DAMAGE AND RELIABILITY OF MATERIALS

Lecture Contacts

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OUTLINE

SPECIFICITIES
INTRODUCTION
TOPICS TO BE TAUGHT
SKILL ASSESSMENTS

SPECIFICITIES (1/2)

- **Main aims:** understanding the damage mechanisms of structural materials that result from mechanical loading and from environment
- **Learning outcomes:**
  - know the main mechanical tests to characterize the fracture resistance of materials and the main methods for corrosion resistance assessment
  - learn the mechanisms of damage: corrosion, the ductile to brittle transition, the coupling effect between stress and environment

SPECIFICITIES (2/2)

- **Prerequisites**
  - Metallurgy
  - Plasticity
  - Analytical chemistry
  - The students should be able to mix concepts from different areas as metallurgy, mechanics, analytical chemistry and possess general knowledge of how large infrastructure works, e.g. power plant

- **Total student workload: 96 hours**
  - Contact hours: 56 hours
  - Personal work hours: 40 hours

INTRODUCTION (1/7)

What hint damage and reliability ?

- Material (metallic alloy, polymer…) is for component manufacturing
- Component has a function e.g. heat exchanger…

but can fail → several causes:

1. Bad design → complain to mechanical and design eng.
2. Bad selection of material → learn Material Selection & Tools → e.g. contact Prof Jan Ivens, KU Leuven
3. Inherent consequence of use of the material because the use conditions are complex, comprise many factors (T, environment, unexpected situation (e.g. overload) and so on

INTRODUCTION (2/7)

What are the impacts of component failure ?

- Cost: replacement of component, plant stop…
- Sustainability: consumption of raw materials, energy paid for processing…
- Safety: accident in transportation…

→ **All these factors impact the acceptance of a technology**

Very typical example: acceptance of nuclear energy

INTRODUCTION (3/7)
Remark

- In the considered background, damage and failure refer to fracture and/or loss of material → structural materials
- It would have been possible to consider failure of functional properties → functional materials

→ electrical resistance R for domestic heating device:

- before service, R is high → efficiency is high
- with service, R is progressively decreasing → efficiency is decreasing → consumption of electricity but no heat

→ The same impacts are observed

INTRODUCTION (4/7)
Identification of failure modes for structural materials

- The lecture concentrates on structural materials
- Identification of failure modes is obtained by an example from a field were safety is crucial: air transportation
- It is important to show a memorable example

INTRODUCTION (5/7)
Identification of failure modes for structural materials

- It is important to show a memorable example

Aloha Airlines Flight 243 B737
April 28, 1988 89 090 flight cycles

INTRODUCTION (6/7)

Identification of failure modes for structural materials

- Identification of failure modes is obtained by an example from a field were safety is crucial: air transportation
- Let's consider the paper written by S.J. Findlay and N.D.Harrison in 2012 in Materialstoday
- It is entitled: *"Why aircrafts fail ?"*

INTRODUCTION (7/7)

Identification of failure modes in aircrafts

Table 1 *Frequency of failure mechanisms.*

	Percentage of Failures	
	Engineering Components	Aircraft Components
Corrosion	29	16
Fatigue	25	55
Brittle fracture	16	-
Overload	11	14
High temperature corrosion	7	2
SCC/Corrosion fatigue/HE	6	7
Creep	3	-
Wear/abrasion/erosion	3	6

From: S.J. Findlay and N.D.Harrison, Materialstoday, p.18,2012

TOPICS TO BE TAUGHT (1/1):
DAMAGE AND RELIABILITY OF MATERIALS

- Refresh on mechanical testing
- Degradation and mechanism of corrosion, prevention against corrosion damage
- Effect of temperature on fracture mode
- Fatigue failure
- Environmentally assisted fracture
- Wear

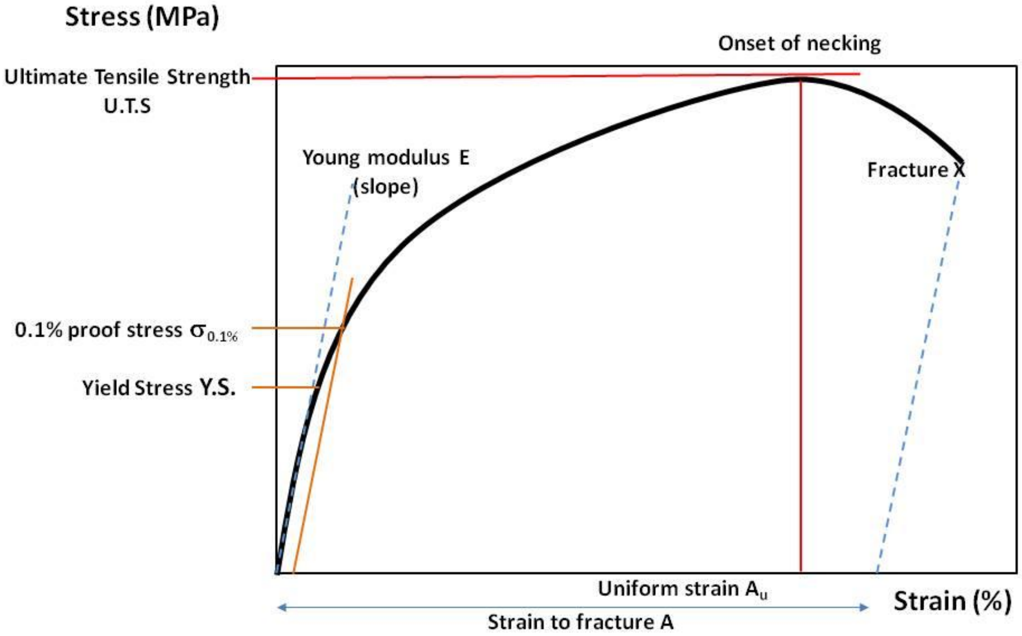
REFRESH ON MECHANICAL TESTING (1/4)

- It is important to distinguish the mechanical tests:
  - aiming at determining the plastic properties of materials and
  - the ones aiming at characterizing the fracture resistance.

