

Energy transition and materials mechanics across the scales

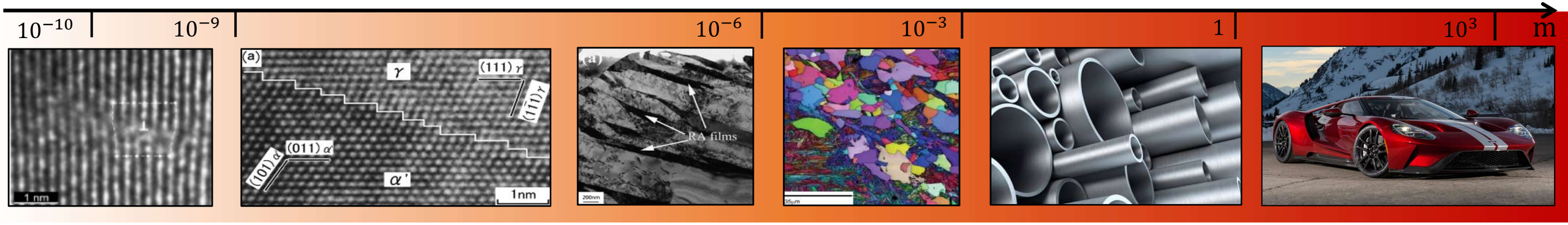
The case of hydrogen embrittlement

Francesco Maresca*

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Mechanics of Materials group

university of groningen



Part I / Basics of Materials Science

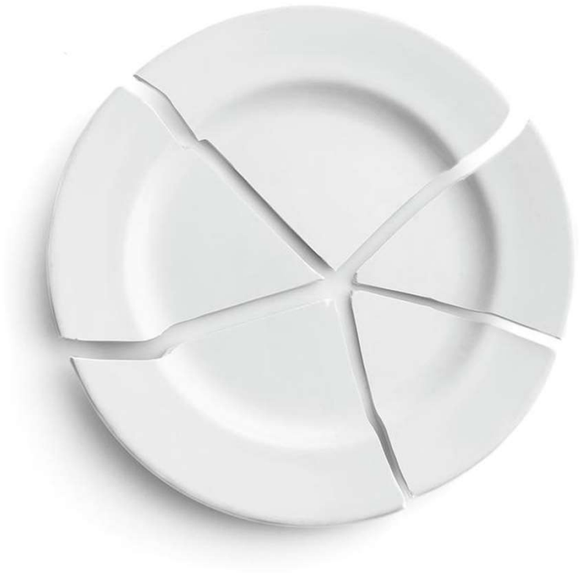
This talk is about...

