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Prediction of creep crack growth behaviour in 316H stainless steel for a range of specimen geometries

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The specimen geometry and constraint effects on the creep crack growth behaviour of Type 316H stainless steel at 550 °C have been examined over a wide range of load levels using finite element simulations. Creep crack growth predictions are performed on a range of specimen geometries by employing stress dependent creep ductility and strain rate trends in creep damage calculations. The predicted creep crack growth rates are characterised using the C^* fracture mechanics parameter and validated through comparison with the existing experimental data. Comparisons have been made between the predicted short term and long term creep crack growth behaviour in different specimens and the results are discussed in terms of the specimen constraint effects on the crack growth behaviour of the material. Two material states including as-received and pre-compressed conditions have been considered and their predicted creep crack growth results are compared in each of the specimen geometries examined.

1. Introduction

An important issue to be considered in high temperature component life assessments is the influence of constraint level on the creep crack initiation and growth behaviour of the material. It is known that in laboratory scale tests the crack tip constraint is strongly dependent on the fracture specimen size (thus thickness) and geometry, loading conditions, crack length and the extent of plastic deformation ahead of the crack tip [1]. It has been shown in Ref. [2] that lower constraint levels lead to lower creep crack growth (CCG) rates for a given value of the steady state creep fracture mechanics parameter C^*. Therefore, it is important to quantify the crack tip constraint level in order to interpret the creep crack initiation and growth data from laboratory tests on various fracture mechanics specimen geometries. The CCG prediction models show that for a given value of C^*, the CCG rates predicted for plane strain conditions are considerably higher than those in plane stress [3–5]. This implies that in addition to the specimen size, geometry and loading conditions, the stress state may also have significant effects on the crack tip constraint level (i.e. the plane strain produces the highest out-of-plane creep constraint induced by specimen thickness, whereas the plane stress represents the lowest constraint level [6]). The creep crack tip constraint level induced by prior loading has been numerically investigated and quantified for a range of fracture mechanics specimens using different approaches by various researches e.g. Refs. [1,2,7]. For instance, the numerical analyses in Ref. [1] have shown that compact tension, C(T), and middle notched fracture specimens have the highest and the lowest creep crack tip constraint level, respectively. This explains why the existing experimental CCG data on various austenitic and ferritic steels have shown higher crack growth trends in C(T) specimens compared with the middle notched samples [8–11]. Further shown in Ref. [1] is that the constraint level decreases as the steady creep fracture mechanics parameter C^* increases in specimens under different loading conditions.

Type 316H stainless steel (SS) is widely employed in industry, particularly for the high temperature components in the UK's Advanced Gas cooled Reactors (AGRs). Creep deformation and crack growth has been identified as a principal failure mechanism in such components. In order to estimate the life time of plant components, CCG tests in laboratory scale are usually performed on high constraint C(T) specimen geometry and the results are used in plant component life assessments [12]. However, the CCG rates from C(T) specimens provide conservative crack growth trends due to the high constraint level in this type of specimen geometry, hence further tests need to be performed on a range of fracture specimen

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Nomenclature

a	crack length
a_0	initial crack length
$\dot{a}$, da/dt	creep crack growth rate
A	power law creep stress coefficient
B	specimen thickness
B_n	net thickness between the side grooves
C^*	steady state creep fracture mechanics parameter
D	constant coefficient in creep crack growth correlation with C^*
H	non-dimensional function of specimen geometry and n
K	stress intensity factor
L	specimen half length
n	power law creep stress exponent
P	applied load
P_{LC}	plastic collapse load
R_i	inner radius in C-shaped cracked specimen in tension
R_o	outer radius in C-shaped cracked specimen in tension
t_r	rupture time
W	specimen width
ε_f	uniaxial creep ductility
ε_f^*	multiaxial creep ductility
$\dot{\varepsilon}$	steady state creep strain rate
$\dot{\Delta}$	load line displacement rate
σ	applied stress
$\sigma_{0.2}$	0.2% proof stress (often taken as yield stress)
σ_e	equivalent stress
σ_m	mean stress
σ_{ref}	reference stress
ω	creep damage parameter
ϕ	the exponent in correlation of creep crack growth rate with C^*
η	geometry dependent function relating C^* to load and displacement measurements

