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Long-term creep data prediction for type 316H stainless steel

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ABSTRACT

Impressive data sets have been produced for 316H stainless steel (18Cr–12Ni–Mo with up to 0.08C) by the National Institute for Materials Science (NIMS), Japan, to reveal the dependencies on stress and temperature of the high-temperature creep and creep fracture behavior of nine batches of tube, six of bar and two of plate. Using these long-term property values, the stresses to produce failure in 100,000 h at various plant exposure temperatures have been determined using the Manson–Haferd parameter. However, by incorporating the 0.2% proof stresses and ultimate tensile strengths of each batch of material at the creep temperatures, new relationships allow accurate prediction of the allowable tensile creep stresses using data from tests lasting only up to 5000 h. Moreover, all of these results can be interpreted straightforwardly in terms of the dislocation processes controlling creep strain accumulation and the cavitation damage causing creep failure.

1. Introduction

The selection of alloy steels for power plant service is usually based on the requirement that creep failure should not occur under the prevailing operating conditions during plant lives of ~250,000 h (>30 years). Although complex stresses and temperatures are often encountered, design decisions are generally made on the basis of the 'allowable tensile creep strengths' of the chosen materials. These strengths are commonly determined [1] as 67% of the average stress (up to 1088 K) or 80% of the minimum stress causing creep rupture in 100,000 h ($\sim 3.6\times 10^{8}$ s) or as the average stress producing a creep rate of 0.01%/1000 h ($\sim 3\times 10^{-11}\,\mathrm{s}^{-1}$).

Unfortunately, with the parametric, numerical and computational methods currently employed, 100,000 h data cannot be predicted by extrapolation of short-term property measurements despite the international efforts being devoted to the different procedures available [2]. Hence, at present, protracted and expensive test programmes lasting 12–15 years are necessary to determine the required long-term estimates. A reduction in this 12–15 year 'materials development cycle' has therefore been defined as the No. 1 priority in the 2007 UK Energy Materials–Strategic Research [3].

With the aim of reducing this 12–15 year cycle, over recent years, a new methodology has been devised which appears to allow 100,000 h property values to be determined precisely by analysis of short-term data [4–7], covering minimum creep rates ($\dot{\varepsilon}_m$), creep rupture lives (t_f) and times to various creep strains (t_ε). Specifically, using the Wilshire equations, 100,000 h strength estimates have been derived accurately by analysis of multi-batch data sets obtained from tests lasting up to only 5000 h for ferritic [7], bainitic [6] and martensitic steels [5]. This new approach quantifies t_f, $\dot{\varepsilon}_m$ and t_ε as functions of stress (σ) and temperature (T) as

$$\frac{\sigma}{\sigma_{TS}} = \exp\left\{-k_1\left[t_f \exp\left(\frac{-Q_c^*}{RT}\right)\right]^u\right\} \quad (1)$$

$$\frac{\sigma}{\sigma_{TS}} = \exp\{-k_2[\dot{\varepsilon}_m \exp(Q_c^* \times RT)]^v\} \quad (2)$$

$$\frac{\sigma}{\sigma_{TS}} = \exp\{-k_3[t_\varepsilon \exp(-Q_c^* \times RT)]^w\} \quad (3)$$

where σ_{TS} is the ultimate tensile strength obtained from high-strain-rate ($\sim 10^{-3}\,\mathrm{s}^{-1}$) tensile tests carried out at the creep temperatures for each batch of material investigated. The various parameters, $Q_c{}^*$, k_1, k_2 and k_3, as well as u, v and w, are easily computed from t_f, $\dot{\varepsilon}_m$ and t_ε measurements made over reasonable stress/temperature ranges [4–7]. Since σ_{TS} is the highest possible stress which can be applied at the creep temperature, Eq. (1)–(3) then provide sigmoidal descriptions of the t_f, $\dot{\varepsilon}_m$ and t_ε values as systematically approaching $t_f = 0$, $t_\varepsilon = 0$ and $\dot{\varepsilon}_m = \infty$ when $\sigma/\sigma_{TS} \to 1$ and $t_f = \infty$, $t_\varepsilon = \infty$ and $\dot{\varepsilon}_m = 0$ as $\sigma/\sigma_{TS} \to 0$.

Although the Wilshire equations have allowed accurate estimation of the 100,000 h creep properties for various steels produced for construction of power generation and petrochemical plant [5–7], as well as for pure copper [4] and aluminum alloys for airframe applications [8], for general applicability, the method must be validated for a wide range of other materials. For this reason, the present study considers type 316H stainless steel (18Cr–12Ni–Mo with up to 0.08% C). For this product, manufactured as tube [9], plate [10] and bar [11], reliable multi-batch $\dot{\varepsilon}_m$ and t_f properties

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have been determined over wide stress-temperature ranges by the National Institute for Materials Science (NIMS), Japan. Using these results, an assessment can be made of

(a) the accuracy with which the Wilshire equations predict measured 100,000 h stress rupture values by analysis of data from tests lasting up to only 5000 h, and
(b) how well the extrapolated 'allowable tensile creep strengths' estimated as 67% of the average stresses giving creep lives of from 100,000 h compares with the predicted stresses giving minimum creep rates of 0.01%/1000 h at the appropriate service temperatures.

In addition confidence in this new extrapolation procedure should be improved if the observed property sets can be discussed sensibly in terms of the processes of deformation and failure controlling creep and creep fracture behavior.

