source: Werner Sölken/wermac.org

Initial crack size detection depends on the selected NDT method
Must be taken into account when designing!

See: https://asnt.org/MajorSiteSections/About/Introduction_to_Nondestructive_Testing.aspx

Mechanical Properties: Fatigue Analysis Tools

ESA’s crack growth analysis tool:

- **ESACRACK package + NASGRO package**
  - https://www.esacrack.net
  - to generate load and stress spectra from load curves associated to events
  - to perform fatigue analysis. It contains fatigue materials database
  - analyze fatigue crack propagation and fracture mechanics for performing assessments of structural life
  - process and store fatigue crack growth properties
  - analyze fatigue crack formation (initiation)
  - compute stresses and stress intensity factors

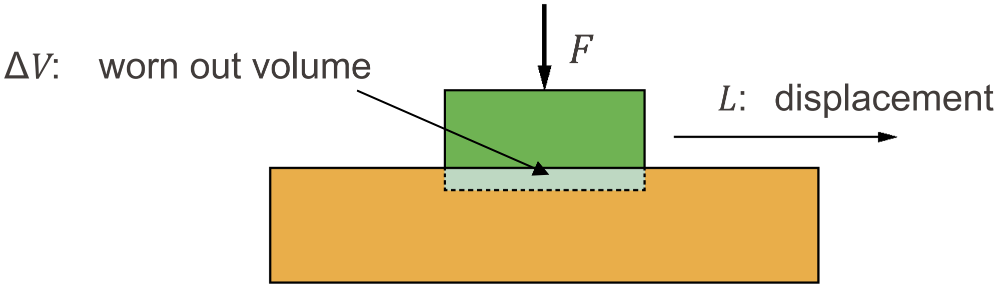
  - Runs under MS Windows.

