Critical Structural Integrity Challenges for the Energy Sector: Stress Corrosion Cracking and Hydrogen Embrittlement

Session 6: View of Digital Technologies as a Tool for Studying Stress Corrosion Cracking

30 de março de 2023

INSTITUTO NACIONAL DE TECNOLOGIA

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

GOVERNO FEDERAL

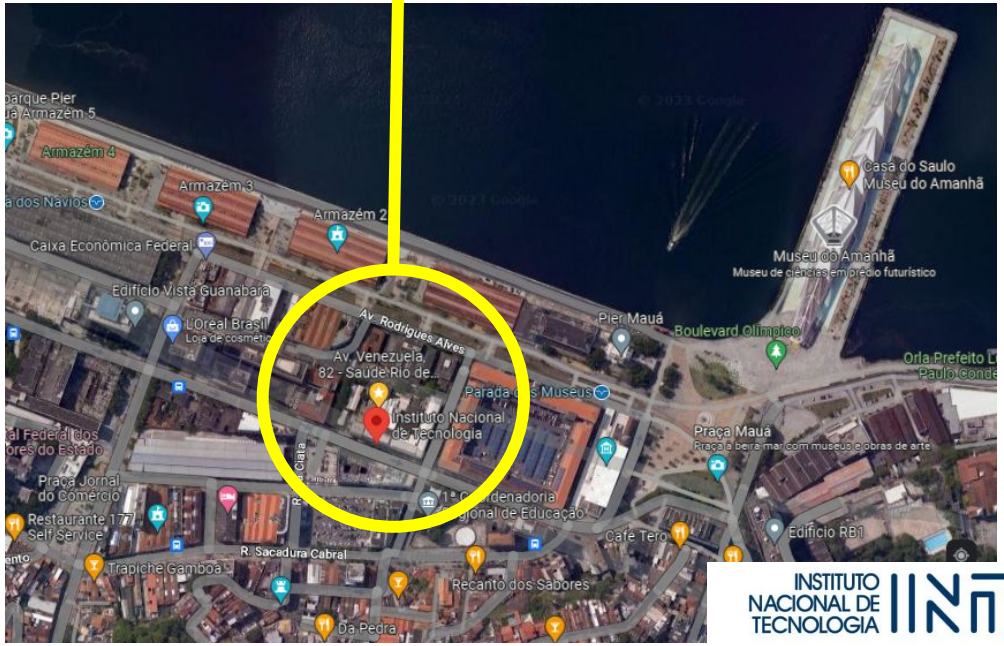
BRASIL

UNIÃO E RECONSTRUÇÃO

Introduction – General Information

National Institute of Technology (NIT)

- NIT is localized in the downtown of Rio de Janeiro and is an institution committed to innovation since 1921.
- NIT is linked to the Ministry of Science, Technology and Innovation (MCTI) and undertakes advanced research aimed at transferring technology to the productive sector, in addition to offering highly complex technological services.
- NIT has 23 laboratories, and their main areas are Catalysis and Biocatalysis; Corrosion; Bioprocessing and Bioproducts; Materials Engineering; Renewable Energies and Energy Efficiency; Evaluation of Processes, and Products; Industrial Design; Additive Manufacturing; and Production Management Technologies.



INSTITUTO NACIONAL DE TECNOLOGIA

The Laboratory of Stress Corrosion Cracking, H2S, CO2, and corrosivity - LAH2S

- LAH_2S plans and executes research and development projects and technological services linked to study the corrosion and degradation of materials exposed to extremely corrosive environments. (Metals / Polymers / Ceramics / Composites)
- LAH_2S gives support to R&D and innovation to O&G, chemical, petrochemical, mining and metallurgical industries.
- The main team is composed by specialists in Chemistry, Physical Metallurgical, Fracture mechanics and Electrochemistry.
- The laboratory had increased your staff with collaboration between NIT's laboratories such as LAMAP, LACPM, CENANO and LACAT and some laboratories from UFF and PUC-Rio
- LAH2S simulates service conditions of High Pressure (**70MPa**) and High Temperature (**300ºC**)

INSTITUTO NACIONAL DE TECNOLOGIA INT

SKILLS - LAH2S

SKILLS

- Chemistry / Electrochemistry
- Physical Metallurgical
- Fluid Mechanics
- Solid Mechanic

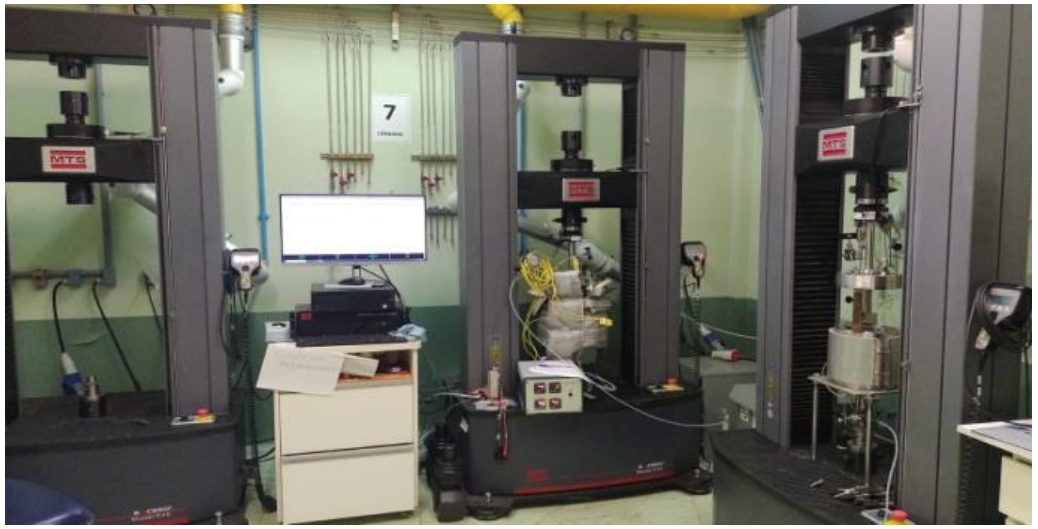
DEVELOPING SKILLS

- Multiphysics Simulation
- Corrosion Management
- Electronic
- Automation of Test Systems

INSTITUTO NACIONAL DE TECNOLOGIA INT

Research, Development and Innovation – LAH2S

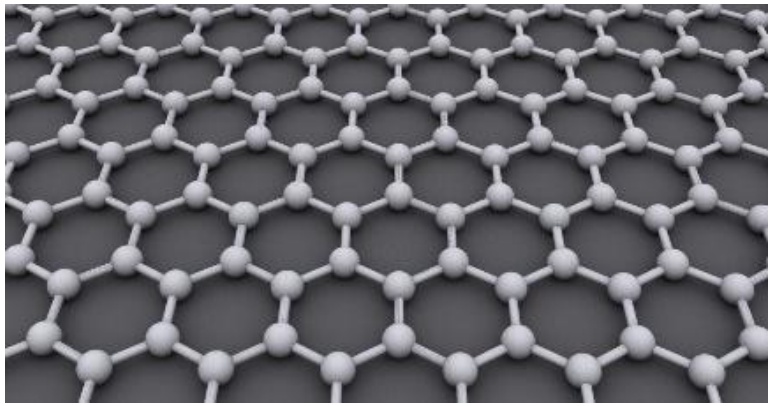
- *Environmentally-Assisted Cracking (H_2, NH_3, H_2S, CO_2, Chlorides and ethanol)*
  - **Fracture Mechanics – Corrosive Environmental**
  - **Fatigue Corrosion (S-N, ε-N, and da/dN)**
  - **Stress Corrosion Cracking**
  - **Hydrogen Induced Cracking**
  - **Hydrogen Embrittlement**
- *Sour and Sweet Corrosion*
- *Localized Corrosion*
- *Corrosion Prevention and Control*
  - **Performance of Corrosion Inhibitors**
  - **Performance of H_2S scavengers**
  - **Performance of Coatings**
- *Failure Analyses*
- *Material Selection for sour service*
- *Polymers degradation in presence of H_2S and CO_2*
- *Well cementing integrity in presence of H_2S and CO_2*



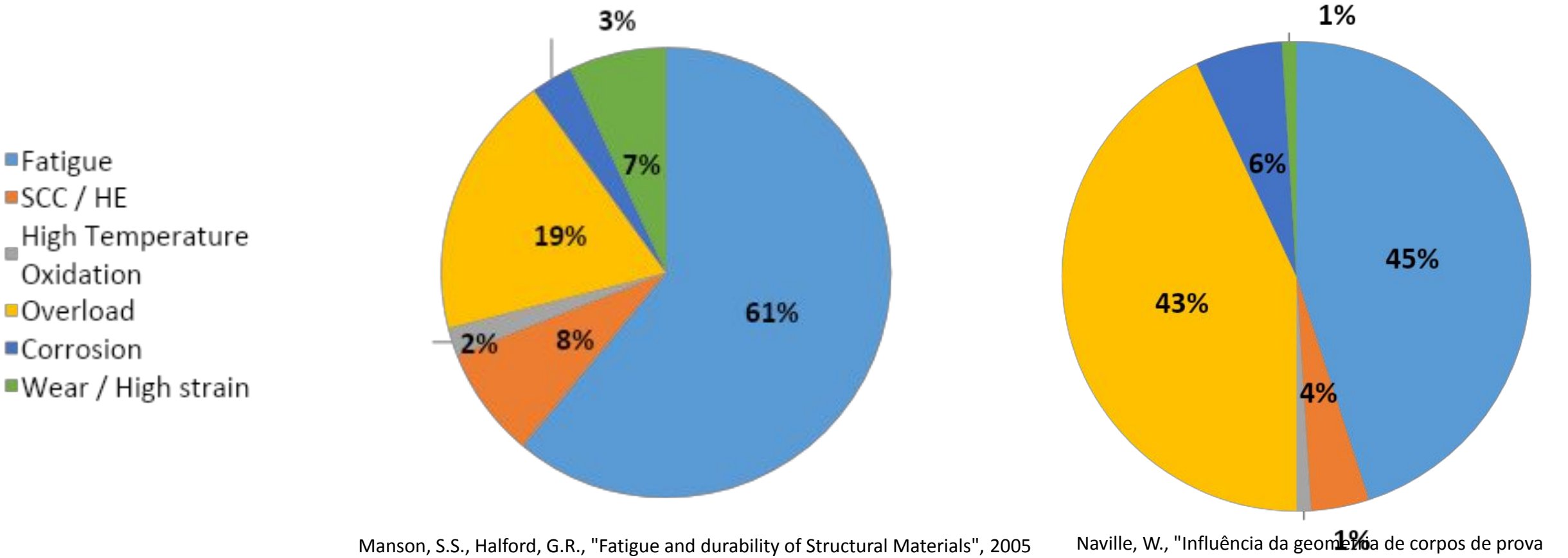
INSTITUTO NACIONAL DE TECNOLOGIA INT

PD&I Applications – LAH2S

- *Oil and Gas*
- *Mining*
- *Steelwork*
- *Additive manufacturing*
- *Removable Energies (hydrogen, ethanol, Syntheses Gas)*
- *Advanced materials (graphene, Titanium)*
- *Chemical*



