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On the applicability of boundary condition based tensile creep model in predicting long-term creep strengths and lifetimes of engineering alloys

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ABSTRACT

Creep behaviour of metal alloys for critical high temperature engineering applications is usually studied by uniaxial tensile creep tests. The stress and temperature dependence of steady-state or minimum creep rate observed in such tests is rationalised at present on the basis of either Norton or MBD equation. But, the stress exponent determined on such basis depend strongly and often irregularly on test temperature and the creep activation energy varies with stress or stress range. Hence, these parameters cannot be used for long-term predictions. Here, it is shown that these difficulties can be removed if a new creep model, which incorporates tensile strength, is used to rationalise the creep data. The stress exponent determined then does not depend on temperature although it depends on stress range, and the creep activation energy does not depend on stress. Thus, there is no relationship between stress exponent value and creep mechanism. Consequently, the new tensile creep model can be used in combination with Monkman-Grant relationship to predict the long-term tensile creep strengths and lifetimes at different temperatures using creep parameters determined from short-term tensile creep tests. Both the deficiencies of the Norton and MBD equations and the predictive quality of the new tensile creep model are demonstrated here using uniaxial tensile creep data and tensile strength data measured for two totally different types of creep resistant engineering alloys: 9Cr-1Mo steel and Ni base superalloy Ni-16Cr-8.5Co-3.5Al-3.5Ti-2.6W-1.8Mo-0.9Nb.

1. Introduction

Creep is a plastic deformation process occurring under a constant stress. For metals and metal alloys, the creep deformation is normally measured under a constant uniaxial tensile stress and temperature. The creep properties that can be determined reasonably accurately from such tests are the steady-state or minimum creep rate and creep rupture time. Relating these properties to testing stress and temperature is of critical importance not only for understanding and rationalising creep properties of materials but also for selection and/or development of materials affecting many industries such as aerospace, chemicals and fossil or nuclear power generation. In all these applications, the long term creep rupture strengths and lifetimes must be reliably predicted from creep parameters determined from short term test data, i.e., from accelerated creep tests at higher stresses and temperatures. This is of particular importance for the design of more energy efficient electrical power generation plants or aero-engines that operate at higher temperatures. For instance, the Gen-IV nuclear power plants have a specified service lifetime of 60 years (Murty and Charit, 2008; Song et al., 2016). Testing materials for such a long period of time is clearly impractical. Hence, such long-term creep strengths and lifetimes at different application temperatures must be predicted on the basis of valid physical models. The purpose of this study is to analyse and validate the applicability of the currently available creep models and the methods associated with them in predicting the long-term tensile creep rupture strengths and lifetimes of engineering alloys at different temperatures using creep parameters determined from short term tensile creep tests and hence to identify a generically applicable basis for characterising and rationalising creep properties of metal alloys.

2. Conventional creep models

Since its introduction in the 1920s, the Norton equation has been the basis for analysing and rationalising the stress (σ) and temperature (T) dependence of the steady-state state or minimum creep rate ($\dot{\varepsilon}_{\min}$) of metal alloys (Norton, 1929; Brown and Ashby, 1980). It is written as:

$$\dot{\varepsilon}_{\min} = A(\sigma/\sigma_0)^n \exp[-Q_c/(RT)] \quad (1)$$

where A is a constant, n the stress exponent, Q_c the activation energy of creep, R the gas constant, T the absolute temperature and σ_0 the

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reference stress. However, even to date, there has been neither a general consensus nor a theoretical basis for determining the value of σ_0. Thus, it is usually taken either as the yield strength or tensile strength at creep temperature (Brown and Ashby, 1980). This ambiguity on how to define or determine the value for σ_0 has not been resolved.

Eq. (1) is a phenomenological model. Written in the way as it is, it is also of theoretical relevance because its stress term is dimensionless and hence the dimension of A does not depend on the value of n. But, probably because of the convenience offered by removing the parameter σ_0, keeping also in mind that σ_0 is not clearly defined, the Norton equation is rewritten and applied in many studies (Golan et al., 1996; Bhadeshia et al., 1998; Anderson et al., 2003; Burt and Wilshire, 2004; Wilshire and Scharning, 2008; Bauer et al., 2012; Whittaker et al., 2013; Athul et al., 2016; Maruyama et al., 2017) in the form of

$$\dot{\varepsilon}_{\min} = A'\sigma^n \exp[-Q_c/(RT)] \tag{2}$$

where A' is another constant, but, here, its dimension depends on the value of n. Eq. (2) is of no theoretical relevance, because the dimension of one of its constants depends on the value of its other constants, which is theoretically unreasonable.

Towards the end of 1960s, the MBD equation was introduced (Mukherjee et al., 1969; Mukherjee, 2002), which is written as:

$$\dot{\varepsilon}_{\min} = B\frac{DGb}{kT}\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{G}\right)^n \tag{3}$$

where D is the lattice diffusion coefficient, G the shear modulus at creep temperature, b the Burger vector, k the Boltzmann's constant, d the grain size and p the grain size exponent, and other parameters have the same meaning as those in Eq. (1). Eq (3) is termed as a semi-phenomenological equation [Brown and Ashby, 1980] as it is based partially on the microstructure-based analysis of diffusion-affected dislocation motion under stress.

However, despite the differences in formulation between Eq. (1) and Eq. (3), they are mathematically the same at any specified temperature, i.e., both can be written as:

$$\dot{\varepsilon}_{\min} = \Phi\sigma^n \tag{4}$$

where Φ is a temperature-dependent constant. Eq. (4) predicts a linear relationship between ln $\dot{\varepsilon}_{\min}$ and ln σ at any specified creep temperature.

