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Creep and Creep-fatigue Behaviour of 316 Stainless Steel

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Abstract

The austenitic stainless steel 316 is of current interest as structural material for the future Gen IV nuclear power plants operating at high temperatures. Although 316 steel grades have been studied for the service conditions of current nuclear and other conventional applications, improved data and models for the long term high temperature properties are needed, especially regarding the primary to tertiary creep strain and creep-fatigue response. The Gen IV technology will need an update for predicting safe life to given strain and rupture in the temperature range of 500-750°C, and to facilitate FEA for complex product forms. Modelling the stress dependence of creep strain and strain rate is particularly challenging due to the need for long term extrapolation and limited (public domain) data. Large variation in mechanical propertiessuch as high temperature yield strength between casts and product forms also need to be addressed for design and life prediction. In the present work, new creep models have been established for predicting creep strain and rupture of 316L and316L(N), using the Wilshire equations and logistic creep strain modelling for improved accuracy. The models have been extended to creep-fatigue and applied to characterize the steels 316FR and 316L in terms of the linear life fraction rule.

Keywords: Creep-fatigue; 316 stainless steel; creep; relaxation; modelling

1. Introduction

Creep is an important limiting damage mechanism for high temperature service, and must be accounted for in design. Creep strength of steels is typically measured from isothermal constant load tests under tension, to provide data such as creep curves (strain vs. time), time to failure and strain to failure. Standards do not however cover new material variants and do not include behaviour at smaller or variable strains encountered in real service. In contrast, the growth rate of fatigue damage is independent of time and the loading frequency. With increasing time spent in the cycle, the damage growth rate will increase with decreasing frequency due to creep. The combined creep-fatigue (C-F) damage is often described by the linear life fraction (Robinson-Miner) rule.

In this work 316 stainless steels (17% Cr–11% Ni–2% Mo) are assessed for creep and creep-fatigue modelling. The grades of interest are 316H, 316L, 316L(N) and 316FR.

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2. Predicting creep rupture and creep strain

The creep rupture models for the steels were assessed according to ECCC recommendations for sub-sized data sets [1] and corresponding creep strain models by utilizing the logistic creep strain prediction methodology (LCSP, [2]). The data sources used for the assessment are given in Table 1. Initial creep rupture models were attained using the DESA software [3] and Wilshire equations (WE, [4]), and complementary creep models suitable for creep fatigue. The 600°C stress rupture predictions for the WE models of the steels are shown in Fig 1a. Creep strain as a function of time, stress and temperature was also successfully modeled with LCSP focusing on the strain rates in the beginning of primary creep for later use in relaxation modeling. The LCSP strain at specified time t_ε is defined as:

$$\log(\varepsilon_t) = \left(\frac{\log(t_r) + C}{\log(t_\varepsilon) + C} - 1 \right)^{1/p} \cdot x_0 \qquad (1)$$

Where t_r is the time to rupture and x_0, p and C are fitting factors. The factor x_0 and p can be described by a multi-linear function of temperature and stress. The measured versus predicted strains of the ECCC 316L(N) data set is shown in Fig.1b.

