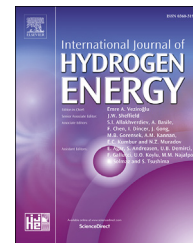


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# Cohesive zone modelling of hydrogen induced cracking on the interface of clad steel pipes

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## ABSTRACT

A coupled finite element hydrogen diffusion and cohesive zone modelling approach has been applied to simulate hydrogen induced fracture initiation in a hot rolled bonded clad steel pipe. The results are compared to experimental fracture mechanical testing in air and under in situ electrochemical hydrogen charging. A best fit to the experimental fracture initiation toughness value in air was achieved for an initial cohesive stiffness  $k_n = 4 \cdot 10^6$  MPa/mm and a critical cohesive stress  $\sigma_c = 1210$  MPa. For simulating under hydrogen influence, the hydrogen induced lowering of the cohesive energy was computed both in terms of the lattice concentration and the total concentration. Two different formulations for calculating the dislocation trap density were considered. The simulated results revealed that both hydrogen in lattice and hydrogen trapped at dislocations can be responsible for the observed hydrogen induced reduction in fracture initiation toughness. The choice of trap density formulation appeared significant only under the assumption that both lattice and trapped hydrogen infer an influence on the hydrogen induced lowering of the cohesive strength. Further effort is needed to provide a reliable description of the interface hydrogen content and distribution.

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## Introduction

Hydrogen induced degradation of structural steels constitute one of the main challenges for the oil and gas industry, attracting extensive research attention. It manifests as loss in ductility, strength and toughness, which may result in unexpected and premature catastrophic failures. For offshore installations and subsea pipeline, the main sources of hydrogen are electrochemical reduction of water resulting from cathodic protection and the presences of moisture during welding. Cracking occurs once a critical combination of susceptible material, hydrogen concentration and stress level is

present. To date, the precise mechanisms underlying hydrogen embrittlement (HE) are still under debate. Several theories have been proposed, while two groups have advanced as the more accepted ones for the case of hydrogen degradation in steel [1]: The Hydrogen Enhanced Decohesion (HEDE) model, in which interstitial atomic hydrogen reduces the bond strength and thus the necessary energy to fracture [2–5]; and hydrogen-affected localized plasticity models, originally suggested by Beachem [6], in which hydrogen stimulates dislocation processes resulting in localized plastic deformation. Two main variations of this notion have advanced; Hydrogen Enhanced Localized Plasticity (HELP) [7,8] and Adsorption Induced Dislocation Emission (AIDE) [9,10].

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The susceptibility of a material to HE is generally quantified by standard fracture mechanical testing under hydrogen exposure, compared with results obtained in a hydrogen free environment [11–13]. Numerical models can offer a supplement to costly experimental test programs, with the possibility of providing increased understanding of the involved processes at reduced time and costs. An effective lifetime prediction tool for hydrogen induced failures of materials used in offshore and pipeline systems should be able to account for the coupled effects between mechanical quantities, hydrogen mass diffusion and damage, while being of general validity. Cohesive zone modelling (CZM) offers this possibility. It has in recent years gained increasing interest as a suitable method for modelling hydrogen induced cracking [13–20]. A thorough review of CZM as an approach for simulating HE has previously been published by the present authors [21].

CZM provides a phenomenological continuum framework for failure analysis. Fracture takes place along an interface of cohesive elements, embedded along the prospective fracture path between solid elements. The constitutive response of the cohesive elements is defined by a so-called traction separation law (TSL) [22], usually characterized by a critical cohesive stress  $\sigma_c$  and a critical separation  $\delta_c$ , while the area embedded by the traction-separation curve defines the separation energy or the cohesive energy  $\Gamma_c$ . Different failure behaviours can be accounted for by modifying the TSL in relation to the actual damage situation.