Structural Integrity: Failure Mechanisms



Manson, S.S., Halford, G.R., "Fatigue and durability of Structural Materials", 2005

Naville, W., "Influência da geometria de corpos de prova na previsão de vida em fadiga de baixo ciclo de chapas de aço (ARBL) bifásicos", 2009

Computational Tools applied to corrosion

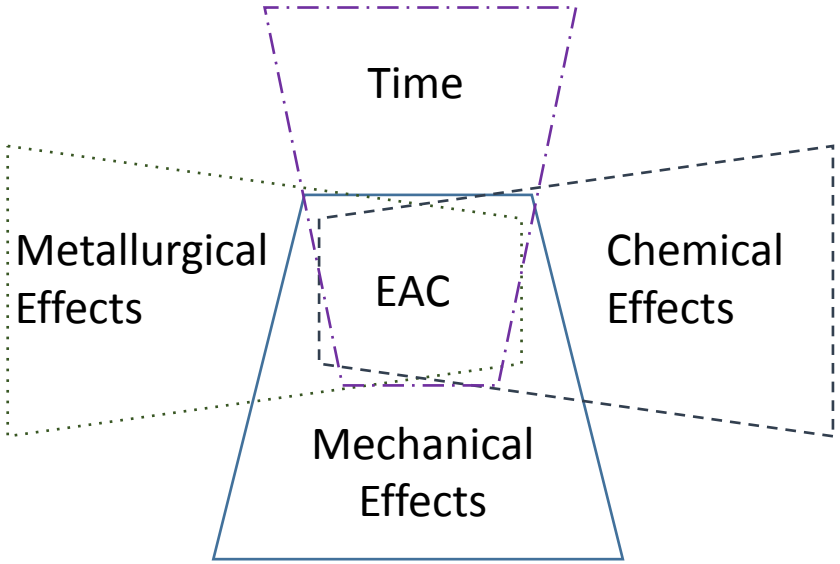
- *Corrosion Management*
  - *AI, Machine Learning, and Digital Twins*
- *Corrosion and Protection*
  - *Multi-physics modelling with data-driven analytics*
- *Recent Challenges:*
  - *How to apply Digital Technologies for SCC and HE*

Computational Tools applied to corrosion

- *Why we should apply digital technologies*
  - *Financial loss due to corrosion (US$65Billion) (NACE-AMPP)*
  - *Corrosion Management can reduce losses in 15% – 20% (NACE)*
  - *It can reduce the number of small and full-scale tests and increase the TRL of Research Projects*
  - *Powerful tools to analyze structural integrity, crack propagation, and some Multiphysics problems are available in commercial software (Comsol, Ansys, Matlab).*
    (Phased field, Corrosion, …).

- *Mechanical driven forces:*

Applied Stress and Stress Intensity Factor



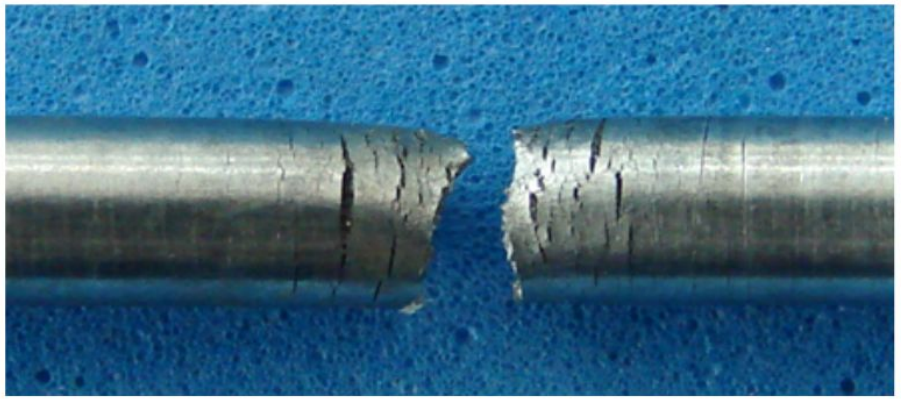
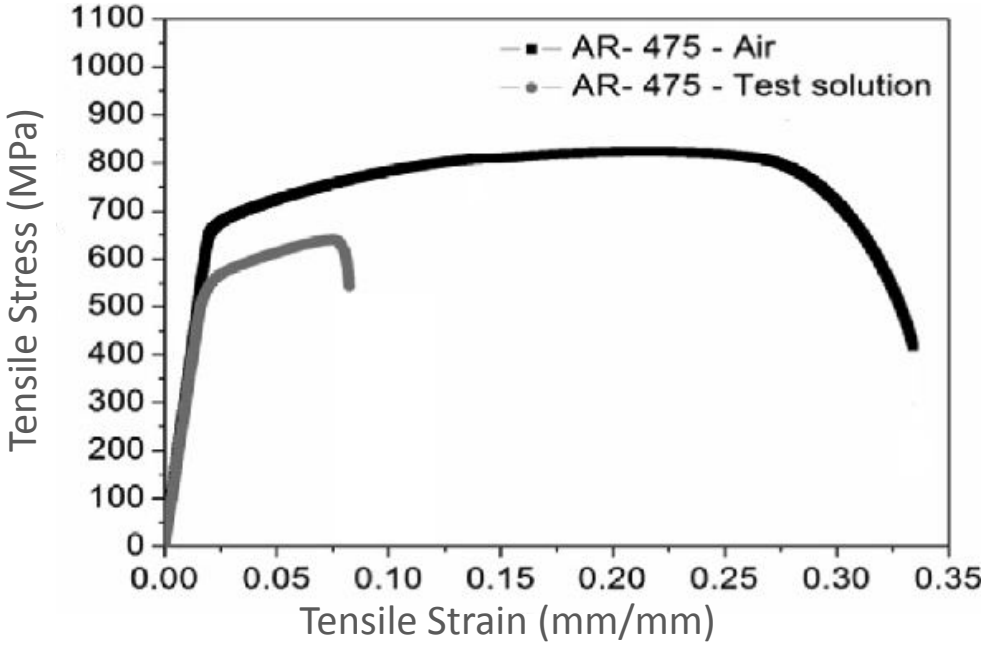


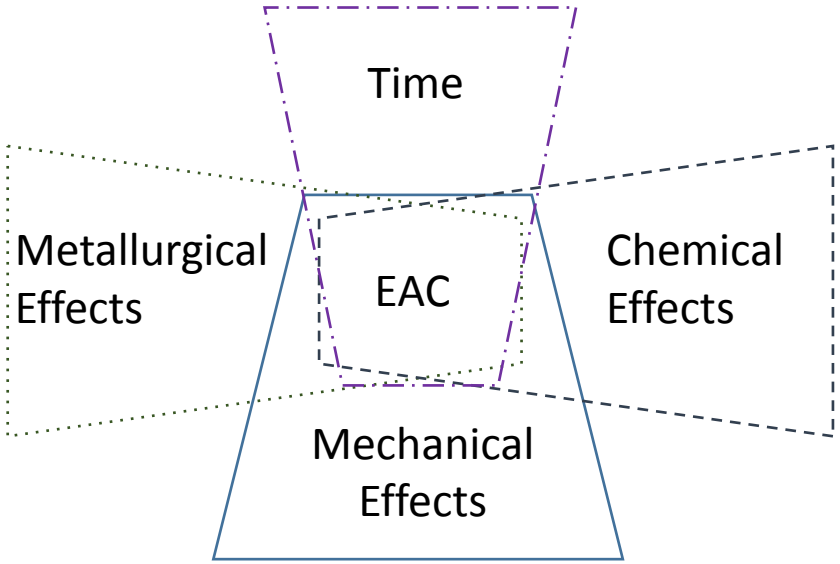
Fig.: SSC on a Martensitic Stainless Steel



