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Influence of Hydrogen on the Fracture Toughness of a X65 Gas Transmission Pipeline Steel

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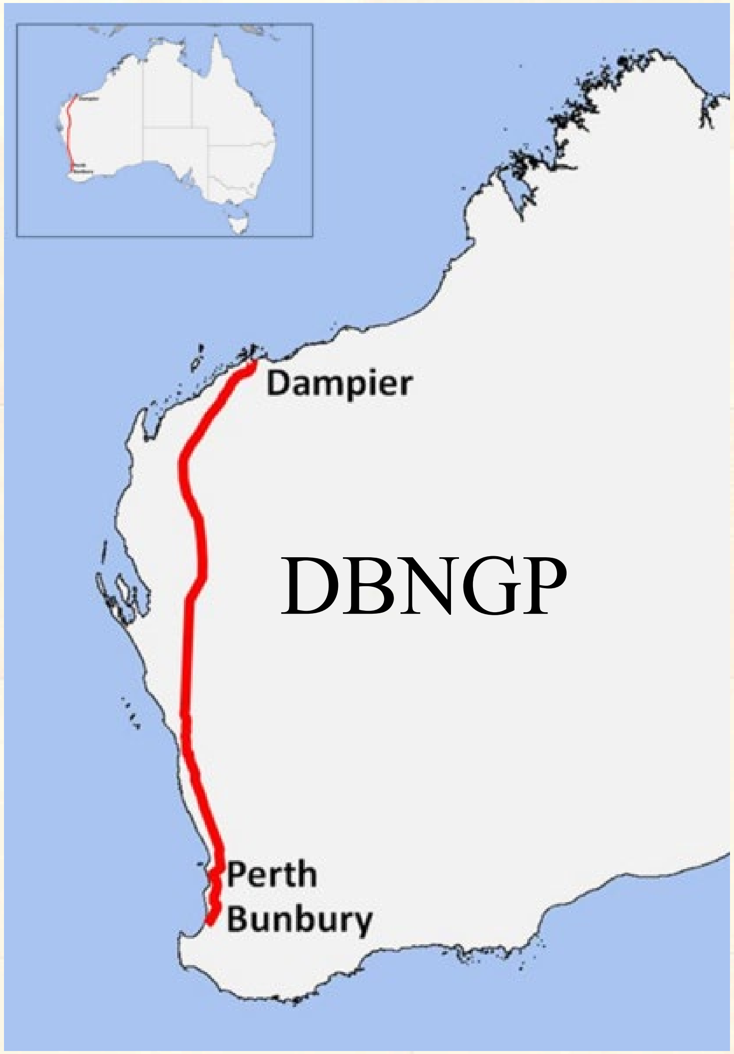
Thanks to: Future Fuels CRC, AGIG

1. Hydrogen and X65D

In Australia, hydrogen is best transported through steel pipelines, but…



TECHNOLOGICAL QUESTION:
"are existing natural gas pipelines fit to carry hydrogen?"

1. Fracture & fracture resistance

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Objectives

- To measure the fracture toughness of DBNGP X65-D pipeline steel for a hydrogen fugactity somewhat greater than in service (200 bar gaseous hydrogen, 9 mA/cm^2).
- To characterise the fracture toughness at a higher hydrogen fugacity.
- To understand the mechanism by which hydrogen facilitates fracture: Hydrogen assisted ductile (HAD) fracture or brittle (HAB) fracture.

Chowdhury et al, Preliminary evaluation of the influence of hydrogen on the fracture toughness of a X65 pipeline steel, *Advanced Engineering Materials*, Article DOI: 10.1002/adem.202400352

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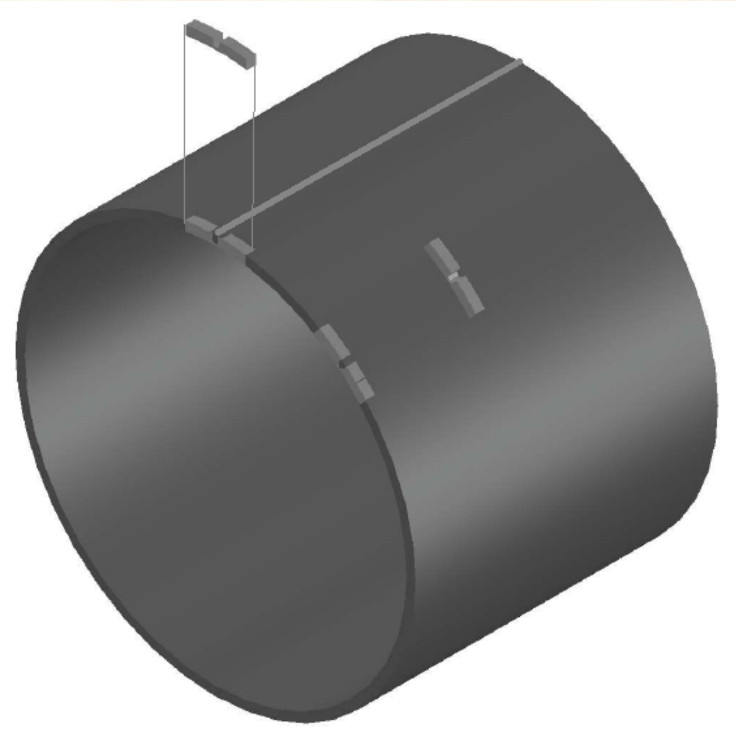
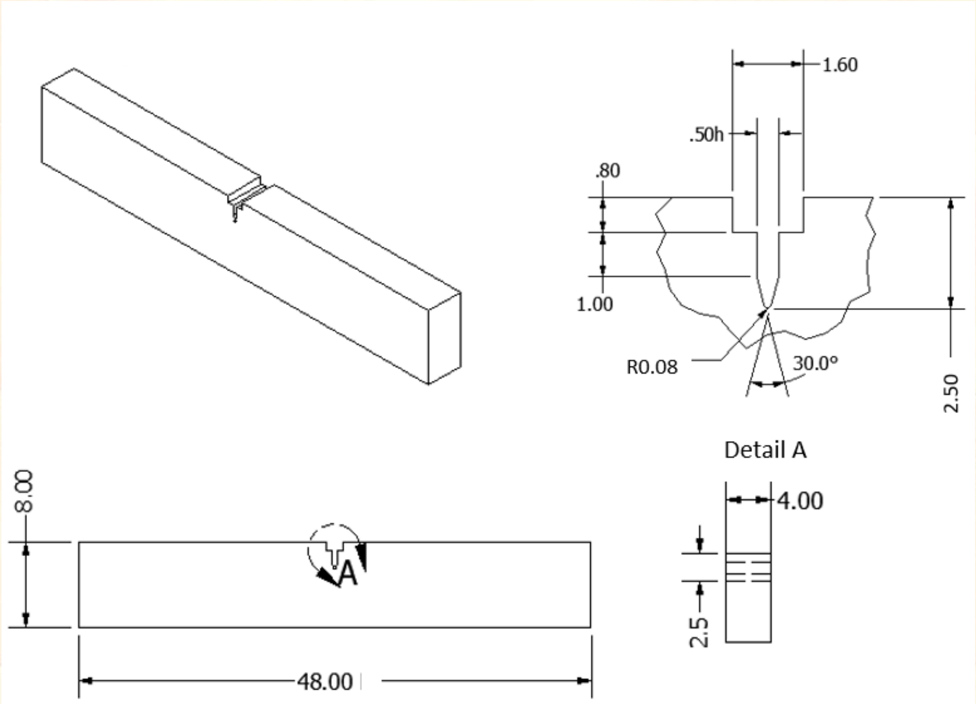
1. Fracture & fracture resistance