… **fracture** = separation of material

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Brittle



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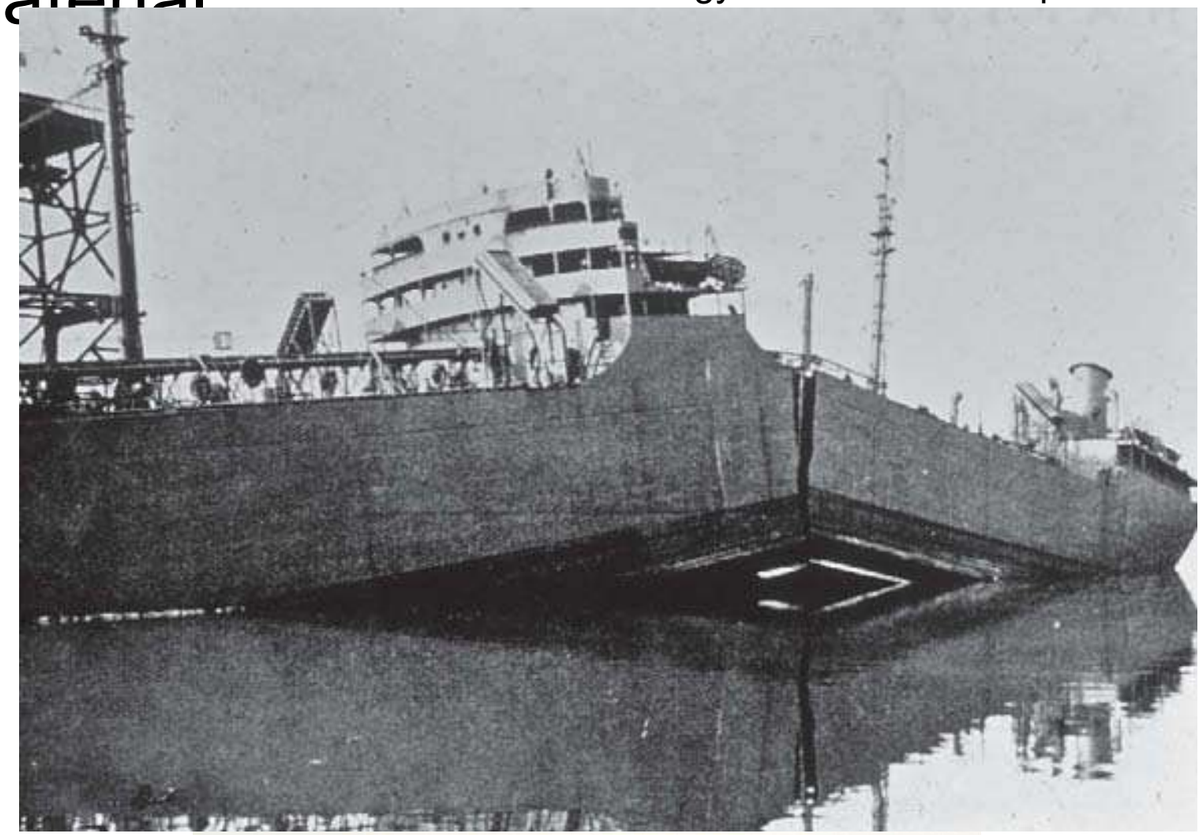
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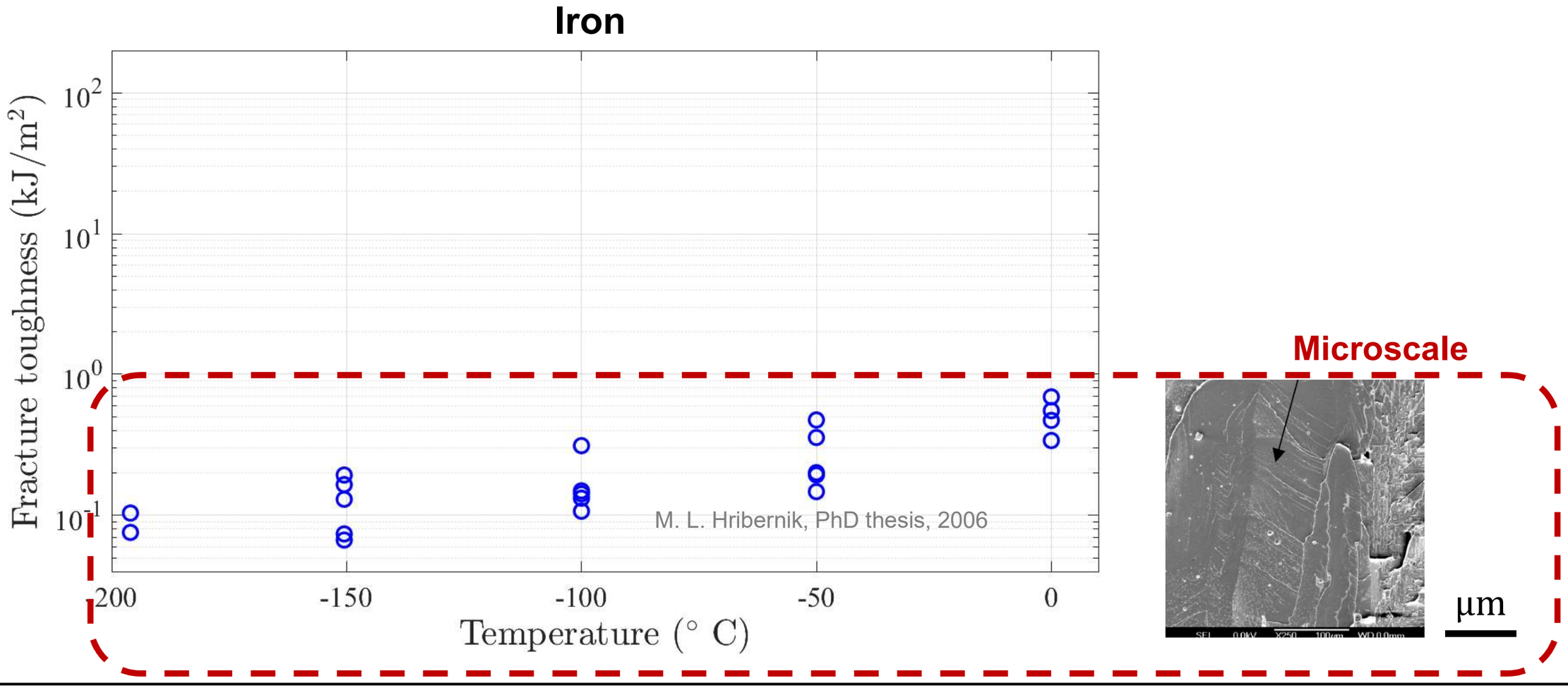
Hydrogen-induced cracking failure of API 5L X60 line pipe.
from http://www.metalspiping.com/whats-hydrogen-induced-cracking-hic-and-hic-test.html
(accessed 27.01.2022)

