Creep-fatigue assessment of welded components

Bilal Dogan
Electric Power Research Institute (EPRI), Charlotte, NC, USA
e-mail: bdogan@epri.com

Keywords

Creep damage, creep-fatigue, defect assessment, inservice lifing.

1. Introduction

Methods for assessing defects in components operating at temperatures high enough for creep to be important were first introduced in the late 1980s [1]. The methods initially only applied to assessment of creep crack growth under steady loading but were later extended to creep-fatigue (C-F) loading conditions. ASME Section III, Subsection NH [2] (which was Code Case N-47) provides design and construction rules for mechanical components which will operate at high temperature. It was the first design code to formally embrace the concept of linear damage summation as a method of predicting material failure at high temperature. The code consists of a fatigue (Miner cycle summation) component and a creep (Robinson time summation) component. In its current form, ASME Code Case NH is conservative. This reflects numerous uncertainties in creep-fatigue life prediction. Use of this Code Case for remaining life assessment of components represents an extremely conservative approach that will lead to premature and unwarranted retirements. Currently a task group within ASME is working on these issues in view of future higher temperature reactors, where the creep-fatigue damage of components will be intensified. The French RCC-MR Code [3] incorporates many of the concepts behind ASME Section III but with modified stress analysis procedures. These modifications appear to provide less conservative estimates of component behavior. The 2002 RCC-MR creep-fatigue rule (RB 3262.112 of the RCC-MR [3]) is based on the use of the cyclic curve considered as representative of the stabilized cycle. The British Energy R5 Code [4] is entitled “Assessment Procedure for the High Temperature Response of Structures”. Thus, in contrast to ASME Section III and RCC-MR, R5 offers guidance on damage development and assessment of in-service components. Subsequently, procedures for assessing defects at high temperature, similar to those in R5, have been included in British Standards [5], the French RCC-M A16 procedure [3] and in API 579 [6]. A similar approach to R5 was taken in a recent EC Thematic Network project FITNET [7] the novel features of which are incorporated into R5. The existing procedures were reviewed and used as a basis in the reported European procedure. This paper first provides an overview of the basic methodology of testing and creep damage assessment procedure [8, 9], followed by the experimental data determination and assessment. Note that there is no standard for creep-fatigue (C-F) testing of metallic materials, yet. However, an EPRI international creep-fatigue experts group [10] is working on the C-F data analysis and assessment methods as well as C-F testing methods. Hence, two standards are recently drafted on C-F crack initiation and C-F crack growth within ASTM E08 which are awaiting balloting for standardization.

2. High temperature component assessment: Codes

The high temperature design and assessment codes specify methods for assessing defects in structures operating under creep and creep-fatigue loading conditions.

The information required to perform an assessment is: the operating conditions; the nature of the defects; materials data; and structural calculations to correlate materials data with the behaviour of complex structures.

Basic advice on the first three aspects is given in e.g. R5 [4] (and FITNET FFS Creep [11]) procedure. Structural calculations are required to assess whether a given defect will grow to an unacceptable size in a given service life under a given loading history. Step-by-step procedures are provided to perform these assessments and methods for following each step are specified. Here, the attention is focused on the specific materials data and required calculations as in the below [121,13].

2.1. Materials data

For some situations, it is possible to take account of an incubation period, t_i , prior to crack extension. Creep crack incubation data may be expressed in terms of a critical crack tip opening displacement, δ_i, or, for widespread creep conditions, by the relationship:

$$t_i (C^*)^\beta = \gamma \qquad (1)$$

where β and γ are material constants.

Creep crack growth data are generally presented as

$$\dot{a} = A(C^*)^q \qquad (2)$$

where A and q are material constants.

Two different methods of calculating creep-fatigue crack growth are given. The method to be applied depends on the defect size and the severity of the applied loading. When the defect is sufficiently small to be embedded in a cyclic plastic zone the crack growth law is a high strain fatigue crack growth law (termed Method II). For larger defects, fatigue crack growth is calculated by a Paris law, modified to allow for crack closure and simply added to a separate calculation of creep crack growth to give the total crack extension. This is termed Method I and is described by

$$\left(\frac{da}{dN}\right)_f = C\Delta K_{eff}^{\ell} \qquad (3)$$

where C and ℓ are material constants and ΔK_{eff} is the stress intensity factor range for which the crack is judged to be open. The Method II crack growth rate law is

$$\left(\frac{da}{dN}\right)_f = B' a^Q \qquad a_{min} \leq a \leq r_p \tag{4}$$

where a_{min} = 0.2 mm is the crack depth below which the crack growth rate is assumed to be constant. B' and Q depend on material, strain range and environment, and can be determined experimentally. This law applies for a total surface strain range $\Delta\bar{\varepsilon}_t$. This condition where Eq.4 applies is called insignificant creep.

