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Plastic pre-compression and creep damage effects on the fracture toughness behaviour of Type 316H stainless steel

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ABSTRACT

The influence of inelastic damage in the form of plastic pre-strain and creep damage, on fracture toughness of Type 316H stainless steel has been examined. Creep damage has been introduced into the 8% pre-compressed material by interrupting creep crack growth tests. Comparisons have been made between the fracture toughness test results from the as-received, pre-compressed and creep damaged materials. Furthermore, the effects of creep crack discontinuities on the crack tip strain fields have been examined by digital image correlation measurements. Inelastic damage was found to reduce the fracture toughness of the material, with creep damage having more severe effects than pre-strain.

1. Introduction

Inelastic damage, in the form of both plastic strain and/or creep damage, is often present in components operating at elevated temperatures and may lead to changes in a material's mechanical response. Plastic strain can be introduced into a component in a number of ways during the fabrication process and creep strains/damage will accumulate with time at stress and temperature during component operation. Type 316H stainless steel (SS) is widely used in the UK's advanced gas cooled reactor's (AGR) high temperature components and therefore plays a key-role in securing the UK's short term energy supplies. Creep deformation and crack growth is the principal failure mechanism for these components, thus in order to increase plant life operating temperatures may be reduced to limit subsequent creep processes. However, in order to ensure structural integrity, the crack growth resistance of existing creep crack in components due to ductile damage process, i.e. the fracture toughness of the material, needs to be examined. Testing has therefore been performed to quantify the influence of inelastic damage on the fracture toughness behaviour of 316H stainless steel.

The influence of plastic pre-straining (introduced by cold rolling, pre-tension, pre-compression, etc) on fracture toughness of engineering materials has previously been examined. For example, it has been shown in [1] that the fracture toughness of an austenitic stainless steel continuously decreases as the level of plastic pre-straining increases from 0% to 15%. A similar reduction in the fracture toughness of the pre-strained 316 material is also reported in [2]. Other studies of the influence of pre-straining on the fracture behaviour of a range of engineering materials can be found in e.g. [3–8]. The results obtained

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Nomenclature

a	crack length
a_0	initial crack length
a_f	final crack length
Δa	increment of crack growth
Δa_{max}	maximum allowable crack extension in fracture toughness tests
B	Specimen thickness
B_e	effective thickness
B_n	specimen net thickness between the side grooves
C	unloading compliance
E	Young's Modulus
E_M	effective Young's modulus in fracture toughness data analysis
$J_{0,k}$	fracture resistance at the *k*th interval
$J_{0.2}$	fracture resistance at the total crack extension of 0.2 mm
$J_{0.2/BL}$	fracture resistance at 0.2 mm of stable crack extension
J_{max}	maximum allowable J in fracture toughness tests
J_{IC}	critical value of J for fracture under Mode I loading conditions
K	stress intensity factor
P	applied load
P_{LC}	Plastic collapse load
U_k	Area under the force *vs.* displacement curve up to the line of constant displacement at the *k*th interval
W	specimen width
η	factor relating J to load and displacement measurements
σ	applied stress
$\sigma_{0.2}$	0.2% proof stress
σ_{ref}	reference stress
σ_{UTS}	ultimate tensile strength
Ω	specimen size independency parameter in fracture toughness data analysis

from these studies have shown that the fracture toughness generally decreases as the tensile or compressive percentage of plastic pre-staining increases in the material.

The influence of prior uniform creep damage on the subsequent tensile and fracture properties of 316 stainless steel has been investigated in [9] where creeping the material at 750 °C and 103 MPa caused a moderate increase in the yield stress, severe reduction in tensile ductility and a rapid drop in the (Charpy) fracture energy. Experiments have also been performed in [10] on 316H at 550 °C and 300 MPa, where round bar creep tests were interrupted at different regions of the creep curve (i.e. primary, secondary or tertiary creep regions) and subsequently tensile tests were performed at a range of strain rates. The tensile ductility was found to be strongly dependent on both the quantity of creep strain introduced into the material and the strain rate in the tensile test. A similar study on 316H specimens which were pre-compressed to 8% plastic strain at room temperature and subsequently crept at 550 °C and 300 MPa [11] has also confirmed that increasing the quantity of creep strain in the material increases its yield stress and decreases its tensile ductility. In addition an assessment of the effect of prior creep cavitation damage, arising from the stress relief heat treatment, on the measured brittle fracture toughness of a CrMoV steel weldment has shown that as the fraction of creep damage increases, a continuous reduction is observed in the fracture toughness of the material [12,13]. However, when the level of cavitation is relatively low, the fracture toughness of the creep damaged material has been found within the scatter band of the undamaged material. Literature therefore suggests that both plastic pre-straining and creep damage reduce the ductile/brittle fracture toughness of steels.

In this work, the influences of plastic pre-compression and creep damage on the subsequent fracture toughness behaviour of Type 316H stainless steel have been examined. Two methods have been considered to introduce creep damage into fracture mechanics samples. A large uniaxial geometry may be uniformly crept until a critical life/strain fraction is achieved and subsequently a fracture sample is extracted from this geometry. Alternatively, a creep crack growth (CCG) test on a fracture geometry may be performed and interrupted after a given amount of creep crack extension and hence creep strain/damage accumulation. The latter approach, denoted the local creep damage (LCD) method, provides a creep process zone local to the crack tip and has been employed in this work.

2. Material and specimen test details

For the present study, Type 316H stainless steel was provided by EDF Energy and taken from an ex-service steam header. All tests have been performed on the standard compact tension, C(T), geometry. The tensile and creep properties of this header material have been previously characterised as detailed in [14].