Liberty ships
metallurgyandmaterials.wordpress.com



Fracture is a multi-scale problem

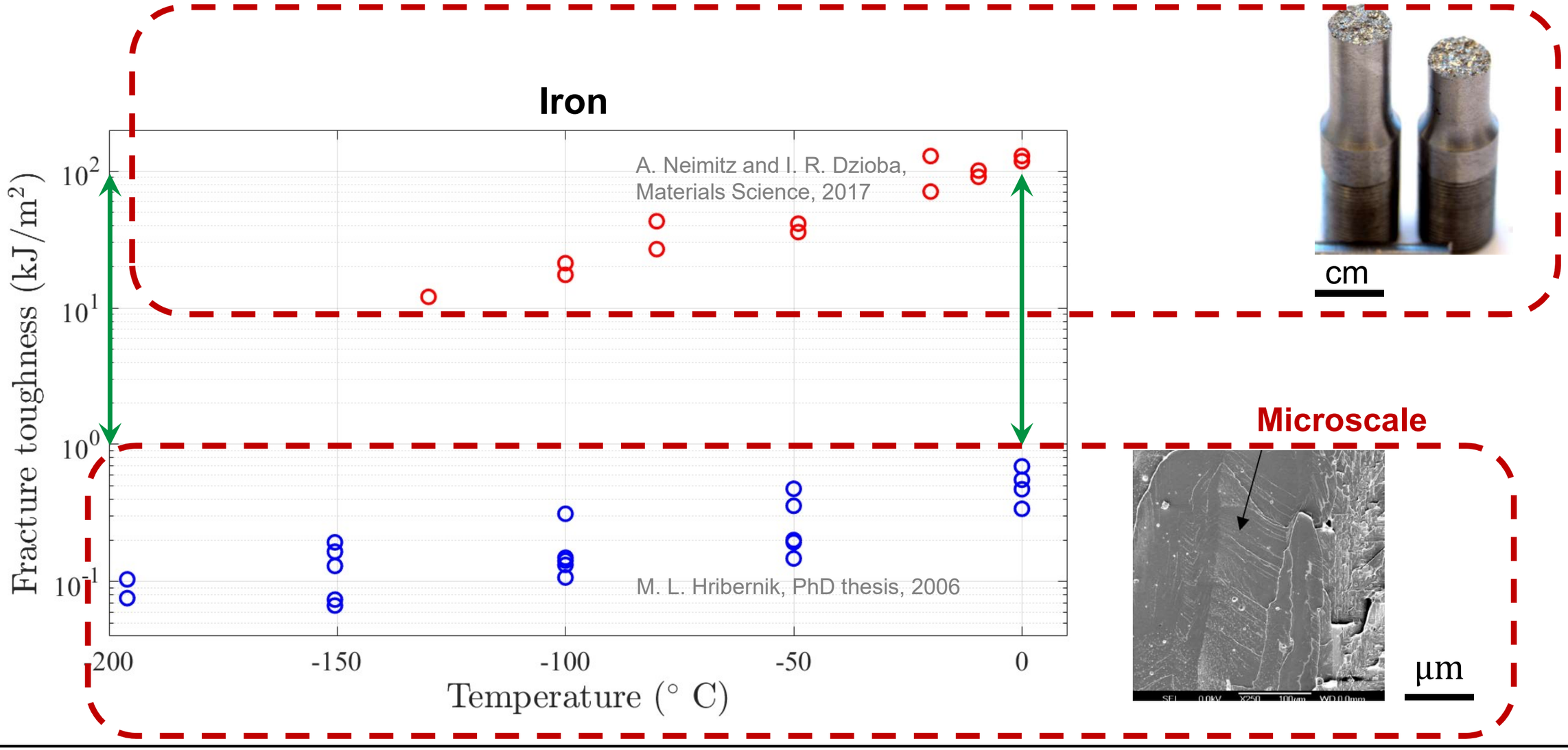
Fracture toughness: energy needed to fracture a material.



Fracture is a multi-scale problem

Fracture toughness: energy needed to fracture a material.

Engineering scale



Microscale

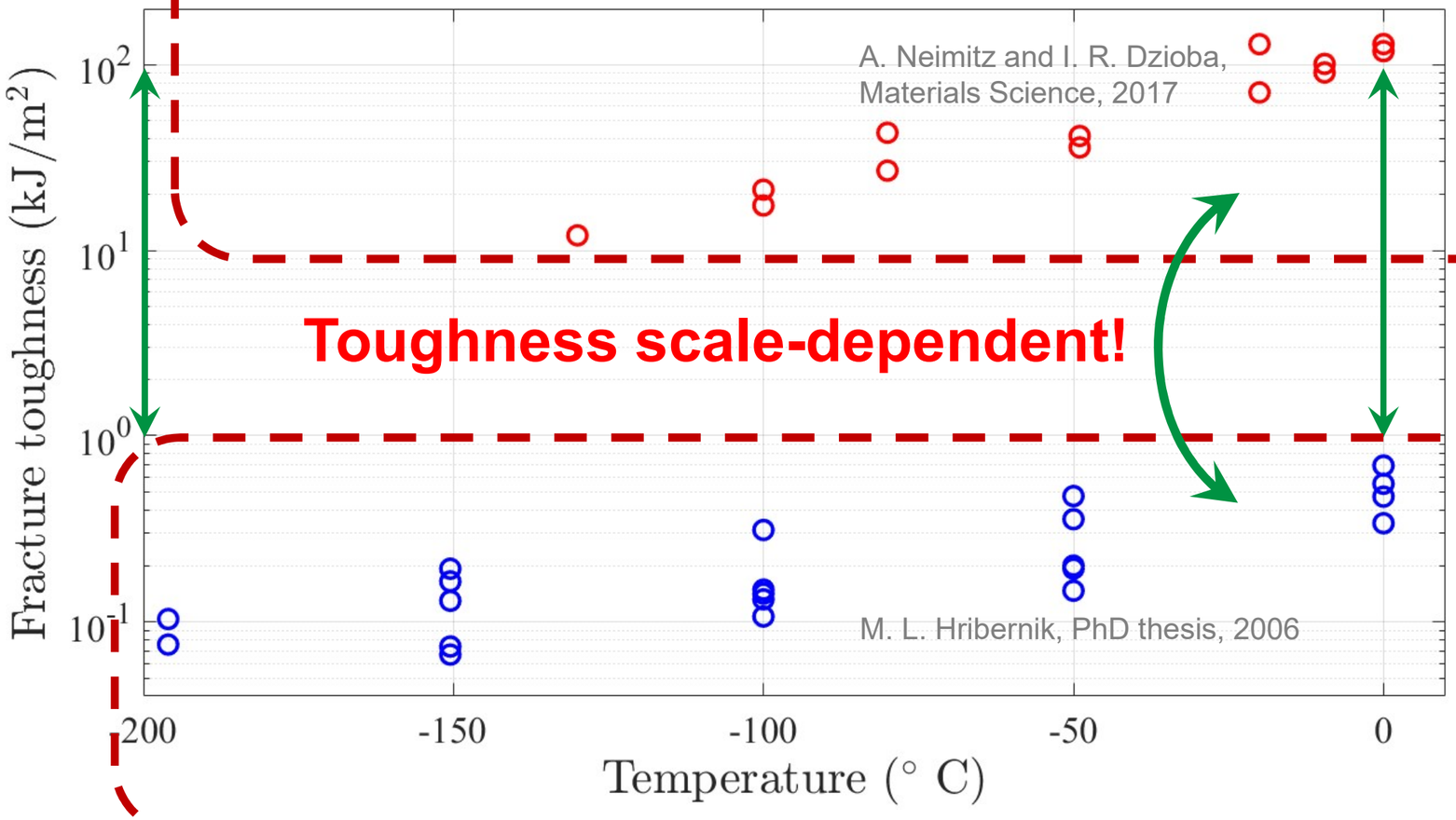
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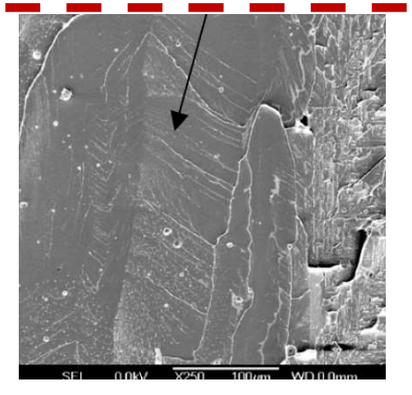