→ Briefly recall these tests (except the low cycle fatigue test which will be described in more details).

REFRESH ON MECHANICAL TESTING (2/4) TENSILE TEST

- Ultimate Tensile Strength (U.T.S)
- Young module (E),
- Yield Strength (Y.S.),
- Total elongation (A)
- Uniform elongation (A_u)
- Reduction of area (Z)

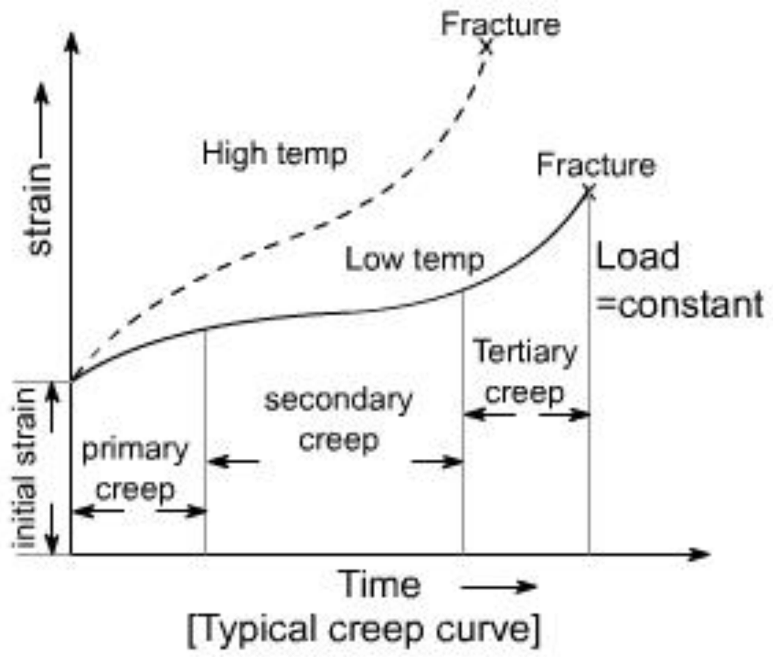


Typical tensile curve of a ductile material

REFRESH ON MECHANICAL TESTING (3/4) CREEP TEST

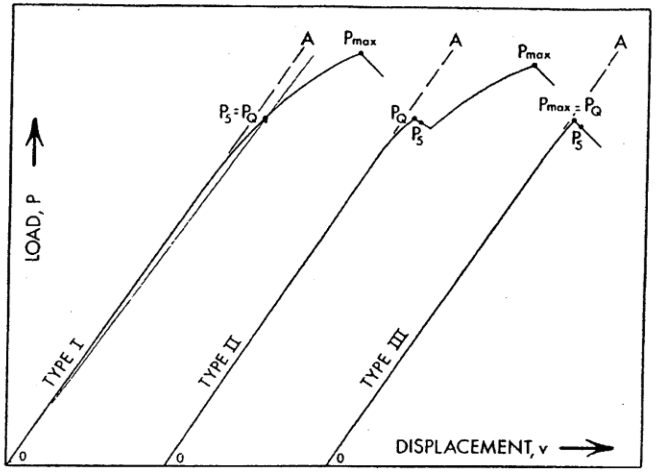
Creep data

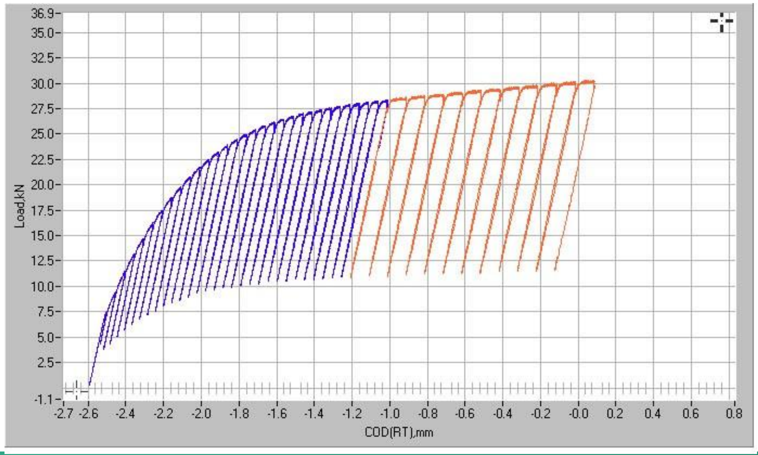
- stress vs. time to rupture
- total elongation vs. time to rupture
- reduction of area vs. time to rupture as function of temperature
- evolution of the creep rate as function of temperature, under various applied stresses.



