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Using the results of creep crack incubation tests on CrMoV steel for predicting long time creep rupture properties

S.R. Holdsworth [a,*], E. Mazza [a,b]

[a] EMPA Swiss Federal Institute for Materials Testing & Research, 8600 Dübendorf, Switzerland
[b] Swiss Federal Institute of Technology, ETH Zürich, Department Mechanical & Process Engineering, Switzerland

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ABSTRACT

The results of a series of creep crack incubation (CCI) tests have been used to examine the effectiveness of the LICON methodology for predicting long duration uniaxial rupture strength of a CrMoV steel at 550° C. The study has revealed that effective long time predictions can be made, but only with the availability of additional information including: an awareness of the short and long time rupture mechanisms and the associated multi-axial rupture criteria obeyed by the material, the results of uniaxial and multi-axial creep tests, and a knowledge of the steady state creep stress conditions existing in the testpieces (structures) forming part of the evaluation.

In order to apply the creep damage enhancement approach to the low alloy creep resistant steel, it has been necessary to establish the steady-state creep stress state in the compact tension testpiece geometry used in the investigation. The new evidence is reviewed.

1. Introduction

On the application of a steady load to a pre-cracked structure at high temperature, the load point displacement increases with time [1]. Creep crack initiation occurs on the attainment of a critical local crack tip strain. With further increase in time, load point displacement and crack size increase until the remaining ligament can no longer support the applied load (Fig. 1). Creep crack incubation times are commonly determined from tests involving compact tension testpieces, but not exclusively so. The data are typically used to construct high temperature failure assessment diagrams (e.g. [2–4]). However, they may also be used to underpin lifetime predictions using the LICON methodology [5,6].

The LICON approach was originally developed in the late 1990s to predict the long term creep rupture behaviour of new generation martensitic 9% Cr steels (including their welded joints) from the results of relatively short duration multi-axial specimen tests. The methodology relies on the acceleration of creep damage development under multi-axial loading conditions to enable extended extrapolation of rupture strength into the long time fracture regime. In its current form, the methodology does not account for the long term thermal ageing effects which can occur during the service duty lifetime of certain materials, and this is a topic of current research. Nevertheless, the approach provides similarity with the loading conditions experienced in real structures and enables a more accurate evaluation of the future in-service performance of welded components for which no long term operating experience exists. Other potential applications include the cast specific remaining life prediction of high temperature components with multi-axial features. The following paper considers the results of an investigation into the effectiveness of the LICON methodology when applied to a low alloy creep resistant CrMoV steel.

2. LICON methodology

The original LICON development was based on the formulation:

$$t_{i,x} = A(T)\cdot(\overline{\sigma})^{-\nu}\cdot(H)^{-\gamma} \tag{1}$$

with $H = \sigma_1/\overline{\sigma}$ where σ_1 is the maximum principal stress and $\overline{\sigma}$ is the relevant effective stress, and where γ varies with material and conditions of temperature and stress and is the significant parameter defining the material's multi-axial creep rupture response [7]. Typically, γ varies between zero for $\overline{\sigma}$-controlled rupture and ν for σ_1-controlled rupture. In the original development, $\overline{\sigma}_{VM}$ was adopted as the effective stress [5,6]. The LICON approach is not limited to this formulation. While the use of H has been demonstrated to work for a number of advanced 9% Cr steels, it is acknowledged that other multi-axiality factors may be more

* Corresponding author. Tel.: +41 44 823 4732; fax: +41 44 823 4252.
E-mail address: stuart.holdsworth@empa.ch (S.R. Holdsworth).

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Nomenclature

a, a_o	Crack length, initial crack length, mm
Δa, Δa_C	Crack extension, creep crack extension, mm
A, A', A'', A_{CT}	Constants in $t(\bar{\sigma})$ formulation, in Regime-1, in Regime-2, for CT testpiece
CCI	Creep crack incubation
CT	Compact-tension testpiece
DCPD	Direct current potential drop
FEA	Finite element analysis
H, H_z	Multi-axiality factor ($\sigma_1/\bar{\sigma}_{VM}$), for a given geometry defined by z
K	Stress intensity factor, MPa$\sqrt{m}$
LPD, LPD(t)	Load point displacement, LPD as a function of time, mm
$R_{p0.2}$, R_m	0.2% proof strength, tensile strength, MPa
t, t_u	Time, time to rupture in a uniaxial testpiece, h
$t_{i,x}$, $t_{i,0.5}$	Time to initiate a crack in a multi-axial testpiece (initiation criterion, $x = \Delta a_C = 0.5$ mm), h
W	Testpiece width, mm
z	Designation for multi-axial feature type, e.g. z = CT
γ, γ', γ''	Multi-axial rupture exponent, in Regime-1, in Regime-2
ν, ν', ν''	Stress exponent, in Regime-1, in Regime-2
σ, σ_o	Stress, initial stress (in constant load uniaxial test), MPa
σ_1	Maximum principal stress, MPa
$\bar{\sigma}$, $\bar{\sigma}_{VM}$, $\bar{\sigma}_{VM(0.5)}$	Effective stress, von Mises effective stress, at a distance of 0.5 mm ahead of initial crack tip, MPa
$\bar{\sigma}_{VM,pl\varepsilon}$, $\bar{\sigma}_{VM,pl\sigma}$	Plane strain and plane stress von Mises equivalent yield reference stresses [10], MPa

appropriate for different material classes in specific T, σ application ranges. In its initial formulation, the LICON model equations characterised the rupture behaviour of advanced 9% Cr steels in two mechanism regimes (Fig. 2), i.e.

