Co-funded by the Erasmus+ Programme of the European Union

Lecture 3B

Fracture and Failure mechanisms of Metals and Alloys

Dr Adeayo Sotayo

Thursday 19th November 2020

Got a question ?

Please use the **"chat"** or **"raise your hand"** functions

Why *study the fracture and failure mechanisms of metals and alloys*

- It is important for engineers and designers to understand:
  - Different failure modes (e.g. fracture, fatigue and creep)
  - How to design components and structures to reduce the possibility of failure
  - How to apply appropriate design principles to prevent in-service failures

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Outline

- Fracture
- Fatigue
- Creep

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Learning Outcomes

- Describe the concept of crack propagation for **ductile** and **brittle modes of fracture** in metals and alloys

- Define **fatigue** and specify the conditions under which it occurs in metals and alloys

- Explain **creep** and specify the conditions under which it occurs in metals and alloys

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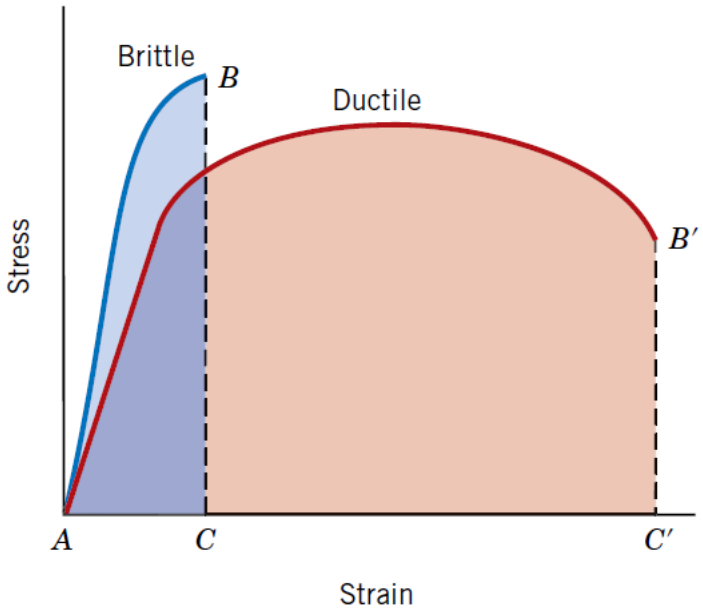
Fracture

- Fracture - separation into two or more pieces in response to an applied stress
- Two major fracture modes of Metals : **Ductile** and **Brittle**
- **Ductile fracture**
  - Substantial plastic deformation with high energy absorption before fracture
- **Brittle fracture**
  - Little or no plastic deformation with low energy absorption before fracture



Callister and Rethwisch (2013)

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Fracture

Ductile fracture

Cup-and-cone fracture in aluminium
(after extensive plastic deformation)

Brittle fracture

Brittle fracture in a mild steel
(rapid crack propagation)

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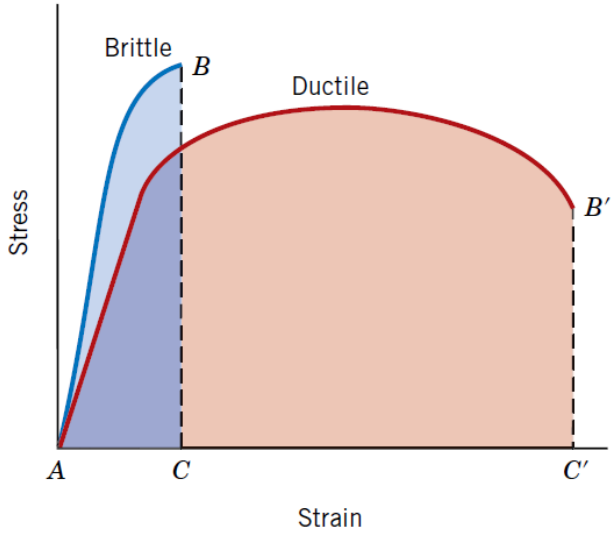
Fracture

Ductile fracture is typically preferred to **Brittle fracture**

- **Ductile fracture** gives warning that failure is imminent, allowing preventive measures to be taken
- For **ductile fracture**, more strain energy is required
- **Brittle fracture** occurs <u>suddenly</u> and <u>catastrophically</u> without any warning



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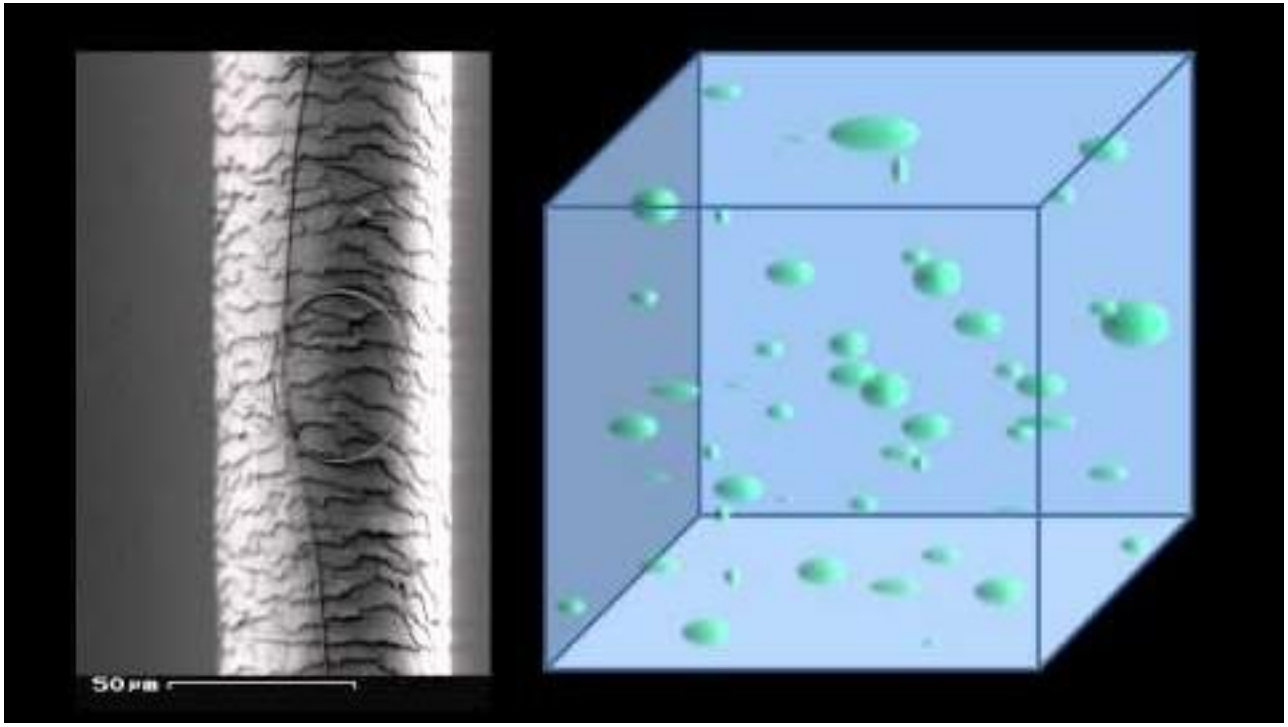
Fracture



