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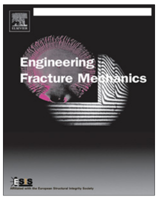

Predicting the effect of constraint on cleavage and ductile fracture toughness using area contour toughness scaling

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ABSTRACT

The influence of constraint on the fracture toughness properties of materials containing defects has long been recognised. To maintain conservative design and assessment principles, lower bound measurements of fracture properties are commonly used. These are measured using test pieces with a high crack tip constraint. With more accurate design processes and tools becoming more widespread, there is a move toward using more representative properties than these lower bound values. The work presented provides a method that can be used to predict the influence of constraint on the cleavage and ductile fracture toughness of a range of ferritic steels, and hence the associated benefit to the onset upper shelf temperature, defined here as the intersection between the fracture toughness loci associated with 5% cleavage fracture and a 50% ductile initiation probability.

The Anderson and Dodds toughness scaling procedure, based on the maximum principal stress, has been used with a range of normalised material tensile properties to generate solutions that allow the constraint benefit to cleavage fracture toughness to be predicted for different ferritic steels. A comparison of predictions with published data shows that this results in conservative predictions, similar to those using the Beremin Weibull stress.

For the purposes of predicting constraint benefits to ductile initiation toughness, defined at 0.2 mm stable tearing, the scaling method proposed by Anderson and Dodds was extended to the Rice and Tracey model as a way to provide solutions for the same matrix of tensile properties. This approach was validated against literature data for constraint effects on ductile initiation.

Finally, a worked example is provided, showing how the influence of crack tip constraint on the onset upper shelf temperature can be predicted using the solutions provided.

1. Introduction

Ferritic steels undergo a transition in fracture mechanism with change in temperature. At low temperatures, fracture proceeds by a cleavage mechanism, in which fracture occurs rapidly by the initiation and catastrophic propagation of a crack along crystallographic planes. Cleavage initiates at microcracks resulting from secondary phase particles within plastically deformed material. It is stochastic in nature and failure occurs when the first critically sized microcrack propagates. This statistical nature of cleavage fracture is best represented by a ‘weakest link’ model and can be described by a Weibull

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Nomenclature

Latin characters

a	effective crack length
A, B, C	constants
A^C	area enclosed by isostress contour for low constraint specimen
A^{SSY}	area enclosed by isostress contour for high constraint (small scale yielding) specimen
C_{ij}, D_{ij}	parameters for general solutions to α and k respectively
E	Young's modulus
G	Shear modulus
J	J integral
J_{Est}	estimate of J for a given time increment
J_{Max}	maximum applied J for finite element model
J_{Mat}	critical J for high constraint specimen
J^C_{Mat}	critical J for low constraint specimen
K_I	mode I stress intensity factor
K_J	mode I stress intensity factor estimated from J
K_{Mat}	mode I fracture toughness for high constraint (small scale yielding) specimen
K^C_{Mat}	mode I fracture toughness for low constraint specimen
n	strain hardening exponent
r	radius
R	outer radius of MBL model
$\left(\frac{R}{R_0}\right)_C$	critical Rice and Tracey parameter
T	T-stress
$u_x^{K_I}, u_y^{K_I}$	boundary displacement applied to generate crack tip stress from K_I
u_x^T, u_y^T	boundary displacement applied to generate crack tip stress from T-stress
V	volume
W	specimen width

Greek characters

α, k	R6 fit constraint parameters
ε	strain
ε^P_{eq}	equivalent plastic strain
ε_y	yield strain
ν	Poisson's ratio
ρ	crack tip radius
σ	stress
σ_{eq}	equivalent flow stress
σ_{ij}	the stress component in the i,j direction
σ_m	hydrostatic stress
σ_{Max}	maximum principal stress
σ_y	yield stress
θ	angle
τ_{Inc}	current time increment in finite element model
τ_{Total}	total step time for finite element model

distribution, where the distribution of secondary phase particles is represented by the shape factor of the distribution (Weibull modulus). The driving force for crack initiation is the crack opening stress the particle experiences [1], and the scaling factor for the probability distribution is, therefore, a function of the crack tip stress field.

By considering the volume of material ahead of a crack exposed to the critical value of opening stress or higher, and the distribution of particles within the steel, a probability of cleavage can be determined. This concept underpins the widely used Beremin [2] model for predicting cleavage. It is also used in the Anderson and Dodds [3] and Nevalainen and Dodds [4] toughness scaling models, whereby the predicted probability of cleavage for a given geometry is considered to be equal to a different geometry provided the volume of stressed material is the same.

The assumption of 'weakest link' statistics becomes less representative of the mechanism of failure as the temperature increases and the size of the plastic zone likewise increases. At higher temperatures, fracture occurs as the result of the initiation, growth and coalescence of voids that form around secondary phase particles, such as inclusions or carbides. Under most circumstances, this fracture mechanism is stable, requiring increasing load or displacement to progress. Rice and Tracey [5] proposed a model in which a void grows as a result of plasticity until it reaches a critical size. The ratio of the critical void size to its initial size is considered a material property defining fracture.