Mechanical Properties

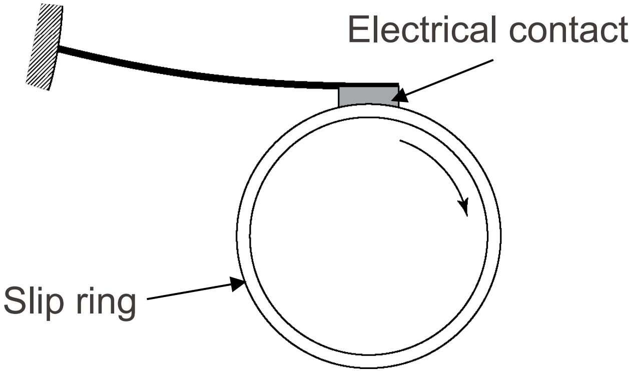
- **Wear resistance**

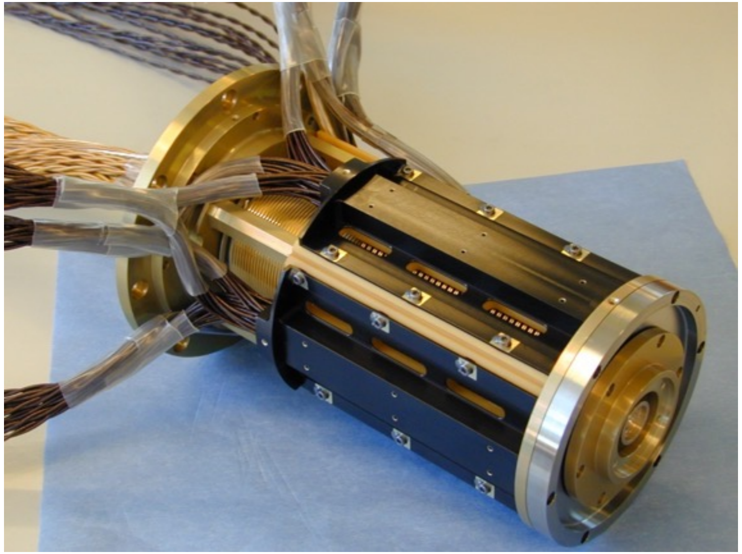
$$\Delta V = k \cdot F \cdot L$$

k: wear coefficient



- Application: electrical contact





Source: Ruag Space

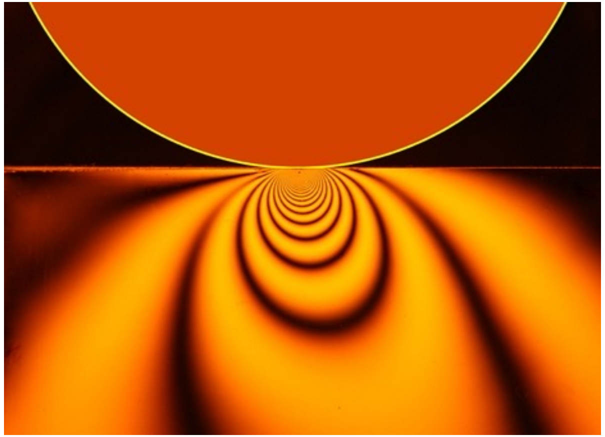
Mechanical Properties

- **Wear**
  - Highly non-linear function of:
    - Materials in contact
      - Wear and friction coefficients: often corelated, but no simple relation between both those values
  - Chemical environment
    - Large variation of the friction in air or in vacuum
      - Example: graphite
  - Temperature
  - Speed of the friction
  - Surface roughness
  - Local pressure

  - The local pressure is characterized through the Hertz Pressure
    - Ball bearings
    - Bolted assemblies
    - Moving parts in friction
    - Hard coating of surfaces

Mechanical Properties

▪ Hertz Pressure: solids into contact



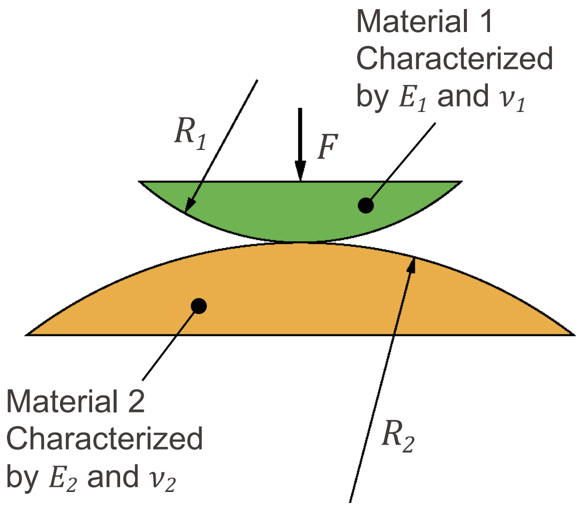
Source: Wikimedia/Reibungsphysik

Surfaces in contact encompass separable and sliding contacts, and bearings [ECSS-E-ST-33-01C Rev.2]

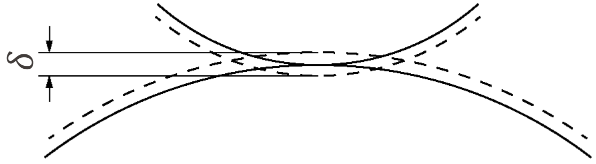
- Assumptions
  - The **strains are small** and within the elastic limit.
  - The surfaces are **continuous and non-conforming.** This implies that the area of contact is much smaller than the characteristic dimensions of the contacting bodies.
  - Each body can be considered an **elastic half-space**.
  - The surfaces are **frictionless**.

Mechanical Properties

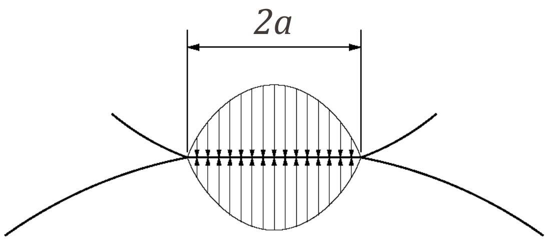
▪ Hertz Pressure



E: Elastic modulus
ν: Poisson's ratio

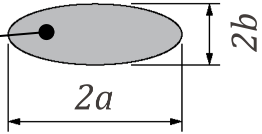


Before loading



After loading

Contact area (ellipse)
a and b acc. to the curvature radius of the solids in contact



The size of the contact ellipse as well as of the normal approach δ of **two ellipsoids** are calculated through the Hertzian theory.