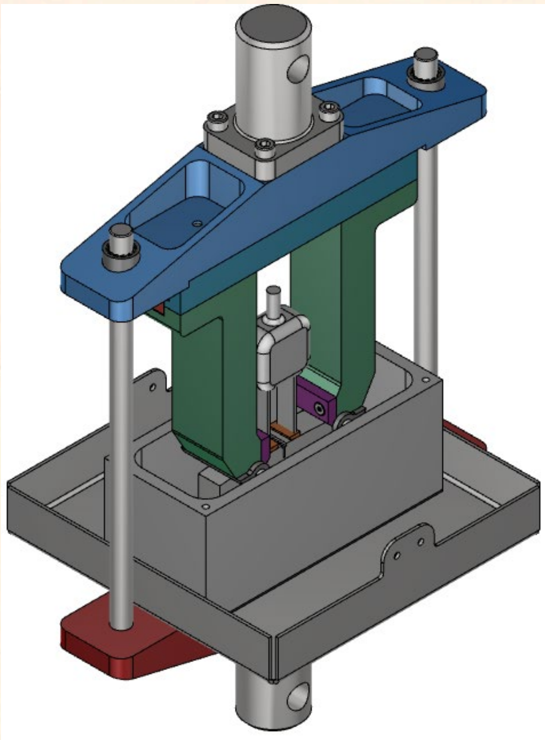


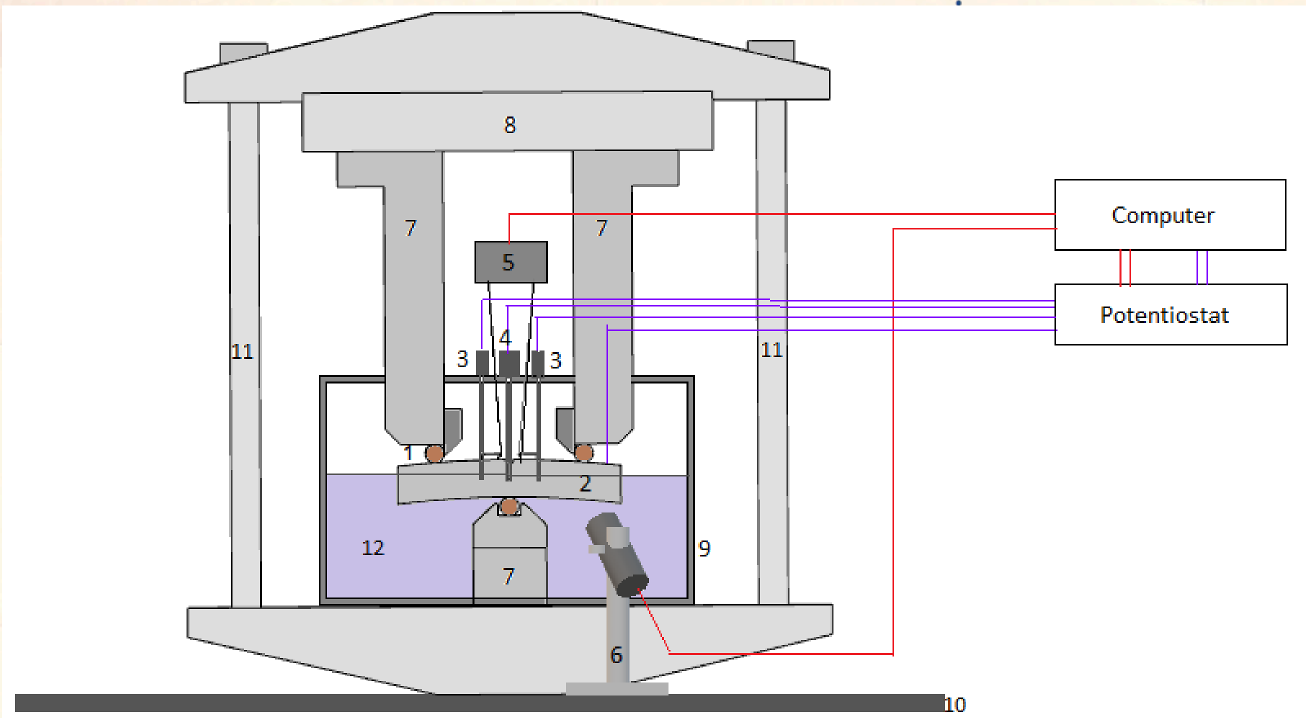
- Single-edge-notched specimen (SENB),
- Longitudinal crack growing in radial direction.
- CR. Circumferential (C) loading direction: perpendicular to the crack plane.
- Radial crack growth direction (R), towards the inside of the pipe.

1. Fracture & fracture resistance

A three-point bend test apparatus was used to measure the fracture toughness using the *J*-integral using a SENB specimen in three-point bending. The crack length was measured optically and using the ASTM partial unloading compliance method.

Cathodic hydrogen charging introduced hydrogen at 9 mA/cm^2.

