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Modeling and experimental study of long term creep damage in austenitic stainless steels

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Abstract

Different batches of austenitic stainless steels (316LN) are subjected to numerous creep tests carried out at various stresses and temperatures between 525°C to 750°C up to nearly 50•10^{3}h. Interrupted creep tests show an acceleration of the creep deformation only during the last 15% of creep lifetime which corresponds to macroscopic necking. The modeling of necking using the Norton flow law allows lifetime predictions in fair agreement with experimental data up to a few thousand hours only. In fact, the experimental results show that, the extrapolation of the 'stress – lifetime' curves obtained at high stress leads to large overestimations of lifetimes at low stress. After FEG–SEM observations, these overestimates are mainly due to additional intergranular cavitation along grain boundaries as often observed in many metallic materials. The modeling of cavity growth by vacancy diffusion along grain boundaries coupled with continuous nucleation proposed by Riedel is carried out. For each specimen, ten FEG–SEM images (about 250 observed grains) are analyzed to determine the rate of cavity nucleation assumed to be constant during each creep test in agreement with many literature results. This constant rate is the only measured parameter which is used as input of the Riedel model. Lifetimes for long term creep are rather fairly well predicted by either the necking model or the Riedel model with respect to experimental lifetimes up to 200000 hours for temperatures between 525°C and 700°C. A transition time as well as a transition stress is defined by the intersection of the lifetime curves based on the necking and Riedel modellings. This is due to a change in damage mechanism. The scatter in lifetimes predicted by the Riedel model induced by the uncertainly of some parameter values is around 50%. This model is also validated for martensitic steels (Lim et al, 2011.) and for other austenitic SSs 304H, 316H, 321H (creep rupture data provided by Dr. F. Abe, NIMS). A transition from

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power-law to viscous creep behavior is reported in the literature at 650°C–750°C. It allows us to predict even better lifetimes up to 200000 hours at very high temperature.

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Keywords: Austenitic stainless steels (SSs); long term creep; necking; intergranular damage; cavity nucleation; cavity growth; grain boundary diffusion.

1. Introduction

The present study of austenitic stainless steels (SSs) is mainly focused on the family of low-carbon and nitrogen-strengthened steels called 316L(N). Multi-batch creep data are provided by CEA, EDF, Creusot-Loire (1987), by the National Institute for Materials Science, Japan, NIMS (1997 & 2013) and by the study of Brinkman (2001). The creep lifetimes of some IVth generation reactors components in austenitic stainless steels require on the one hand to carry out very long term creep tests (>20years) and on the other hand to understand and to model the damage mechanisms in order to propose physically-based extrapolations towards 60 years of service. Two fracture mechanisms are in fact involved during creep rupture tests, depending on stress, temperature and lifetime: either necking or intergranular cavity nucleation and growth (Auzoux (2004)).

The lifetime model was developed by Hart (1967) to account for creep damage by necking, which was first studied by Considère (1885) and more recently by Dumoulin et al. (2003). For viscoplastic materials, this model obeys the Norton power-law equation. The reduction in cross-section at fracture is studied in order to define the failure criterion. It predicts the creep curves and the creep to failure time of steels at various temperatures at least for most stress levels. Extensive necking leads to large overestimations of long term creep lifetimes. Therefore, the necking model is used only for predict short to medium term creep fracture. The next step is to include intergranular damage in the fracture modeling (Morris et al. (1978) or Yoshida (1985)). Fracture of long-term creep specimens is governed by diffusional growth and coalescence of intergranular cavities. Creep cavities along coarse intergranular carbides or other inter-metallic phases, and "triple point cracks" at grain boundary intersections are observed by SEM-FEG. Hence, these observations allow us to validate the hypothesis of dominant intergranular damage.

Experimental 'creep failure stress - lifetime' curves are plotted for tests carried out at temperatures between 500°C and 750°C. The extrapolation of the data obtained at high stress leads to overestimated lifetimes at low stress which differ by a factor of five with respect to experimental data. A model based on the continuous nucleation and growth of cavities by vacancy diffusion has been adapted from the work of Riedel (1987). According to numerous measurements carried out after interrupted tests, Dyson (1983) suggested that the cavities nucleate at a constant rate during each creep, $\dot{N}_0$ which is proportional to the minimum creep strain rate, $\dot{\varepsilon}_{min}$, with a pre-factor denoted as α'. Experimental results from a database of nineteen creep tests carried out up to failure on 316L(N) SSs at CEA/SRMA and EDF are examined so as to determine experimentally at various stresses and temperatures this parameter, α', which is used in the Riedel model.

These two fracture models are used in order to compare the predicted creep lifetimes with the experimental creep results at temperatures between 525 and 700°C. Thus, validation of this new prediction technique requires evidence if its applicability to a wide range of stainless steels.

Nomenclature

t_R	time to rupture
t_{min}	time at which the minimum creep strain rate $\dot{\varepsilon}_{min}$ is reached
ε_{min}	strain at which the minimum creep strain rate $\dot{\varepsilon}_{min}$ is reached
δD_r	initial variation in diameter divided by the average diameter of the specimen
N	exponent of the Norton power-law
$\dot{N}_0$	cavity nucleation rate (nucleation of cavities par unit grain boundary area and per unit time)
α'	factor of proportionality