geometries to reduce the level of conservatism in CCG life assessments. The conventional specimen geometries recommended for CCG testing in ASTM E1457 standard [13] other than C(T) specimen are the single edge notched specimen in tension, SEN(T), the double edge notched specimen in tension, DEN(T), the middle cracked specimen in tension, M(T), the single edge notched specimen in bending, SEN(B) and the C-shaped cracked specimen in tension, CS(T). In order to characterise the creep deformation and crack growth behaviour of Type 316H SS at elevated temperatures, which is typically around 550 °C in service conditions, accelerated CCG tests at relatively high loads, which result in reasonably short test durations, were performed on a range of laboratory specimen geometries with different constraint levels [12,14]. Considering the fact that the plant components are often subjected to low load levels, which are much smaller than the ones applied in accelerated CCG tests, longer term tests have been running to investigate the influence of test duration and load level on the CCG behaviour of the material. Some results from the completed long term tests on high constraint C(T) specimens and lower constraint DEN(T) specimens are available in Refs. [12,14]. As shown and explained in Ref. [14] based on the experimental CCG data available on a range of specimen geometries at 550 °C, a noticeable increase in CCG rates in long term tests at low C^* values has been observed in C(T) specimens compared to the shorter term test data on the same specimen geometry. However, due to the limited data available on other specimen geometries, subjected to relatively high loads, no particular constraint effects induced by various load levels on the CCG behaviour of different specimen geometries have been identified because of significant plasticity in accelerated high load tests.

Due to the relatively low yield stress of 316H steel at 550 °C a significant plastic zone may form at the crack tip in a fracture specimen during CCG tests, particularly in high load tests, which can cause a loss of constraint in a specimen and hence lead to lower CCG rates [15]. In order to limit the plastic zone size ahead of the crack tip in a fracture specimen made of as-received (AR) material and to characterise the CCG behaviour of the material in the absence of significant plasticity, low load (long term) CCG tests must be performed on AR specimens. Pre-compression (PC) of 316H to 8% plastic strain at room temperature has been found to harden the material and thus limiting the extent of plasticity during specimen loading [16]. Material pre-compression has been found a suitable way to obtain CCG data in reasonable time scales whilst retaining high constraint in a standard C(T) fracture mechanics geometry by limiting the plastic zone size ahead of the crack tip [16]. Pre-compression however is known to significantly affect the tensile and creep properties of 316H SS [16,17]. The CCG behaviour of the PC material, from the tests on C(T) specimens, has been found consistent with the long term CCG trend of the AR material obtained from the same specimen geometry, when the data are correlated with the C^* fracture mechanics parameter [16]. It has been also found that for a given value of C^*, the CCG rates in PC material are around an order of magnitude higher than the short term AR data and the CCG trend is similar to that of obtained from the heat affected zone (HAZ) weldment specimens tested at the same temperature [18], possibly indicating similar tensile and creep properties in 8% PC and HAZ materials.

The observed increase in the CCG rates of the AR material in long term tests on C(T) specimens at 550 °C, compared to the short term data, implies that accelerated tests may not represent low load, long term CCG behaviour of the material due to the dependency of creep properties and also plasticity on the applied load level and their subsequent effects on the CCG behaviour of the material. To account for the plasticity effects on the creep deformation behaviour of 316H, a new approach has been developed to estimate the creep ductility trends for Type 316H SS as a function of the applied stress normalised by the yield stress (taken as 0.2% proof stress) at a wide range of temperatures [19]. The estimated creep ductility trends from this study [19] were employed in finite element (FE) simulations to predict the CCG behaviour of the C(T) specimens made of AR and 8% PC materials at 550 °C in Refs. [19] and [20], respectively, and good agreements were found between FE predictions and the experimental data. In this work, the influence of specimen geometry (thus constraint effects) on the CCG behaviour of the AR and PC 316H materials at 550 °C has been examined over a wide range of load levels (thus a wide range of C^* values) by employing the stress dependent creep ductility trends in FE simulations, assuming the same uniaxial creep ductility trends [21] and average creep strain rate properties in PC and AR materials [16]. Five specimen geometries have been considered including low constraint M(T), SEN(T), DEN(T), and intermediate constraint level SEN(B) and CS(T). The predictions have been validated through comparison with the available test data for each of the specimen geometries examined. Comparisons have also been made between the predicted trends for the considered geometries and that of predicted for high constraint C(T) specimen [19].