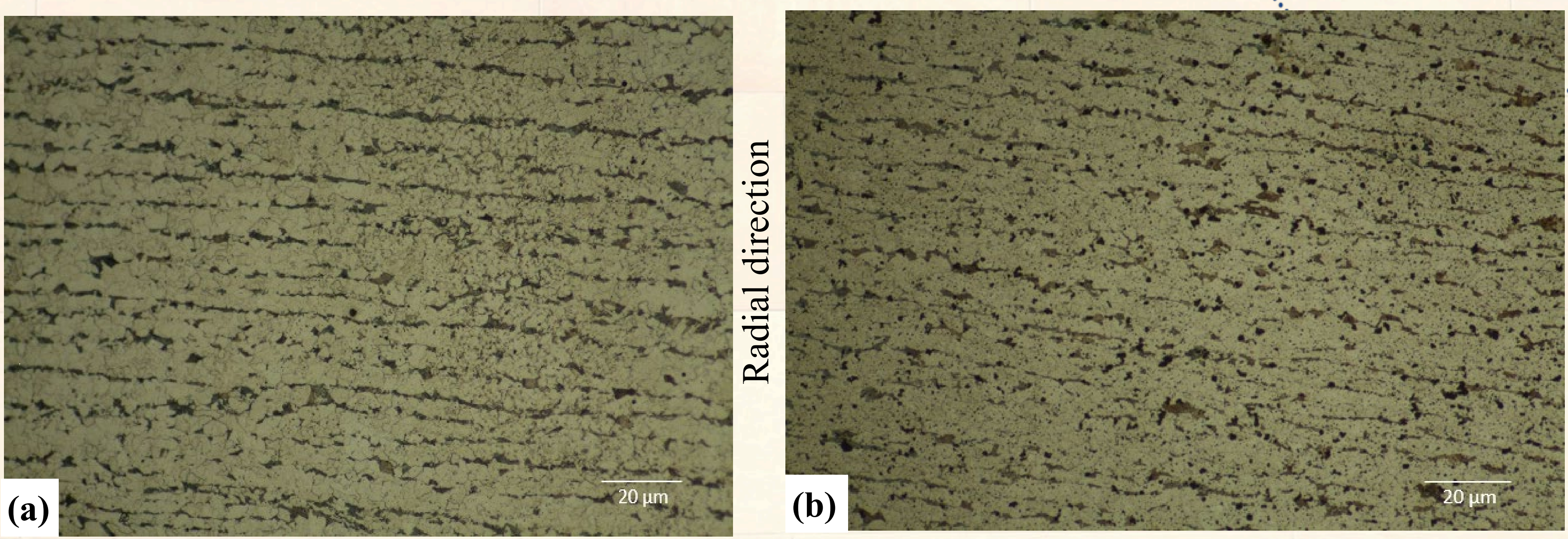




1. Fracture & fracture resistance

The DBNGP X65-D pipeline steel had a ferrite matrix containing some pearlite, elongated in working direction:

(a) the radial – transverse plane and (b) the radial - longitudinal plane.

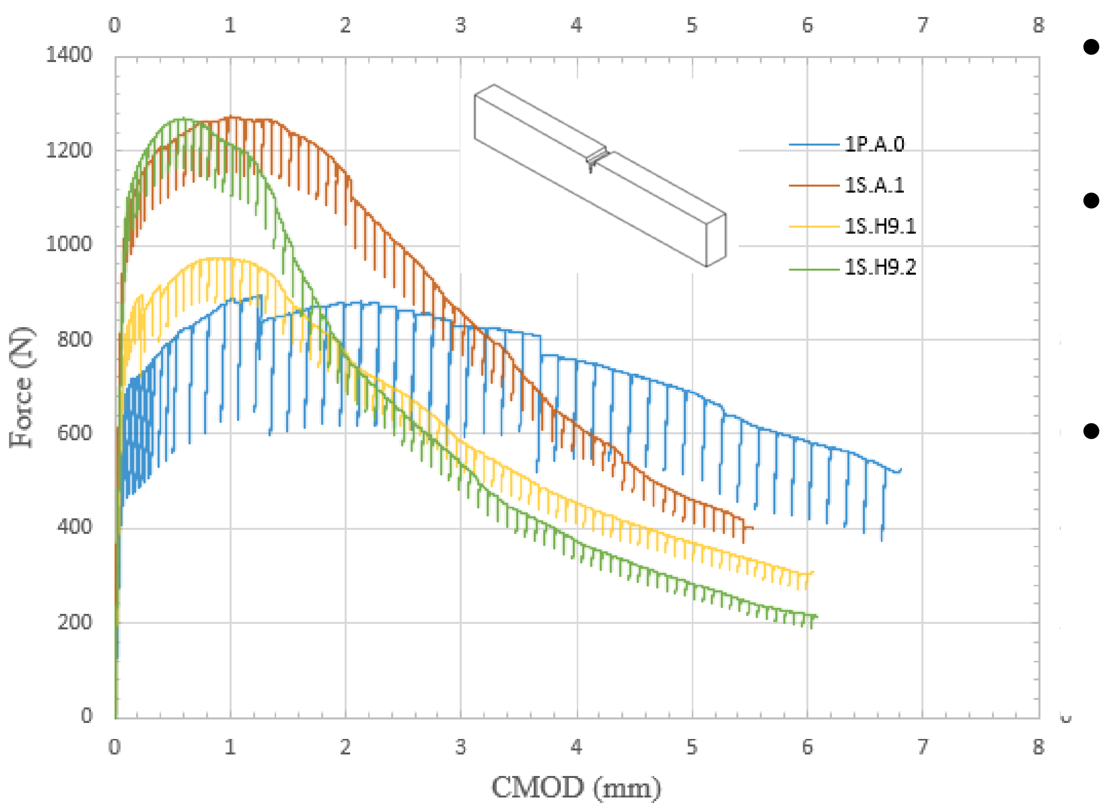


Transverse direction

Longitudinal direction

1. Fracture & fracture resistance

Force vs CMOD for: 1P.A.0 (plain tested in air); 1S.A.1 (side grooved tested in air); 1S.H9.1 (side grooved tested with hydrogen); 1S.H9.2 (side grooved tested with hydrogen at 9 mA/cm^2).



CMOD is the crack mouth opening displacement

- *J* determined by area under curve at each loading step.
- Crack length, *a*, determined optically and from unloading compliance by ASTM E1820.
- Crack length determined from compliance was in good agreement with optical measurement.

