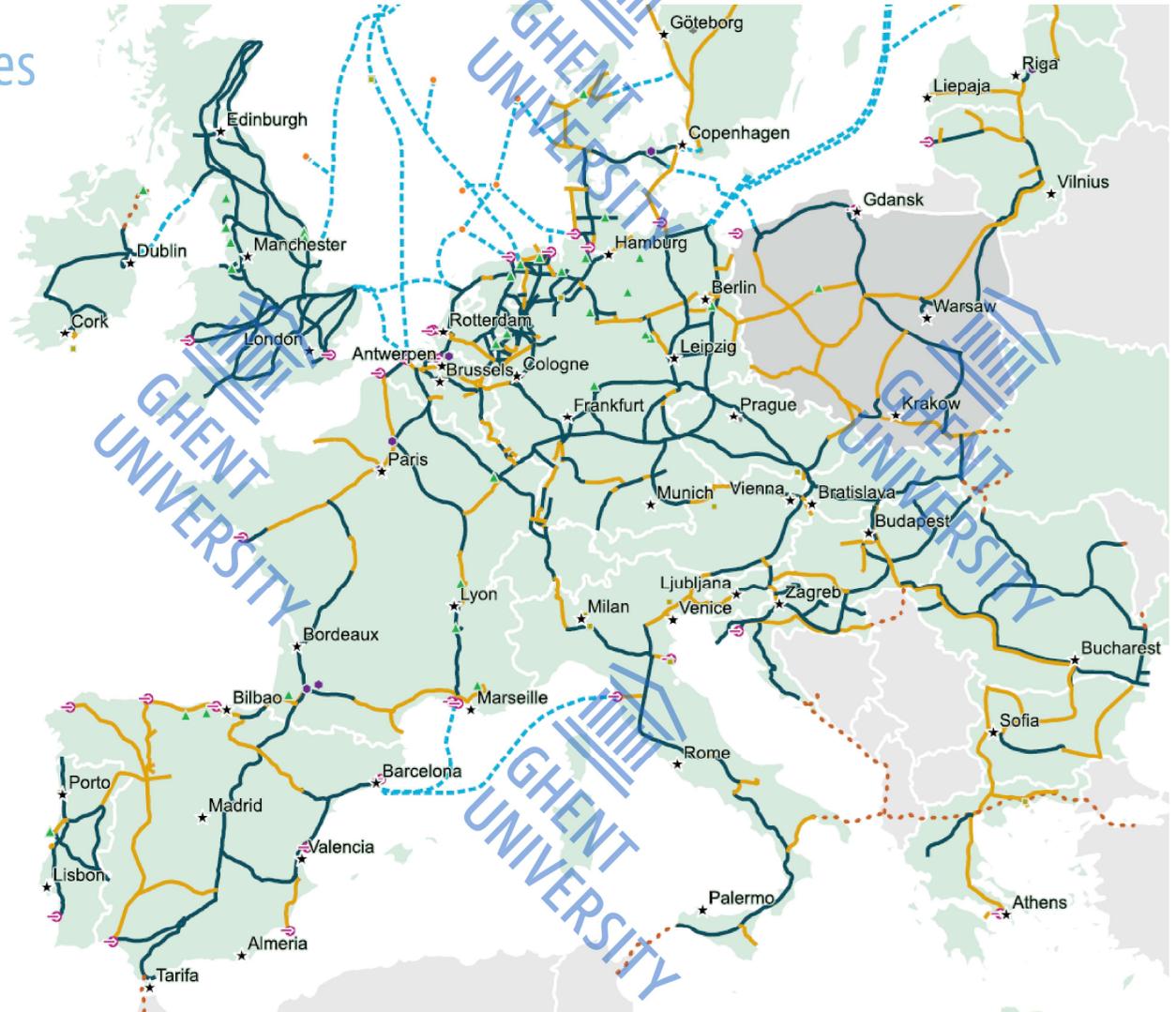


# Evaluation of the Hydrogen Influence on the Strain Capacity of Girth Welded Connections Containing a Workmanship Flaw Through Curved Wide Plate Tests

