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Effects of plastic pre-straining level on the creep deformation, crack initiation and growth behaviour of 316H stainless steel

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ABSTRACT

The effects of the material pre-straining level, in the form of plastic pre-compression at room temperature, on the tensile, creep deformation, creep crack initiation and growth behaviour of 316H stainless steel have been examined at 550 °C. Experiments have been performed on the 4%, 8% and 12% pre-compressed specimens and the results are compared with existing data on the pre-compressed material to investigate the change in mechanical response, creep failure, creep crack initiation and growth behaviour of 316H over a range of plastic pre-straining levels. Comparisons are also made to short term and long term test data on the as-received material. It has been found that creep ductility and rupture times decreased with an increase in pre-strain levels considered. The test results obtained from different material states are discussed in terms of the influence of material pre-straining level on the microstructural deformation, mechanical response, creep deformation and crack growth behaviour of the material.

1. Introduction

The influence of plastic pre-strain on the deformation and creep behaviour of 316H stainless steel has been the focus of many studies in recent years (see Refs. [1–5]). Understanding the effects of plastic pre-strain on the behaviour of structural components is essential for structural integrity assessments as some degree of plastic strain is introduced into components by most manufacturing processes including forging and welding (see e.g. Refs. [1,2]).

As discussed in Ref. [1] power plant components are often manufactured by forming (plastic pre-straining) of stainless steel tubes which are subsequently welded into the required shapes. The extent of prior plastic strains introduced into the material can significantly change the mechanical properties and consequently affect the residual stresses after welding [1]. The material pre-straining effects on subsequent mechanical and fracture behaviour of engineering alloys have previously been investigated by other researchers [3,6–11]. A study of the creep behaviour in polycrystalline copper samples pre-strained to different amounts at room temperature and high temperature in Ref. [6] has shown that the creep ductility in this material had reduced due to pre-straining; however, the creep strain rate and rupture life increased or decreased depending on the testing conditions. A similar study on Nimonic 80A pre-tensioned to different plastic strain levels of up to 15% at room temperature has shown that the creep ductility decreases by increasing the material pre-straining amount [7]. It has been shown in Ref. [8] that small pre-straining of AISI 304 stainless steel at high temperature improves the creep strength of the material. The creep tests on ex-service 316 material subjected to room temperature pre-straining up to 39% in Ref. [9] showed that by increasing the percentage of pre-strain, the rupture life, minimum creep strain rate and creep ductility reduce significantly. A review of the previous studies on various engineering alloys show that the creep ductility of the examined materials always continuously decreased by increasing the amount of plastic pre-straining at room temperature.

The material examined is this study is Type 316H stainless steel (SS) which is widely used in the advanced gas cooled reactor (AGR) plant components which often operate at temperatures of around 550 °C. It has been shown in Ref. [12] that material pre-strain on Type 316H may change the average grain size; however, no change in grain size was observed in Ref. [13] where the material was uniformly pre-compressed (PC) to 8% plastic strain at room