2.2. Basic creep-fatigue calculations

In the absence of cyclic plasticity in the un-cracked body, the effective stress intensity factor range ΔK_{eff} is

$$\Delta K_{eff} = q_o \Delta K \tag{5}$$

where $\Delta K = K_{max} - K_{min}$ and q_o is the fraction of the total load range for which a crack is judged to be open. This may be estimated conservatively from:

$$\begin{aligned} q_o &= 1 && R \geq 0 \\ q_o &= (1-0.5R)/(1-R) && R < 0 \end{aligned} \tag{6}$$

where $R = K_{min} / K_{max}$.

For creep rupture and crack growth evaluation, it is necessary to evaluate a reference stress. The reference stress for simple primary loading is determined by the methods of limit analysis and is defined by:

$$\sigma_{ref}^p = P\sigma_y / P_L(\sigma_y, a) \tag{7}$$

In cases of cyclic loading the load P is evaluated from the stress, produced by the shakedown analysis, at the time in the cycle corresponding to the creep dwell. P_L is the value of P corresponding to plastic collapse assuming a yield stress σ_y.

For steady state creep, the crack tip stress and strain rate fields (and hence creep crack growth rates) are characterized by the C^* parameter. A reference stress estimate of C^* is

$$C^* = \sigma_{ref}^p \dot{\varepsilon}_c[\sigma_{ref}^p(a), \varepsilon_c] R' \tag{8}$$

Here, $\dot{\varepsilon}_c$ is the creep strain rate at the current reference stress and creep strain, ε_c, accumulated under the reference stress history up to time t. The characteristic length, R' is defined by

$$R' = (K^p / \sigma_{ref}^p)^2 \tag{9}$$

where K^p is the stress intensity factor due to primary load only. As both K^p and σ_{ref}^p are directly proportional to the loading P, the value of R' is independent of the magnitude of P. However, R' does vary with crack size and, when crack growth is being considered, both K and σ_{ref}^p should be calculated for the defect size equal to the size of the original crack plus the amount of creep crack growth. The value of R' is also different at the surface and deepest points of a semi-elliptical surface defect due to differences in the values of K^p.

For other than simple primary loadings, estimates of C^* are given below in the section describing novel features of the FITNET creep module, which are incorporated into R5.

Time is required for stress redistribution due to creep from the initial elastic state at the start of a creep dwell. The requirement for the stress redistribution to be complete and widespread creep conditions to be established is expressed in terms of a redistribution time, t_{red}. This is defined conveniently in terms of the reference stress for cases of primary load only as

$$\varepsilon_c[\sigma_{ref}^p(a), t_{red}] = \sigma_{ref}^p(a)/E \tag{10}$$

where $\varepsilon_c[\sigma_{ref}^p(a), t]$ is the accumulated creep strain at the reference stress for time, t, and crack length, a, from uniaxial creep data.

Equation (10) applies for steady creep loading under primary stresses. When calculating crack growth under significant cyclic loading, it may be necessary to consider the early cycles before the steady cyclic state is reached. Time is required for the material response to the cyclic loading to reach a steady cyclic state or shakedown. This time, t_{cyc}, can be estimated in terms of the reference stress for the first cycle, $\sigma_{ref}^{cyc=1}$, and the reference stress under steady cyclic conditions for combined primary and secondary loading, σ_{ref}, as:

$$\varepsilon_c\left[\frac{(\sigma_{ref}^{cyc=1} + \sigma_{ref})}{2}, t_{cyc}\right] = Z\frac{(\sigma_{ref}^{cyc=1} - \sigma_{ref})}{E} \tag{11}$$

where Z is an elastic follow-up factor, which controls the rate of stress relaxation to steady state creep.

For times less than the redistribution time, it may be necessary to calculate the transient crack tip parameter C(t). An interpolation formula for C(t) during the transition between initial elastic loading and steady state secondary creep is

$$\frac{C(t)}{C^*} = \frac{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)}}{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)} - 1} \tag{12}$$

where ε_c is the accumulated creep strain at time t, ε_e is the elastic strain and q is the exponent in the creep crack growth law of equation (2) with $q \simeq n/(n+1)$ where n is the creep stress exponent. For times in excess of the redistribution time, C(t) approaches C^*.

2.3. Assessment calculations

Calculate rupture life, t_{CD}

Both stress-based and strain-based approaches may be used for assessing creep damage. For loadings which are predominantly constant and primary, the stress is well known and stress/time-to-rupture relationships are used. For predominately primary loading, the time, t_{CD}, for creep damage to propagate through a structure and lead to failure is

$$t_{CD} = t_r[\sigma_{ref}^p(a)] \tag{13}$$

where $t_r(\sigma)$ is the rupture time at stress, σ, from conventional stress/time-to-rupture data. If t_{CD} is less than the remaining assessment time then remedial action must be taken. For damage due to cyclic relaxation, the strain accumulated is limited in each cycle and ductility methods replace equation (13).

