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Use of the failure assessment diagram to deduce ductile fracture toughness of the RAFM steel EUROFER97

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ABSTRACT

In the current work we use the failure assessment diagram (R6) to deduce ductile fracture toughness for the reduced activation ferritic/martensitic steel EUROFER97 by applying Small Specimen Testing Technology. Fracture parameters have been determined in quasi-static three-point-bend experiments. The fracture toughness results obtained with option 1 curve of R6 are sensibly independent of specimen geometry, constraint state and initial crack length and agree well with the results obtained by the analysis of crack resistance curves. Application of option 2 curve of R6 results into less conservative fracture toughness values.

1. Introduction

Development of Small Specimen Testing Technologies (SSTT) is of essential importance in a view of qualification of irradiated structural materials for future fusion power plants [1]. The key SSTT criteria are reduced specimen size and reliably scalable experimental results. Determination of quasi-static fracture toughness (K_{IC}) on miniaturized specimens well above the transition temperature is a huge challenge because of (a) supposed size dependence of fracture behaviour and (b) required minimum specimen thickness for ensuring high constraint conditions along the crack front [2]. Furthermore, high irradiation cost together with the restricted volume of irradiation facilities such as International Fusion Materials Irradiation Facility (IFMIF) [3] will require application of a single specimen technology using partial specimen uploading procedure. Estimation of crack grows by using either compliance [4] or calibrated electric potential [5] method, however, is supposed to introduce additional uncertainties in the fracture toughness value of irradiated specimens. Above mentioned reasons make application of reliable failure assessment criteria concerned with the initiation of fracture very attractive. The failure assessment diagram (FAD) R6 has been proved by a large body of numerical and experimental data to provide an approximate, conservative approach for component defect assessment [6,7]. In the current work we studied the applicability of FAD concept to deduce ductile fracture toughness for the reduced activation ferritic/martensitic (RAFM) steel EUROFER97 using specimens that are too small for toughness to be validly deduced in a conventional way.

2. Failure assessment diagram

Originally developed for high strength ferritic steels, the defect assessment procedure R6 was proved to be also applicable for austenitic steels [6]. To apply the R6 procedures, calculation of two parameters K_r and L_r is necessary for a particular load P and initial crack length a_0

$$K_r = \frac{K_I(P, a_0)}{K_{IC}} \tag{1}$$

$$L_r = \frac{P}{P_L(a_0, \sigma_y)} \tag{2}$$

where K_I is the elastic stress intensity factor, which for a *three-point-bend* specimen is given by

$$K_I = \frac{PS}{B\sqrt{W^3}} f\left(\frac{a_0}{W}\right) \tag{3}$$

with S being the span of bend fixtures (distance between supports), B the specimen thickness, W the specimen width and $f(a_0/W)$ being the geometry function for bending [8]. $P_L(a_0,\sigma_y)$ is the *plastic collapse* load assuming an elastic–ideal plastic behaviour with

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Notation list

a_0	initial crack length
B	specimen thickness
B_N	specimen net thickness
C	parameter for description of crack resistance curve
Δa	stable crack extension
Δa^*	in-plane components of stable crack extension
E	Young's modulus
f	geometry function for bending
f_1	option 1 curve
f_2	option 2 curve
J	*J*-integral
$J_{0.2}$	critical value of *J*-integral at 0.2 mm stable crack extension
J_{el}	elastic component of *J*-integral
J_{IC}	critical value of *J*-integral at the onset of stable crack growth
J_{pl}	plastic component of *J*-integral
K_{el}	elastic component of stress intensity factor
K_I	stress intensity factor
K_{IC}	critical stress intensity factor
K_r	ratio of applied K_I to K_{IC}
L_r	ratio of applied load to *plastic collapse* load
L_r^{max}	plastic collapse limit of L_r
n	strain hardening exponent
p	exponent for description of crack resistance curve
P	applied load
P_c	load level leading to a macroscopic appearance of crack initiation
P_L	*plastic collapse* load
S	span of bend fixtures
U	deformation energy
W	specimen width
α	parameter in Ramberg–Osgood description of stress–strain curve
δ_{tx}	crack-tip blunting
ε	strain
ε_{ref}	reference strain
ε_y	yield strain
ν	Poisson's ratio
σ_F	flow stress
σ_{ref}	reference stress
σ_u	ultimate tensile stress
σ_y	yield stress

