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Fracture toughness behavior in the ductile–brittle transition region of the tempered martensitic Eurofer97 steel: Experiments and modeling

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Abstract

The fracture toughness of the tempered martensitic stainless steel Eurofer97 has been experimentally characterized in the ductile-to-brittle transition (DBT) region with sub-sized compact tension specimens. The median fracture toughness–temperature curve in the lower transition region has been found to deviate somewhat from the master curve as described in the ASTM E1921-03 standard. Two-dimensional finite element simulations of the compact tension specimen have been performed. The analysis of the stress fields around the crack tip have been used to define a local criterion for cleavage based upon the attainment of a critical stress over a critical area. This local criterion has been used to reconstruct the lower bound in the transition region. The calibration procedure of the critical parameters has been discussed in detail as well as the uncertainty in the critical values. It is shown in particular that the critical stress is well defined while the model leads to a rather larger uncertainty in the determination of the critical area.

Keywords: Cleavage fracture; Tempered martensitic steels; Ductile-to-brittle transition; Local approach

1. Introduction

The calculation of the stress and strain fields generated by a crack in a loaded body using finite element (FE) analysis is a technique widely used in fracture mechanics studies. It is possible to study in detail the stresses and strains acting in complex structural parts and/or machine components. In particular, we can account for the presence of flaws and cracks in these components by calculating the corresponding stress and strain fields generated by these flaws. These facts have promoted the development of the so-called "local approaches", which are based on the assumption that fracture occurs as soon as a local critical condition(s) is (are) attained in the crack tip region. The critical conditions are expressed in terms of the stress and strain fields at the continuum level. These techniques have been developed for the last two decades with the aim of

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providing a physically-based description of the fracture mechanisms in relation to the local microstructure at the crack tip. In addition, they are foreseen to be used to address important issues like the problem of the "transferability" of results from laboratory scale specimens to structural components.

For brittle fracture in the ductile-to-brittle transition (DBT) region, two types of local approaches can be distinguished. The first one derives from the work of Beremin's group [1] and accounts for the stochastic nature of cleavage fracture in steels in the DBT region. The model is based on the Weibull stress concept (σ_W), which is regarded as a measure of the driving force for fracture. In this model, several parameters need to be calibrated (typically four) [2]. The second type of local approach derives from the early work of Ritchie, Knott and Rice (RKR) [3] who proposed that unstable crack propagation occurs as soon as the stress level acting on a critical distance ahead of the crack tip (λ^*) exceeds a critical threshold value, σ^*. The RKR-type models have been used in the past to estimate the evolution of K_{IC} with the temperature T and strain rate $\dot{\varepsilon}$ in steels (see [4] and references herein). Here, the dependence of K_{IC} with T and $\dot{\varepsilon}$ is assumed to result from the dependence of the yield stress with these parameters. In the early works, analytical solutions for the stress and strain fields (mainly HRR fields for Ramberg–Osgood materials) were used. In contrast to the model based on the σ_W concept, the RKR-type models do not provide any insight into the characteristic scatter of the experimental results.

Based on the RKR approach, Anderson, Dodds and coworkers [5–8] presented a model to account for the *constraint loss effects* on the fracture toughness values at a given temperature. The early version of the model relies on the assumption that the probability of brittle fracture in a fracture specimen (or a structural part in real applications) depends on the *area* of material over which the principal stress exceeds a critical value σ^*. They proposed a method to *scale* each fracture toughness value as determined from specimens having low constraint level in such a way that the scaled values correspond to those that would have been obtained from testing highly-constrained specimens. The main goal of the scaling toughness model was to deal with the problem of the in-plane constraint loss, characteristic in the case of shallow cracks or deep cracks loaded up to large strains. The approach was further used in 3D numerical studies [9] were the concept of an "effective thickness" B_{eff} was introduced. Explicit corrections to account for the out-of plane loss of constraint were proposed in their work.

Odette and coworkers have extended the scale toughness model beyond its original scope of scaling low constraint toughness data at a constant temperature [10–12]. They developed the so-called "critical stress–critical area" model, σ^*–A^*, which was aimed at describing the evolution of fracture toughness with temperature in the DBT region. The σ^*–A^* model (and its extensions) are based on the two following hypotheses:

(a) brittle fracture is triggered when a critical area A^* (or volume V^*) of material encompasses a critical stress level σ^*.
(b) the critical values σ^* and A^* (or V^*) are usually assumed to be material properties independent of the temperature. However, a modest temperature dependence of σ^* was considered and discussed in [10].

Following [9], this approach was subsequently developed, giving rise to the σ^*–V^* model, where the critical volume V^* was now estimated as $B_{eff} \cdot A^*$. This extension allows accounting not only for the effects of the out-of-plane constraint level but also the statistical size effect on fracture toughness.

In this study, we use the σ^*–A^* approach to model the temperature dependence of the "lower bound" of fracture toughness in the DBT transition region for the *reduced-activation* steel Eurofer97. The Eurofer97 steel is a tempered martensitic stainless steel of the 7–9 wt% Cr class, which is one of the reference materials of the European Fusion material program for structural reactor applications.

2. Material and mechanical properties of the Eurofer97 steel

2.1. Material

The Eurofer97 plates have been produced by Bölher AG as rolled plates of 8, 14 and 25 mm. In this work, we have studied the 25 mm plate, heat No. 83697. The final heat treatment applied to the 25 mm plate consisted of austenitization during 0.5 h at 980 °C + air cooling followed by tempering 1.5 h at 760 °C + air cool-