Laura De Pue, L. Claeys, K. Verbeken, T. Depover, W. De Waele

# Plans for European hydrogen pipeline network by 2040

Mainly repurposing existing pipelines



- Repurposed
- New

- Import / Export
- UK
- Subsea

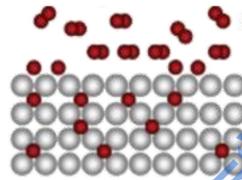
### Other

- ★ Cities
- Energy Island
- ↻ Gas-import Terminals

# Hydrogen interacts with pipeline steels

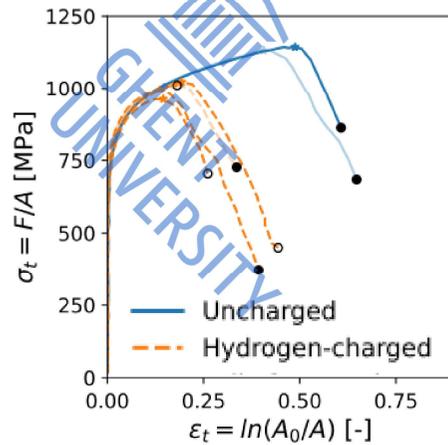
And affects mechanical properties

Hydrogen uptake in the material

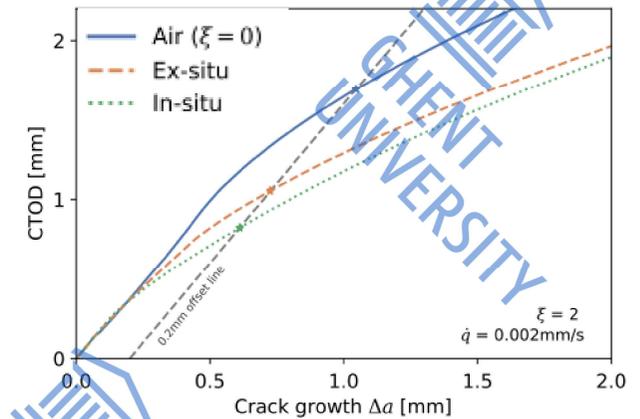


Mechanical degradation

Ductility loss



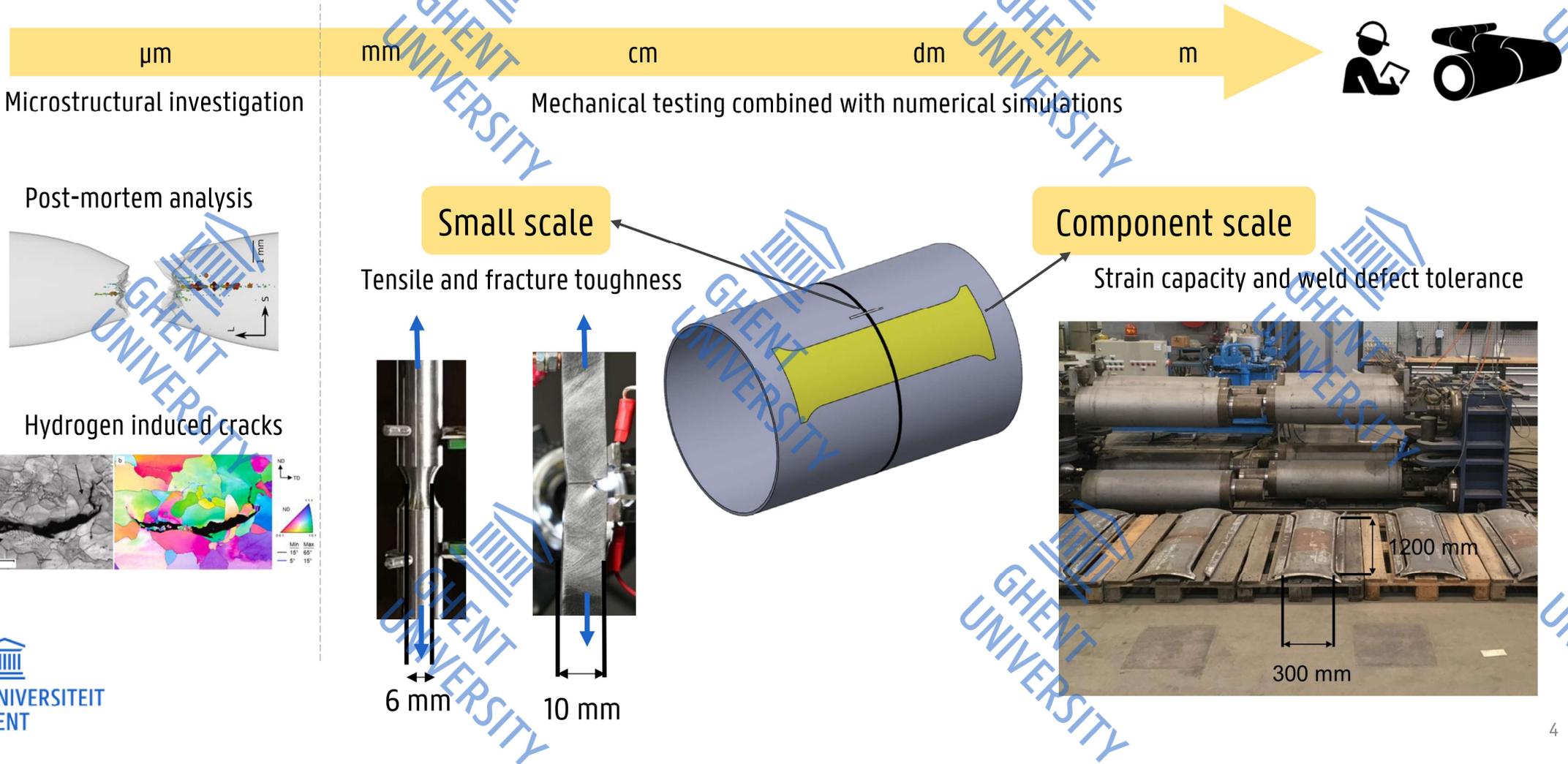
Fracture toughness loss



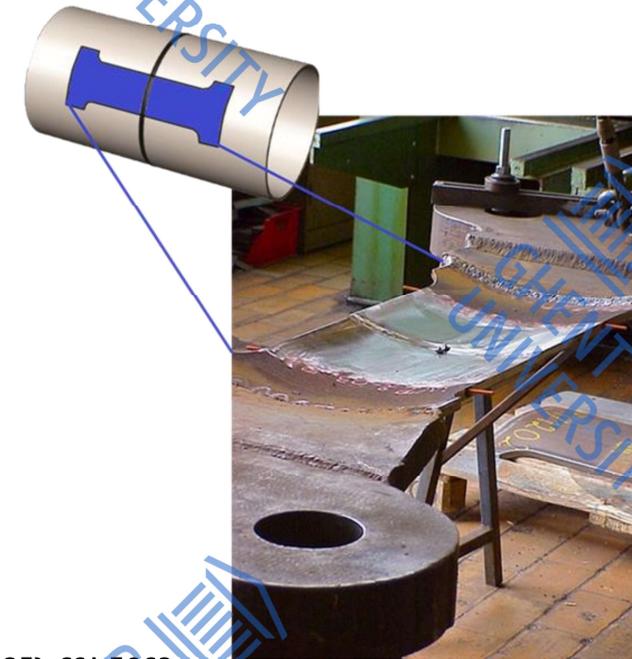
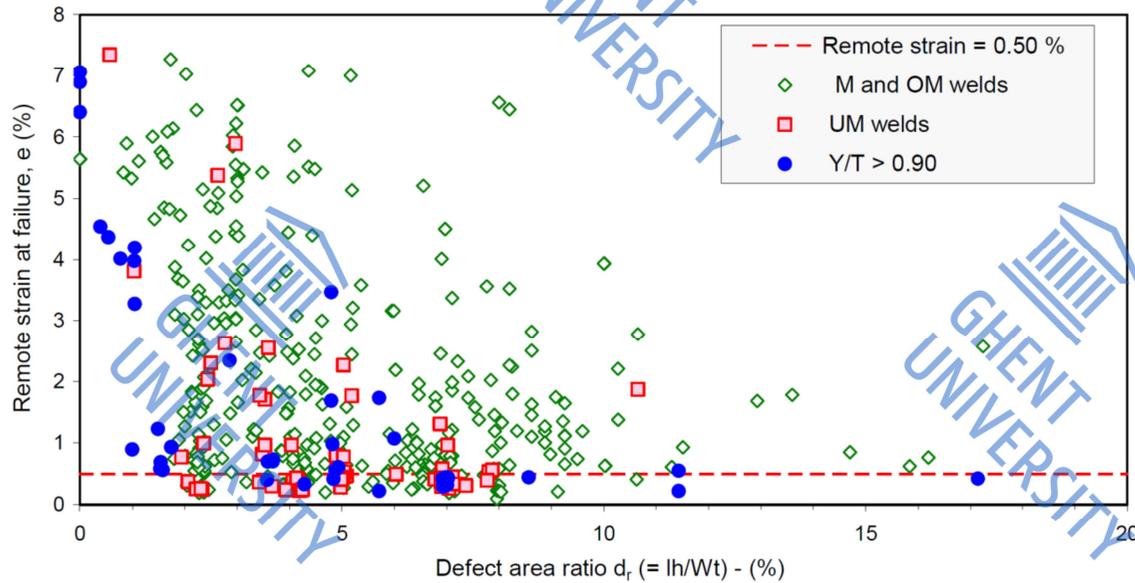
Depraetere, Robin, et al. "Influence of Stress Triaxiality on Hydrogen Assisted Ductile Damage in an X70 Pipeline Steel."

Depraetere, Robin, et al. "Single Edge Notched Tension Testing for Assessing Hydrogen Embrittlement: A Numerical Study of Test Parameter Influences."

# Multi-scale testing strategy of HyFit



# Curved wide plate tests led to empirical insights



Empirical insights on effects of weld strength mismatch, Y/T ratio, interaction of defects,...

EPRG guidelines (Tier 2) for girth weld defect assessment (adopted by EN 12732 and AS 2885), CSA Z662

# Flaw acceptability assessment of girth welded pipelines

Combining CWP test results, and numerical predictions of tolerable defect sizes

→ Need to update defect limits in (EPRG Tier 2) guidelines for pipelines transporting hydrogen?

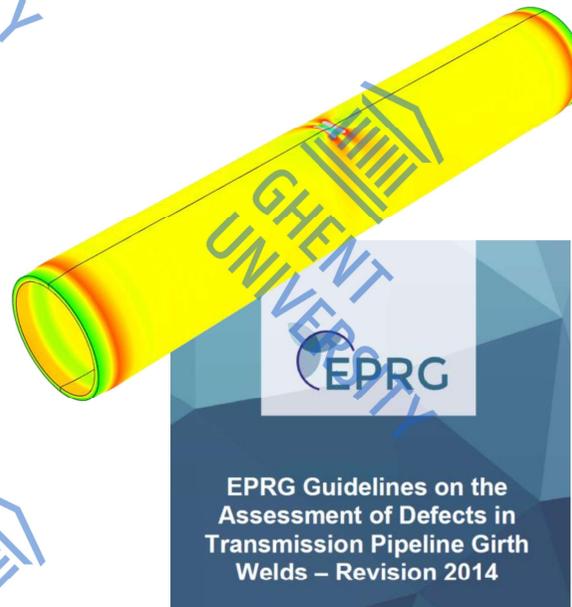
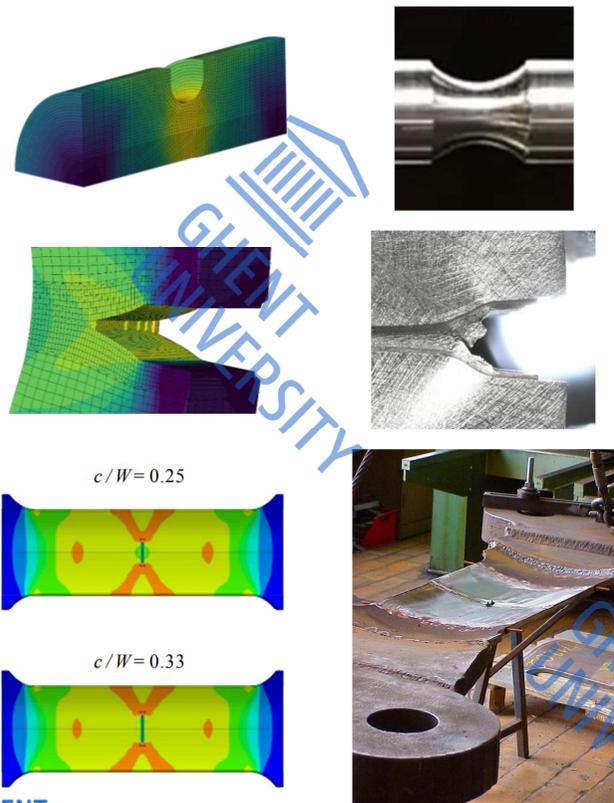


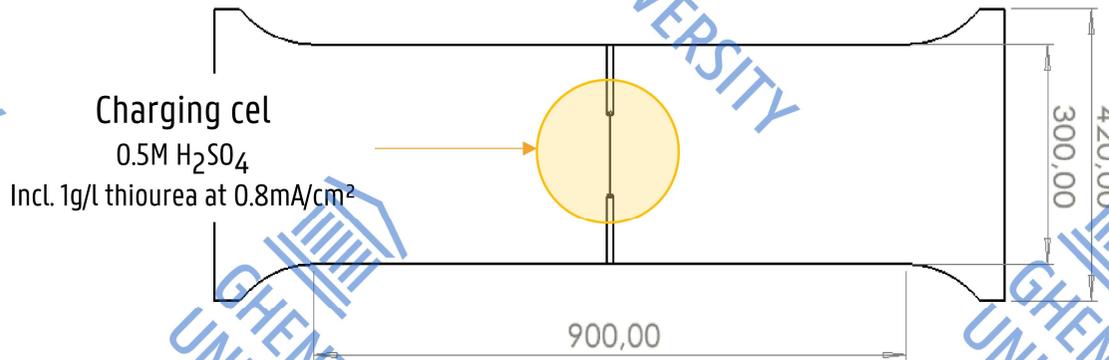
Table 2 Allowable defect length limits for single planar defects at Tier 2

