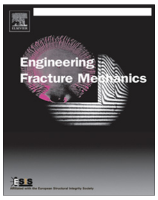
Engineering Fracture Mechanics 160 (2016) 147–169

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



A cleavage fracture framework: New perspectives in cleavage modeling of ferritic steels

M. Scibetta *

SCK•CEN, Boeretang 200, B-2400 Mol, Belgium

ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form 26 February 2016
Accepted 8 March 2016
Available online 7 April 2016

Keywords:
Cleavage fracture
Local approach
Ferritic steel

ABSTRACT

A wide variety of cleavage fracture models based on local approach and weakest link concepts applicable to ferritic steels are published in the open literature, characterized by various levels of complexity, type of microstructural information included and embedded physical laws. Here, a Cleavage Fracture Framework (CFF) is developed, within which each model finds a rational location, allowing one to classify models and to know what each model is implicitly assuming or neglecting. This CFF is demonstrated to be a powerful tool to develop advanced models, closer to physical phenomena. This work also identifies the need for a better understanding of physical phenomena in conjunction with microstructural investigation and appropriate modeling.

1. Introduction

The development of fracture mechanics knowledge and the improvement in the production and control of ferritic steels and welds for thick section component structures have greatly contributed to dramatically reduce the occurrence of cleavage fractures, commonly observed in the 1940s [1]. Nevertheless, potential cleavage fracture of reactor vessels acting as a primary safety barrier remains a subject of concern for the nuclear industry. Failure of this component is considered unacceptable by most regulators [2] or this risk should be extremely low according to the US nuclear regulatory commission [3]. A particularity of reactor pressure vessels is that they are subject to aging and after degradation they might be exposed to potentially severe accidental loading conditions. Thermal aging and neutron irradiation detrimentally affect the steel toughness. Recent improvements in ultrasonic non-destructive examinations applied in stringent inspection programs and the increase of the inspection area of vessels has revealed flaws that can act as triggering location for brittle failure. For example, 33 under-clad cracks were revealed in the 1990s on 10 French NPP [4] while hydrogen flakes were detected in two Belgian plants in 2012 [2]. Normal or accidental conditions such as pressurized thermal shock could challenge the integrity and need to be carefully studied to fulfill all safety requirements.

A basic ingredient of any integrity safety assessment is the knowledge of the material properties. Such properties are determined under well controlled conditions in accredited laboratories. Typical current reactor vessel conditions such as the constraint level, the biaxial ratio, the warm pre-stressing loading path and the irradiation and temperature history are however not fully represented by laboratory conditions. Therefore, the transferability of laboratory data to structural components and realistic complex loading conditions can be questioned in the absence of proper fundamental understanding of the underlying micromechanical mechanisms. In the recent past, improved understanding of yield strength evolution

---

* Tel.: +32 14 333043; fax: +32 14 321216.
E-mail address: mscibett@sckcen.be

http://dx.doi.org/10.1016/j.engfracmech.2016.03.047
0013-7944/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

A	defect size
a_0	parameter of a defect size distribution
a_c	crack size corrected for plastic zone size
B	thickness
B_{1T}	reference one inch thickness
BCC	Body-Centered Cubic
C_i	constants used in various models
E	Young's modulus
$f(t), g(t)$	arbitrary functions
$f_n, f_{p/n}, f_{p/na}, f_{p/np}, f_{p/npa}$	conditional probabilities (see Table 1)
$f_{\vec{\mu}}(\vec{\mu})$	probability density for a defect to be characterized by a microstructural variable
$f_{\mu_i}(\mu_i)$	contribution of μ_i to the probability density
F	cumulative failure probability of the structure
F_d	cumulative probability of a defect to be subjected to nucleation followed by defect failure and propagation through the structure
F_n	cumulative nucleation probability of a defect
$F_{n(p)(a)\ldots}$	cumulative probability of a defect to nucleate followed by a series of propagations and arrests (examples provides after Eq. (3))
F_{V_0}	cumulative failure probability of a RVE
CFF	Cleavage Fracture Framework
h	stress triaxiality
$H(t)$	Heaviside function
$H_t(t)$	Heaviside function translated to unity
$H_1(t,p), H_2(t,p)$	smooth approximations of the Heaviside function of parameter p
$H_{t1}(t,p), H_{t2}(t,p)$	smooth approximations of the Heaviside function translated to unity
i, j, k, l	integer index
I_1	first order integral operator
I_2	second order integral operator
k_{af}	arrest fracture toughness of the ferrite
k_{cf}	static fracture toughness of the ferrite
k_{max}	maximum opening stress intensity factor of an infinitesimal kink in a cleavage plane along the crack front
K_J	applied stress intensity factor
K_0	fracture toughness at 0.63% percentile
M	parameter of a defect size distribution
n_d	volume density of defects
NPP	Nuclear Power Plant
$\vec{p}$	vector of parameters
R	Ratchet operator
RVE	Representative Volume Element
S_{ijkl}	generalized Hooke's compliance tensor
SSY	Small Scale Yielding
t, t_1, t_2	time variables
V	volume of the structural component
V_0	volume of a RVE
$w(t)$	wall function
$w_t(t)$	wall function translated to unity
$w(t,p)$, $w_1(t,p)$, $w_2(t,p)$	smooth approximations of the wall function of parameter p
$w_t(t,p)$, $w_{t1}(t,p)$, $w_{t2}(t,p)$	smooth approximations of the wall function translated to unity
α_{ij}	expansion coefficient tensor
$\delta(t)$	Dirac function
$\delta_t(t)$	Dirac function translated to unity
$\delta_1(t,p)$, $\delta_2(t,p)$	smooth approximations of the Dirac function of parameter p
$\delta_{t1}(t,p)$, $\delta_{t2}(t,p)$	smooth approximations of the Dirac function translated to unity
ΔT	temperature relative to the temperature free of thermal stresses
ε_{ij}	strain tensor
ε_1	principal strain
ε_{pl}	cumulative plastic deformation
$\varepsilon_{pl,0}$	plastic deformation scaling factor
γ_{cf}	surface fracture energy