SCC and Hydrogen Embrittlement

- *Mechanical driven forces:*

Applied Stress and Stress Intensity Factor

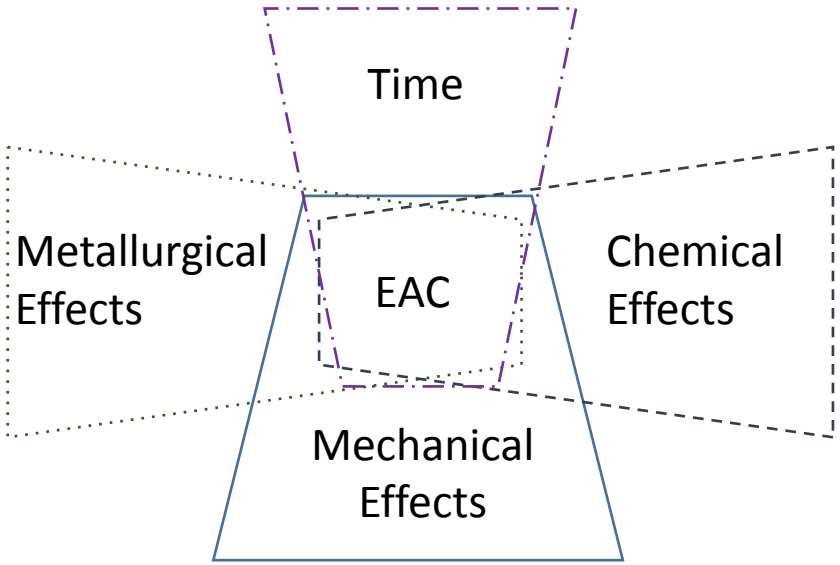


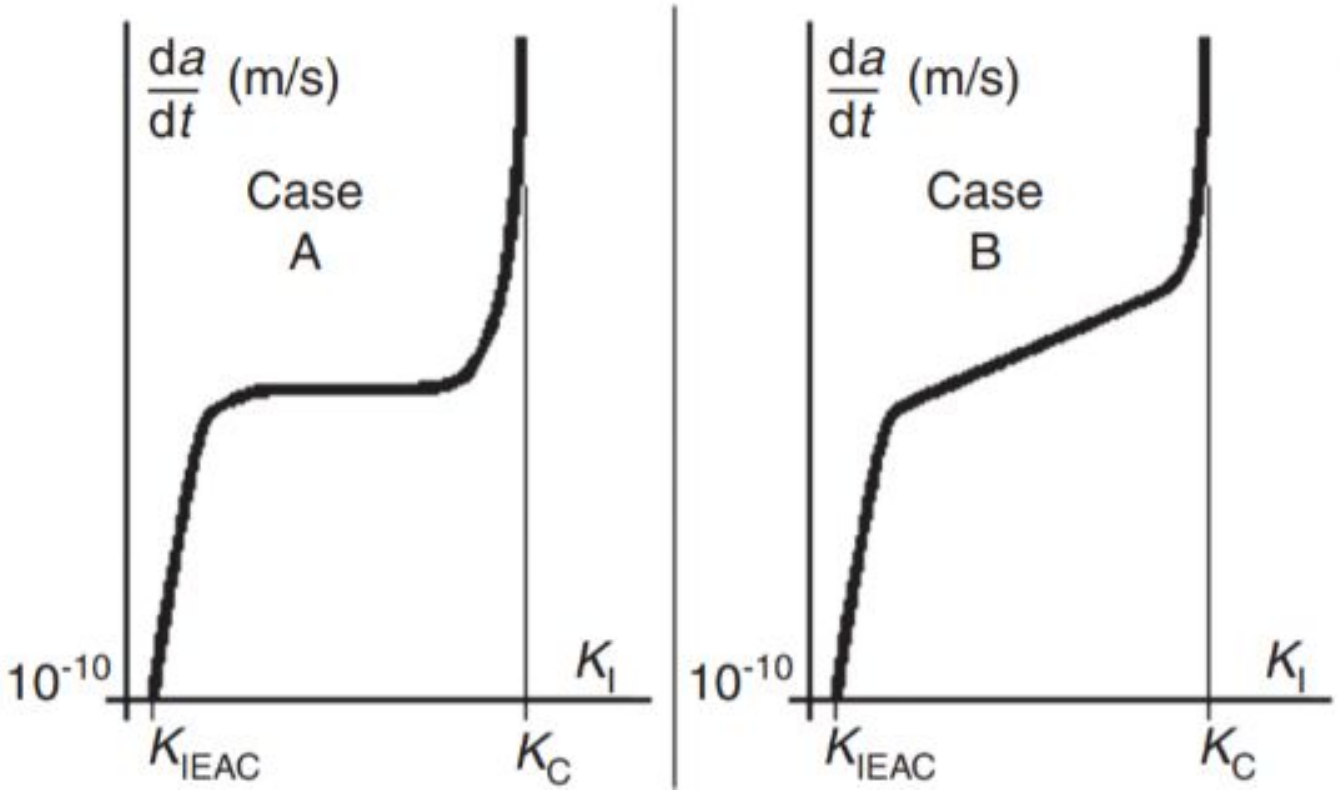
Typical S x t curve obtained from smooth specimens

INSTITUTO NACIONAL DE TECNOLOGIA INT

- *Mechanical driven forces:*

Applied Stress and Stress Intensity Factor



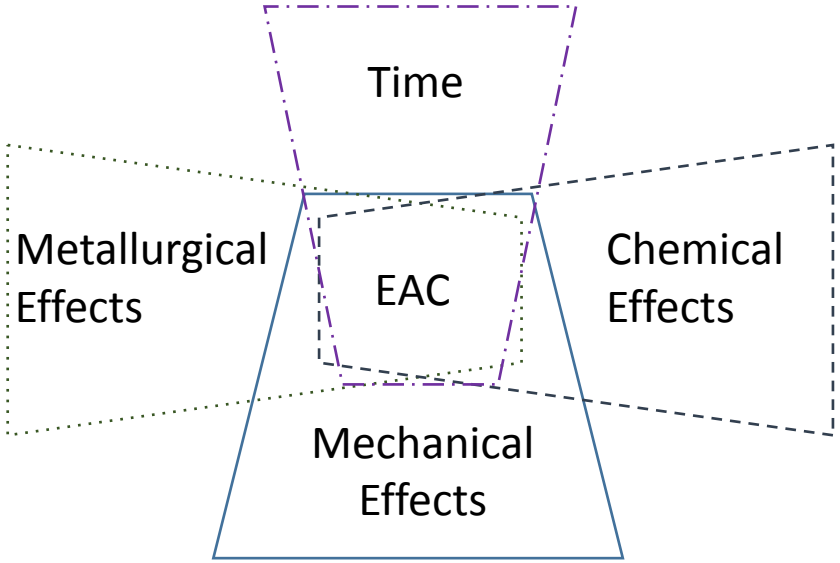


Typical da/dt x K_I crack growth under EAC

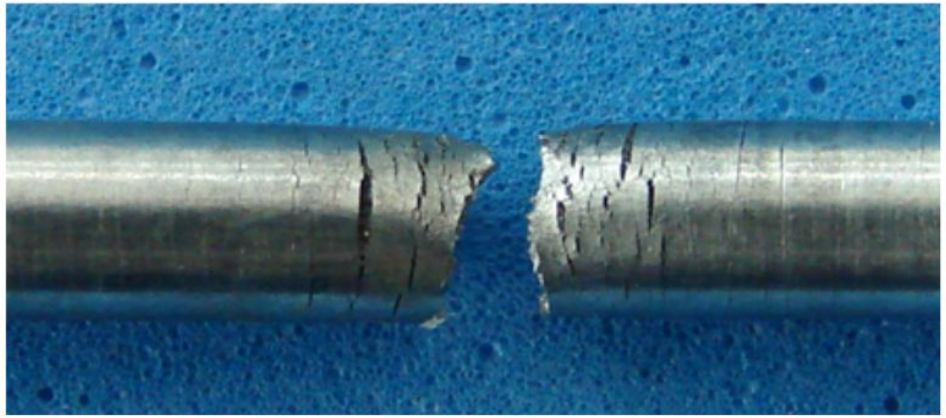
SCC and Hydrogen Embrittlement

- *Mechanical driven forces:*

Applied Stress and Stress Intensity Factor

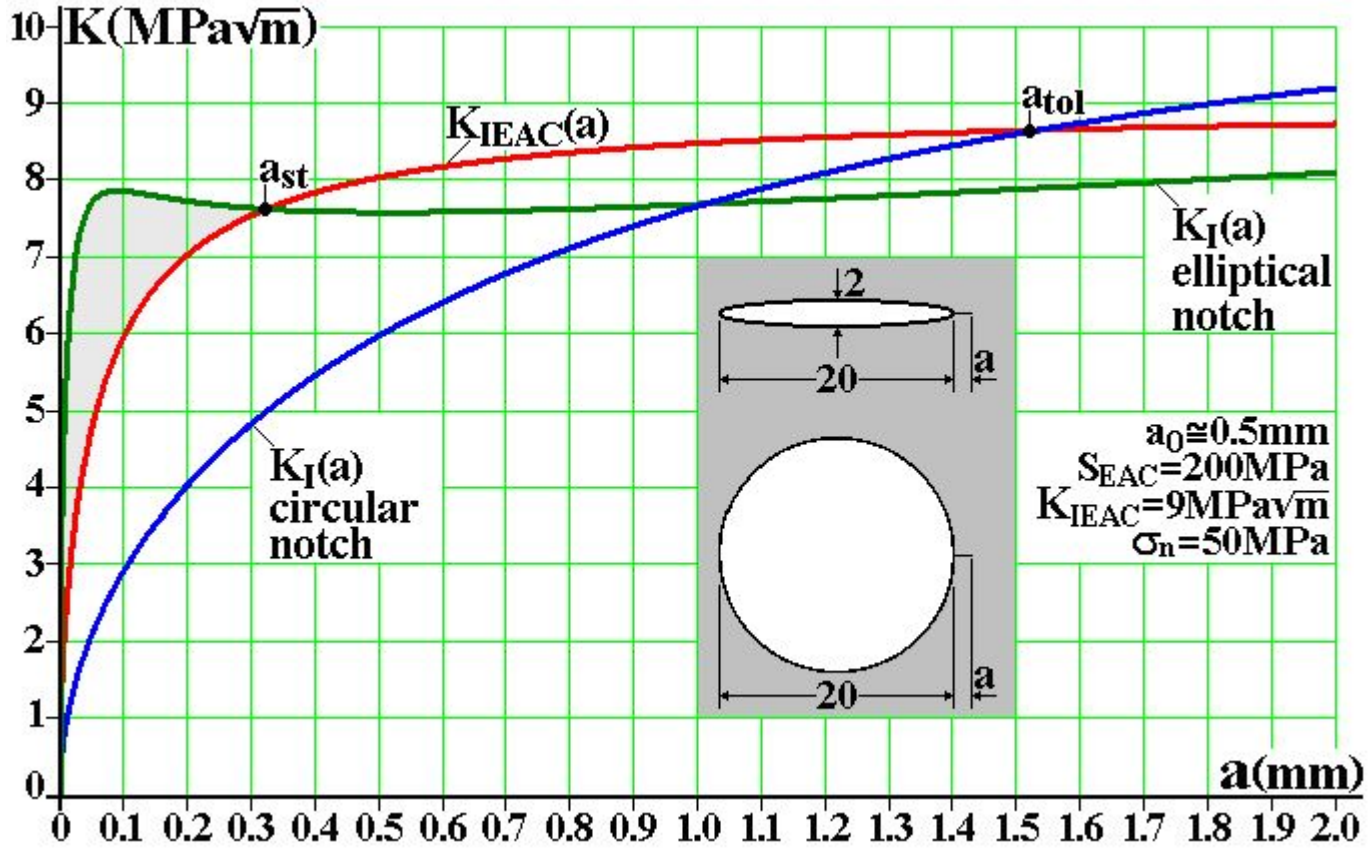


Corrosion Management: *Avoid Cracks!*



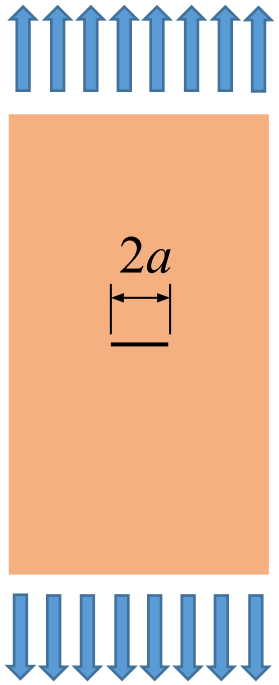
How can we avoid SCC and HE propagating cracks

