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Constitutive equations of the minimum creep rate for 9% Cr heat resistant steels

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ABSTRACT

This study addresses the overestimation of the time–temperature-parameter (TTP) method on the allowable creep strength of 9–12% Cr heat resistant steels. Creep data of 9% Cr heat resistant steels are divided into several data sets according to the creep controlling mechanism. Constitutive equations of the minimum creep rate $\dot{\varepsilon}_m$ depending on applied stress σ and temperature T have been constructed, and the modeling results are found to be well in agreement with the experimental data. The influence of the second phase particles in the power-law-breakdown (PLB) region on 9% Cr heat resistant steels is well reflected by introducing a parameter, σ_0, into the equation. Furthermore, the construction of constitutive equations of $\dot{\varepsilon}_m$ from the PLB region to the power-law (PL) region for 9% Cr heat resistant steels has been shown to be feasible.

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1. Introduction

In order to assure safe and economical operations, life assessment is always the major concern for materials serviced in power plants. Among those methods that have been developed for the assessment, the time–temperature-parameter (TTP) method is most commonly used. As 9–12% Cr heat resistant steels [1–3] have been quickly developed for the last four decades to manufacture the components that can withstand more severe service conditions, it has been found that the TTP method shows a risk of over-estimating the allowable creep strength of the materials served at high temperature [4,5]. This is so called "premature failure" [6].

Comparing with heat resistant steels with lower Cr contents, there are more second phase particles in microstructures of 9–12% Cr heat resistant steels [7–9], which are of significant impact in providing the superior creep behavior of these steels. This study addresses the influence of second phase particles in the overestimations made by the TTP method. The relation among the minimum creep rate $\dot{\varepsilon}_m$, applied stress σ and temperature T for 9% Cr heat resistant steels is analyzed, and constitutive equations of $\dot{\varepsilon}_m$ are constructed by taking the influence of the second phase particles into account. This approach of providing accurate estimation also brings along some other advantages, for instance, $\dot{\varepsilon}_m$ of heat resistant steels can also be used for the selection and design of structural materials in power plants based on the well-known Monkman–Grant relation [10]

$$\dot{\varepsilon}_m \cdot t_f = C \tag{1}$$

where C is a constant and t_f is the time of failure [11]. Another merit for the present study on $\dot{\varepsilon}_m$ is that the over-estimation of the allowable creep strength generated by the change of creep mechanism can be avoided.

2. Creep mechanism under different stresses for second phase particles strengthened materials

Three separable stress regions can be divided by the change of stress exponent n in the creep rate change with stress for the second phase particles strengthened steels, as shown in Fig. 1 [12,13]. At the lower stress level which usually happens at elevated temperatures, a stress exponent of $n \sim 1$ is observed (region 1 in Fig. 1). It is well known that the deformation in this scenario can occur through the migration of vacancies. There are two types of models to describe this deformation: diffusional creep and Harper–Dorn (H–D) creep [14]. At higher stress level, the stress exponent n is higher than 1, and the creep is dominated by the glide of dislocations rather than the migration of vacancies. Two possible mechanisms have been proposed for dislocations overcoming the second phase particles in metals [15]: climbing and Orowan mechanisms. When dislocations by-pass second phase particles with climbing mechanism, it is taken as a "power-law" (PL) region and the stress exponent n is typically between 3 and 7 (region 2 in Fig. 1). Whereas when dislocations by-pass the second phase particles by Orowan mechanism, it is considered as a "power-law-breakdown" (PLB) region and the stress exponent n is higher than 5 (region 3 in Fig. 1).

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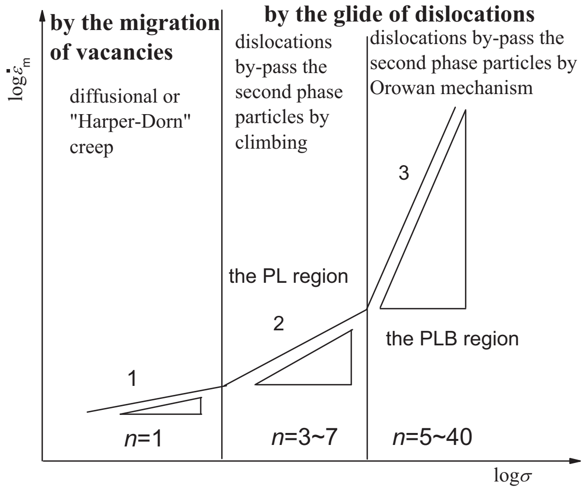

Fig. 1. Minimum creep rate $\dot{\varepsilon}_m$ dependence on applied stress σ for second phase particles strengthened materials.

3. Constitutive equations of the minimum creep rate $\dot{\varepsilon}_m$ in the PLB region for 9% Cr heat resistant steels at various temperatures

3.1. Stress exponent n in PLB region for heat resistant steels with different Cr contents

Heat resistant steels with different Cr contents are typical second phase particle strengthened materials. Fig. 2 shows the relationship between $\dot{\varepsilon}_m$ and σ in the PLB region at various temperatures for these steels [16–19]. It can be seen that the stress exponent n strongly depends on temperature for 9–12% Cr heat resistant steels such as the Grade 91, Grade 92 and Grade 122 steels. Over the relevant range of test conditions, the stress exponent n decreases intensively with increase of the testing temperature. At the testing temperature of 550 °C, the stress exponent n is much bigger than 10, when the testing temperature is increased up to 750 °C, the stress exponent n changes to about 5. However, the stress exponent n only changes slightly with temperature increase for the Grade 23 steel. It can be seen that when the testing temperature is increased from 550 °C to 700 °C, the stress exponent n only decreases from 7.8 to 6.3.

