Journal of Nuclear Materials 465 (2015) 196–203

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Parameter correlation of high-temperature creep constitutive equation for RPV metallic materials

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
6 May 2015
Accepted 11 May 2015
Available online 9 June 2015

Keywords:
Creep
Constitutive equation
Coefficient model
RPV metallic material
Data fitting

ABSTRACT

Constant-temperature and constant-load creep tests of SA-508 stainless steel were performed at six temperatures, and the creep behavior and properties of this material were determined. Constitutive models were established based on an isothermal creep method to describe the high-temperature creep behavior of SA-508. Material parameter k, stress exponent n_σ, and temperature exponent n_t of the established constitutive models were determined through experimental data via numerical optimization techniques. The relationship of k, n_σ, and n_t was evaluated, and a new coefficient model of k–T, n_σ–T, n_t–T, and n_t–n_σ was formulated through the parameters of the isothermal creep equation. Moreover, the isothermal creep equation for this material at every temperature point from 450 °C to 1000 °C was obtained from the models. This method can serve as a reference for isothermal creep analysis and provide a way for the safety assessment of components of reactor pressure vessels.

1. Introduction

As engineering parts, reactor pressure vessel (RPV) SA-508 metal materials and components interact with thermal and mechanical loads. Therefore, evaluating the mechanical properties of these materials is particularly important under thermal and mechanical load conditions. Recent studies on high-temperature material properties are mainly concentrated on creep and stress relaxation [1,2]. Furthermore, stress relaxation and creep studies tend to obtain different forms of constitutive equations through mechanism analysis. These constitutive equations can be applied to engineering and theoretical research to explore temperature-induced failure mechanisms of materials and predict creep damage.

Constitutive equations such as power law, continuum damage, and θ projection concept have been investigated in the past three decades to describe creep behavior and aging process of metals [3–7]. Phaniraj et al. [8] established a relationship with the steady state creep rate, where this rate is found to meet the first-order kinetics for the tertiary creep of the hot creep behavior of AISI 304 stainless steel at 873 and 973 K. At 590 °C, Dyson et al. [9] studied an optimized procedure to calibrate the constitutive parameters of a continuum damage mechanics model for 1/2Cr–1/2Mo–1/4 V ferritic steel and obtain other constitutive parameters over a wider temperature range. By investigating the properties of Mg–5Li–Al–0.5Ca and Mg–5Li–3Al–1Ca at different temperatures and under applied stresses, Jiang et al. [10] developed a power law equation to predict minimum creep strain rates. Kimura et al. [11] have studied the long-term creep deformation properties of 9Cr–1Mo steel; results showed that the creep strain magnitude at the beginning of the accelerating creep stage decreases when the stress level is reduced. Farid Vakili Tahami [12] has mentioned that creep constitutive parameters are calculated for two forms of constitutive equations, namely, Norton power law and Prandtl law, which can be used to estimate creep behavior of structures at different operating conditions.

Creep constitutive equations in various studies are specific. A creep expression is only suitable for certain conditions because of lack of versatility and inability to obtain creep equations through other expression under specific conditions. This drawback is not related to the constitutive equation parameters under different temperatures. A material model based on experimental results was used for analysis; data and design parameters are also required in actual design. Moreover, SA-508 Gr.3 Cl.1 is an important RPV material in nuclear power engineering. Therefore, experimental studies on creep test are significant. In this study, an improved creep equation for SA-508 Gr.3 Cl.1 is obtained through a creep experiment, and the relationship of the parameters in the new model is obtained by analyzing the parameters of the creep

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http://dx.doi.org/10.1016/j.jnucmat.2015.05.032
0022-3115/

equation. The new model can be used to acquire creep constitutive equations even if no experimental data are available under other conditions.

2. Creep constitutive equation

Creep is a performance feature of a material at high temperatures. This feature is a long-term process of accumulation of inelastic deformation under a constant stress. Studies show that elastic strain can be calculated according to the Hook's theorem. Plastic strain is provided by the appropriate flow rule, thus, a function of the creep strain relationship can be obtained based on stress, temperature, and time [13].