Calculate crack incubation time, t_i

The incubation time, t_i, is defined for engineering purposes as corresponding to 0.2mm crack extension. The method for representing incubation data then depends on observed specimen response. For steady state creep conditions with an essentially constant displacement rate, the incubation time in test specimens is correlated with experimental estimates of C^* by equation (1). Use of the estimate of C^* from equation (8) for the initial crack size a_0, then provides an estimate of t_i. More generally, incubation times can be related to measurements of a critical crack opening displacement, δ_i, which can then be used to calculate a critical reference strain as

$$\varepsilon_c[\sigma^p_{ref}(a_0), t_i] = [\delta_i / R'(a_0)]^{n/(n+1)} - \sigma^p_{ref}(a_0)/E \qquad (14)$$

For elliptical or semi-elliptical defects, the incubation time should be taken as the lower of the values obtained at points corresponding to the major and minor axes of the ellipse or semi-ellipse.

Calculate crack size after growth, a_g

The extent to which crack growth calculations are required depends on the relative magnitudes of the service life to date, t_o, the desired future service life, t_s, and the incubation time, t_i. This may be summarized as follows.

- If $t_o + t_s < t_i$, the crack will not incubate and $a_g = a_0$.
- If the crack incubates during the assessment time, then it is necessary to calculate the crack size, a_g, after growth in time $t_o + t_s - t_i$.
- If the crack has incubated prior to the assessment, then it is necessary to calculate the crack size, a_g, after growth in time t_s.

The time required for the crack to propagate by an amount Δa_g is denoted t_g. There are a number of different regimes for calculations of crack growth and these are set out below.

(A) Cracks growing inside the cyclic plastic zone, r_p*, at the surface of the component.*

In this regime the Method II high strain creep-fatigue crack growth law should be used. This is equation (4) for insignificant creep. When creep is significant, the creep-fatigue crack growth per cycle is given by:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_f (1 - D_c^{surf})^{-2} \qquad (15)$$

where $(da/dN)_f$ is the fatigue crack growth per cycle from equation (4) and D_c^{surf} is the total surface creep damage (taking account of stress state, if necessary) accumulated up to the current time from every cycle.

$$D_c^{surf} = \sum_{j=1}^{N} (d_c^{surf})_j \qquad (16)$$

where $(d_c^{surf})_j$ is the creep damage accumulated in the j'th cycle and the summation is carried out up to the current time. The term $(d_c^{surf})_j$ is evaluated at the surface of the un-cracked component and is given by the ductility exhaustion method as

$$(d_c^{surf})_j = \int_0^{t_{h,j}} \frac{\dot{\varepsilon}_c}{\bar{\varepsilon}_f(\dot{\varepsilon}_c)} dt \qquad (17)$$

where $0 \le t \le t_{h,j}$ is the j'th creep dwell period, $\dot{\varepsilon}_c$ is the instantaneous equivalent creep strain rate during the dwell and $\bar{\varepsilon}_f(\dot{\varepsilon}_c)$ is the creep ductility at that strain rate, accounting for stress state. The strain rate is evaluated at the instantaneous stress during the dwell obtained from stress relaxation data.

When $D_c^{surf} \to 1$, equation (15) predicts an infinite crack growth rate. However, this should not be interpreted as predicting the failure of the component. This corresponds to the exhaustion of creep ductility at the surface and the instantaneous crack depth, a, should be set to the depth of the cyclic plastic zone, r_p. If r_p is greater than the crack depth that the structure can safely tolerate then remedial action should be taken. Otherwise, cracks deeper than r_p are subjected to nominally cyclic elastic

deformation and the Method I growth law should be used as set out below.

(B) Crack length, a, greater than the cyclic plastic zone size, r_p*, at the surface of the component.*

In this regime, the Method I crack growth rate law of equation (3) is used and the total crack growth per cycle, da/dN, is obtained as the simple sum of the contributions due to cyclic and creep crack growth rates:

$$da/dN = (da/dN)_f + (da/dN)_c \qquad (18)$$

The fatigue crack growth per cycle $(da/dN)_f$ is given by equation (3) with the constants modified for hold-time effects only if creep-fatigue interactions are shown to be significant. If fatigue crack growth is insignificant, this term is omitted. The creep crack growth per cycle in equation (18) also depends on loading regime as set out in (i) - (iv), below.

(i) Steady state creep crack growth for times $t > t_{red}$, with insignificant cyclic loading

For the load controlled case and the attainment of steady state creep conditions the creep crack growth is obtained from creep crack growth data in the form of equation (2).

Equation (8) is used to estimate C^* for crack sizes between a_0 and a_g for use with equation (2).