REFRESH ON MECHANICAL TESTING (4/4) TOUGHNESS TEST

- K_{IC} for brittle materials
- J_{IC} for ductile materials





DEGRADATION BY CORROSION (1/4) INTRODUCTION

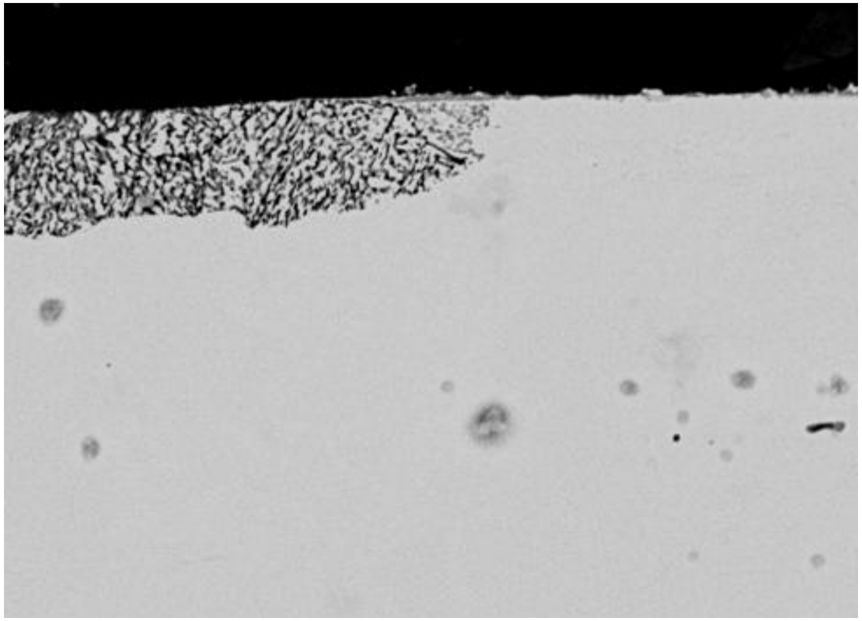
- Refresh on what is corrosion: gradual destruction of materials by chemical reaction with their environment
- Invite students to give example of corrosion in the domestic life
- Mention that corrosion concerns all sectors of the industry
- Give cost of corrosion: according to NACE, corrosion costs the US oil and gas exploration and production industry $1.4 billion a year

DEGRADATION BY CORROSION (2/4) INTRODUCTION

- Corrosion requires knowledge on thermodynamics, electrochemistry and also on metallurgy
- Mention that corrosion can occur in dry and wet environments
- Mention that sometimes corrosion can produce beneficial effect e.g. oxide formation can protect against environment

DEGRADATION BY CORROSION (3/4)
FORMS OF CORROSION

- General corrosion
- Localized corrosion
- Galvanic corrosion
- Pitting
- Selective corrosion



SEM pictures of cross section of 316L corroded at 500°C during 2 012h in LBE (From Martinelli et al, CEA France)

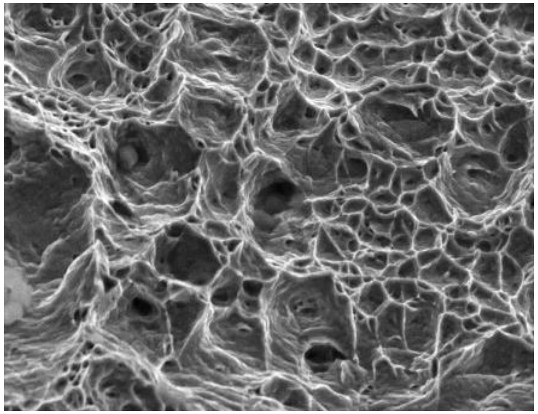
DEGRADATION BY CORROSION (4/4) PREVENTION OF CORROSION

- Corrosion is an issue that cannot be hidden → see the photograph: the painting, in the present case, has not solved the corrosion problem nor succeeded in hiding it

- Design
- Coating
- Inhibitors
- Cathodic protection

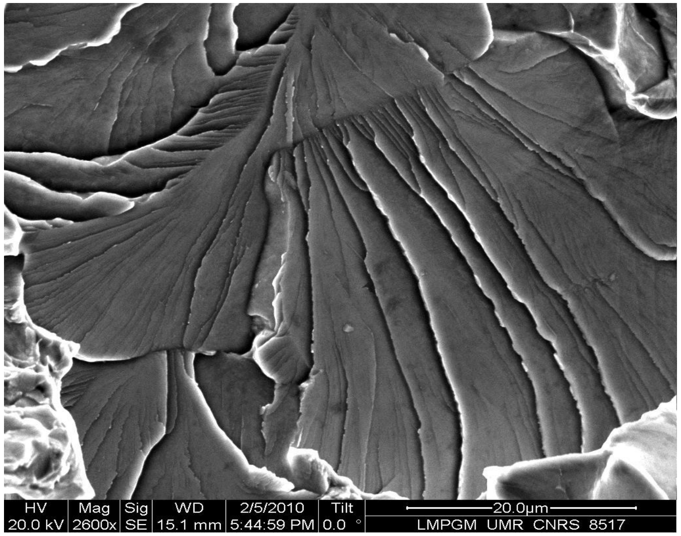
FRACTURE (1/3)
EFFECT OF TEMPERATURE ON FRACTURE MODES

- It is important to mention that ductile materials are preferred and selected but should retain these properties during service
- Mention the ductile to brittle behaviour
- Comment first on the ductile behaviour and the typical features: macro plasticity, necking, fracture surface with dimples



FRACTURE (2/3) EFFECT OF TEMPERATURE ON FRACTURE MODES

- Generally, decreasing temperature results in ductile to brittle behaviour but it is managed → existing alloys for low temperature applications: FCC materials, Fe9Ni steels
  - Show example how brittle fracture looks like: inter and trans granular



Exemple of a ductile to brittle transition

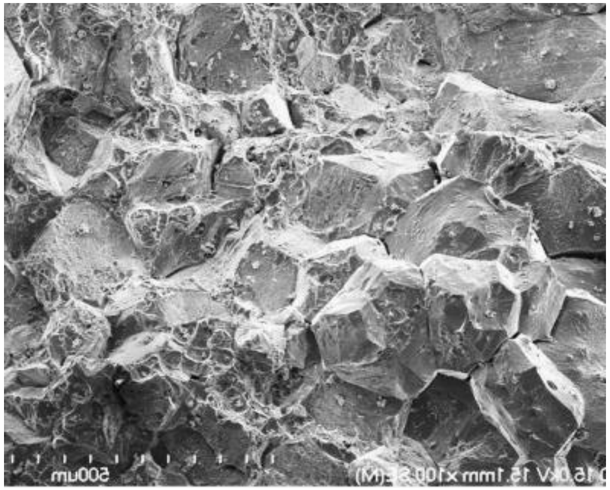
FRACTURE (3/3)
EFFECT OF TEMPERATURE ON FRACTURE MODES

- But mention that brittle fracture can also occur at high temperature → the so called Brittle Intergranular Fracture

and also it is managed:

single crystals

Ultra High Temperature Materials for Turbines:
EC project ULTMAT Contract No.: AST3-CT-2003-502977



