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FACULTY OF ENGINEERING AND ARCHITECTURE

Hydrogen effects on fracture micromechanisms in pipeline steels and their welds

Margo Cauwels[1], Robin Depraetere[2], Jubica[1], Lisa Claeys[1], Laura De Pue[2], Wim De Waele[2], Stijn Hertelé[2], Kim Verbeken[1], Tom Depover[1]

[1]*Sustainable Materials Science, Department of Materials, Textiles and Chemical Engineering, Ghent University, Belgium*

[2]*Soete Laboratory, Department of ElectroMechanical, Systems and Metal Engineering, Ghent University, Belgium*

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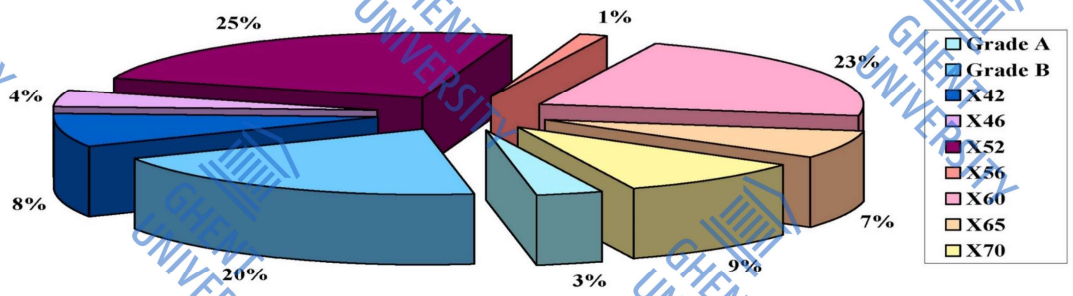
METALS GHENT UNIVERSITY

fluxys

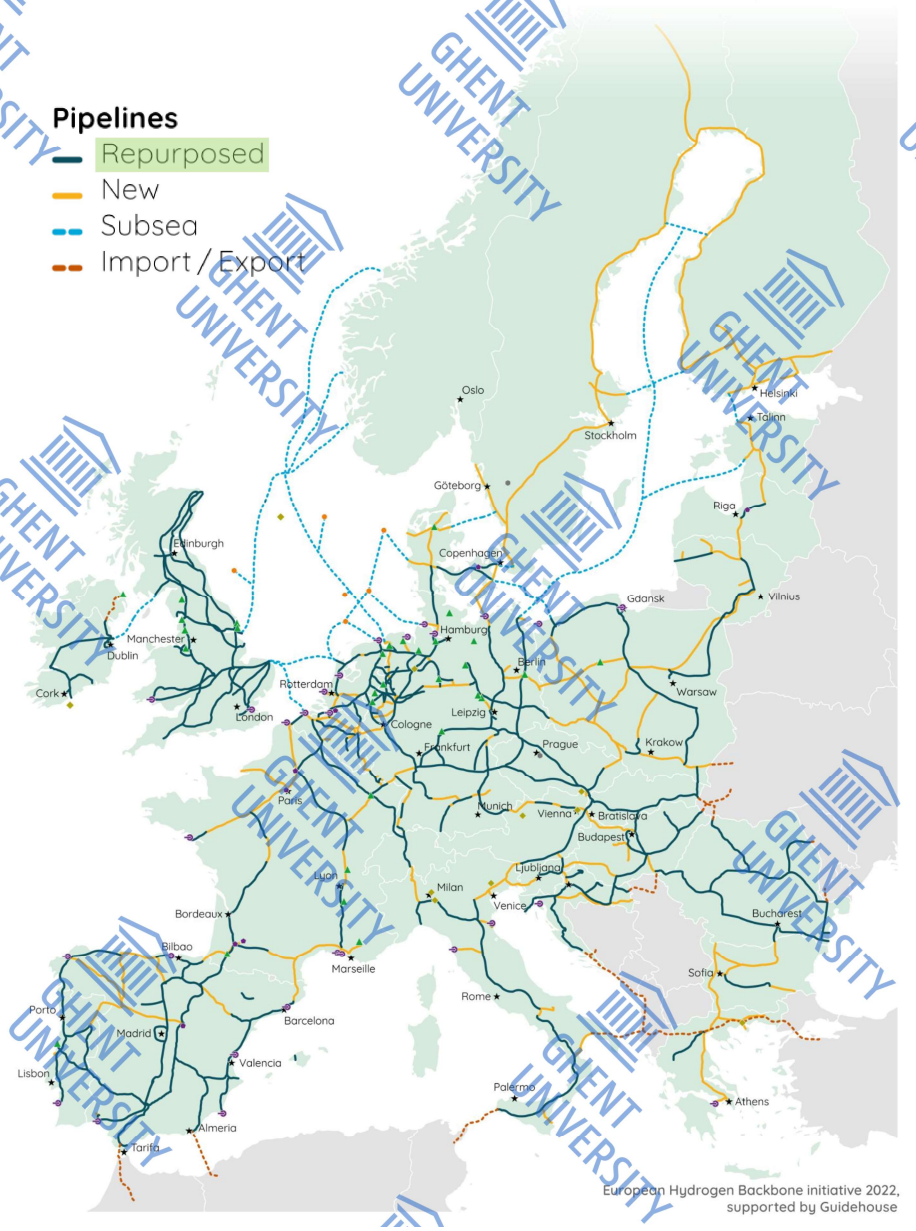
economie

Research context



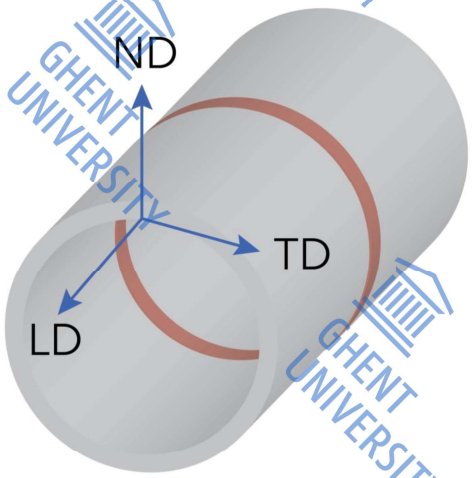
European pipeline grid (% by length)

Pluvinage Int J Press. Vessel Pip. 2021



Presentation content

From fundamental research...



In-depth study X70

Screening H sensitivity of pipeline steels

Mechanical characterisation

Correlation analysis

Link to gaseous H_2 testing

... To application oriented research

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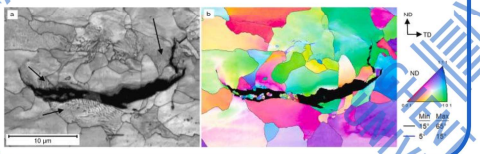
In-depth investigation of an X70 pipeline steel BM

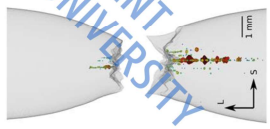
μm — mm — cm — dm — m

Microstructural and hydrogen characterization
Phases – Grain size – Inclusions
Solubility – Diffusivity – Inhibition

Hydrogen-induced cracking

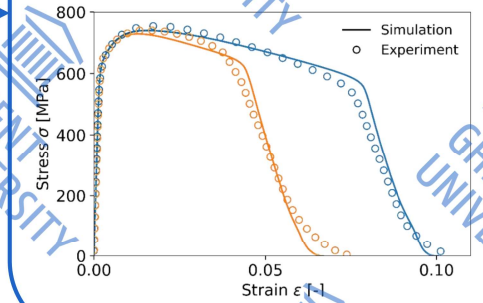


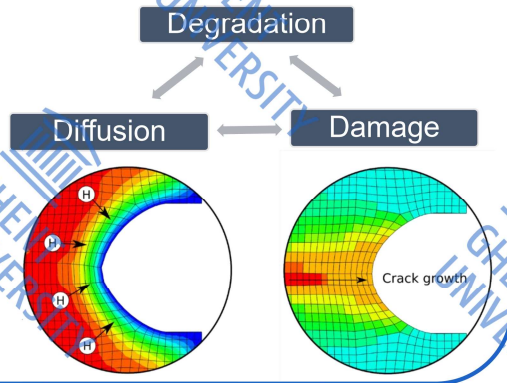
Post-mortem analysis
Quasi-cleavage – Voids – Hydrogen-assisted cracking



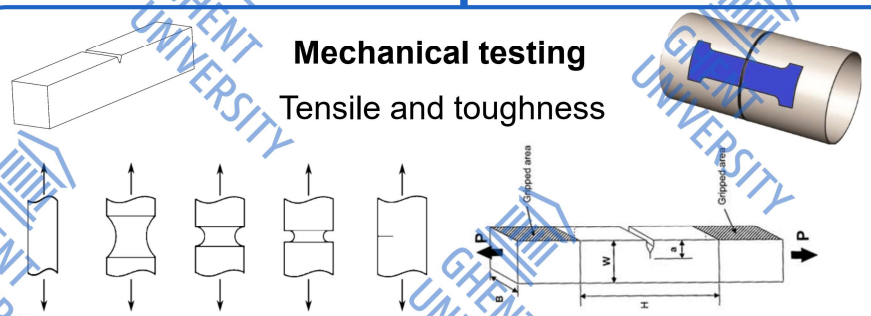
Numerical simulation

SIMULIA ABAQUS





Mechanical testing
Tensile and toughness



In-situ and ex-situ

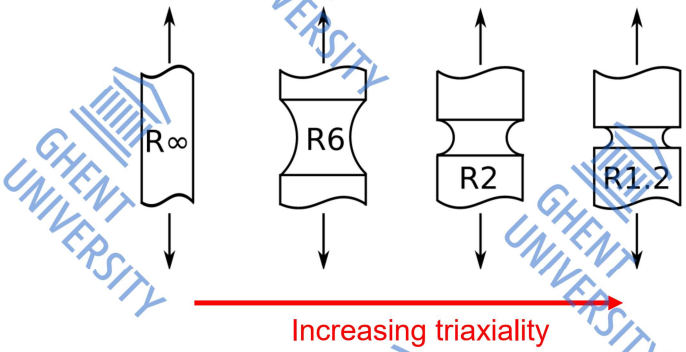
Prediction for fitness-for-service?