1. Fracture & fracture resistance

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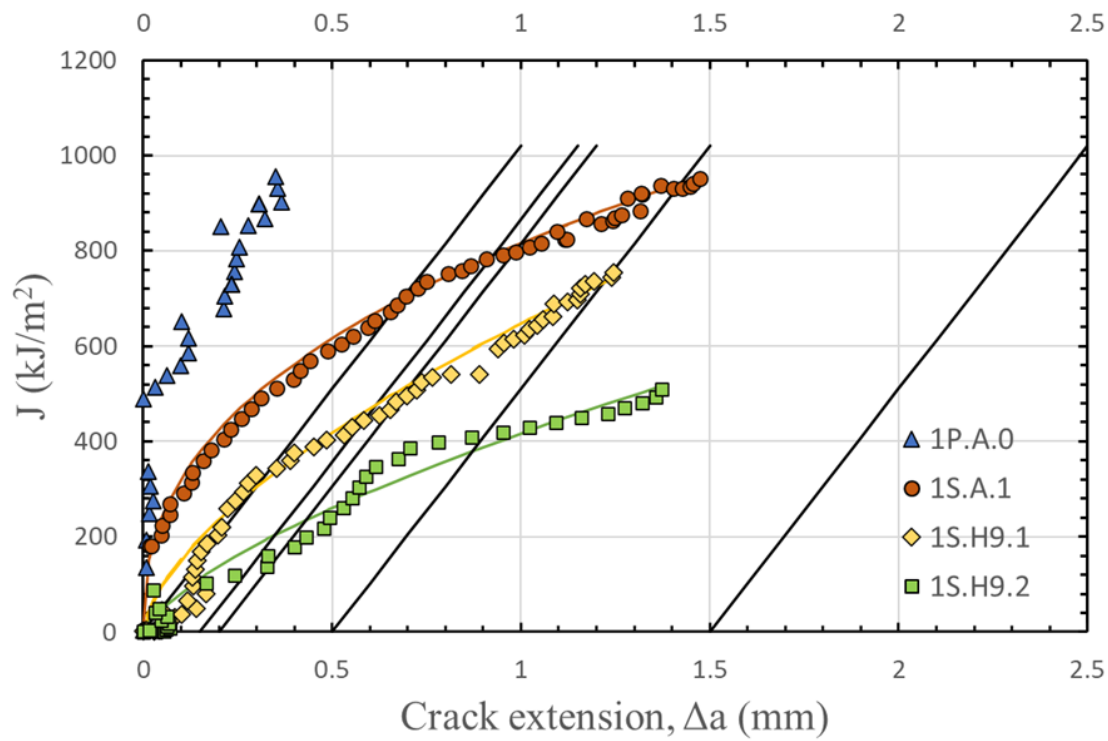
J-Δa curves (& ESIS construction lines $J = m' \sigma_y \Delta a$, $m' = 4.23$) for: 1P.A.0 (plain specimen in air); 1S.A.1 (side grooved in air); 1S.H9.1 (side grooved with hydrogen charging); 1S.H9.2 (side grooved with hydrogen charging at 9 mA/cm^2).



- ESIS is the European Structural Integrity Society.
- J_Q was determined from the intersection of the J curve & the 0.2 construction line.
- "J_Q is analogous to yield stress."

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1. Fracture & fracture resistance

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- The ESIS construction line $J = m' \sigma_y \Delta a$, $m' = 4.23$ produced more conservative values of fracture toughness than that using ASTM E1820 ($J = 2\sigma_y \Delta a$) because it is somewhat steeper.
- ESIS is the European Structural Integrity Society.

- J_Q was determined from intersection of J- Δa curve & 0.2 construction line.
- Values of J_Q can be compared between similar specimens.
- $J_Q = J_{IC}$ if B, $b_0 > \frac{10 J_Q}{\sigma_y}$; B is specimen thickness, b_0 is initial ligament.
- J_{IC} is an ASTM-valid measurement of fracture toughness.
- J_{IC} can be used in structural integrity evaluation for any structure.

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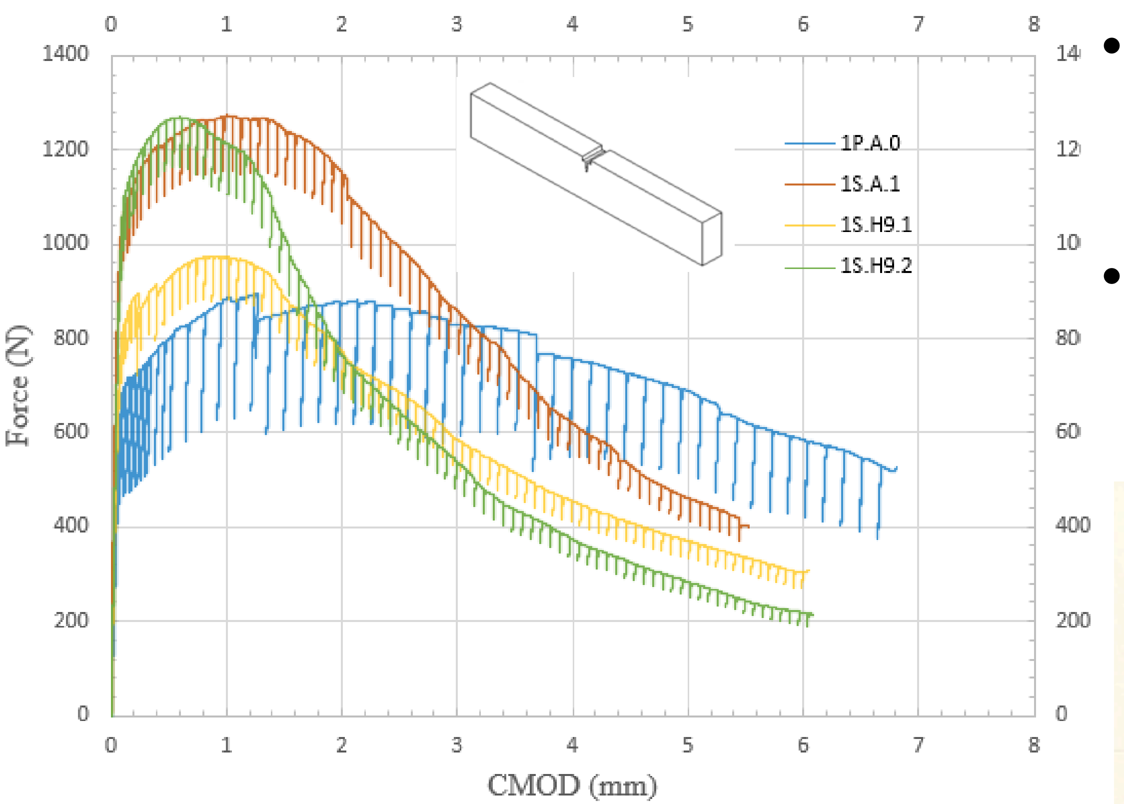
1. Fracture & fracture resistance

Force vs CMOD for SENB: 1P.A.0 (plain in air); 1S.A.1 (side grooved in air); 1S.H9.1 (side grooved with hydrogen); 1S.H9.2 (side grooved with hydrogen at 9 mA/cm^2).