C.-M. Kuoa et la, MSE A 510–511 (2009) 289–294)

FATIGUE FAILURE (1/4) INTRODUCTION

- Fatigue: progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses or strains. And this may result in cracks or fracture after a sufficient number of fluctuations
- It is important to mention that analysing fatigue of materials is not limited to fatigue life measurement but can also cover the analysis of the modification of microstructure and of mechanical characteristics

FATIGUE FAILURE (2/4) DIFFERENT APPROACH

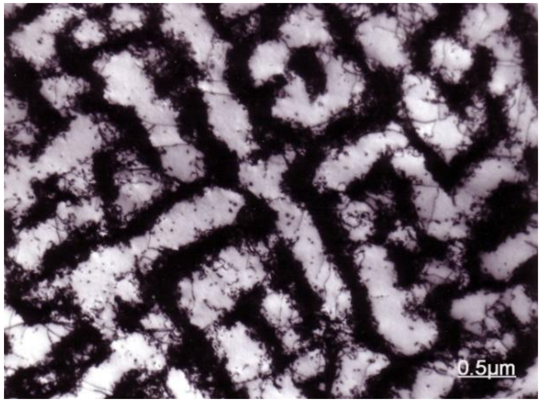
- Emphasize that the engineer must consider fatigue of uncracked components and fatigue of cracked components
- Mention the different approaches
  - Stress life approach
  - Strain life approach
  - Fatigue crack propagation approach

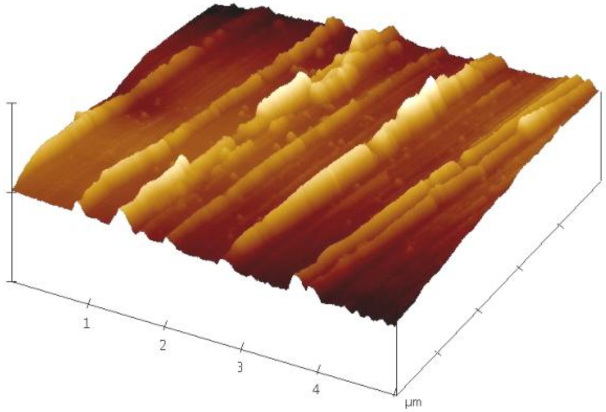
FATIGUE FAILURE (3/4)
FATIGUE MECHANISMS

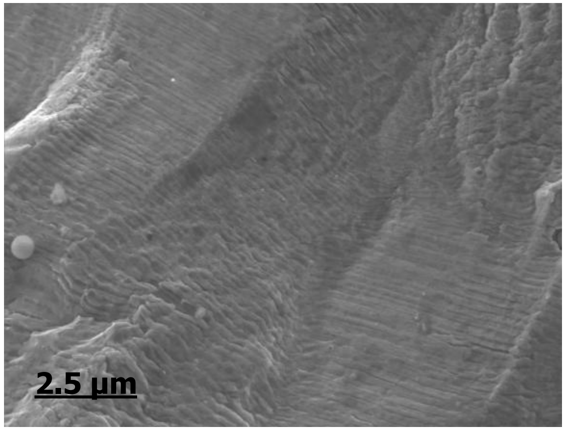
- Consider the different steps of fatigue damage:
  - Cyclic accommodation
  - Short crack initiation
  - Short crack growth at the surface and formation of the long crack
  - Long crack propagation in the bulk
  - Final fracture of tensile type

FATIGUE FAILURE (4/4)
FATIGUE MECHANISMS

- Illustrate with micrographs so that the student can appreciate the microstructural scales involved and the analytical tools to be used:
- TEM AFM SEM







- From this, it becomes obvious that the knowledge in plasticity, metallurgy … is of prime importance