The creep crack extension per cycle, $(da/dN)_c$, is evaluated as the integral of equation (2) over the dwell period, t_h:

$$\left(\frac{da}{dN}\right)_c = \int_0^{t_h} A(C^*)^q dt \qquad (19)$$

(ii) Non-steady state creep crack growth, $t < t_{red}$, when cyclic loading is insignificant.

For times less than the redistribution time ($t<t_{red}$), equation (2) is generalized to

$$\dot{a} = A[C(t)]^q \qquad (20)$$

For situations where $t_i + t_g > t_{red}$, the effects of the redistribution period can be allowed for by using the crack growth rates of equation (2) multiplied by a factor of 2 for $t<t_{red}$, i.e.

$$\dot{a} = 2A(C^*)^q \quad \text{for } t_i \le t < t_{red}$$
$$\dot{a} = A(C^*)^q \quad \text{for } t \ge t_{red} \qquad (21)$$

If the total time for the assessment does not exceed t_{red}, then this simplified treatment of transient creep is not adequate and it is necessary to use the parameter C(t) explicitly, from equation (12), to estimate creep crack growth. The creep crack extension per cycle, $(da/dN)_c$, including transient effects is then evaluated over the dwell period, t_h, as in equation (19).

(iii) Early cycle creep crack growth, $t < t_{cyc}$, when cyclic loading is significant.

For a component outside strict shakedown a mean estimate of C^* during the transient period, $\overline{C}^*$, may be used up to t_{cyc} of equation (11). Where only elastic analysis is available, $\overline{C}^*$ is defined as:

$$\overline{C}^* = (\sigma_{ref}^{cyc=1} + \sigma_{ref})\dot{\varepsilon}R'/2 \qquad (22)$$

where $\dot{\varepsilon}$ is evaluated as $\dot{\varepsilon}[(\sigma_{ref}^{cyc=1} + \sigma_{ref})/2]$. As crack growth is approximately linearly dependent on C^*, the crack growth during the time t_{cyc} is not particularly sensitive to the value of t_{cyc} but depends primarily on the accumulated creep strain, $Z(\sigma_{ref}^{cyc=1} - \sigma_{ref})/E$. For the early cycles, prior to structural shakedown, the creep crack extension per cycle, $(da/dN)_c$, is evaluated over the dwell period, t_h, as in equation (19).

(iv) Steady cycle creep crack growth, $t > t_{cyc}$, when cyclic loading is significant.

At $t \ge t_{cyc}$, $\overline{C}^*$ is replaced by C^* calculated from the loads in the steady cycle obtained from a shakedown analysis.

The recent developments including novel features of the procedure and the probabilistic approaches are reported in details in [13].

3. High temperature component assessment: Deterministic approach

3.1. Creep crack initiation and crack growth tests

Constant load (CL) or constant displacement rate (CDR) tests are carried out for obtaining creep crack initiation (CCI) and creep crack growth (CCG) data. The load, potential drop (PD) and load line displacement (LLD) data are logged all the way to full load starting from pre-load for the subsequent analysis of the data for determination of crack size, and crack tip parameters C* and K. In addition the load/displacement measured will give the specimen's elastic compliance for the initial crack length. The tests are done following the ASTM standard [14] and the recent code [9] and the data are analyzed for CCI and CCG correlations used in defect assessment in TDFAD approach [4,15].

3.2. Crack size determination

Direct current potential drop (DCPD) method is applied to monitor the crack initiation and growth during testing. The crack size is determined from PD data using Johnson's formula given for C(T) geometry [14].

The scatter in crack size using PD method is increased by the crack channeling with unbroken ligaments as observed on fracture surfaces of cracked opened specimens. An accurate measure of the initial (a_o) and final (a_f) crack front and crack size were made when the specimen was broken open outside the furnace after testing.

3.3. Defect assessment methods: Time dependent failure assessment diagram (TDFAD)

Failure assessment diagram (FAD) methods, such as those in R6 [16], have been extensively developed to assess components containing defects. The FAD method has been extended to the creep regime, named as the time dependent failure assessment diagram (TDFAD) [17]. The advantages of using the TDFAD method are: a) detailed calculations of crack tip parameters such as C_p are not needed, b) it is not necessary to establish the fracture regime in advance and c) the TDFAD can indicate whether failure is controlled by crack growth in the small-scale or widespread creep regime or by creep rupture.

In the TDFAD, the parameters K_r and L_r are defined as:

$$K_r = K / K_{mat}^c \quad \text{and} \quad L_r = \sigma_{ref} / \sigma_{0.2}^c \text{ b} \qquad (23)$$

where, *K* is the stress intensity factor, K_{mat}^c is the material CCI toughness corresponding to a given crack extension (e.g. 0.2mm) at a given time, and $\sigma_{0.2}^c$ is the stress corresponding to 0.2% inelastic (creep and plastic) strain from an isochronous stress–strain curve at a particular time and temperature.