Iron



Toughness scale-dependent!

Microscale



Fracture is a multi-scale problem

Fracture toughness: energy needed to fracture a material.

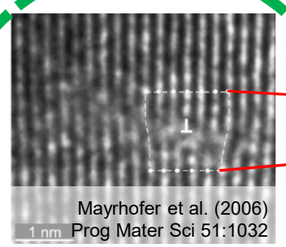
Engineering scale

Engineering components

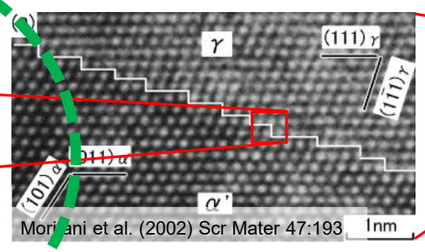




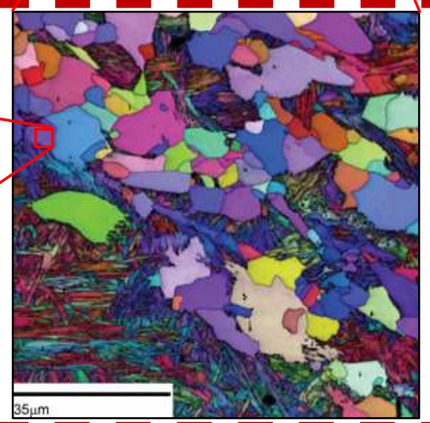
Microscale



Dislocations



Interfaces



Microstructures

Conclusions / Part I

1. **Materials are <u>multi-scale</u> and <u>complex</u>**
   Engineering properties are the results of different processes that occur at multiple scales

2. **Fracture toughness**
   Property that depends on processes activating at multiple scales

→ Predicting **engineering-scale fracture**
requires understanding of all the relevant processes that occur across multiple scales

Part II / Hydrogen-induced fracture

Environmentally assisted cracking in metals & Energy transition

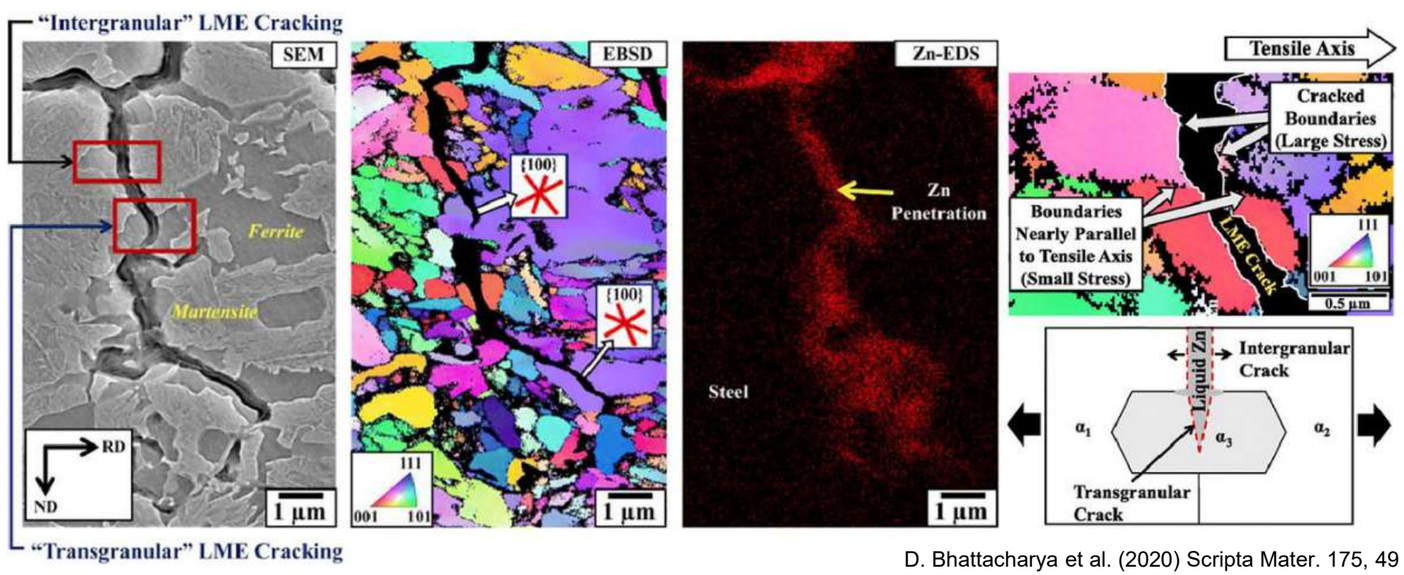
Fracture of metals is favored by aggressive environments. Examples are:

1. **Hydrogen Embrittlement (HE)**
2. **Liquid metal embrittlement (LME)**
3. **Stress corrosion cracking (SCC)**: crack propagation driven by anodic corrosion.
4. **Corrosion Fatigue (CF)**: fatigue failure enhanced by electrochemical reactions.