How and When Metals Fail - https://youtu.be/EeiwCbtJWyI

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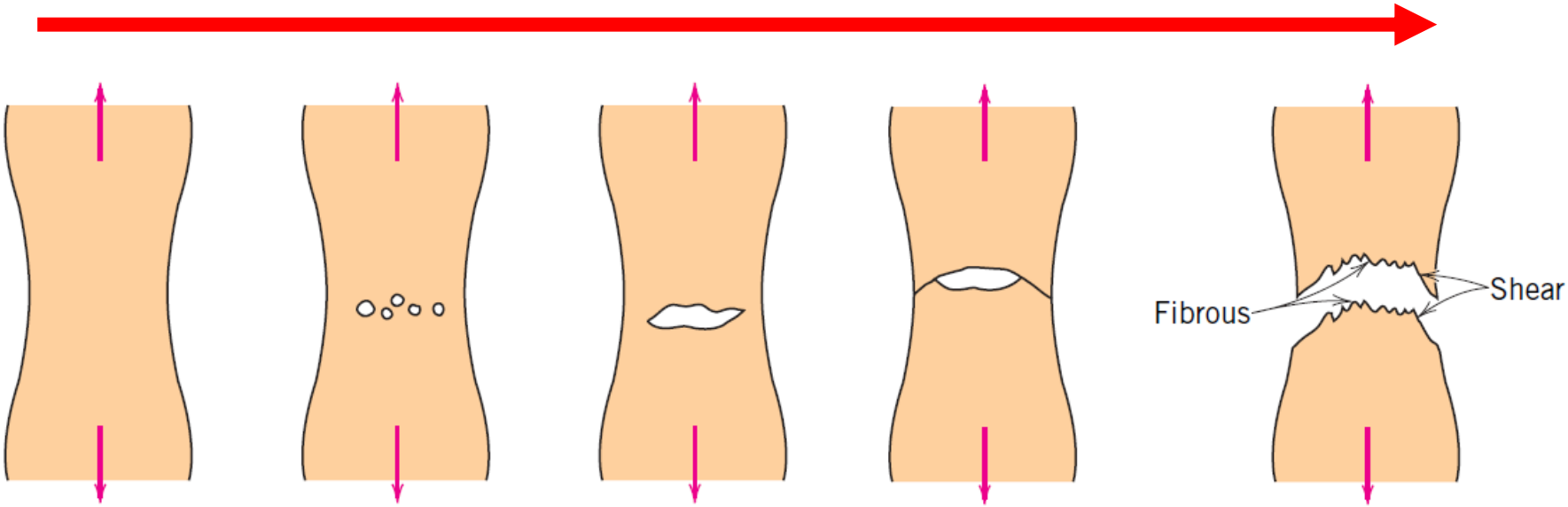
Fracture

Stages of the cup-and-cone fracture (ductile fracture)



Initial necking

Small voids/cavity formation

Merging of cavities form a crack

Crack propagation

Final fracture

Callister and Rethwisch (2013)

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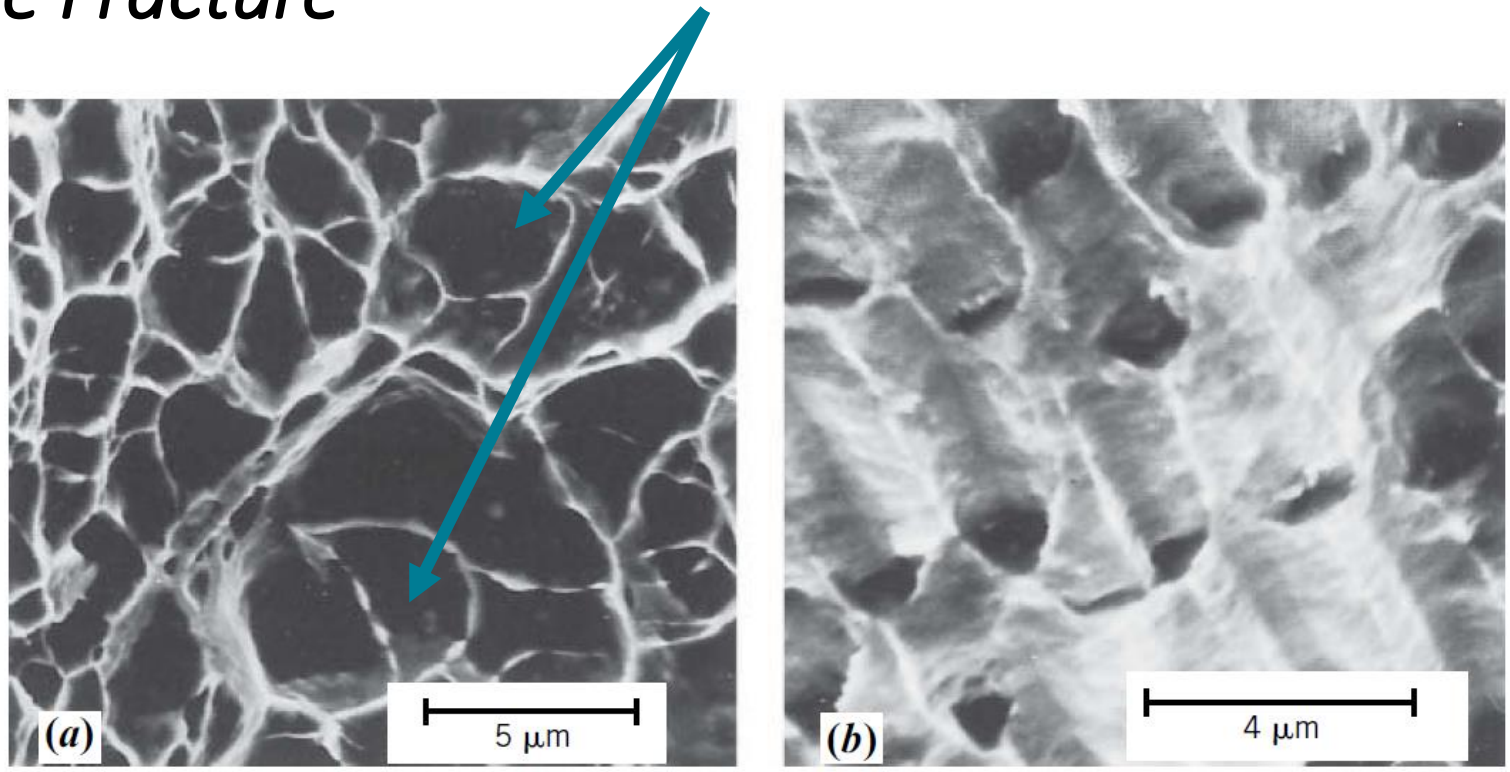
Ductile Fracture



Callister and Rethwisch (2013)

Scanning Electron Microscopy (SEM) showing ductile fracture

Spherical “dimples” correspond to microvoids that initiate crack formation

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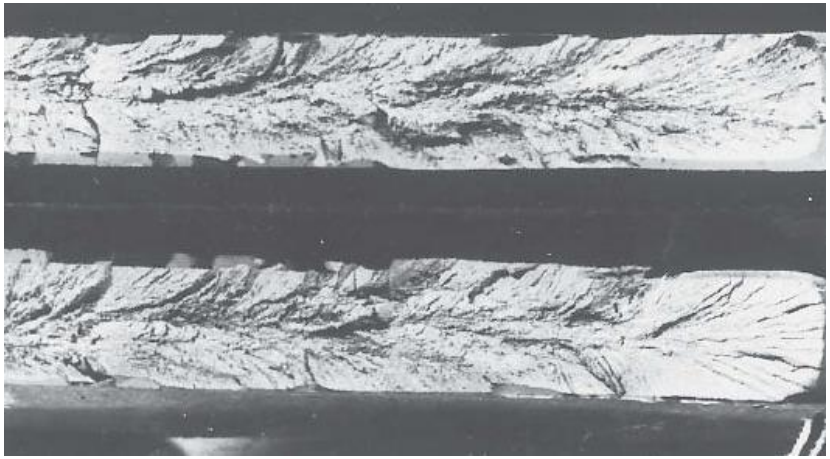
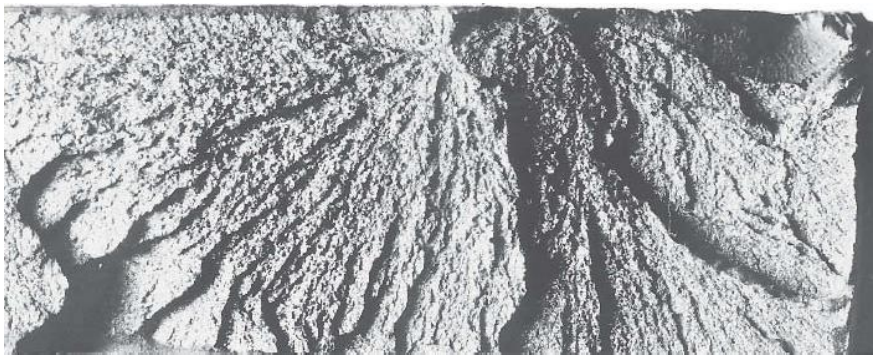
Brittle Fracture