K_{mat}^c is the fundamental concept for TDFAD, at a particular time and crack extension. The details of the TDFAD assessment approach and the K_{mat}^c concept are given in [17].

3.4. Experimental results: Creep crack initiation

Creep crack initiation and growth tests were carried out on compact tension, C(T), C-Shape in tension, CS(T), and round notch bar in tension, RNB(T), specimens following the procedure in [9] on P22 steel at 550 °C. The deformation, crack initiation and growth behaviors were studied aimed at eventual component assessment.

The behavior of components under creep loading conditions is described by load line displacement – time diagrams. On application of steady (constant) load to a pre-cracked component the load point displacement increases with time [18]. The microstructural damage occurs as a consequence of accumulation of creep strain. Initiation of creep crack requires attainment of critical local strain at the crack tip. The magnitude of time to initiate a creep crack, t_i, depends on the increment of crack extension, Δa_i, determined for the definition of crack initiation, x_c,[19]. Therefore, determination of Δa_i, by using either PD method or partial unloading compliance is of engineering importance as it directly affect the life of a structural component.

The time to generate critical displacement, therefore damage, to initiate a microcrack i.e. x_c=10 μm grain size, will be significantly less than a microcrack, i.e. x_c=0.2 or 0.5 mm as in engineering definition adopted in testing and assessment codes. In engineering terms, detection of a crack using non-destructive testing (NDT) is required in service components that correspond to the adopted engineering macro crack initiation size.

In component defect assessment, the data analyzed to determine crack growth rate vs. crack tip parameter K or C* that gives an initial "tail" with a decreasing growth rate prior to steady-state growth rate. The tail represents the transition depends on material properties and loading conditions. However, the data prior to crack growth initiation that reflects the stress redistribution and development of damage need to be recorded and analyzed as it may cover a large part of component life in service. Initial microcrack extension occurs at a relatively low rate with small defect size where the magnitude of crack tip parameter, i.e. C*, may be negligible. The experimental data obtained on P22 steel welds are shown in Figure 1. The data correlation with K for crack initiation defined for initiation time at $\Delta a=0.2$ is depicted.

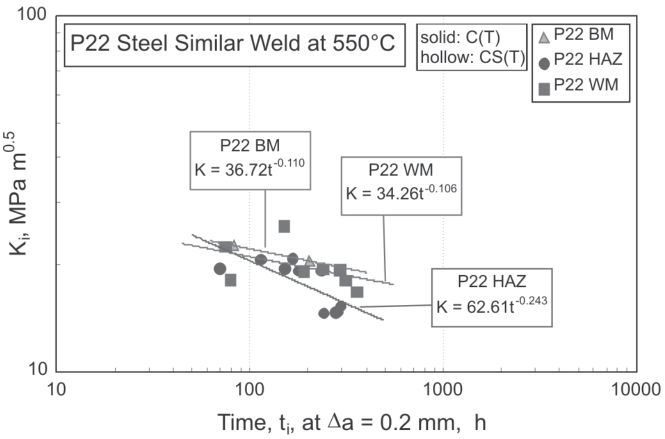

Figure 1. Variation of K at crack initiation, t_i, for $\Delta a=0.2$mm for C(T) and CS(T) specimens of P22 steel weldments at 550 °C.

The micromechanical approach taken by specialists [20] relies on C* to predict CCI time that involves the use of C* vs. time diagrams, established for a material at temperature and crack initiation criterion. A typical crack size for initiation is taken as 50 µm, based on direct experimental observation. This approach is also based on the argument that the use of C* to describe creep crack behavior is only rigorously valid for stationary cracks hence, it is employed for only to correlate CCI times. Therefore, C* vs. crack initiation time data is presented in Fig 2 for P22 in order to shed some light on the crack initiation defined in terms of micro and macro crack size. The scatter increases slightly in the C* correlation compared with K correlation directs attention to the choice of crack tip parameter for crack initiation studies.

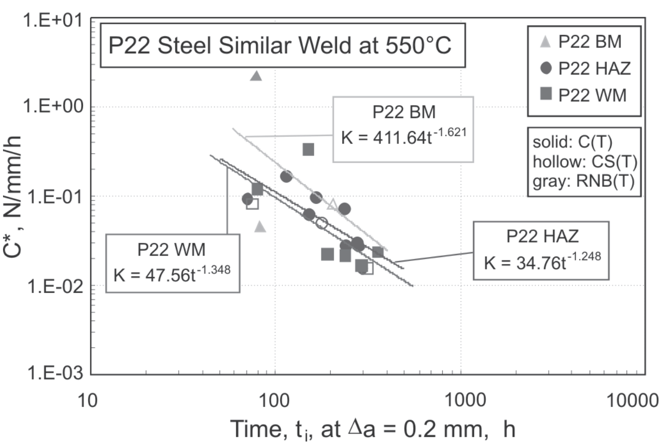

Figure 2. Variation of C* at crack initiation at time, t_i, for $\Delta a=0.2$mm for C (T), CS(T) and RNB(T) specimens of P22 steel weldments at 550°C.