The creep equation can be expressed as Eq. (1):

$$\varepsilon_C = f(\sigma, t, T) \tag{1}$$

Both first and second fields in this study have similar geometric properties. The constant temperature and load uniaxial creep tests in Eq. (1) can be expressed as:

$$\varepsilon_C = f(\sigma)f(t). \tag{2}$$

The behavior of the creep constitutive model of metallic materials can be described as an exponential function and two kinds of hyperbolic sine function. As an exponential function constitutive model, the creep strain rate and stress relationship can be described by Eq. (3):

$$f(\sigma) = A\sigma^{n_\sigma} \tag{3}$$

In most creep processes of metallic materials, time function can be expressed by Eq. (4):

$$f(t) = Bt^{n_t} \tag{4}$$

Therefore, the creep constitutive Eq. (5) can be obtained under isothermal conditions of stress according to Eqs. (2)–(4).

$$\varepsilon_C = k\sigma^{n_\sigma}t^{n_t} \tag{5}$$

where ε_C is the creep strain, σ is the stress, t is the time, and k, n_σ, and n_t are the dependent material constants.

The current creep constitutive equation is derived from certain temperature conditions. A few studies have focused on the relationship between the creep equation coefficient and temperature under different conditions. In the present study, the material and physical parameters for the creep constitutive equations are calculated using experimental data. Therefore, test SA508 samples were prepared in accordance with ASTM A276-05a specification. Constant-temperature and constant-load uniaxial creep tests are performed at six temperatures (450, 550, 650, 750, 900, and 1000 °C) under certain initial stresses. The creep constitutive parameters are calculated through constitutive Eq. (5), and the relationship model between parameters T–n_σ and T–n_t are discussed.

3. Materials and creep test

Nuclear RPV is the most critical pressure boundary component in a light–water reactor in terms of plant safety. Therefore, this vessel requires superior integrity during plant operation, and studying the creep behavior of SA508 is necessary. The test specimens with a gauge length of 100 mm and a diameter of 10 mm were fabricated from bars (Fig. 1), in accordance with ASTM E8M–04 [14]. Table 1 shows the chemical composition of the material. This table presents both standard and tested values. The tested values were obtained from quantometric measurements of the specimens under investigation.

Uniaxial creep tests were performed using an Instron test machine in accordance with ASTME139 [15]. The lever arm loading ratio was 20:1 with an accuracy of ± 0.5%. The temperature range of the furnace or chamber of the machine reached up to 1050 °C with an accuracy of ± 1 °C. The testing machine also provided displacement–time graphs with an accuracy of ± 0.0001 mm. The maximum extension of the specimen was 10 mm.

4. Experimental results

In general, the total strain (ε_{total}) during the creep experiments can be divided into elastic strain ($\varepsilon_{elastic}$, loading stage), plastic strain ($\varepsilon_{plastic}$, loading stage), and creep strain (ε_{creep}, creep stage) [16,17]:

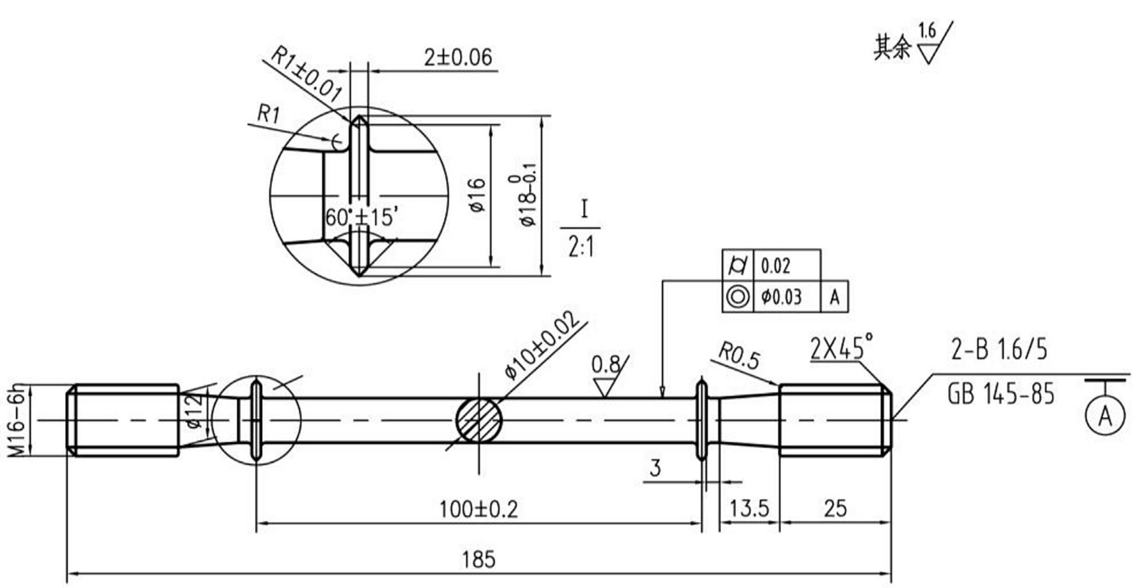

Fig. 1. Standard creep specimen (unit: mm).