Callister and Rethwisch (2013)

- Crack propagation is very fast
- Little or no plastic deformation
- Crack propagates almost perpendicular to the direction of the applied stress

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Fatigue

- **Fatigue** means **failure** due to **repeated** **(cyclic)**

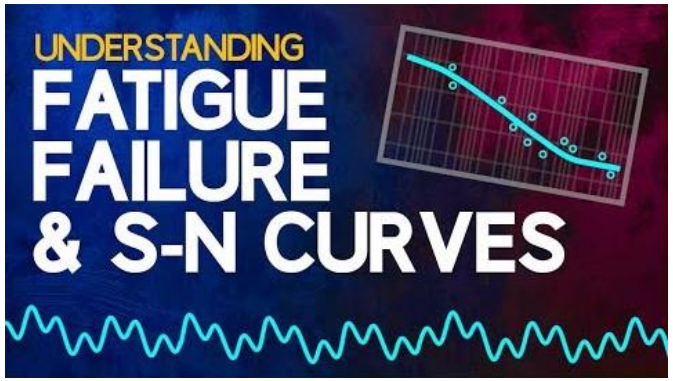
  stresses or strains

- Fatigue may occur lower than the tensile or yield

  strength of the material under a static load

- Causes ~ **90%** of all **metallic failures**

- Brittle failure, sudden and catastrophic



Animation of fatigue -
https://youtu.be/o-6V_JoRX1g

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Fatigue


Cracks in bicycle frame


Helical gear


Spring


Steering arm


Pedal


Stub axle


Bolt


Shaft - torsion

Engineering Insider (2018) https://engineeringinsider.org/prevent-fatigue-failure/

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Fatigue

Fuselage damage caused by **metal fatigue** to Aloha Airlines Boeing 737 aircraft in 1988 (65 injured, 1 death)

Airways mag (2020) https://airwaysmag.com/airlines/32-years-aloha-flight-243-accident/

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Fatigue

Damaged engine caused by **metal fatigue** to Air France Airbus A380 plane in 2017

LSP Technologies (2020) https://www.lsptechnologies.com/resources/metal-fatigue-in-aircraft/

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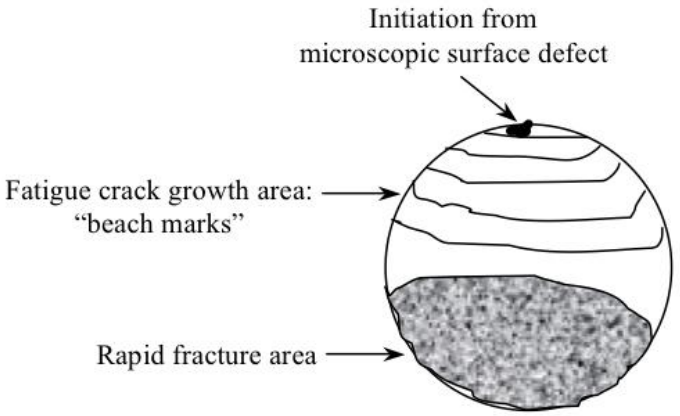
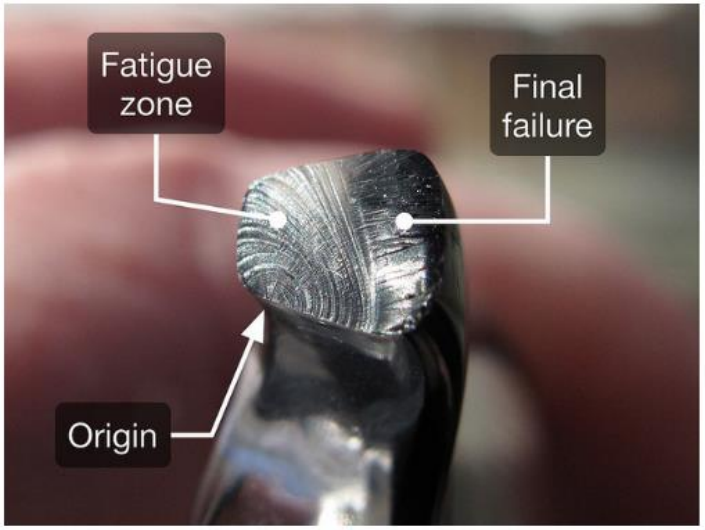
Fatigue (Three main stages)

- **Crack initiation**
  - Point of stress concentration (e.g. corners, scratches)
  - Surface quality is important
- **Crack propagation**
  - Crack grows with each stress cycle
- **Final failure**
  - Rapid failure





Fatigue Life LLC (2020) https://fatigue-life.com/fatigue-physics/

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Quiz time *– A cup-and-cone fracture occurs in what type of fracture?*

Website – Sli.do

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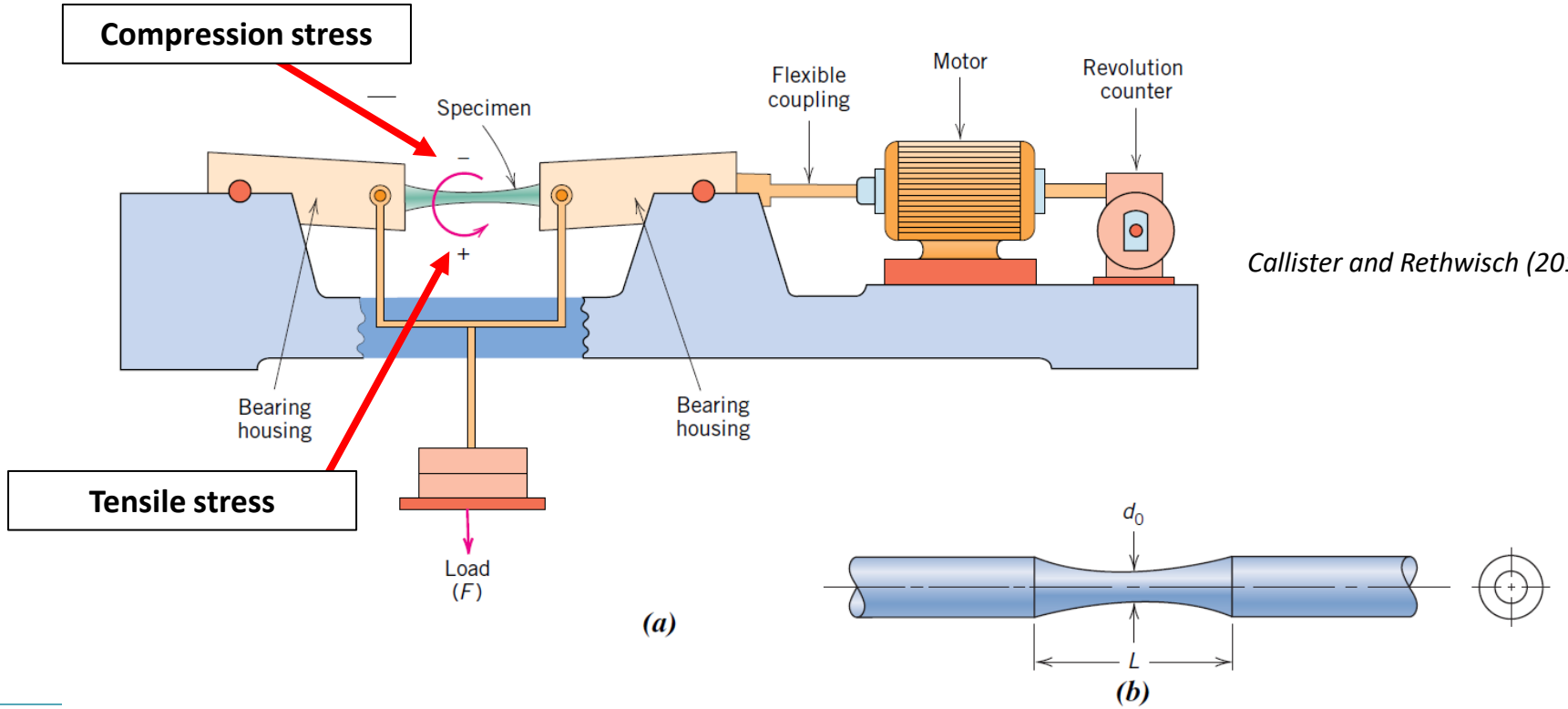
Fatigue tests

