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Micro-structural reliability design of brittle materials

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Abstract

The paper analyses the effects of statistical distribution of micro-structural defect sizes concerning a scatter of brittle material fracture toughness. The results can be utilized for reliability assessment of selected engineering components operating under conditions of imminent brittle fracture. The reliability, taken as a complementary probability of brittle fracture initiation, is discussed, taking into account the character of the defect size statistical distribution, material mechanical properties, and varying loading and stress conditions of the component. Application of this method on Ni–Cr steel has demonstrated that there is very good agreement of the fracture behaviour predicted scatter with experimental results. This probability approach is compared with a deterministic reliability method originating from computations of safety factors. Its rational evaluation, as a function of the acceptable probability of fracture instability, provides a highly effective tool for designing of engineering components.

Keywords: Cleavage strength; Brittle fracture; Fracture toughness; Fracture probability; Reliability; Safety factor

1. Introduction

Engineering components made from brittle materials such as ceramics, inter-metallics, glasses or carbon steels at low-temperatures must be designed with regard to flaws, holes, and inclusions in structure. The load applied to the component causes the local stress concentrations around these defects which initiates micro-cracking. If these micro-cracks extend further and interact with each other, fracture instability occurs and macroscopic failure may arise. The usual combination of high strength and low fracture toughness of brittle materials leads to a relatively small critical crack size, detected with great difficulty by current non-destructive evaluation methods. As a result, service reliability of components made from brittle materials is very sensitive to micro-structural parameters such as micro-crack size distribution, micro-crack shape, their orientation and spatial allocations in the component stress field.

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Nomenclature

A_0	material constant
A_α	constant
b	characteristic width of the crack front
d_p	micro-crack size
d_{pf}	critical size of micro-crack
d_{pmax}	the largest carbide
d_{pmin}	the smallest carbide
d_{p0}	size parameter of function $\psi(d_p)$
E	Young's modulus
$h_{ij}(\theta)$	dimensionless function of θ in elastic stress field
I_n	dimensionless parameter in HRR stress field
J	path independent J-integral
J_c	J-integral at the onset of cleavage fracture
k_p	safety factor
k_{p0}	the safety factor corresponding to survival probability for loading
k_{Ia}	micro-crack arrest toughness
K_I	Mode I stress intensity factor
K_{Ic}	fracture toughness
K_{Jc}	elastic–plastic fracture toughness
m	number of micro-cracks
n	work hardening exponent
N_A	area density of carbides
N_V	volume density of carbides
p_f	probability of micro-crack initiation in a carbide
P_f	total fracture probability
r	radial coordinate of the polar system, centred at crack tip
δV	volume element
V	volume
α	deviation between applied stress direction and perpendicularity to the cleavage plane
α_0	size parameter of $\phi_1(\sigma_{emax})$ function
β	micro-crack shape factor
β_0	shape parameter of $\phi_1(\sigma_{emax})$ function
γ_{eff}	effective surface energy
δ	crack tip opening displacement
δ_0	shape parameter of function $\psi(d_p)$
ε_0	yield strain
$\zeta(\delta V, i)$	Poisson's distribution function
θ	angular coordinate of the polar system, centred at crack tip
$\kappa(k_p)$	statistical distribution of the safety factor
v	Poisson's ratio
$\xi(\alpha)$	probability density function of disorientation angle α
σ	stress
σ_{emax}	local maximum effective stress
σ_{fmax}	the highest local strength
σ_{fmin}	the lowest local strength
σ_f	local cleavage strength
$\sigma_{ij}(r,\theta)$	stress field around the crack tip
σ_0	yield stress