Creep Modeling for Life Evaluation of Heat-resistant Steel with a Martensitic Structure

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A tertiary creep model, the Ω method, previously proposed for creep life prediction was modified so as to be applicable to martensitic steels with a pronounced primary creep region. Primary creep behavior was described by a logarithmic creep equation with two parameters dependent on stress and temperature. Correlations between newly introduced primary creep parameters and tertiary ones were studied. The proposed creep model, which takes into account for primary and tertiary creeps, described the creep curves satisfactorily and predicted creep life accurately.

KEY WORDS: Ω method; primary creep; modified Ω method; Creep life; initial strain rate; logarithmic creep; strain rate acceleration factor.

1. Introduction

Incessant and devotional efforts have been made to develop new heat-resistant steels aimed at the increase of thermal efficiency of power plants and consequent lower fuel costs, as well as environmental protection¹⁾. Most of the newly developed heat-resistant steels, as well as those under development, are characterized by tempered martensitic structures, pronounced primary creep, and the higher strength under severe operational conditions²⁾. As the newly developed steels have come to be used extensively because of their high performance, further understanding of large and prolonged primary creep becomes important from the standpoint of remaining creep life assessment technology and also alloy design.

The objectives of the present study are to formulate the creep behavior of a Mod. 9Cr-1Mo steel³⁾ with a tempered martensitic structure using certain parameters, to correlate the newly introduced parameters for primary creep to

those used thus far in tertiary creep modeling, and to examine the performance of a proposed model for creep life prediction.

2. Experimental procedures

The Mod.9Cr-1Mo steel (T91) used in the present study has a single phase tempered martensitic structure, and its chemical composition is listed in **Table 1**. The heat treatments subjected to the as-received material were normalizing at 1313K and tempering at 1003K or higher, based on ASTM, A213. The creep test specimens had a diameter of 6 mm and a gauge length of 30 mm. The test temperature was 873 to 923 K, using the constant load creep test and initial stress of 107.9 to 235.3 MPa.

3. Results

3. 1 Relationship between strain rate and true strain

Table 1. Analyzed chemical compositions and ASME specification for Mod.9Cr-1Mo steel (ASME 213 T91) (mass %)

Mod.9Cr-1Mo steel	C	Si	Mn	P	S	N	Cr	Mo	Nb	Al	V	N
Analyzed	0.1	0.25	0.4	0.016	0.005	0.04	8.4	0.9	0.07	0.005	0.21	0.044
Specification	0.08~0.12	0.2~0.5	0.3~0.6	≤0.02	≤0.01	≤0.4	8.0~9.5	0.85~1.05	0.06~0.10	≤0.04	0.18~0.25	0.03~0.07

Creep curves of the Mod9Cr-1Mo steel were obtained under constant load in a range of stress and temperature from 147.1 to 196.1 MPa and from 883 to 923 K. The change of strain rate with strain is shown in Figs. 1 and 2 on a semi-logarithmic scale. The logarithm of the strain rate is expressed well by the following equation over a wide range of tertiary creep, irrespective of stress and temperature⁴⁻⁷⁾.

$$\ln \dot{\varepsilon} = \ln \dot{\varepsilon}_0 + \Omega \varepsilon, \quad \dots \dots \dots [1]$$

where, $\dot{\varepsilon}$ is the creep rate, $\dot{\varepsilon}_0$ is the imaginary initial strain rate, and Ω is the strain rate acceleration factor. As Figs. 1 and 2 show, the magnitude of Ω increases with decreasing both stress and temperature. On the other hand, it is rather difficult to express the primary creep rate using an equation similar to Eq. [1], especially at higher stresses, and the following type of equation was employed to describe primary creep in the present study.

$$\ln \dot{\varepsilon} = \ln \dot{\varepsilon}_0^* - \Omega^* \varepsilon, \quad \dots \dots \dots [2]$$

where ε is the strain in the primary region, t is the time, and $\dot{\varepsilon}_0^*$ and Ω^* are constants. Integration of Eq. [2] with respect to time yields the following logarithmic creep equation:

$$\varepsilon = (1/\Omega^*) \ln(\Omega^* \dot{\varepsilon}_0^* t + 1), \quad \dots \dots \dots [3]$$

Figure 3 is a schematic illustration of the relationship between the logarithm of the strain rate and true strain of a tempered martensitic steel. The solid and dotted lines with the slope of Ω and $-\Omega^*$ represent the relationships given by Eqs. [1] and [2], respectively. As shown in Fig. 3, the definitions of $\dot{\varepsilon}_0$ and $\dot{\varepsilon}_0^*$ are strain rates corresponding to the intersection of the solid and dotted lines with the vertical axis, respectively.