- **Rotating–bending fatigue test:** alternating tensile and compression stresses
- Stress cycling to replicate possible in-service stress conditions



Callister and Rethwisch (2013)

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Fatigue tests (Put in context)

Fatigue Test of Aluminum Sample - https://youtu.be/hASl6d3z3BM

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Fatigue tests (S – N curves)

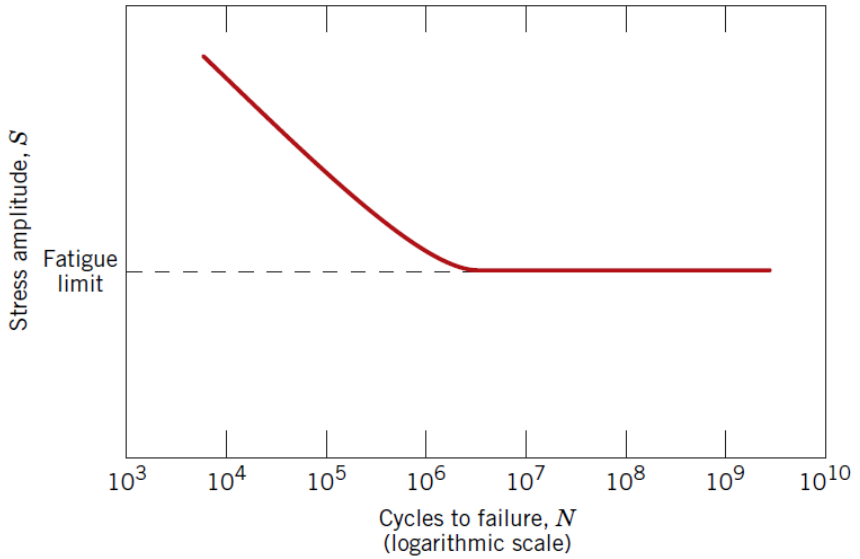
- **Stress amplitude (S)** versus **Number of cycles (N)** to fatigue failure

- **Fatigue Limit** - largest stress that will not cause failure for essentially an infinite number of cycles

- Examples include **Ferrous and Titanium alloys**
  - Steel
  - Titanium Ti-6Al-4V Alloy

- S – N curve becomes flatter at cycles

- For Steel, **Fatigue limit** ranges between 35% and 60% of the tensile strength



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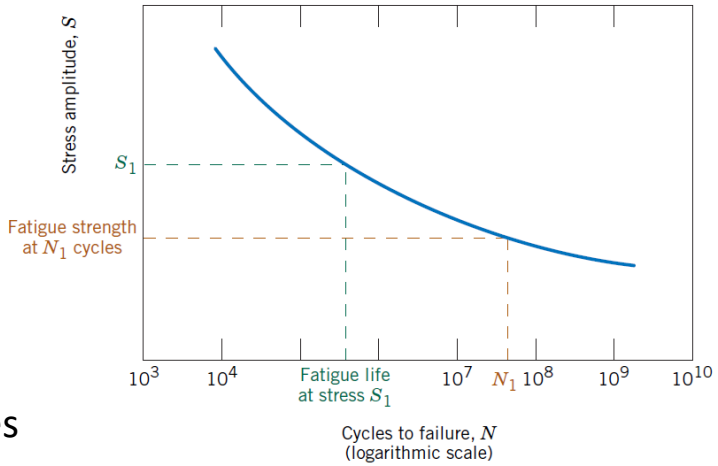
Fatigue tests (S – N curves)

Callister and Rethwisch (2013)

- Most nonferrous alloys do not have a fatigue limit, e.g.
  - Aluminium
  - Copper



- S–N curve continues a downward trend at greater N values

- Fatigue will ultimately occur (regardless of stress magnitude)

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Fatigue tests (S – N curves)

- **Stress amplitude (S)** versus **Number of cycles (N)**

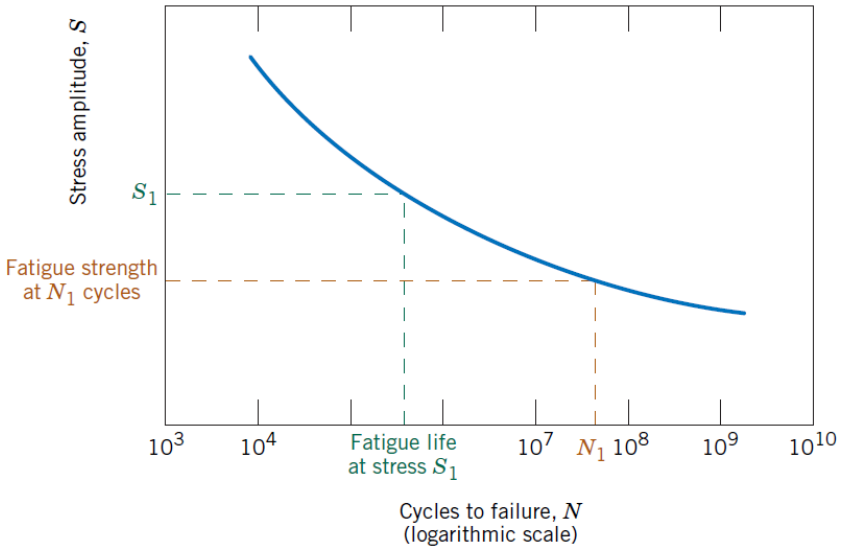
  to fatigue failure

- **Fatigue strength:** stress at which fracture occurs

  after a specified number of cycles

- **Fatigue life:** Number of cycles to fail at a specified

  stress level



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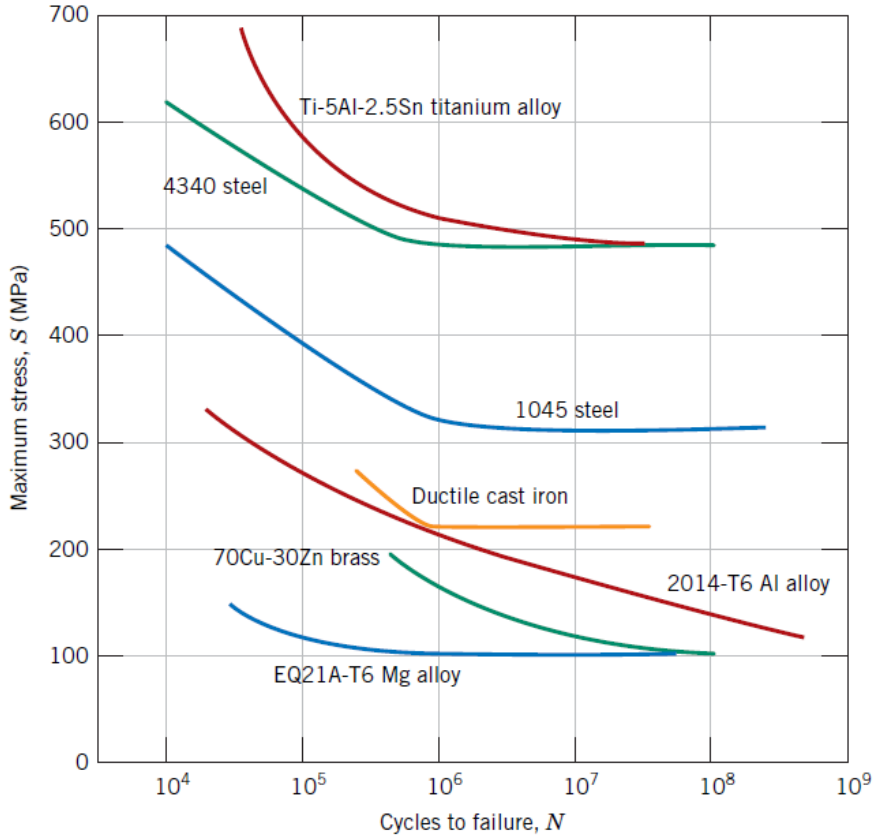
Fatigue tests (S – N curves)

