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Prediction of creep crack initiation behaviour in 316H stainless steel using stress dependent creep ductility

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ABSTRACT

The creep crack initiation behaviour of Type 316H stainless steel at 550 °C has been predicted by implementing a stress dependent creep ductility and average creep strain rate model in finite element analyses. Simulations were performed on five specimen geometries: C(T), CS(T), DEN(T), M(T) and SEN(T). The predicted results have been characterised using the C^* fracture mechanics parameter and the short-term, long-term and transition creep crack initiation trends are predicted for each of the specimen geometries examined. The prediction results have been validated through comparison with experimental data available in the literature. The predicted short-term and long-term creep crack initiation trends have also been compared with NSW prediction lines. The predicted results, from each specimen geometry, are compared to each other and the differences in crack initiation trends have been discussed in terms of the specimen geometry, in-plane constraint and stress level effects on the creep crack initiation behaviour of the material. A mesh sensitivity analysis has also been performed to find the optimum mesh size for performing crack initiation simulations.

1. Introduction

It is known that Creep Crack Growth (CCG) is the main failure mechanism in many of the engineering components operating at elevated temperatures. In order to assess the structural integrity of these high temperature components, it is necessary to characterise the creep properties of the material in order to predict the creep crack initiation (CCI) and growth behaviour of the components. Type 316H stainless steel (SS) is widely used in the UK power plant components, with an operating temperature of around 550 °C. Significant research has previously been done to characterise the CCI and CCG behaviour of this material at high temperatures to provide reliable remaining life estimates for the components made of this material. Although CCG has been the main focus of most of the experimental testing programmes, the period of time required to initiate a crack from a pre-existing defect introduced in fracture mechanics specimens may take up to 80% of the test duration (Webster and Ainsworth, 1994). Therefore, in component life assessments, it is essential to predict the CCI behaviour of the material. The onset of crack growth from a pre-existing defect is often denoted incubation time and in this paper is referred to as creep crack initiation time.

A large number of experimental and numerical CCI and CCG investigations have previously been carried out on a range of fracture specimen geometries made of 316H SS to determine the long-term and short-term behaviour of the material (Nikbin et al., 1984; Oh et al., 2011a; Yatomi et al., 2003; Yatomi et al., 2008; Dean and Gladwin, 2007; Davies et al., 2007; Davies, 2009; Davies et al., 2006). In the majority of the existing analytical and numerical CCG prediction models, the uniaxial creep ductility (i.e. creep strain at failure) and uniaxial creep properties have been assumed constant and unchanged in short-term and long-term tests. Thus, accelerated high load (i.e. short-term) CCG predictions have been extrapolated to predict the long-term behaviour of the material. However, it has been noted that short-term (i.e. high load) tests can influence the plastic zone size ahead of the crack tip, due to the relatively low yield stress of the material ($\sigma_{0.2} = 170$ MPa at 550 °C), which can cause reduction in the specimen constraint level and subsequently lower CCG rates (Davies et al., 2006; European Code, 2007; Davies et al., 2009). An experimental investigation of the CCG behaviour in 316H at 550 °C in Davies et al., (2009) has confirmed that due to the change in the specimen constraint level under different loads, a different CCG trend was observed in long-term tests compared to the short-term experimental data.

A study was recently conducted to show that the uniaxial creep properties in 316H SS are different from short-term to long-term tests, resulting in a new approach to estimate creep ductility trends that are dependent on the applied stress normalised by