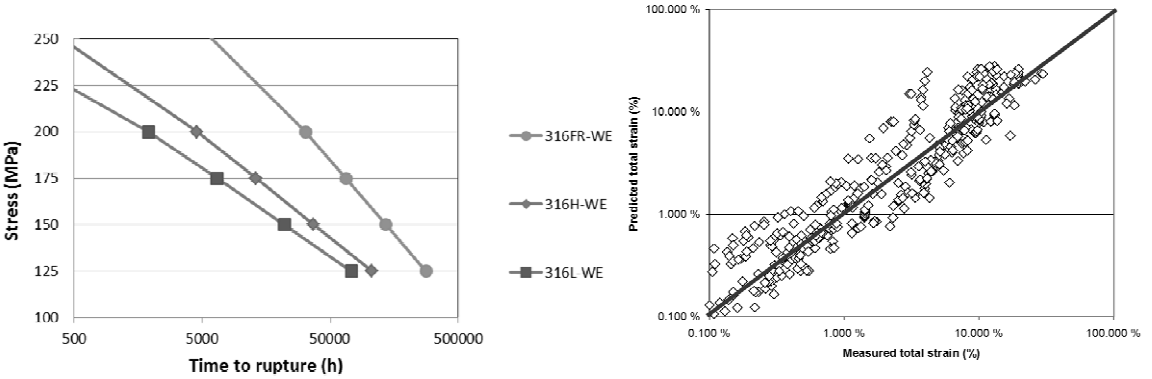

Fig. 1. (a) Creep rupture strength at 600 °C for 316FR, 316H and 316L using Wilshire model. (b) LCSP predicted creep strain for 316L(N) steel against measured strains of a large multi-heat data set. Note that the initial (instant) strain at loading has been removed.

Table 1. Data used in the assessments

Material	Creep	Creep strain	Creep-Fatigue	Note
316L(N)	ECCC data [10,11]	ECCC data [10,11]	-	Shape parameters for strain models
316FR	Takahashi [7]	-	Takahashi [6]	Creep-fatigue interaction model
316H	NIMS [12]	NIMS [12]	-	Creep and creep strain models
316L	EN-10216-5 [13]	-	In-house data	Preliminary CF interaction model

3. Predicting creep-fatigue life from creep properties and cyclic peak stresses

Creep-fatigue tests were conducted on 316L stainless steel at 600°C. The creep fatigue test results correspond well with the results of [5] as shown in Fig. 2. The strengthening and softening phases a creep fatigue test is shown in Fig.3. The relaxation ratio ($\sigma_{relaxed}/\sigma_{peak}$) is rapidly stabilizing to a value of about 0.92.

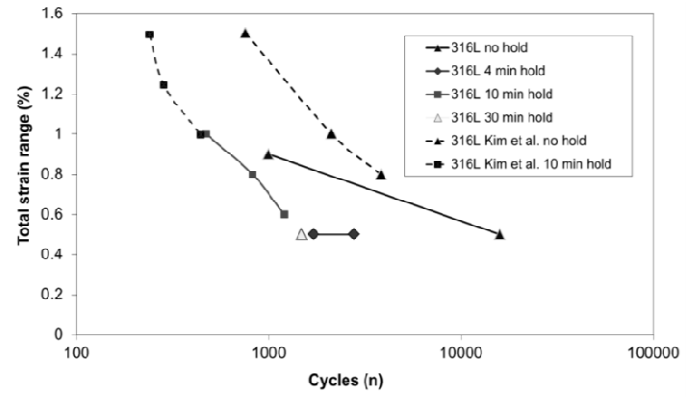

Fig. 2. Creep fatigue and high temperature low cycle fatigue results for 316L at 600°C.

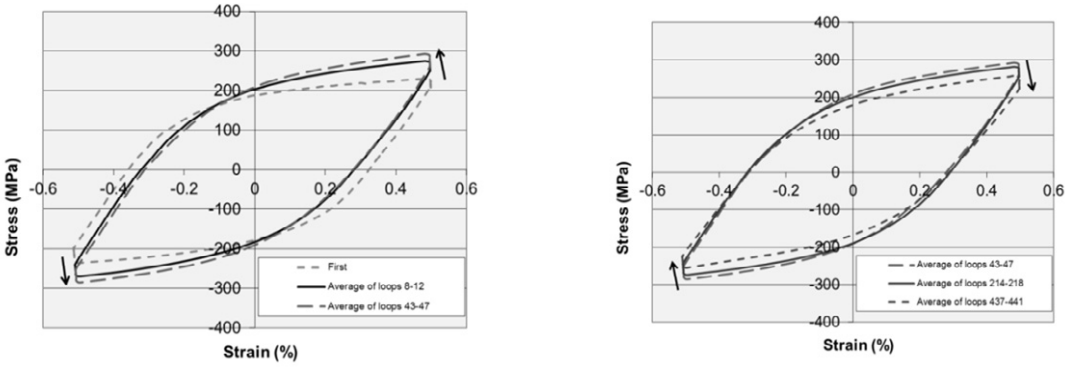

Fig. 3. Stress-strain plot of the (a) hardening phase and (b) softening phase of the test at 600°C / 0.5% total strain range, 10 min hold in both tension and compression (R=-1).

