

Hydrogen Embrittlement at the Interface of Clad Steel Pipe Produced by Hot-Roll Bonding

Lise Jemblie ^a, Vigdis Olden ^b, Odd Magne Akselsen ^{a,b}, Antonio Alvaro ^b, Helena Bjaaland ^a
^a Department of Engineering Design and Materials, NTNU, 7456 Trondheim, Norway
^b SINTEF Materials and Chemistry, 7456 Trondheim, Norway

Background and Objective

In steel pipelines for the oil and gas industry, an inner layer of corrosion resistant alloy (so called clad) is increasingly used as an option for corrosion management. The interface between clad and pipeline steel represents an area with large potential for trapping of hydrogen due to residual stresses and carbide precipitations, especially after repair welding. Cracking along or adjacent the interface of dissimilar metals welds is a known problem caused by hydrogen embrittlement [1].

In the present work, the susceptibility of hydrogen induced fracture at the interface between clad and base material produced by hot roll bonding is studied through fracture mechanical testing and cohesive zone modelling.

Material

Two clad steel pipe samples are investigated in this study, with material combination as presented in Table 1. Sample A contains a Ni-interlayer between the base metal (BM) and the clad, while Sample B has no interlayer. The chemical composition of each material is presented in Table 2.

Figure 1 displays micrographs of the interface microstructure. The more pronounced grain boundaries in Sample B are attributed to a higher level of carbide precipitates, which is a result of carbon diffusion across the interface. Hardness measurements across the interface region confirms carbon diffusion (Fig. 2). The Ni-interlayer is found to limit carbon diffusion and carbon accumulation in the CRA.

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

	C	Cr	Ni	Mo	Si	Mn	P	S
316L	0.035	16.0-18.0	10.0-14.0	2.00-3.00	1.00	2.00	0.045	0.030
X60/X65	0.16	≤ 0.50	≤ 0.50	≤ 0.50	0.45	1.65	0.020	0.010

Table 2: Chemical composition (wt%).

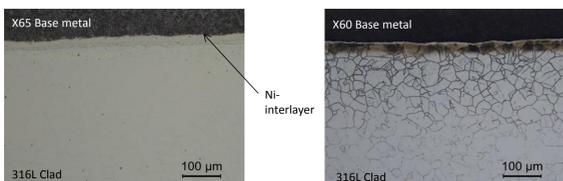


Figure 1: Micrographs of the interface microstructure. Left: Sample A, Right: Sample B.

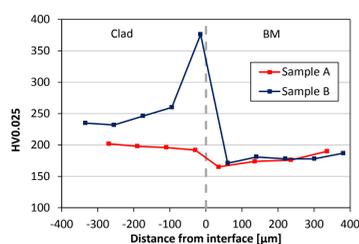


Figure 2: Vickers microhardness profiles across the interface, region for Sample A and Sample B.

Modelling framework

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 (e.g. dislocations) 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 [4]:

$$\frac{C_L + C_T(1 - \theta_T)}{C_L} \frac{\partial C_L}{\partial t} = D \nabla^2 C_L + \frac{D \nabla_H}{RT} \nabla C_L \nabla p + \frac{D \nabla_H C_L}{RT} \nabla^2 p - \theta_T \frac{dN_T}{d\varepsilon_p} \frac{\partial \varepsilon_p}{\partial t}$$

2. A versatile cohesive zone element with the capability to handle solute mass diffusion. This reduces the analysis procedure from the previous three steps to one single step.

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 [5]:

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

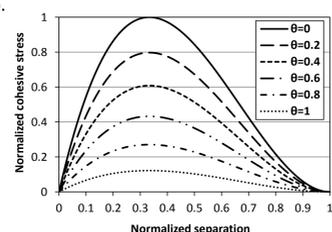


Figure 6: Normalized hydrogen informed TSL.

Fracture Mechanical Testing

Fracture mechanical toughness tests are conducted in accordance with BS 7448-1 [2] and BS 7448-4 [3]. The CT test specimens are machined with the notch tip position at the bi-metallic interface, see Figure 3.

Tests are conducted both in air and under cathodic protection (CP). A monotonically increasing load of 0.74 N/min is applied until global fracture occurs. Prior to testing under CP conditions, the samples are submerged for 24 hours in a 3.5 wt% NaCl solution at room temperature with a cathodic potential of -1050 mV_{SCE}.

The resulting load vs. plastic CMOD (V_p) curves are plotted in Figure 4. Preliminary results indicate that the CTOD values relate in the following manner:

$$CTOD_{Sample B - air} > CTOD_{Sample A - air/CP} > CTOD_{Sample B - CP}$$

Figure 5 displays the fracture morphology in the crack initiation areas.

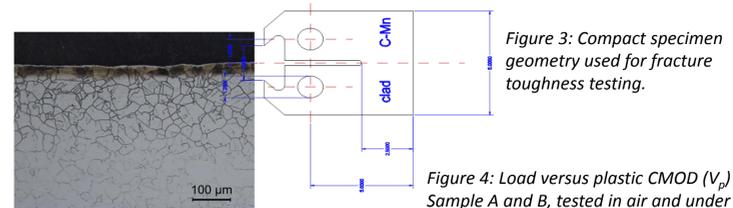


Figure 5: Fracture morphology in the crack initiation area. Sample A and B, tested in air and under CP. For Sample A the crack path is in the BM-Ni interface when tested in air. Under CP, fracture initiates in the BM followed by propagation in the BM-Ni interface. For Sample B the crack path is on the BM-clad interface for both air and CP.

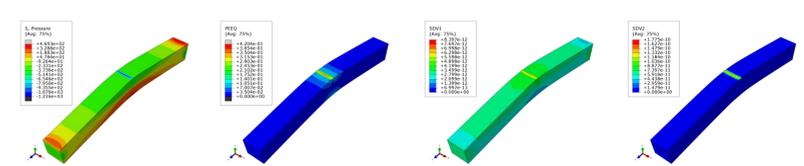


Figure 7: FE simulation for verification of the hydrogen transport model implementation: encased beam subjected to thermo-mechanical boundary conditions. From left to right: 1) Hydrostatic pressure (p [MPa]), 2) Equivalent plastic strain (ε_p), 3) Lattice hydrogen concentration (C_L [mol/mm³]), 4) Trapped hydrogen concentration (C_T [mol/mm³]).

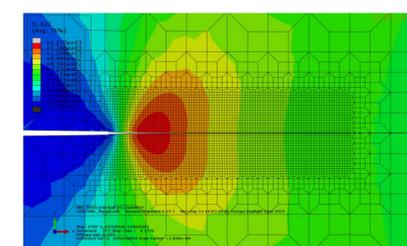


Figure 8: Stress distribution in a 2D MBL cohesive zone model of a growing crack at the interface between clad and base metal. The upper part of the model is the base metal while the lower part is the clad material.

Further Work

The next step in this work is to investigate the susceptibility of hydrogen induced fracture in welded clad pipes through cohesive zone modelling and fracture mechanical testing.

A procedure for importing hydrogen concentration fields and residual stresses from WeldsimS into Abaqus as initial boundary conditions has been developed. This procedure will be applied in cohesive zone modelling of hydrogen induced fracture of repair welded clad pipes. The material and mechanical properties of the bi-metallic interface in the heat affected zone will be established and input into the model. Fracture mechanical test of the HAZ in welded clad pipes will be performed in air and under CP.

Acknowledgments

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