- *KI applied below the red line*

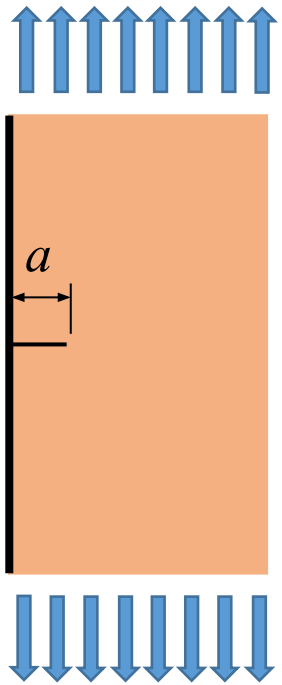


INSTITUTO NACIONAL DE TECNOLOGIA

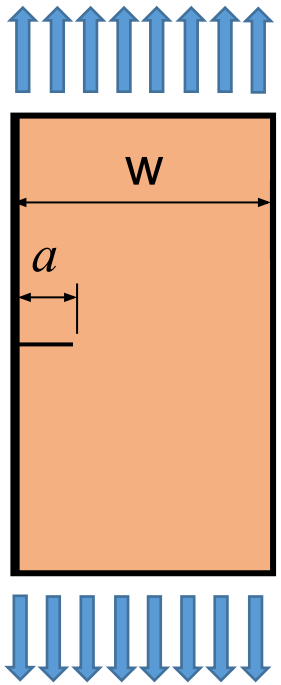
How can we avoid SCC and HE propagating cracks



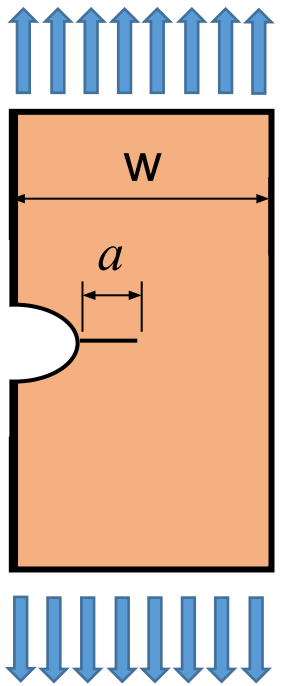
$K_I = \sigma\sqrt{\pi a}$



$K_I = \boldsymbol{\eta}\,\sigma\,\sqrt{\pi a}$



$K_I = \eta\,\sigma\,\sqrt{\pi a}\,\boldsymbol{f}(^{a}/_{w})$



$K_I = \eta\,\sigma\,\sqrt{\pi a}\,f(^{a}/_{w})\,\boldsymbol{\phi}(^{\boldsymbol{a}}/_{\boldsymbol{w}})$

Stress Gradient (FEM)

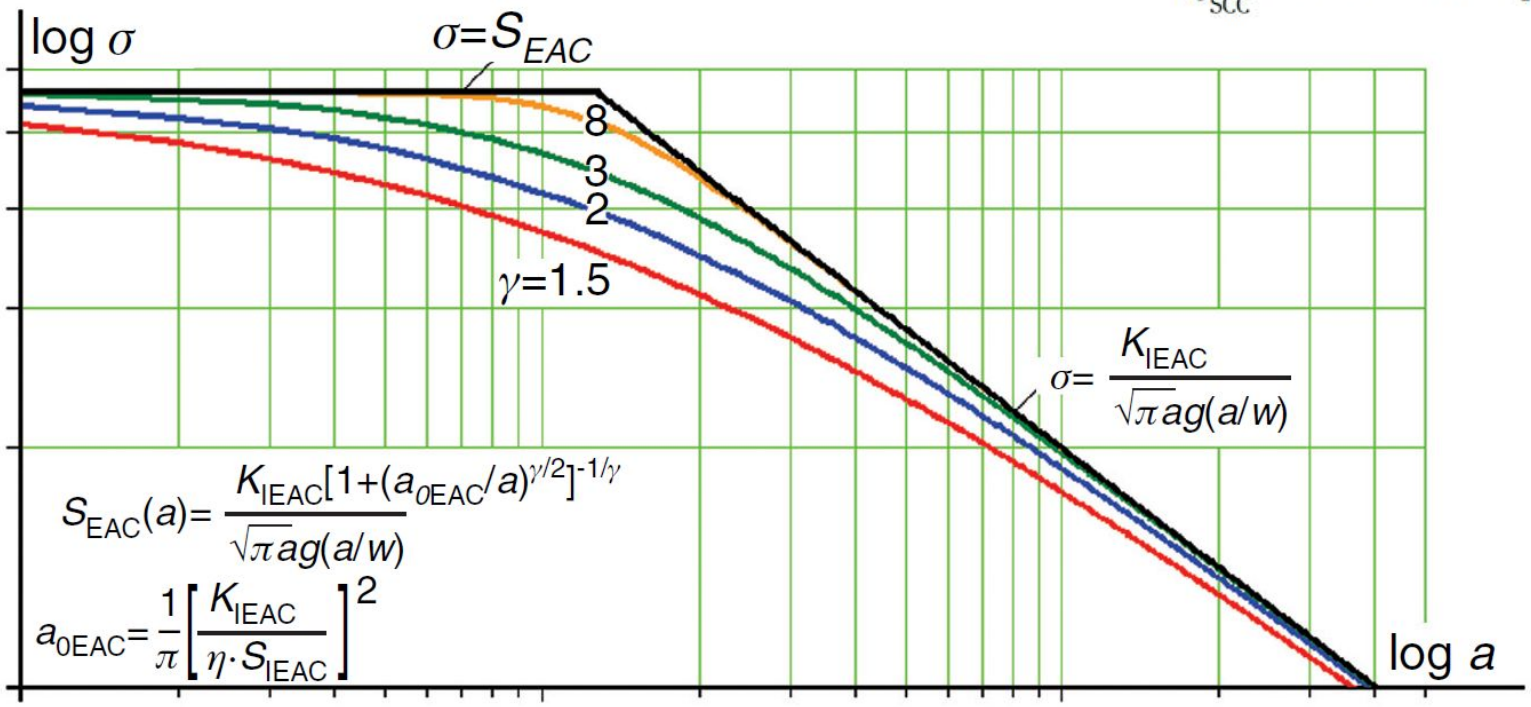
Stress Intensity Factor

INSTITUTO NACIONAL DE TECNOLOGIA INTI

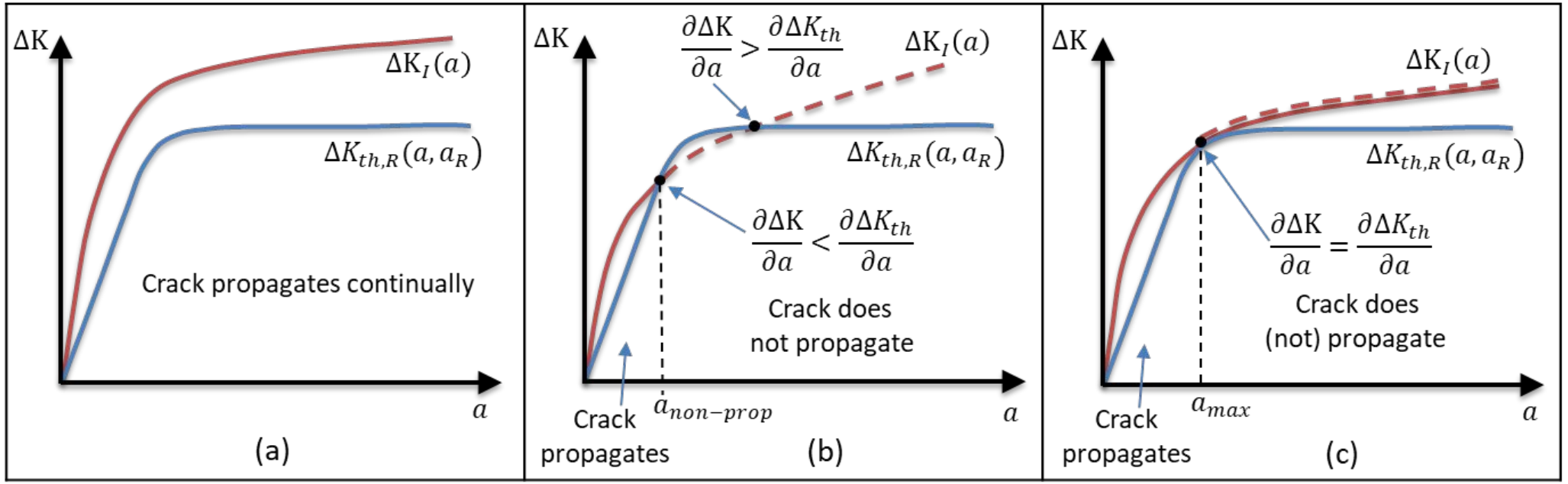
How can we avoid SCC and HE propagating cracks

$$\sigma_{max} \leq K_{ISCC} \Big/ \left\{ \sqrt{\pi a} \cdot g(a/w) \cdot \left[1 + (a_{0_{SCC}} / a)^{\gamma/2} \right]^{1/\gamma} \right\}$$