<u>Hertz Pressure</u>

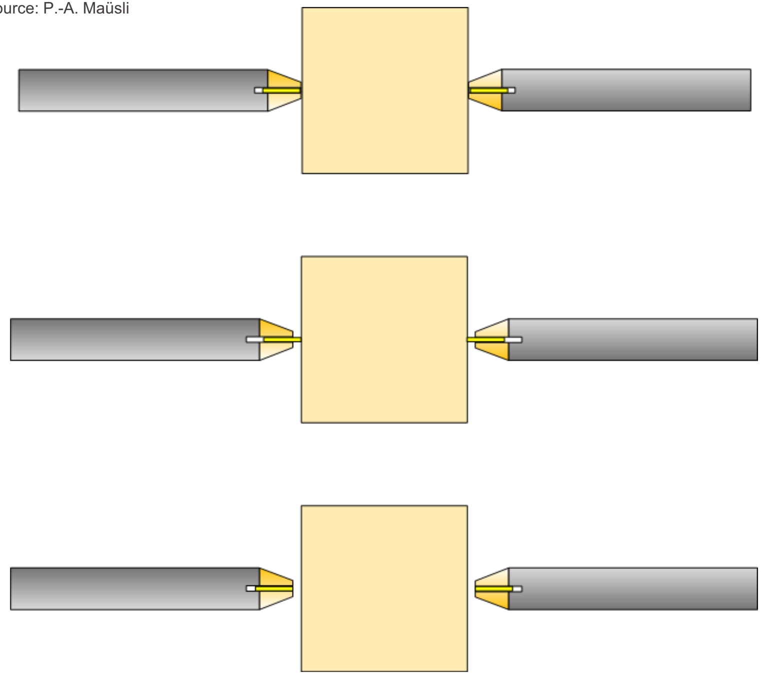
Maximum: $$\boldsymbol{P_{H\,max}} = \frac{3 \cdot F}{2 \cdot \pi \cdot a \cdot b}$$

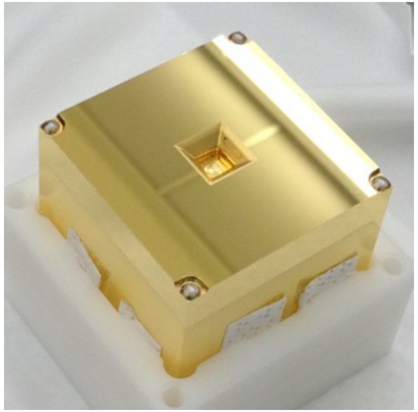
Average: $$P_{H\,avg} = \frac{2}{3} P_{H\,max}$$

