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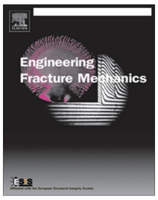

A uniform hydrogen degradation law for high strength steels

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ABSTRACT

The degrading effect of hydrogen on high strength steels is well recognized. The hydrogen degradation is dependent not only on hydrogen content, but also on geometric constraints or equivalently, level of stress triaxiality, which means the hydrogen degradation locus is not likely to be a unique material property. Experimental data on notched tensile tests reported by Wang et al. are analyzed via cohesive zone modeling, and a cohesive strength based uniform hydrogen degradation law is proposed upon normalization of hydrogen degradation loci with different specimen geometries. Since the effects of hydrogen content and geometric constraints are decoupled during normalization, the proposed law is applicable to all the specimen geometries as a material property. This law is subsequently applied to simulate the constant loading tests performed on the same material. Excellent agreement is observed between the simulation and test results in terms of incubation time for fracture initiation and highest permissible initial hydrogen content. The inconsistency observed in one of the cases is discussed, suggesting that the effects of strain rate and stress relaxation need to be taken into account in order to improve the transferability of the degradation law calibrated from tensile tests to constant loading situations.

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1. Introduction

Hydrogen induced degradation of mechanical properties, often referred to as hydrogen embrittlement (HE), is a well recognized problem for structural steels [1,2]. Extensive studies have been done both experimentally [3–9] and numerically [10–13], yielding a number of models accounting for this phenomenon. The real mechanism behind HE, however, remains controversial due to the complexity in microstructures, hydrogen absorption and trapping sites and fracture modes [14]. Two representative mechanisms with different natures are the hydrogen enhanced decohesion model (HEDE) and the hydrogen enhanced localized plasticity model (HELP). The HEDE model assumes that dissolved hydrogen reduces the cohesive strength of the iron lattice [15]; The HELP model, on the other hand, assumes that solute hydrogen enhances dislocation motion leading to localized plastic deformation at the crack tip [16]. Either model is supported by a number of atomistic calculations [17–19] and experimental observations [20–24] and is regarded as the dominating factor in particular fracture scenarios [25]. While the HEDE mechanism is commonly assumed to be dominant in cases where brittle intergranular fracture surfaces are observed, the HELP mechanism is correlated to the situations where shear localization bands, slip traces or small shallow dimples are present [24,26]. In reality, both brittle and ductile characteristics could be observed on the same fracture

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Nomenclature

δ_c	critical cohesive separation
η	level of stress triaxiality
$\langle C_L \rangle$	lattice hydrogen concentration
σ_c	critical cohesive stress, or cohesive strength
σ_h	local hydrostatic stress
σ_h^∞	remote hydrostatic stress
$\sigma_{c,H=0}$	cohesive strength without hydrogen
ζ	viscosity for numerical regularization
C_I	initial homogenous hydrogen concentration
C_L	local lattice hydrogen concentration at failure
CLT	constant loading test
CSRT	conventional strain rate tensile test
CZM	cohesive zone modeling
D	diffusion coefficient
HE	hydrogen embrittlement
HEDE	hydrogen enhanced decohesion
HELP	hydrogen enhanced localized plasticity
R	gas constant
r	notch radius
SSRT	slow strain rate tensile test
T^Z	absolute zero temperature
TSL	traction separation law
V_H	partial molar volume of hydrogen

surface [4,7], indicating a possible combined effect of both mechanisms. In such situations, the part played by the HELP model is usually more pronounced at lower levels of hydrogen content.

Despite the lack of a universally accepted micro-mechanism for HE, considerable progress has been made on the continuum level. Hardie and Liu [3] investigated the effect of geometrical constraints on HE susceptibility by performing notched tensile tests in gaseous hydrogen. Wang et al. [4–7] performed notched tensile tests as well as constant loading tests on hydrogen pre-charged specimens made from AISI 4135 high strength steel. Moro et al. [8] performed notched tensile tests on X80 steel in high pressure gaseous hydrogen environment and discussed the influence of strain rate. Nanninga et al. [9] performed similar tests and compared the HE susceptibility among three pipeline steels. Olden et al. performed constant loading tests in sea water under cathodic protection on single edge notched tension (SENT) specimens made from 25%Cr duplex stainless steel [1] and API X70 pipeline steel [12]. The experimental work leads to a general conclusion that the HE susceptibility increases with increasing levels of strength and increasing levels of stress concentration, or equivalently, stress triaxiality. Some established failure criteria in hydrogen free situations can be adapted in the engineering HE failure analysis with modifications accounting for the hydrogen effect. Enos and Scully [27] adapted the so-called stress modified critical strain criterion in HE prediction by calibrating the hydrogen degradation law on critical strain from notched tensile tests in presence of hydrogen. Since the effects of stress triaxiality is incorporated in the original stress modified critical strain criterion [28], this method can inherently account for the geometry effects in HE prediciton. Similarly, Wang et al. [29] adapted the strain based failure criterion with a hydrogen degradation law on critical strain calibrated for a boron bearing steel. For a different high strength steel AISI4135, they applied the stress based failure criterion and presented a hydrogen degradation law on critical stress [4,7]. In both situations, the degradation relation was proposed as power law and was concluded as triaxiality independent. Most recently, Ayas et al. [13] re-analyzed the test data reported by Wang et al. [4,7] and Hagihara et al. [30] and treated the critical axial stress based hydrogen degradation law as a unique material property. Recall the micro-mechanisms discussed above, we can see that the hydrogen affected critical strain criterion is closely related to the HELP model while the hydrogen affected critical stress criterion to the HEDE model.

By utilizing the cohesive zone modeling (CZM) technique, it is possible to incorporate contributions from HELP as well as from HEDE. In CZM, damage is processed inside a layer of cohesive elements that are inserted along the fracture path between solid elements. The constitutive behavior of cohesive elements is described by the so-called traction separation law (TSL) [31]. The TSL is usually characterized by the critical cohesive stress σ_c which gives the strength of the cohesive element and the critical separation δ_c which defines the failure point. The area below the traction separation curve is called the separation energy or the cohesive energy Γ_c. For detailed information regarding CZM and TSL, the readers are referred to [32,33]. CZM provides a phenomenological continuum framework for failure analysis [34–36]. Different failure scenarios and factors affecting the failure behavior can be accounted for by manipulating the TSL. The bilinear TSL, for instance, is often employed for brittle fracture [37,34,38] and the trapezoidal TSL for ductile situations [39,40]. The effects of stress triaxiality [41,42] and strain rate [11] have also been considered by adding new items into the TSL. The degradation effect of hydrogen

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