Defect height, h (mm) (with $h \leq 0.5t$ )	$\leq 3$	$3 < h \leq 4$	$4 < h \leq 5$
Allowable defect length limit, l (mm)	$\leq 7t$	$\leq 5t$	$\leq 3t$

Type of requirement	Tier 1 <sup>(a)</sup>	Tier 2	Tier 3 <sup>(b)</sup>
Geometry			
Wall thickness (t)	$7 \leq t \leq 25.4$ mm wall thickness outside this range by agreement	$5 \leq t \leq 30$ mm	$7 \leq t \leq 25.4$ mm
Defect height	No requirement	Table 2	$\leq 3$ mm (single weld run)
Additional remarks	Surface breaking non planar defects should be treated as planar defects	Only girth welds between pipes of equal thickness	Only girth welds between pipes of equal thickness
Toughness			
Charpy and CTOD values for the weld at minimum design temperature	CVN - Average $\geq 40$ J CVN - Minimum $\geq 30$ J	Sub-size specimens have the required impact reduced pro rata with their dimensions	CTOD - Average $\geq 0.15$ mm CTOD - Minimum $\geq 0.10$ mm
Strength			
Cross weld tensile tests with weld reinforcement removed	Acceptable if the specimen breaks in the weld metal with a tensile strength $\geq$ the specified minimum tensile strength (SMTS)	Specimen breaks in the base material or when it breaks in the weld metal with a tensile strength $\geq$ the specified minimum tensile strength	Material or when it breaks in the weld metal with a tensile strength $\geq$ the specified minimum tensile strength
Pipe yield strength Specified minimum yield strength in transverse direction (SMYS)	No limit specified	$\leq 555$ N/mm <sup>2</sup>	$\leq 485$ N/mm <sup>2</sup>
Yield strength matching	Tests can be carried out by special agreement to ensure that $YS(weld) \geq SMYS(pipe) + 80$ N/mm <sup>2</sup>	$YS(weld) \geq$ minimum $YS(pipe) + 100$ N/mm <sup>2</sup> in longitudinal direction (C)	Measurement of the yield strengths, location, type, and number of specimens by agreement. These measurements and the specific acceptance criterion should ensure that the weld metal strength overmatches the pipe strength in all cases. The Tier 2 strength requirements should be satisfied together with the requirements from any alternative fitness-for-purpose method.
Yield to tensile strength ratio (Y/T)	No requirement	$Y/T (pipe) \leq 0.90$ in longitudinal direction	$Y/T (pipe) \leq 0.85$
Additional requirement		Only girth welds between pipes of equal grade	Only girth welds between pipes of equal grade
Loading			
Applied strain/stress	Not specified	Strain $\leq 0.5\%$	Stress $\leq YS(pipe)$
Additional remark	Onerous fatigue duty, or severe environmental effects are not included		

# Embrittlement at component scale

CWP testing of hydrogen charged specimens

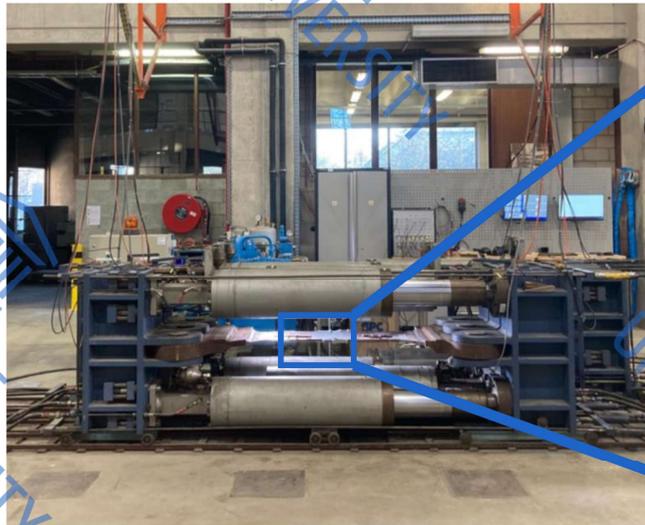
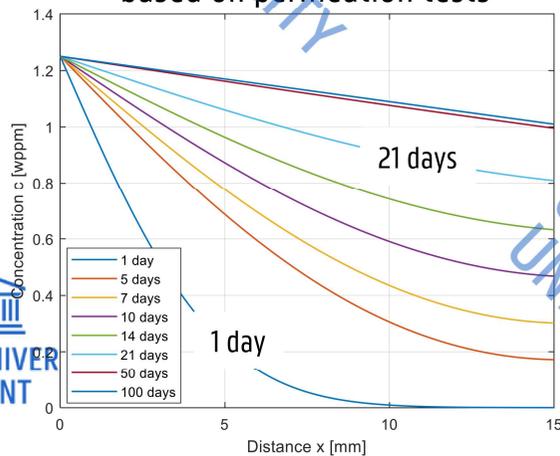


Large-scale tension test on CWP with artificial weld defect

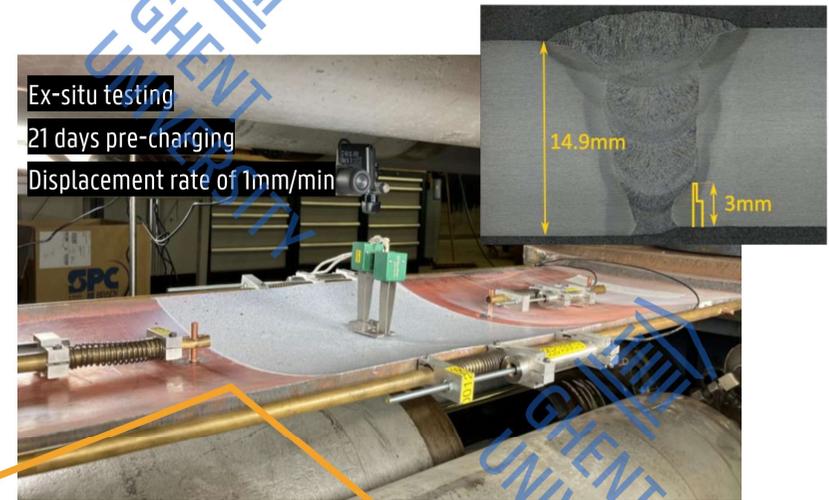
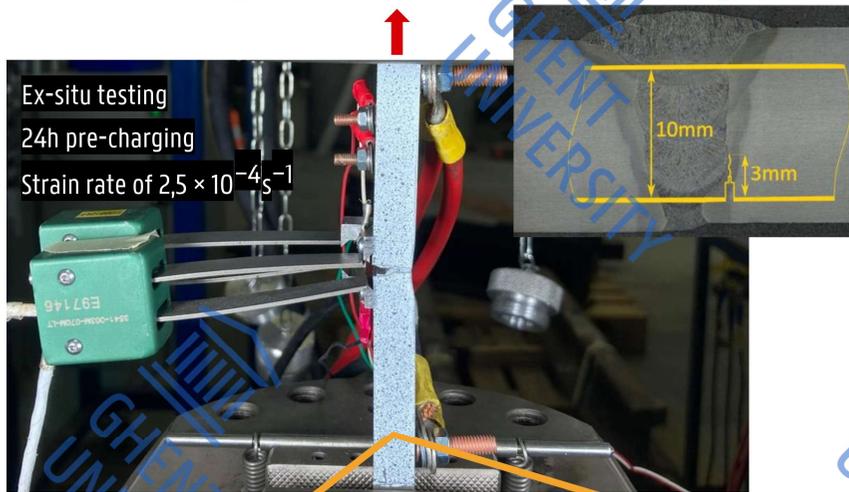
HAZ notch of 3mm height and length equal to 7t (EPRG Tier 2)