M. Cauwels, R. Depraetere, W. De Waele, S. Hertelé, K. Verbeken, T. Depover, *Effect of stress triaxiality on the hydrogen embrittlement micromechanisms in a pipeline steel evaluated by fractographic analysis,* Mat Sci Eng A, Vol. 886, 2023, 145689, 10.1016/j.msea.2023.145689

In-depth investigation of an X70 pipeline steel BM

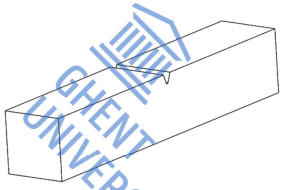
Tensile tests with hydrogen charging

Round bar testing



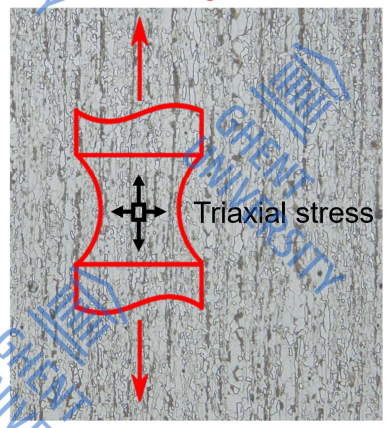
Toughness tests with hydrogen charging

Charpy impact testing

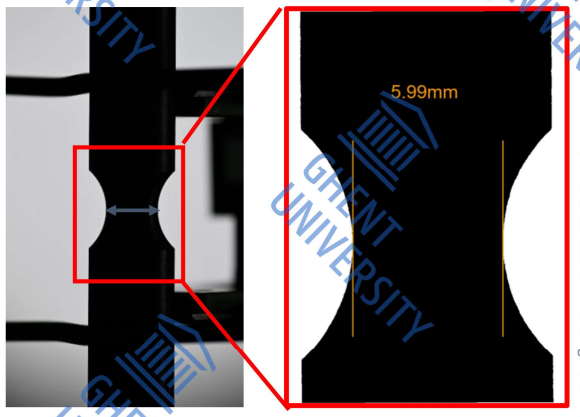


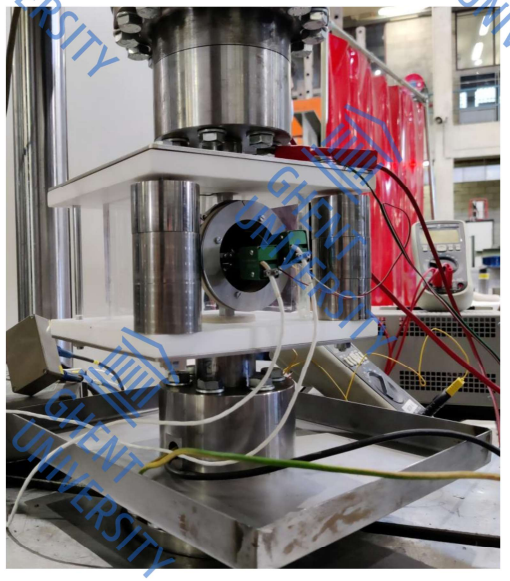
SENT toughness test

Uniaxial loading…

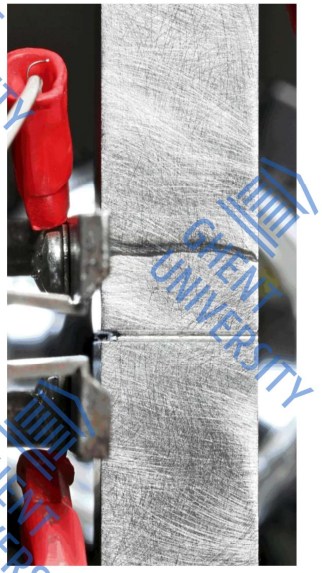


Diameter reduction monitoring





In-situ SENT setup

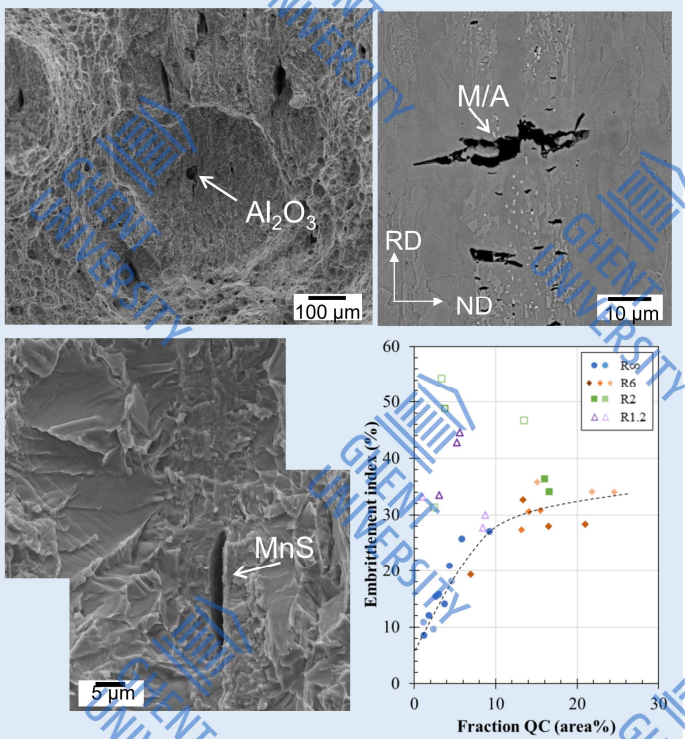


Ex-situ SENT

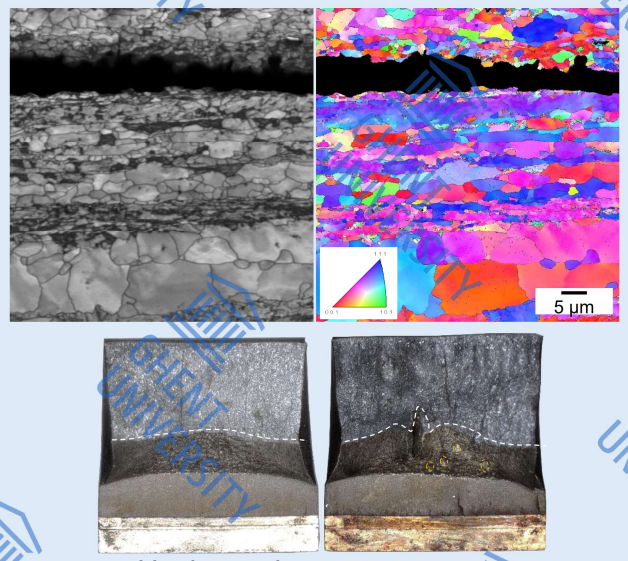
In-depth investigation of an X70 pipeline steel BM

Three main H-assisted degradation mechanisms

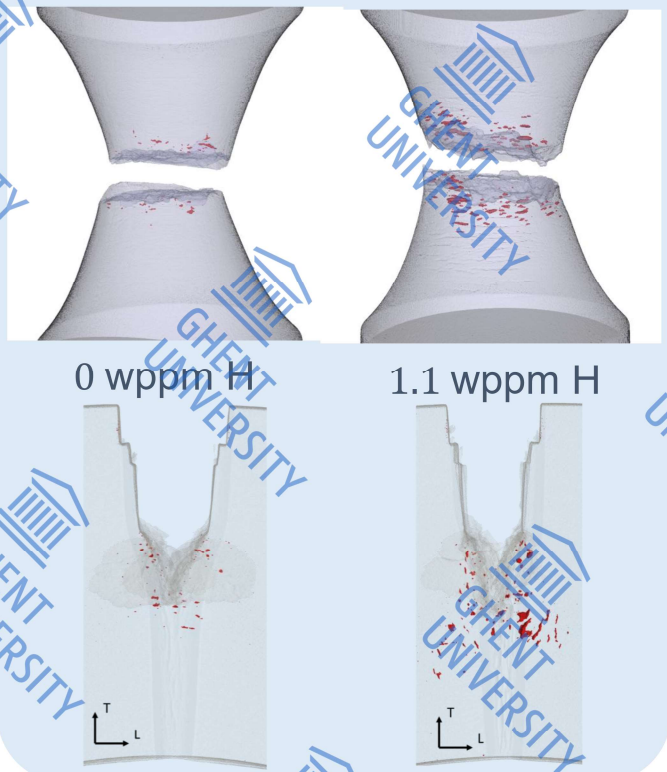
Quasicleavage ~ microstructure



Splitting/delaminations



Enhanced void nucleation & void shape change



R. Depraetere, W. De Waele, M. Cauwels, T. Depover, K. Verbeken, S. Hertelé, *The effect of hydrogen and notch orientation in SENT specimens on the fracture toughness of an API 5L X70 pipeline steel,* ENGINEERING FRACTURE MECHANICS, 300, 2024, 109995, http://doi.org/10.1016/j.engfracmech.2024.109995

M. Cauwels, R. Depraetere, W. De Waele, S. Hertelé, K. Verbeken, T. Depover, *Effect of stress triaxiality on the hydrogen embrittlement micromechanisms in a pipeline steel evaluated by fractographic analysis,* Mat Sci Eng A, Vol. 886, 2023, 145689, 10.1016/j.msea.2023.145689

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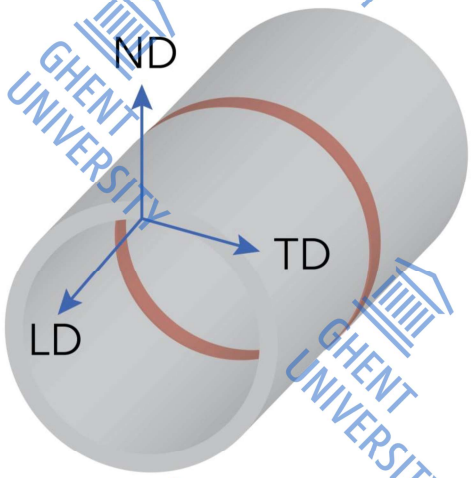
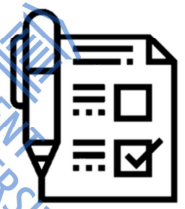