For the 316FR steel [6] it can be shown that the stress to rupture for the creep fatigue cyclic peak stress (stress rupture curves determined from data in [7]) is closely related to the stress σ_{ref} to cause rupture at the sum of hold times (at a specific strain range in tension hold). In Fig 4, the required correction factor SCF= $\sigma_{peak}/\sigma_{ref}$ is shown as a function of the sum of hold times ($\sum$th) showing the nearly log-linear trend of increasing SCF at constant strain range. Plotting SCF against the cyclic peak stress and a time-temperature parameter (Larson-Miller) calculated with the test hold time (not the sum), a function can be extracted to predict the SCF as a function of peak stress (or strain range), hold time and temperature.

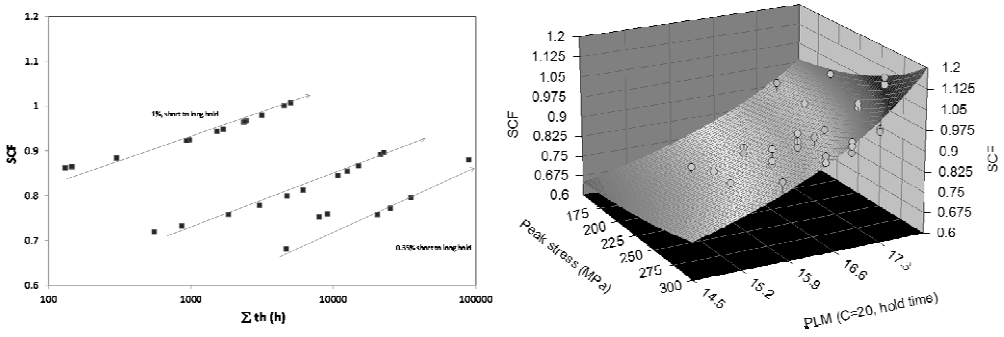

Fig. 4. 316FR creep fatigue data (tension hold) presented in a form where the SCF is plotted against (a) sum of hold times (th) and b) as a function of peak stress and PLM.

The SCF is defined as:

$$SCF = \frac{\sigma_{peak}(\Delta\varepsilon, T)}{\sigma_{ref}(\Delta\varepsilon, t_h, T)} = g(\Delta\varepsilon, t_h, T) \quad (2)$$

where $g(\Delta\varepsilon,t_h,T)$ is defined by the time-temperature parameter fit. The sum of hold times leading to creep-fatigue end criterion with the WE creep rupture is defined as follows:

$$t_{CF}(\Delta\varepsilon, t_h, T) = -\frac{1}{k}(\ln(\frac{\sigma_{peak}(\Delta\varepsilon, T)}{\sigma_{UTS}(T)}) - \ln(SCF(\Delta\varepsilon, t_h, T)))^{1/u} \cdot \exp(\frac{Q}{R \cdot T}) \quad (3)$$

where k and u are constants obtained by fitting to the test data, Q_c^* is the apparent activation energy and σ_{UTS} is the tensile strength at the specified temperature.

The predicted cycles to end criterion is:

$$N_f(\Delta\varepsilon, t_h, T) = \frac{t_{CF}(\Delta\varepsilon, t_h, T)}{t_h} \quad (4)$$

Using the above methodology the predicted versus measured $\sum t_h$ at 600°C is presented for 316FR in Fig. 5a. The corresponding predictions for 316L (also at 600°C) using the SCF function optimized for 316FR is also shown. Predictions for 316FR can be made within a factor of 2 in comparison to measured time or number of cycles. For 316L it can be shown that directly using the SCF model (316FR behaviour) can lead to overly conservative prediction by up to a factor of 4. This indicates that the SCF function for 316FR steel cannot be directly transferred to represent the behaviour of 316L. This is though expected since the 316FR has much higher creep strength and differs in relaxation behaviour.