The CCG rate data is correlated with C* in Figure 3. The data was reduced to include only those data with $\Delta a>0.2$mm, where the materials ductility effect on crack growth behavior is demonstrated. The figure include data from C(T) and CS(T) specimens. At higher loads, the fast crack growth involves plastic deformation in creep ductile ferritic material. Brittle crack behavior is emphasized in the initiation which was conventionally omitted and named as transition range or "tails". This is an important issue which the present work is concentrating on. These observations are substantiated with metallographic and analytic results for CCI.

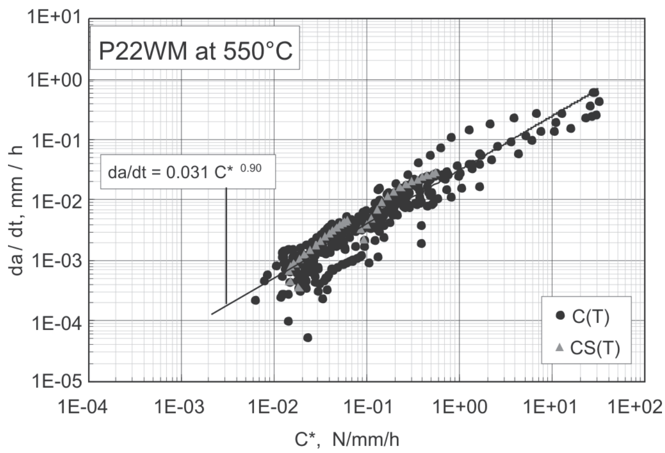

Figure 3. CCG rate as a function of C* for C(T) and CS(T) specimens of P22 steel WM at 550 °C.

3.5. Time dependent failure assessment diagram (TDFAD) approach

A central feature of the TDFAD approach is the definition of an appropriate CCI toughness, K^c_{mat}. When used in conjunction with the failure assessment diagram, it ensures that crack growth in the assessment period is less than a value Δa. Crack initiation toughness values may be estimated indirectly from conventional creep crack incubation and growth data or evaluated directly from experimental load versus displacement information [21]:

$$K^c_{mat} = \left[K^2 + \frac{n}{n+1} \frac{E\,P\,\Delta_c}{B_n (W-a)} \eta \right]^{1/2} \qquad (24)$$

where η is the geometric factor used for determining C*, K is the stress intensity factor of the specimen and Δ_c is the experimental load line displacement due to creep at the time for which the crack extension is equal to Δa.

The TDFAD method is applied to P22 similar weld data shown in Figure 4. TDFAD is constructed for various times of interest starting from t = 0 h to 100,000 h, and K_r and L_r are calculated for crack initiation times for Δa = 0.2 mm and 0.5 mm. The positions of the specimens on the TDFADs in Figure 4 reveal that the method is conservative in predicting CCI times for P22 WM. The comparison of different types of specimens which is given in Figure 4 shows that the TDFAD method yields consistent results for P22 WM, regardless of the use of different specimen geometries.

The TDFAD is used either to determine crack extension of Δa in a given time, or the time required for a limited crack extension to occur. Hence, approximate initiation times are obtained for defined crack length for crack growth initiation of 0.2 or 0.5 mm.

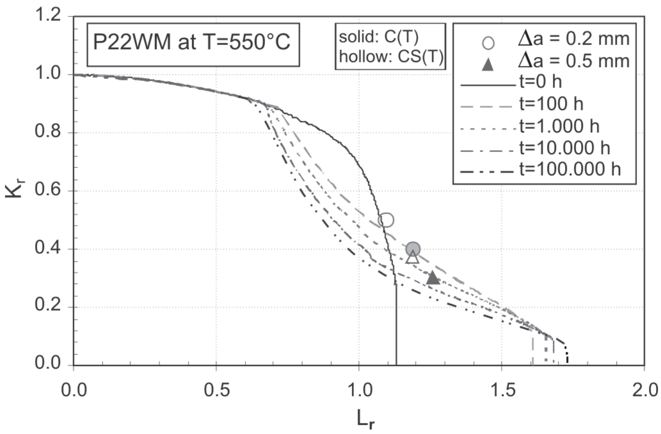

Figure 4. TDFAD Diagram for P22WM at 550 °C, Δa=0.2mm and Δa=0.5mm

The TDFAD was developed based on the experience on austenitic steels where the material behavior may differ from that of ferritic materials. The data obtained from P22 ferritic steel as seen in Figure 5. The sensitivity of TDFAD approach to cumulative effect of specimen geometry and load variation by Monte Carlo simulation is depicted [22].

