Hydrogen Embrittlement at the Interface of Clad Steel Pipes – Fracture Mechanical Testing and FE Simulations

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Objective

Investigate the effect of interface microstructure on the fracture toughness and hydrogen embrittlement susceptibility of clad pipes. Develop a coupled hydrogen diffusion – cohesive zone numerical model for assessing the effect of hydrogen on the fracture susceptibility.

Background

- Composite pipes with an inner layer of corrosion resistant alloy are increasingly used in the oil and gas industry as an option for corrosion management.
- During bonding by hot rolling, considerable transport of elements across the interface may occur, resulting in the formation of intermetallic compounds and hard zones which may significantly degrade the interface, making it prone to hydrogen induced cracking.
- The presence of an electroplated Ni-interlayer between the base metal and the clad layer limits element diffusion across the interface, thereby preventing the formation of precipitates and hard zones.

Material

- Two different clad steel pipes are investigated in this study, presented in Table 1 as Sample A and Sample B.
- The interface microstructure of both samples are presented in Figure 1. A continuous area of carbide precipitates is visible on the clad side of Sample B, attributed to carbon diffusion across the interface.
- Microhardness measurements across the interface confirmed carbon diffusion, with an average clad value of 210 HV for Sample A and 350 HV for Sample B.

	BM	Clad	Ni-interlayer
Sample A	X65	316L	Yes
Sample B	X60	316L	No

Table 1: Investigated samples

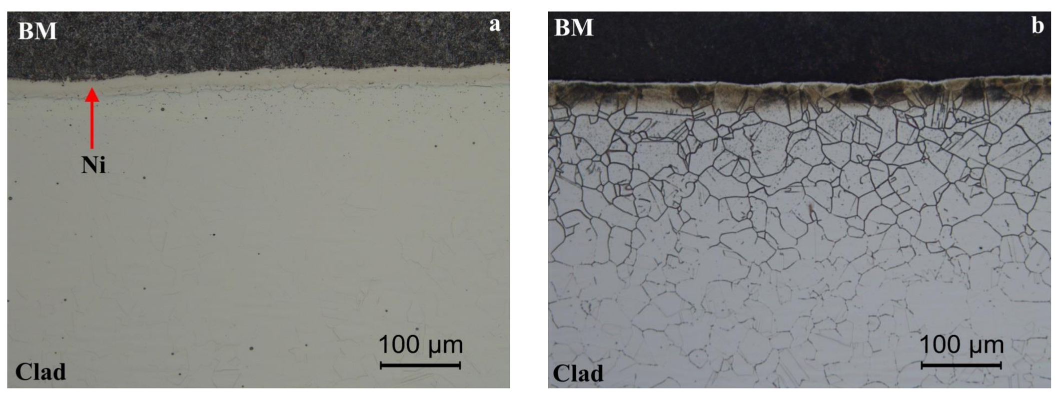


Figure 1: Interface microstructure of (a) Sample A with a Ni-interlayer and (b) Sample B.

Fracture toughness testing

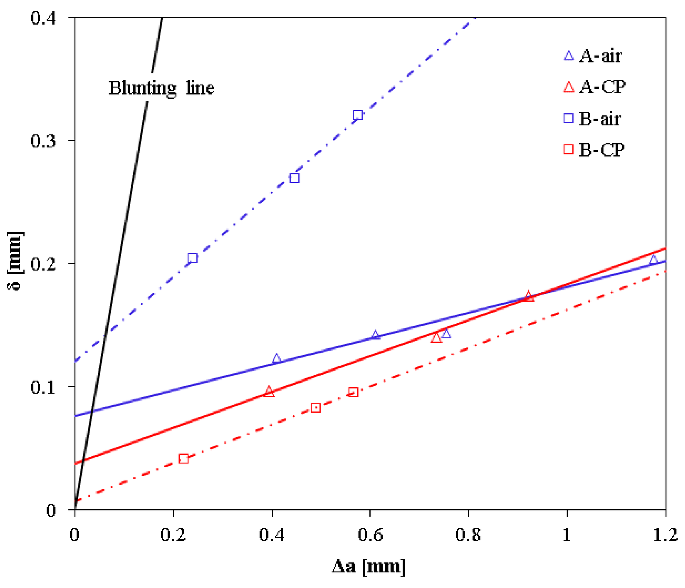
Method

- CT specimens were machined with the notch at the dissimilar interface using EDM.
- Fracture mechanical testing was performed in air and under CP, with a constant loading rate of 0.74 N/min.
- Prior to testing under CP, the specimens were pre-charged for 24 hours at -1050 mV_{SCE}.
- A multiple specimen procedure was applied to establish CTOD-R curves and fracture initiation values following standard BS 7448-4 [1].