- **Metals with Fatigue limits**
  - Titanium alloy
  - Magnesium alloy
  - Steel alloy
  - Cast iron
- **Metals without Fatigue limits**
  - Brass
  - Aluminium alloy



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Quiz time *– How can we reduce the likelihood of fatigue in metals and alloys ?*

Website – Sli.do

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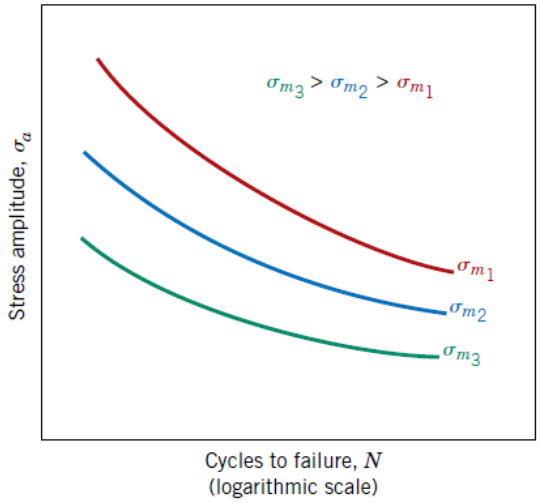
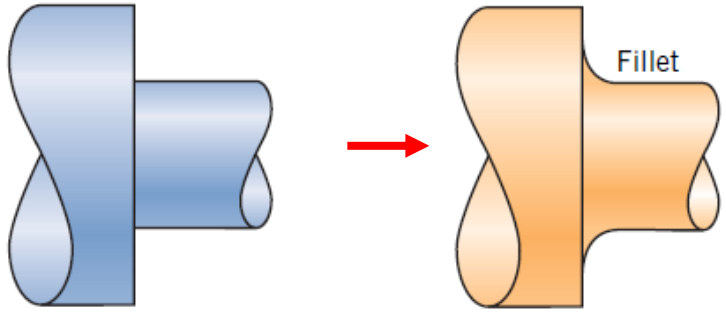
Factors that affect fatigue

- **Stress magnitude**
  - ➢ increasing the mean stress level leads to a decrease in fatigue life



Callister and Rethwisch (2013)

- **Surface quality (corners, scratches)**
  - ➢ Optimised design - fatigue lifetime can be improved by incorporating a rounded fillet
  - ➢ Polishing (removes machining flaws etc.)



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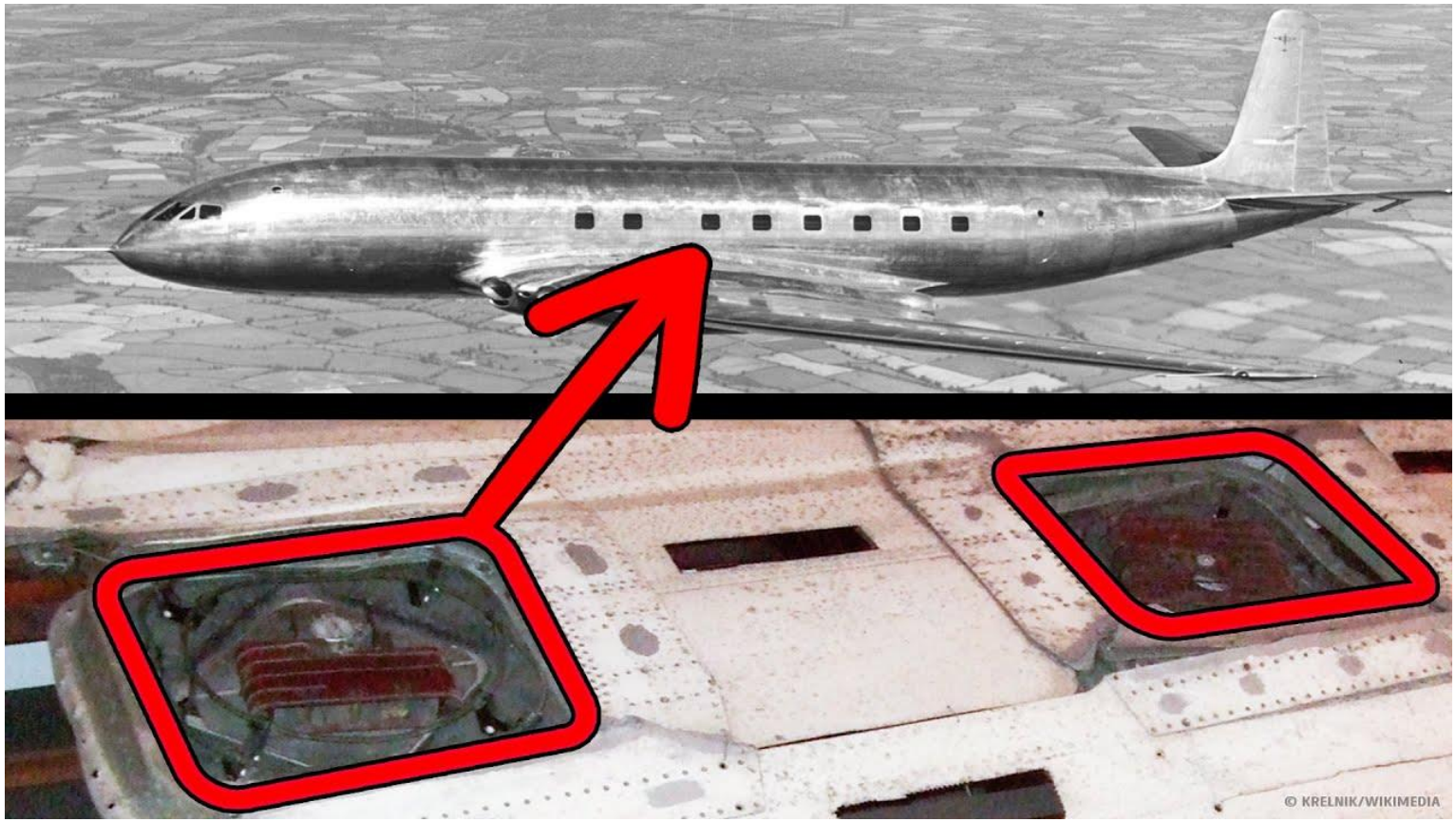
Factors that affect fatigue (Case study)



BOAC Flight 781 in 1954 - de Havilland Comet – Source - https://youtu.be/rfSycoKU6xA