Mechanical Properties

- Grabbing, Position and Release Mechanism (GPRM) of LISA Pathfinder

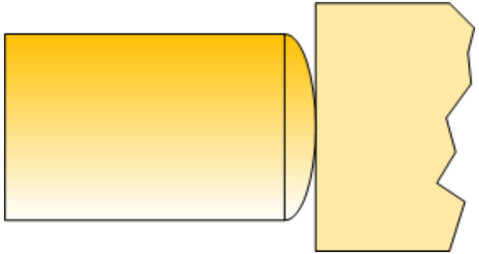
Source: P.-A. Maüsli





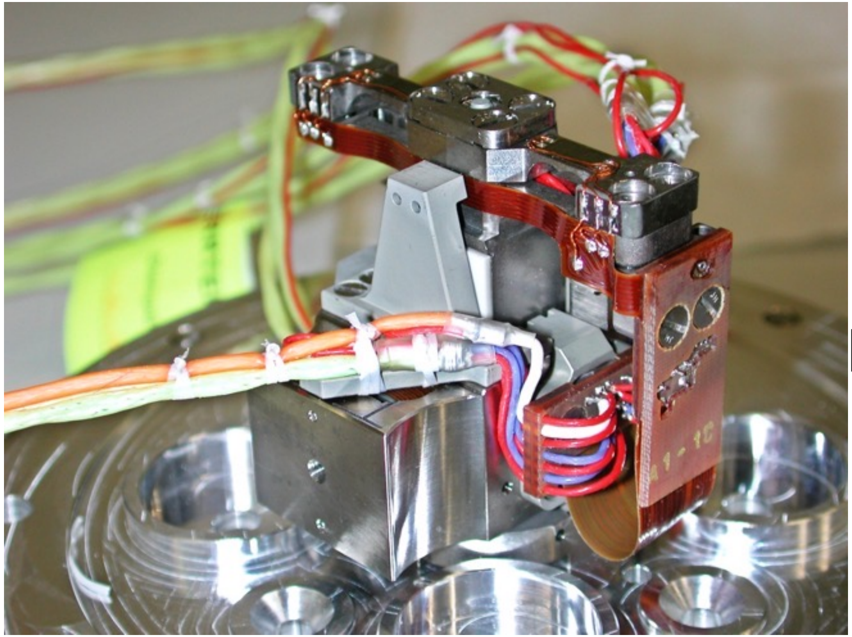
Source: CGS Spa/ESA

Source: ESA/ATG medialab

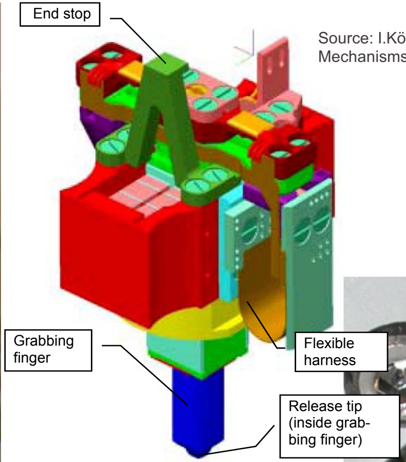


Mechanical Properties

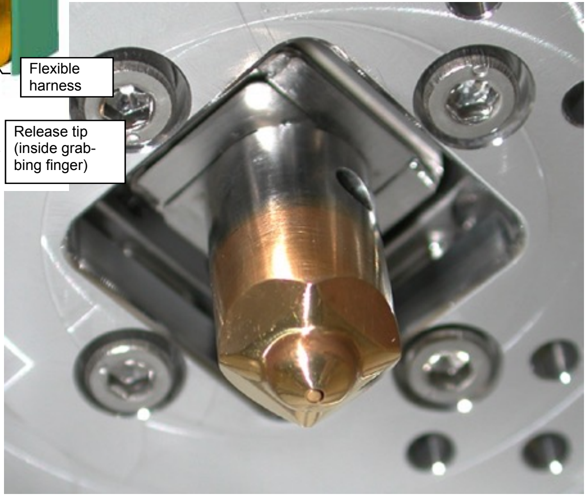
- Grabbing, Position and Release Mechanism (GPRM) of LISA Pathfinder



Source: RUAG Space/P.-A. Maüsli



Source: I.Köker et al., Proceedings of the 15th European Space Mechanisms and Tribology Symposium (ESMATS 2013)



Source: RUAG Space/P.-A. Maüsli

Mechanical Properties - Friction

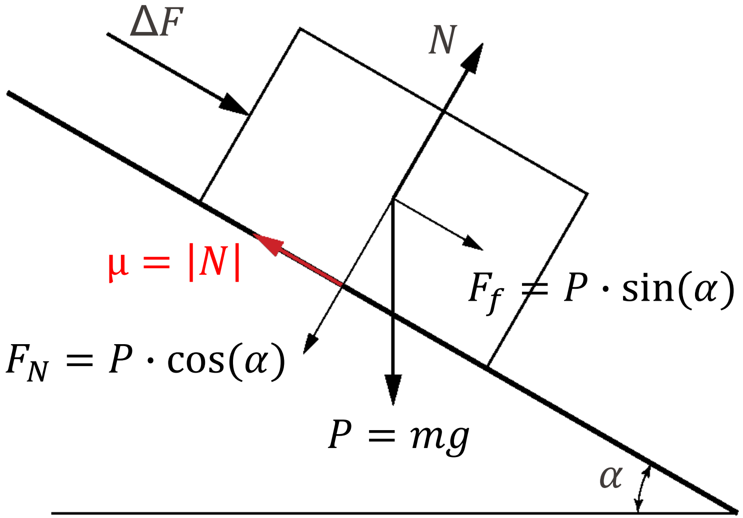
- **Friction**: the force resisting to sliding
- Friction coefficient μ:

$$F_f = \mu \cdot F_N$$

- Sliding condition:

