High-temperature Creep Tests and Analyses for T23 and T24 Steels

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Abstract. T23 and T24 heat-resistant steels are ideal metal materials for high-temperature and high-pressure boilers of ultra-super critical (USC) power plants. In the present work, the creep activation energy of T23 and T24 steels was studied based on the relationship between creep rate and temperature under different stresses. Long-time creep tests at high temperatures were carried out for T23 and T24 steels. Manson-Haferd model was adopted to predict the creep life of the two steels, the results of which demonstrate that the data from the creep tests were in good accordance with the data from Manson-Haferd model prediction. Manson-Haferd model is useful in the high-temperature creep study for the T23 and T24 steels.

1. Introduction

Ultra-super critical (USC) power plants have been developing rapidly under urgent demands for clean energy and global environment protection. Construction of USC power plants requires materials with excellent high-temperature creep strength and resistance to hot corrosion [1]. Generally, creep rupture lives of 100,000 hours under a stress of 100 MPa at temperatures of 650 ℃ or above are expected [2]. T/P23 and T/P24 steels are relatively new steel grades that allow welding without post weld heat treatment [3]. These steels are preferable materials for fabricating large water wall panel used in boilers. Since safe and economical operations of power plants are extremely important, life prediction becomes a major concern for the steels serviced in boilers [4, 5]. In this study, the creep activation energy of T23 and T24 steels was investigated by analyzing the relationship between creep rate and temperature under different stresses. In addition, long-time high-temperature creep tests were performed and Manson-Haferd (M-H) model was utilized to predict the creep life of the two steels.

2. Experimental

2.1. Materials

The T23 and T24 steels sampled from new boilers of a power station were studied. The chemical compositions of the two steels were determined using an Optical Emission Spectrometer (ARL 4460, Thermo Scientific), and the results are shown in Table 1.

Table 1. Chemical compositions of T23 and T24 steels (at.%).

Steel	C	Si	Mn	P	S	Cr	Mo	Nb	V	N	W	Ti
T23	0.054	0.349	0.336	0.011	0.003	2.33	0.152	0.057	0.210	0.011	1.55	/
T24	0.079	0.293	0.504	0.010	0.003	2.51	0.959	/	0.219	0.006	/	0.068

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 two steels. Standard cylindrical samples according to DIN50125 B 4×20 were used.

3. Results and discussion

3.1. Creep activation energy

Creep activation energy is an important parameter for studying the high-temperature creep behavior of steels [6]. Arrhenius equation is often used to calculate the creep activation energy. For most steels, Arrhenius equation can be expressed as:

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

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:

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

The ε_m of T23 and T24 steels has been determined through creep tests at varied temperatures and stresses, based on which the creep activation energy of T23 and T24 steels can be calculated, respectively. The results are listed in Tables 2. and Tables 3.

Table 2. Creep activation energy values of T23 steel at different temperatures and stresses.

T (℃)	σ (MPa)					
	180	160	140	120	80	60
550-600	795.3	764.1	659.4	601.0	--	--
600-650	--	718.2	675.3	588.1	527.4	--
650-700	--	--	--	606.8	547.5	462.3

Table 3. Creep activation energy values of T24 steel at different temperatures and stresses.

T (℃)	σ (MPa)					
	180	160	140	120	80	60
550-600	810.4	788.5	671.3	611.6	--	--
600-650	--	730.4	692.0	600.9	531.0	--
650-700	--	--	--	615.7	555.2	463.9

It is evident that for both of the steels, the creep activation energy increases with the increase of temperature under the same stress. At the same temperature, the creep activation energy decreases with reduced stress. Moreover, the high-temperature creep performance of the T24 steel is better than the T23 steel, as reflected by the fact that the creep activation energy of the T24 steel is higher than that of the T23 steel at the same temperatures and stresses.

