CRACK INITIATION AND DEFECT ASSESSMENT AT HIGH TEMPERATURES

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ABSTRACT

The integrity and residual life assessment of high temperature structures rely on the determined defects and their behaviour in components in service. The effort has been made to develop tools to detect flows in service-components and determine crack growth using metallography and fracture mechanical testing. However, less work is done on creep crack initiation and assessment.

The experimental determination of creep crack initiation on specimens of P91 steels and weldments and its significance in defect assessment of components are reported. An attempt is made to define creep crack initiation using both creep rupture and fracture mechanics test data. Test methods, data analysis and defect assessment approach are addressed.

1 INTRODUCTION

The progress made in defect assessment and lifing procedures contribute substantially to safety and reliability of plants [Nikbin, 1]. Development of harmonized procedures for material testing and data analysis stems from the industrial need for material development, component design for engineering applications and in-service defect assessment for lifing.

Recent reviews of high temperature defect assessment procedures [Dogan, 2] and defect assessment at low to high temperature [Dogan, Ainsworth, 3] emphasize the need for reliable data for design and in-service assessment. Design codes generally consider defect free structures, whereas assessment codes address flaws and their treatment. There is no provision made in the ASME N-47 Code [4] for the assessment of short defects. The ‘no initiation’ criterion is based on factored laboratory endurance data where this constitutes failure of a specimen typically 8 mm in diameter. The British Standard document BS 7910 [5] contains some specialized data for creep crack growth assessment.

The problem of initiation and growth of defects from an assessment point of view has been presented step-by-step in 7 volumes in R5 [6]. The A16 procedure [7] for the initiation and growth of short cracks combines the RCC-MR concept of evaluating damage at a distance, d, from the crack tip which will lead to a finite size defect [8].

2 TESTING AND ESTIMATION OF CRACK INITIATION TIME

Constant load (CL) or constant displacement rate (CDR) tests were carried out for obtaining CCI and 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 crack size and crack tip parameters C* and K determination. In addition the load/displacement measured will give the specimen’s elastic compliance for the initial crack length.

The incubation period can be estimated from the equations where data are not available for the material used in the component. The incubation time is calculated using [9]

$$t_I = 0.0025\left[\frac{\sigma_{ref} t_{R(ref)}}{\left(K_a^p\right)^2}\right]^{0.85} \tag{1}$$

3 THE CRACK INITIATION ASSESSMENT METHODS

3.1 Time Dependent Failure Assessment Diagram (TDFAD)

The advantage of using TDFAD [10] to assess components containing defects are: a) detailed calculations of crack tip parameters such as C* 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:

$$K_r = K / K^c_{mat}, \quad \text{and} \quad L_r = \sigma_{ref} / \sigma^c_{0.2} \tag{2}$$

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

3.2 Application of Two Criteria Diagram (2CD)

For the description of crack initiation using 2CD approach there are three parameters, namely; the stress intensity factor K_I, the path independent integral C* and the nominal stress in the far field/ligament, σ_n [11]. Among these parameters, K_I is chosen to be used in 2CD, which is designated as K_{Iid}, which is the fictitious elastic K that describe the crack tip stress state. K_{Iid} parameter is being used to characterize crack tip geometry since K_I solutions are available for a wide range of geometries.

The component loading parameters are normalized by time and temperature dependent data, which indicates material resistance,

$$R_\sigma = \sigma_{n0} / R_{mt}, \quad \text{and} \quad R_K = K_{Iid0} / K_{Ii} \tag{3}$$

where R_σ is the far field stress ratio and R_K is the crack tip stress intensity ratio. R_{mt} is the creep rupture strength obtained from tensile specimens. K_{Iid0} is the fictitious elastic value at time zero at the crack tip of the component. K_{Ii} is the creep crack initiation value of the material, which is a material property.

4 EXPERIMENTAL DATA

4.1 Creep Crack Initiation

In component defect assessment, the data analysed 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 that depends on material properties and loading conditions. However, the data prior to crack growth initiation that reflect the stress redistribution and development of damage need to be recorded and analysed 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 two P91 steel welds of butt weld (BW) and narrow size electron beam weld (EBW) are shown in Figure 1. The data correlation with K for crack initiation defined for initiation time at Δa=0.2 mm is depicted in Figure 1.

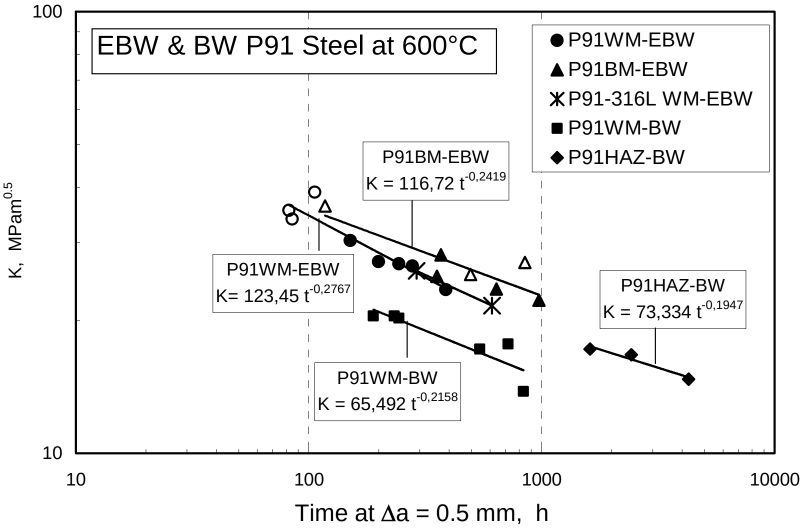

Fig.1. Variation of K at crack initiation at 600°C, at time, t_i, for Δa=0.2mm .

