Creep Tests and Modeling Based on Continuum Damage Mechanics for T91 and T92 Steels

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Abstract. 9-11%Cr ferritic steels play an important role in high-temperature and high-pressure boilers of advanced power plants. In this paper, a continuum damage mechanics (CDM)-based creep model was proposed to study the creep behavior of T91 and T92 steels at high temperatures. Long-time creep tests were performed for both steels under different conditions. The creep rupture data and creep curves obtained from creep tests were captured well by theoretical calculation based on the CDM model over a long creep time. It is shown that the developed model is able to predict creep data for the two ferritic steels accurately up to tens of thousands of hours.

1. Introduction
Construction of advanced power plants requires materials with improved high-temperature strength and superior resistance to high-temperature corrosion. Enhancing the operating temperature and pressure of boilers has led to the development of creep-resistant steels [1,2]. During the past decades, continuous efforts have been devoted to the developing creep-resistant 9-11%Cr ferritic steels. The complex microstructure of 9-11%Cr steels has hindered the establishment of a convincing and comprehensive model for creep deformation of these alloys. This in turn has caused problems with reliable extrapolation of creep behavior from short-term tests [3-5]. The MIKORA model considered subgrain walls to be the main source of strengthening, and their effect was modeled by considering them to be hard regions surrounded by a soft ferritic matrix [6]. Another model by Semba et al. was on the basis of continuum damage mechanics (CDM) and a large amount of work in this area over the past years [7,8]. Semba et al. regarded nanosized MX carbonitride particles as the obstacles to dislocation motion, whose spacing was used to define the reference stress. The back stress was assumed to arise as a result of stress redistribution between hard and soft regions in the alloy [9].

Notwithstanding the lack of complete knowledge of the various microstructural features, there have been attempts to construct CDM-based creep models for bainitic steels [10]. In the present study, the CDM framework was used to develop a creep model for 9-11%Cr ferritic steels. The calculated results based on the creep model were compared with the experimental results for T91 and T92 steels. The creep tests lasted for a period of over 20,000 h.
2. Experimental

2.1. Materials
The T91 and T92 steels sampled from 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.

| 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 various temperatures 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 model description
The most important property of heat-resistant steels is the creep rupture strength. Therefore, a set of CDM equations utilized for the T91 and T92 steels studied here is as follows.

Master equation: \( \dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{Q_c}{RT}\right) \sin h\left[\frac{1-H^*(1-D_S)}{\sigma_o(1-D_P)}\right] \) (1)

Primary creep: \( \dot{\sigma}_o = K_1(1-\sigma_o/K_2)\dot{\varepsilon} \) (2)

Subgrain evolution: \( \dot{D}_S = \frac{k}{S_1}(K_{S1} + K_{S2}\exp\left(-\frac{Q_S}{RT}\right)) \times (1-D_S)^2 \) (3)

MX evolution: \( \dot{D}_P = K_P/P^*\exp\left(-\frac{Q_P}{RT}\right)(1-D_P)^4 \) (4)

The corresponding parameters for the set of equations are listed in Table 2.

| Parameter | Units | T91      | T92      |
|-----------|-------|----------|----------|
| \( \dot{\varepsilon}_0 \) | s\(^{-1}\) | 7.23×10\(^6\) | 1.06×10\(^7\) |
| \( K_1 \) | MPa   | 5.81×10\(^3\) | 6.67×10\(^3\) |
| \( K_2 \) | MPa   | 11.7     | 11.8     |
| \( H^* \) | None  | 0.45     | 0.45     |
| \( Q_c \) | kJ mol\(^{-1}\) | 360       | 360       |
| \( Q_p \) | kJ mol\(^{-1}\) | 270       | 286       |
| \( Q_S \) | kJ mol\(^{-1}\) | 282       | 294       |
| \( K_P \) | m\(^3\) s\(^{-1}\) | 3.4×10\(^{-16}\) | 4.5×10\(^{-17}\) |
| \( K_{S1} \) | m s\(^{-1}\) | 4.10×10\(^{-6}\) | 3.95×10\(^{-6}\) |
| \( K_{S2} \) | m s\(^{-1}\) | 2.97×10\(^{-12}\) | 5.9×10\(^{-12}\) |
| \( P_1 \) | nm    | 7.22     | 3.89     |
| \( S_1 \) | nm    | 245      | 263      |

3.2. Creep rupture analysis
CDM prediction curves as well as the experimental rupture data at four specific temperatures for T91 and T92 steels are shown in Figure 1. For both steels, the creep rupture stress decreased with
increasing temperature, as the creep rupture becomes severer at higher temperatures. Subjected to higher loads, it took shorter time periods for the two steels to rupture, as expected. In addition, the T92 steel is more creep resistant than T91 steel, since the creep rupture stress of the T92 steels was higher than that of the T91 steel under the same conditions. The experimental rupture data were captured well by the predicted curves based on the CDM model. It is thus possible to describe most of the features of the creep curves of ferritic steels with the proposed CDM model.

3.3. Creep curves

Figure 2 shows experimental creep curves as well as predicted creep curves based on the CDM model for T91 and T92 steels under different conditions. For the T92 steel, a pronounced primary creep can be found in the curves with similar magnitudes, despite the significantly different stresses and temperatures applied. The CDM curves agreed perfectly with the experimental data, especially at the creep time shorter than 15000 h. In the case of T91 steel, the experimental data were also predicted well by the CDM model in the data range, further indicating the reliability of the proposed model. Besides, the T91 steel seemed to behave much differently under the two conditions, implying that the creep behavior of this ferritic steel is affected greatly by temperature and loading.

4. Conclusions

In conclusion, we have successfully established a CDM-based creep model for typical 9-11%Cr ferritic steels, i.e., T91 and T92 steels. Creep tests were performed for the T91 and T92 steels, the
results of which indicate that the set of equations works well in describing and predicting high-temperature creep behavior for both T91 and T92 steels. The soundness and reliability of the proposed CDM model have been confirmed.

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