In-depth study X70

Screening H sensitivity of pipeline steels

Mechanical characterisation



Correlation analysis

Link to gaseous H_2 testing

... To application oriented research

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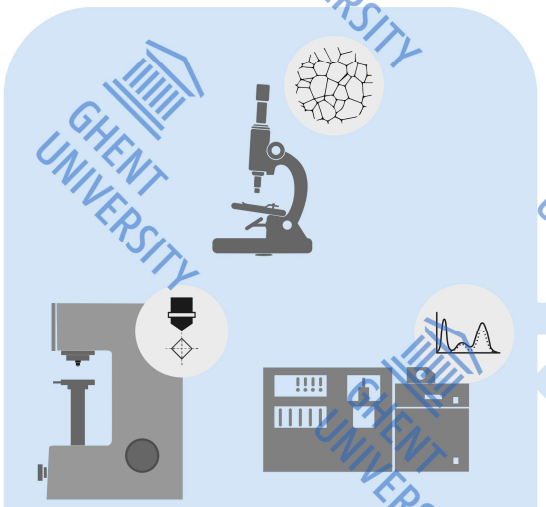
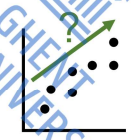
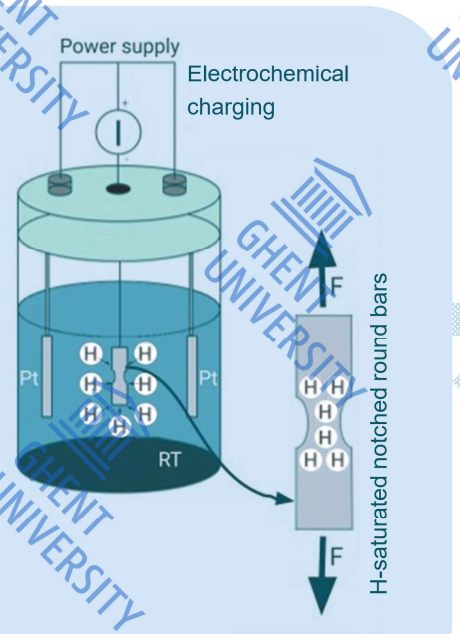
Initial screening of materials

- What material parameters should guide the (initial) selection of suitable pipeline steels?
- Preliminary assessment of HE sensitivity + identification of relevant (microstructural) parameters

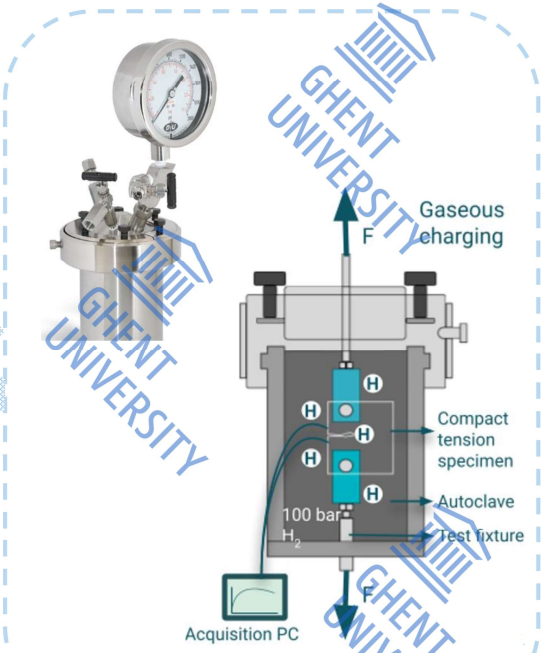


Full microstructural, hydrogen, ... characterisation





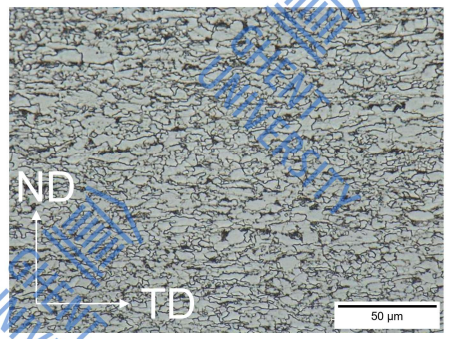
Ex-situ mechanical tests



Screening methodology – Base materials

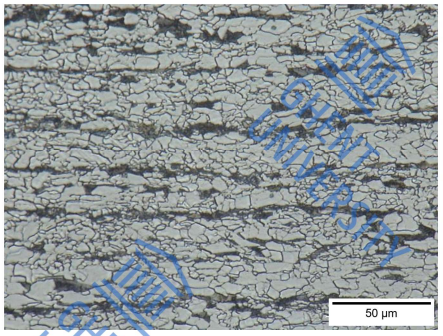
Stock

BM1



L485 (2009)

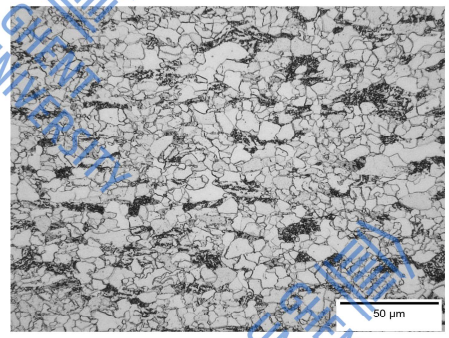
BM2



L485 (2009)

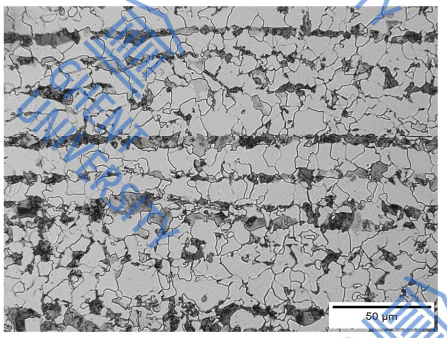
Excavated

BMB



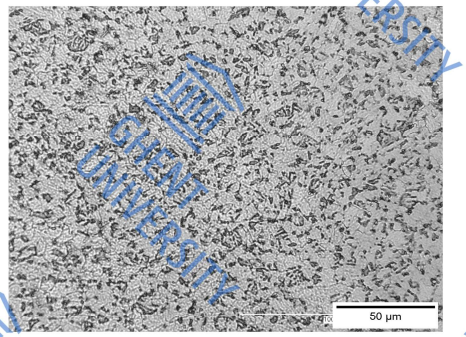
X70 (1980)

BMC



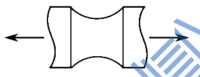
St. 60.7 (1972)