Hydrogen transport storage & production

Sustainable vehicle design

Nuclear reactors (GenIII, GenIV)



D. Bhattacharya et al. (2020) Scripta Mater. 175, 49

HE and Hydrogen economy

gasunie
crossing borders in energy

Nederlands menu

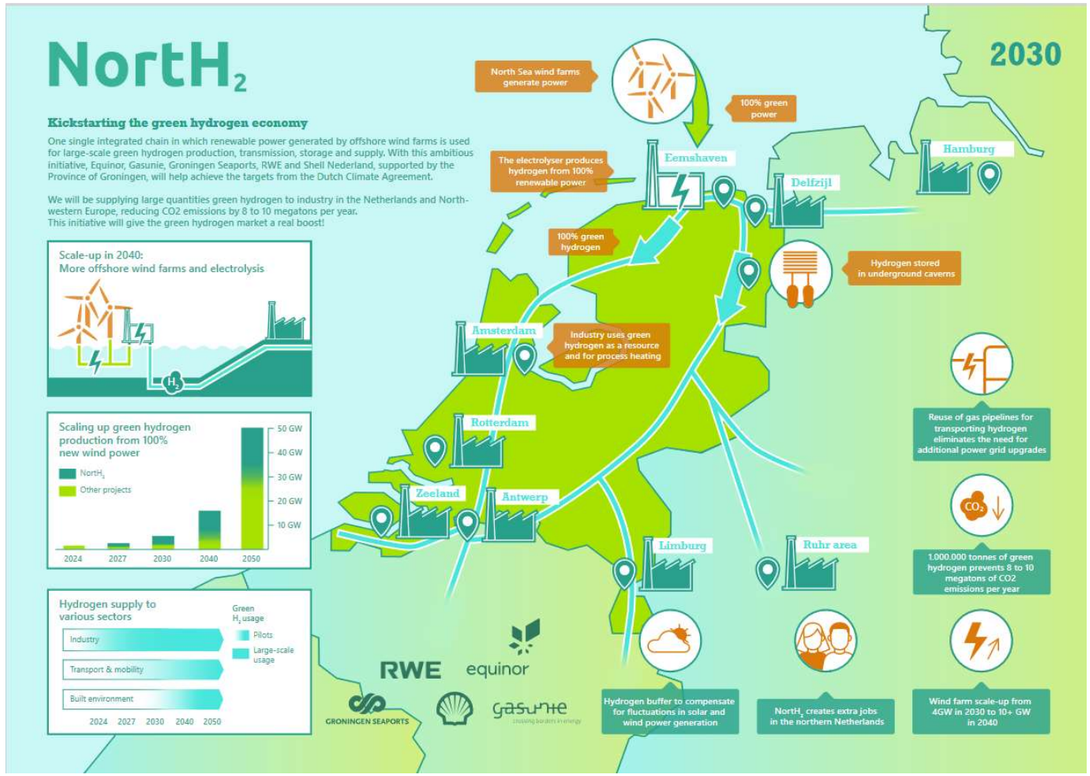
27 Feb 2020

Europe's largest green hydrogen project starts in Groningen

A consortium of Gasunie, Groningen Seaports and Shell Nederland has launched ambitious NorthH_2 green hydrogen project