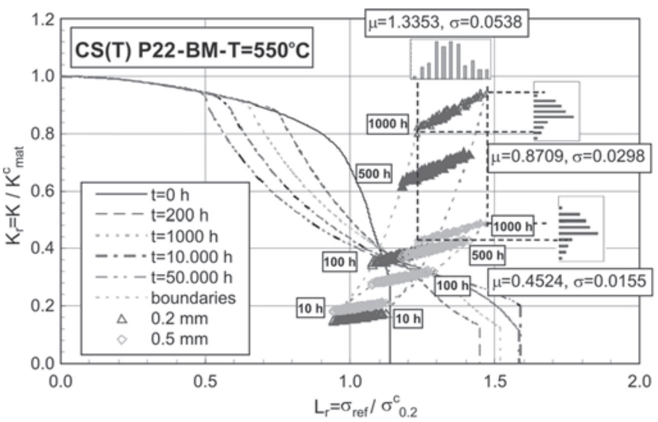

Figure 5. Cumulative effect of variation at W, B, B_n, a_o, af and F on TDFAD diagram of a P22 BM CS(T) specimen at 550 °C.

The TDFAD method is applied to P22 steel with TDFADs are determined for various times of 100 to 100,000 h. K_r and L_r values are calculated for crack initiation times defined at crack growth of Δa = 0.2 mm and 0.5 mm for experimental CCG specimens (lines for 0 - 50 000h). Furthermore, in order to predict the crack initiation time for a specimen, a locus of data points at times of 10, 100, 500 and 1000 h has been constructed on the TDFAD. Note that predicted loci depends also on plane stress and plane strain limit load solutions. The lowest L_r or K_r locus corresponds to the lowest time of 10 hrs. Locus points increase with increasing time to 100, 500 and 1000 h. Furthermore, for a certain prediction line (i.e. for t = 200 - 50 000h in Fig. 5), the K_r and L_r values do not vary with the same rate with increasing time, neither do the tendencies agree. This is intrinsic, due to the difference between rates of reduction in $\sigma^c_{0.2}$ and K^c_{mat} with time. Thus the determined loci points enable prediction of crack initiation for a specimen for 0.2 mm and 0.5 mm crack with respect to the TDFAD for times 100 to 100,000 h.

The above discussion emphasizes an important aspect of data reliability, measured in terms of sensitivity of the TDFAD parameters to variation of load, geometry and defect size in structural assessment of flawed components.

4. Discussion

An update on codes and standards for fitness-for-service assessment of high temperature components is presented. The methodology for creep-fatigue data assessment still remains to be addressed for a range of materials of industrial interest.

The present reported work addresses the need for establishing guidelines for testing and assessment of crack initiation and crack growth. The location and orientation of the crack in the specimen also need to be consistent with the defect orientation in the component being assessed. These are addressed in the recent Code of Practice (CoP) that covers both crack initiation and growth [8, 9]. This is of particular concern when testing material obtained from components containing welds in both virgin and service exposed conditions as is the experimental material P22 steel which is in service over 3 decades.

The CCG rate value at a given C* can vary as a result of inherent scatter in material response if all other variables such as geometry, specimen size, crack size, loading method and temperature are kept constant. This scatter may be increased further by variables such as microstructural differences as in weldments, loading precision, environmental control and data processing techniques. Confidence in the data will increase with the number of tests performed on any one batch of material [23]. Using reduced number of tests rather than full set of available tests to characterize the CCG behavior of a material may yield unreliable results. A valid set of data for use in subsequent structural analysis should include analysis of the data together with information from metallographic examination of the test specimens. Particular emphasis is placed on the crack size determination and elaboration of crack initiation.

The effect of creep ductility of weldment zones are studied in ferritic P22 and steel and their welds. The extent of plasticity and the level of crack tip deformation will influence the short time tests with test durations under 5000 h, depending on the tensile strength of the test material zones. Therefore, it is advisable to maximize test durations as far as possible. Otherwise, when using short-term data to assess long term component life the analysis should be treated with caution. It is commonly observed that creep rupture ductility decreases with increasing test duration. Intergranular cavitation increasingly dominates the failure mechanism at longer times. In crack initiation and growth tests, the multi-axial stress state ahead of a crack promotes low displacement failures. For material in weld zones that cavitate readily, such mechanisms may be reproduced by testing at higher stress levels. However, in materials where the low stress mechanism is replaced by matrix deformation dominated failure at higher stresses, it may be necessary to accelerate tests by increasing temperatures rather than stresses. In either case, it is essential that the mechanisms operative in the test specimen lead to deformation resembling the service conditions.