BMD

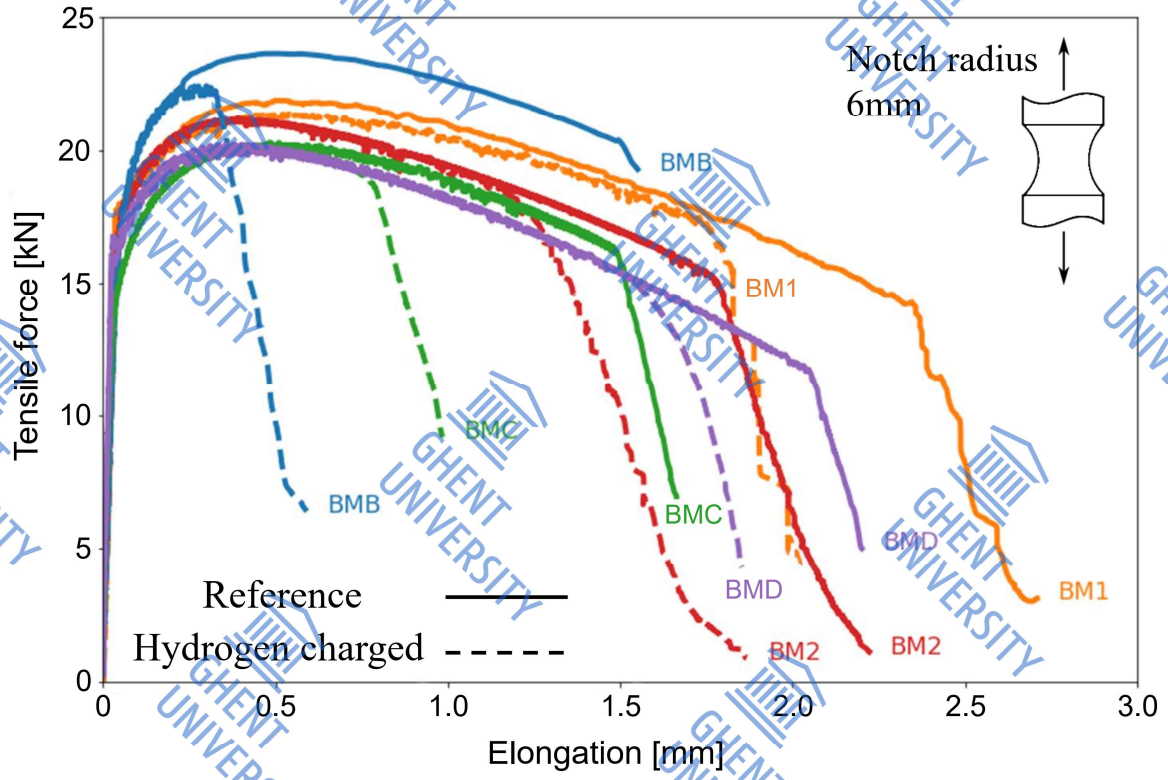


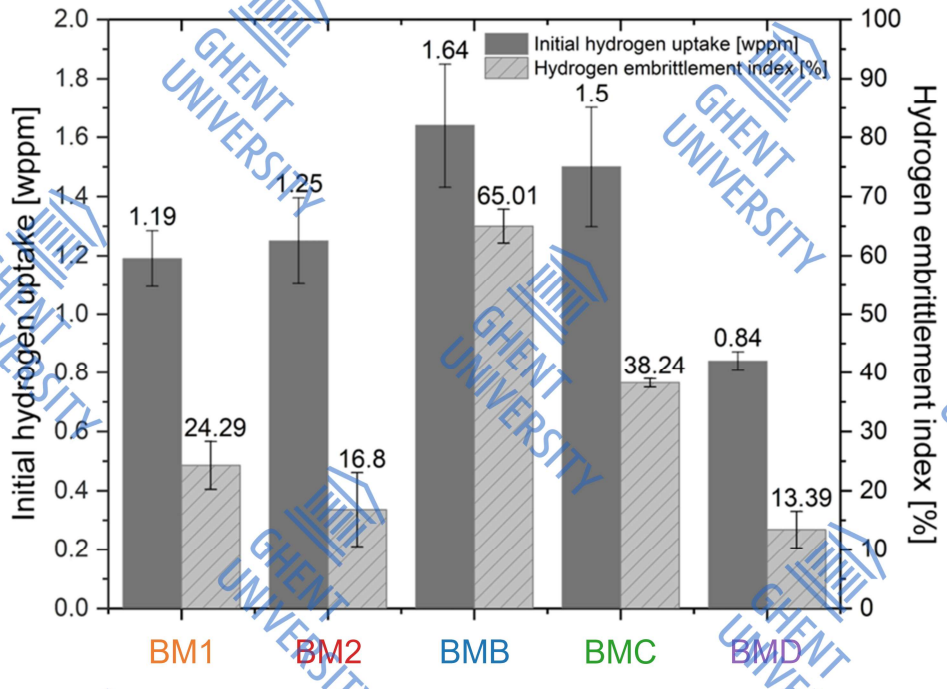
L415 (2013)

Comparison of base materials: mechanical performance



Ex-situ quasi-static tensile testing





Embrittlement index = $(1 - \frac{Elongation_{hydrogen}}{Elongation_{air}}) \cdot 100\%$

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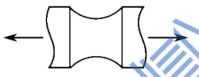
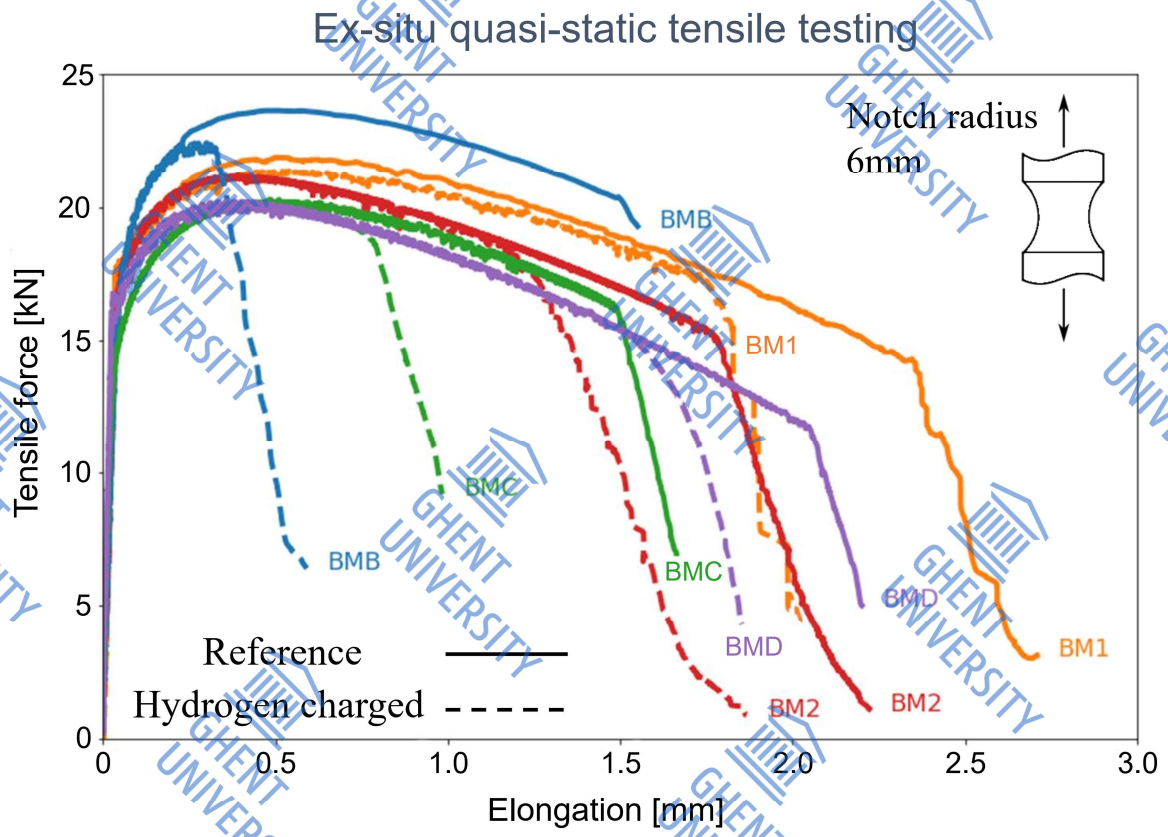
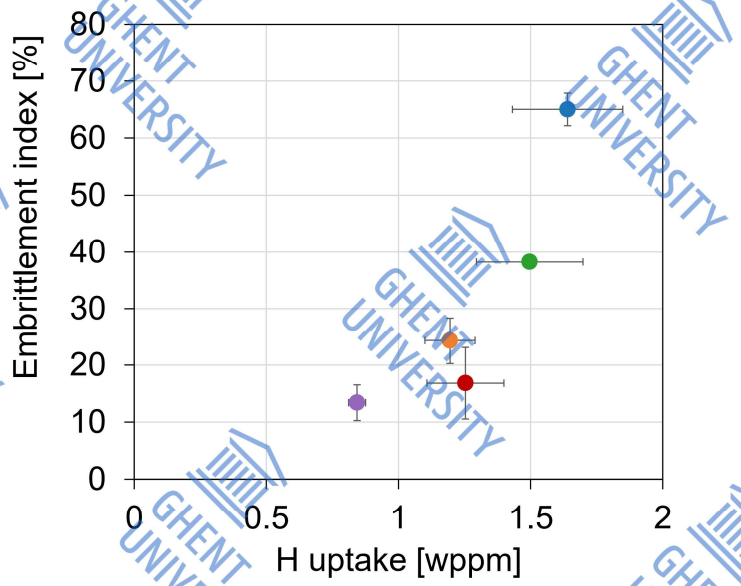
Comparison of base materials: mechanical performance

