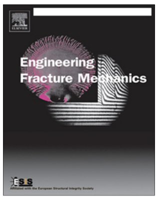
Engineering Fracture Mechanics xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech



Prediction model on cleavage fracture initiation in steels having ferrite–cementite microstructures – Part I: Model presentation

Kazuki Shibanuma [*], Shuji Aihara, Katsuyuki Suzuki

Department of Systems Innovation, The University of Tokyo, Japan

ARTICLE INFO

Article history:
Received 3 October 2014
Accepted 7 March 2015
Available online xxxx

Keywords:
Cleavage fracture initiation
Brittle fracture
Fracture toughness
Fracture stress
Monte Carlo method
Local approach
Multiscale simulation
Weakest link mechanism
Prediction model
Ferrite–cementite steel

ABSTRACT

A prediction model on a cleavage fracture initiation in ferrite–cementite steels is presented. The model requires only information of microstructures without any adjustable parameters. The model is characterized in a multiscale framework based on the Monte Carlo method. A fracture process of three stages is assumed; (I) crack nucleation at cementite particle; (II) crack propagation into ferrite matrix; (III) crack propagation across grain boundary. An active zone is divided into volume elements where microstructures are assigned. Cleavage fracture is assumed to initiate at the time when all the fracture conditions are simultaneously satisfied in any one of the volume elements.

1. Introduction

There are a lot of researches attempting to predict the cleavage fracture initiation in steels. Although there is a strong correlation between fracture toughness and microstructures in steels, quantitative relationship between fracture toughness and microstructures has not been sufficiently clarified. It is crucial to establish a generalized model to quantitatively predict the cleavage fracture initiation in order to not empirically but theoretically develop or improve the material design of steels.

It is widely known that the fracture appearance transition temperature in Charpy impact test linearly changes with reciprocal of the square root of grain size [1]. It is also known that the fracture toughness depends on the size of brittle phase such as cementite [2]. Petch proposed an estimation model of transition temperature considering the sizes of ferrite grain and cementite particle [3]. Following his study, Bingley examined the model for a wide range of ferrite pearlite steels [4]. These studies are based on the dislocation theory with an assumption of a non-equilibrium behavior of a crack in a cementite particle. However, their models are too simple to achieve a sufficient accuracy for actual use. Particularly, the Bingley's study was not able to clarify the dependence of cementite particle size on fracture toughness. It has therefore been difficult to quantitatively predict the fracture toughness based only on the information of microstructures.

---

[*] Corresponding author.
E-mail address: shibanuma@struct.t.u-tokyo.ac.jp (K. Shibanuma).

http://dx.doi.org/10.1016/j.engfracmech.2015.03.048

Please cite this article in press as: Shibanuma K et al. Prediction model on cleavage fracture initiation in steels having ferrite–cementite microstructures – Part I: Model presentation. Engng Fract Mech (2015), http://dx.doi.org/10.1016/j.engfracmech.2015.03.048

Nomenclature

a	notch depth of specimen
b	Burgers vector
c	crack length at cementite particle
c_c	critical crack length at cementite particle
C	fitting parameter (coincident with p_θ at cementite particle of unit thickness)
C_0,m	fitting parameters
d	grain diameter
d_{ave}	average grain diameter
D	diameter of 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)
$f(t)$	distribution function to approximate distribution of cementite particle thickness
$f_0(t)$	lognormal distribution function
$g(t)$	distribution function to approximate distribution of crack length at cementite particle
$h(w)$	probability density function of w
k	locking parameter in the Hall–Petch relationship ($= 21\ \mathrm{MPa}\sqrt{\mathrm{m}}$)
K	stress intensity factor
n	strain hardening exponent
$\mathbf{n}_m$	unit normal vector of m-th {1 0 0}-plane in Grain A
N	number of dislocation
p_θ	probability of crack nucleation at cementite particle
R	bounding radius of stress field
r_E	ratio of Young's modulus (=$E_\theta/E_{\alpha i}$)
r_p	rotation factor (=0.4) in the CTOD estimation formula
r_σ	ratio of the principal stresses (=$\sigma_{\mathrm{min}}/\sigma_{\mathrm{max}}$)
s	length of slip plane
t	cementite particle thickness (μm)
t_{max}	maximum cementite particle thickness (μm)
T	temperature (°C)
V_p	plastic component of notch opening displacement
w	weight function to calculate s and D
W	width of specimen
W_c	energy of crack
α	strain hardening coefficient (=0.02)
$\gamma_{\alpha\alpha}$	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 J/m^2)
δ	quasi-CTOD
δ_c	critical quasi-CTOD
ε_p	equivalent plastic strain
$\bar{\varepsilon}_p$	equivalent plastic strain normalized by ε_Y
ε_Y	yield strain (=σ_Y/E_α)
ν	Poisson's ratio
ν_α	Poisson's ratio for ferrite phase (=0.3)
ν_θ	Poisson's ratio for cementite phase (=0.26)
σ	von Mises stress (MPa)
$\boldsymbol{\sigma}$	applied stress tensor
σ_0	materials constant in the Hall–Petch relationship (=90 MPa)
$\bar{\sigma}_e$	component of $\bar{\sigma}_\theta$ depending on elastic deformation
$\sigma_{\mathrm{F}\alpha\alpha}$	fracture stress of ferrite matrix in Stage III (MPa)
$\sigma_{\mathrm{F}\theta\alpha}$	fracture stress of ferrite matrix in Stage II (MPa)
$\bar{\sigma}_p$	component of $\bar{\sigma}_\theta$ depending on plastic deformation
σ_{max}	maximum principal stress (MPa)
$\bar{\sigma}_{\mathrm{max}}$	maximum principal stress normalized by σ_Y
σ_{min}	minimum principal stress (MPa)
σ_n	maximum normal stress acting on three {1 0 0} planes in Grain A (MPa)
σ_Y	yield stress (MPa)
σ_{Y0}	yield stress at room temperature (MPa)
σ_θ	internal maximum principal stress at cementite particle (MPa)
$\bar{\sigma}_\theta$	internal maximum principal stress at cementite particle normalized by σ_Y

Please cite this article in press as: Shibanuma K et al. Prediction model on cleavage fracture initiation in steels having ferrite–cementite microstructures – Part I: Model presentation. Engng Fract Mech (2015), http://dx.doi.org/10.1016/j.engfracmech.2015.03.048