$$a_{0_{SCC}} = (1/\pi)[K_{ISCC} / \eta \cdot S_{SCC}]^2 .$$

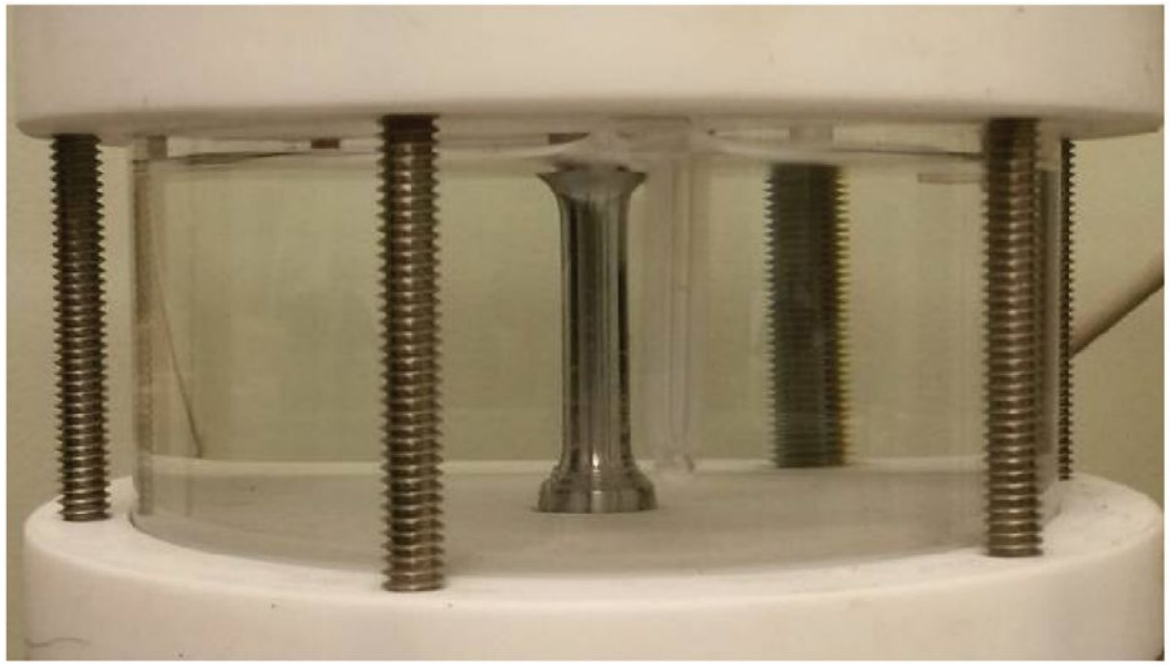


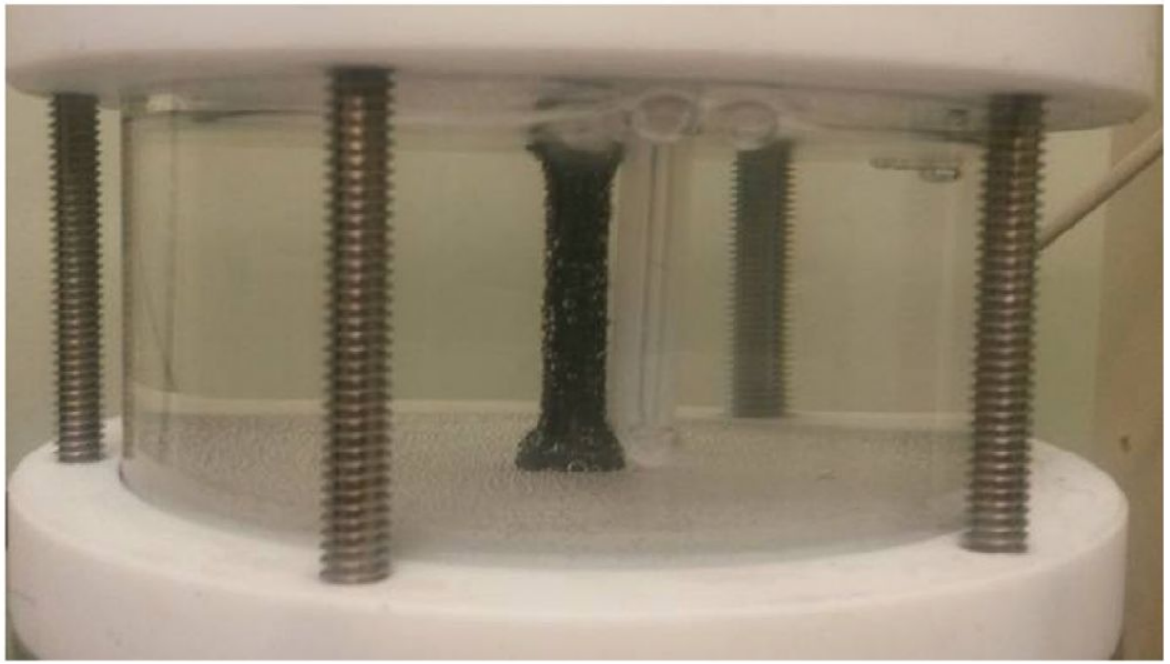
How can we avoid SCC and HE propagating cracks



Mengen Liu et al., "Plastic stress concentration effects in fatigue strength, International Journal of Fatigue", Vol. 168, 2023. https://doi.org/10.1016/j.ijfatigue.2022.107394.

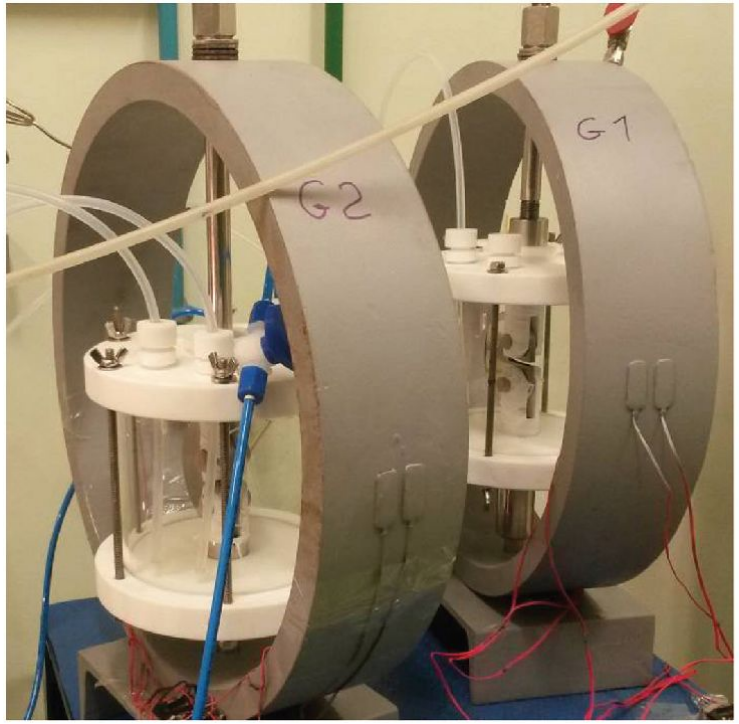
- *NACE TM177 method A Sol. B| Carbon Steel 4140*

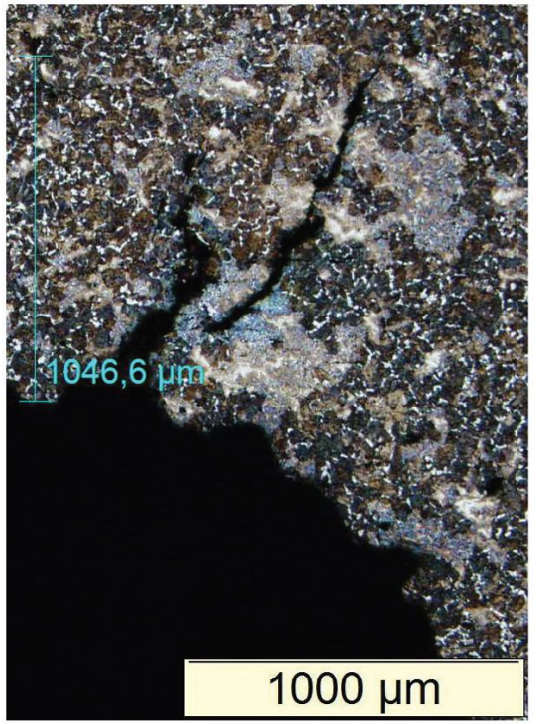


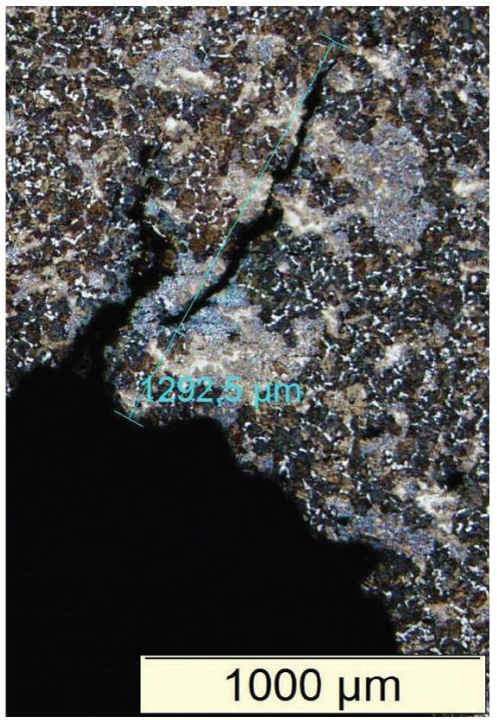


SCC and Hydrogen Embrittlement

- *NACE TM177 Sol. B| Carbon Steel 4140*
- *Constant load test | Non propagating crack*



