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Prediction of creep crack growth properties of P91 parent and welded steel using remaining failure strain criteria

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ABSTRACT

Old grades of creep resistant materials such as P11 and P22 have been studied in depth and data and prediction models are available for design and fitness for service assessment of creep rupture, creep crack growth, thermo-mechanical fatigue, etc. However, as the 9%Cr material is relatively new, there is relatively limited data available and understanding with respect to quantifying the effect of variables on life prediction of components fabricated from P91 is more difficult. Since grade P91 steel was introduced in the 1980s as enhanced ferritic steel, it has been used extensively in high temperature headers and steam piping systems in power generating plant. However, evidence from pre-mature weld failures in P91 steel suggests that design standards and guidelines may be non-conservative for P91 welded pressure vessels and piping. Incidences of cracking in P91 welds have been reported in times significantly less than 100,000 h leading to safety and reliability concerns worldwide. This paper provides a review and reanalysis of published information using properties quoted in codes of practice and from recent research data regarding the creep crack growth of P91 steel, and uses existing models to predict its behaviour. Particular areas where existing data are limited in the literature are highlighted. Creep crack growth life is predicted based on short-term uniaxial creep crack growth (CCG) data. Design and assessment challenges that remain in treating P91 weld failures are then addressed in light of the analysis.

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1. Introduction

Modified 9Cr–1Mo alloy, known as grade P91 steel, has been extensively used for high pressure and high temperature piping and headers in conventional power plants mainly in the outlet section of the boiler such as final superheater and also main steam piping which are subject to the creep damage [1]. The weld P91 material, which is also subject to damage could be the weakest link in the structure and would need to have validated laboratory data available in order to make meaningful life assessment predictions.

Although creep life of most components is characterised by a continuum damage mechanism CDM where failure is controlled by either creep rupture or creep strain failure mode, creep crack initiation (CCI) and growth (CCG) in some cases tend to dominate the total life of the component [2]. Examples of this situation include components containing fabricating flaws or thick components such as headers, high pressure/temperature piping and body of the high temperature hydroprocessing reactors.

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In both power generation plants and the chemical industries there is, therefore, a need to assess the significance of defects which may exist in high temperature equipment operating in the creep regime. With further understanding of creep crack growth behaviour and improvements in NDE methods, fracture mechanics assessment approach is increasingly being used. This method assumes the presence of a crack of finite size in a component and then evaluates its propagation due to creep to determine the remaining life of the component. This approach also is widely used for fitness for service assessment of components known to contain crack-like flaws. Several design and assessment procedures are available for CCG assessment such as British Energy R5, ASME/API RP 579, BS 7910, French RCC-MR (Appendix 16) etc. [3–6].

2. Predictive models for steady-state creep crack growth

At elevated temperature metals exhibits a stress dependent deformation rate. This high temperature deformation (creep) rate may be related to the stress by a power law;

$$\dot{\varepsilon} = A\sigma^n \tag{1}$$

This deformation is usually composed of three regions, known as primary, secondary (or steady-state) and tertiary creep stage. In practical applications, service load and temperature, the steady-state region usually dominates the life of the component subjected to creep deformation. For a cracked body operates in elevated temperature where creep is dominant, time dependant crack growth is observed. To identify the CCG behaviour in such component, several fracture mechanics parameters have been applied such as stress intensity factor, K, and creep fracture mechanics parameter C^* integral. The relationship for growth rate given for steady-state creep dominant conditions in engineering alloys has been shown to be [7]:

$$\dot{a} = A'K^m \tag{2}$$

$$\dot{a} = DC^{*\phi} \tag{3}$$

The selection of a suitable parameter to describe crack growth at elevated temperature will depend on material properties, loading condition, size, geometry and the period of time during which crack growth is observed [8].

For a power law creeping material which follows Eq. (1), the steady crack tip stress field and strain rate distributions at coordinates (r, θ) are expressed by [7]:

$$\sigma_{ij} = \sigma_o \left(\frac{C^*}{I_n \sigma_o \dot{\varepsilon}_o r}\right)^{1/(n+1)} \tilde{\sigma}_{ij}(\theta, n) \tag{4}$$

$$\dot{\varepsilon}^c_{ij} = \dot{\varepsilon}_o \left(\frac{C^*}{I_n \sigma_o \dot{\varepsilon}_o r}\right)^{n/(n+1)} \tilde{\varepsilon}_{ij}(\theta, n) \tag{5}$$

By assuming a creep process zone at a crack vicinity, the material starts to experience creep damage when it enters the process zone at $r = r_c$, at the time $t = 0$, and accumulates creep strain ε^c_{ij} by the time it reaches a distance r from the crack tip, the condition for crack growth is given using the ductility exhaustion criterion as;

$$\varepsilon^c_{ij} = \int_0^t \dot{\varepsilon}^c_{ij} dt \tag{6}$$

If is implicitly assumed that failure occurs at the crack tip when the available material creep ductility is exhausted at the value of θ at which $\tilde{\varepsilon}_{ij}(\theta, n)$ reaches its maximum value of unity ($\tilde{\varepsilon}_{ij} = 1$), integrating for a constant growth rate at constant C^* gives [7];

$$\dot{a}_{\text{NSW}} = \frac{(n+1)\dot{\varepsilon}_o}{\varepsilon^*_f} \left(\frac{C^*}{I_n \sigma_o \dot{\varepsilon}_o}\right)^{n/(n+1)} r_c^{1/(n+1)} \tag{7}$$

This model is known as NSW model and indicates that crack growth rate should be inversely proportional to the creep ductility ε^*_f appropriate to the state of stress at the crack tip. To estimate the ratio of the multiaxial to uniaxial failure strain, $\varepsilon^*_f/\varepsilon_f$, using Cocks and Ashby void growth and coalescence model suggests for most relevant engineering materials, the ratio between the extreme multiaxial, plain strain, and uniaxial, plain stress conditions is recommended to be a factor of 30 [9]. This assumption is used in the analysis work carried out in this paper.

Nikbin et al. [10] demonstrated that the power dependence of C^* varies only over the range 0.7–1.0 and that crack growth rate can be predicted for plane stress conditions approximately within a factor of about 2 by:

$$\dot{a} = \frac{3C^{*0.85}}{\varepsilon^*_f} \tag{8}$$

Eq. (8) is called NSW engineering creep crack growth law where the predicted bounds cover the extreme conditions of stress state and creep ductility.

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