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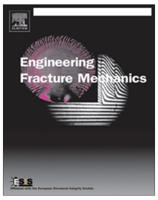

Prediction model on cleavage fracture initiation in steels having ferrite–cementite microstructures – Part II: Model validation and discussions

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ABSTRACT

The proposed prediction model on a cleavage fracture initiation in ferrite–cementite steels is applied to the fracture toughness tests using notched specimens of steels with various sizes of ferrite grain and cementite particle. The prediction results of fracture toughness and fracture initiation site showed good agreement with the experimental results for all the steels and temperatures tested. The results of parametric studies using hypothetical steels successfully show the influence of the sizes of microstructures on fracture toughness. The results also show that the transition of bottleneck process in the fracture initiation with increasing temperature.

1. Introduction

It is widely known that a resistance of cleavage fracture initiation i.e., fracture toughness, depends on steel microstructures [1]. For example, the finer ferrite grain leads to the higher fracture toughness. In addition, the toughness depends on the size of second phase particles such as cementite or martensite–austenite constituent. However, the relationship between the fracture toughness and microstructures is not sufficiently clarified. It is therefore difficult to quantitatively predict fracture toughness based on only information of microstructures.

The cleavage fracture of steels is generally interpreted by the weakest-link mechanism, differently from yielding and work hardening. A scatter is thus found in fracture toughness as an essential feature. A formulation to evaluate the scatter of fracture toughness was proposed by Beremin [2,3] based on the weakest-link theory. The effectiveness of this model has been widely accepted, because it enables the quantitative evaluation of the scatter and the size effect of a structure on fracture toughness. However, the model was limited to empirical treatment in the past. Moreover, it cannot clarify the relationship between fracture toughness and microstructures.

In the first part of this paper [4], a prediction model on a cleavage fracture initiation in steels having ferrite–cementite microstructures was presented. The model requires only two kinds of material information: size distributions of ferrite

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Nomenclature

a	notch depth of specimen
B	thickness of specimen
c_c	critical crack length at cementite particle
d	grain diameter
d_{ave}	average grain diameter
$d_{\max}$	maximum grain diameter
D	diameter of the cleavage plane in Grain A formed after Stage II
E	Young's modulus
E_α	Young's modulus for ferrite phase ($=210$ GPa)
E_θ	Young's modulus for cementite phase ($=189$ GPa)
$f(d)$	probability distribution function for volume fraction of ferrite grain diameter
$g(t)$	probability distribution function for volume fraction of cementite particle thickness
$h(w)$	probability density function of w
k	locking parameter in the Hall-Petch relationship ($=21\ \mathrm{MPa}\sqrt{\mathrm{m}}$)
K	stress intensity factor
L	span of the specimen
n	strain hardening exponent
N_α	number of cleaved ferrite grains
N_θ	number of cracked cementite particles
$\mathbf{n}_m$	unit normal vector of m-th {1 0 0}-plane in Grain A
C, m, p, q	fitting parameters
p_θ	probability of crack nucleation at cementite particle
P	load
r_p	rotation factor ($= 0.4$) in the CTOD estimation formula
s	length of slip plane
t	cementite particle thickness
t_{ave}	average cementite particle thickness
$t_{\max}$	maximum cementite particle thickness
T	temperature
$T_{0.1}$	temperature corresponding to $\bar{\delta}_c = 0.1$ mm
V_p	plastic component of notch opening displacement
w	weight function to calculate s and D
W	width of specimen
x	normalized ferrite grain diameter ($= d/d_{\max}$) or cementite particle thickness ($= t/t_{\max}$)
x_c	distance from the notch root
α	strain hardening coefficient ($= 0.02$)
$\beta(x)$	beta distribution function
$\gamma_{\alpha\alpha}$	effective surface energy for a cleavage crack to propagate across grain boundary
$\gamma_{\theta\alpha}$	effective surface energy when a cementite crack propagates into ferrite ($= 10\ \mathrm{J/m^2}$)
δ	quasi-CTOD
δ_c	critical quasi-CTOD
$\bar{\delta}_c$	average critical quasi-CTOD
ε_p	equivalent plastic strain
ε_Y	yield strain ($= \sigma_Y/E_\alpha$)
ν	Poisson's ratio
σ	von Mises stress
$\boldsymbol{\sigma}$	applied stress tensor
σ_0	materials constant in the Hall-Petch relationship ($= 90$ MPa)
$\sigma_{F\alpha\alpha}$	fracture stress of ferrite matrix in Stage III
$\sigma_{F\theta\alpha}$	fracture stress of ferrite matrix in Stage II
$\sigma_{\max}$	maximum principal stress
σ_n	maximum normal stress acting on three {1 0 0} planes in Grain A
σ_Y	yield stress
σ_{Y0}	yield stress at room temperature
σ_θ	internal maximum principal stress at cementite particle

grains and cementite particles and a true stress–strain curve, without any adjustable parameters. The prediction model is composed of the two parts, i.e. the preparatory part and evaluation part. In the former part, an active zone is discretized into volume elements. The microstructures of each volume element were modeled based on the size distributions using the