High-temperature creep properties and life predictions for T91 and T92 steels

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Abstract. 9-11%Cr heat-resistant steels are widely used in high-temperature and high-pressure boilers of advanced power plants. In the current paper, high-temperature creep behaviors of T91 and T92 steels have been investigated. Creep tests were performed for both steels at varied temperatures. The creep mechanisms of T91 and T92 steels were elucidated by analyzing the creep rupture data of the two steels. In addition, Manson-Haferd model was employed to predict the creep life of T91 and T92 steels, the results of which indicate that the Manson-Haferd model works well for the two steels.

1. Introduction
Construction of advanced power plants requires materials with improved high-temperature strength and superior resistance to high temperature corrosion. 9-11%Cr tempered martensite ferritic steels are imperative high-temperature materials frequently used for critical components of fossil-fired power plants that operate in the temperature range of 500-650 °C [1, 2]. Usually, service lives exceeding 100,000 h are expected for power plant boilers. In order to guarantee safe and economical operations, life prediction is always a major concern for the materials serviced in power plants [3, 4]. In the present work, we took samples from new boilers of a power station that belong to T91 and T92 steels, respectively. The creep mechanisms of the two 9-11%Cr steels were elucidated through analyzing the data from creep tests. Moreover, Manson-Haferd (M-H) model was utilized to predict the life of the steels to be serviced in boilers.

2. Experimental
2.1. Materials
The T91 and T92 steels sampled from newly-installed 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 listed in table 1.

| Table 1. Chemical compositions of T91 and T92 steels (%) |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Steel | C    | Si   | Mn  | P   | S   | Cr  | Mo  | Nb  | V   | N   | Ni  | W   | Ti  |
|-------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| T91   | 0.083 | 0.314 | 0.403 | 0.009 | 0.002 | 8.59 | 0.918 | 0.074 | 0.202 | /   | /   | /   |
| T92   | 0.09  | 0.378 | 0.4  | 0.012 | 0.003 | 8.68 | 0.374 | 0.049 | 0.19  | 0.048 | 0.187 | 1.54 | 0.003 |
2.2. Creep tests
Tensile creep tests in air at 500 °C, 550 °C, 600 °C and 650 °C with preset load were conducted using an electronic high temperature creep & rupture testing machine (GWT2105, MTS) to determine the creep rupture times. Standard cylindrical samples according to DIN50125 B 4×20 were used.

3. Results and discussion

3.1. Creep mechanisms
Compared with heat resistant steels with lower Cr contents, more second-phase particles exist in microstructures of 9-11 %Cr steels [5, 6], which play a pivotal role in providing superior creep properties of these steels. In minimum creep rate versus applied stress plots of second-phase strengthened materials, three separable stress regions can be divided according to the stress exponent $n$ values [7]. At low stress levels usually occurring at elevated temperatures, the stress exponent $n$ is found at $\sim 1$. At higher stress levels, however, the $n$ values are larger 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 steels, i.e., climbing and Orowan mechanisms [8]. When dislocations bypass second-phase particles by the climbing mechanism, the $n$ is typically between 3 and 5. When the second-phase particles are bypassed by Orowan mechanism, the region is called a “power-law-breakdown” (PLB) region and the $n$ exceeds 7.

As shown in figure 1, both T91 and T92 steels were increasingly sensitive to the applied stress with decreasing temperature, as reflected by the growing $n$ values. In the data range, the $n$ values of both the steels are larger than 7 or at least close to 7 at the testing temperatures, indicating that Orowan mechanism dominates the second-phase particles by-pass and is thus the dominant creep mechanism. It is also found that the $n$ values of the T92 steels were larger than those of the T91 steels under the same conditions, showing that the creep rate of the T92 steels is more sensitive to the applied stress.

Figure 1. Minimum creep rate versus applied stress for (a) T91 and (b) T92 at different temperatures. The data are linearly fitted and the $n$ values represent the slopes of the fitting lines.

3.2. Manson-Haferd model
As well known, Larson-Miller (L-M) model is popular in life prediction of conventional heat-resistant steels. For the life prediction of 9-11%Cr steels, however, the L-M model is not an ideal choice. The Manson-Haferd (M-H) model is expected to be more effective in predicting the creep rupture life of T91 and T92 steels, which can be described by the following equation:

$$P_{MH}(\sigma) = (\text{lgt}_r - \text{lgt}_a)/(T - T_a)$$

where $\sigma$ is the applied stress (MPa); $\text{lgt}_a$ and $T_a$ are characteristic parameters of the model. In M-H model, the relationship between $\text{lgt}$ and $T$ is linear when the $\sigma$ is fixed. To obtain the optimal values of $\text{lgt}_a$ and $T_a$ is critical for creep rupture life prediction. Here the $\text{lgt}_a$ and $T_a$ were calculated by
determining the point whose distance from the isostress lines is at a minimum. The following equation was used for calculation:

\[ d = \min \left( \sum_{i=1}^{8} (a_i x + b_i y + c_i) / \sqrt{a_i^2 + b_i^2} \right) \]  

(2)

where \( d \) is the distance of the optimal point from the isostress lines; \( a_i, b_i, \) and \( c_i \) are the coefficients of isostress lines; \((x, y)\) is the coordinate values of the optimal point. We limited the \( x \) value in the range of 500-800 and the \( y \) value in the range of 10-20. MatLab was used for calculation and fitting, and the obtained optimal parameters are listed in table 2.

**Table 2. Manson-Haferd model parameters.**

| \( a_0 \)  | \( a_1 \)  | \( a_2 \)  | \( a_3 \)  | \( \text{lgT}_a \) | \( T_a \) |
|-------|-------|-------|-------|-------|-------|
| 0.2518 | -0.4992 | 0.2933 | -0.06522 | 14.02 | 665.89 |

3.3. Creep curves

The changes of stress with creep time and the M-H predictions for T91 and T92 steels at different temperatures over a period of more than 10000 h are shown in figure 2. It can be seen that the M-H prediction curves fit the experimental data well for both the steels at the three selected temperatures, indicating that the M-H model has high prediction accuracy for 9-11% Cr heat-resistant steels. Besides, the T92 steel exhibited a little better mechanical performance than the T91 steel during the high-temperature creep tests, as reflected by higher stress under the same testing conditions.

![Figure 2. Changes of stress with creep time (scatter) along with M-H predictions (curve) for (a) T91 steel and (b) T92 steel at different temperatures.](image)

4. Conclusions

In conclusion, we have studied the high-temperature creep behaviors of T91 and T92 steels. Creep tests were conducted at selected temperatures, the results of which indicate that Orowan mechanism is the dominant creep mechanism of both two steels at high temperatures. Manson-Haferd model has been utilized to predict the creep life of the steels. The results of calculation and experiments demonstrate that the Manson-Haferd model is suitable for the two steels.

**Acknowledgment**

This work is financially supported by the Quality and Technology Supervision of Zhejiang Province (Grant No. 20170251) and The National Key Research and Development Program of China (Grant No. 2017YFF0210702).

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