3.2. Manson-Haferd model

As a popular model in life prediction of heat-resistant steels, the Manson-Haferd (M-H) model was adopted to predict the creep rupture life of T23 and T24 steels. This model can be described by the following equation:

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

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 when the σ is fixed. It is crucial to determine the optimal values of lgt_r and T for creep rupture life prediction. In this study, 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 calculated according to 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 T23 and T24 steels. Eq. (3) can be further 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 used for calculation and fitting, and the resultant optimal parameters are listed in Table 4.

Table 4. Manson-Haferd model parameters for T23 and T24 steels.

	a_0	a_1	a_2	a_3	lgt_a	T_a
T23	0.2401	-0.4706	0.2749	-0.05937	14.52	733.89
T24	0.2436	-0.4821	0.2791	-0.05886	14.67	765.33

3.3. Creep curves

The experimental data of stress versus creep time as well as the M-H model predictions for the T23 and T24 steels at different temperatures over a long period are shown in Figure 1. It is clear that the M-H model prediction curves agree with the experimental data fairly well for both T23 and T24 steels at the selected temperatures, demonstrating the high prediction accuracy and applicability of the M-H model for the T23 and T24 steels. The T23 steel has similar creep behaviour to the T24 steel at 650 ℃, but has a little lower creep performance than the T24 steel at 550 and 600 ℃. Both T23 and T24 steels maintained ca. 30 MPa stress at the temperature of 650 ℃ after a creep time of over 20,000 hours, indicating that the steels may have long high-temperature creep life and can meet the demands of high-temperature and high-pressure boilers in USC power plants.
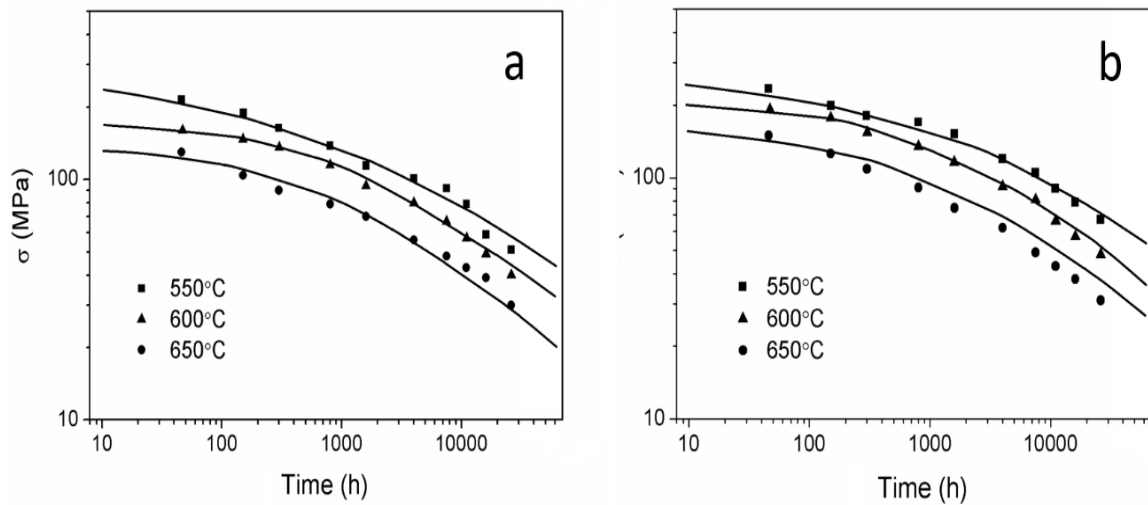
Figure 1. Changes of stress with creep time (scatter) as well as M-H model predictions (curve) for (a) T23 steel and (b) T24 steel at different temperatures.

4. Conclusions

To sum up, the creep activation energy of T23 and T24 steels has been evaluated and their high-temperature creep performance was examined by long-time creep tests at selected temperatures and Manson-Haferd modeling. The T24 steel has higher creep activation energy than the T23 steel. The data from long-time creep tests at high temperatures agreed well with the data from Manson-Haferd model prediction. It was also found that both of the steels have long high-temperature creep life and can serve well for high-pressure boilers in USC power plants.

Acknowledgment

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