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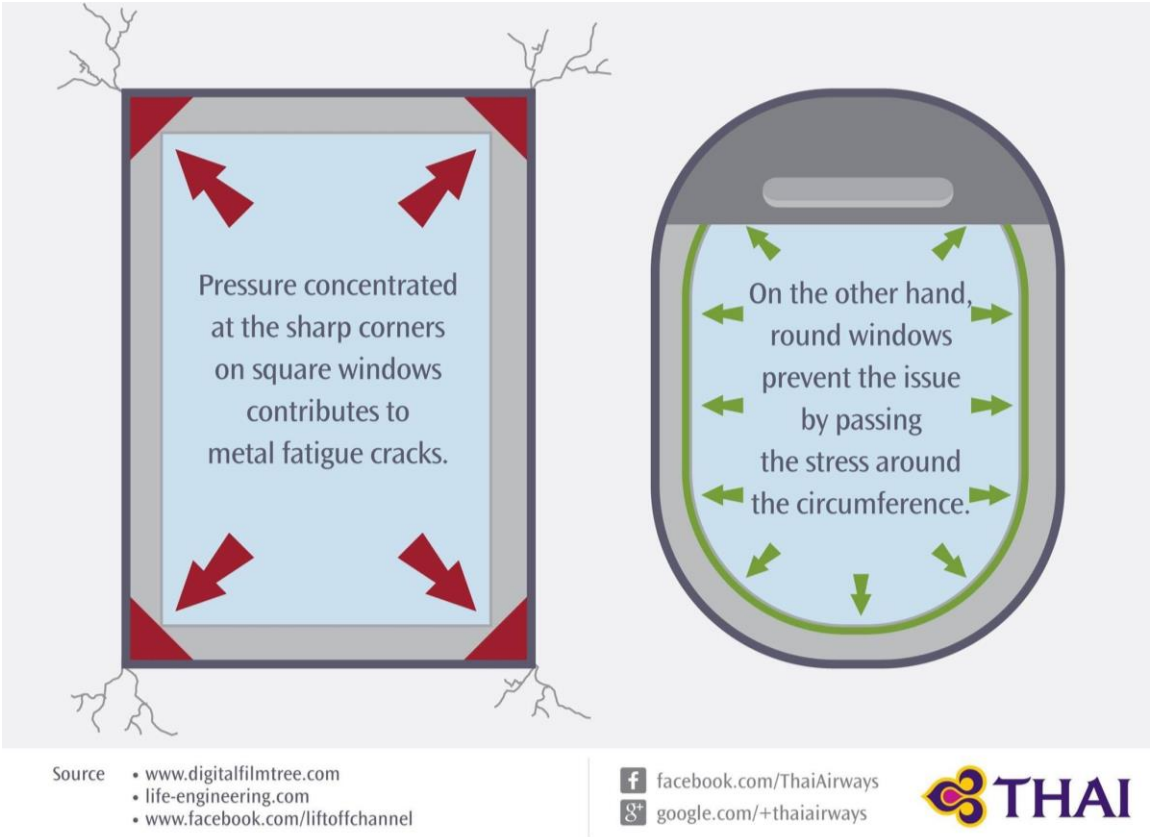
Factors that affect fatigue (Case study)



Source – Thai Airways Twitter - https://twitter.com/ThaiAirways/status/448779233934864384/photo/1

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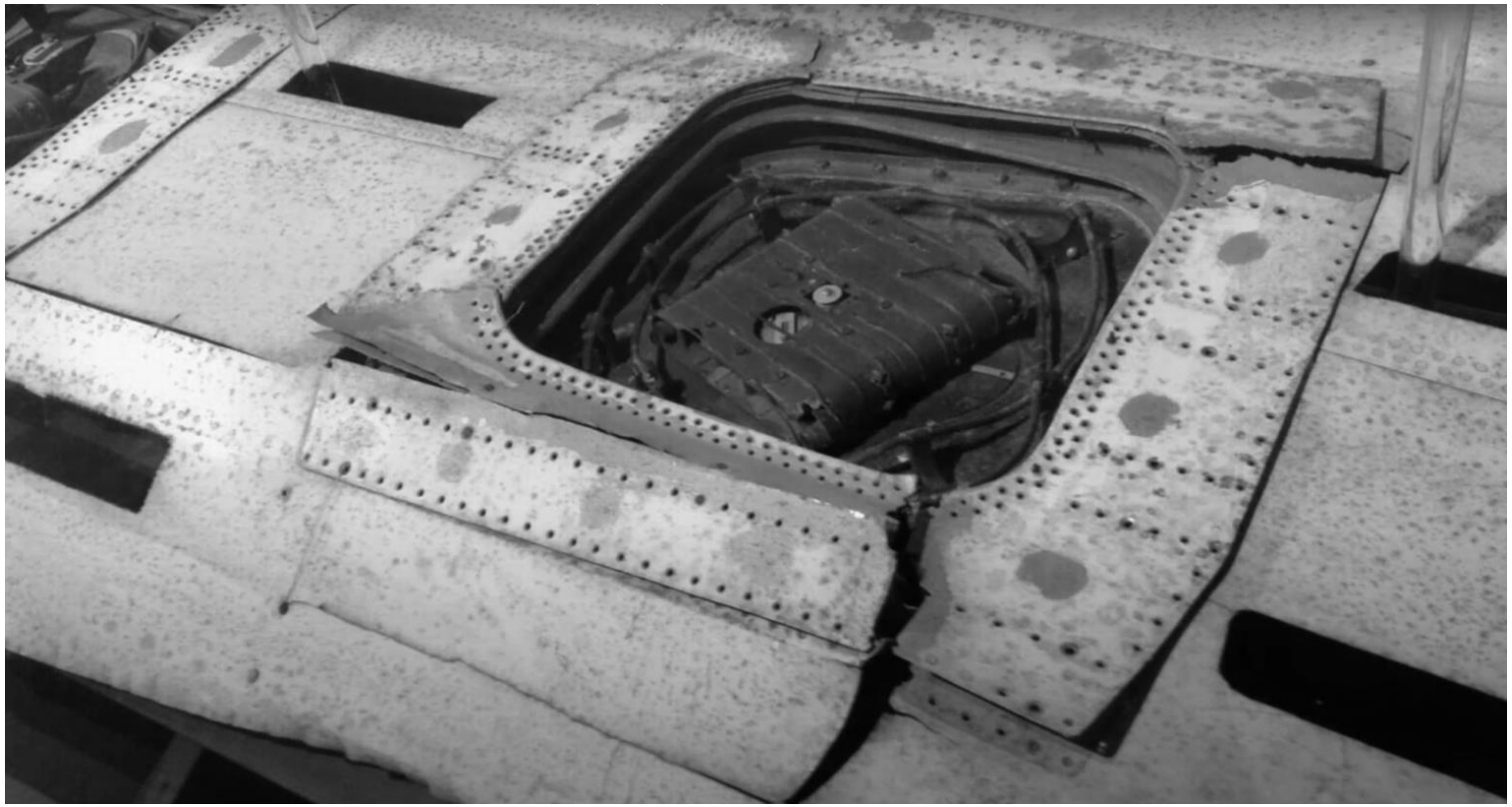
Factors that affect fatigue (Case study)



BOAC Flight 781 in 1954 - de Havilland Comet – Catastrophic failure mid air (deaths)

