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Code of practice for high-temperature testing of weldments

B. Dogan[a,*], K. Nikbin[b], B. Petrovski[a], U. Ceyhan[a], D.W. Dean[c]

[a] GKSS Research Center, Max-Planck-Str.1 D-21502 Geesthacht, Germany
[b] Imperial College, Exhibition Road, London SW7 2AZ, UK
[c] British Energy Generation Ltd., Barnwood, Gloucester GL4 3RS, UK

Abstract

The present paper reports on a code of practice (CoP) for high-temperature testing of weldments for industrially relevant specimens. Novel aspects of the CoP include advice for testing weldment zones using different specimen geometries. Those specimens differ from the standard compact tension C(T) specimen recommended in the only available creep crack growth (CCG) testing standard ASTM E1457. Recommendations for the required number of tests, techniques for testing, treatment of test records, reduction of test data and data analysis are presented. Associated specimen selection guidelines for industrial creep crack initiation (CCI) and growth testing are also described. Validation tests carried out on P22 and P91 weldments, and base metals of 316H steel and C-Mn steel using relevant specimen geometries are briefly described. The CoP contains recommended K and C^* solutions, Y functions and η factors, which are used to determine values of the fracture parameters K and C^* for the specimen geometries considered. Information from these new tests, together with a review of previous CCG tests on non-standard geometries, have been used in recommending the best method of analysis for CCI and CCG data for a range of creep brittle to creep ductile welded materials.

Keywords: Code of practice; Fracture mechanics; Weldments; Creep crack initiation; Creep crack growth; C^*; Specimen geometry; η-factor

1. Introduction

The available codes for high-temperature crack growth testing and characterization of materials are limited in scope and international acceptance. The most widely used standard for creep crack growth (CCG) testing of metallic materials [1] mainly addresses testing homogeneous materials in compact tension, $C(T)$, type specimens. Therefore, the outstanding need for high-temperature characterization of weldments for creep crack initiation (CCI) and growth in alternative industrial specimens has been the subject of collaborative efforts of ESIS TC11 and the European project CRETE [2]. They had the objective of harmonizing testing procedures for these specimens in order to obtain data for use in defect tolerance assessment of components. Recent reviews of high-temperature defect assessment procedures [3] and of the significance of creep in defect assessment procedures for low to high temperature [4] emphasize the need for reliable CCG data. The British Standard document BS7910 [5] contains some indicative data for CCG assessment, whereas the R5 [6] procedure does not explicitly supply CCG data, except where specifically used to validate the procedures. The present paper outlines the guidelines of a code of practice (CoP) for experimental determination and analysis of CCI and CCG rate data of weldments including base metal (BM), heat affected zone (HAZ) and weld metal (WM). CCI is defined as the extension of a pre-existing defect by a small amount of growth, typically 0.2 mm or 0.5 mm. Novel aspects of the CoP include interpretation of potential drop (PD) records, crack size determination and measurement on tested specimen surfaces, crack tip parameter (K, C^*) solutions, $Y(a/W)$ functions and η factors for six specimen types. Validation tests were carried out on P22 and P91 steel weldments, and base materials of Type 316H steel and a C-Mn steel using relevant specimen geometries. Selected results on P22 weldments are presented.

*Corresponding author. Tel.: +49 4152 872 563; fax: +49 4152 872 595.
E-mail address: bilal.dogan@gkss.de (B. Dogan).

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Nomenclature

a	crack length
a_o, a_f	initial and final crack length measurements
Δa	amount of crack growth
$\dot{a}$, da/dt	crack growth rate
B, B_n, B_e	specimen thickness, net specimen thickness, effective specimen thickness
CCG, CCI	creep crack growth, creep crack initiation
CMOD	crack mouth opening displacement
C_o	compliance at time zero
CoP	code of practice
$C(T)$	compact tension specimen
CRETE	EC Project CRETE (Ref. [2])
CS(T)	C-shape specimen in tension
C_t	crack tip parameter for transient to extensive creep
C^*	steady-state creep fracture mechanics parameter
$C^*(t)$	experimentally determined value of C^* at test time, t
DEN(T)	double edge notch tensile specimen
D', D'_i	material constant in $\dot{a}$ correlations with K
D_o, D_i	material constant in $\dot{a}$ correlations with C^*
EDM	electrical discharge machining
ESIS	European structural integrity society
E	elastic modulus
E'	effective elastic modulus for plane strain
FS	fracture surface
HAZ	heat-affected zone
H	specimen height
H^{LLD}	geometric function to calculate C^* from load line displacement rate
H^{CMOD}	geometric function to calculate C^* from crack mouth opening displacement rate
J	J-integral crack tip parameter
K, K_n	stress intensity factor, stress intensity factor for net section thickness
K^c_{mat}	creep crack initiation toughness
L	half span length
LLD	load line displacement
LVDT	linear variable displacement transducer
M	bending moment
m'	material constant in $\dot{a}$ correlations with K
$M(T)$	middle crack tension specimen
N	stress exponent in power-law plasticity
n	power-law creep stress exponent
P	applied load
PD	potential drop
R_i	inner radius of CS(T) specimen
R_0	outer radius of CS(T) specimen
SEN(B)	single edge notch specimen in bending
SEN(T)	single edge notch specimen in tension
TC	technical committee
t_i	time for crack initiation (at $\Delta a = 0.2$ and 0.5 mm)
t_T	transition time from primary to steady-state creep
U	area under load–displacement curve
V_i	value of the PD measurement at initiation
V_0, V_f	initial and final values of the PD measurement
W	specimen width or half width
$Y(a/W)$	geometry factor to calculate K
$\dot{\Delta}_c$	creep component of load line displacement rate
Δ^{LLD}, $\dot{\Delta}^{LLD}$	load line displacement, load line displacement rate
$\dot{\Delta}^{LLD}_c$	component of the load line displacement rate directly associated with the accumulation of creep strains
$\dot{\Delta}^{LLD}_i$	component of the load line displacement rate directly associated with instantaneous (elastic and plastic) strains
$\dot{\Delta}^{LLD}_{i,e}$	component of the load line displacement rate directly associated with instantaneous elastic strains
Δ^{CMOD}, $\dot{\Delta}^{CMOD}$	crack mouth opening displacement, crack mouth opening displacement rate
ε^c_f	creep ductility
$\dot{\varepsilon}^c$	creep strain rate
η^{CMOD}	geometric factor to calculate C^* from crack mouth opening displacement rate
η^{LLD}	geometric factor to calculate C^* from load line displacement rate
ϕ	material constant in $\dot{a}$ correlations with C^*
λ	non-dimensional crack velocity
σ	stress
σ_b	nominal bending stress
σ_m	membrane stress
σ_{ref}	reference stress
v	Poisson's ratio

2. CoP for high-temperature testing of weldments

2.1. Scope and use

The present CoP aims to provide recommendations and guidance for a harmonized procedure for measuring and analyzing CCI and CCG characteristics of metallic-welded materials using a wide range of industrial fracture mechanics specimen geometries. It will allow laboratories with limited test material to carry out tests on different specimen geometries [7] machined out of various zones of weldments.

2.2. Specimens

The emphasis in the presented CoP is placed on the inclusion of component-relevant industrial specimen