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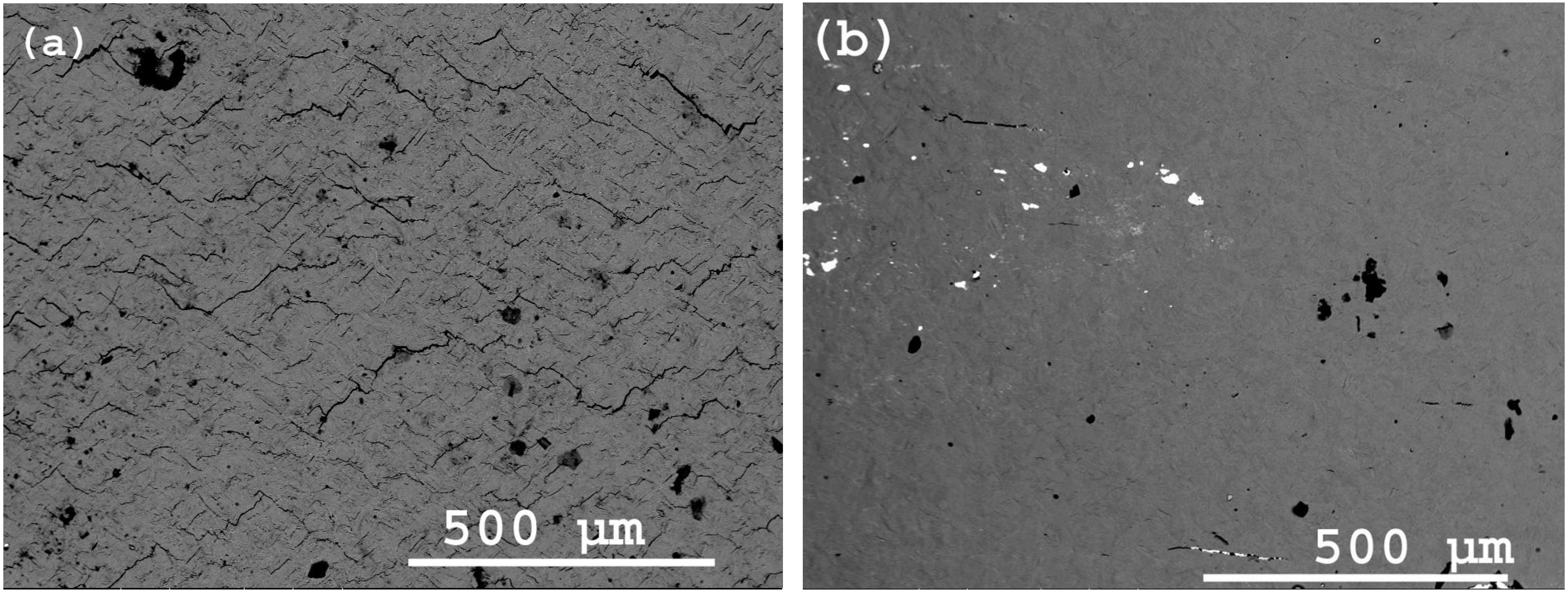
FATIGUE FAILURE
FATIGUE MECHANISMS

- Illustrate with micrographs the role of structural barriers, the fatigue crack densities and the fatigue life



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Chimie Lille ÉCOLE NATIONALE SUPÉRIEURE DE CHIMIE

ENVIRONMENTALLY ASSISTED FRACTURE (1/8)
INTRODUCTION

- Ductile material loaded in presence of an environment can become brittle
- Corrosion mechanism can be different according the material is or not under stress

  → the strain resulting from loading and the corrosion resulting from the environment interact
- *It is important to mention that the damage produced when both factors are in presence is superior to the sum of the damage produced by each one taken separately*

ENVIRONMENTALLY ASSISTED FRACTURE (2/8)
INTRODUCTION

- The different cases of environmentally assisted fracture are:
  - stress corrosion cracking (SCC)
  - hydrogen embrittlement (HE)
  - liquid metal embrittlement (LME) and
  - corrosion-fatigue (CF)

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ENVIRONMENTALLY ASSISTED FRACTURE (3/8)
SCC

- Generally concern passivable materials such as stainless steels, zirconium alloys
- Parameters that control SCC are the repassivation kinetics and the strain rate.
- Other mechanisms are film induced cleavage or the corrosion tunnel model

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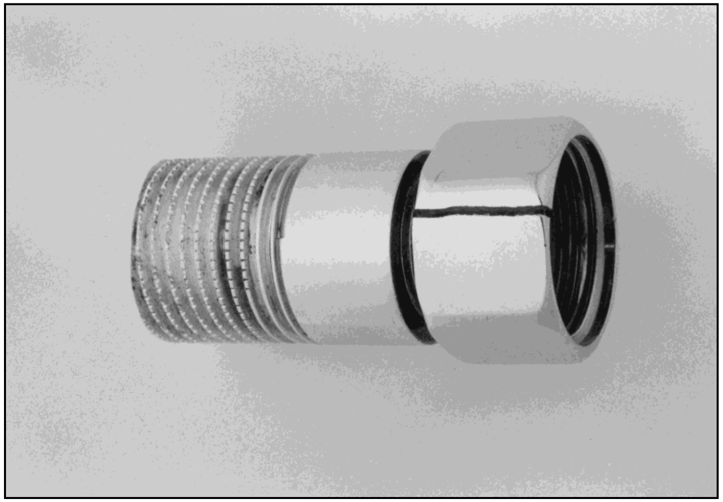
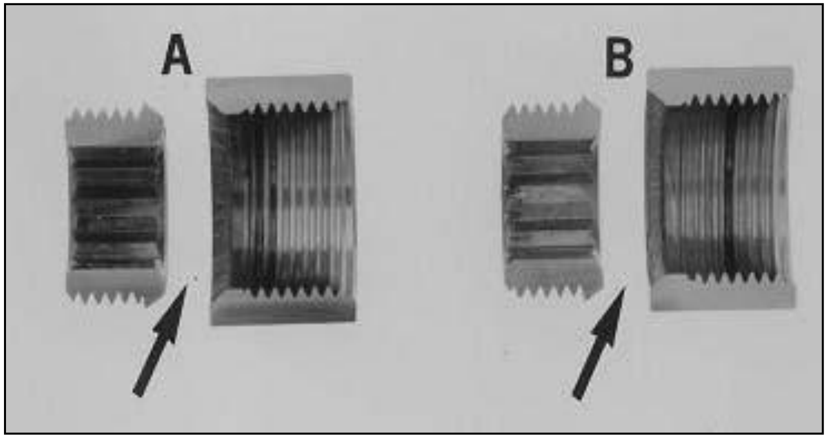
ENVIRONMENTALLY ASSISTED FRACTURE (4/8)
SCC

- *It is important to mention the importance of the passive film properties: stability against environment (e.g.: presence of Cl^- is detrimental), mechanical resistance and thickness. Also it is important to mention that even weak variation in chemistry of environment or in material microstructure, a material which was not prone to SCC can become sensitive*