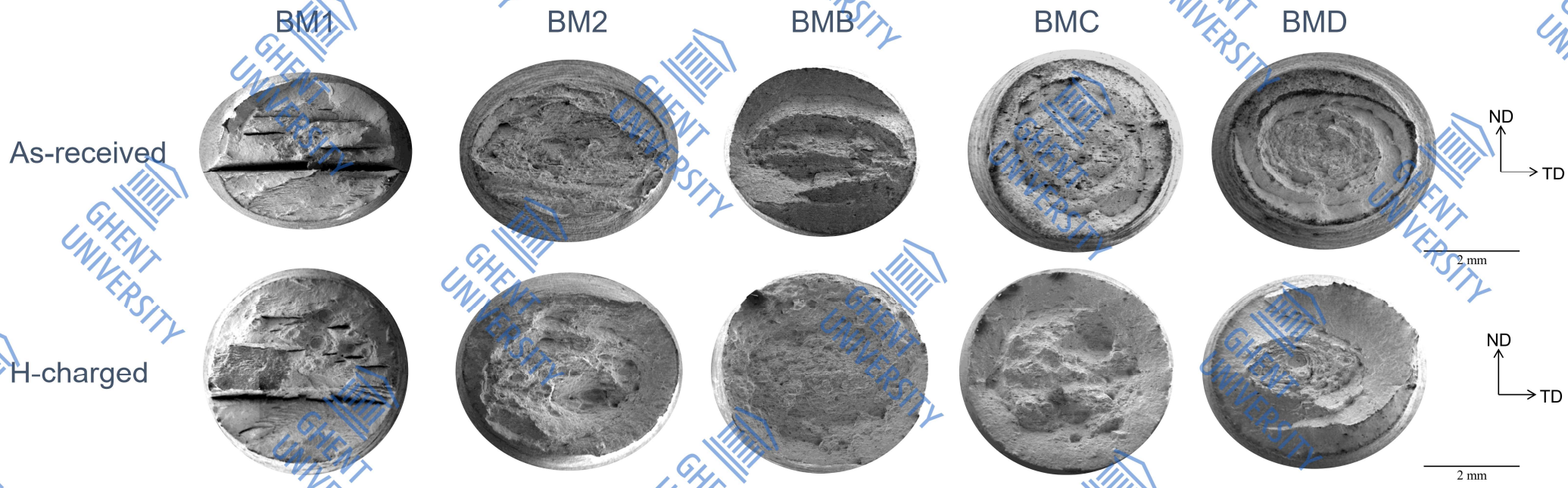




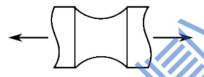


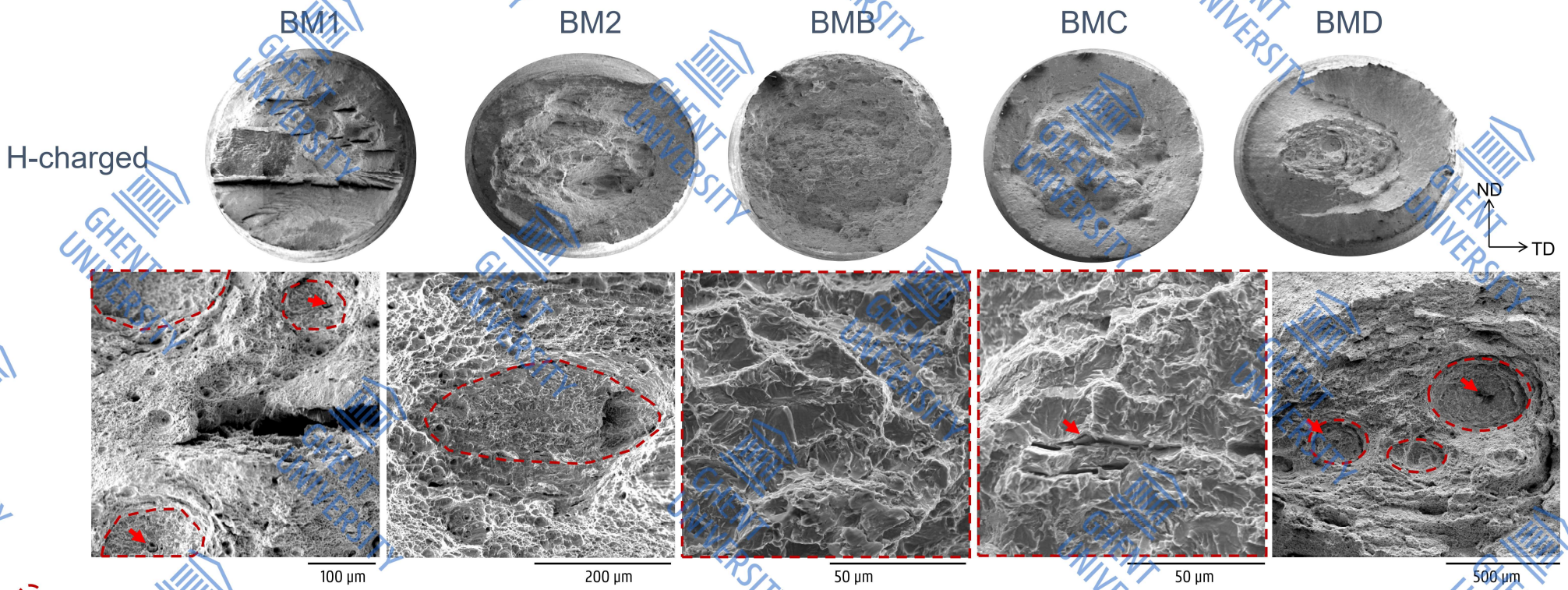
H uptake capacity is good predictor of embrittlement sensitivity

Comparison of base materials: post-mortem fractography



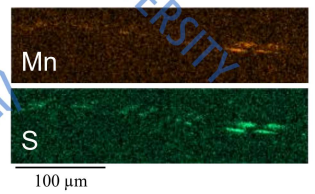
Comparison of base materials: post-mortem fractography





Quasicleavage areas

QC originating from inclusions



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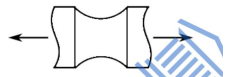
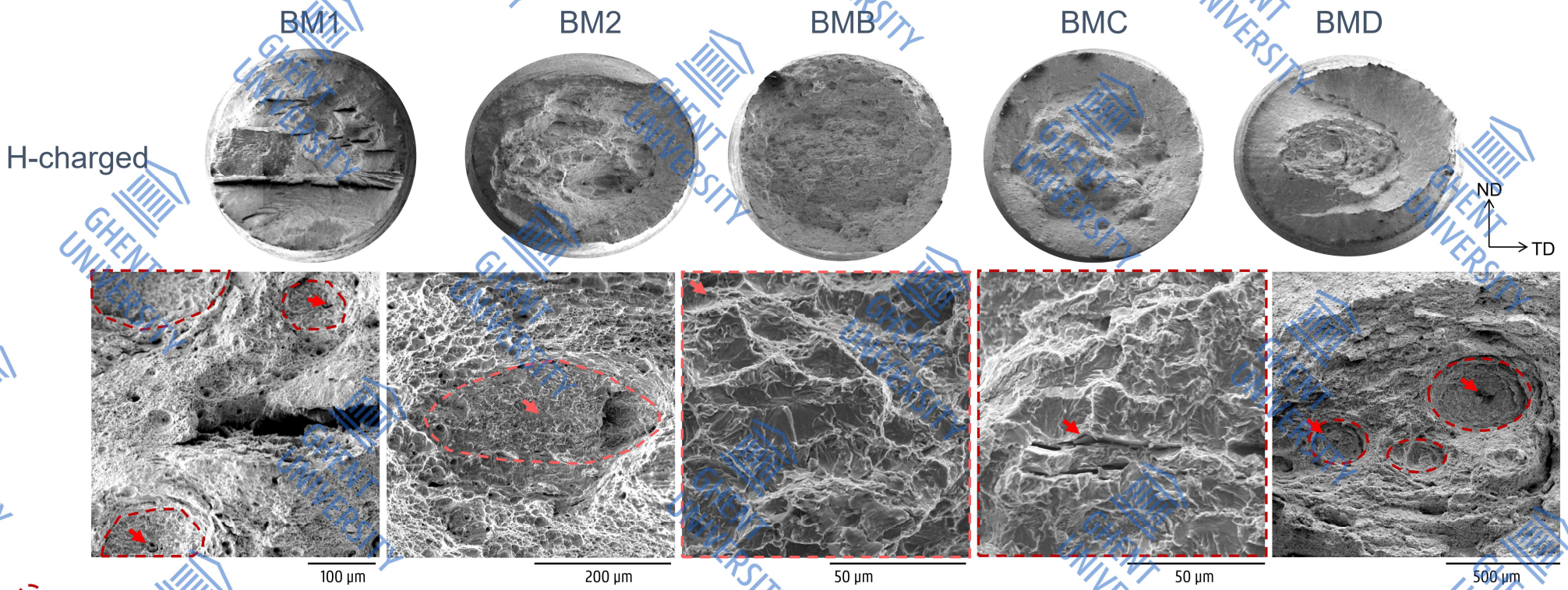
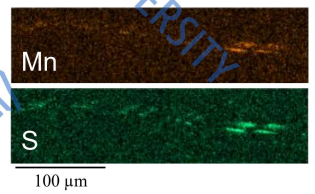
Comparison of base materials: post-mortem fractography



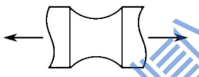


- Quasicleavage areas
- QC originating from inclusions
- QC originating from bainitic segregation bands



H content ↑ ➔ QC area ↑ ➔ Embrittlement ↑

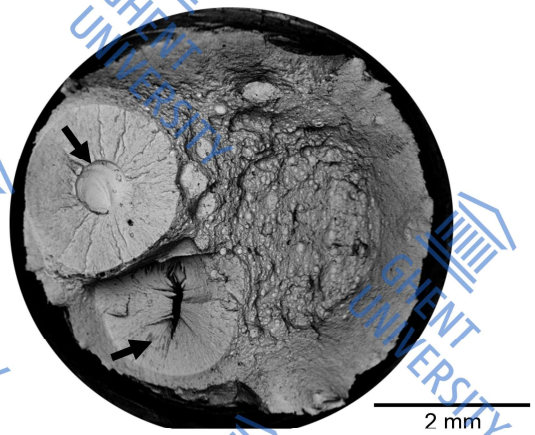
Comparison with welds: post-mortem fractography