Uncharged and hydrogen pre-charged specimens

Electrochemical charging conditions determined based on permeation tests



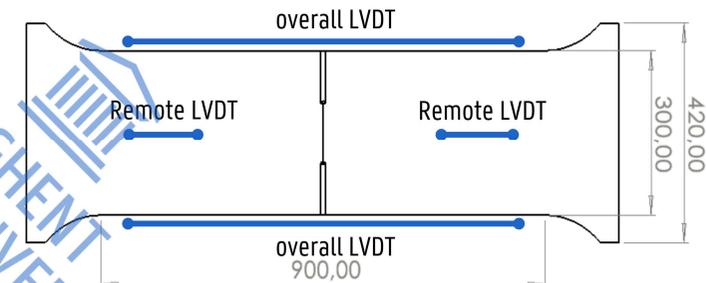
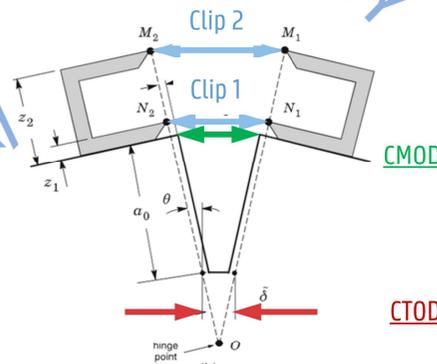
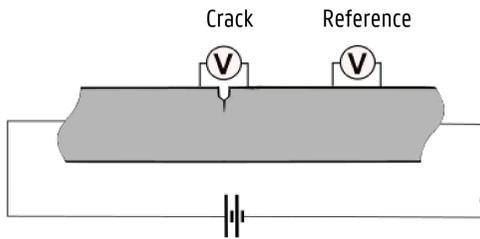
# Data acquisition during small and component scale tests



DCPD → Crack growth

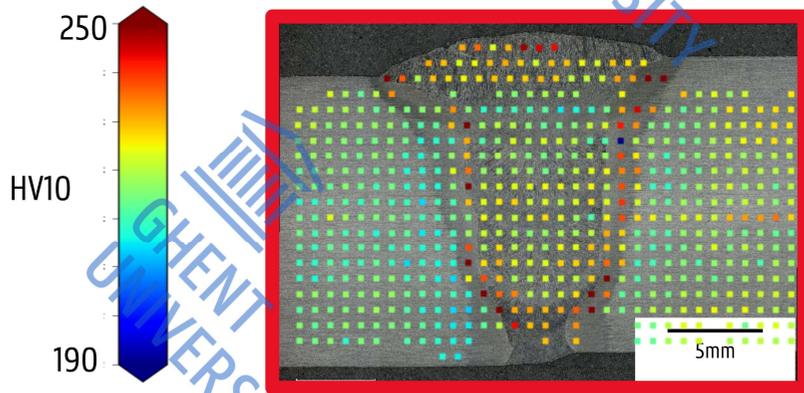
Clip gauges → Crack Tip Opening Displacement (CTOD)

LVDT → strain in base material and overall



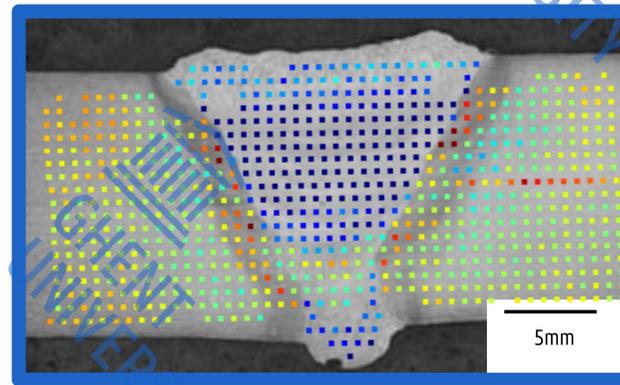
# Pronounced differences in girth welds

L485MB DN1000x14,9mm  
 Stock of 2009  
 Reproduced weld



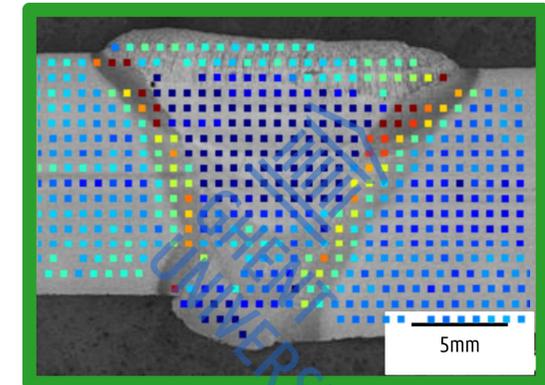
	YS [MPa]	UTS [MPa]
Base material	507±8	608±3
Weld material	571±8	640±6

X70 DN900x15,18mm  
 In service since 1982



	YS [MPa]	UTS [MPa]
Base material	488±17	661±18
Weld material	550±30	623±47

St60.7 ø937,8x13,7mm  
 In service since 1973

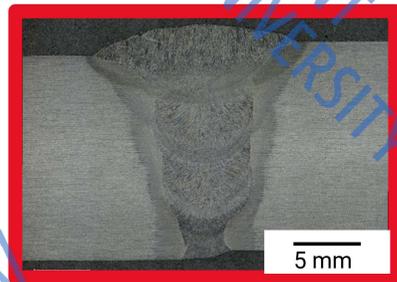


	YS [MPa]	UTS [MPa]
Base material	415±15	593±8
Weld material	476±5	569±9

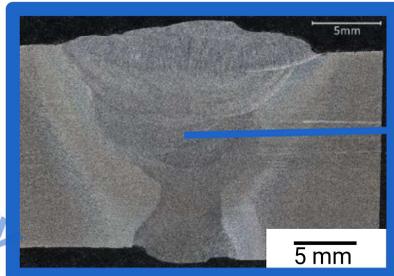
# 3 weld materials

Retained austenite increases the hydrogen concentration

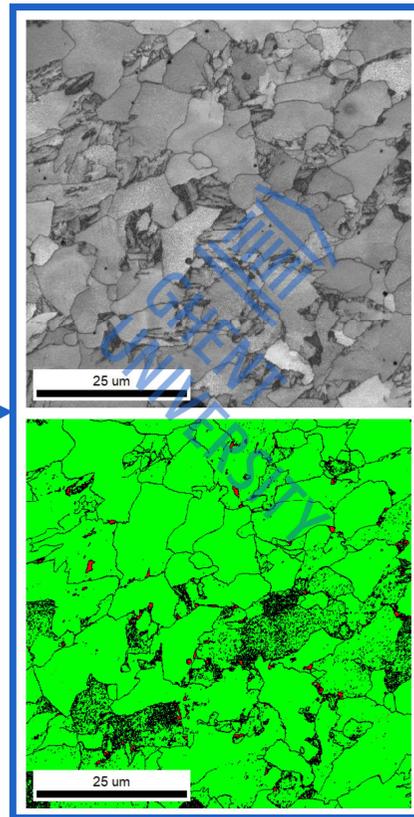
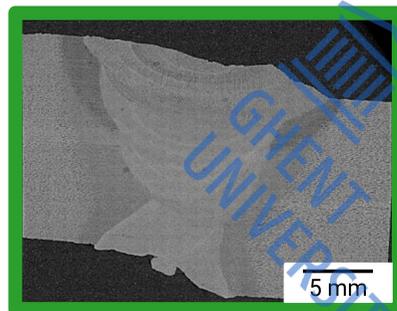
L485MB  
Stock of 2009  
Reproduced weld