- There were some unstable crack extensions in air and for 1S.H9.1.
- A fracture toughness value can be evaluated corresponding to each instability.

CMOD is the crack mouth opening displacement

1. Fracture & fracture resistance

Criteria check for valid J_{1C} or J_{1H} for type 1 specimens using the construction line $J = 4.23\sigma_y \Delta a$.

Test condition	Specimen	B, mm	W, mm	a_{oq}, mm	b_0, mm	σ_y, MPa	J_Q, kJ/m^2	K_Q, MPa$\sqrt{m}$	$\frac{10J_Q}{\sigma_y}$	B, $b_0 > \frac{10J_Q}{\sigma_y}$
In air	1S.A.1	4	8	4.58	3.42	510	590	369	15.84	No
9 mA/cm^2	1S.H9.1	4	8	4.93	3.07	510	97*	150	-	-
9 mA/cm^2	1S.H9.2	4	8	4.65	3.35	510	155	189	3.33	Yes

*Designated as J_{QC}; there are difference size requirements

Literature Comparison for DBNGP X65-D

1. J_Q in air: 590 and 778 N/mm (369 MPa√m and 424 MPa√m).
2. J_Q at ~ 200 bar H_2 (at 9 mA/cm^2) < J_Q in air.
3. J_{1C} at ~ 200 bar H_2: 155 and 97 N/mm (189 and 150 MPa√m).
4. ASTM-valid fracture toughness of K_{IC} = 189 & 150 MPa√m with H_2.

Steel	Environment	Fracture Toughness	Ref* (year)
X42, X52, X60, X70, X80	6.9 MPa H_2	95 – 111 MPa√m	38 (2012)
A516 G70	Air	150 MPa√m	41 (2019)
	3.5 MPa H_2	119 MPa√m	41
	6.9 MPa H_2	102 MPa√m	41
	20.7 MPa H_2	89 MPa√m	41
	34.5 MPa H_2	82 MPa√m	41
X42	Air	147 MPa√m	43 (1982)
	4 MPa H_2	85 MPa√m	43
	6.5 MPa H_2	69 MPa√m	43
X70	Air	205 MPa√m	48 (2021)
	10 MPa H_2	104 MPa√m	48

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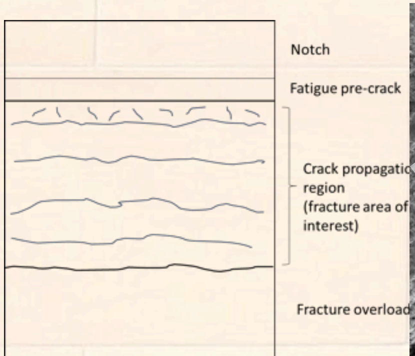
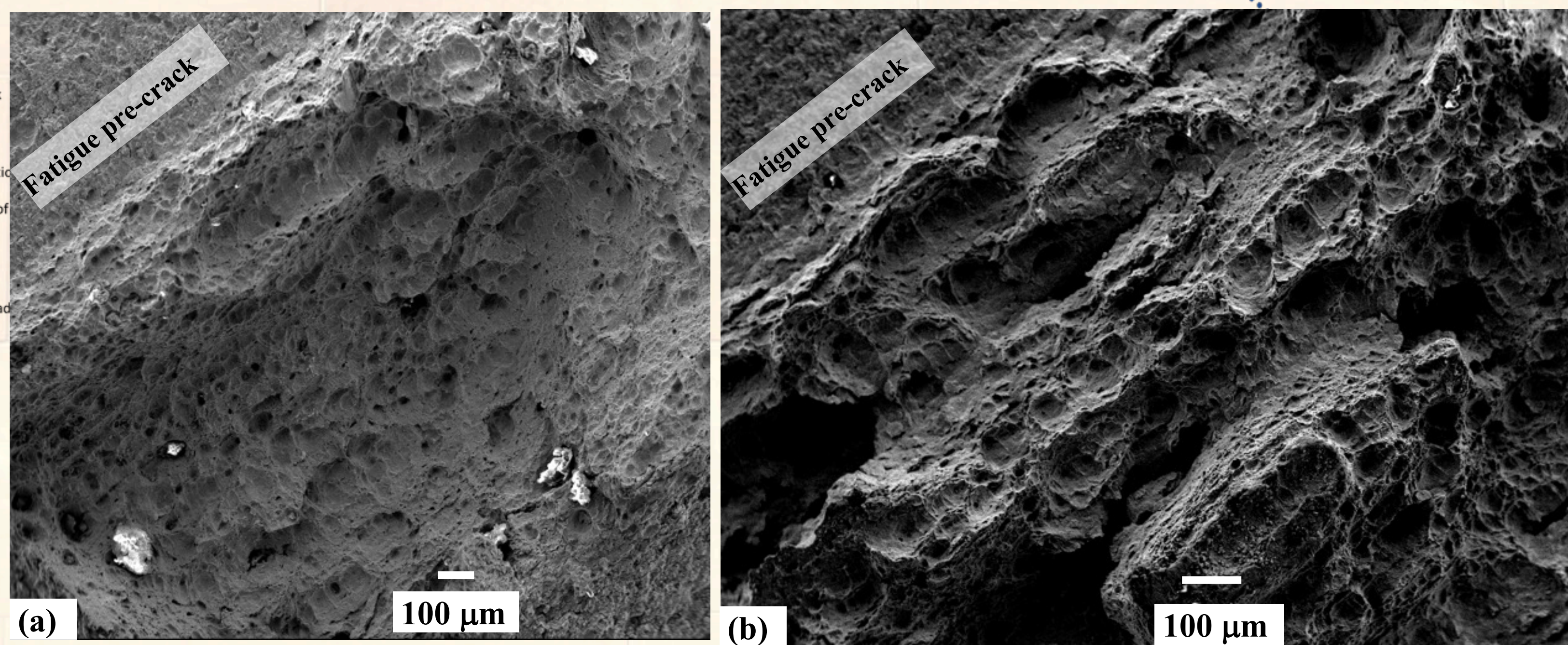
1. Fracture & fracture resistance

Fractography indicated ductile fracture: (a) specimen 1S.A.1 (tested in air) and (b) specimen 1S.H9.2 (pre-charged with hydrogen and hydrogen charged at 9 mA/cm^2 during the fracture toughness test).