4. Implications of the new creep-fatigue model

The approach to creep-fatigue assessment proposed in this paper is related to an approach by [8] relating a hold time reduction factor N_f/N_{f0} with the cycles to failure. Together with this factor and the strain range partitioning method [9] it was shown for P22 steel that the impact of hold time could be predicted. The proposed new methodology is introducing a SCF function to incorporate the impact of cycling on the stress required to produce creep-fatigue failure in a time defined by the sum of hold times. The methodology appears to be robust when the stress range is within the limits of the creep data. The creep-fatigue testing at high strain ranges results in peak stresses that need creep models for shorter term properties than what are usually targeted in conventional creep modeling. A classical presentation of the creep-fatigue response by a linear life fraction diagram is shown in Fig. 5b for 316FR and 316L. The proposed creep-fatigue model has the advantage that it is does not need detailed separation of creep and fatigue components. The simple functions defining N_f enable summation of different type of cycles to any predefined damage limit, for instance as in the Miner rule $\sum[Ni(\Delta\varepsilon,th,T)/\sum Nf(\Delta\varepsilon,th,T)] = D$. This feature should be further validated for larger data sets and mixed cycle creep-fatigue. This would allow for optimised SCF functions to incorporate all desired variables.

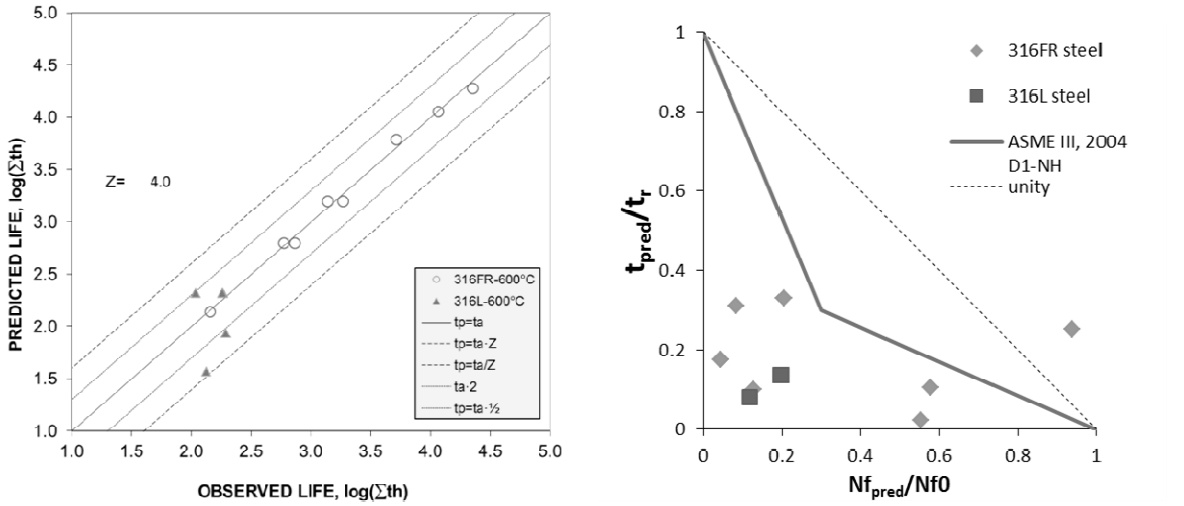

Fig. 5. a) 316FR creep fatigue data (hold in tension) presented as observed vs. predicted life. The 316 FR results show very good agreement whereas 316L life can be predicted within a factor of two for low strain range (0.5%) but may be conservative for the higher strain ranges (0.6% & 0.8%). Note that 316L data has both tension and compression hold; b) the creep-fatigue performance presented in terms of the linear life fraction rule.

Acknowledgements

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