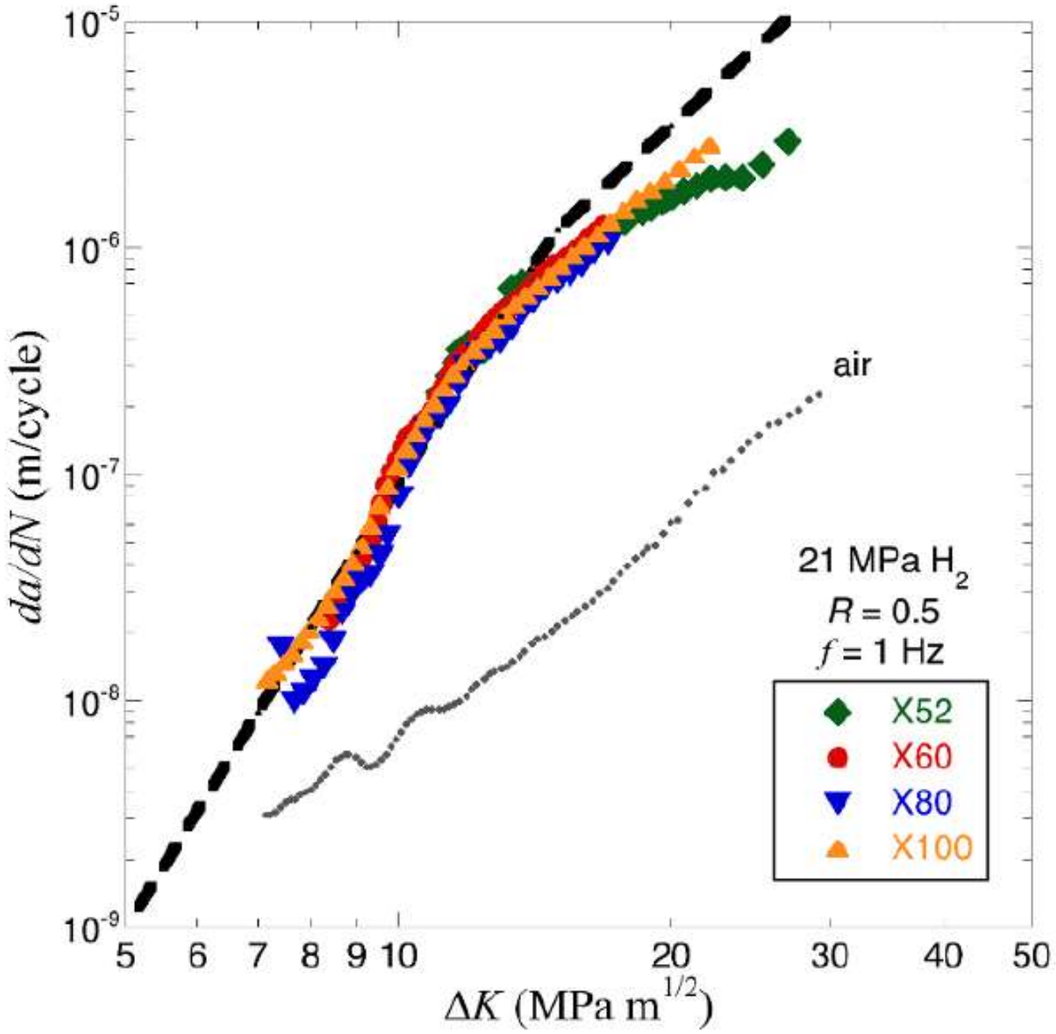
www.gasunie.nl

Current plan:
use existing pipelines
to transport H2



www.groningen-seaports.com/en/hydrogen

Observed impact of H on pipeline steel lifetime



- Hydrogen exposure reduces pipeline steel lifetime

- Lifetime predictions uncertain:

"There exists a need for additional testing on both steel and plastic pipeline materials implemented in the U.S. natural gas pipeline system to identify and confirm relationships between hydrogen presence and fatigue, crack growth, and failure rates."

Topolsky et al. (October 2022) Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology Technical Report, NREL/TP-5400-81704

What is Hydrogen Embrittlement (HE)

William Johnson (1875) *Proc. R. Soc. London 23, 168-179.*

*"**iron wire became more brittle** after a few minutes' immersion ... in strong hydrochloric or dilute sulphuric acid"*

["any acid which liberates hydrogen"]

a)



ductile

a) https://en.wikipedia.org/wiki/Fracture (accessed on 27.01.2022)

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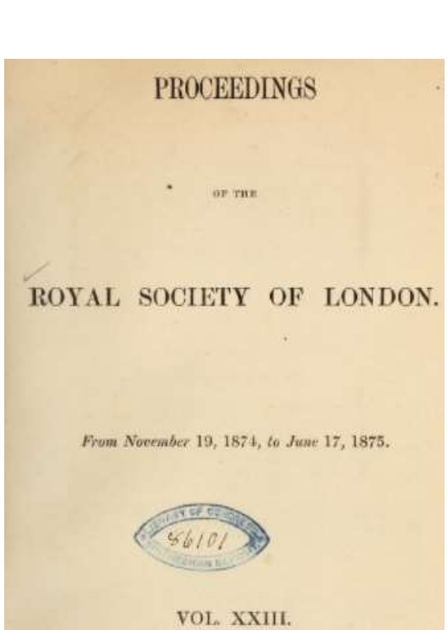
ductile → ***brittle***

a) https://en.wikipedia.org/wiki/Fracture (accessed on 27.01.2022)
b) Mild steel, from Callister, Materials Science and Engineering

What is unsolved about HE?

