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Cohesive zone based axisymmetric modelling of hydrogen-assisted cracking in a circumferentially notched tensile specimen

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ABSTRACT

The paper presents an axisymmetric finite element model to study hydrogen-assisted cracking (HAC) in a circumferentially notched tensile (CNT) specimen of a high-strength steel. The model includes an axisymmetric 2-D stress analysis coupled with an axisymmetric 1-D hydrogen diffusion analysis. Crack initiation is handled through cohesive elements whose strength is adjusted depending on the local hydrogen concentration. The model successfully predicted the critical SIFs of tempered AISI 4340 under different hydrogen charging conditions in rising displacement tests. Furthermore, the model is able to simulate of typical delayed failure of specimens under HAC conditions in constant load tests. Reported HAC of three different microstructures of AISI 4340 was simulated under rising displacement condition, and the respective model parameters were then also used to simulate crack initiation in the same microstructures under constant load condition. Closeness of critical SIFs from both the simulations indicates that the model parameters calibrated through slow strain rate tests are transferable to constant load situations. Moreover, it is shown that the present 2-D analysis, while being computationally advantageous, is an acceptable alternative of a 3-D model reported earlier.

Introduction

Degradation of mechanical properties of structural steels due to hydrogen embrittlement is a well-known challenge for several industries. Hydrogen atoms can easily diffuse into the lattice of steel alloys and lead to embrittlement for some susceptible steels [1]. The fracture toughness thereby gets severely affected and the crack growth under such situations is referred to as hydrogen-assisted cracking (HAC) [2–4].

The most important fracture-related design parameter for the structures operating under HAC conditions is the threshold stress intensity factor (K_{ISCC}) of the material. This is due to the fact that a SIF below the K_{ISCC} acting on a structure does not cause any crack propagation and the structure remains safe. The K_{ISCC} of a material is generally determined experimentally using pre-cracked specimens through a series of constant load tests [5]or rising displacement/load tests at very low loading rates [6]. The tests are done in a corrosive

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environment, which is usually arranged through cathodic polarisation of the specimen. Constant load tests with single-edge-notch-tension (SENT) specimens of duplex stainless steel are reported by Olden et al. [7]. Rising displacement or slow strain rate tests with circumferentially notched tensile (CNT) specimens have also been performed to examine hydrogen-assisted fracture of AISI 4340 steel [8,9].

Besides the experimental methods, there are many reported numerical studies which generally include finite element based cohesive zone modelling of HAC for various grades of steels [10–17]. These models involve the use of cohesive elements in the fracture plane whose failure represents crack extension. A detailed review of the numerical models is available in Ref. [16].

The study of HAC using CNT specimens offers some advantages. The specimen can be easily machined because of cylindrical geometry and it ensures plane strain condition even with a small specimen size [18]. In addition to the experimental studies [8,9], two numerical models have been proposed to analyse hydrogen-assisted cracking in a CNT specimen using finite element method [12,15]. One of them is a 2-D model [12] in which plane strain elements are used and their out-of-plane thickness is selected as per the cylindrical geometry of the specimen. Unequal pre-crack depths at the left and right ends of the notched region bring in the effect of asymmetry of the pre-crack; however, the model could not incorporate the variation of hydrogen concentration and stresses normal to the plane of the model. These limitations of the 2-D modelling are overcome by 3-D stress analysis coupled with 2-D diffusion solution in the fracture plane [15]. A drawback of the 3-D finite element approach is the high computation cost arising out of a large number of degrees of freedom. Further, the meshing requirements and the handling of user-subroutine for the non-standard diffusion analysis are rather complicated. The present study explores the possibility of simplifying the analysis and achieving computational advantage without affecting the accuracy of results. Specifically, an axisymmetric 2-D model is explored for modelling HAC in a CNT specimen.

The present paper successfully demonstrates the effectiveness of an axisymmetric FE model to predict the critical stress intensity factors for hydrogen-assisted fracture of AISI 4340 during rising displacement tests and constant load tests. Two sets of experimental studies under rising displacement are analysed – HAC of three microstructures of AISI 4340, and HAC of tempered AISI 4340 under different hydrogen charging conditions. The simulated critical SIFs are compared with the reported experimental values. Constant load tests are also simulated for the three microstructures using the model parameters obtained from the analysis for the rising displacement tests. The predicted K_{ISCC} are compared with the values obtained from the rising displacement tests to establish the possibility of transferring the model parameters between these two types of tests.

CNT specimen

Circumferentially notched tensile (CNT) specimen (Fig. 1) is generally fatigue pre-cracked using the rotating bending

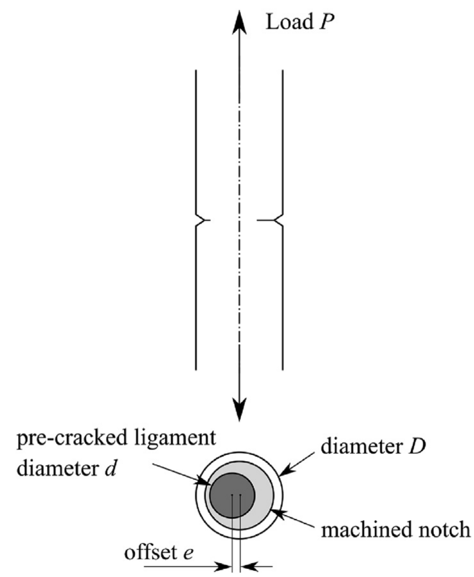

Fig. 1 – Circumferentially fatigue pre-cracked CNT specimen. The pre-crack is typically offset with respect to the specimen axis.

technique [8,9,18–20]. The extent of pre-crack in a specimen is visible only after the failure of the specimen in a fracture test. As observed by various investigators [8,9,18–20] the pre-crack is generally not perfectly symmetric but slightly offset with respect to the axis of the specimen. The offset in the pre-crack induces an additional bending load during a tensile test of the specimen. Ibrahim and Stark [20]suggested a relation which incorporates the effect of the bending load along with the tensile load and gives the corrected stress intensity factor (SIF) for a given load P:

$$K_I = (\sigma_t + \sigma_b)\sqrt{a\pi F_0} \quad (1)$$

where $\sigma_t = 4P/(\pi D^2)$ is the nominal tensile stress, $\sigma_b = 16Pe/(\pi D^3)$ is the nominal bending stress, $a = (D\text{-}d)/2$ is the crack length, D is the diameter of the specimen, d is the diameter of the pre-cracked ligament, e is the offset of the ligament, P is the load, $F_0 = F\exp(\alpha e/D)$, $F = 1.25/(1-(2a/D)^{1.47})^{2.4}$ and $\alpha = 22.188 \exp(-4.889(2a/D))$.

The present work, however, ignores the offset and assumes a symmetrical pre-crack for the numerical modelling.

The SIF formula for a specimen with symmetrical pre-crack is obtained from Eq. (1) by assigning $e = 0$ leading to F_0 getting reduced to F and omission of bending stress σ_b:

$$K_I = \sigma_t\sqrt{a\pi F} \quad (2)$$

Cohesive zone model

The assumption of a symmetrical pre-crack leads to axisymmetry in the system under axial loading, and hence a 2-D axisymmetric finite element model has been developed using ABAQUS-Standard [21]. Mode-I fracture has been modelled using a row of cohesive elements in the fracture plane, whose behaviour is governed by a traction-separation