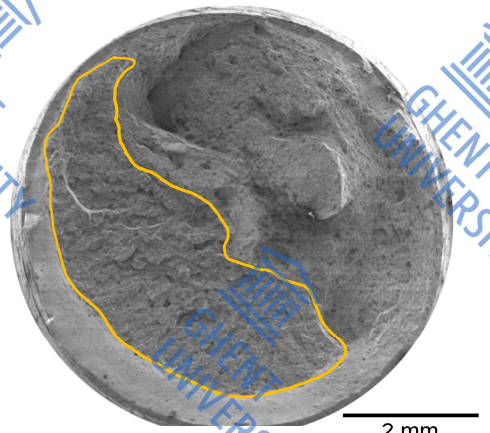


Girth weld A – HAZ

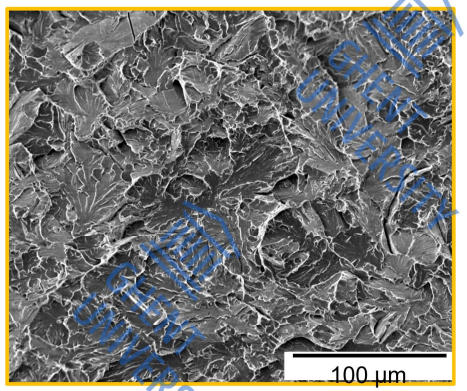
Girth weld B – weld metal

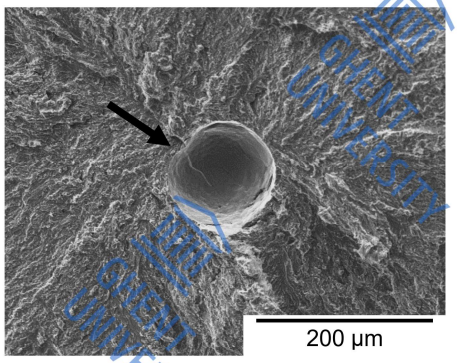
H-charged



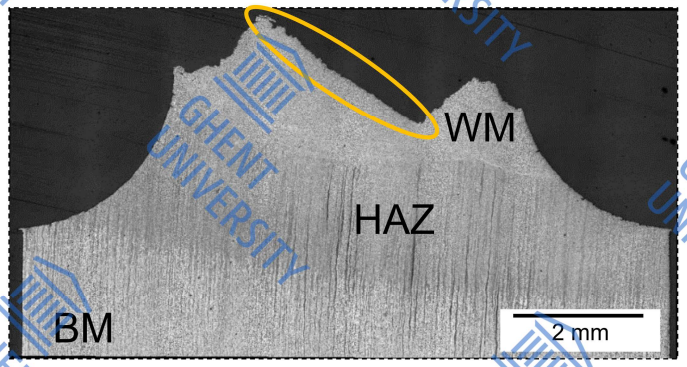


Transgranular cleavage



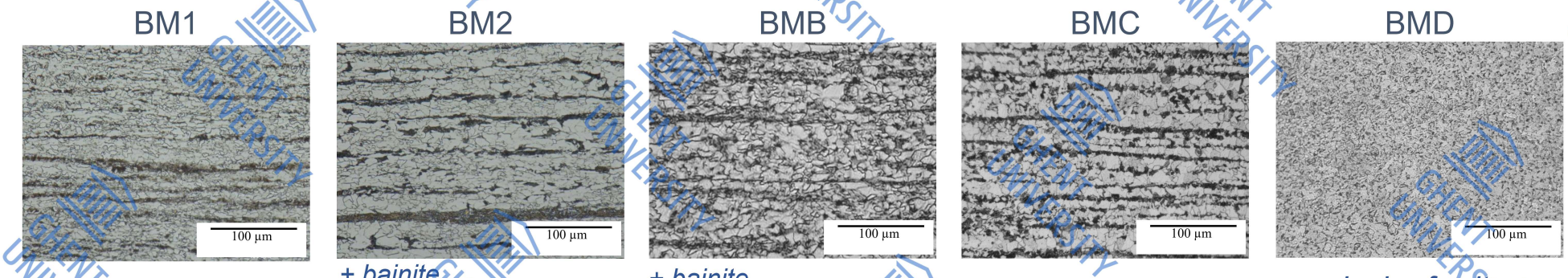


Weld flaws
as QC crack initiation spots



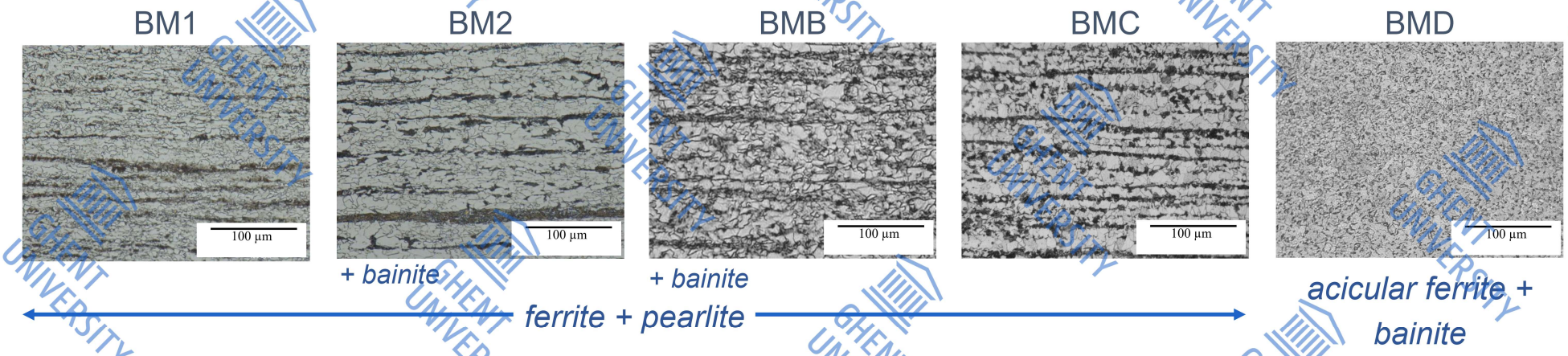
Weld specific fracture!

Quantifying microstructural determinants



Material	*Ferrite GS (µm)*	*Pearlite fraction (%)*
BM1	3.8 ± 0.2	13 ± 1
BM2	5.1 ± 0.4	20 ± 1
BMB	4.9 ± 0.5	20 ± 4
BMC	6.2 ± 0.2	24 ± 2
BMD	-	-

Quantifying microstructural determinants



Material	*Ferrite GS (µm)*	*Pearlite fraction (%)*	*GBD (m^{-1})*
BM1	3.8 ± 0.2	13 ± 1	568 ± 5
BM2	5.1 ± 0.4	20 ± 1	470 ± 27
BMB	4.9 ± 0.5	20 ± 4	521 ± 18
BMC	6.2 ± 0.2	24 ± 2	416 ± 24
BMD	-	-	488 ± 17

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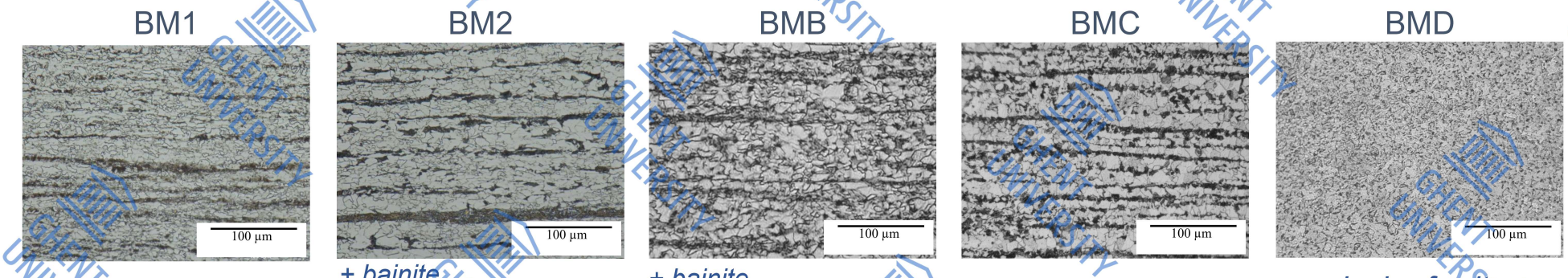
Quantifying microstructural determinants



Material	*Ferrite GS (µm)*	*Pearlite fraction (%)*	*GBD (m^{-1})*	*Dislocation density (m^{-2})*
BM1	3.8 ± 0.2	13 ± 1	568 ± 5	$5.9E^{15}$
BM2	5.1 ± 0.4	20 ± 1	470 ± 27	$6.8E^{15}$
BMB	4.9 ± 0.5	20 ± 4	521 ± 18	$9E^{15}$
BMC	6.2 ± 0.2	24 ± 2	416 ± 24	$2.3E^{15}$
BMD	-	-	488 ± 17	$6.7E^{15}$

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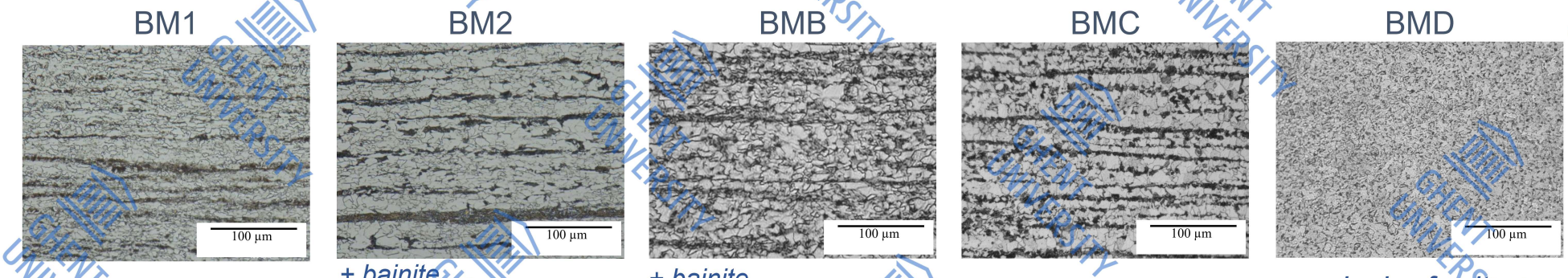
Correlating microstructural parameters with hydrogen uptake



Material	*Ferrite GS (µm)*	*Pearlite fraction (%)*	*GBD (m^{-1})*	*Dislocation density (m^{-2})*
BM1	3.8 ± 0.2	13 ± 1	568 ± 5	$5.9E^{15}$
BM2	5.1 ± 0.4	20 ± 1	470 ± 27	$6.8E^{15}$
BMB	4.9 ± 0.5	20 ± 4	521 ± 18	$9E^{15}$
BMC	6.2 ± 0.2	24 ± 2	416 ± 24	$2.3E^{15}$
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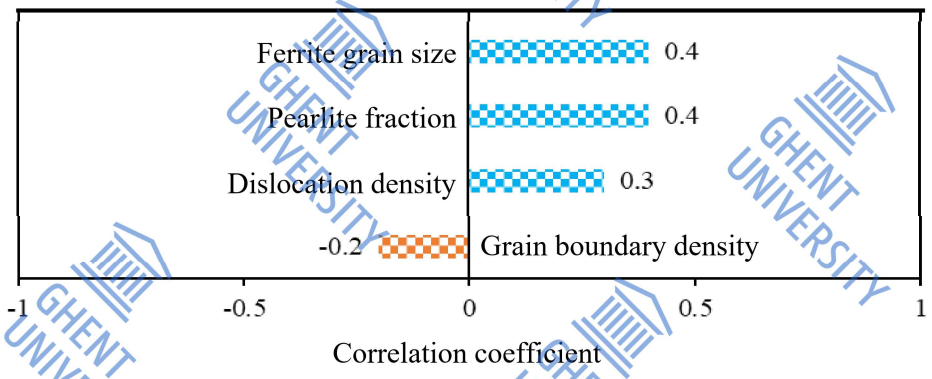
Spearman's correlation coefficient