… ever since, plenty of research

Searched on 27.01.2022


PROCEEDINGS

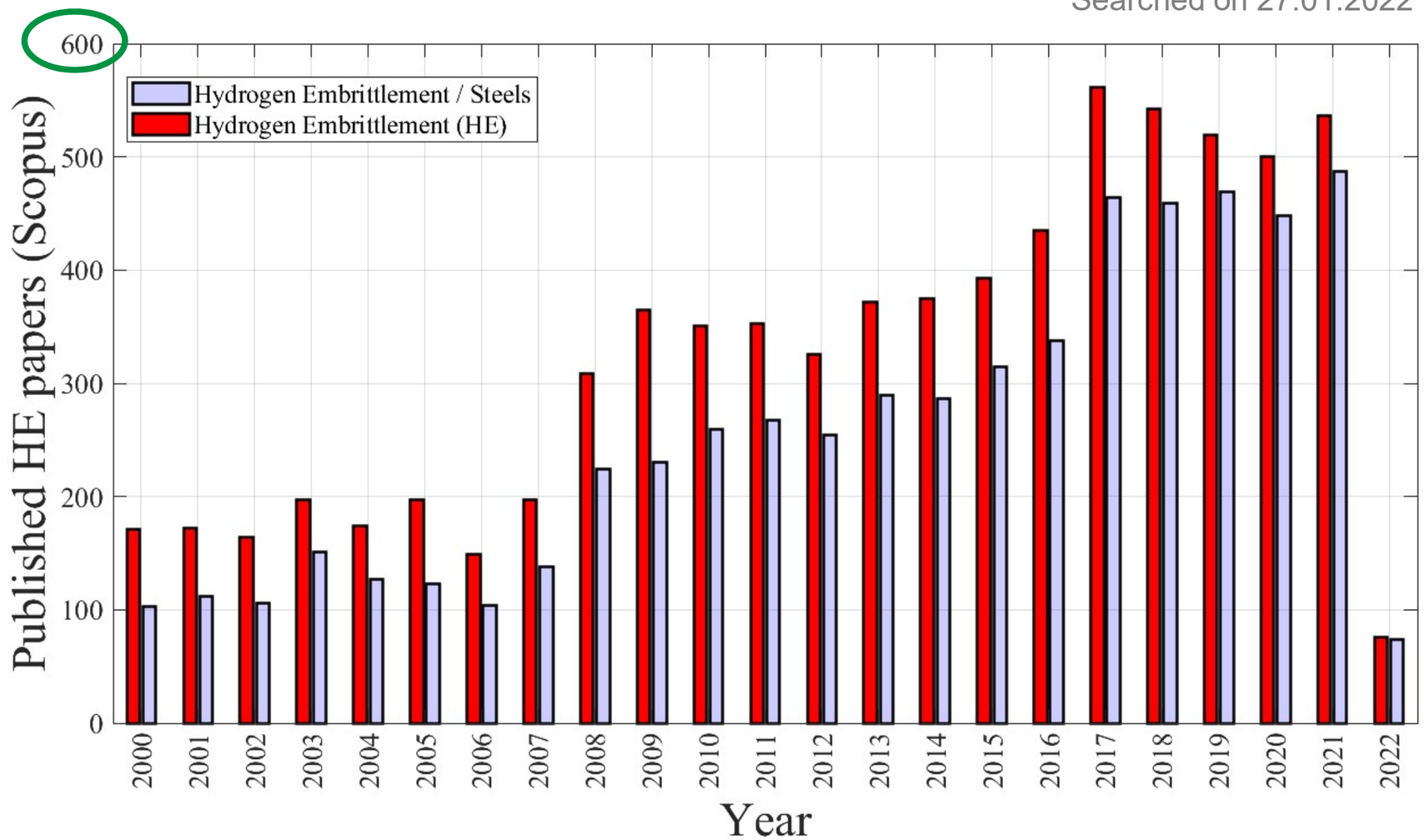
OF THE

ROYAL SOCIETY OF LONDON.

From November 19, 1874, to June 17, 1875.

VOL. XXIII.

…



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1. H gas **embrittles most metals** (e.g. Steels, Ni, Ti, Al)



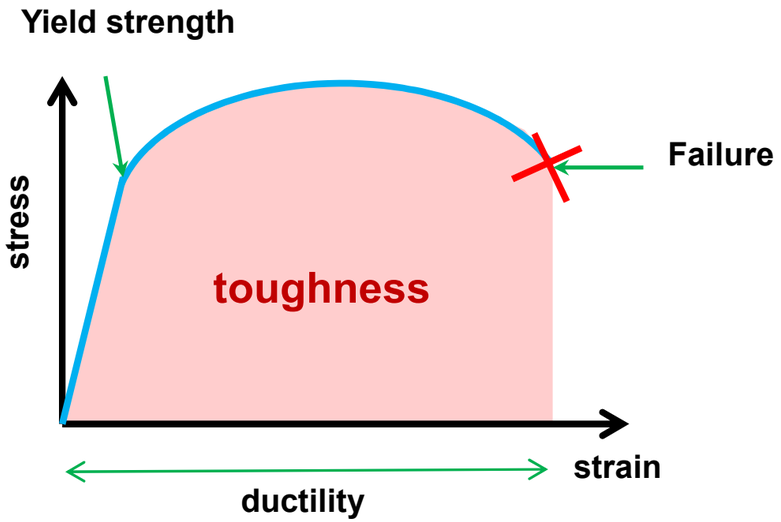
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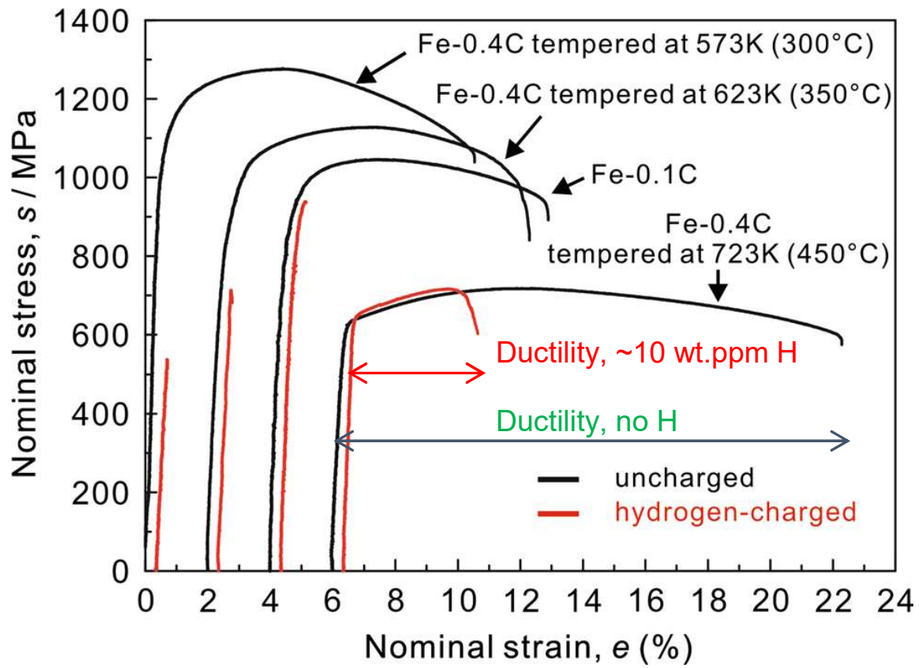
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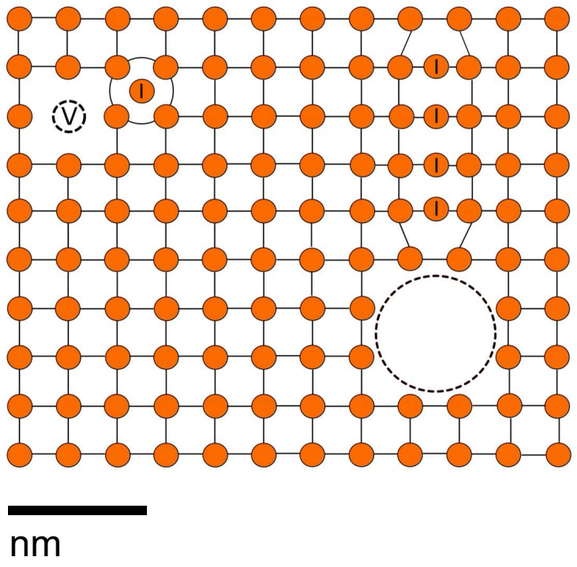