Source – Robert DuHamel - https://youtu.be/2rvx-r2itrE

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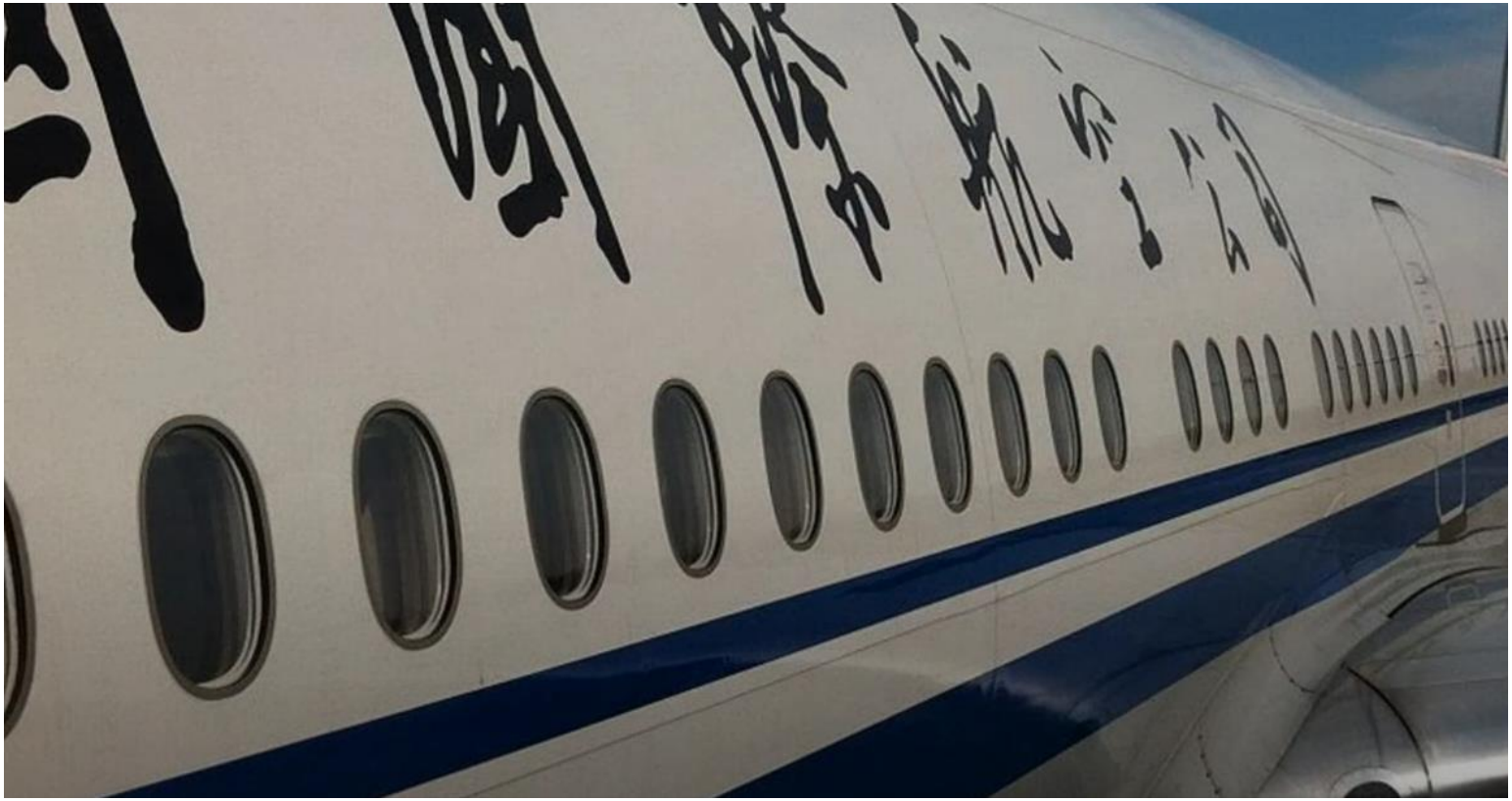
Factors that affect fatigue (Case study)



Source – Robert DuHamel - https://youtu.be/2rvx-r2itrE

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Coffee Break

We will continue at **11:05am GMT**

Got a question ?

Please use the "**chat**" or **"raise your hand"** functions

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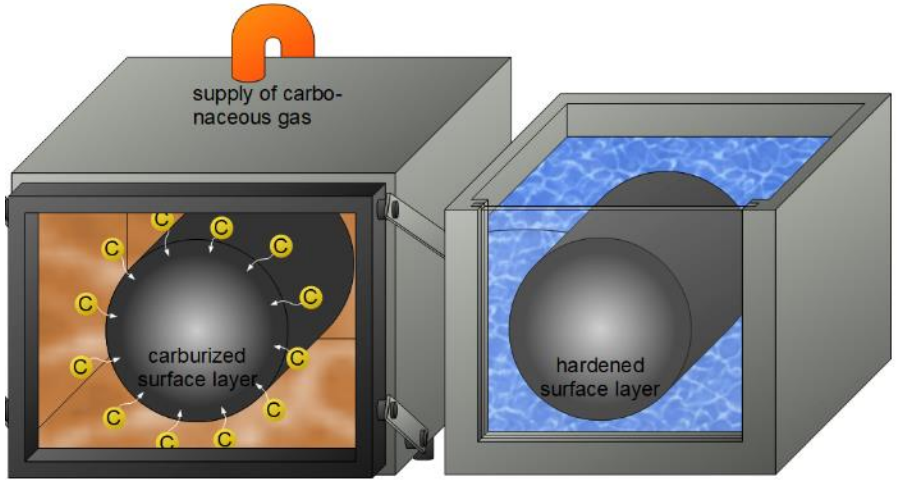
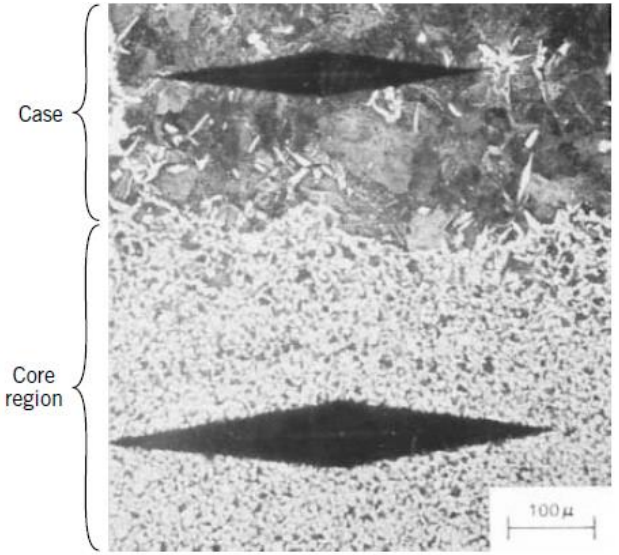
Surface treatment

- **Surface treatment - case hardening**
  - Carbon- or Nitrogen-rich outer surface layer (or case) in Steels
  - Exposed to a **carbonaceous or nitrogenous atmosphere** at elevated temperature
  - Makes harder outer layer



Tec Science (2018) https://www.tec-science.com/



Callister and Rethwisch (2013)

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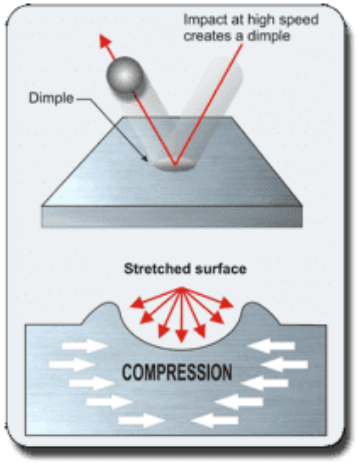
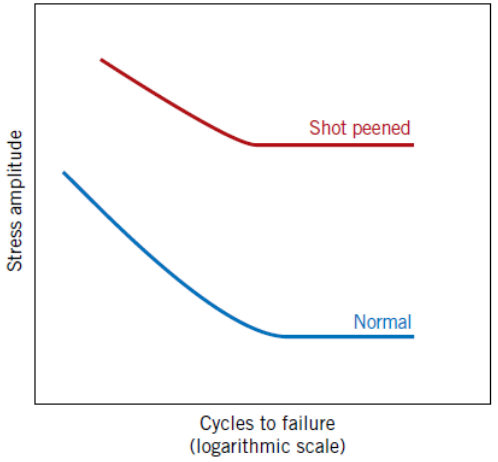
Surface treatment

- **Surface treatment – shot peening**
  - Introducing compressive stresses on the surface (suppresses cracks from propagating)
  - Commercially called “shot peening”
  - Small, hard particles (shot) are projected at high velocities onto the surface to be treated



International Surface Technologies (2020) https://istsurface.com



Callister and Rethwisch (2013)