4.2 Time Dependent Failure Assessment Diagram (TDFAD) Approach

A central feature of the TDFAD approach is the definition of an appropriate creep crack initiation 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 [Dean, Hooten, 12].

The TDFAD method is applied to P91 similar weld data shown in Figure 2.

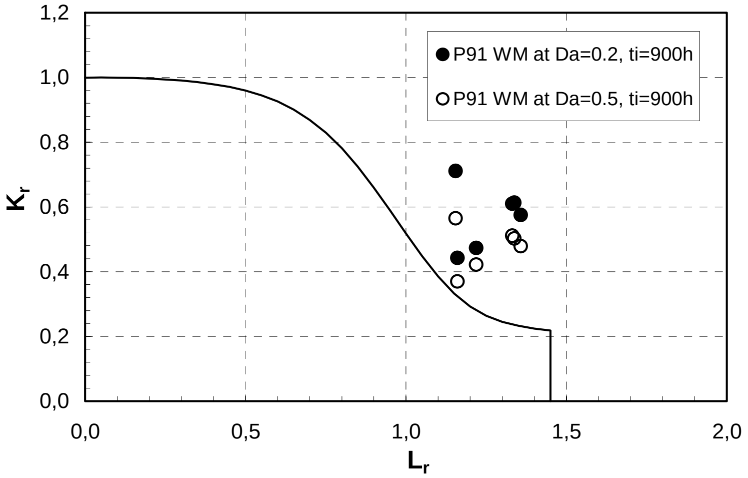

Fig.2. TDFAD Diagram for P91WM at 600°C, Δa=0.2mm (solid symbols) and Δa=0.5mm (hollow symbols) for crack initiation time of 900h.

Taken a crack initiation time of 900 hrs, TDFAD is constructed, and K_r and L_r are calculated for crack initiation times for Δa=0.2 mm and 0.5 mm. In calculating K_{mat}^{c} only the creep component of total strain energy is used. The results given in Figure 2, agree well with the P91 WM data. However, P91 HAZ data needs further assessment, the work is in progress

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.

4.3 Two Criteria Diagram (2CD) Approach

The 2CD has been developed to assess creep crack initiation in ferritic steels [Ewald, Keienburg, 13]. Crack tip and ligament damage parameters, R_K and R_σ, respectively, are used in 2CD approach, which are similar to the TDFAD parameters K_r and L_r. The critical stress intensity factor, K_{Ii}, is used as a measure of crack initiation resistance rather than the creep crack initiation toughness, K_{mat}^{c}, that is used in TDFAD approach. The experimental data from P91 similar BW zones of BM, HAZ and WM, are used for 2CD as depicted in Figure 3.

All data fall in the mixed mode damage zone as also confirmed metallographically on tested and fractured C(T) (W=25 mm, B=12.5 mm) type specimens. Note that the parameter K_{Ii} characterising the creep crack initiation of the material need to be determined from high constrained specimens with high K_{Iid}/σ_{npl}. For the specimens on which higher loads were applied higher nominal stress, σ_{no}, hence R_σ is increased leading to CCI with higher ligament damage.

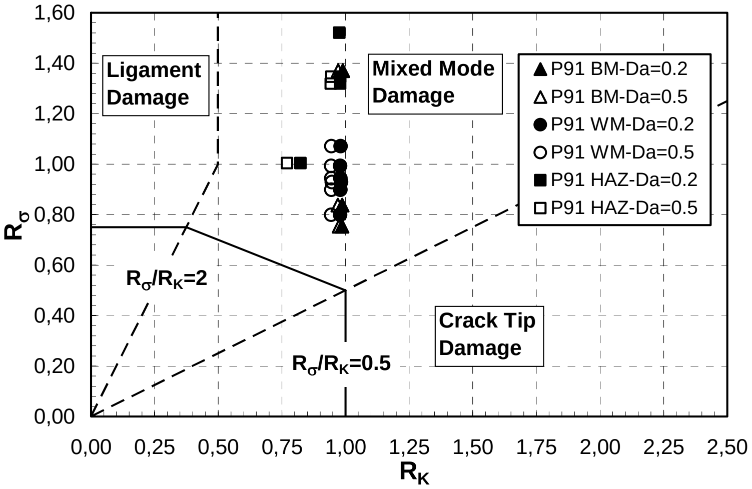

Fig.3. Two criteria diagram for P91 weld zones(BM,HAZ,WM)at 600°C for Δa=0.2mm (solid symbols) and Δa=0.5mm (hollow symbols)

5 DISCUSSION AND SUMMARY

The behaviour of components under creep loading conditions is described by load line displacement – time diagrams. 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 [Holdsworth, 14]. Therefore, determination of Δa_i, by using either PD method or partial unloading compliance is of engineering importance as it directly affects 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.

The industrial relevance, therefore, importance of the CCI has been recognised and international European effort continues addressing the issue. 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 occur predominantly in functionally graded materials of weldments.

The reported work is considered as preliminary results of a planned long term study of different approaches for CCI of weldments. However, present study directs attention to the needs and contributes to a) experimental aspects of CCI and CCG testing, b) choice of crack tip parameter, c) definition of CCI, and d) approaches for CCI in components for service assessment.

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