Air

Hydrogen

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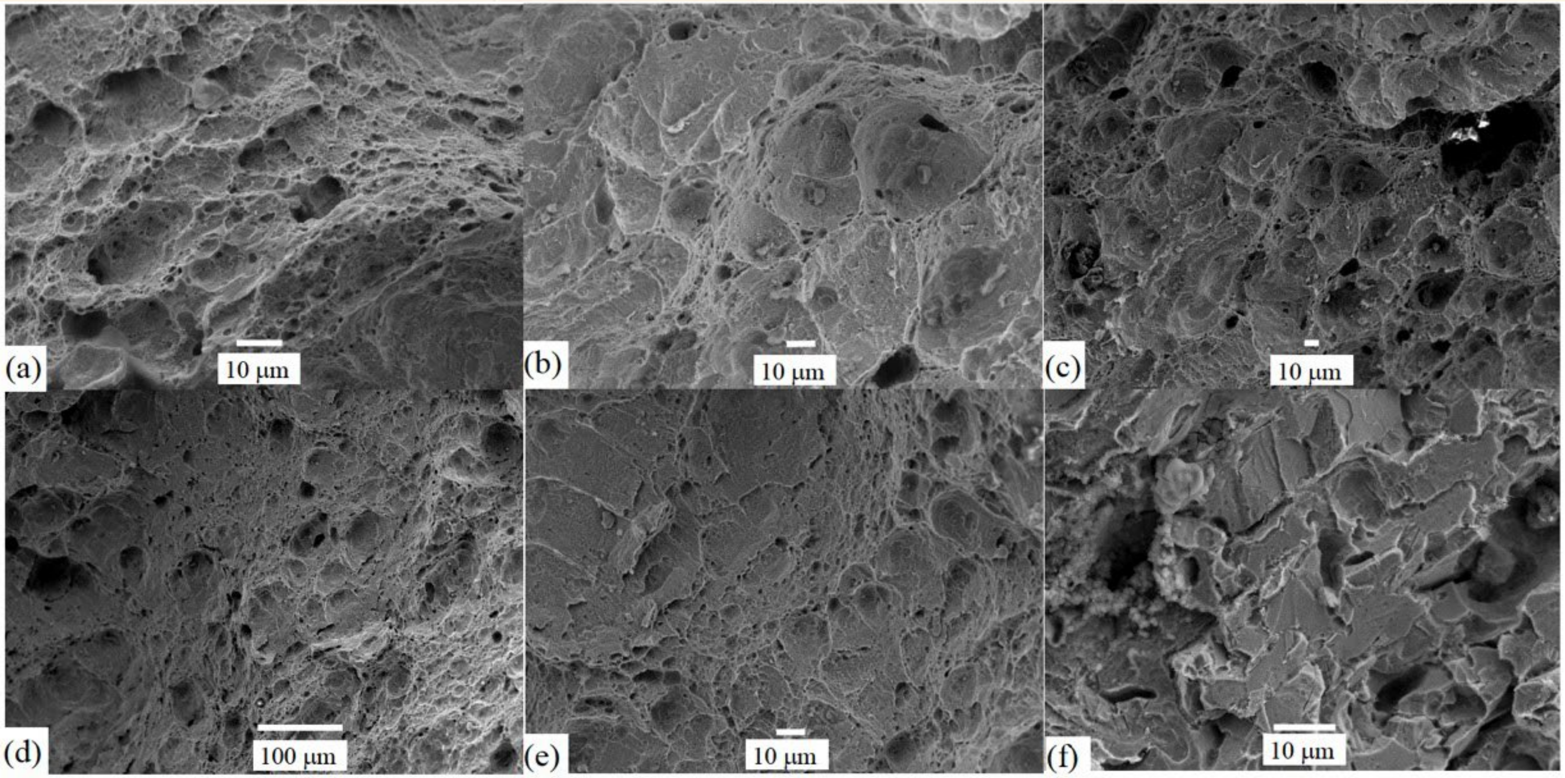
Fracture of specimen 1S.A.1 (tested in air) was (a)-(e) ductile, and (f) brittle for the overload fracture of the remaining ligament of the specimen broken open after cooling in liquid nitrogen.



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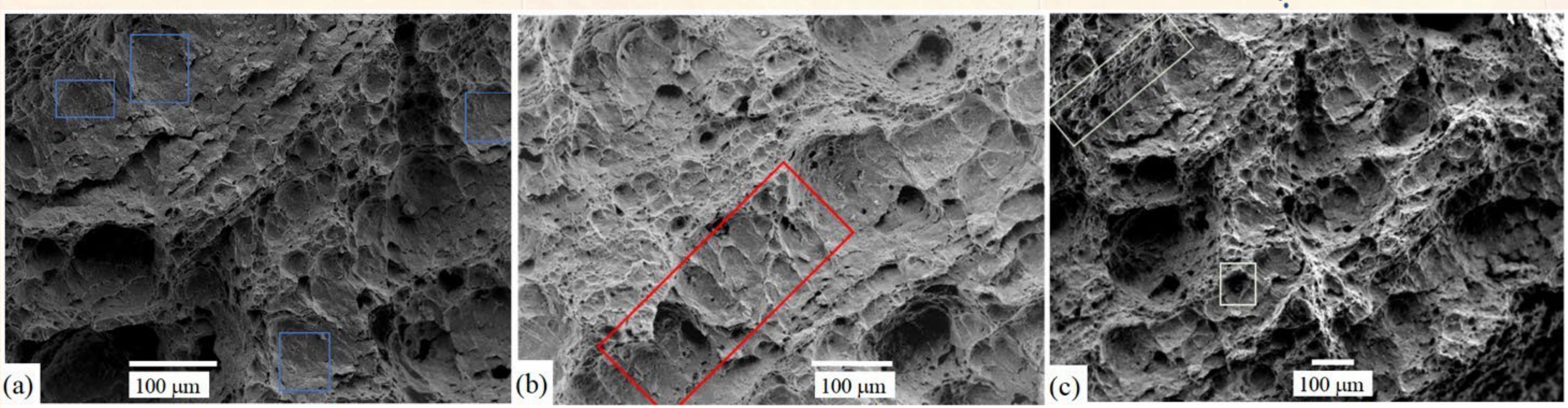
4. Fracture & fracture resistance

Ductile fracture with hydrogen (specimen 1S.H9.2, specimen 2 specimen type 1 with hydrogen at 9 mA/cm^2).



