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High-temperature creep behaviour of 15CrMoG heat-resistant steel

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Abstract. Rapid increase in power plant efficiency requires development of heat-resistant steels for use in the boiler and piping systems. In this study, the creep activation energy of 15CrMoG steel was first investigated on the basis of the relationship between creep rate and temperature subjected to different stresses. Long-time creep tests at selected temperatures were performed for the 15CrMoG steel. Manson-Haferd model was utilized to predict the creep behavior of the steel, the results of which indicate that the experimental creep data agreed well with the data from the Manson-Haferd model prediction. Besides, the strain vs. creep time curves obtained from the creep tests were in good accordance with theoretical calculation based on the CDM model over a long creep time. Both Manson-Haferd model and CDM model are powerful tools in studying the high-temperature creep behaviour of the 15CrMoG steel.

1. Introduction

15CrMoG steel is a type of pearlitic heat-resistant steel, which has been extensively used in power plants and petrochemical industry [1]. In many cases, heat-resistant steels with long creep rupture lives under a constant stress at temperatures of ~500 ℃ are expected as the materials used for boilers [2]. Creep behaviour evaluation and life prediction for those steel materials are receiving growing attention as safe and economical operations of power plants are important for industry and people's life [3-5]. In this work, high-temperature creep tests were performed for 15CrMoG steel samples under different conditions. The creep activation energy of 15CrMoG steel was evaluated by analyzing the relationship between creep rate and temperature under various stresses. Manson-Haferd model and CDM model proved to be applicable for the creep behaviour prediction of the 15CrMoG steel.

2. Experimental

2.1. Materials

The 15CrMoG steel sampled from new boilers of a power station was used for study. The chemical composition of the steel was determined by an Optical Emission Spectrometer (ARL 4460, Thermo Scientific), and the results of two samples are shown in Table 1.

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Table 1. Chemical compositions of 15CrMoG steel (at.%).

Sample	C	Si	Mn	P	S	Cr	Mo
1	0.142	0.233	0.508	0.0087	0.0054	0.982	0.458
2	0.144	0.232	0.511	0.0089	0.0051	0.980	0.461

2.2. Creep tests
Tensile creep tests at different temperatures were conducted in the open air using an electronic high temperature creep & rupture testing machine (GWT2105, MTS) with constant loads to investigate the creep properties of the 15CrMoG steel. Standard cylindrical samples according to DIN50125 B 4×20 were used.

3. Results and discussion

3.1. Creep activation energy
Creep activation energy is a key parameter for studying the high-temperature creep behavior of heat-resistant steels [6]. Arrhenius equation is useful for calculating the creep activation energy of most steels:

$$\varepsilon_m = A\sigma^n \exp[-Q_c/(RT)] \quad (1)$$

where ε_m is the minimum creep rate; A is a material-dependent constant; n is the stress exponent; σ is the applied stress (MPa); Q is the creep activation energy (kJ/mol); R is the gas constant; T is the absolute temperature (K).

When the stress keeps constant, the creep activation energy can be calculated by the following equation:

$$Q_c = -R[\partial ln\dot{\varepsilon}_m/\partial(1/T)]_\sigma \quad (2)$$

The ε_m of 15CrMoG steel has been determined by creep testing at different temperatures and stresses, based on which the creep activation energy of 15CrMoG steel can be calculated. The obtained results are listed in Table 2. From the data shown in Table 2, we found that the creep activation energy decreases with decreasing stress at the same temperature. Under the same stress, however, the creep activation energy does not change much with the increase of temperature. These results indicate that the stress exerts greater effects on the creep activation energy.

Table 2. Creep activation energy values of 15CrMoG steel at varied temperatures and stresses.

T (℃)	σ (MPa)					
	200	180	160	140	100	80
450-500	840.3	778.9	664.7	590.5	--	--
500-550	--	725.2	689.8	601.4	542.0	--
550-600	--	--	--	612.6	550.1	477.4

3.2. Manson-Haferd model
As a frequently used model for life prediction of heat-resistant steels, the Manson-Haferd (M-H) model was chosen to predict the creep rupture life of 15CrMoG steel [7]:

$$P_{MH}(\sigma) = (lgt_r - lgt_a)/(T - T_a) \quad (3)$$

where σ is the applied stress (MPa); lgt_a and T_a are two characteristic parameters of the M-H model. In this model, the lgt_r is linear with the T if the σ is fixed. It is important to determine the optimal values of lgt_r and T for creep rupture life prediction. In the present work, the lgt_r and T were calculated according to the point whose distance from the isostress lines is minimal. The distance of the optimal point from the isostress lines can be determined by the following equation:

$$d = \min(\sum_{i=1}^{n}(a_i x + b_i y + c_i)/\sqrt{a_i^2 + b_i^2}) \tag{4}$$

where d is the distance between a point and the isostress lines; n equals 8 herein. a_i, b_i and c_i are the coefficients of the isostress lines; (x, y) is the coordinate values of the optimal point. The x and y values were limited within a certain range based on the characteristic properties of the 15CrMoG steel. Thus, the Eq. (3) can be expressed as:

$$lgt_r = (T - T_a)(a_0 + a_1 lg\sigma + a_2 lg^2\sigma + a_2 lg^3\sigma) + lgt_a \tag{5}$$

where a_0, a_1, a_2 and a_3 are all constants. MATLAB was adopted for calculation and fitting, and the resultant optimal parameters are listed in Table 3.