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Nomenclature

a	Crack length
a_0	Initial crack length
$\dot{a}$	Creep crack growth rate
$\dot{a}_0$	Initial creep crack growth rate
$\dot{a}_{NSW}$	Creep crack growth rate predicted by NSW model
Δa	Crack extension
A	Power law stress coefficient
A_A	Average power law stress coefficient
B	Specimen thickness
B_n	Specimen net thickness
B_r	Temperature dependent rupture constant
C^*	Steady state creep fracture mechanics parameter
D	Material constant coefficient in correlation of creep crack growth rate with C^*
E	Young's modulus
H	Non-dimensional function of specimen geometry and n
I_n	Non-dimensional function of n
K	Stress intensity factor
L	Specimen half-length
MSF	Multiaxial strain factor
n	Power law creep stress exponent
n_A	Average power law creep stress exponent
P	Applied load
P_{LC}	Plastic collapse load
r_c	Creep process zone
R_i	C shaped cracked specimen inner radius
R_o	C shaped cracked specimen outer radius
t	Time
$t_{0.2}$	Time for 0.2 mm crack extension
$t_{0.5}$	Time for 0.5 mm crack extension
t_i	Creep crack initiation time
t_r	Creep rupture time
v_r	Creep rupture stress exponent
W	Specimen width
$\dot{\Delta}$	Load line displacement rate
ε_f	Uniaxial creep ductility
ε_f^*	Multiaxial creep ductility
$\dot{\varepsilon}_s$	Steady state creep strain rate
$\dot{\varepsilon}_A$	Average creep strain rate
$\dot{\varepsilon}_c$	Equivalent creep strain rate
η	Non dimensional function of specimen geometry
θ	Crack tip angle
σ	Applied stress
$\sigma_{0.2}$	0.2% proof stress
σ_e	Equivalent stress
σ_m	Mean stress
σ_{ref}	Reference stress
σ_y	Yield stress of the material
ϕ	Material constant exponent in correlation of creep crack growth rate with C^*
θ_i	Creep crack initiation angle
ω	Creep damage parameter
$\dot{\omega}$	Creep damage rate
CCG	Creep Crack Growth
CCI	Creep Crack Initiation
NSW	Nikbin, Smith and Webster creep crack growth model
NSW-MOD	Modified version of Nikbin, Smith and Webster creep crack growth model
FE	Finite Element
PE	Plane strain
PS	Plane stress

the yield stress, thus accounting for the plasticity effects on the creep behaviour of the material (Mehmanparast et al., 2014). The result of this work implies that the use of short-term data to predict long-term behaviour is inappropriate, due to the observed difference in short-term and long-term creep tests. Since components are usually subjected to relatively low load levels compared with those applied in accelerated short-term tests, the new estimated trends presented in Mehmanparast et al., (2014) provide a more accurate approach for the analysis and design of high temperature components operating at low stresses. The stress dependent creep ductility trends developed in Mehmanparast et al., (2014) were implemented in finite element (FE) simulations to predict the CCG behaviour in compact tension, C(T), 316H specimens, and good agreements were found between FE predictions and experimental data (Mehmanparast et al., 2014; Davies and Mehmanparast, 2013).

It is evident in the literature that the focus of CCG experimental testing programmes has mainly been on standard C(T) specimen geometry since it provides conservative CCI and CCG trends due to the high constraint level. However, the ASTM standard (ASTM, 2007) and European CoP (European Code, 2007) recommend, within the possibilities, performing tests on different fracture specimen geometries, specimen size and dimensions, in order to increase the confidence in the material crack growth data produced. The characterisation of the CCI and CCG behaviour in other specimen geometries allows the data to be used in defect tolerance assessment of components (European Code, 2007) as well as more realistic and reasonable predictions for components that are compatible with lower constraint specimens. According to the ASTM standard (ASTM, 2007) and the European CoP (European Code, 2007), additional industrial-relevant geometries valid for CCI and CCG testing are C-shaped cracked specimen in tension, CS(T), double edge notched specimen in tension, DEN(T), middle cracked specimen in tension, M(T) and single edge notched specimen in tension, SEN(T).

Loading conditions, crack length, specimen size and geometry affect the state of stress at the crack tip, which can subsequently influence the CCI and CCG behaviour of the material (ASTM, 2007; Masaaki et al., 1991; Budden and Ainsworth, 1999; Wang et al., 2012; Wang et al., 2010; Zhang et al., 2015a; Zhang et al., 2014). It has been observed that CCG rates in steel generally increase with specimen thickness (Masaaki et al., 1991) and decrease with a reduction in the constraint level (Budden and Ainsworth, 1999), while recent studies have found that the creep behaviour is also stress regime dependent (Mehmanparast et al., 2014; Zhang et al., 2015b; Zhang et al., 2014; Zhang et al., 2015a; Mehmanparast, 2014). Furthermore, the effects of fracture mechanics specimen geometry on the crack tip constraint level and subsequently crack growth behaviour of the material have been numerically investigated in Wang et al., (2012) and experimentally observed in Budden and Dean, (2007); Bettinson et al., (2002); Ozmat et al., (1991); Takahashi et al., (2005); Davies et al., (2011). The findings show that CCG rates in the C(T) specimen are about five times higher compared to the M(T) specimen, therefore determining that for a given thickness and loading condition the C(T) specimen geometry induces a higher constraint level compared to the M(T) geometry.

In recent work by Mehmanparast (Mehmanparast, 2014), the CCG behaviour of 316H stainless steel at 550 °C was predicted for a range of specimen geometries, using a stress dependent creep ductility model, and good agreement was found between the predicted trends and the experimental data. The new stress depen-