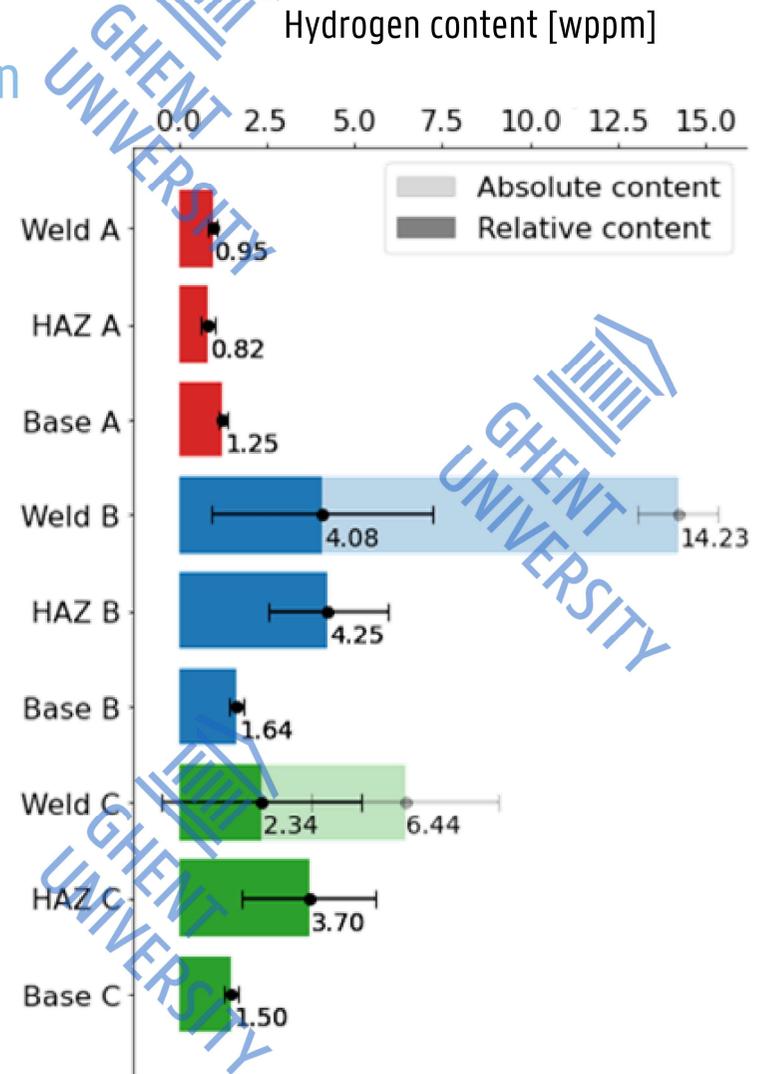
X70  
In service since 1982



St60.7  
In service since 1973



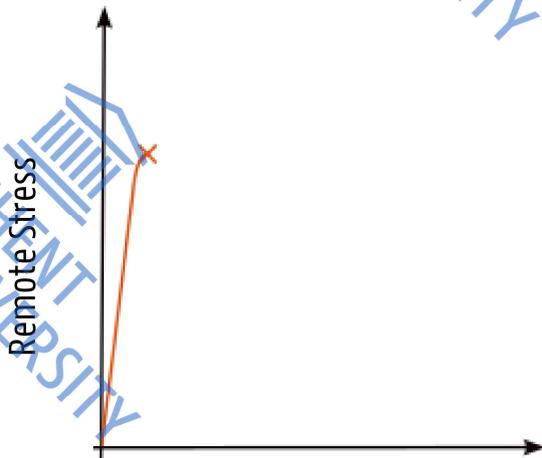
ND  
LD



# Main types of net section failures in CWP testing

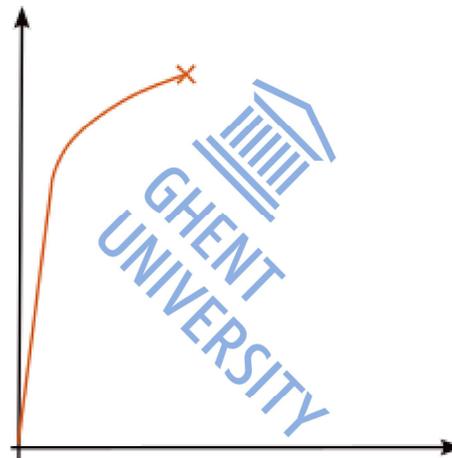
## Elastic fracture

*Unstable brittle fracture prior to remote yielding*



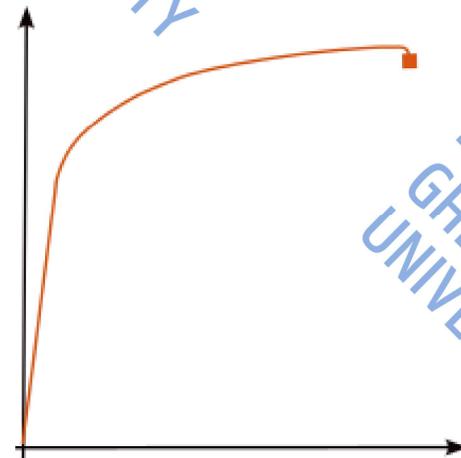
## Post-yield 'unstable' fracture

*Complete fracture prior to a maximum load plateau*



## Plastic collapse

*Stable up to a maximum load plateau*



Remote Strain

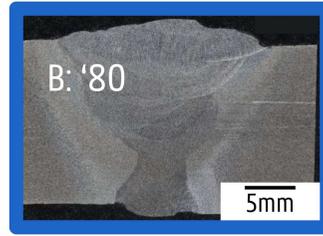
Remote Strain

Remote Strain



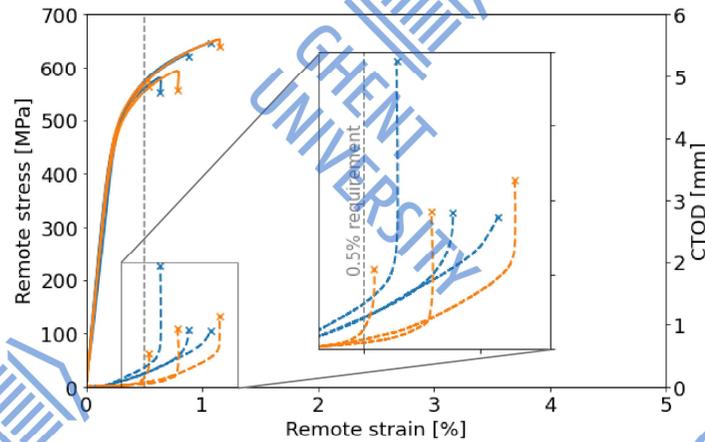
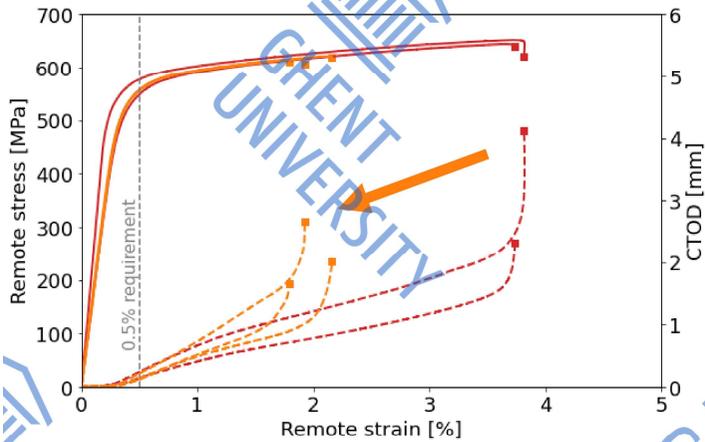
- Stopped after UTS
- ✗ Fracture

# Hydrogen effect on strain capacity differs within same steel grade



— Reference  
— Hydrogen

— Reference  
— Hydrogen



Stable ductile tearing towards plastic collapse

All ended with a post-yield fracture, influenced by presence of lack of fusions

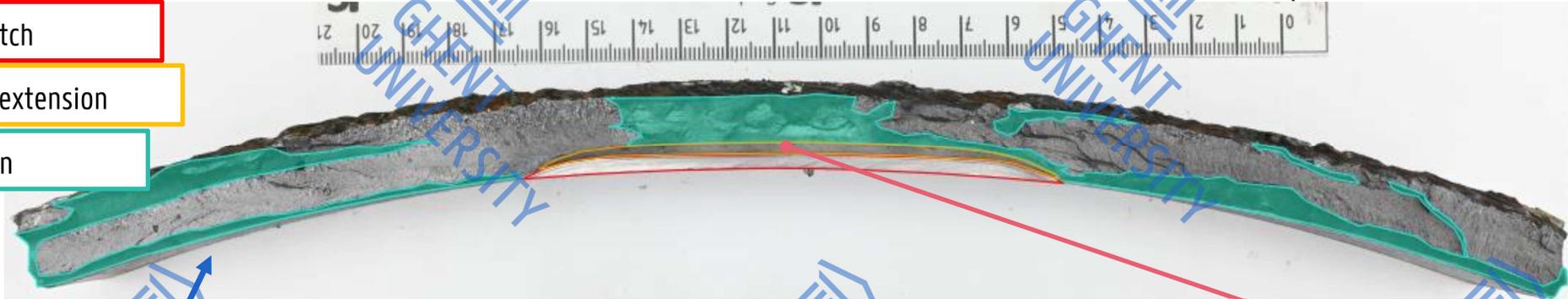
# Failure of B is influenced by lack of fusion

Example: 2<sup>nd</sup> test of B

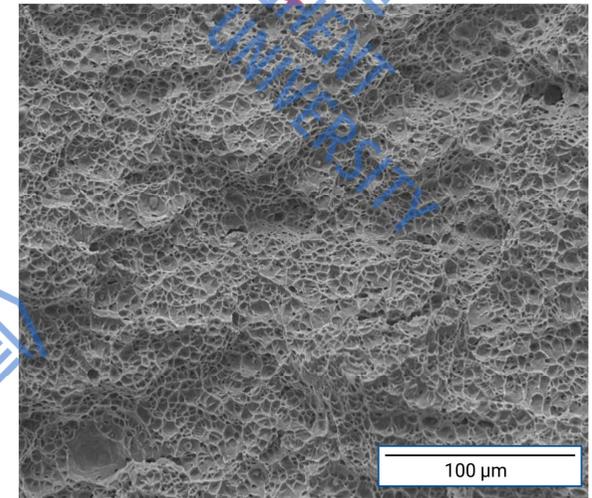
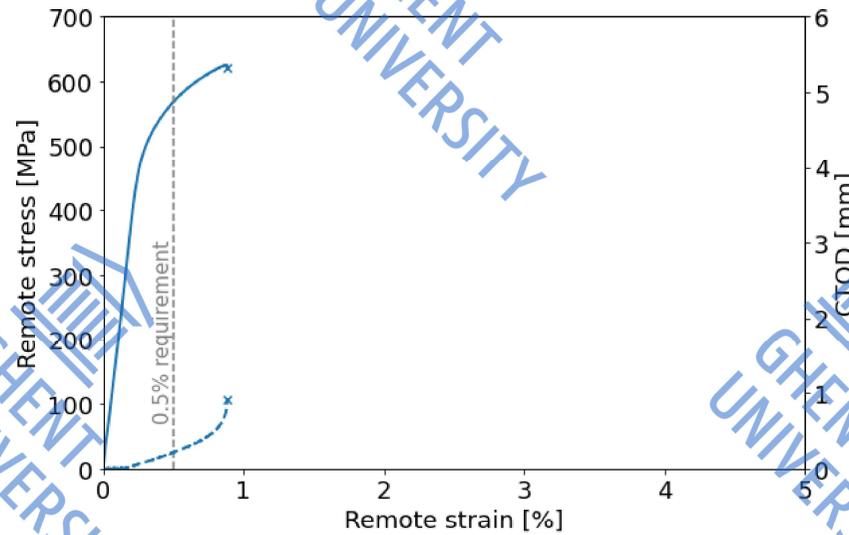
Machined notch