1. Fracture & fracture resistance

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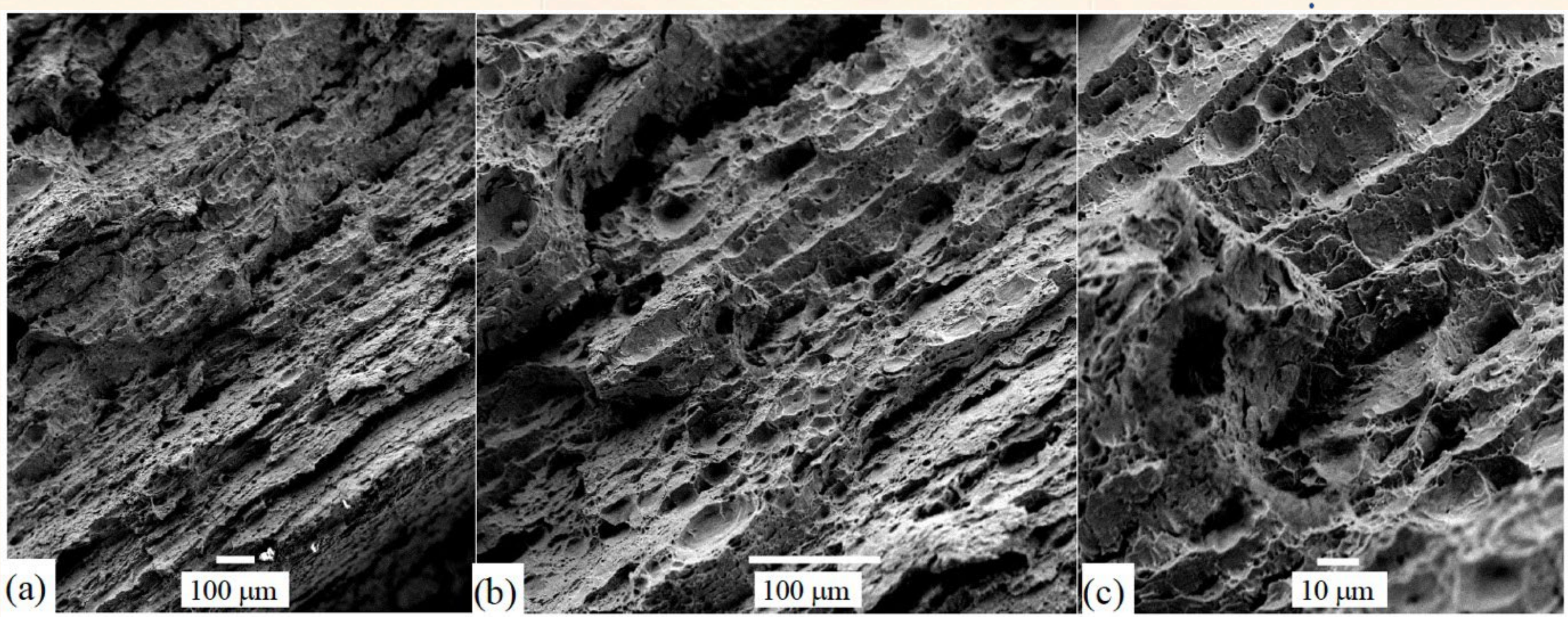
Ductile fracture with hydrogen (2S.H9.2 at 9 mA/cm^2).



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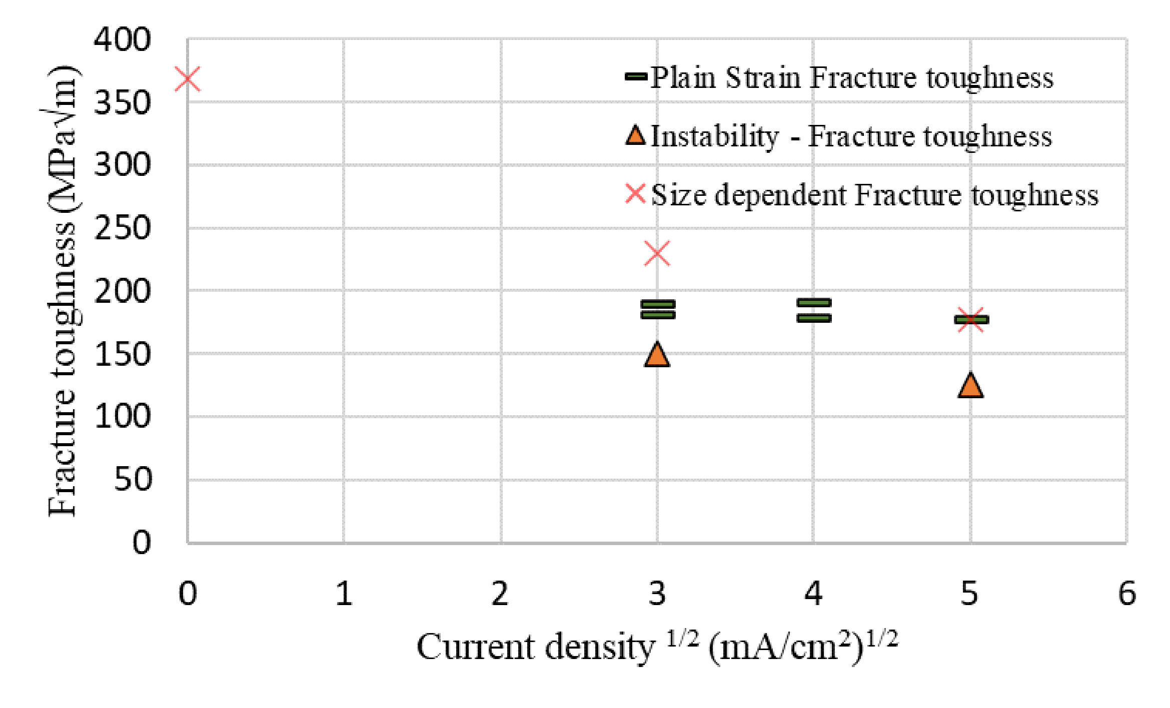
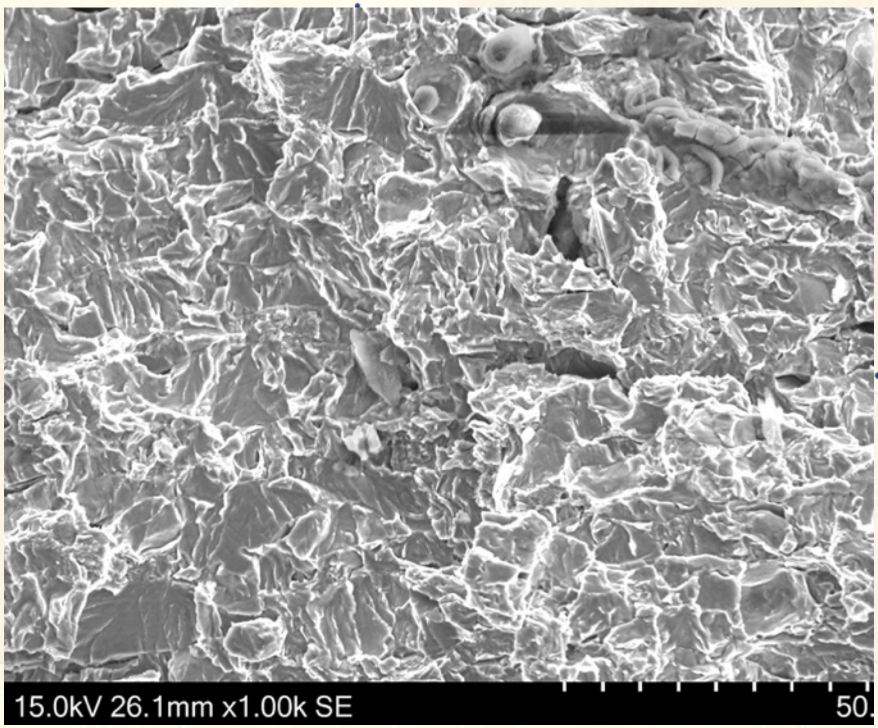
Fracture toughness at higher hydrogen fugacity.





