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Creep failure simulations of 316H at 550 °C: Part I – A method and validation

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ABSTRACT

This paper proposes a method to simulate creep failure using finite element damage analysis. The creep damage model is based on the creep ductility exhaustion concept, and incremental damage is defined by the ratio of incremental creep strain and multi-axial creep ductility. A simple linear damage summation rule is applied and, when accumulated damage becomes unity, element stresses are reduced to zero to simulate progressive crack growth. For validation, simulated results are compared with experimental data for a compact tension specimen of 316H at 550 °C. Effects of the mesh size and scatter in uniaxial ductility are also investigated.

1. Introduction

Predicting creep crack initiation and growth is important for crack-like defect assessment of plant components operating at elevated temperatures. Due to its significance, a number of works on modelling creep fracture have been already reported in literature. Based on the model to describe the creep damage accumulation, existing works may be broadly divided into two groups. One group is stress-based models which have been used extensively [1–6]. Employed stress-based damage model is similar to the Kachanov-type one [7] to estimate the creep damage evolution and subsequent creep rupture. When combined with a special technique to simulate the loss of load-carrying capacity when the damage level becomes critical, this method can be also used to simulate creep crack growth [8]. The second group is strain (or ductility) based models. Webster and co-workers [9,10] introduced models for creep crack initiation and growth using analytical stress and strain fields at a crack tip. Assuming that crack initiation and subsequent growth are due to accumulated damage of creep strain in a process zone, models for predicting the time to creep crack initiation and the rate of creep crack growth were presented in terms of uni-axial creep ductility and the C^*-integral. More recently, Yatomi and co-workers [11–14] presented a finite element (FE) method of creep crack growth simulations using the ductility exhaustion concept and node release technique. They used two-dimensional (2-D) FE damage analysis using power law creep models with the average creep rate to simulate compact tension (C(T)) creep crack growth testing. Simulated creep crack growth rates in terms of C^* were compared with experimental data.

Recently the authors proposed a method to simulate ductile failure using FE analysis [15,16]. The method is based on the ductility exhaustion concept with a phenomenological stress-modified fracture strain model where the fracture strain for ductile fracture depends exponentially on the stress state [17–25]. The stress-modified fracture strain model was determined by combining FE analysis and notched bar tensile test results. The incremental damage was defined by the ratio of

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Nomenclature

a	crack length
A_i, n_i, m_i	coefficients in the creep constitute model, Eq. (1), (i = 1–3)
B, B_N	specimen thickness and net-thickness
C^*	C^*-integral
E	Young's modulus
h	stress triaxiality, see Eq. (2)
P	applied load
R	notch radius in notched bars
r	minimum radius in smooth and notched bars
n	creep exponent for power law creep
t	time
W	specimen width
ε_c, $\Delta\varepsilon_c$	equivalent creep strain and its increment
ε_f, ε_f^*	multi-axial and uni-axial fracture strain, respectively
σ	stress, general
$\bar{\sigma}$, σ_m	effective stress and mean normal stress, respectively, see Eq. (2)
σ_1, σ_2, σ_3	principal stress components
ω, $\Delta\omega$	accumulated damage and incremental damage
C(T)	compact tension
FE	finite element

plastic strain increment and the fracture strain. When the accumulated damage becomes unity (at a FE gauss point), all stress components (at the gauss point) were reduced to a small value to simulate progressive failure. Comparisons of simulated results using the proposed method with extensive fracture test data showed overall good agreements [15,16]. This phenomenological model based on the ductility exhaustion concept is fundamental and is believed to be easily extended to creep fracture simulation, which is a topic of this paper. To validate the proposed method, simulated results are compared with creep crack growth test results of a 316H C(T) specimen at 550 °C.

Section 2 briefly summarizes experimental results of 316H at 550 °C. Section 3 introduces the proposed damage model, together with the determination of creep law and creep fracture strain. Section 4 compares simulated results with experimental data, and effects of the mesh size and scatter in creep ductility are also investigated. The present work is concluded in Section 5.

2. Summary of experimental data

2.1. Tensile and creep test data

The material considered in this work is 316H stainless steel. Specimens for tensile and creep tests are extracted from ex-service superheater headers (see Table 1 for chemical compositions). Tensile test was performed at 550 °C using standard round bars (see Fig. 1a). Resulting true stress–strain data from tensile test are shown in Fig. 2. Yield (0.2% proof) and tensile strengths, determined from round bar tensile tests, were about 170 MPa and 588 MPa, respectively, as summarised in Table 1. Creep tests of smooth bars were also performed at 550 °C. The diameter of smooth bars was 6.68 mm with gauge length of 36 mm. Various constant loads were applied, ranging from 290 MPa to 366 MPa. Resulting creep strains are shown in Fig. 3 as a function of time. These tensile and creep test data using smooth bars, shown in Figs. 2 and 3, will be used as input to elastic–plastic–creep FE damage analysis. Creep ductility data from smooth bars will be also used to determine multi-axial creep ductility for damage analysis.

Creep tests using notched bars with three kinds of notch radii were also performed at 550 °C. Geometry of notched bars is schematically shown in Fig. 1b. The minimum diameter of notched bars was 5.64 mm with gauge lengths of 36 mm. Creep

Table 1
Compositions of chemical component and tensile data of material.

Material	Cr	Ni	Mo	Mn	Si	Cu	C	Co	V	W	P	S	Ti
wt. %	17.1	11.1	2.4	1.5	0.3	0.09	0.05	0.05	0.042	0.03	0.02	0.01	0.01

Young's modulus E (GPa)	Poisson's ratio	Yield strength (MPa)	Tensile strength (MPa)
140	0.3	170	588