The deleterious effect of hydrogen can be implemented into the TSL in various manners. Most known attempts capture the embrittlement phenomenon by a reduction in the cohesive energy with increasing local hydrogen concentration [13–18], corresponding to the HEDE concept. Brocks et al. [19] introduced hydrogen-enhanced softening in the continuum elements, while also accounting for hydrogen reduced cohesive strength, apparently representing a combined concept of HEDE and HELP. A similar approach has been described by Liang and Sofronis [23]. The HEDE approach is attractive due to its ease of implementation. Further, since CZM is indeed phenomenological in nature, the failure behaviour is captured by suitable adjustment of the cohesive parameters, while not explicitly representing a specific micromechanism [18].

Pipes with an inner layer of corrosion resistant alloy (CRA), so called clad pipes, are increasingly used in the oil and gas industry as an economical viable option for corrosion management, combining the mechanical properties of the base material (BM) with the corrosive properties of the CRA [12]. The prevention of leakage and fracture must however still be addressed, where a complex interface region may offer new challenges with respect to integrity management. To date, there is no repair contingency available for these pipelines, and relevant knowledge must be built. In previous work by the present authors [12], the fracture toughness and hydrogen embrittlement susceptibility of a 316L austenitic stainless steel - X60 carbon steel hot roll bonded clad pipe interface was investigated through compact tension (CT) fracture mechanical testing in air and under in situ electrochemical hydrogen charging. The results revealed a strong influence of hydrogen on the fracture resistance, with a reduction in crack tip opening displacement (CTOD) fracture initiation toughness of 85%.

In the present study, a combined experimental and finite element (FE) cohesive zone modelling approach for prediction of hydrogen induced fracture initiation in a hot roll bonded clad steel pipe is proposed. A valid material model representative of the bi-material interface is established, and 2D coupled hydrogen diffusion and cohesive zone modelling is performed in order to simulate hydrogen induced crack initiation. The model is calibrated and the results validated in terms of previously reported experimental findings [12].

One of the main disadvantages with electrochemical hydrogen charging is the lack of suitable methods for accurately estimating the hydrogen content and distribution in the material [15,24]. Nor is it possible to accurately measure the relative partitioning of absorbed hydrogen between the various microstructural sites. Finally, there is no consensus as to which component of the hydrogen concentration that should affect the cohesive energy reduction; lattice, trapped or both. Various approaches are reported in literature [14,16,17,19,24]. As previously shown, the choice may significantly affect the decohesion [21].

In this work, the sensitivity of a model clad steel pipe to lattice and dislocation trapped hydrogen is analysed. Two different models for calculating the dislocation trap densities are considered, which has previously been shown to impose significant influence on the hydrogen distribution in front of a notch [21]. It is assumed that fracture progresses in a HEDE manner. Previous work with a similar approach has proven to give reasonable agreement with experimental results on pipeline steel [16,25]. The various approaches for numerically estimating the hydrogen distribution and its effect on the cohesive energy reduction are compared and discussed in relation to the experimental findings, as reported previously in Ref. [12]. The objective is to provide a realistic description of the hydrogen content and accumulation, while investigating the model's capability of predicting hydrogen induced fracture. Finally, the general validity of the hydrogen concentration dependent cohesive model is addressed by simulation of pure ferritic specimens.

## Formulation and numerical procedure

2D finite element coupled diffusion, mechanical and damage analysis is performed using ABAQUS Standard version 6.13. The applied modelling approach simulates transient hydrogen diffusion, plastic deformation and material damage using cohesive elements. Section 2.1 gives a brief summary of the experimental testing applied for calibration and verification of the model. The system characteristics, FE model, diffusion model and cohesive zone modelling is described in detail in Sections 2.2–2.4. A thorough review of the modelling approach has previously been published [21].

## Experimental testing

A detailed description of the experimental testing and results can be found in Ref. [12]. Compact tension specimens consisting of hot roll bonded API X60 base material and 316L clad were machined with the notch tip at the dissimilar interface. For comparative reasons and in order to verify the finite

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