For over half a century, the variation of the minimum creep rate $\dot{\varepsilon}_m$ with applied stress σ and temperature T has been quantified by a power law equation as follows [19]:

$$\dot{\varepsilon}_m = A\sigma^n \exp\left(-\frac{Q}{RT}\right) \tag{2}$$

where R is the universal gas constant, Q is the activation energy, n is the stress exponent, and A is a constant. For the Grade 23 steel, the stress exponent n does not have big change with temperature, so the activation energy Q can be considered as a constant. However, for 9–12% Cr heat resistant steels, the n value changes significantly with increase of the testing temperature, so the activation energy Q cannot be considered as a constant.

Change of the activation energy Q is the very reason for the overestimation of the allowable creep strength by various TTP methods

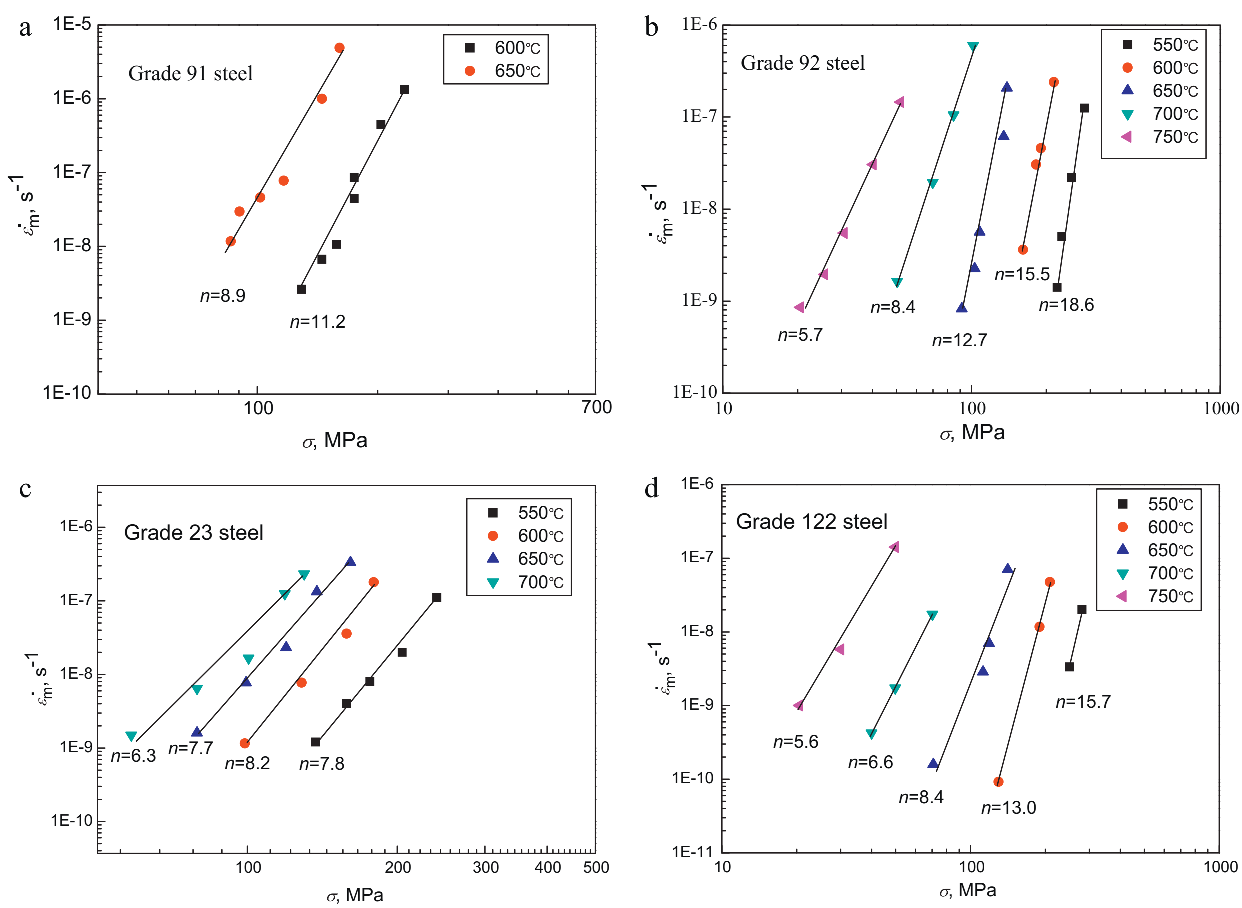

Fig. 2. Minimum strain rate $\dot{\varepsilon}_m$ dependence on applied stress σ at various temperatures for (a) Grade 91 [16], (b) Grade 92 [17], (c) Grade 23 [18] and (d) Grade 122 [19] steels.

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