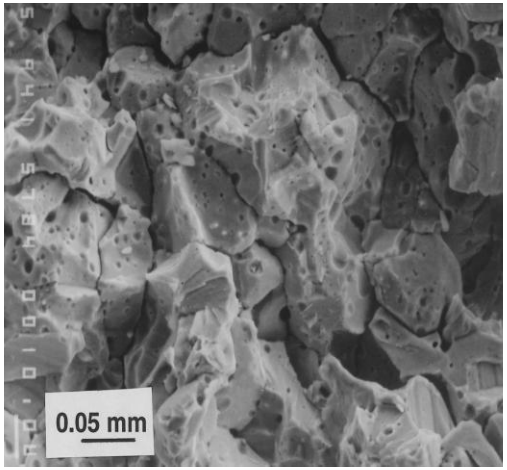
Damaged plumbing parts made of cold worked $CuZn37\alpha+\beta$ brass



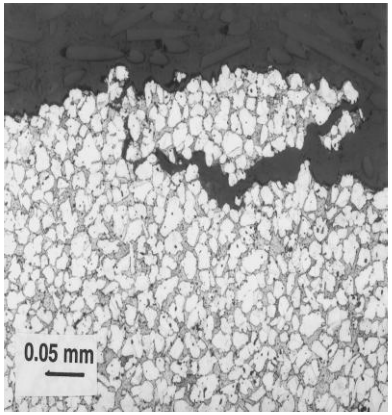
Longitudinal crack in brass fitting



Faucet extension made from brass showing fracture (A), (B) and cracking (C)

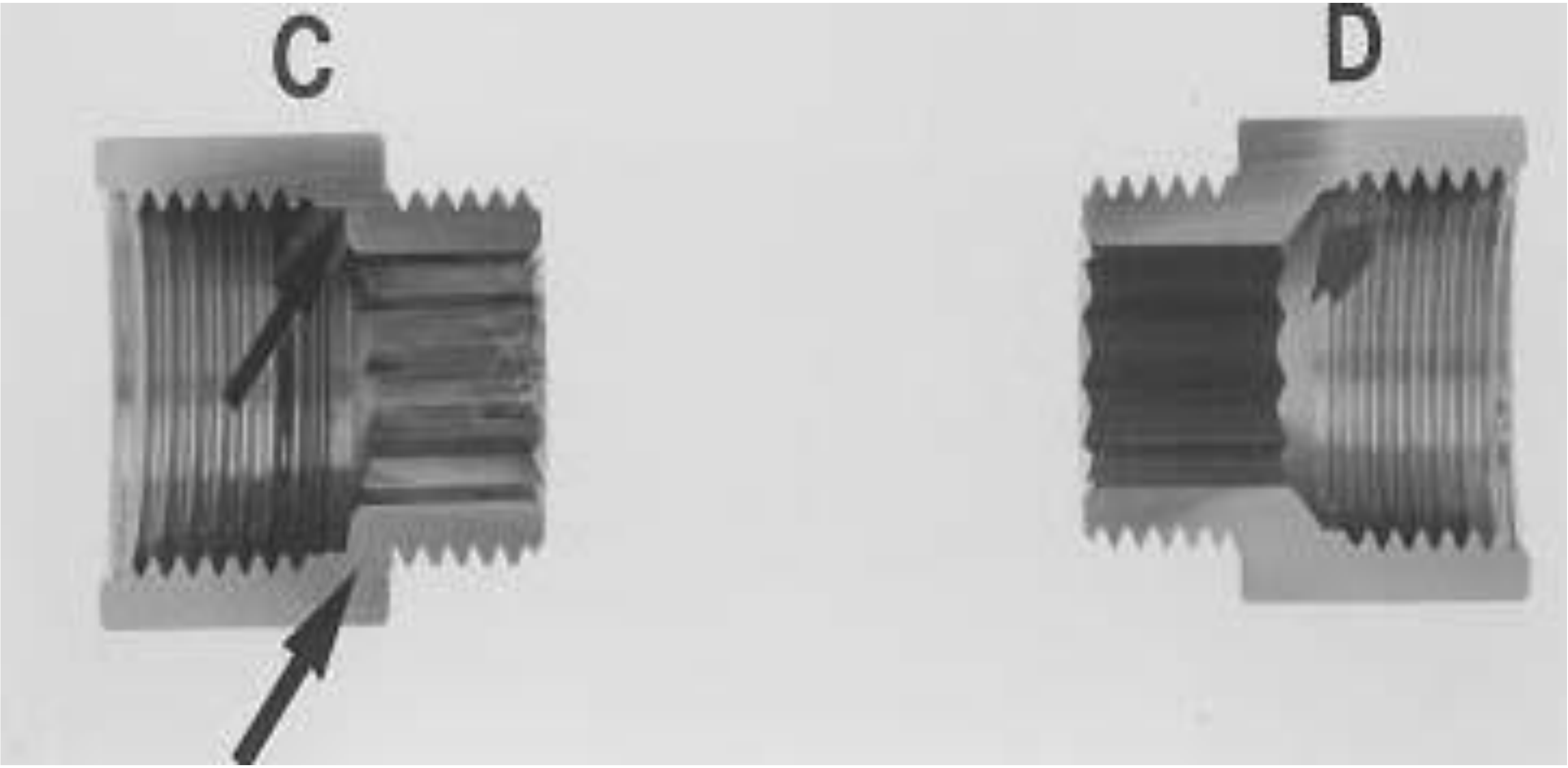


Intercrystalline fracture surface.



Damaged plumbing parts made of cold worked CuZn37α+β brass

The tap extension with the transition of the cross-section also indicates a location with stress concentration. The modification to the design (D) should help to reduce the stress peaks on the transition of the cross-section.



