Available online at www.sciencedirect.com
ScienceDirect
Engineering Fracture Mechanics 75 (2008) 2333–2351
Engineering Fracture Mechanics
www.elsevier.com/locate/engfracmech

Application of hydrogen influenced cohesive laws in the prediction of hydrogen induced stress cracking in 25%Cr duplex stainless steel

Vigdis Olden [a,b,*], Christian Thaulow [a], Roy Johnsen [a], Erling Østby [b], Torodd Berstad [b]

[a] *NTNU, Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Engineering Design and Materials, NO-7465 Trondheim, Norway*
[b] *Sintef, Institute of Materials and Chemistry, Department of Applied Mechanics and Corrosion, NO-7465 Trondheim, Norway*

Received 27 April 2007; received in revised form 22 August 2007; accepted 4 September 2007
Available online 18 September 2007

Abstract

Cohesive zone finite element modeling is applied in the simulation of hydrogen induced stress cracking in 25%Cr duplex stainless steel. Hydrogen influence is implemented in linear and polynomial cohesive laws. Suitability of the laws in prediction of hydrogen induced stress cracking is investigated by applying models of U and V-notched tensile specimens representing a 25%Cr duplex stainless steel component submerged in sea water under cathodic protection (CP). Fracture prediction is performed by a three step procedure; elastic plastic stress analysis, stress assisted hydrogen diffusion and cohesive stress analysis. Local cohesive stress fields as well as the time to fracture initiation are investigated as a function of the shape of the traction separation laws and the element size for three levels of tensile stress. Simulated results are also compared with results from laboratory tensile tests and discussed with respect to the suitability of describing fracture initiation and fracture mechanism of the steel. The results show that the polynomial law and a mesh size of 0.5 μm gives the most accurate description of the local cohesive stress field. The simulated time to fracture is closest to laboratory test results for stresses of 0.85–0.9 times the yield strength.

Keywords: Stainless steels; Cohesive zone modeling; Environmentally assisted cracking; Structural assessment; Pipelines

1. Introduction

A challenging problem in the framework of finite element analysis is the prediction of failure in materials and structures. In later years the cohesive zone modeling (CZM) technique has become greatly facilitated and

* Corresponding author. Address: NTNU, Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Engineering Design and Materials, NO-7465 Trondheim, Norway. Tel.: +47 98230434.
E-mail address: Vigdis.Olden@sintef.no (V. Olden).

0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2007.09.003

Nomenclature

bcc	body centred cubic crystal lographic structure
CP	cathodic protection
CZM	cohesive zone modeling
FE	finite element
HEDE	hydrogen enhanced decohesion
HELP	hydrogen enhanced local plasticity
HISC	hydrogen induced stress cracking
SCE	saturated calomel electrode
TSL	traction separation law
C, C_E, C_{Ni}, c_0, c_s	hydrogen concentration: general, average in FE element, in nodes, in bulk, sub-surface
D	diffusion coefficient
E	Young's modulus
Δg_b^0	Gibbs free energy difference
J	hydrogen flux
k_{IH}	local hydrogen induced stress intensity/fracture toughness
K_{IC}	limit stress intensity
$K_{I_{th}}, K_{HISC}$	threshold stress intensity: general, HISC-induced
p	hydrostatic stress
R	gas constant
s	solubility
t	time
T, T^Z	temperature, absolute temperature
V_H	partial molar volume of hydrogen in iron
α	ferrite
α'', β'	fitting parameters
$\delta, \delta_1, \delta_N, \delta_T$	separation of cohesive element: general, at critical stress of linear law, normal, transverse,
δ_c, δ_M	critical separation in normal direction, maximum value for transverse separation
$\varDelta$	element mesh length
ϕ	normalized hydrogen concentration: in stressed state, in unstressed state
γ	austenite
$\gamma(0)$, $\gamma(\theta)$	surface energy: without hydrogen influence, with hydrogen influence
$\varGamma, \varGamma_c, \varGamma_{HISC}$	cohesive energy: general, critical, HISC related
κ_p	stress factor in diffusion
v	Poisson's ratio
σ_y	yield stress
σ, $\sigma(\delta)$, σ_N, σ_T, σ_M	cohesive stress, general, normal, transverse, maximum value for transverse stress
σ_c,$\sigma_c(0)$, $\sigma_c(\theta)$	critical cohesive stress: general, without hydrogen influence, with hydrogen influence
θ	hydrogen coverage

gained renewed interest in the field of fracture modeling. Fracture takes place at an interface of cohesive zone elements embedded in a finite element model; no continuum elements are damaged in a cohesive model. In this respect the method is effective in fracture modeling of large geometries. The cohesive elements can be pictured as two faces separated by a thickness, which is close to zero. The relative motion of the top and bottom faces in the thickness direction represents opening or closing of the interface. The relevant constitutive "material" response is a traction separation description; an evaluation which gives the amount of energy required to create new surfaces. A traction separation law (TSL) is a function described by the cohesive stress (σ) and separation (δ). The area below the curve represents the cohesive energy, $\varGamma_c$. There are a variety of shapes of the TSL proposed by different authors. Two TSL's will be applied in the present paper, see Fig. 1. Nguyen and