CCI and CCG data may be produced following the recent CoP for creep brittle/ductile materials including weldments. The produced data will have an acceptable experimental scatter that is suitable for used in assessment of service performance of high temperature weldments. Thus determined data is needed for lifing and fitness-for-service assessment of components in high temperature service.

5. Conclusions

An update on codes and standards for fitness-for-service assessment of high temperature components is presented. The methodology for creep-fatigue data assessment still remains to be addressed for a range of materials of industrial interest.

Significance of crack initiation for defect assessment of components in high temperature service is addressed. The industrial relevance, therefore, importance of the CCI has been recognized. Furthermore, assessment of weldments stands as a challenge for industry and academia alike due to its direct relevance to engineering structure where damage and CCI occurs predominantly in functionally graded materials of weldments.

The present paper only partly addresses this important issue which requires international collaborative effort. The reported work is considered as preliminary results of a planned systematic study of different approaches to CCI of weldments. Particularly, the data presented for TDFAD method application will be further assessed when additional data on material as well as from different specimen sizes and geometries of industrial interest will be available. A further issue is the effect of residual stresses that will be addressed in international VAMAS TWA31. However, present study directs attention to the needs and contributes to a) experimental aspects of CCI and CCG testing, b) methods for crack size monitoring, c) choice of crack tip parameter, d) definition of CCI, and e) approaches for assessment of CCI in components for service assessment using TDFAD method.

6. Acknowledgements

Kind contributions of Dr. R.A. Ainsworth of BE-UK and the members of the European Commission supported Thematic Network, FITNET, Creep Group are kindly acknowledged. Thanks are also due to members of ESIS TC11, WG on high temperature testing weldments which produced the CoP on high temperature testing of weldments.

7. Nomenclature

a	crack size
a_0	initial crack size
a_g	crack size after growth
a_{min}	crack size below which the crack growth rate is assumed to be constant
$\dot{a}$	crack growth rate
A	material constant (creep crack growth)
B'	material constant (cyclic crack growth)
C	material constant (cyclic crack growth)
$C(t)$	transient crack tip parameter
C^*	steady state crack tip parameter
$\overline{C}^*$	mean estimate of C^* during early cycles
da/dN	crack growth per cycle
$(da/dN)_c$	creep crack growth per cycle
$(da/dN)_f$	fatigue crack growth per cycle
d_c^{surf}	surface creep damage accumulated in a cycle
D_c^{surf}	total surface creep damage
E	elastic modulus
K_{Iid}	stress intensity factor (TDFAD)
K_{mat}^c	creep crack initiation toughness (TDFAD)
K_{max}	maximum stress intensity factor in cycle
K_{min}	minimum stress intensity factor in cycle
K^p	stress intensity factor due to primary load
K^s	stress intensity factor due to secondary loading
K_r	stress intensity factor ratio (TDFAD)
ℓ	material constant (cyclic crack growth)
L_r	load ratio P/P_L
L_r^{max}	cut-off on TDFAD
n	creep stress exponent
P	load
P_L	limit load
q	material constant (creep crack growth)
q_o	fraction of total load range for which crack is judged to be open
Q	material constant (cyclic crack growth)
r_p	size of the cyclic plastic zone
R	stress intensity factor ratio ($= K_{min}/K_{max}$)
R'	length in estimate of C^*
t	time
t_i	initiation time
t_{cyc}	time to reach steady cyclic state
t_o	service life to date
t_g	time required for the crack to propagate by an amount Δa_g
t_h	hold time at high temperature
t_r	rupture time
t_{red}	redistribution time
t_s	desired future service life
t_{CD}	time for continuum damage failure
w	section width
Z	elastic follow-up factor
β, γ	material constants (creep crack initiation)
δ_i	critical crack tip opening displacement (creep crack initiation)
Δa_i	crack growth corresponding to initiation
Δa_g	crack growth
$\Delta\bar{\varepsilon}_t$	total surface strain range (cyclic crack growth)
ΔK	stress intensity factor range
ΔK_{eff}	stress intensity factor range for which crack is open
$\dot{\bar{\varepsilon}}_c$	equivalent creep strain rate
ε_c	creep strain
ε_e	elastic strain
$\dot{\varepsilon}_c$	creep strain rate
$\bar{\varepsilon}_f$	creep ductility
$\bar{\sigma}$	short-term flow stress
$\sigma_{0.2}$	0.2% proof strength
$\sigma_{0.2}^c$	0.2% creep strength
$\sigma_{1.0}^c$	1.0% creep strength
σ_{ref}	reference stress
$\dot{\sigma}_{ref}$	reference stress rate

$\sigma_{ref}^{cyc=1}$ reference stress for first cycle
σ_{ref}^{p} reference stress for primary loading
σ_R creep rupture strength
σ_y yield stress
σ_u ultimate tensile stress

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