Stable crack extension

Lack of fusion



UNIVERSITEIT  
GENT



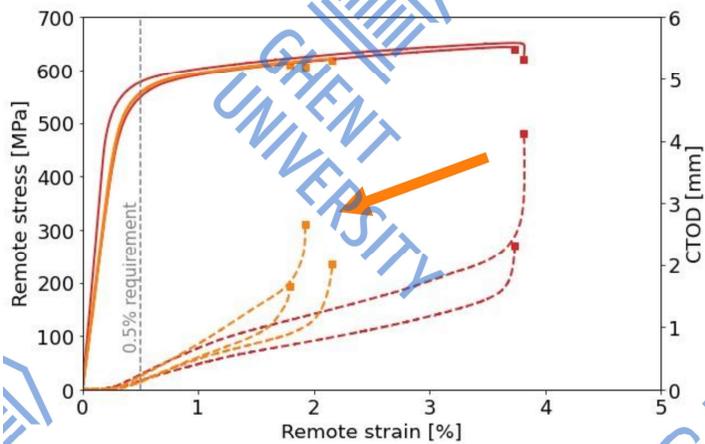
# Weld defect is more dominant than hydrogen effect?



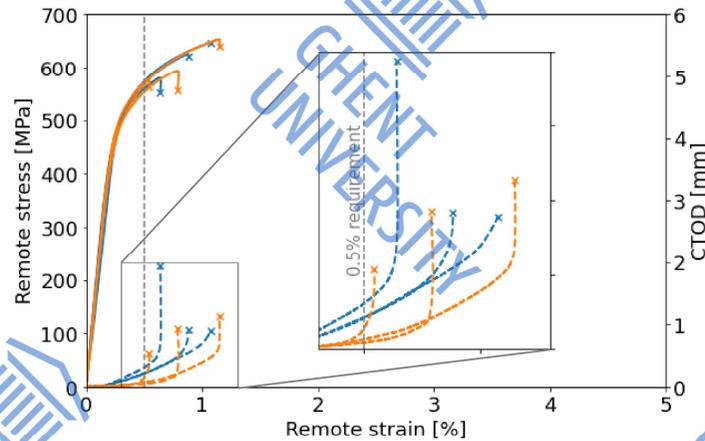
— Reference  
— Hydrogen

— Reference  
— Hydrogen

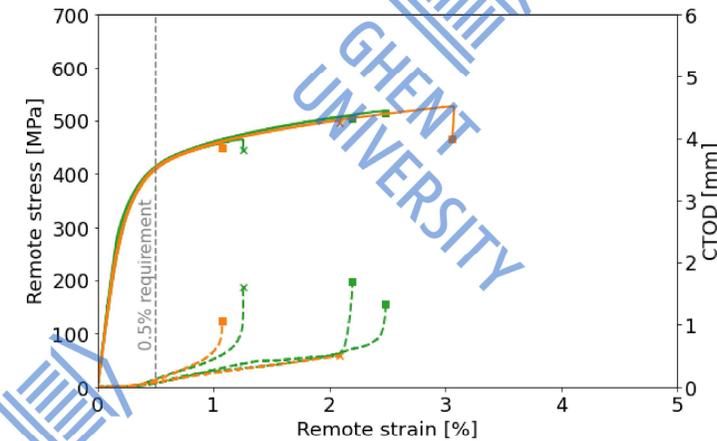
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— Hydrogen



Stable ductile tearing towards plastic collapse



All ended with a post-yield fracture, influenced by presence of lack of fusions

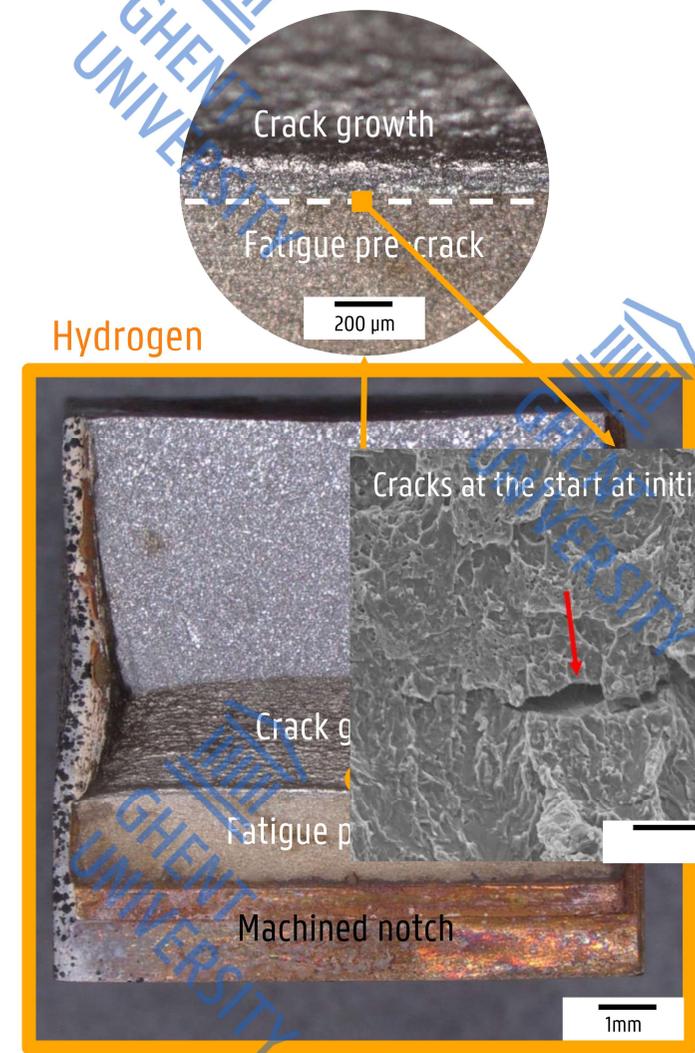
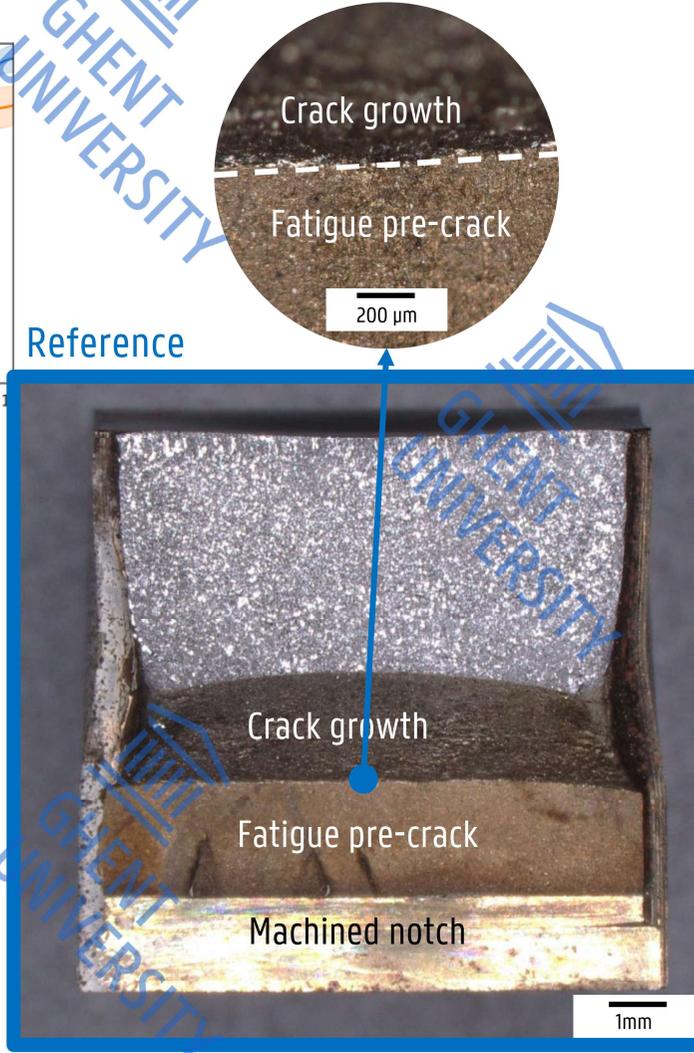
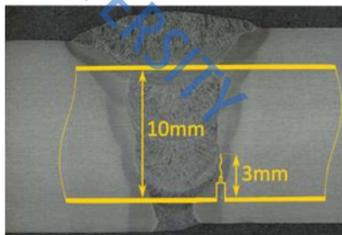
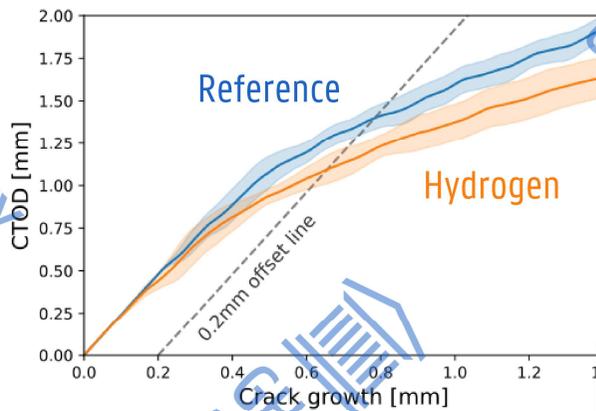


