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

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ABSTRACT

One of the main challenges for some reactors components in austenitic stainless steels at high temperature in-service conditions is the demonstration of their behavior up to 60 years. The creep lifetimes of these stainless steels require on the one hand to carry out very long term creep tests and on the other hand to understand and to model the damage mechanisms in order to propose physically-based predictions toward 60 years of service. Different batches of austenitic stainless steels like-type 316L with low carbon and closely specified nitrogen content, 316L(N), are subjected to numerous creep tests carried out at various stresses and temperatures between 525 °C and 700 °C up to nearly $50 \cdot 10^3$ 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 viscoplastic power-law allows lifetime predictions in fair agreement with experimental data up to a transition time of about ten thousand hours which is temperature dependent. In fact, one experimental result together with literature ones, shows that the extrapolation of the 'stress–lifetime' curves obtained at high stress data leads to large overestimations of lifetimes at low stress. After FEG–SEM observations, these overestimates are mainly due to additional intergranular cavitation as often observed in many metallic materials in the long term creep regime. 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 measured constant rate is the only measured parameter which is used as input of the Riedel damage model. Lifetimes for long term creep are rather fairly well evaluated by the lowest lifetime predicted by the necking model and the Riedel model predictions. This holds for experimental lifetimes up to 200,000 h and 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 predicted by the necking and Riedel modelings. This corresponds to the change in damage mechanism. The scatter in lifetimes predicted by the Riedel model induced by the uncertainty of some parameter values is less than a factor of three, similar to experimental scatter. This model is also validated for various other austenitic stainless steels such as 304H, 316H, 321H (creep rupture data provided by NIMS). A transition from power-law to viscous creep deformation regime is reported in the literature at 650 °C–700 °C

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for steel 316H. Taking into account the low stress creep rate law, it allows us to predict lifetimes up to 200,000 h at very high temperature in fair agreement with experimental data.

1. Introduction

The Larson–Miller relationship ([1–3]) is a parametric equation used to extrapolate creep experimental data and creep rupture lifetimes of engineering materials. Fig. 1 shows experimental creep failure data for various materials using this relationship. The specific material constant is approximately equal to twenty for most materials. As can be observed, a transition in the lifetime regime appears for each material. It may be due to a change in fracture mechanisms. Likewise for some IVth generation reactor components in austenitic stainless steels, experimental 'creep failure stress–lifetime' curves of the steel 316L(N) are plotted for tests carried out at temperatures between 525 °C and 700 °C (Fig. 2). The extrapolation of these curves based on high stress data leads to overestimated lifetimes. For example, the extrapolation of curve at 700 °C differs by a factor of ten at low stress with respect to available experimental data. Therefore, long-term creep lifetimes cannot be predicted by the extrapolations based on short-term data.

Viscoplastic instability called 'necking' was shown to be the main mechanism of rupture of austenitic stainless steels at high temperature (Morris et al. [4], Yoshida [5] and Auzoux [6]). Hart [7] developed a necking modeling in the viscoplastic framework. Necking was first studied by Considère [8] in the plasticity framework and more recently by Dumoulin et al. [9]. For viscoplastic materials, this material obeys the Norton power-law equation. Necking model predicts the creep curves and the creep to failure time of steels at various temperatures and stresses. The lifetime predictions using the necking model leads to large overestimations of long term creep lifetimes [10]. Therefore, the necking model is used only for predicting short to medium term creep fracture.

For austenitic stainless steels, creep tests leading to intergranular failure at high temperatures were studied by Morris et al. [4], Needham et al. [11], Gandhi et al. [12] and Riedel [13]. Meanwhile, the intergranular cavities creep along grain boundaries were observed by SEM for the long term creep lifetimes. The main cause of intergranular cavitation is that vacancies become mobile at elevated temperature. At typical service temperatures of creep-resistant alloys, diffusion along grain boundaries predominates. Vacancy diffusion along grain boundaries can aggregate to form cavity nuclei. And additional vacancies are applied leading to cavity growth. After that, the study of cavity growth in metallic solids subjected to creep at high temperature has been carried out by Raj and Ashby [14]. The applicability domain of the diffusion cavity growth models can be assessed using a length parameter, L_R, usually called 'Rice length' which is the ratio between viscoplastic cavity radius rate and diffusion cavity radius rate. For creep tests under study, considering only diffusion cavity growth is sufficient; if the criterion suggested by Needleman and Rice [15] is satisfied. That means if the ratio between the measured cavity radius and the Rice length is lower than 0.2; then cavity growth is controlled by diffusion alone and growth by viscoplasticity can be neglected. In reality, cavities do not nucleate at the same time but continuously one after another. A phenomenological kinetics law of nucleation of intergranular cavities has been proposed by Dyson [16], who 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'. This is the only measured no fitted parameter used in the Riedel model.

We intend to determine experimentally the different mechanisms leading to the creep failure of austenitic stainless steels for large ranges of stress and temperature. According to the literature results, we consider two fracture models which are 'necking model for short term creep' and 'Riedel model for long term creep'. These two models are compared with the experimental creep results. The present study of austenitic stainless steels (SSs) is mainly focused on the family of low-carbon and nitrogen-strengthened steels.

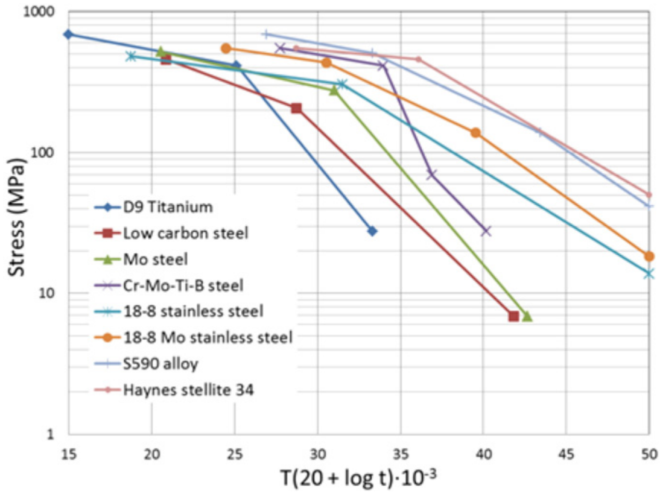

Fig. 1. Curves plotted for very different materials using the Larson–Miller relation [1,2] $\log(\sigma) = Function[T(C + \log(t))]$. Larson–Miller proposed that the constant C may have a universal value of 20 [3].