a flow stress equal to material yield stress (σ_y). Component failure is avoided if (i) there is avoidance of fracture under linear elastic condition ($K_r \le 1$) and (ii) avoidance of failure by *plastic collapse* ($P \le P_L(a_0,\sigma_F)$ or equivalently $L_r \le L_r^{max}$). $P_L(a_0,\sigma_F)$ is the *plastic collapse* load assuming an elastic–ideal plastic behaviour with a flow stress (σ_F) which is often determined taking into account the material hardening as the average of the ultimate tensile strength (σ_u) and the yield stress (σ_y), i.e. $\sigma_F = (\sigma_u + \sigma_y)/2$. Consequently, L_r^{max} equals σ_F/σ_y. For side grooved specimens the thickness B in Eq. (3) is replaced by $(BB_N)^{1/2}$ [2], where B_N is a net thickness of a specimen (i.e. distance between the roots of side grooves).

For a *three-point-bend* specimen with an original crack length of a_0 the *plastic collapse* load can be calculated by

$$P_L(a_0,\sigma_y) = \frac{4}{3}\frac{BW^2}{S}\sigma_y\left(1-\frac{a_0}{W}\right)^2 \quad (4)$$

For side grooved specimens the thickness B in Eq. (4) is replaced by $(BB_N)^{1/2}$.

Component failure in the intermediate elastic–plastic region is often predicted by various FADs, see e.g. [7]. In [6] it was demonstrated that in the intermediate elastic–plastic region the material-specific curve, termed option 2 which is derived from uniaxial stress/strain data describes well the fracture behaviour of parent austenitic steels and their welds in a wide temperature range. The option 2 curve is given by

$$f_2(L_r) = K_r = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{L_r^2\sigma_{ref}}{2E\varepsilon_{ref}}\right]^{1/2} \quad (5)$$

where

$$\sigma_{ref} = L_r\sigma_y \quad (6)$$

and ε_{ref} is a true strain at a true stress level of σ_{ref} and E is the Young's modulus.

For strain hardening materials the stress–strain relationship is often well described by the Ramberg–Osgood equation

$$\frac{\varepsilon}{\varepsilon_y} = \frac{\sigma}{\sigma_y} + \alpha\left(\frac{\sigma}{\sigma_y}\right)^n \quad (7)$$

where ε_y is the strain corresponding to the material yield stress σ_y, and α and n are material-specific parameters.

Application of Eq. (5) requires detailed knowledge of the stress/strain curve (e.g. Eq. (7)) which is often not available for the user. For this reason, empirically derived material independent lower bound to option 2 curve, the so called option 1 curve of R6 is often used for a reliable failure assessment for a variety of materials. The option 1 curve (Revision 4) is given by

$$f_1(L_r) = K_r = \left[1+0.5L_r^2\right]^{-1/2}\left[0.3+0.7\exp\left(-0.6L_r^6\right)\right] \quad (8)$$

where L_r is defined by Eq. (6).

Often *J*-integral can be estimated as

$$J = J_{el}[f(L_r)]^{-2} \quad (9)$$

where J_{el} is the elastic component of *J*-integral and $f(L_r)$ is either option 1 or option 2 curve.

3. *J*-integral calculation

A multi-specimen method is often applied for construction of the crack resistance J–Δa curves. For this purpose the specimens are loaded to different deformation levels to achieve different crack-growth. For each deformation level *J*-integral can be represented as the sum of its elastic (J_{el}) and plastic (J_{pl}) components, i.e.

$$J = J_{el} + J_{pl} \quad (10)$$

For *three-point-bend* specimen the elastic component of J is given by

$$J_{el} = \frac{\left(1-\nu^2\right)K_{el}^2}{E} \quad (11)$$

where, elastic stress intensity factor K_{el} is obtained with Eq. (3).