3.2 Constitutive equations for $\dot{\varepsilon}$ and Ω

As seen in Figs. 1 and 2, the imaginary initial strain rate and Ω depend on stress and temperature, and the previous work showed that their dependencies could be expressed in the form :

$$\dot{\varepsilon}_0 = A_{\dot{\varepsilon}_0} \cdot \sigma_0^{n_{\dot{\varepsilon}_0}} \cdot \exp(-Q_{\dot{\varepsilon}_0}/RT) \quad \dots \dots \dots [4]$$

and

$$\Omega = A_{\Omega} \cdot \sigma_0^{-n_{\Omega}} \cdot \exp(Q_{\Omega}/RT) \quad \dots \dots \dots [5]$$

where $A_{\dot{\varepsilon}_0}$ and A_{Ω} are constants independent of stress and temperature, $n_{\dot{\varepsilon}_0}$ and n_{Ω} are stress exponents for the imaginary initial strain rate and Ω , respectively, Q is the apparent activation energy and Q_{Ω} is a constant showing the temperature dependence of Ω . The magnitude of these constants are listed in Table 2. The temperature-compensated $\dot{\varepsilon}_0$, i.e. $\dot{\varepsilon}_0 \cdot \exp(-Q_{\dot{\varepsilon}_0}/RT)$ is plotted against σ_0 in Fig. 4 which confirms that $\dot{\varepsilon}_0$ can be described by Eq. [4]. The figure is not given here, but the validity of Eq. [5] was also ascertained.

3.3 Constitutive equations for $\dot{\varepsilon}_0^*$ and Ω^*

Figure 5 shows the change of Ω^* with initial stress on a double logarithmic scale. It is seen that a set of data at the same temperature falls nearly along a single line, and the slope of the line is much the same at least in the

Fig. 1 Relationship between creep rate and creep strain at various stresses.

Fig. 2 Relationship between creep rate and creep strain at various temperatures.

Fig. 3 Schematic illustration of logarithm of strain rate plotted against true strain of the Mod.9Cr-1Mo steel.

range of temperature from 873 to 923 K. The effect of temperature on the magnitude of Ω^* is shown as a function of the reciprocal of temperature in Fig. 6. All the data points at the same stress fall again nearly along straight lines with the same slope, Q_{Ω^*} . From these results, the magnitude of Ω^* can be expressed by the following type of equation.

$$\Omega^* = A_{\Omega^*} \cdot \sigma_0^{-n_{\Omega^*}} \cdot \exp(Q_{\Omega^*}/RT) \quad \dots \dots \dots [6]$$

where A_{Ω^*} , n_{Ω^*} and Q_{Ω^*} are constants independent of stress and temperature, and their magnitudes are listed in Table 2. In order to examine the validity of Eq. [6],

Table 2. The magnitude of various constants.

A_o	A_Ω	n_o	n_Ω	Q_o	Q_Ω	A_{Ω^*}	n_{Ω^*}	Q_{Ω^*}	$A_{\Omega^*/\Omega}$	$n_{\Omega^*/\Omega}$	$Q_{\Omega^*/\Omega}$
$1.08 \times 10^8 / s$	0.15	13.0 ± 0.2	-1.46	751 ± 5	101 ± 1	2.77×10^2	2.94 ± 0.5	103 ± 1	2.05×10^3	2 ± 0.1	21 ± 1
				(kJ/mol)	(kJ/mol)			(kJ/mol)			(kJ/mol)

 Fig. 4 Temperature-compensated $\dot{\epsilon}_o$ versus initial stress.

 Fig. 5 Double logarithmic plot of Ω^* versus initial stress, σ_o for different temperatures.

 Fig. 6 Semi-logarithmic plot of Ω^* versus $1/T$ at different stresses.

 Fig. 7 Effect of temperature on the magnitude of stress-compensated Ω^* value.

stress-compensated Ω^* , i.e., $\Omega^* \cdot \sigma_o^{n_{\Omega^*}}$ is plotted against $1/T$ in Fig. 7. There is some scattering of the results, however, almost all data fall on a single line showing the validity of the constitutive equation. The validity of Eq. [6] is shown in Fig. 8, where the vertical axis shows the measured Ω^* and horizontal axis shows the calculated Ω^* . Although there is some scattering of the data points, the calculated data fall nearly on a diagonal line.