Stable and unstable crack extension

Unstable fracture in hydrogen influenced by corrosion in the notch

■ Stopped after UTS      — Remote stress  
 X Post-yield fracture      - - - CTOD

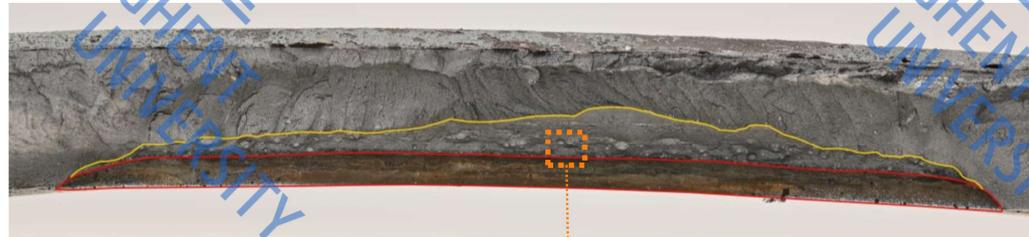
# Small toughness loss observed with SENT



# Similar damage mechanisms observed for SENT and CWP

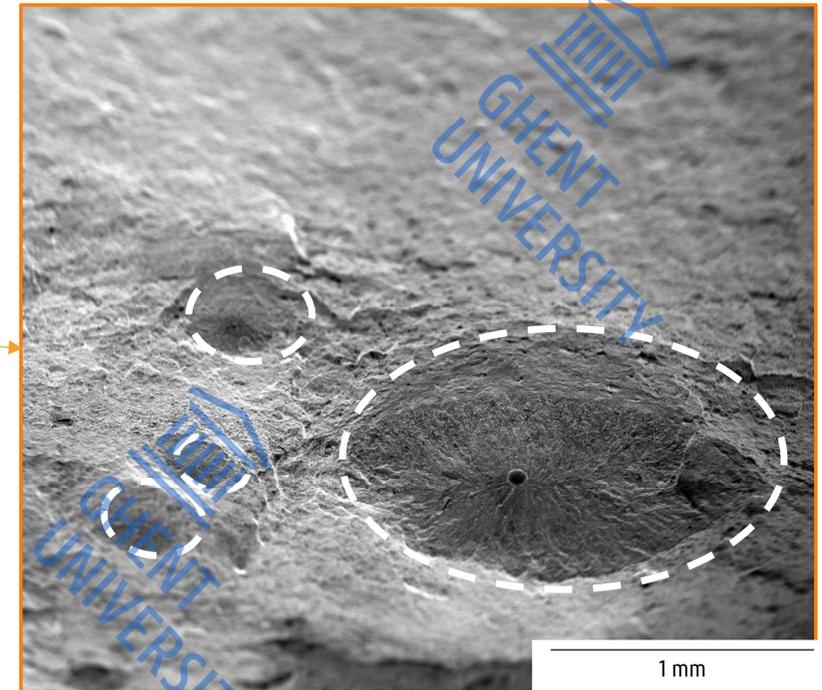
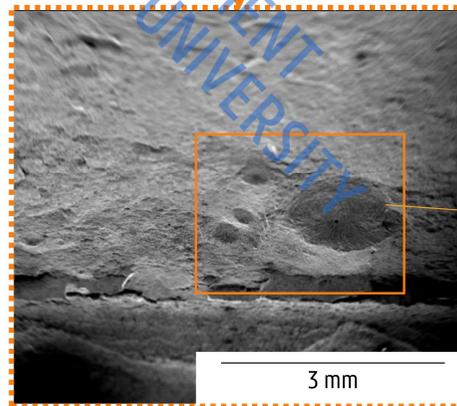
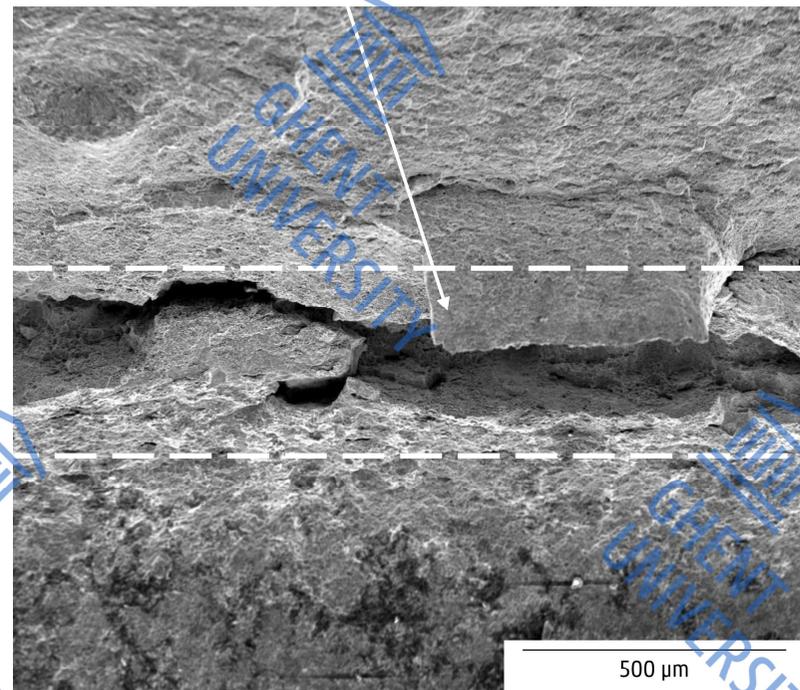
Machined notch

