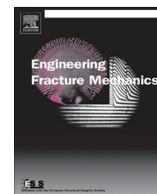




Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Fracture mechanical testing of single crystal notched α -iron micro-cantilevers

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ARTICLE INFO

Article history:

Received 29 July 2016

Received in revised form 24 January 2017

Accepted 30 January 2017

Available online xxxx

Keywords:

Crack growth

Micromechanics

Pure iron

Fracture mechanics

J-integral

Ductile-to-brittle transition

ABSTRACT

Fracture mechanical testing of micro-sized cantilevers was conducted in order to quantify the fracture toughness and modes of fracture for the $(100)[0\bar{1}1]$ and $(10\bar{1})[101]$ crack systems in α -iron. The testing was performed at both room temperature and at -75°C . Previous molecular dynamics analysis has indicated brittle behavior for the $(100)[0\bar{1}1]$ and ductile behavior for the $(10\bar{1})[101]$ orientation, giving rise to the question; could this be achieved with testing at the micro-level. Elastic-plastic fracture mechanics was applied due to the small sample size, rendering the cantilevers out of bounds in relation to linear-elastic fracture mechanics boundaries. Conditional fracture parameters, K_Q and J_Q , were determined through the load-displacement curves where the change in unloading stiffness was used to determine crack growth. The crack growth was corrected to fit micrograph measurements. By normalizing the J_Q vs. crack growth curves with its critical values, a new characterization tool was deemed applicable and proved promising in characterizing fracture behavior.

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1. Introduction

The industrial activity in the Arctic is expanding. An ever increasing demand for energy is forcing the production of oil further north, where accidents may cause severe ecological ramifications. Rough climate conditions and temperatures as low as -60°C require materials with superior mechanical properties. The materials must display sufficient fracture and wear resistance at low temperatures, while avoiding excessive maintenance and maintaining lifetime integrity. In order to overcome these challenges, fracture mechanisms and properties must be understood. An enhanced understanding of the fracture behavior at lower temperatures will ensure safe utilization of the materials and reduce production and operation costs through design criteria in addition to reducing over dimensioning.

Body-centered cubic structures undergo a rapid transition from ductile to brittle fracture. This concept is not yet fully understood, however, it is considered to be caused by a combination of restricted mobility of screw dislocations, a reduced number of available slip systems, and initiation of local fractures at preferred sites as the temperature is lowered [1,2]. It is noted that the mobility of screw dislocations is considered to play a major role in the low temperature fracture in bcc metals. The change in fracture mode from ductile to brittle occurs over a temperature range that is closely interconnected with the change in deformation energy as the materials ability to absorb energy decreases. As an attempt to enhance the understanding of the local fracture mechanisms in individual grains, small-scale testing has been utilized.

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Nomenclature

a	crack length
a_i	crack length at unloading step i
a_o	initial crack depth
A_{pl}	the area beneath the load-displacement curve
b	cantilever thickness
CMOD	crack mouth opening displacement
CTOD	crack tip opening displacement
E	Young's modulus of elasticity
EPFM	elastic-plastic fracture mechanics
ESEM	environmental scanning electron microscope
$f(a/b)$	dimensionless shape factor
F	applied force
F_Q	force determined according to the ASTM E399 standard
J_i	J-integral value at unloading step i
J_c	critical J-value
J_Q	conditional J-integral value
k	unloading stiffness
K	stress intensity factor
K_{Ic}	critical Mode I stress intensity factor
K_Q	conditional stress intensity factor
$K_{Q,LEFM}$	conditional stress intensity factor determined using linear-elastic fracture mechanics
L	distance from the point of loading to the notch
LEFM	linear-elastic fracture mechanics
Std Err	standard error
W	cantilever width
SEM	scanning electron microscope
δ	vertical beam deflection
Δa	crack growth
Γ	fitting parameter
η	factor equal to 2
σ_y	yield strength
ν	Poisson's factor
ω	plastic zone size

Traditionally, fracture mechanics research has been conducted at a macroscopic or large scale with focus on statistical treatment of fracture, ductile to brittle transition, and determination of the critical parameters inducing fracture through a local approach [3–8]. Quantifying fracture values and understanding the different steps in the fracture process is considered crucial in order to understand the deformation mechanisms at a microstructural level. Therefore, refinement of tests able to quantify values, as well as obtaining local fracture mechanical values, that serve as input in models like multiple barrier models has been the motivation for conducting the present micromechanical examinations.

The amount of papers presenting fracture experiments on micro-sized cantilevers is somewhat limited, but steadily increasing [9–19]. However, most of these experiments employ linear-elastic fracture mechanics in their procedures, limiting the number of studies where elastic-plastic fracture analysis has been considered, see e.g. [11–13,15,18]. When the sample size shifts to the micrometer regime semi-brittle and ductile materials will experience a different fracture behavior. As the specimen size is reduced, the plastic zone ahead of the crack tip will increasingly influence the results. Small scale yielding is considered a prerequisite for using linear-elastic fracture mechanics, demanding that the plastic zone is significantly smaller than the sample dimensions. Since this restriction can be difficult to satisfy at small scales, elastic-plastic fracture mechanics needs to be considered. Linear-Elastic fracture mechanics, however, is still able to yield meaningful information, even though the standardized criteria are not fulfilled. In macroscopic samples, fracture toughness has been successfully determined during large-scale yielding using methods like the J-integral, the crack tip opening displacement, or the crack tip opening angle [20].

Determining the critical J-value is the basis of obtaining the different fracture mechanical parameters in this work. This critical value is determined by two different approaches; initiation of critical crack growth transferred to a critical J, and evaluating the intersection of (1) the initial part of the J - Δa curve for all cantilevers by a linear fit and (2) linear fit from the end of the J - Δa curve for all cantilevers individually.

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