2. Processing of materials

The data sets produced by NIMS reported the 0.2% proof stresses (σ_{PS}) and ultimate tensile strengths (σ_{TS}), as well as the initial specimen extensions on loading (ε_0), the $\dot{\varepsilon}_m$, t_e and t_f values, the elongations to failure (ε_f) and the reductions in area at fracture (RoA) for nine batches of 316 tube at 873–1023 K (600–750 °C), for six batches of bar and two of plate at 873–1123 K (600–850 °C). These samples were labeled by NIMS as AAA to AAN for the tube [9], as ADA to ADF for the bar [11] and AaA to AaB for the plate [10]. In sets of three, the tube was heat treated as

(a) rotary pierced and cold drawn, followed by water quenching from 1373 K (1100 °C),
(b) hot extruded and cold drawn, followed by water quenching from 1403 K (1130 °C) and
(c) hot extruded and cold drawn followed by solution treatment [9].

For the bar, two of the six samples were processed after hot rolling [11] for

(i) 2 h at 1353 K (1080 °C), before water quenching
(ii) 70 min at 1373 K (1100 °C), then water quenched and
(iii) 110 min at 1333 K (1060 °C) and water quenching.

The two plate specimens were hot rolled and held at 1323 K (1050 °C) for either 40 min or 80 min before water quenching [10].

3. Traditional approaches to creep and creep fracture

For well over half a century, the $\dot{\varepsilon}_m$ and t_f values been described using power law equations as

$$\frac{M}{t_f} = \dot{\varepsilon}_m = A\sigma^n \exp\left(-\frac{Q_c}{RT}\right) \qquad (4)$$

where $Q_c \neq Q_c{}^*$) is the activation energy determined from the temperature dependence of $\dot{\varepsilon}_m$ and t_f at constant σ, not at constant (σ/σ_{TS}) as with Eq. (1)–(3). With Eq. (4), Q_c as well as the parameters (M and A) and the stress exponent (n) vary depending on the stress/temperature ranges considered. With all forms of the 316H samples studied, these variations are illustrated in Figs. 1 and 2, where the standard $\log\sigma/\log\dot{\varepsilon}_m$ and $\log\sigma/\log t_f$ plots show that n decreases from 13 to about 4 with decreasing stress and increasing temperature, with Q_c varying from 270 to 730 kJ mol^{-1}.

With the variations in n and Q_c evident from Figs. 1 and 2, power law relationships cannot be used to predict long-term properties from short-term results. Thus, to estimate the stresses giving creep lives of 100,000 h [9–11], use was made of the Manson–Haferd parameter (P), namely [12],

$$P = \frac{\log t_f - \log t_a}{T - T_a} \qquad (5)$$

where T is in degrees Kelvin and t_f is the time to rupture (h), while t_a and T_a are optimized constants. The NIMS results obtained using Eq. (5) are listed for tube, bar and plate in Table 1 [9–11], as illustrated for the bar samples in Fig. 3.

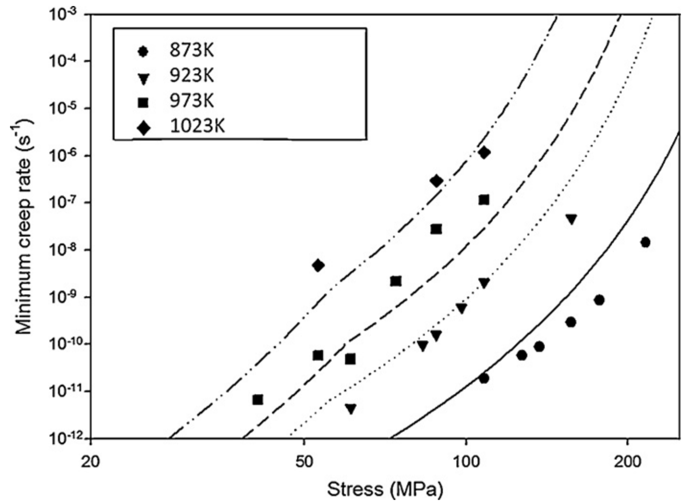

Fig. 1. The variations of the minimum creep rate with stress expressed using Eq. (4), together with the lines calculated from Eq. (2) and the data in Table 2 for type 316H stainless steel tube.

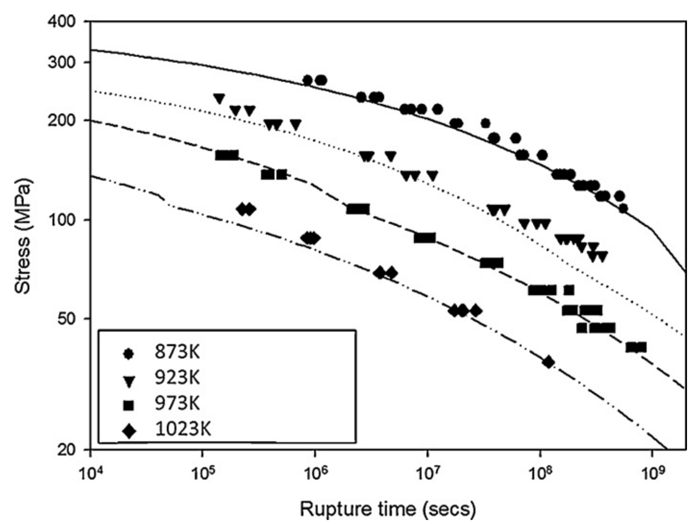

Fig. 2. The variations in creep life with stress expressed using Eq. (4), together with the lines calculated from Eq. (1) and the data in Table 4 for type 316H stainless steel tube.

Table 1
The average stresses calculated to give creep lives of 100,000 h for tube, bar and plate samples of 316H stainless steel at 873–1123 K. These stresses were determined by applying the Manson–Haferd equation [12] to long-term NIMS data [9–11].

	Tube	Plate	Bar
873	120.0	136.5	106.5
923	65.9	65.5	54.8
973	36.4	38	32.2
1023	22.9	22.5	19.5
1073	18.6	17	13.5
1123	15.5	14.5	10