Stable crack extension



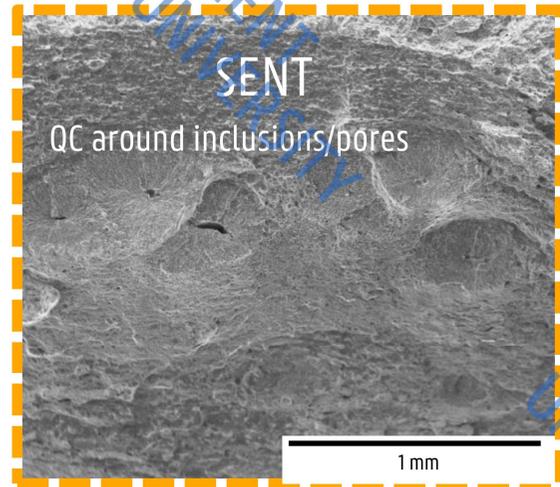
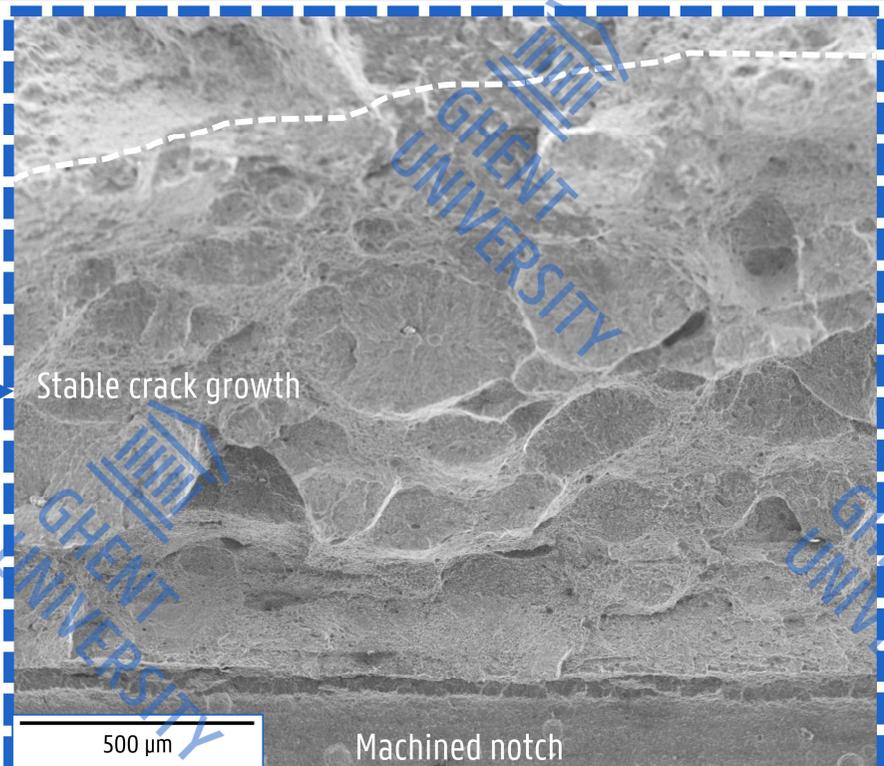
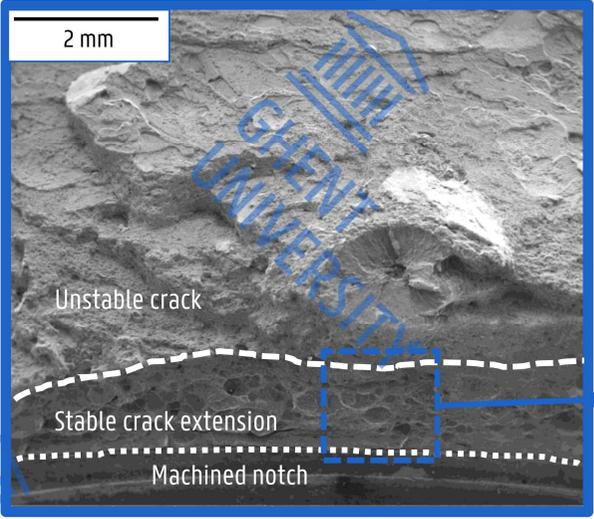
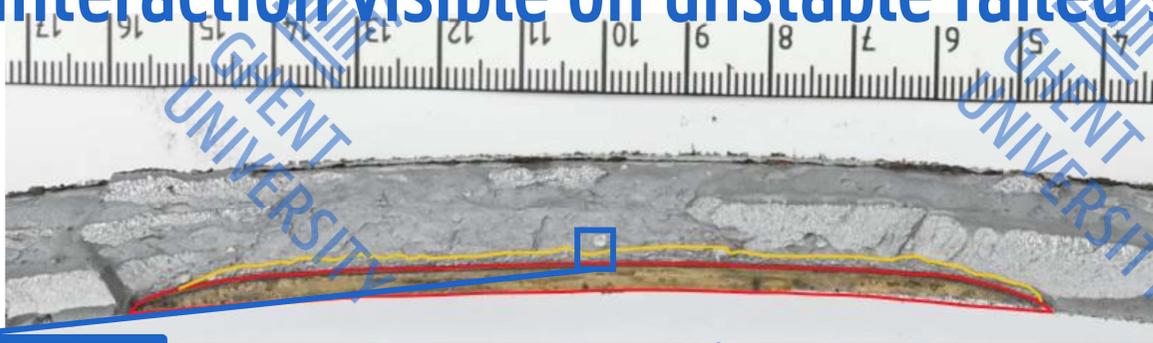
Cracks at initial crack front

Quasi-cleavage around inclusions



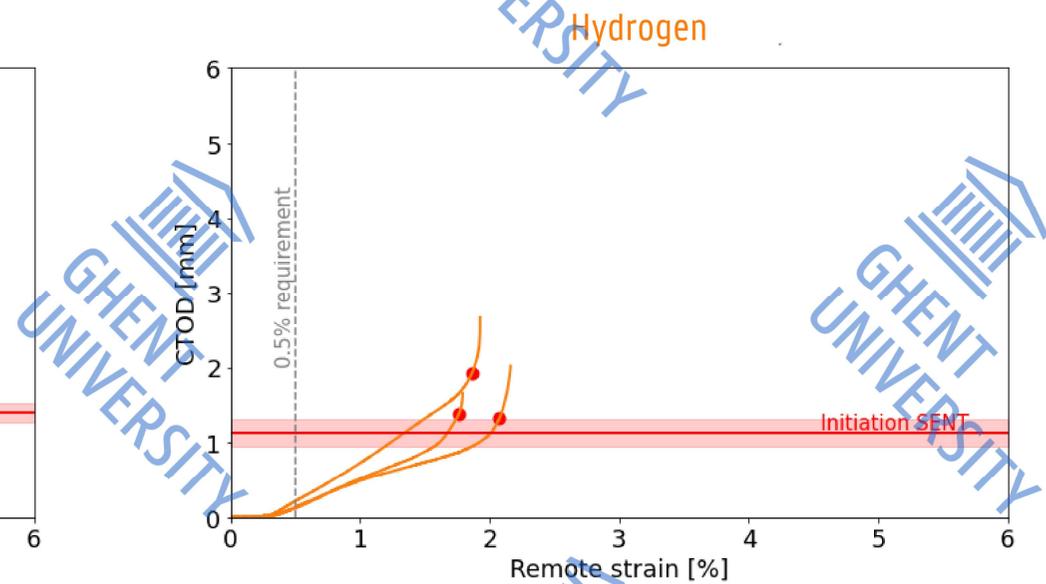
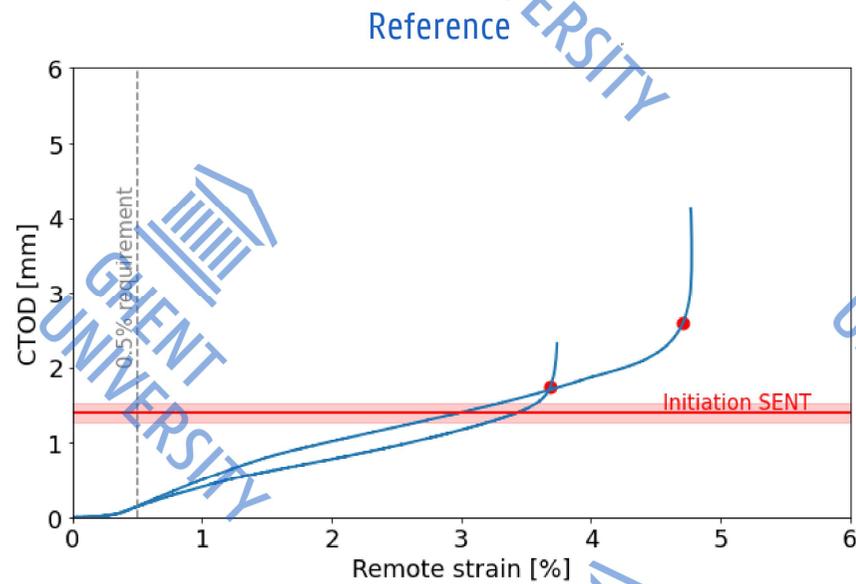
# Hydrogen interaction visible on unstable failed specimens

Machined notch  
Stable crack extension



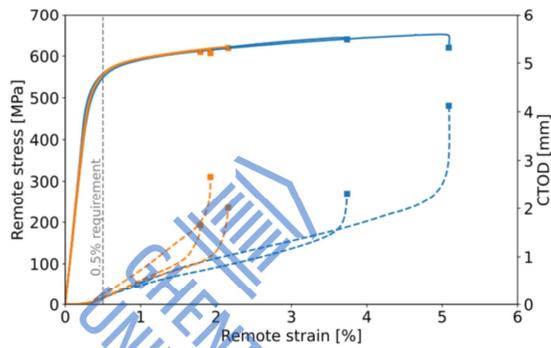
# Hydrogen affects strain capacity

Crack initiates at higher CTOD compared to SENT in both conditions



# Key messages of component-scale testing

## Macro-mechanical effects

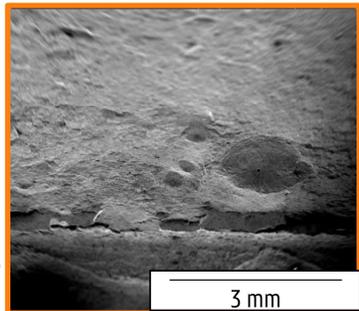


Component scale testing less conservative than small scale

All tested specimens match the 0,5% remote strain requirement of EPRG

Hydrogen charged CWP loses strain capacity unless lack of fusion dominated

## Microstructural post-mortem comparison



Similar damage indications on fracture surface over the multi-scale specimens

Cracks at initial crack front might explain the loss in toughness and strain capacity

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