$\mu_s = \mathrm{tg}(\alpha)$ μ_s : static coefficient of friction

- Types of friction
  - Sliding
  - Rolling
  - Fretting
  - Dry vs. Lubricated
  - Effects of the vacuum, the temperature and the pressure: sudden change of the friction regimes



Mechanical Properties - Friction

- Usual behavior of the friction depending on:
  - Pressure (normal to the contact surface)
    - At low pressure: μ nearly constant (independent of the apparent area of contact. Friction depends only on the normal force).
    - At intermediate pressure: little increase of μ (effect of surface roughness).
    - At high pressure: rapid increase of μ that can lead to seizure (cold welding).
  - Sliding speed
    - Dry
      - At low speed: very little dependency of μ wrt speed (starting friction).
      - At intermediate speed: μ tends to decrease.
      - At high speed: possibility of jamming (increase of the contact temperature).
    - Lubricated
      - At low speed: μ is about proportional to the speed.
      - At high pressure: μ starts to decrease with the speed (kinematic regime), then increase with v^2 (dynamic regime).
  - Temperature
    - Large effect on the lubrication regimes.
  - Environment
    - Under air: highly dependent on the humidity for certain materials (e.g. graphite).

Thermal Properties

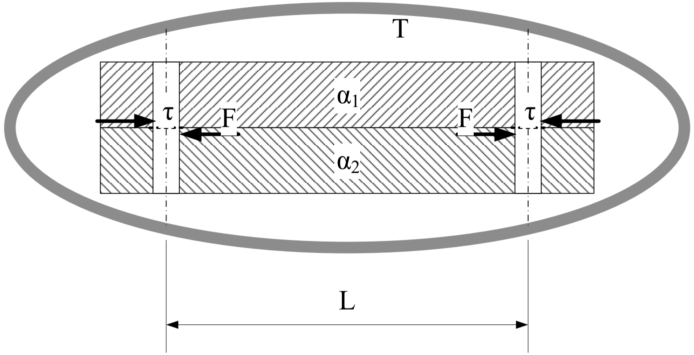
- Thermal expansion coefficient α [1/°C]
  - Key property for proper operations of space mechanisms
- Creep
  - Plastic deformation (e.g. loss of bolt preload)
  - Activated by a temperature increase
- Thermal conduction
- Specific heat
- Reflectivity, transmissivity, emissivity, absorptivity
- Phase transitions
  - Transition temperatures (liquidus, change of crystal state)
  - Stability of the phase towards temperature
  - Diffusion, segregation

Thermal Expansion

- Linear approximation

  $$l(T) = l_0 \cdot (1 + \alpha(T - T_0))$$

  - With
    - α: thermal expansion coefficient
    - $l(T)$: characteristic length of a part at temperature T
    - l_0: characteristic length (same part) at reference temperature T_0



- Bimetal effect
  - Force F:
    - Depends on both materials (α_1, α_2)
    - Does not depend on L

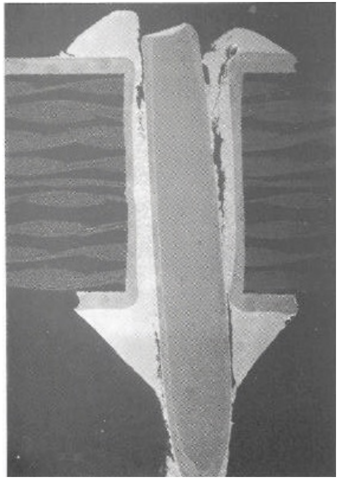
      ⇒ the shear stress depends only on the difference between both thermal expansion coefficients (α_1 - α_2)

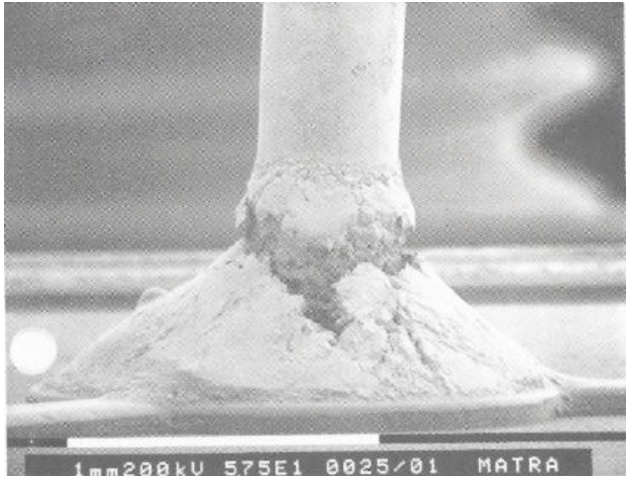
Thermal Expansion

Example:

Fatigue of thermally cycled solders

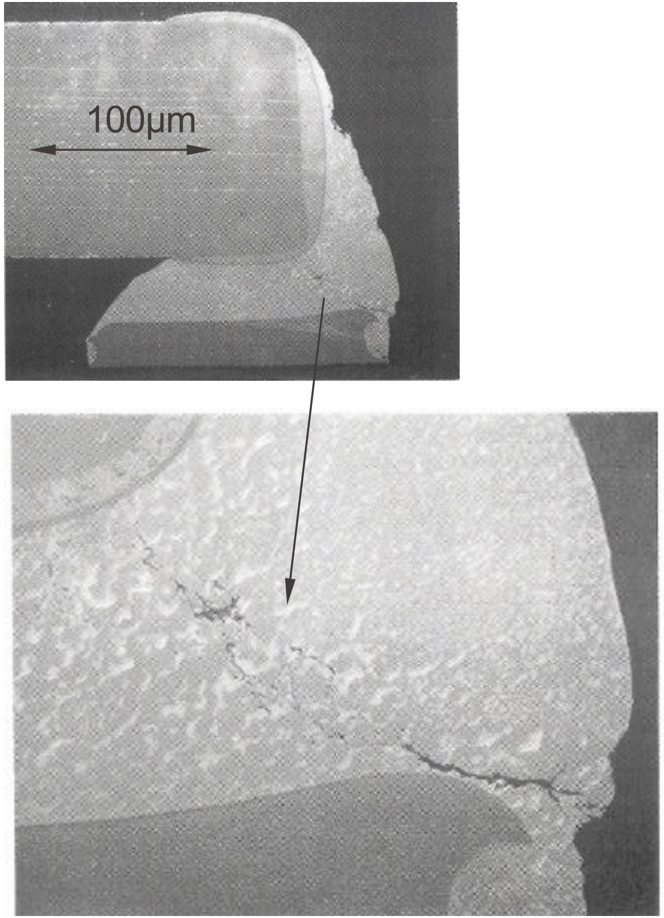
- Shear stresses at the interfaces
- Combined stresses (tensile/shear) in the solder
- Differential thermal expansion of the material outside of the elastic domain
  - Fatigue
  - Initiation of crack
  - Crack growth
  - Fracture

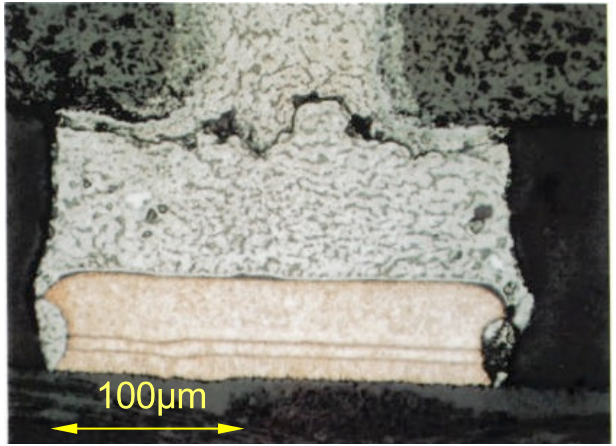


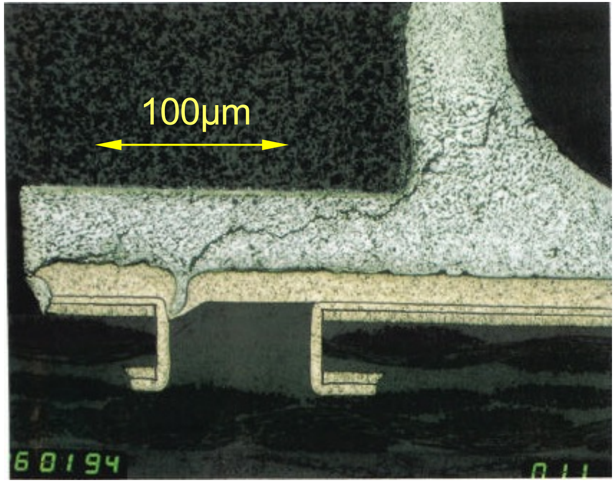


Source: D.B. Dunn, P. Desplat, “Evaluation of conformal coatings for future spacecraft applications”, ESA SP-1173, août 1994