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Nomenclature

a	Crack length
a_0	Initial crack length
$\dot{a}$ (or da/dt)	Creep crack growth rate
Δa	Increment of crack growth
A	Creep stress coefficient in minimum creep strain law
A_A	Creep stress coefficient in average creep strain law
B	Specimen thickness
B_n	Net specimen thickness between the side grooves
B_r	Coefficient of rupture law
C^*	Steady state creep fracture mechanics parameter
D	Constant coefficient in creep crack growth correlation with C^*
E	Elastic (Young's) modulus
E'	Effective Young's modulus
K	Stress intensity factor
n	Creep stress exponent in minimum creep strain law
n_A	Creep stress exponent in average creep strain law
P	Applied load
$t_{0.2}$	Time for 0.2 mm crack extension
$t_{0.5}$	Time for 0.5 mm crack extension
t_f	Creep crack growth test duration
t_i	Initiation time
t_{red}^{eng}	Engineering redistribution time
t_r	Time to rupture in a uniaxial creep test
t_T	Transition time from small scale creep to widespread creep conditions
W	Specimen width
η	Geometry function in C^* relation
ε_f	Uniaxial creep strain at failure (creep ductility)
$\dot{\varepsilon}_s$	Steady state creep strain rate
$\dot{\varepsilon}_A$	Average creep strain rate
ν_r	Creep rupture stress exponent
ϕ	Exponent in correlation of creep crack growth rate with C^*
Δ	Load line displacement
Δ_c	Creep load line displacement
Δ_e	Elastic load line displacement
$\dot{\Delta}$	Load line displacement rate
$\dot{\Delta}^c$	Component of displacement rate directly associated with the accumulation of creep strains
$\dot{\Delta}^i$	Component of displacement rate directly associated with instantaneous (elastic and plastic) strains
$\dot{\Delta}_e^i$	Component of displacement rate directly associated with instantaneous elastic strains
$\dot{\Delta}^T$	Total load line displacement rate
σ	Stress
$\sigma_{0.2}$	0.2% proof stress
σ_{ref}	Reference stress
AR	As-received material
CCG	Creep crack growth
CCI	Creep crack initiation
LLD	Load line displacement
PC	Pre-compressed material
SS	Stainless steel
UTS	Ultimate tensile strength

temperature. Significant work has been done recently to investigate the mechanical and creep deformation and crack growth behaviour of 316H SS material pre-compressed to 8% plastic strain at room temperature [5]. It has been shown in Ref. [5] that material pre-compression to 8% plastic strain increases the yield stress (thus the hardness) of 316H SS, reduces the creep ductility and rupture time in uniaxial creep tests, and increases the creep crack growth (CCG) rates by around an order of magnitude when compared to the results obtained from the as-received (AR) material. Preliminary results on both 4% and 8% PC 316H at 550 °C suggest that the creep ductility reduces as the level of plastic strain increases [5,14,15]; however, in order to quantify this effect further tests were required at a range of plastic strain levels.

In this work additional tensile, uniaxial creep and CCG tests have been performed on specimens uniformly pre-compressed to 4%, 8% and 12% plastic strain at room temperature. The new test results from specimens with different extents of pre-strain are compared with the existing data on the PC material to investigate the change in mechanical response, creep failure, creep crack initiation (CCI) and growth behaviour of 316H over this range of plastic pre-straining levels.

2. Material pre-straining and specimen design

The material utilised in this study is ex-service Type 316H stainless steel extracted from a steam header provided by EDF Energy. Blocks of material were uniformly pre-compressed to 4%, 8% and 12% plastic true strain at room temperature and a number of uniaxial round bar specimens or a single compact tension, C(T), sample were extracted from each pre-strained block. The round bar samples used for tensile and uniaxial creep rupture tests had the same dimensions of 8 mm diameter and 36 mm gauge length. All C(T) specimens had the same width of $W = 50$ mm and the total thickness of $B = 25$ mm. The starter crack in C(T) specimens was introduced by an EDM (Electrical Discharge Machining) pre-crack of notch root radius 0.125 mm. All specimens were extracted from the same header, denoted Header A. Previous tests, to which these results will be compared, have however been extracted from three different headers of similar composition.

3. Creep deformation, crack initiation and growth relations

3.1. Uniaxial creep deformation and rupture

For power law, creeping materials under steady state conditions, the minimum creep strain rate, $\dot{\varepsilon}_s$, may be correlated with the equivalent stress, σ, by the Norton creep law [16] using the relation

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

where n and A are the power law creep stress exponent and coefficient, respectively. Similarly, at a given temperature the rupture time may be described by the power law relationship

$$t_r = B_r\sigma^{-\nu_r} \tag{2}$$

where B_r and ν_r are the rupture life power law stress coefficient and exponent, respectively. In order to account for the deformation in different creep regions, the average creep strain rate, $\dot{\varepsilon}_A$, is often employed which is defined as

$$\dot{\varepsilon}_A = \varepsilon_f \Big/ t_r \tag{3}$$