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Effect of notch acuity on the apparent fracture toughness

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ABSTRACT

The fracture behaviour of a component or specimen that contains a sharp notch is governed essentially by the same theoretical relations known from cracks. The blunt notch root only causes an increase of the resistance against crack initiation, which depends on the fracture mechanism. In the present paper, the relation between fracture toughness and notch toughness is investigated by simple analytical models. The derived formulas were compared with experimental results obtained from fracture toughness tests on RPV-steel 24 NiCrMo 3-7 at various temperatures. 1T-CT- and 0.4T-SEB-specimens that contained a sharp notch with a root radius of 0.06 mm introduced by spark erosion (EDM) instead of the standard fatigue crack were used. The predictions were found to agree well with the experimental data. The effect of the notch radius on fracture toughness is most pronounced in the brittle to ductile transition regime, where fracture toughness can be characterized by the master curve and the corresponding reference temperature T_0 according to ASTM E1921. Accordingly, the effect of the notch radius can be quantified by a shift of T_0. Since the shape of the transition curve depends on the notch radius, the procedure of ASTM E1921 to determine T_0 is not applicable. An alternative is suggested. As limiting cases, ductile tearing and brittle fracture are also considered.

1. Introduction

Fracture toughness represents the resistance of a pre-cracked component against fracture. However, the toughness in presence of a blunt notch instead of a crack can be of interest, too, for example in cases of corrosive or mechanical surface damage. As far as testing is concerned, sharp notches can serve as simpler substitute of a crack, since introduction of a well defined fatigue crack can be difficult and expensive, for example in component testing or to characterize fracture toughness of welds. In the latter case, crack should be well positioned in the most brittle zone, which is hard to achieve by fatigue. In metals it is much easier to introduce a sharp notch by electric discharge machining (EDM) in metals. Many non-metallic materials like ceramics, concrete or fibre-reinforced plastics do often not develop a well-defined fatigue crack under cyclic loading, so other methods to introduce a crack-like defect have to be used, which in general do not result in a perfectly sharp tip. In all these cases the behaviour of sharp notches and its relation to cracks should be understood qualitatively and known quantitatively.

Like in the case of a crack, the stress field in the vicinity of a sharp notch is governed by the stress intensity factor (SIF) or the J-integral, respectively, which means that the loading state of a notch can be characterized by the SIF or J as well.

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Nomenclature

Abbreviations

0.4T	specimen thickness 10 mm
1T	specimen thickness $B = 25.4$ mm
CT	compact tension specimen
CTOD	crack-tip opening displacement
DBT	ductile-to-brittle transition
EDM	electric discharge machining
J–R	J-resistance curve
MC	Master Curve according to ASTM E1921
RPV	reactor pressure vessel
SEB	single edge cracked specimens under bending
SIF	stress intensity factor
UTS	ultimate tensile strength

Symbols

a	crack length
a_0	initial crack or notch depth, respectively
A_5	standard fracture strain of uniaxial tensile test
A_g	uniform plastic strain at maximum force of uniaxial tensile test
B	specimen thickness
C, c	nondimensional constants
E	Young's modulus
G	energy release rate
G_c	critical energy release rate
J	J-Intergral
J_{Ic}	fracture toughness in terms of J according to ASTM E 1820
J_R	ordinate of J–R-curve of a crack
K_c	critical stress intensity factor
K_{cN}	critical SIF in case of a notch
K_I	stress intensity factor in Mode I
K_{Ic}	plane strain fracture toughness
K_J	K_I calculated from J
K_{Jc}	critical K_I calculated from J_{Ic} according to ASTM E1921
m	constraint parameter
R_m	ultimate tensile strength
$R_{p0.2}$	yield strength
s_N	slope as defined in Fig. 5
T	temperature
T_0	reference temperature according to ASTM E1921
T_{0N}	apparent T_0 in case of a notch
T_{US}	temperature between upper shelf and DBT-range
U_f	plastic energy density at fracture
W	specimen width
Z	standard reduction in area in uniaxial tensile testing

Greek symbols

α	notch angle
γ	non-dimensional peak stress in the vocinity of a crack or notch
Δa	crack extension
ΔT_{0_N}	shift of T_0 due to the notch radius
δ	crack-tip opening displacement (CTOD)
ε	true strain
ν	Poisson's ratio
ρ	notch root radius
σ	true stress
σ_c^*	stress required for local cleavage
σ_f	flow stress (mean value of $R_{p0.2}$ and R_m)