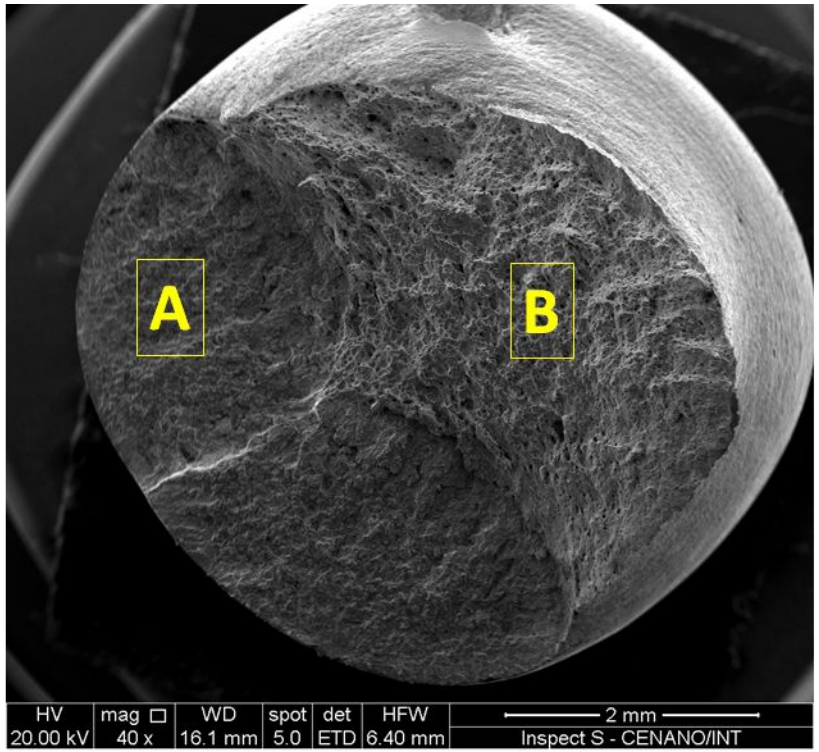


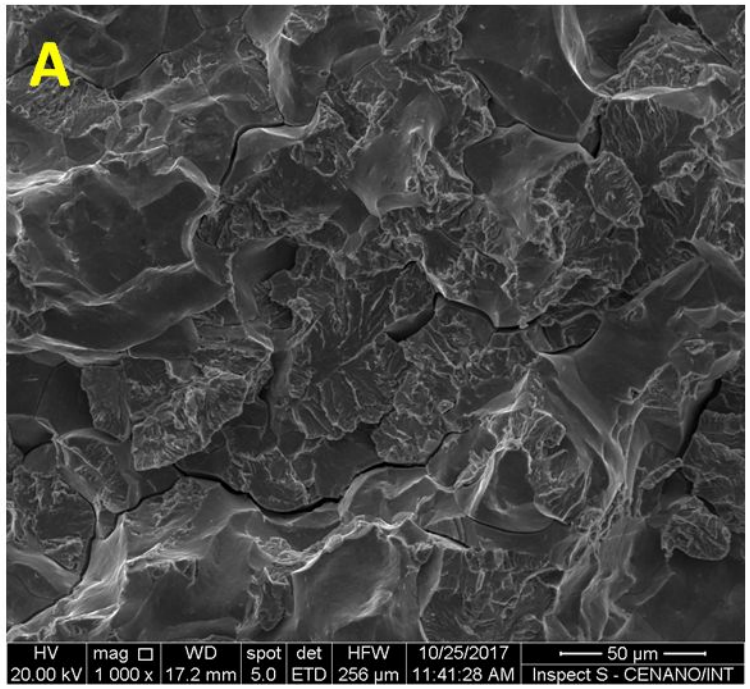


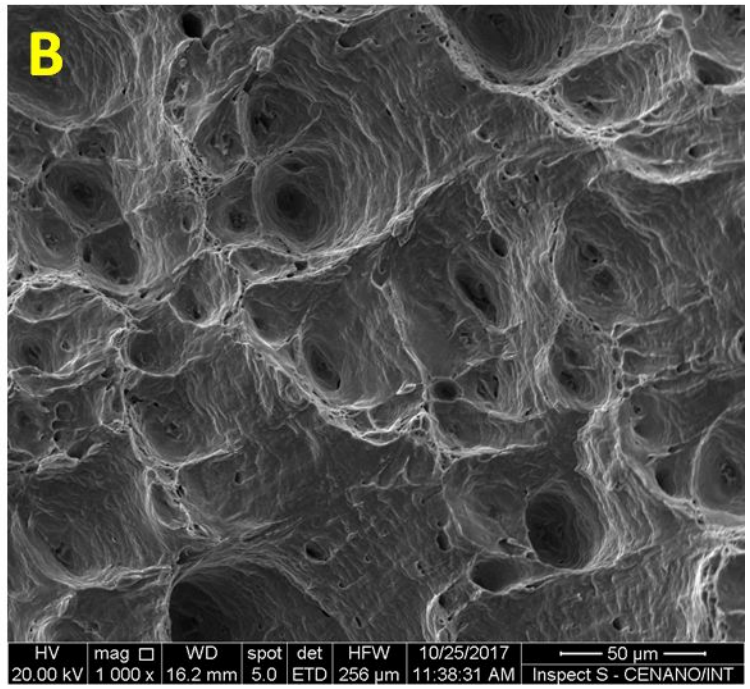
Carbon Steel Sample with

SCC and Hydrogen Embrittlement

- *Tests with S13Cr UNS41426 | Brine solution (100g/L NaCl) pH 4, 250mbar H_2S, 750mbar CO_2*

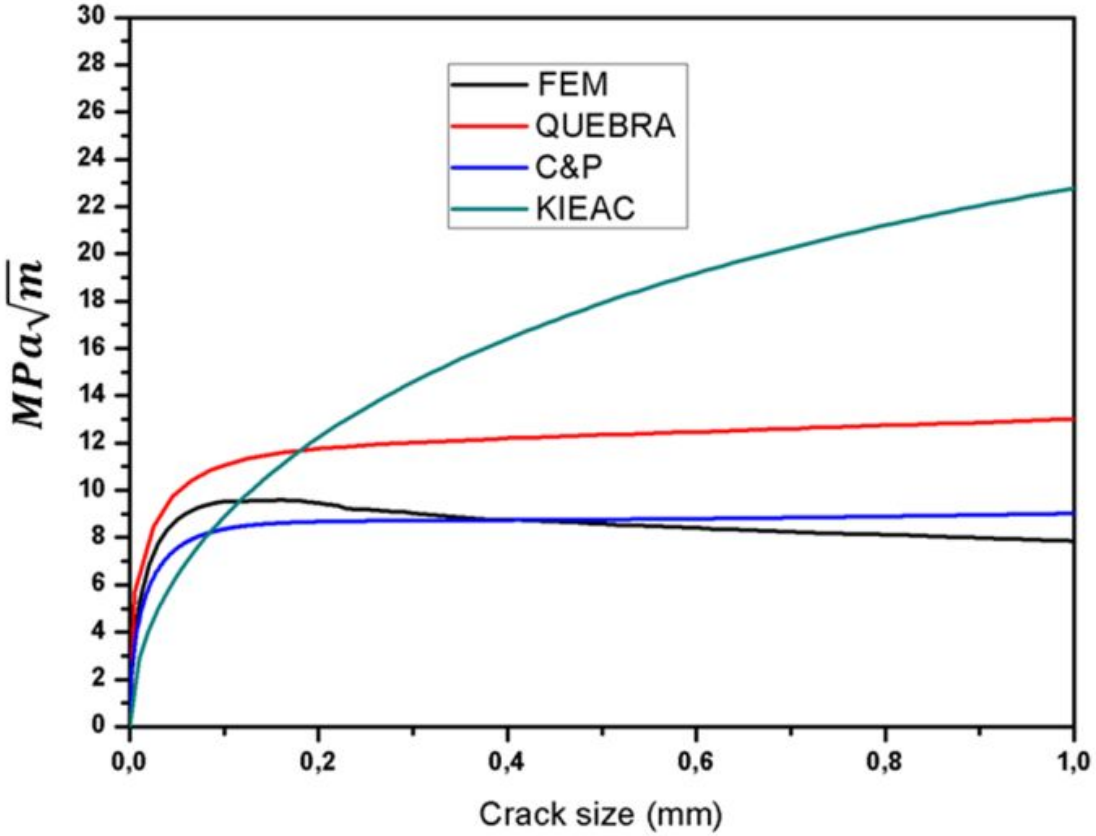


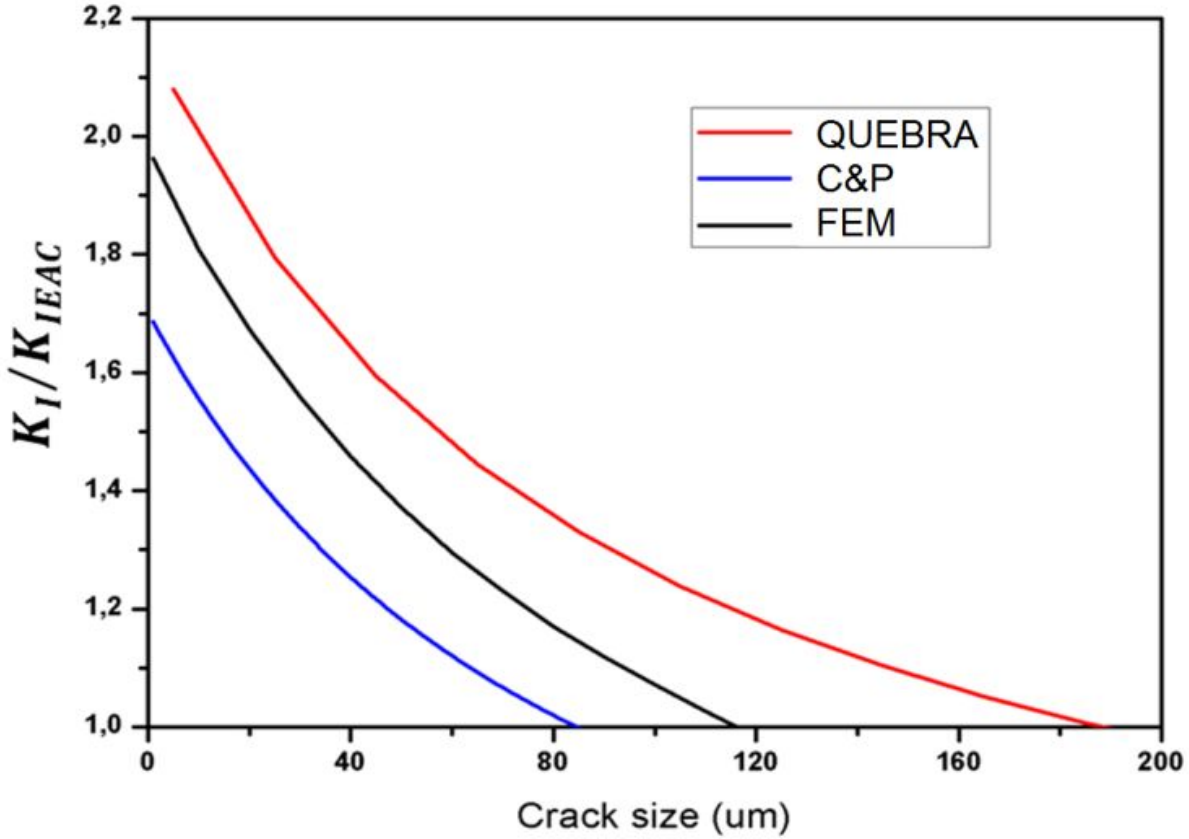




INSTITUTO NACIONAL DE TECNOLOGIA INT

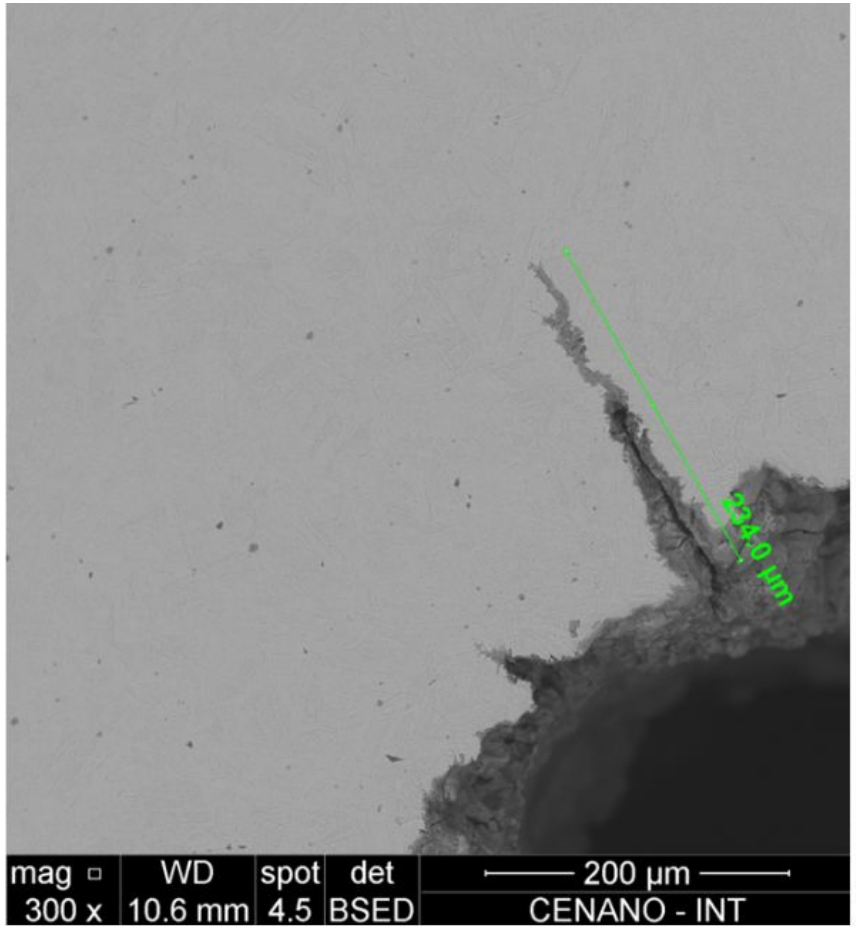
- *Tests with S13Cr UNS41426 | Brine solution (100g/L NaCl) pH 4, 250mbar H_2S, 750mbar CO_2*