Results

- Figure 2 compares the linear best fit crack growth resistance curves, illustrating a significant influence of hydrogen on Sample B, while little to no influence of hydrogen on Sample A.
- Figure 3 presents the fracture surface profiles of Sample A and B tested under CP.
- Hydrogen reduced the CTOD fracture initiation toughness with 20 % for Sample A and 85 % for Sample B.
- The presence of a Ni-interlayer reduced the fracture initiation toughness with 44 % for testing in air, while it raised the fracture initiation toughness with 216 % for testing under CP.
- Fractographic investigations confirmed hydrogen influence, with a change in fracture surface appearance from dimpled ductile to cleavage morphology.
- For Sample A, fracture occurred mainly in the Ni-interlayer, with initiation in the BM for testing under CP. Sample B revealed an alternating crack path, shifting between the dissimilar interface and the BM, and with initiation in the BM for all samples.

Figure 2: Linear best fit CTOD-R curves for Sample A and Sample B tested in air and under CP. The fracture initiation toughness is defined as the intersection between the R-curve and the analytical blunting line. The highest fracture toughness was obtained for Sample B tested in air, followed by Sample A tested in air and CP. The lowest fracture toughness was obtained for Sample B tested under CP.



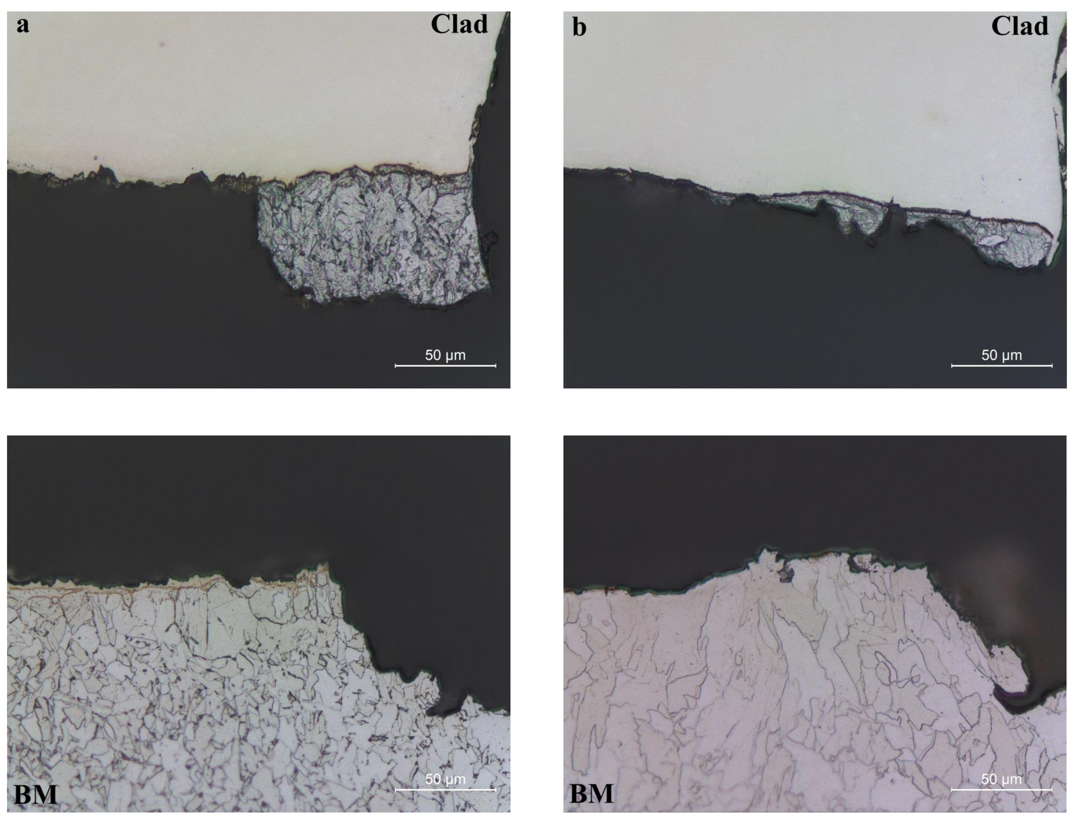


Figure 3: Light microscopy micrographs showing the fracture profile of the CT samples tested under CP. (a) Sample A, upper image displays the clad layer and lower image displays the BM. The Ni-interlayer is visible as the pale, featureless band above the BM in the lower image. (b) Sample B, upper image displays the clad layer and lower image displays the BM.

FE modelling