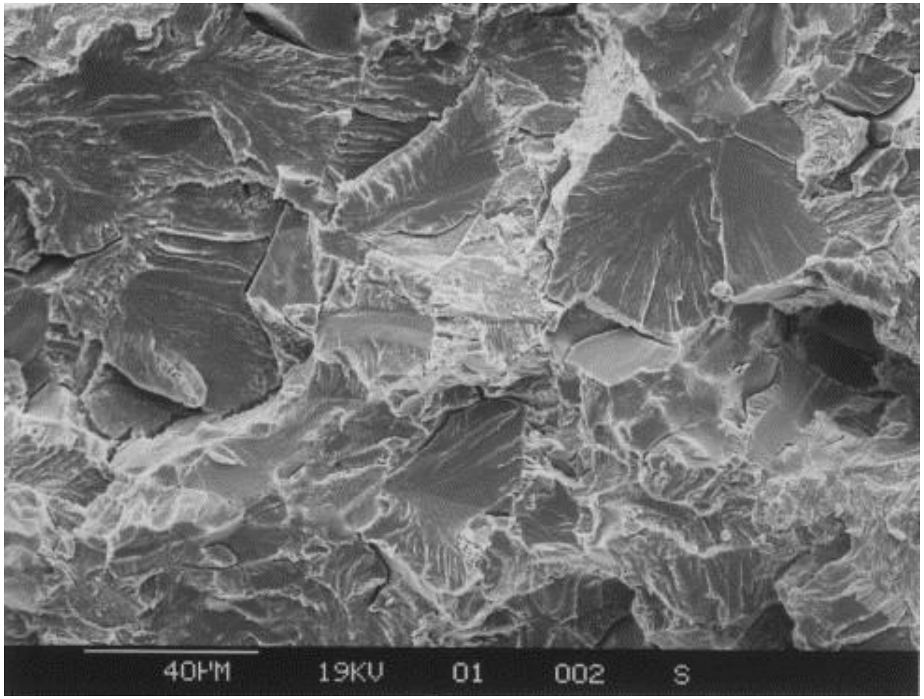
ENVIRONMENTALLY ASSISTED FRACTURE (5/8)
HE

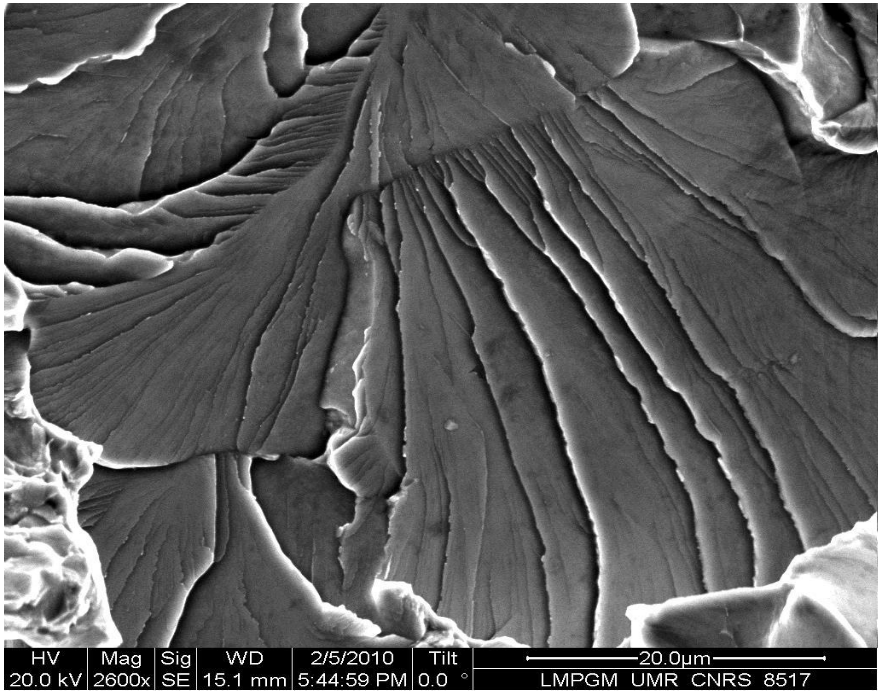
- Comment about the word HYDROGEN: H^+? H? H_2?
- Comment about the specificities of H atom: size, diffusion, solubility limit
- Show fractograph of HE failed material to show the similarity with brittle fracture at low temperature
- Emphasize on the importance of this phenomenon

→ sources of H are very numerous: even water can lead to HE

→ FCC metal are not brittle at low temperature but can be HEed

ENVIRONMENTALLY ASSISTED FRACTURE (5/8)
HE
similarities of brittle fracture
in HE and low temperature





J. Woodtli, R. Kieselbach Engineering Failure Analysis 7 (2000) 427-450

ENVIRONMENTALLY ASSISTED FRACTURE (6/8)
HE

- Comment the mechanism according to the temperature:
  - Low Temperature Hydrogen Attack (LTHA)
  - High Temperature Hydrogen Attack (HTHA)
- LHTA: comment regarding H concentration with solubility
  - Internal pressure (blistering and fish eyes)
  - Reduction in surface energy by adsorbed atoms
  - Reduction in cohesive strength by absorbed atoms
  - Hydride precipitation