Table 3. Manson-Haferd model parameters for 15CrMoG steels.

a_0	a_1	a_2	a_3	lgt_a	T_a
0.2409	-0.5011	0.2782	-0.06303	13.75	718.13

3.3. Rupture stress vs. creep time curves

Figure 1 shows the experimental data and the M-H model prediction data of rupture stress vs. creep time for the 15CrMoG steel at varied temperatures over a period of more than 20000 h. It is evident that the M-H model prediction curves were in perfect accordance with the experimental data at the three temperatures, indicating the suitability of the M-H model for the 15CrMoG steel. At the initial stage of the creep tests, the rupture stress shows a relatively slow decrease. As the creep time exceeds 100 h, the stress decreases more rapidly. Subjected to the creep tests for up to 20000 h, the 15CrMoG steel maintains at a rupture stress of ca. 60 MPa at 450 ℃ and over 40 MPa at 500 ℃. At the temperature of 550 ℃, the stress decreases to ca. 30 MPa after 19000 h at 550 ℃. It can be concluded that the 15CrMoG steel has high creep performance at the temperatures of below 550 ℃.

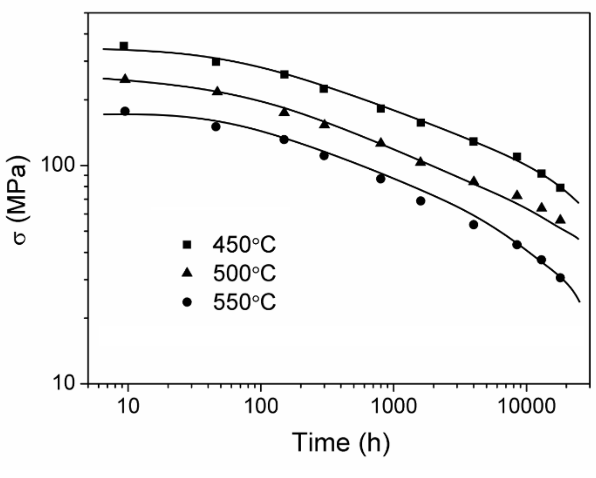

Figure 1. Changes of rupture stress with creep time (scatter) as well as M-H model predictions (curve) for 15CrMoG steel at different temperatures.

3.4. Strain vs. creep time curves

The experimental creep curves together with the predicted creep curves based on the CDM model for the 15CrMoG steel under two conditions are shown in Figure 2. In spite of the different stresses and temperatures applied, a significant primary creep is observed in both experimental curves. Throughout the creep processes, the sample tested at 150 MPa and 550 ℃ shows smaller strains. The CDM curves captured the experimental creep data well, especially for the sample tested at 210 MPa and 500 ℃, indicating the applicability of the CDM model for predicting the creep behaviour and creep life of the 15CrMoG steel.

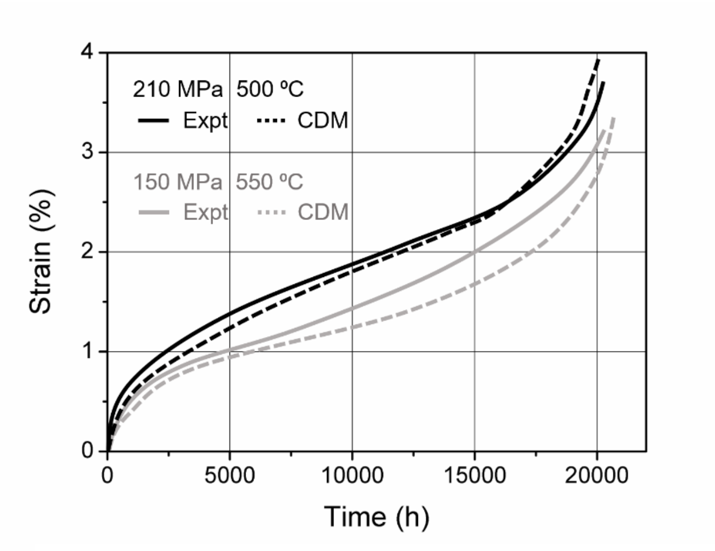

Figure 2. Comparison of experimental and CDM prediction creep curves for 15CrMoG steel under two conditions.

4. Conclusions

In conclusion, the creep activation energy of the 15CrMoG steel has been evaluated and its high-temperature creep behaviour has been studied by long-lasting creep tests at appropriate temperatures. The applicability and reliability of M-H model and CDM model have been evaluated. The rupture stress vs. creep time data and the strain vs. creep time data agree well with the M-H model and the CDM model, respectively, demonstrating that the long-time high-temperature creep behaviour of the 15CrMoG steel can be well predicted by appropriate modeling. The 15CrMoG steel has excellent long-time creep performance at the temperatures of below 550 ℃.

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