A new modelling framework for coupled mass diffusion, mechanical and cohesive analysis has been developed. This includes the following:

1. A finite element formulation for bulk mass diffusion which assumes that hydrogen resides either at normal interstitial lattice sites (NILS) or are trapped at microstructural defects and which accounts for both the concentration gradients and the mechanical state of the material (stress and strains) on the hydrogen distribution. The hydrogen transport model is given as follows [2]:

$$\frac{C_L + C_T(1-\theta_T)}{C_L}\frac{\partial C_L}{\partial t} = D\nabla^2 C_L + \nabla\cdot\left(\frac{D\bar{V}_H}{RT}C_L\nabla p\right) - \alpha\theta_T\frac{dN_T}{d\varepsilon_p}\frac{d\varepsilon_p}{dt}$$

2. A versatile cohesive zone element with the capability to handle solute mass diffusion. The constitutive response of the cohesive elements is given by the traction separation law (TSL), a relationship between the crack separation, cohesive stress and cohesive energy. Hydrogen influence is built into the TSL by a reduction of the cohesive energy at total failure [3].

$$\theta = \frac{C_L}{C_L + \exp(-\Delta g_b^0/\mathrm{RT})}$$

$$\frac{\sigma_c(\theta)}{\sigma_c(0)} = 1 - 1.0467\theta + 0.1687\theta^2$$

- C_L: Lattice hydrogen concentration
- C_T: Trapped hydrogen concentration
- D: Diffusion coefficient
- N_T: Trap density
- θ: Hydrogen coverage
- Δg_b^0: Gibbs energy
- σ_c: Critical cohesive stress
- δ_c: Critical separation

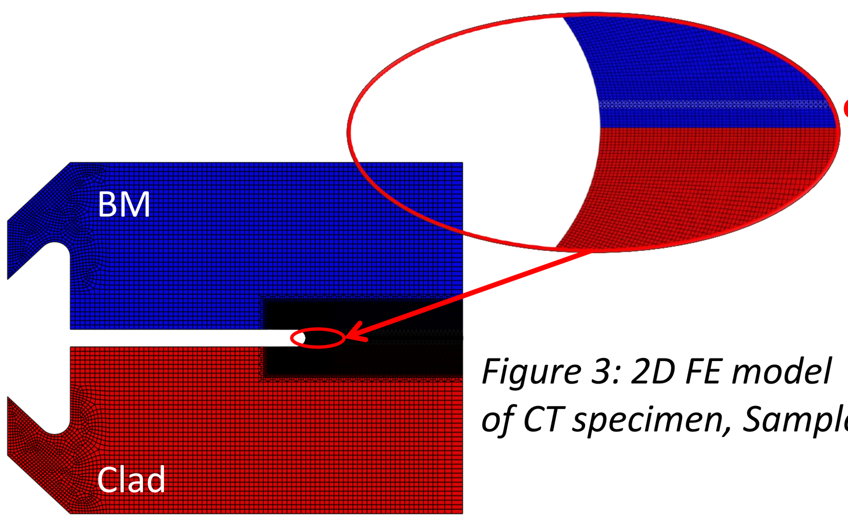


Figure 3: 2D FE model of CT specimen, Sample B.

- Cohesive elements implemented in the BM, adjacent to the interface.
- Material properties representative of each individual material

	BM	Clad
Young's modulus [MPa]	158000	167000
Poisson's ratio	0.3	0.3
Yield stress [MPa]	335	442

Table 2: Material properties for CT specimen numerical model.