As suggested from Figs. 1 and 2, the stress and temperature dependence of $\dot{\epsilon}_o^*$ can be expressed by an equation similar to Eq. [1]. However, we gave up deriving the constitutive equation of $\dot{\epsilon}_o^*$ because of the large scattering of results. To avoid this difficulty, the relation between $\dot{\epsilon}_o^*$ and $\dot{\epsilon}_o$ was examined, and the result is shown in Fig. 9. It is seen that the magnitude of $\dot{\epsilon}_o^*$ can be estimated from the magnitude of the imaginary initial strain rate expressed in the form:

$$\dot{\epsilon}_o^* = 0.138 \cdot \dot{\epsilon}_o^{0.725} \quad \dots \dots \dots [7]$$

4 Discussion

4.1 Correlation between parameters

Four parameters, $\dot{\epsilon}_o$, $\dot{\epsilon}_o^*$, Ω and Ω^* , were introduced in the present study, in order to describe the characteristics of both primary and tertiary creep. However, they seem to have something to do with each other. Actually, as a glance at Fig. 3 confirms, the magnitude of $\dot{\epsilon}_o$ decreases steadily in response to the increase of the magnitude of Ω . In fact, it should be noted that both $\dot{\epsilon}_o$ and Ω are expressed as a function of initial stress and temperature as shown by Eqs. [4] and [5]. Thus, elimination of σ_o from the two equations yields the following:

 Fig. 8 Comparison of calculated Ω^* with measured one.

 Fig. 9 Relationship between $\dot{\epsilon}_o$ and $\dot{\epsilon}_o^*$.

$$\dot{\epsilon}_o = A_o A_{\Omega}^{(n_o/n_{\Omega})} \Omega^{-(n_o/n_{\Omega})} \exp\left[-\left\{Q_o - (n_o/n_{\Omega})Q_{\Omega}\right\}/RT\right] \quad \cdot \cdot [8]$$

Furthermore, one of the parameters for tertiary creep, $\dot{\epsilon}_o$, also has a close connection with a primary parameter, $\dot{\epsilon}_o^*$ as given by Eq. [7]. Since Ω and Ω^* are both two-valued functions of σ_o and T as given by Eqs. [5] and [6], it is possible to express Ω^* as a function of Ω and T or σ_o . However, Ω^*/Ω can be expressed in terms of σ_o and T for convenience as below:

$$\Omega^*/\Omega = A_{\Omega^*/\Omega} \cdot \sigma_o^{-n_{\Omega^*/\Omega}} \cdot \exp(Q_{\Omega^*/\Omega}/RT), \quad \cdot \cdot [9]$$

where $A_{\Omega^*/\Omega}$ is a constant independent of stress and temperature, $n_{\Omega^*/\Omega}$ is the stress exponent of Ω^*/Ω , and $Q_{\Omega^*/\Omega}$ is a constant to show the temperature dependence of Ω^*/Ω . The magnitude of all these constants are listed in Table 2.

As can be understood from the foregoing discussion, the four parameters, $\dot{\epsilon}_o$, $\dot{\epsilon}_o^*$, Ω and Ω^* , are not independent. In plain terms, an independent variable is one out of four parameters excepting the external variables of initial stress and temperature. This means that the knowledge of the stress and temperature dependence of only one parameter allows us to predict creep rate, creep life, and also the profiles of primary and tertiary creep curves making use of the interrelations among these parameters.

4.2 Creep life prediction based on tertiary creep modeling

When the duration of primary creep is short enough for substantial description of the creep curve using Eq. [1], the creep life can be expressed by the following equation⁴⁻⁷.

$$t_r = 1 / \Omega \dot{\epsilon}_o \quad \cdot \cdot \cdot \cdot [10]$$

Actually, steels with tempered martensitic structures exhibit a pronounced primary creep region, so the life prediction based on Eq. [10] allows us only a crude estimation. It is, however, worthwhile to examine the accuracy of Eq. [10] when it is applied to the Mod.9Cr-1Mo steel. The calculated creep life from Eq. [10] is compared with the measured life in Fig. 10, where open circles denote the calculated creep life, and an explanation of the solid squares is given in section 4.3 below. It is seen in Fig. 10 that the measured creep life is always shorter than the creep life calculated from Eq. [10]. This is because the primary creep of this steel accounts for a large share of the total creep life. Primary creep must therefore be taken into account in order to improve the accuracy of creep life prediction.

Fig. 10 Comparison of calculated creep life with experimental one.