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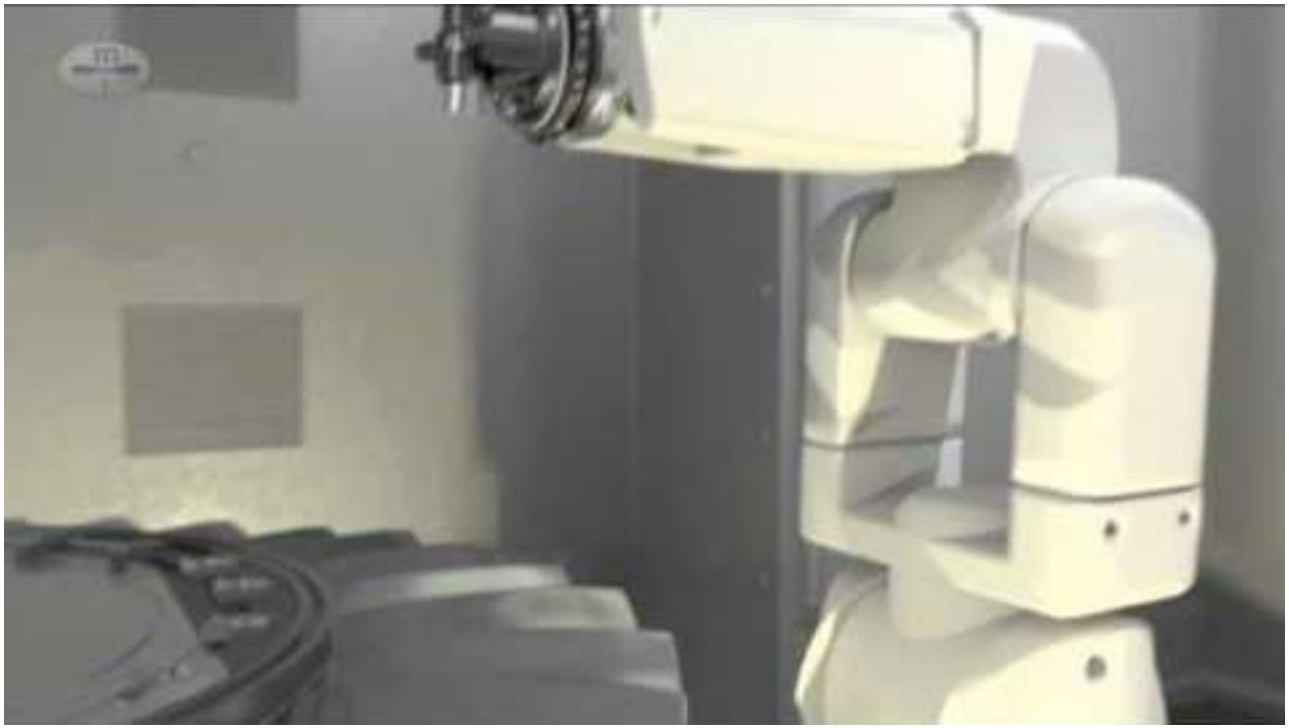
Surface treatment

- **Surface treatment – shot peening**



Shot Peening Animation from Curtiss-Wright Surface Technologies (2013) https://youtu.be/AgPsxoZnEa0?t=30

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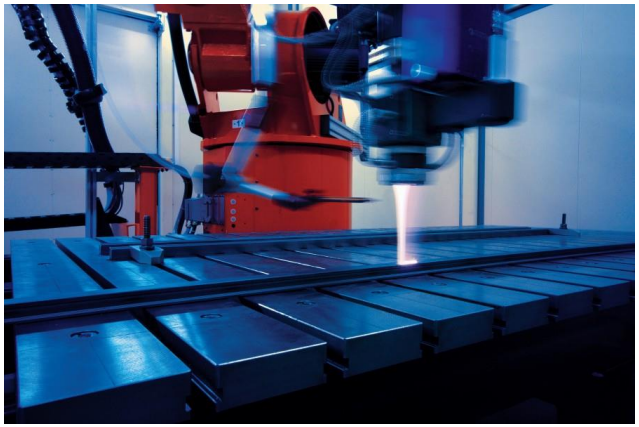
Surface treatment

- **Surface treatment – laser hardening**
  - Surface-hardening process in which a laser beam (i.e. heat source) is used to heat the surface of a metal
  - The surface layer is heated to the hardening temperature (between 900°C & 1300°C to create a hardened layer) to create a hardened layer
  - No oil or water is required for quenching (rapid cooling)



Härterei Gerster AG (2020) https://www.gerster.ch/

TLM Laser Ltd (2020) https://www.tlm-laser.com/laser-products/laser-hardening

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Surface treatment

- **Surface treatment – laser hardening**

BBL BuBenLaser (2016) https://youtu.be/FTGRFFH9P-w?t=35

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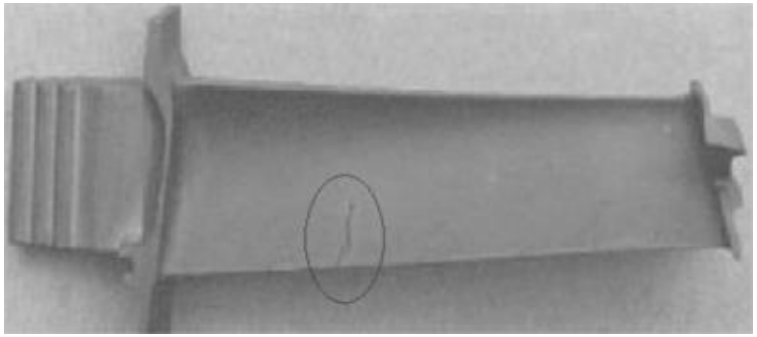
Creep

- **Time-dependent and permanent** deformation of materials when subjected to a constant load or stress at a high temperature
  - > 0.4 T_m for metals
- Important for high-temperature applications (e.g. Turbines in jet engines)
- **Creep Test - Constant load or stress** at **constant temperature**
  - Deformation is measured as a function of time



Cracked (failed) steam turbine blade due to creep Mouritz (2012)

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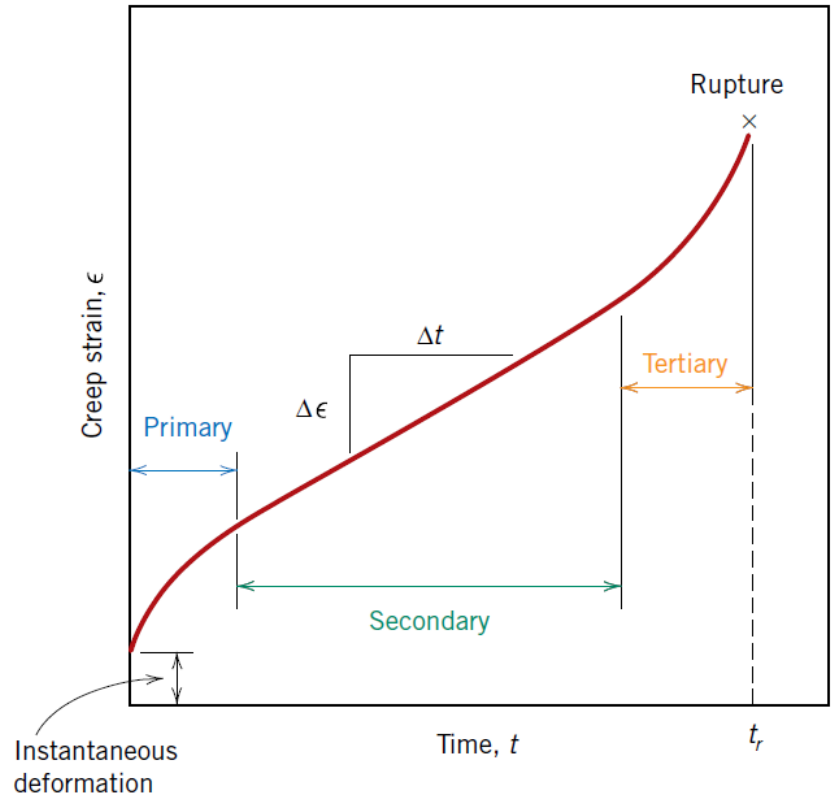
Stages of creep

1. **Instantaneous deformation** (elastic)
2. **Primary/transient creep**
   - Slope decreases with time
   - Increase in creep resistance (**strain hardening**).
   - Deformation is more difficult.
3. **Secondary/steady-state creep**
   - Rate of straining is constant
   - Longest duration
   - Most important for long-term applications
4. **Tertiary**
   - Rapidly accelerating strain rate up to **rupture/failure**
   - Formation of internal cracks, voids, necking



Callister and Rethwisch (2013)

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Quiz time *– Which of the following respective pairs of failures in metals are due to (1) Repeated (cyclic) stresses or strains and (2) Time-dependent deformation at elevated temperature and constant stress?*

Website – Sli.do

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Creep

- **Creep can be minimised by using Materials with:**

  - High melting temperature

  - High elastic modulus (e.g. Stainless Steel)

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Recap

- Fracture
- Fatigue
- Creep

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Any Questions ???

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