Shibata et al. (2017) Mater. Sci. Tech. 33, 1524

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Courtesy of Dr. Varun Shah

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PROBLEM

No consensus on what causes HE

→ **HE unpredictable**

The proposed mechanisms at the origin of HE

1960, Troiano: Hydrogen-enhanced decohesion (HEDE)

1972, Beachem: Hydrogen-enhanced localized plasticity (HELP)

1998, Nagumo et al.: Hydrogen-enhanced strain-induced vacancies (HESIV)

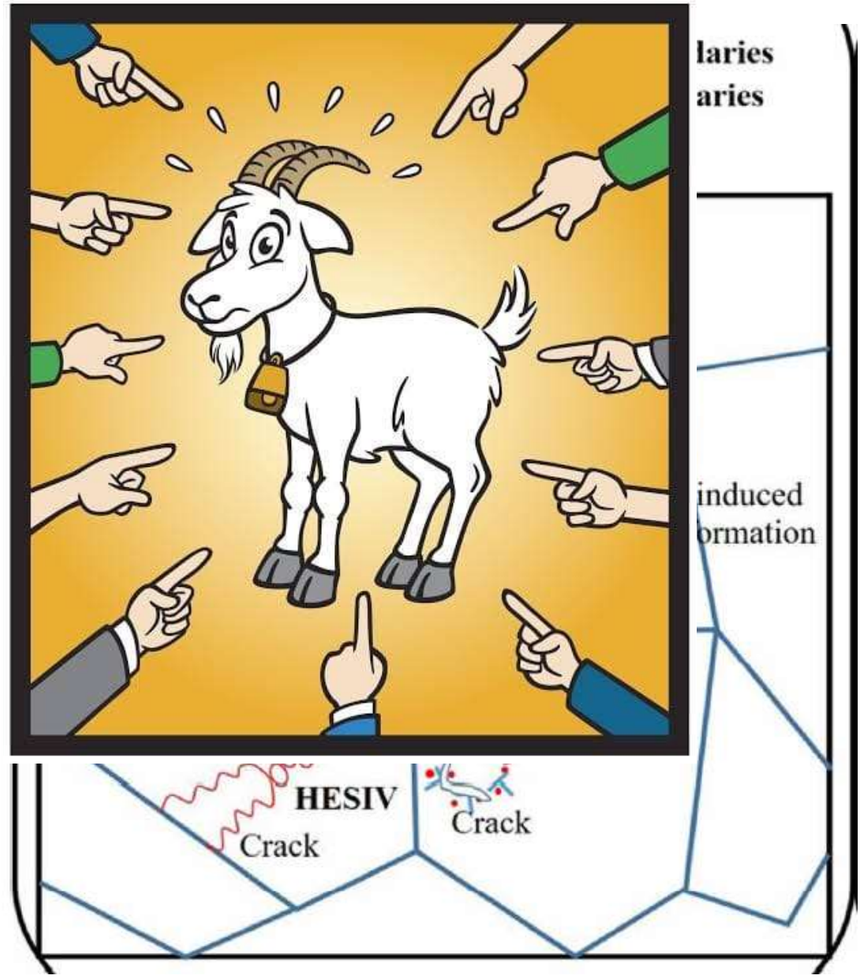
2011, Song and Curtin: Nano-hydride formation theory

2018, Nagao et al.: Combination of HEDE + HELP

2020, Shishvan et al.: Hydrogen Induced Fast Fracture (HIFF)

→ **So, what controls HE?**

https://www.theblacksheep.community/scapegoat-theory/



Gong et al. (2020) Science Adv. 6, eabb6152

Conclusions / Part II

1. **Hydrogen embrittlement (HE)**
   Well-known problem (~150 years old), origin still poorly understood

2. **Predicting hydrogen-induced fracture**
   Limited by poor understanding. Different, sometimes contradicting mechanisms proposed

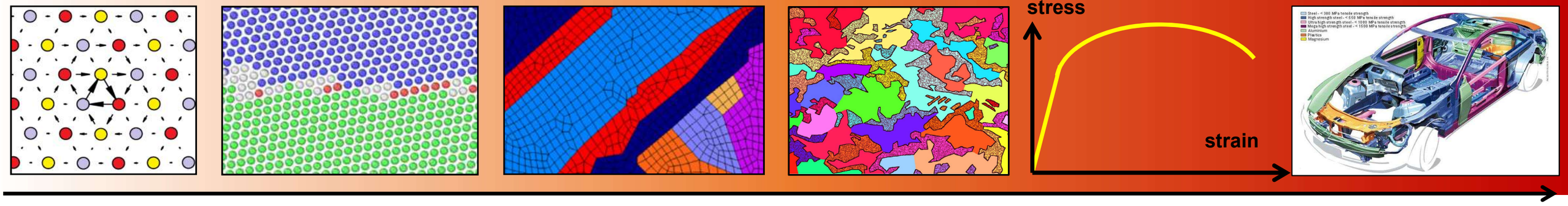
→ Lack of predictive model for **hydrogen-induced fracture**
poses a challenge for hydrogen transport in pipelines

(including lifetime assessment of all metal components in contact with hydrogen)

→ Lack of **standards** (e.g. Eurocode) for structures in H environment
ASME standards present, yet with significant uncertainty (e.g. lifetime fatigue)

> Motivates ongoing research efforts within HyTROS programme: https://groenvermogennl.org/project/hytros/
(Hydrogen Transport, Offshore and Storage)

groen vermogennl | Accelerating and realising the green hydrogen and green chemistry economy



Energy transition and materials mechanics across the scales

The case of hydrogen embrittlement

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