2.1. Mechanism regime-1

$$t_u = A' \cdot (\sigma_o)^{-\nu'} \quad \text{unaxial} \tag{2a}$$

$$t_{i,x} = A' \cdot (\bar{\sigma}_{VM})^{-\nu'} \cdot (H_z)^{-\gamma'} \quad \text{e.g. with } \gamma' \to 0 \quad \text{multi-axial} \tag{2b}$$

Typically for ferritic steels in *Regime-1*, the damage mechanism is predominantly void nucleation due to particle/matrix decohesion, rupture is $\bar{\sigma}_{VM}$-controlled, and $\gamma' \to 0$. In Eq. (2b) and below, subscript 'x' relates to the crack initiation criterion adopted to indicate the equivalent rupture life in the multi-axial feature under consideration (e.g. $\Delta a_C = 0.5$ mm). The subscript 'z' provides a reference to the multi-axial feature (e.g. z = CT for a compact-tension testpiece). In the present study, multi-axial laboratory data is collected using the CT testpiece geometry, and 'z' is set to CT, when appropriate, in the following text.

2.2. Mechanism regime-2

$$t_{i,x} = A_{CT} \cdot (\bar{\sigma}_{VM})^{-\nu''} \quad \text{multi-axial} \tag{3a}$$

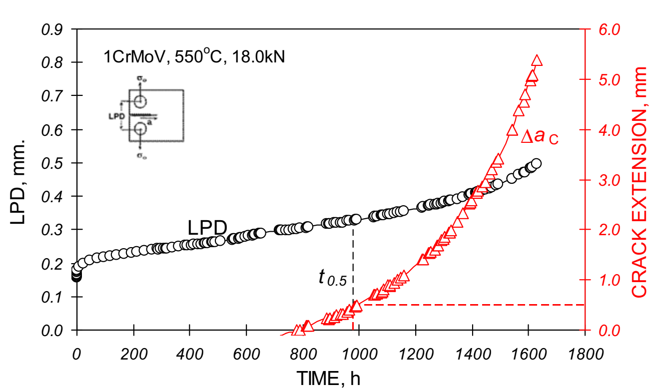

Fig. 1. Variation of load point displacement and creep crack extension, with time, during a creep crack incubation test at 550 °C.

$$t_{i,x} = A_{CT} \cdot (\bar{\sigma}_{VM})^{-\nu''} \cdot \left(\frac{H_{CT}}{H_z}\right)^{-\gamma''} \quad \text{e.g. with } \gamma'' \to \nu'' \quad \text{multi-axial} \tag{3b}$$

$$t_u = A''.(\sigma_o)^{-\nu''} \quad \text{unaxial} \tag{3c}$$

and

$$A'' = A_{CT}.(H_{CT})^{-\gamma''} \quad \text{e.g. with } \gamma'' \to \nu'' \tag{3d}$$

In *Mechanism Regime-2* in ferritic steels, damage typically nucleates and develops at grain/lath boundaries, rupture is σ_1-controlled, and $\gamma'' \to \nu''$. The methodology is not limited to materials exhibiting regimes involving only these two mechanisms.

The *Regime-2* equation set (i.e. Eqs. (3a–d)) may be used for different purposes. For example, having determined the parameters for Eq. (3a) from the results of a series of tests using a multi-axial specimen geometry such as a CT-testpiece, these may be used to predict either long term uniaxial rupture behaviour using Eqs. (3c,d) or the life of a component with a multi-axial feature using Eq. (3b). In this case, for example, H_{CT} is the steady-state triaxiality factor for the adopted CT multiaxial testpiece geometry and H_z is the steady-state triaxiality factor relating to the stress state at a component critical feature. H_z on the attainment of steady-state

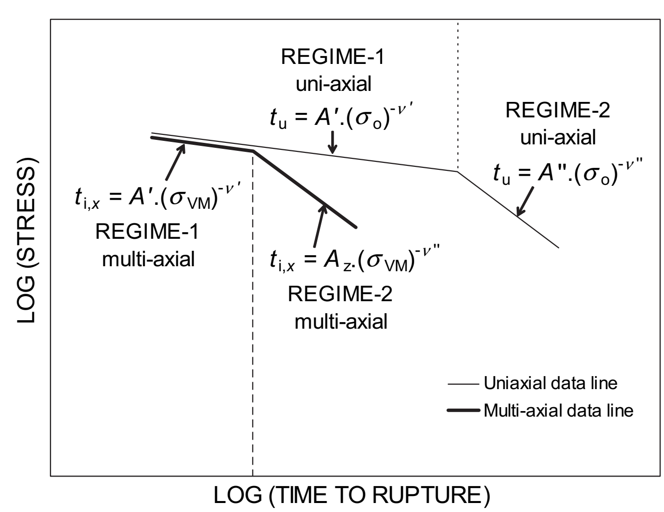

Fig. 2. Schematic representation of the LICON concept (in the present study $x = 0.5$ and z = CT).