At 9 mA/cm^2- hydrogen assisted ductile (HAD) fracture by H assisted void nucleation, growth, and linkage, and dislocation emission at crack tip.

Hydrogen assisted brittle (HAB) fracture at 25 mA/cm^2

Concluding Remarks

This study provided significant understanding of the influence of hydrogen on the fracture toughness of the X65 pipes used on the DBNGP:

- Hydrogen fugacities were greater than the operating pressures used on the DBNGP.
- Fractographic results provided understanding of the fracture mechanism at different hydrogen fugacities.
- Increasing hydrogen content resulting in decreasing fracture toughness and of the X65 steel.
- The experiment data also provided information required for the evaluation of the critical defect length and operating pressure.
- ASTM – valid fracture toughness values were measured for cathodic hydrogen charging for various charging conditions.
- The fractography showed a ductile to brittle transition as the hydrogen content increased.

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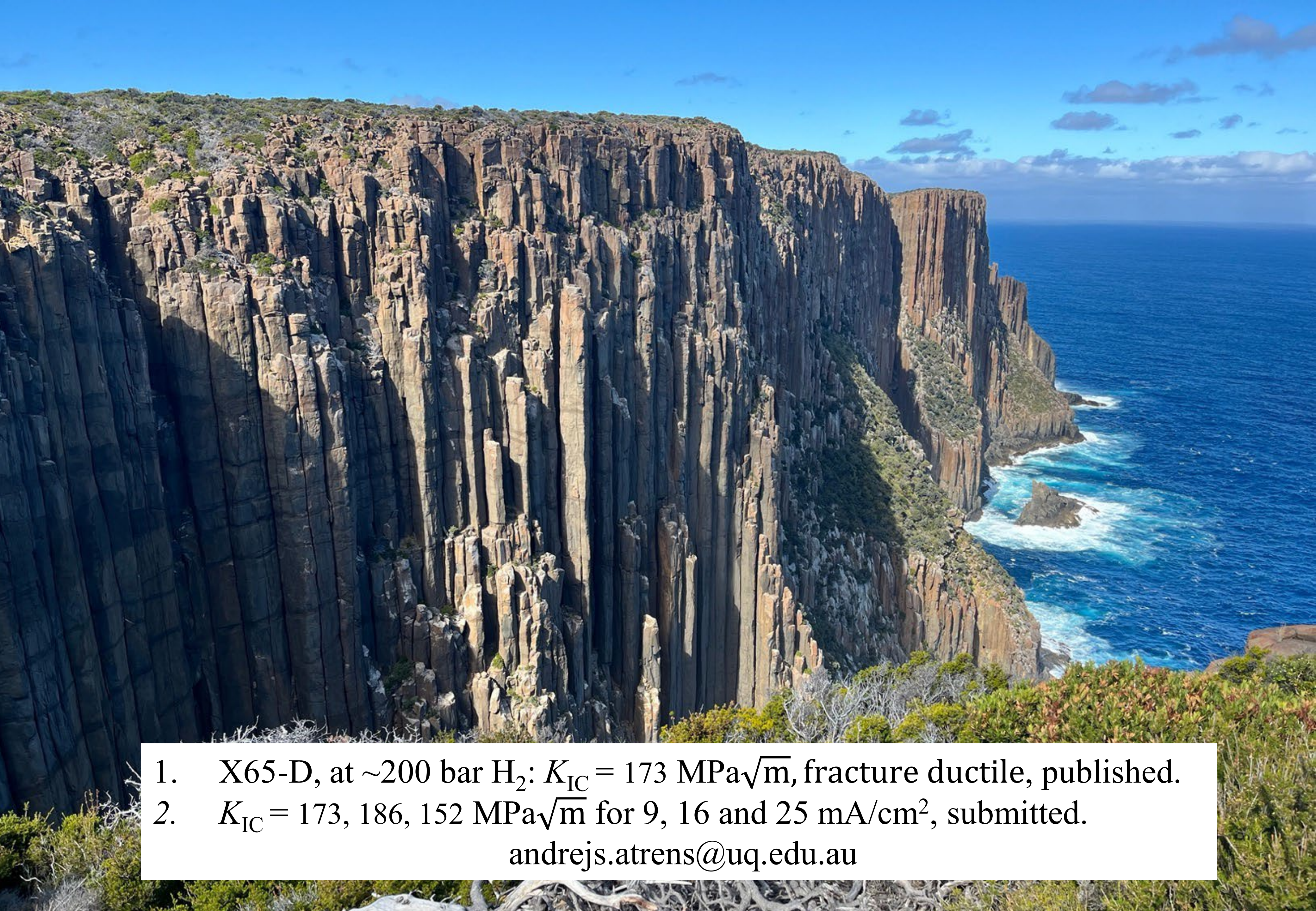

1. X65-D, at ~200 bar H_2: K_{IC} = 173 $MPa\sqrt{m}$, fracture ductile, published.
2. K_{IC} = 173, 186, 152 $MPa\sqrt{m}$ for 9, 16 and 25 mA/cm^2, submitted.

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