Thermal Expansion







Source: D.B. Dunn, P. Desplat, "Evaluation of conformal coatings for future spacecraft applications", ESA SP-1173, août 1994

Thermal Expansion

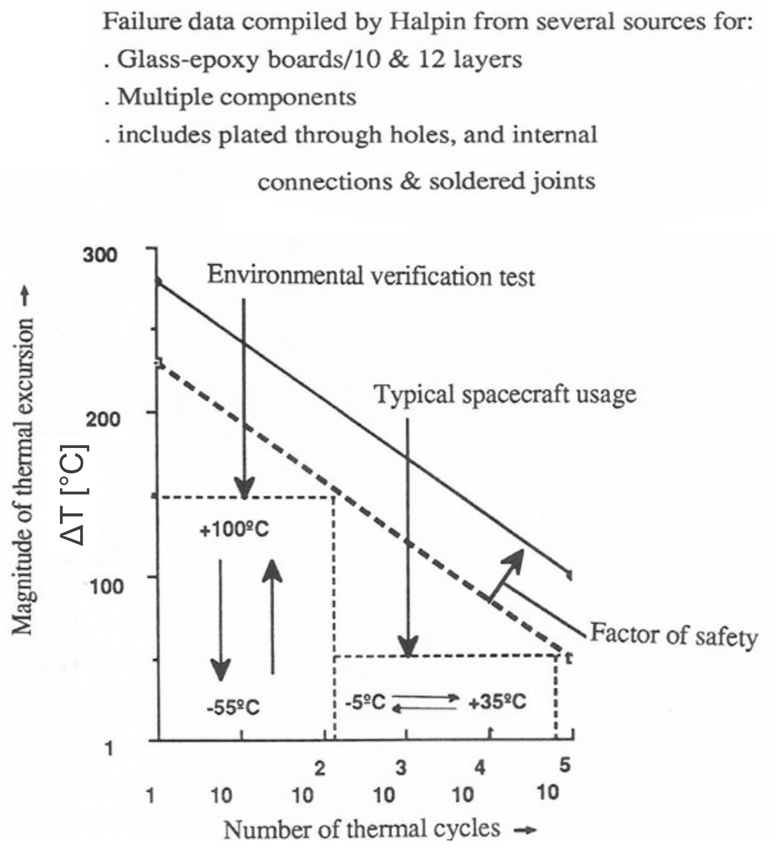
Example:

Fatigue of thermally cycled solders

- The thermal range defines the amplitude of the stresses
- The cracks are growing after each thermal cycle

▪ Qualification testing of the solder

- Typically 200 thermal cycles
- Temperature range: -55°C to +100°C
- Accelerated test:
  - Increase of the temperature range amplitude
    - ⇒ Reduction of the number of thermal cycles



Source: J.C. Halpin, Proc. Of 31st Annual Tech. Meeting of Inst. of Environmental Science, Las Vegas, April 30-May 2, 1985, pp. 206-218

Theme 4 – Part 1 Summary

- Mechanical Properties:
  - Strength
    - Hooke's Law
    - Ultimate and Yield Strength
  - Fatigue strength
    - Stress-intensity factor
    - Three regions of crack growth
    - Crack initiation (material, size of defect, geometry, environment, loads)
  - Wear
  - Hertz Pressure
  - Friction
  - Thermomechanical effects
    - Thermal expansion
    - Fatigue

Next week

- Theme 4 – Part 2: Materials, continued

- Exercises 4.1, 4.2
- Mini Project part 1 Understanding of Technical Requirements (cf. EE580_MP1_2025_v1 Statement.pdf)