Hydrogen uptake ↔ microstructural features



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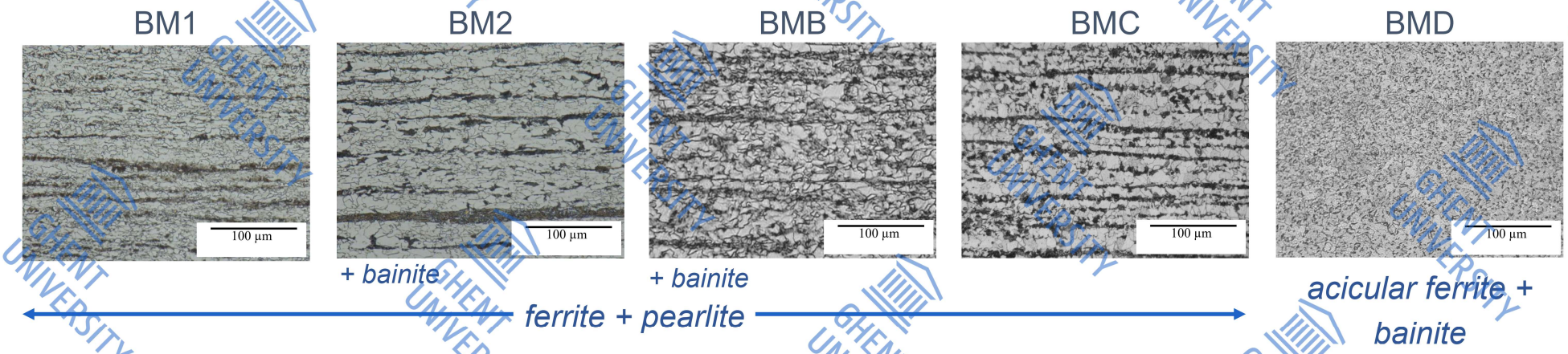
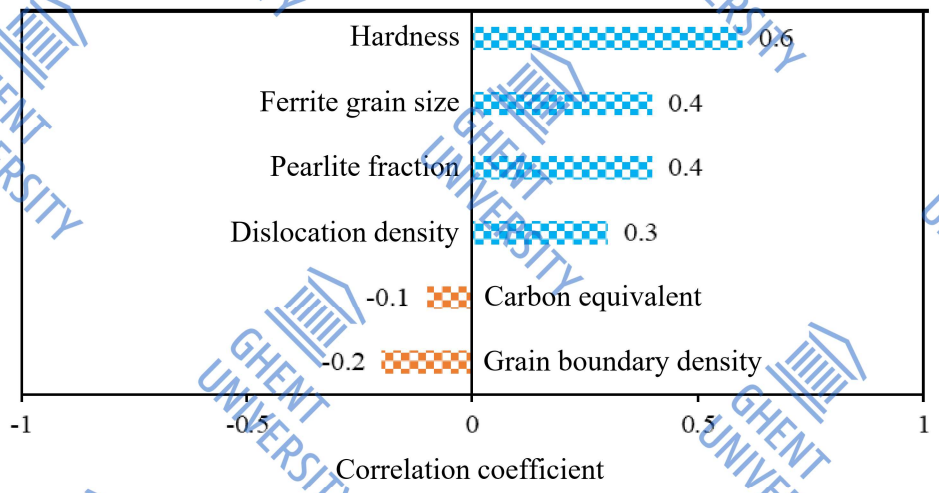
Correlating material parameters with hydrogen uptake



Material	*Carbon equivalent*	*Hardness (HV10)*
BM1	0.404	212 ± 5
BM2	0.404	211 ± 4
BMB	0.433	220 ± 1
BMC	0.445	199 ± 2
BMD	0.490	196 ± 4

Hydrogen uptake ↔ material parameters



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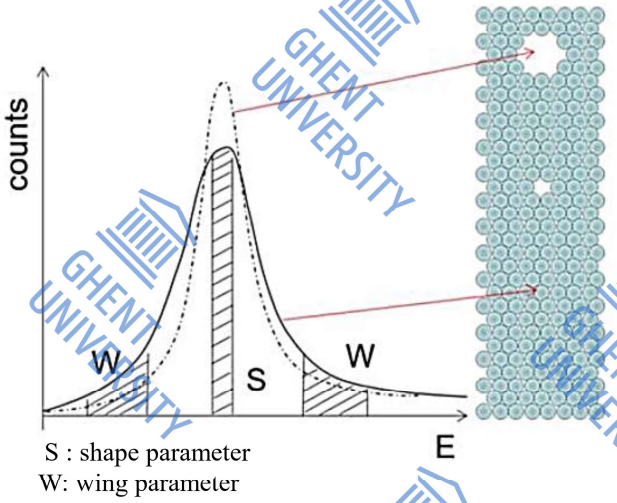
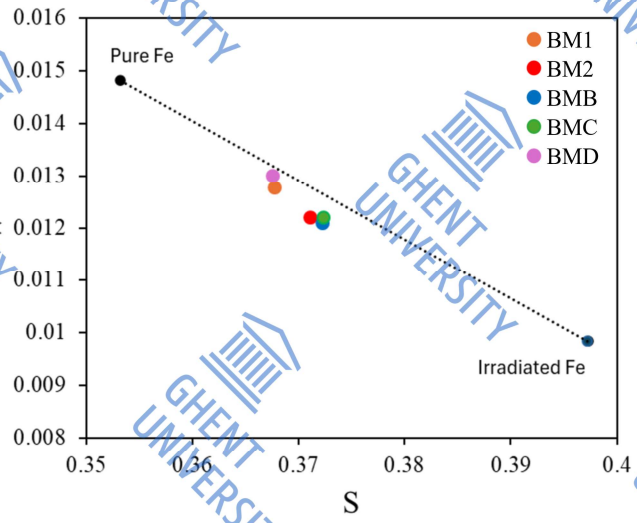
Positron annihilation spectroscopy



- Positrons annihilate with electrons → emit gamma rays
- Energy spectrum of gamma rays reflects electron momentum
- Defects change electron environment → affect peak shape (W,S)



~ open volume defects:

vacancies, vacancy clusters, voids, dislocations

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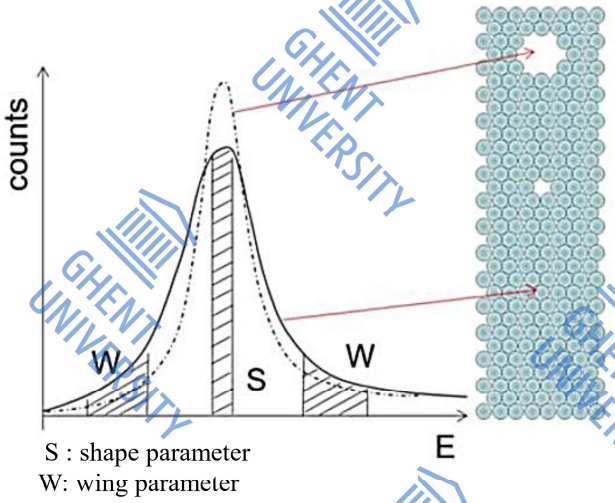
Positron annihilation spectroscopy



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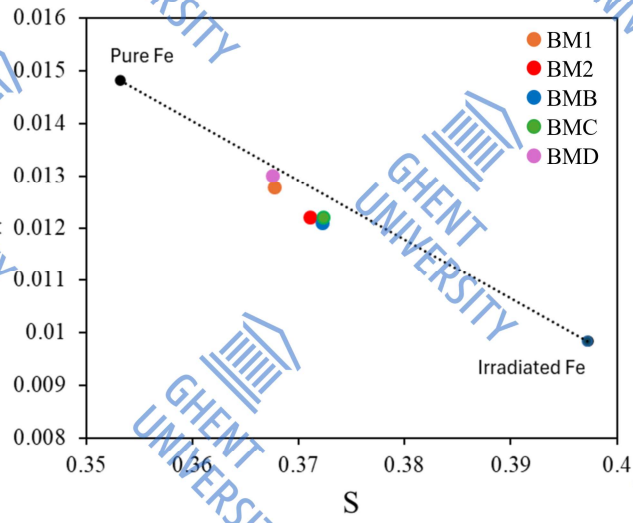

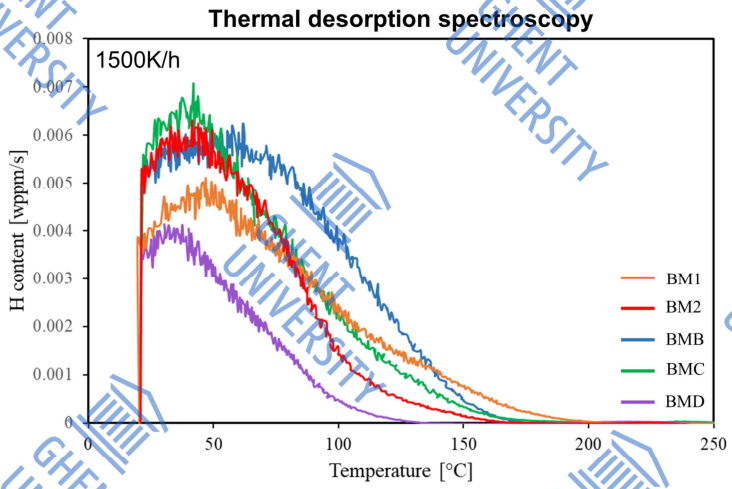

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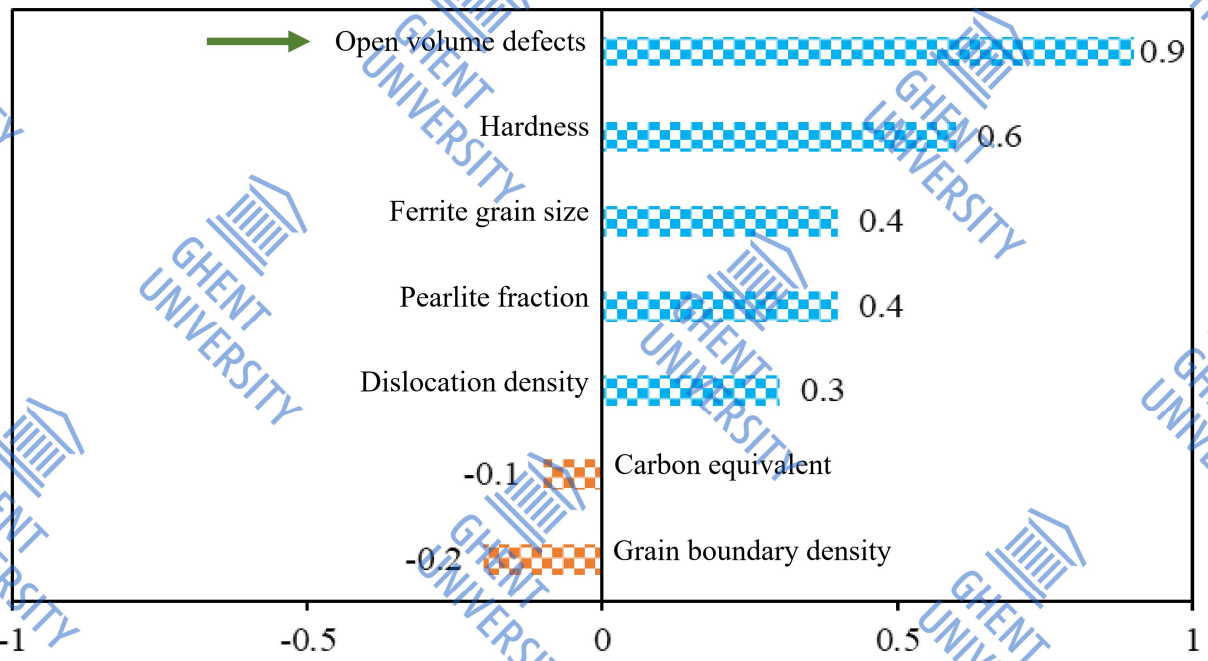
Positron annihilation spectroscopy