Eq. (4) is the basis for determining the stress exponent n in nearly all creep studies at present. For many metal alloys, the n value determined on this basis depends strongly on temperature and also, in many cases, on stress range, i.e., it depends strongly on testing conditions. This problem is illustrated in Fig. 1, where ln $\dot{\varepsilon}_{\min}$ is plotted versus ln σ for two sets of results measured for two totally different engineering alloys. One set of data is measured by Japan Atomic Energy Agency (JAEA) for the modified creep resistant steel 9Cr-1Mo (Fig. 1a) and the other by National Institute for Materials Science (NIMS), Japan, for the Ni base superalloy Ni-16Cr-8.5Co-3.5Al-3.5Ti-2.6W-1.8Mo-0.9Nb. Both sets of data are measured over a period of more than 10 years.

For the steel (Fig. 1a), the stress exponent n decreases with temperature continuously from 40.8 at 450 °C to 13 at 650 °C and a change in stress exponent n occurs at 500 °C but not at other temperatures. This continuous decrease in n with increasing temperature cannot be explained and no explanation can be given as to why the n value changes in different stress ranges at 500 °C but not at other temperatures.

For the Ni base alloy (Fig. 1b), two straight lines are obtained at each temperature. In the high stress region, the stress exponent n decreases from 10.3 at 750 °C to 8.7 at 850 °C, but then increases to 9.6 at 900 °C. In the low stress region, it decreases from 6.5 at 750 °C to 4.3 at 850 °C, but then increases to 5.7 at 900 °C. Again, it is not possible to rationalise this irregular temperature dependence of stress exponent n in both high and low stress ranges. Furthermore, the transition stress, i.e., the stress at which the stress exponent n changes its value, depends strongly and irregularly on temperature, which are unpredictable on

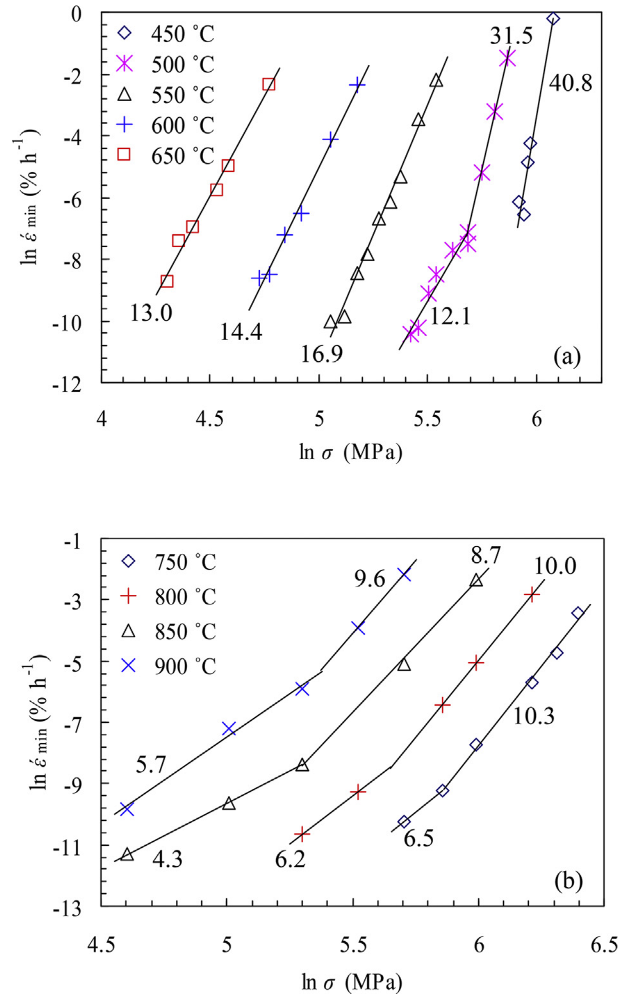

Fig. 1. Plots of ln $\dot{\varepsilon}_{\min}$ versus ln σ where the numerical values are the stress exponent n values determined on the basis of Eq. (1) or (3): (a) for steel 9Cr-1Mo (F6); (b) for Ni base alloy Ni-16Cr-8.5Co-3.5Al-3.5Ti-2.6W-1.8Mo-0.9Nb.

the basis of either Eq. (1) or (3). It is also important to note that, when the creep data are presented in the way as shown in Fig. 1, the stresses in low stress range at a lower temperature can fall into both high and low stress range at a higher temperature (Fig. 1b).

The strong and unpredictable temperature dependence of stress exponent n and transition stress shown in Fig. 1 are not special or isolated cases. Many similar results are reported in the literature for other types of alloys, for instance, Ni base single-crystal superalloys (Golan et al., 1996; Rae and Reed, 2007), Co-base superalloys (Aghaie-Khafri and Binesh, 2010; Bauer et al., 2012), magnesium alloys (Han and Dunand, 2001; Hyun and Kim, 2014; Athul et al., 2016), NiAl hardened austenitic steel (Satyanarayana et al., 2002), aluminium alloys (Burt and Wilshire, 2004), titanium alloys (Whittaker et al., 2013), copper or copper alloys (Wilshire and Battenbough, 2007) and other grades of 9-12Cr steels (Wilshire and Scharning, 2008; Kimura et al., 2008). Thus, neither Eq. (1) nor (3) has predictive quality, i.e., long-term predictions cannot be made if the creep parameters such as n and A are determined only from short-term creep tests in all these cases.

3. The cause of deficiencies of conventional creep models

It may be argued that any mathematical model for a physical phenomenon must at least satisfy its boundary conditions. For the creep under a constant tensile stress, there are two boundary conditions. Firstly, when there is no stress applied, creep rupture will no occur, i.e.,