C_{L0} [wppm]	σ_c [MPa]	δ_c [mm]
0.004	1192	0.005

Table 3: Input cohesive properties and initial lattice hydrogen concentration for CT numerical modelling of Sample B.

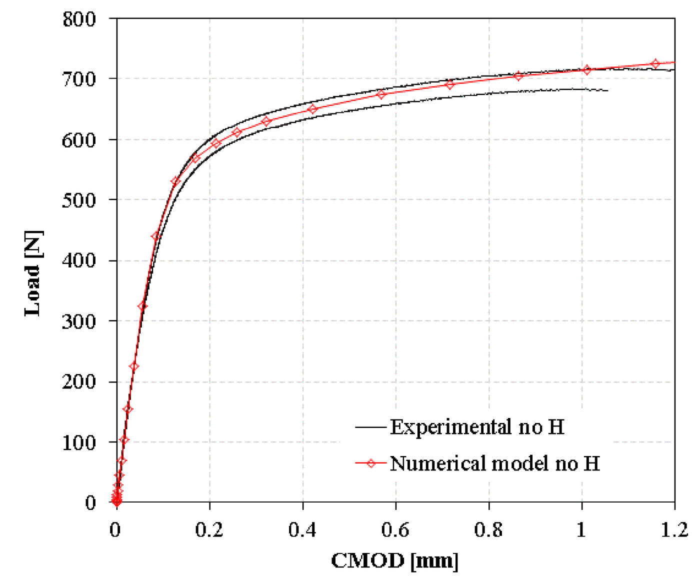


Figure 4: Comparison of load-CMOD curve for experimental testing and CT numerical model for Sample B.

	CTOD fracture initiation toughness [mm]	
	Experimental	Numerical model
Air	0.176	0.174
CP/Hydrogen	0.025	0.026

Table 4: Resulting CTOD fracture initiation toughness from experimental testing and CT numerical modelling of Sample B.

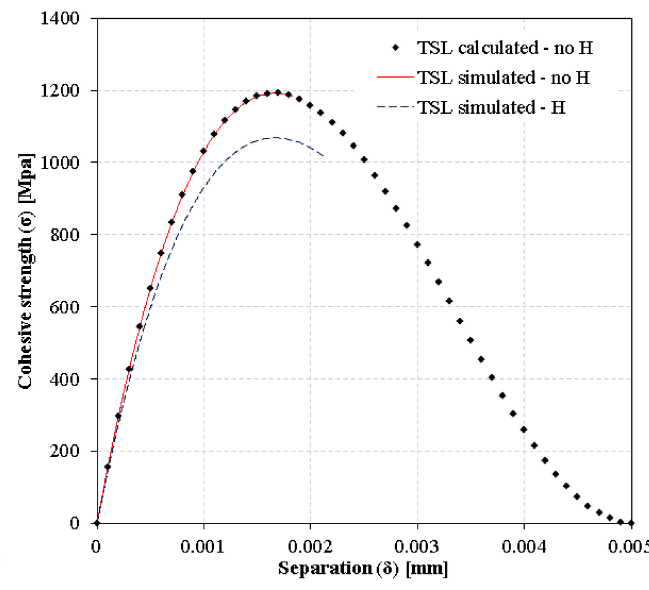


Figure 5: Comparison of calculated and simulated TSL, with and without hydrogen.

Conclusion and further work

- The presence of a Ni-interlayer between clad and pipeline steel was found to reduced the fracture initiation toughness with 44 % for testing in air, while it raised the fracture initiation toughness with 216 % for testing under CP.
- Fracture mechanical testing of the weld heat-affected zone clad interface is currently being conducted in air and under CP.

- A coupled mass diffusion and cohesive analysis framework has been developed for numerically assessing the effect of hydrogen on the fracture toughness. Initial results were presented and compared with experiments.
- Nanomechanical testing is being considered as an option for establishing the mechanical properties at the bi-metallic interface, for input to the numerical model.
- A procedure for importing hydrogen concentration fields and residual stresses from WeldsimS into Abaqus as initial boundary conditions has been developed, and will be applied in cohesive zone modelling of hydrogen induced fracture of repair welded clad pipes.

Acknowledgements

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