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Influence of static strain aging on the cleavage fracture of a C–Mn steel

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ABSTRACT

Recent advances in the constitutive modeling of strain aging effects in elastoviscoplasticity are used to predict the ductile-to-brittle transition curve for a C–Mn steel depending on pre-straining and heat treatment. The parameters of the Beremin model are identified from a large experimental basis of Charpy tests. 3D finite element simulations of Charpy V-notched specimens based on a constitutive model accounting for static strain aging, are performed for the first time to predict the fracture behavior of the pre-strained and aged material. The constitutive model includes the strain localization phenomena occurring in the notch due to Lüders effects. Good agreement between experiment and modeling is demonstrated. The introduction of kinematic hardening improves the prediction of the lower part of the ductile-to-brittle transition region. The proposed approach aims at optimizing pre-strain values and heat treatments for nuclear steels.

1. Introduction

The local approach to fracture is based, first, on a detailed metallurgical description of deformation and fracture mechanisms in metals and alloys, second, on a precise constitutive modeling of the elastoviscoplastic material behavior and, third, on coupled or uncoupled fracture criteria [13,39]. One major recent success of this approach has been to reconcile the interpretation in terms of fracture toughness of Charpy test results and fracture of Compact Tension specimens. In particular, some of the difficulties in the experimental and computational analysis of the Charpy test have been overcome in a series of works [45,43,44,27,26,52,53,47,49]. These works address in particular the Charpy tests at low temperature and the ductile-to-brittle transition in nuclear steels.

At low temperature and in the transition, cleavage is the main mechanism for brittle fracture in the ferritic nuclear steels, even though cleavage is always accompanied locally by intragranular plastic slip which becomes dominant with increasing temperature [41]. The fracture properties in the low temperature and transition regimes are statistical by nature due to the distribution of defects including inclusions or second phase in the material. They are very often satisfactorily described by means of the Beremin model which relates the Weibull distribution of fracture probability to a power-law distribution of defects and plasticity phenomena [10,11]. Such statistical fracture models can be applied to fracture mechanics samples like CT specimens [60], Charpy tests and structural components. They benefit from a detailed knowledge of the distribution of defects [51] and can incorporate the influence of loading rate [42]. More elaborate statistical models of fracture can be found in Bordet et al. [15].

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Nomenclature

CVN	Charpy V-notch impact energy (J)
$\underset{\sim}{\boldsymbol{D}}$	strain rate tensor
E_a	activation energy (eV)
$J_2(\underset{\sim}{\boldsymbol{\sigma}})$	von Mises equivalent stress
k_B	Boltzmann constant (1.38e−23 J/K)
$\underset{\sim}{\boldsymbol{L}}$	gradient of velocity field
m	Weibull exponent
p	cumulated plastic strain
$\dot{p}$	cumulated plastic strain rate (s^{-1})
P_r	failure probability
$\underset{\sim}{\boldsymbol{Q}}$	material rotation
t_a	current aging time (s)
t_{a0}	initial aging time (s)
T	temperature (K)
$\underset{\sim}{\boldsymbol{T}}$	Cauchy stress tensor (MPa)
V_a	activation volume
$\underset{\sim}{\boldsymbol{X}}$	kinematic hardening stress tensor (MPa)
$\underset{\sim}{\boldsymbol{\alpha}}$	hardening internal variable
$\underset{\approx}{\boldsymbol{\Lambda}}$	tensor of elastic moduli (MPa)
ρ	current dislocation density (m^{-2})
ρ_0	initial dislocation density (m^{-2})
$\rho_{5\%}$	dislocation density for the 5% pre-strained state (m^{-2})
$\underset{\sim}{\dot{\varepsilon}}$	observer invariant strain rate tensor
$\underset{\sim}{\dot{\varepsilon}}_e$	elastic strain rate tensor
$\underset{\sim}{\dot{\varepsilon}}_p$	plastic strain rate tensor
$\underset{\sim}{\boldsymbol{\sigma}}$	observer invariant stress tensor (MPa)
σ_w	Weibull stress (MPa)
σ_I	maximum principal stress (MPa)

Strain aging characterizes the mechanical behavior of most nuclear steels due to the interaction of solute atoms present in the alloys and dislocations [16,54]. Static strain aging (SSA) is observed at lower temperature for instance in the form of Lüders peak stress and plateau accompanied by the propagation of plastic strain localization bands along the sample or at geometrical singularities in structural components. In service conditions at higher temperatures very often correspond to the domain of dynamic strain aging (DSA) which can be associated with the Portevin–Le Chatelier effect, i.e. the formation and propagation of plastic strain rate localization bands. In the context of fracture mechanics, the Lüders and Portevin–Le Chatelier effects are usually not taken into account in the computational modeling of fracture processes. Heuristic rules are chosen to fix the initial yield stress and the strain localization phenomena are not incorporated. DSA effects are smoothed out and the possible negative strain rate sensitivity is usually not accounted for. However, reliable constitutive equations have been available for more than ten years that include the strain aging effects in the elastoviscoplastic material laws. The associated instabilities have been investigated by Mesarovic [35], Benallal [6], and Benallal et al. [8,7]. Finite element (FE) simulations of plastic strain and strain rate phenomena in tensile or fracture mechanics samples were first performed by Zhang et al. [63] and Graff et al. [20,21] for aluminum alloys and mild steel. The constitutive models are mature for full 3D implicit FE computations and detailed comparison with experimental data like strain field measurements, as done for the Lüders effect by Ballarin et al. [4,3], Hallai and Kyriakides [23,24], Marais et al. [30], and Hallai and Kyriakides [25]. The simulations include the local stress and strain rate concentration induced by the development of spatio-temporal instabilities.

The importance of strain aging on the fracture properties of engineering steels is well recognized in the mechanical metallurgy community. DSA effects in C–Mn steels were investigated by Wagner et al. [55–57], for CT specimens but also in welded zones, taking heat treatments into account. More recent works are based on constitutive modeling of dynamic strain aging and explicit modeling of PLC bands in notched and CT specimens [5,58,59,9]. In the latter work, it was shown that a reduction of ductility is observed in the DSA domain of material behavior. The impact of static strain aging on fracture toughness was first addressed in Houssin et al. [28] and Amar and Pineau [1] in the case of CT specimens. Recent contributions make use of Zhang and McCormick's model for the computation of the elastoviscoplastic response of a CT specimen, including a detailed 3D analysis of strain localization phenomena at the crack tip by Wenman and Chard-Tuckey [61].

What is missing in the literature is the direct use of strain aging constitutive models for the prediction of brittle-to ductile transition curves. This is the objective of the present work in the case of a C–Mn nuclear steel. For that purpose, the proposed methodology combines the tools of local approach to fracture as presented in Pineau [40] and the detailed elastoviscoplastic