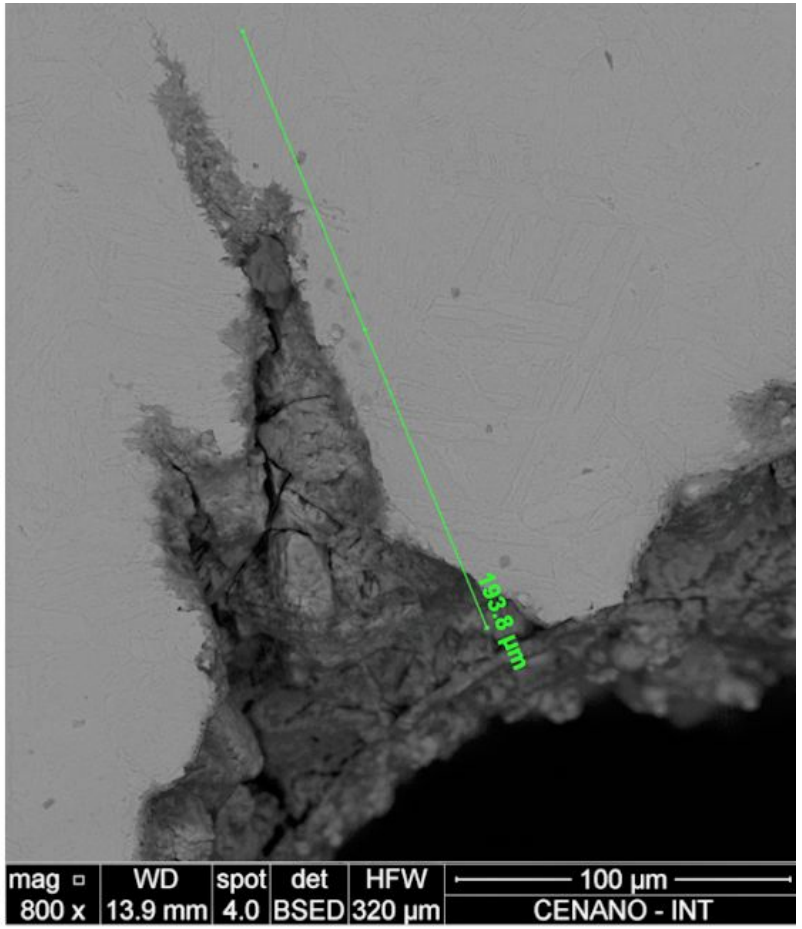




SCC and Hydrogen Embrittlement

- *Tests with S13Cr UNS41426 | Brine solution (100g/L NaCl) pH 4, 250mbar H_2S, 750mbar CO_2*



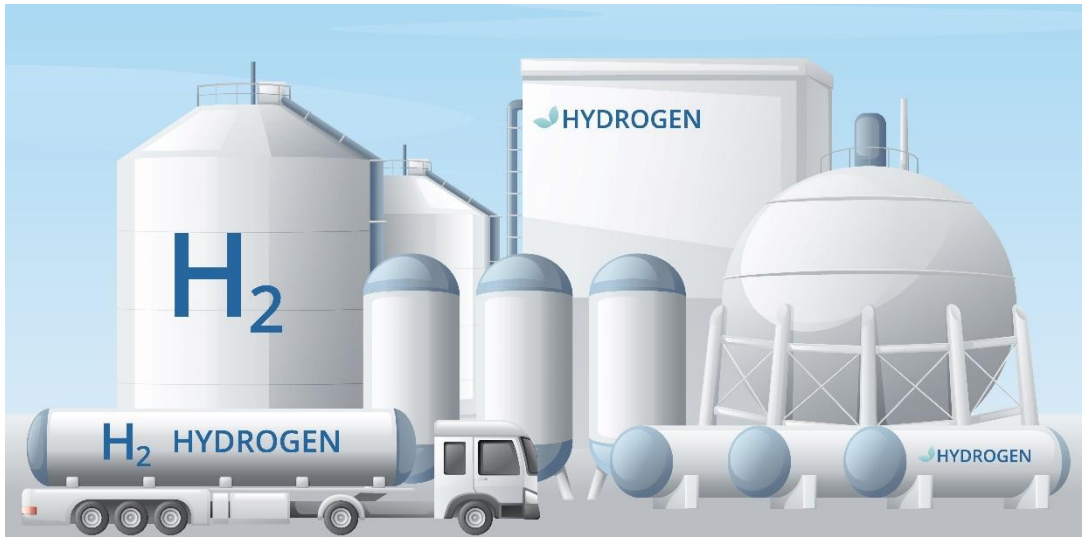


INSTITUTO NACIONAL DE TECNOLOGIA INT

SCC and Hydrogen Embrittlement

- *FEM allows to find* $\boldsymbol{\phi}(^{a}/_{w})$.

$$K_I = \eta\,\sigma\,\sqrt{\pi a}\,f(^{a}/_{w})\boldsymbol{\phi}(^{\boldsymbol{a}}/_{\boldsymbol{w}})$$



https://br.freepik.com/

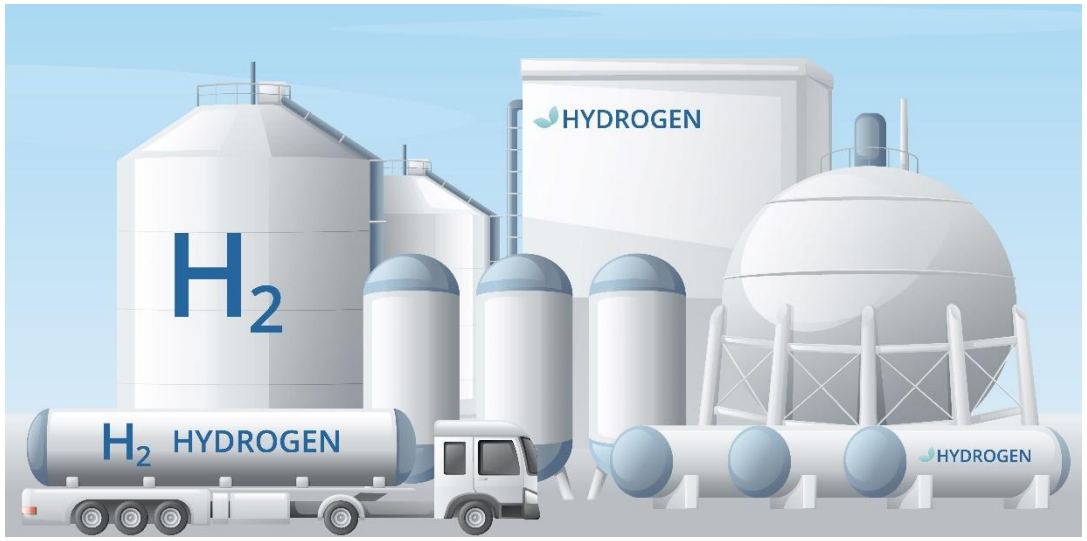
- *KI_{EAC} and S_{EAC} will change for each material/corrosive environment.*

Multiphysics challenge!

INSTITUTO NACIONAL DE TECNOLOGIA INT

SCC and Hydrogen Embrittlement

- *Multiphysics approach for HE under high pressure Gaseous Hydrogen*



https://br.freepik.com/

- *KI_{EAC} and S_{EAC} will change for each material/corrosive environment.*

Multiphysics challenge!

INSTITUTO NACIONAL DE TECNOLOGIA INT

Hydrogen Embrittlement under High Pressure Gaseous H_2

- *Recent projects with Multi-physics modelling to Hydrogen Embrittlement in High Pressure Gaseous H_2*

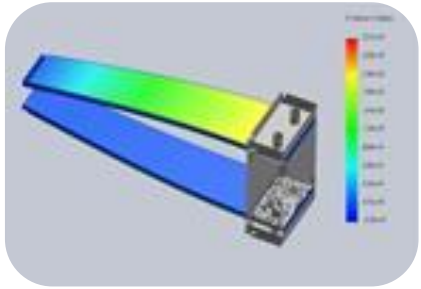
$S_{L\text{-}H2}$ (H_2)
Autoclave System up to 70MPa

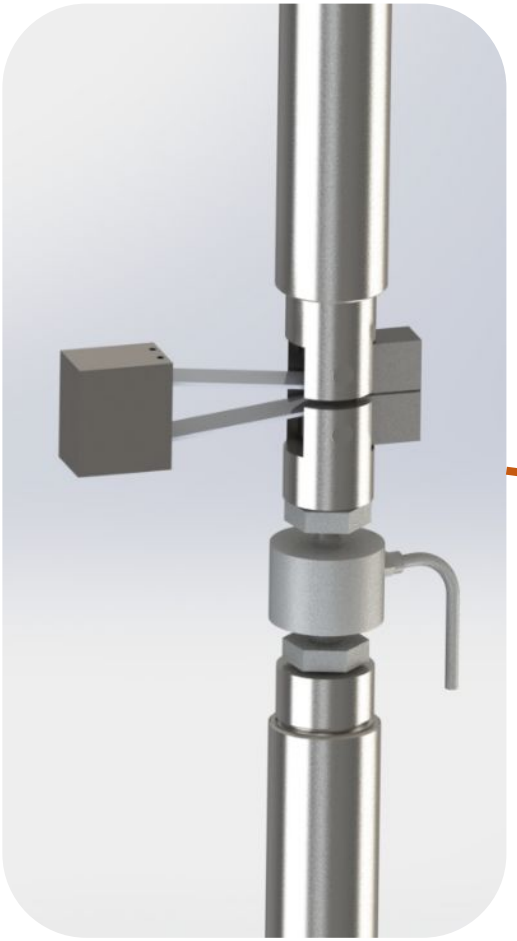
$KI_{TH\text{-}H2}$ (H_2)
Autoclave System up to 35MPa