- S parameter ~ open volume defects: vacancies, vacancy clusters, voids, dislocations



Open volume defects best microstructural predictor of hydrogen uptake

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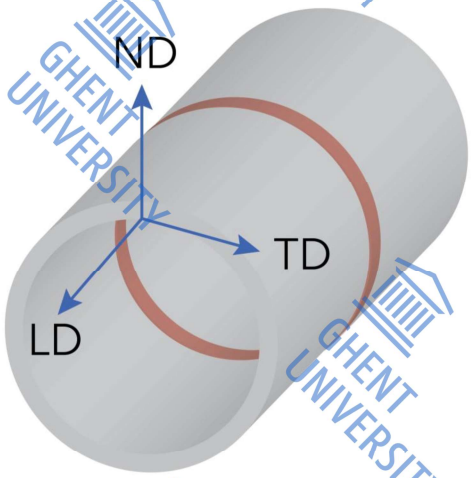
Presentation content

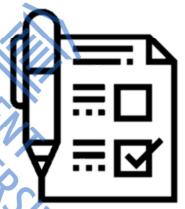
From fundamental research...



In-depth study X70

Screening H sensitivity of pipeline steels

Mechanical characterisation



Correlation analysis

Link to gaseous H_2 testing

... To application oriented research

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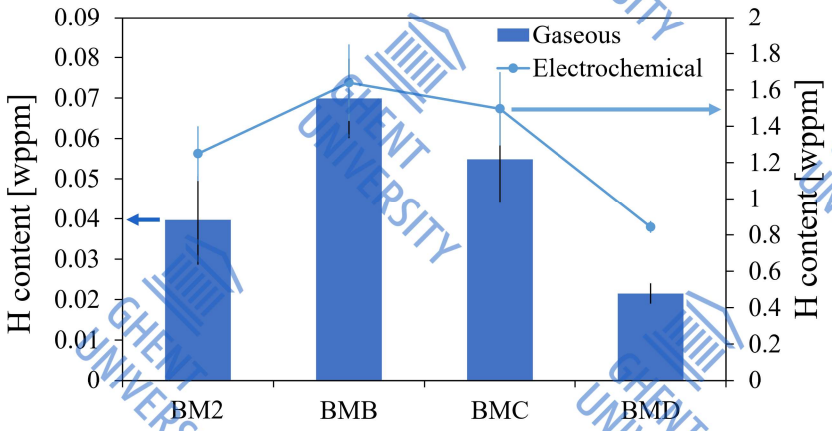
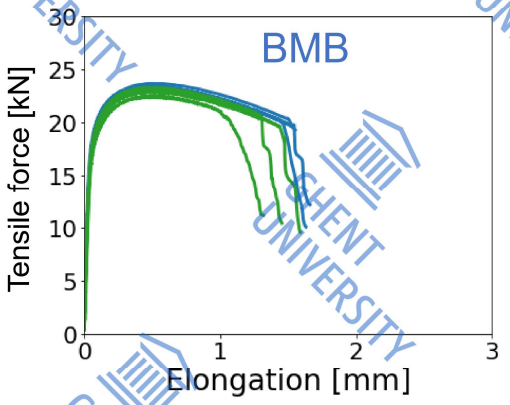
Gaseous hydrogen charging: pure H_2

80°C
100 bar
2 days

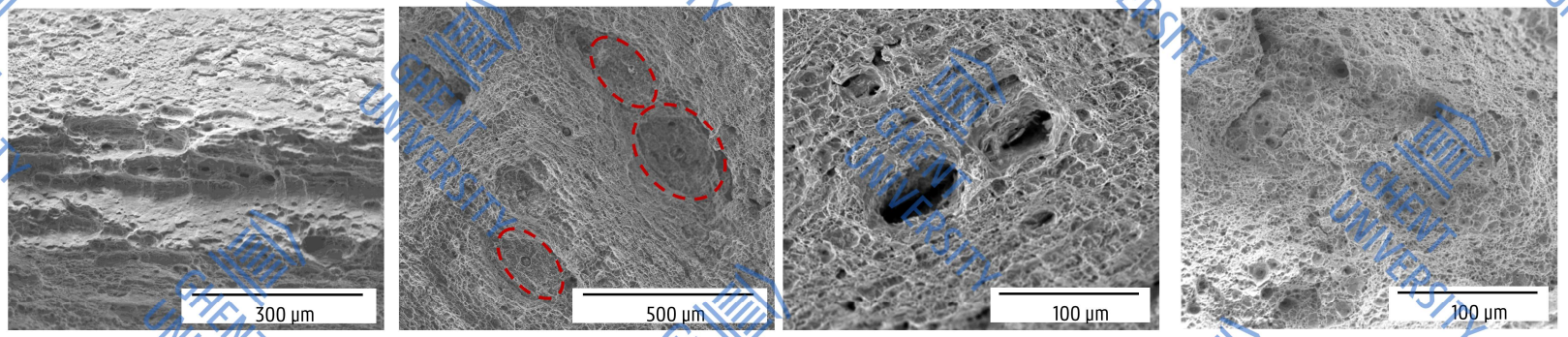




cfr. poster P120, Jubica

Role of gaseous charging parameters on hydrogen uptake in pipeline steels

BM2 BMB BMC BMD



Material ranking preserved
Similar type of embritteling mechanism

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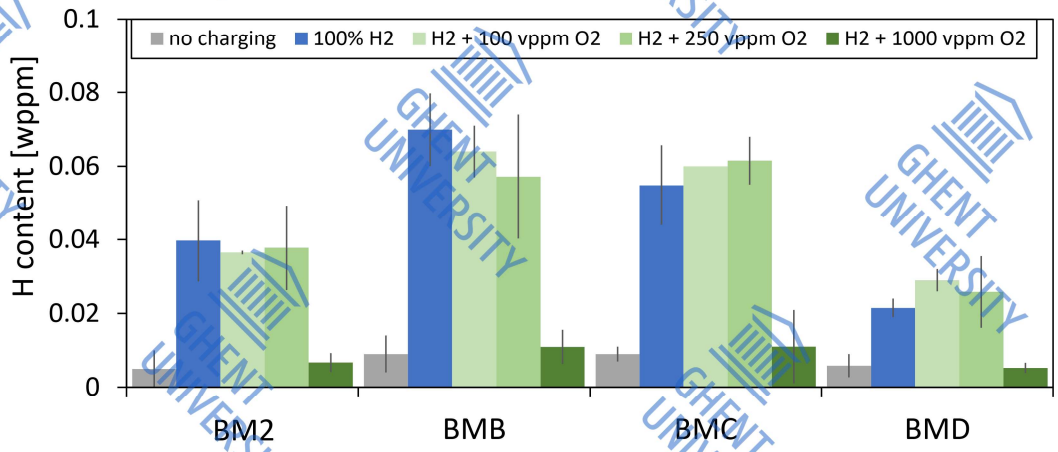
Gaseous hydrogen charging: oxygen inhibitors

80°C
100 bar
2 days



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Role of gaseous charging parameters on hydrogen uptake in pipeline steels

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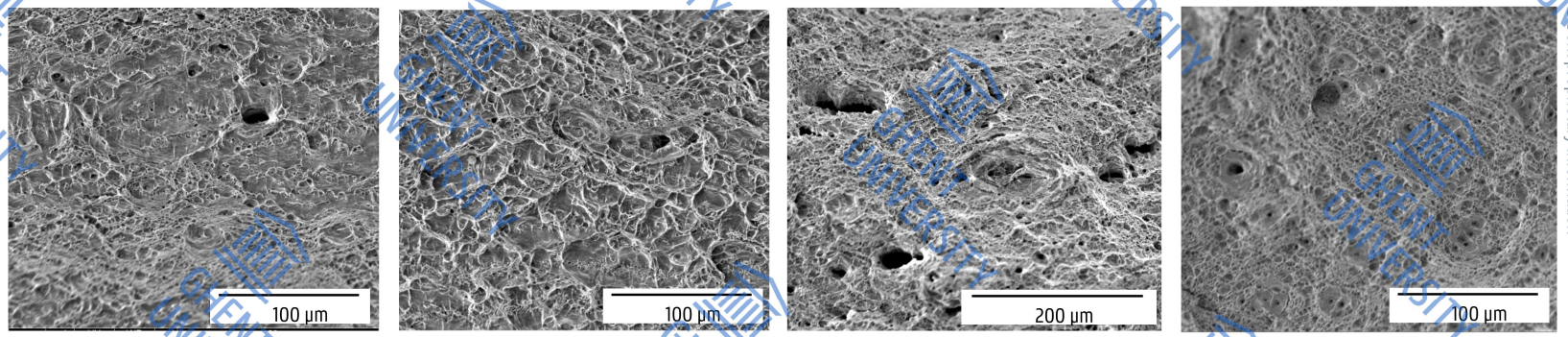

Gaseous oxygen addition inhibits hydrogen uptake
(for the tested conditions)

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Key take-aways

- Hydrogen embrittlement sensitivity correlates to hydrogen uptake capacity
- H uptake capacity is linked to material microstructure

  → combined influence of microstructural parameters

  → limited link to hardness

  → ~open volume defects (reversible hydrogen traps)
- Material ranking preserved for electrochemical versus gaseous pre-charging

  → similar fracture micromechanism