4.3 Modification of current tertiary creep modeling

Equation [10], which is based on tertiary creep modeling, gives us a simple tool for predicting creep life. However, the calculated creep life was always longer by a factor of about two when it was applied to the Mod.9Cr-1Mo steel. In this section, the effect of primary creep will be taken into account to improve the accuracy of creep life prediction. First of all, the regions where eqs. [1] and [2] are applicable must be determined by eliminating time, t from these equations. The resultant equation is as follows:

$$\epsilon^* = \left\{ \ln(\dot{\epsilon}_o^*/\dot{\epsilon}_o) \right\} / (\Omega + \Omega^*) \quad \cdot \cdot \cdot [11]$$

Since the stress and temperature dependencies of the four parameters have already been decided so far, the magnitude of ϵ^* is readily obtainable for any creep conditions. As shown in Fig. 3, Eq. [1] is valid when the strain is larger than ϵ^* , while Eq. [2] is applicable when the strain is less than ϵ^* . Figure 3 also shows that the actual creep rates

are always greater than those calculated from Eqs. [1] and [2] when creep strain is around ε^* . However, this difference does not have a serious effect on creep life prediction as will be seen later. Although the magnitude of ε^* is not exactly the same as ε_m , the creep strain corresponding to minimum creep, it is nevertheless a good measure for the estimation of strain to minimum creep.

Once the magnitude of ε^* is determined, t^* corresponding to ε^* can be readily derived from Eq. [3] as below:

$$t^* = \left\{ \exp(\Omega^* \varepsilon^*) - 1 \right\} / (\Omega^* \dot{\varepsilon}_o^*) \quad \dots [12]$$

On the other hand, the integration of Eq. [1] between t^* and rupture life, t_r , gives the following equation:

$$t_r - t^* = \left\{ \exp(-\Omega \varepsilon_r) - \exp(-\Omega \varepsilon^*) \right\} / (\Omega^* \dot{\varepsilon}_o^*), \quad \dots [13]$$

where ε_r is the rupture strain. Since the magnitude of $\exp(-\Omega^* \varepsilon_r)$ is negligibly small in general, the following equation results:

$$t_r = t^* + \exp(-\Omega \varepsilon^*) / (\Omega^* \dot{\varepsilon}_o^*) \quad \dots [14]$$

Using Eq. [14] in which primary creep is taken into account, creep life can be predicted with the knowledge of the stress and temperature dependence of the four parameters, $\dot{\varepsilon}_o$, $\dot{\varepsilon}_o^*$, Ω and Ω^* . As discussed in section 4.1, the four parameters are not independent variables as Eqs. [7], [8] and [9] show. In other words, Eq. [14] can be expressed by only one out of the four parameters. The solid circles in Fig. 10 were thus obtained from the knowledge of the stress and temperature dependence of only one parameter. It is seen from Fig. 10 that the solid circles fall neatly along the diagonal line, showing that Eq. [14] is able to predict creep life properly even if the specimens exhibit a pronounced primary region.

4.4 Reproducibility of the creep curve

So far, an attempt has been made to describe creep behavior using four parameters although there are some interrelations among them. Hereafter, reproducibility of the creep curve will be examined using these parameters. Integration of Eq. [1] gives the following equation:

$$\varepsilon = (1/\Omega) \ln [1/(1 - \Omega \dot{\varepsilon}_o t)] \quad \dots [15]$$

As a matter of course, Eq. [15] is valid when time t exceeds t^* .

Since the stress and temperature dependencies of the four parameters were already determined, the magnitudes of ε^* and t^* can be obtained from Eqs. [11] and [12], respectively. When the time exceeds t^* , a strain increment during tertiary creep can be obtained by substituting $(t - t^*)$ for t in Eq. [15]. An example of the resultant normalized creep curve is shown in Fig. 11. As Figure 11 shows, the reproduced normalized creep curve agrees well with the measured one. On the other hand, in the case of the creep curve, there is some difference between the actual creep life and the reproduced one. However, the maximum difference in creep life was found to be less than 12% in the present study.

Fig. 11 Comparison between calculated and measured creep curve of Mod.9Cr-1Mo steel.

5. Conclusions

Constant load creep testing was conducted on the Mod.9Cr-1Mo steel in the range of stress and temperature from 107.9 to 235.3 MPa and 873 to 923 K, and creep curve analysis was performed in order to derive constitutive equations to enable us to predict creep life and to depict creep curves at any conditions. The results obtained are as follows:

- (1) A Mod.9Cr-1Mo steel with a martensitic structure showed extended duration of the primary creep region, which accounts for about 30% of the total life.
- (2) Creep life predicted using creep modeling of the tertiary creep region alone was longer by a factor of about 2 than the measured creep life.
- (3) A logarithmic creep equation was employed for quantitative description of primary creep, and the dependence of stress and temperature of the constants in the equation was determined for reproduction of primary creep behavior and creep life prediction.
- (4) Tertiary creep behavior was analyzed on the basis of a tertiary creep modeling, the Ω method, and the constants appearing in the constitutive equations were determined as functions of stress and temperature.
- (5) Four parameters, which were introduced to describe both primary and tertiary creep, were correlated to each other.
- (6) Creep life was predicted satisfactorily from the proposed creep model, in which the duration of primary creep was taken into account.

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