INSTITUTO NACIONAL DE TECNOLOGIA INNT

Hydrogen Embrittlement under High Pressure Gaseous H_2

- JI_{H2} *in gaseous* H_2 *(up to 20MPa)*

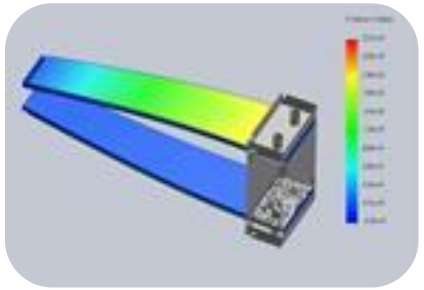


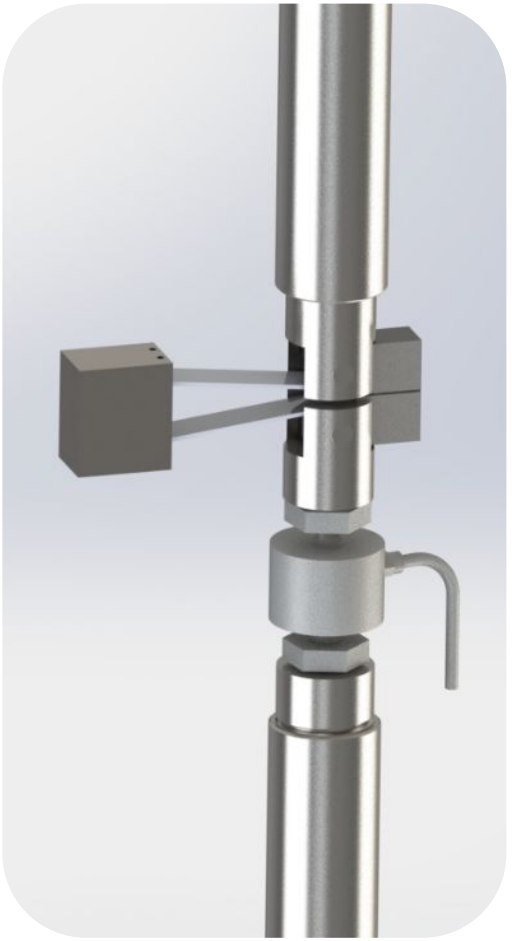


INSTITUTO NACIONAL DE TECNOLOGIA

Hydrogen Embrittlement under High Pressure Gaseous H_2

- ΔK_{TH-H2} *in gaseous* H_2 *(up to 20MPa)*



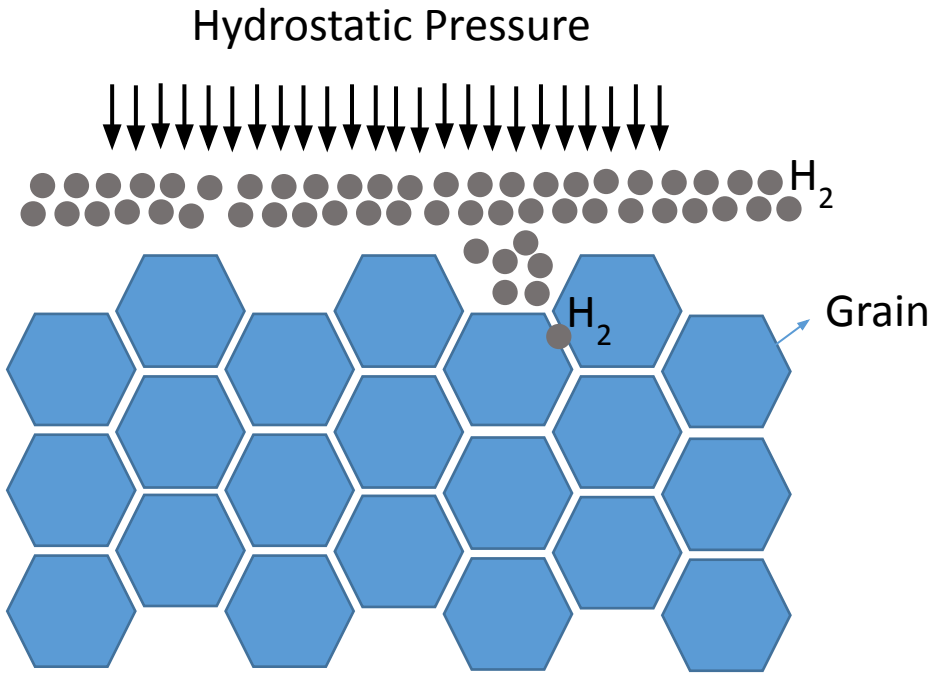


INSTITUTO NACIONAL DE TECNOLOGIA INT

Hydrogen Embrittlement under High Pressure Gaseous H_2

- *On going research: Consider H_2 fugacity in a phased field model for Corrosion Fatigue and Short cracks models.*

- *Consider the $f\,H_2$ effect in $S_{L\text{-}H2}$, $KI_{th\text{-}H2}$, JI_{H2}, and $\Delta\, KI_{th\text{-}H2}$*

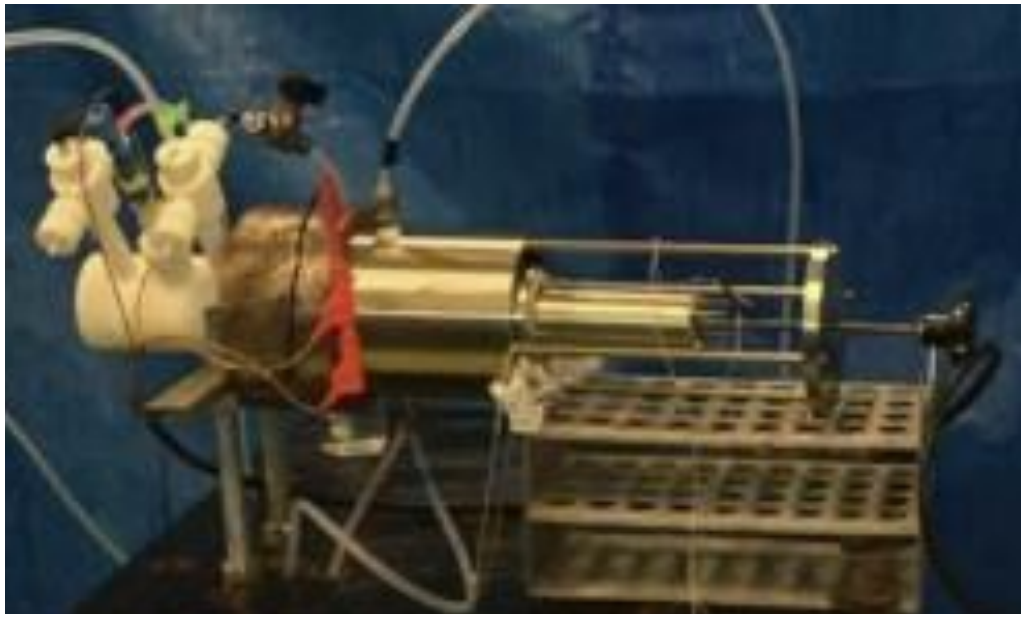


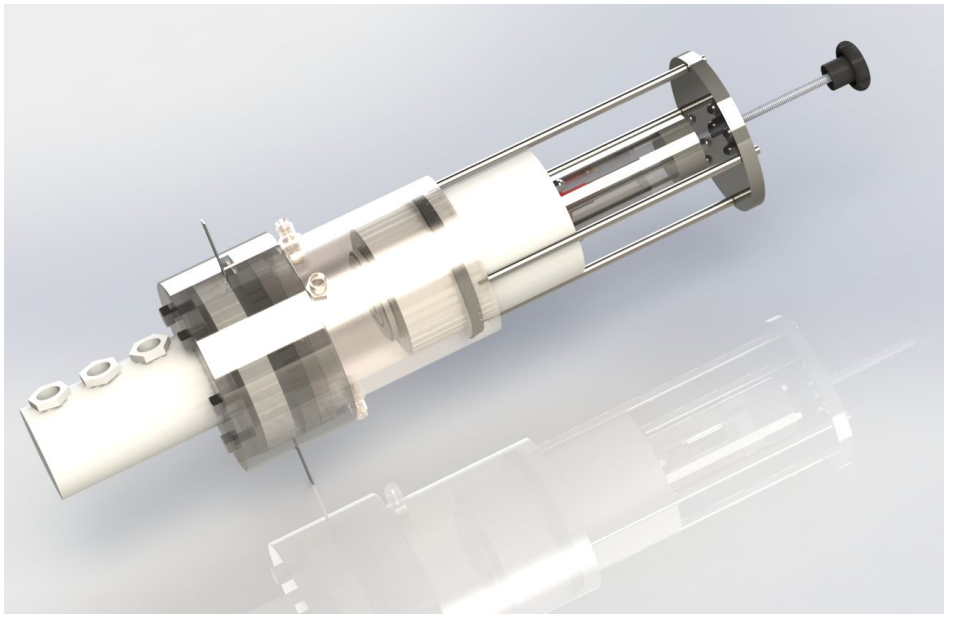
Increasing $f\,H_2$

$S_{L\text{-}H2}$, $KI_{th\text{-}H2}$, JI_{H2}, $\Delta\, KI_{th\text{-}H2}$ *may decrease*

Hydrogen Embrittlement under High Pressure Gaseous H_2

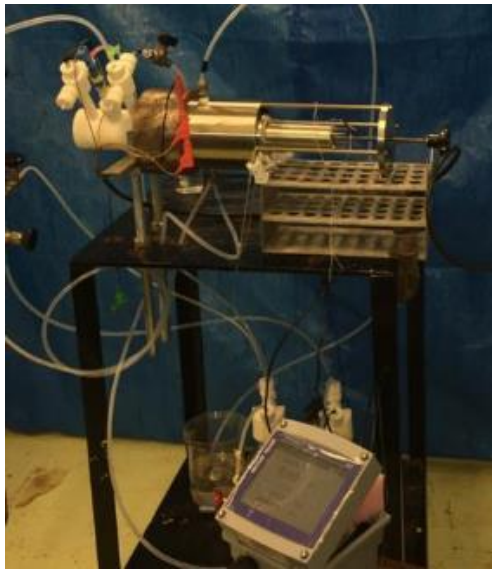
- *Hydrogen Permeation through electrochemical autoclave*





SCC and Hydrogen Embrittlement

- *Electrochemical devices developed to study SCC-CO_2 that can be used to produce data for Multiphysics analysis*



Thank you!

Rodrigo Landim

Mechanical Engineer - INT

Av. Venezuela, 82 - Praça Mauá.
20081-312 Rio de Janeiro RJ
Tel: (21) 2123-1025
rodrigo.landim@int.gov.br
www.int.gov.br

INSTITUTO NACIONAL DE TECNOLOGIA INT

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO

GOVERNO FEDERAL BRASIL UNIÃO E RECONSTRUÇÃO