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Calibration of Beremin model with the Master Curve

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ABSTRACT

The calibration of local approaches to cleavage fracture is important topic in structural integrity analysis. In this paper, a method to calibrate the Beremin model based on the Master Curve is studied. The temperature dependence of Beremin model parameters is investigated in the ductile-to-brittle (DBT) transition region. The Weibull modulus, m, increases with temperature over the lower transition range and remains a constant in the lower-to-mid transition region. The Weibull scale parameter, σ_u, increases with temperature over the investigated temperature range. Compared to the unirradiated material, σ_u of the irradiated material decreases while m is almost constant over the DBT region.

1. Introduction

Ferritic steels for reactor pressure vessels (RPVs) in nuclear power plants exhibit a transition from ductile to brittle fracture mechanism with decreasing temperature, which is known as ductile-to-brittle transition (DBT). Over the DBT region, cleavage fractures exhibit a weakest link behavior, which means the whole specimen fails at the moment when the normal stress exceeds the local fracture stress and a cleavage crack propagates from a second phase, e.g. carbide particle, to the ferritic matrix. The potential failure by cleavage fracture is a key issue in the integrity assessment of nuclear structures made of ferritic steels [1–6].

There exist several approaches, e.g. the global and local approaches, to assess the integrity of structures constructed of ferritic steels. The global approach evolves directly from elastic–plastic fracture mechanics and describes the fracture driving force in terms of global parameters such as K and J [4–6]. Over the last two decades, the global approach has been used to quantitative understand the DBT behavior and to characterize the scatter and temperature dependence of material toughness. Among these efforts, Master Curve method, developed by Wallin and adopted in ASTM E1921 [1], describes cleavage fracture toughness measured by using high-constraint deep-cracked specimens. Master Curve describes the toughness-temperature variation over the DBT region with a reference temperature T_0, at which the median toughness of 1T size specimens is 100 MPa m$^{0.5}$. An advantage of the Master Curve is that T_0 can be calibrated by as few as six specimens. However, the Master Curve requires that high constraint and small scale yielding conditions exist at fracture in each tested specimen. Small size specimens are widely used in experiment, whereas in engineering applications the crack front often experiences constraint loss. In such cases, constraint loss leads to higher toughness and thus too conservative T_0. Thus, the limitation of Master Curve motivates the development of micromechanical models to address the transferability of cleavage fracture toughness across varying levels of crack front constraints. Local approaches to cleavage fracture (micro mechanics model),

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Nomenclature

a	crack depth, mm
B	specimen thickness, mm
E	Young's modulus, MPa
J	J-integral, MPa m
j	rank number
K	stress intensity factor, MPa m$^{0.5}$
K_0	fracture toughness value at 63.2% fracture probability
K_I	Mode I linear elastic stress intensity factor, MPa m$^{0.5}$
K_J	stress intensity factor derived from J-integral, MPa m$^{0.5}$
K_{Ic}, K_{Jc}, $K_{Jc(i)}$	material fracture toughness, MPa m$^{0.5}$
m, m_n	parameter in Beremin model, Beremin modulus
N	total simulation number
P_f	failure probability
r_c	critical radius, mm
T	temperature, °C
T_0	index temperature in Master Curve, °C
V	cleavage fracture process volume, mm^3
V_0	reference volume, mm^3
W	specimen width, mm
σ_1	first principal stress, MPa
σ_0	yield stress, MPa
$\sigma_w, \sigma_{w(i)}$	Weibull stress, MPa
σ_u	parameter in Beremin model, MPa
σ_f	cleavage fracture stress, MPa
ν	Poisson's ratio
λ	constant factor
γ_s	surface energy, J/m^2
w_p	half the plastic work done per unit of area in propagating the crack, J/m^2
CT	compact tension
DBT	ductile-to-brittle transition
FE	finite element
RPV	reactor pressure vessel

which couple macroscopic fracture behavior with micro scale deformations, captures the constraint effect on cleavage due to crack geometry and loading.

One of the most widely used local approaches to fracture is the Beremin model. The Beremin model [3] is a statistical model based on the micromechanisms of cleavage fracture at a local scale and incorporates a weakest link concept. The advantage of Beremin's model is that model parameters are assumed to be material properties and can be transferred from one specimen geometry or constraint level to another. The Beremin model has two material parameters, namely the Weibull modulus m and the scale parameter σ_u. However, the two parameters should be calibrated from the known fracture data before the Beremin model can be used.

The calibration of the parameters in the Beremin model has been the subject of extensive research. Different methods have been developed to calibrate the variation of the two parameters with temperature [6–15]. Two typical methods are linear regression and maximum likelihood methods [9–13]. Since the probabilistic nature of the failure process, it requires testing of a large number of specimens in order to gain a reasonable calibration. Khalili and Kramp [10] demonstrated that although the maximum likelihood method was able to provide more reliable results than a least squares method, it was still necessary to have fracture data from more than 30 specimens to obtain consistent and reliable results. Testing such amount of specimens is prohibitively expensive. Recently, a new calibration method of the Beremin model has been published based on the toughness scaling in [14,15]. Instead of iteratively finding the slope and intercept of the best fit straight line through the fracture data, this calibration is performed to the mean fracture toughness value. In order to reduce the amount of experiment test, a Monte Carlo method can be taken in the calibration process by simulating the results of experiments. In the simulation a large number of samples are randomly drawn from the probability distribution function. The maximum likelihood method is applied to the simulated data to obtain the Beremin parameters.

The effects of temperature and loading on the parameters, m and σ_u remain problematic. Gao et al. [16] found the temperature invariance of m for modified A508 steel in the transition region. Wasiluk et al. [8] investigated the effect of