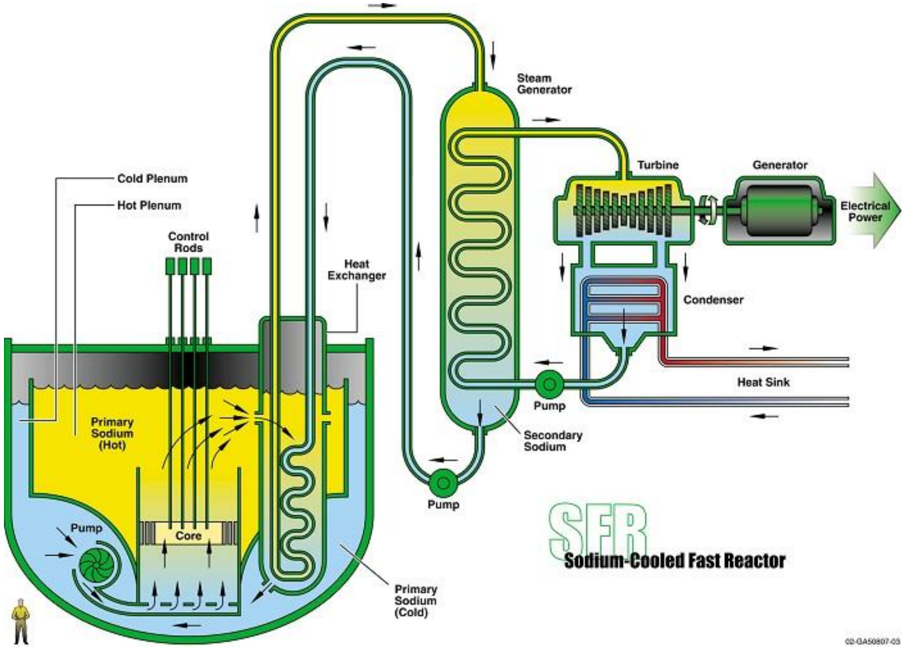
ENVIRONMENTALLY ASSISTED FRACTURE (7/8)
LME

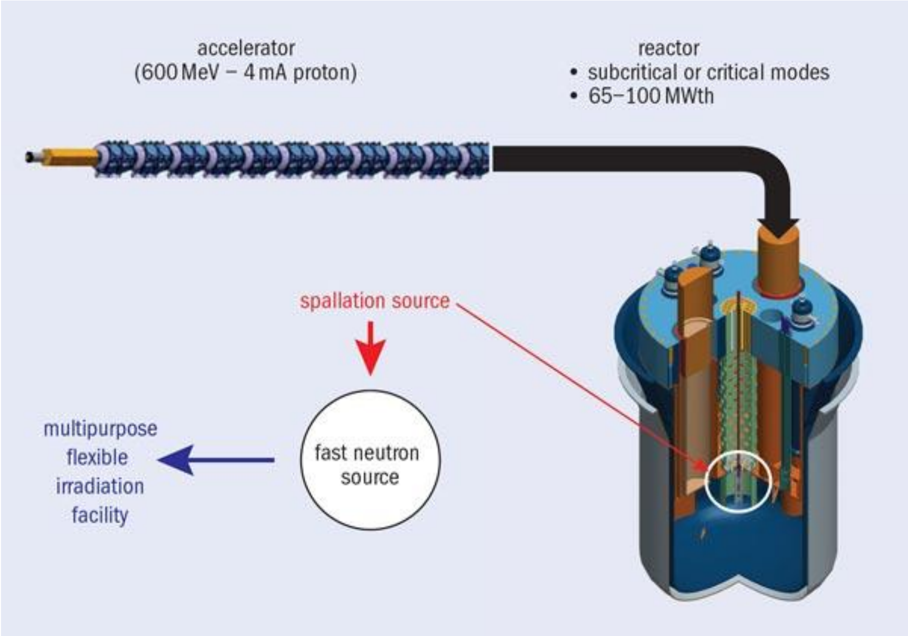
- Less known phenomenon than HE and SCC but real
- Rapid fracture of a solid metal if stressed in a liquid metal
- Occur not only in high technology components
- Invite student to think when LM are involved: *low melting point materials are employed for several applications e.g. in welding (Sn, Pb), surface treatment (Cd, Zn), cooling fluids (Na, Pb, Bi). A typical example is LME of galvanized structures*

ENVIRONMENTALLY ASSISTED FRACTURE (7/8)

LME

- Show examples in high technology international projects such Gen IV
- ASTRID (France) and MYRRHA (Belgium)





ENVIRONMENTALLY ASSISTED FRACTURE (8/8)
LME

- Nevertheless some similarities exit between HE mechanisms
- Comment on the requirements:
  - Intimate contact or wetting of the solid metal by the liquid metal is necessary → angle contact of the liquid drop on the solid substrate.
  - The solid metal must be loaded enough to develop plasticity.
  - High strength materials are more sensitive than low strength materials.

WEAR (1/2) INTRODUCTION

- *It is important to set the wear inside tribology.*
- Tribology: technology of interactive surfaces in relative motion, incorporating the science of friction, lubrication and wear.
    - Friction: resistance to motion between two surfaces that are forced to slide relative to each other.
    - Wear: result of frictional properties of materials in intimate contact when such contacts side, impinge or oscillate relative to each other.
- *Invite the students to suggest when they have been concerned with wear → e.g. during the metallurgy lab when they polished steel with SiC paper*

WEAR (2/2)
PRIMARY TYPES OF WEAR

- **Abrasive wear:** removal of material from a surface by the sliding of hard or sharp particles (e.g. mineral particle) or protuberance (e.g. surface asperity) imposed on and moving on a (softer) surface
- **Adhesive wear:** frequently occurs because of shearing at points of contact or asperities that undergo adhesion or cold welding
- **Erosive wear:** loss of material from a solid surface due to relative motion in contact with a fluid that contains solid particles
- **Fatigue wear:** occurs when contact cycles are present, then fatigue wear also called fretting wear occurs

SKILL ASSESSMENTS

At the end of the lectures, the students:

- know the main fracture mechanisms
- can select a candidate alloy for a typical operation
- possess good knowledge allowing to make work component in safety conditions
- can use these concepts for expert assessment, failure analysis
- can contribute to the development of new high performance materials