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Investigation of residual stress effects on creep crack initiation and growth using local out-of-plane compression

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ABSTRACT

The effects of residual stress on creep crack initiation and growth behavior were investigated. It has been shown that higher compressive residual stress ahead of crack tips delays creep crack initiation and increases creep initiation life. The mechanism of residual stress effect on the creep crack initiation behavior was analyzed by distributions of equivalent stress and stress triaxiality ahead of crack tips. The residual stress essentially has no effect on creep crack growth rate. In creep life assessments of high temperature components, the effect of residual stress on creep crack initiation should be mainly considered.

1. Introduction

Residual stress can be invariably introduced into components during fabrication and service by thermal gradients and non-uniform plastic deformation. It can be superimposed on any primary loads, and may contribute early failure from crack or notch defects. The creep crack initiation and growth can occur in components operating at high temperature due to residual stress relief [1]. Post weld heat treatment (PWHT) can reduce the magnitude of residual stresses, but not completely remove them. Furthermore, PWHT is expensive and may lead to excessive distortion or material property degradation [2]. Therefore, it is important to have a detailed understanding on the effect of residual stress on creep damage, crack initiation and growth in materials and structures.

Under high temperature creep conditions, the creep damage, crack initiation and growth ahead of defects in specimens or structures with various geometries and loading modes are mainly controlled by the amplitudes of crack-tip stress fields [3–6]. The residual tensile or compressive stress can change the amplitudes of crack-tip stress fields. If the accumulated creep strains under the action of the crack-tip stress field are sufficient to exhaust the creep ductility of a material, the creep crack will initiate and propagate. Thus the effect of residual stress can be estimated by the additional creep strain accumulated during the creep process, and the ductility exhaustion model is usually used to predict the creep crack initiation [7–9].

An accurate structural integrity assessment and design of actual components with residual stress is very difficult due to complex geometry, residual stress state, microstructure and local multiaxial creep ductility. So it is usually investigated using laboratory specimens containing residual stress fields [9]. The residual stress fields are usually introduced in a controlled manner into specimens using pre-compression method, and then the influence of the residual stress field on subsequent creep damage and fracture can be investigated. Turski et al. [9], Zhao et al. [10] and Chen et al. [11] employed in-plane

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Nomenclature

a	crack length
A_1, A_2	constants in 2RN creep model
B	specimen thickness
C^*	C^* integral analogous to the J integral
c_1, c_2	constants in stress dependent creep ductility formula
da/dt	creep crack growth rate
E	Young's modulus
K	strain-hardening coefficient
m	constant in stress dependent creep ductility formula
n	strain-hardening exponent
n_1, n_2	stress exponents in 2RN creep model
R	punching tool radius
t_i	creep crack initiation time
W	specimen width
$\dot{\varepsilon}_c$	creep strain rate
ε_f^*	multiaxial creep ductility
ε_f	uniaxial creep ductility
ε_{f1}	lower shelf creep ductility
ε_{f2}	upper shelf creep ductility
δx	distance between the punching tool center and the crack tip
δy	distance between the punching tool center and the crack plane
Δa	average creep crack growth length
σ_y	yielding stress
σ_e	equivalent stress
σ_m	mean normal stress
ω	damage parameter
$\dot{\omega}$	damage rate

Abbreviations

2RN	two-regime Norton creep model
3-D	three-dimensional
CCG	creep crack growth
CCI	creep crack initiation
C3D8R	eight-node linear 3-D element
CREEP	a user subroutine in ABAQUS for creep analysis
C(T)	compact tension
FE	finite element
LOPC	local out-of-plane compression
LS	lower shelf
PWHT	post weld heat treatment
US	upper shelf
USDFLD	a user subroutine in ABAQUS

pre-compression method to introduce the residual stress fields into notched C(T) specimens, and then investigated the effects of residual stress on creep damage and crack initiation. Their results showed that the residual tensile stress promotes creep damage and crack initiation ahead of notch tips. However, the in-plane pre-compression method used to introduce local residual stress in Refs. [9–11] is only suitable for notched specimens, and only the local tensile residual stress at a notch tip can be introduced and changed by changing notch radiuses and pre-compression displacements. But in actual cracked structures, local tensile or compressive residual stress may exist at the tips of crack defects. The in-plane pre-compression method to introduce tensile residual stress fields into notched C(T) specimens [9–11] cannot be used to investigate the effects of tensile and compressive residual stresses on creep crack initiation (CCI) behavior at the crack tips.

For investigating and understanding the effects of local tensile or compressive residual stress ahead of a crack tip on creep crack initiation and growth behavior, the local tensile or compressive residual stress fields need to be introduced in a controlled manner into cracked specimens. This can be realized by using the local out-of-plane compression (LOPC) method [12]. Different magnitudes and distributions of tensile or compressive residual stress ahead of crack tips can be introduced by moving the position of local compression on the sides of the specimen. Hossain et al. [13] used the LOPC method to create different distributions of residual stress near the crack tip in C(T) specimen. The residual stress fields were obtained by the finite element (FE) simulation of LOPC, and the Neutron diffraction measurement of residual stress confirmed the finite