Structural changes of 12Cr1MoVG steel during high-temperature creep

Jinping Pan¹,², Bo Xu²,³, Xinwei Zhu¹, Xuefen Yu³,⁶, Lianjiang Tan⁴,⁶

¹Jiaxing Special Equipment Inspection Institute, Jiaxing 314051, China;
²Ningbo Special Equipment Inspection and Research Institute, Ningbo 315048, China;
³Zhejiang Academy of Special Equipment Science, Hangzhou 310020, China;
⁴School of Materials Science and Engineering, Shanghai Institute of Technology, Shanghai 201418, China

⁵These authors contributed equally to the paper.
⁶Email: 1046794280@qq.com; tanlianjiang@126.com

Abstract. Heat-resistant steels are key metal materials for high-temperature and high-pressure boilers of ultra-super critical (USC) power plants. A lot of steels have been designed for heat resistance purposes, among which 12Cr1MoVG steel is a good alternative but has not been studied intensively for its high-temperature creep properties. In the current work, the 12Cr1MoVG steel was subjected to long-term creep at different temperatures. The 20000 h creep rupture stress showed obvious decrease with increasing temperature in the data range. The structural changes of the 12Cr1MoVG steel during the high-temperature creep tests was investigated by analyzing the cavitation and metallographic structure before and after the creep tests. The results indicated that the structural changes had close relationships with the creep behavior and mechanical properties of the steel. This work gives insights into the high-temperature creep study of heat-resistant steels.

1. Introduction

Steels are the most useful metal materials in human life [1,2]. Ultra-super critical (USC) power plants have been developing intensively due to the urgent demands for clean energy and environment protection. Construction of USC power plants requires materials with excellent high-temperature creep strength and resistance to hot corrosion [3]. In general, a long creep rupture life under a stress of over 100 MPa at the temperatures of ~600 °C are required [4]. Varieties of heat-resistant steels have been studied with regard to creeping at high temperatures [5-7]. 12Cr1MoVG steel is a preferable material for fabricating large water wall panel used in boilers. Since safe and economical operations of power plants are crucial, structural changes and cavitation of the heat-resistant steels used in boilers have become a major concern [8-10]. Nevertheless, systematic study for the long-time creep of 12Cr1MoVG steel at high temperatures is insufficient. In the current work, creep tests at high temperatures were performed for 12Cr1MoVG steel. The creep cavitation was investigated to unveil the cavities evolution in the 12Cr1MoVG steel over long-term period of high-temperature creep. Besides, metallographic structure before and after the long-term creep was compared.
2. Experimental

2.1. Materials
The samples of 12Cr1MoVG steel in this work were provided by a USC power plant. The elementary composition was determined by an Optical Emission Spectrometer (ARL 4460, Thermo Scientific). The elementary composition is shown in Table 1.

| Table 1. Chemical composition of 12Cr1MoVG steel (at.%) |
|--------------------------------------------------------|
| C | Si | Mn | Cr | Mo | V | P | S |
|---|----|----|----|----|---|---|---|
| 0.109 | 0.252 | 0.451 | 1.110 | 0.2859 | 0.186 | 0.022 | 0.013 |

2.2. Creep tests
Tensile creep tests for 12Cr1MoVG samples were carried out at selected temperatures on a high-temperature electronic creep and rupture testing machine (GWT2105, MTS) with constant loads. The samples were processed into rectangular specimen (50*15*3 mm), and two samples were measured in each test.

2.3. Metallographic analysis
12Cr1MoVG steel specimens were processed using a metallographic mosaic machine (CitoPress-10, Struers) to obtain samples with appropriate sizes and shape. Then the samples were processed by an automatic polish-grinding machine (Tegramin-30, Struers) and were etched with 4 % nitric acid in ethanol. The resultant samples were washed thoroughly with ethanol and were observed by an inverted optical microscopy (GX51, Olympus).

3. Results and discussion

3.1. Creep rupture strength
Through tensile creep tests at varied temperatures, the creep rupture strength at 20000 h of 12Cr1MoVG was measured. Figure 1 shows the plot of creep rupture strength at 20000 h versus temperature. As the temperature increased from 450 °C to 625 °C, the creep rupture strength at 20000 h decreased from 130 to 20 MPa, demonstrating the significant effects of temperature on the creep rupture life of the 12Cr1MoVG steel. In the temperature range characteristic of the boilers in operation, the creep behavior of the 12Cr1MoVG steel is sensitive to the temperature changes. The data of creep rupture strength help to evaluate the work conditions of the 12Cr1MoVG steel and predict the service life of the 12Cr1MoVG steel under the work conditions.

![Figure 1](image)

**Figure 1.** Changes of creep rupture strength at 20000 h with temperature for the 12Cr1MoVG steel.
3.2. Structural changes

Materials have various creep damage mechanisms. Nevertheless, some characteristics are common, such as growth and coalescence of cavities into microcracks, and then into macroscopic cracks that become detectable by conventional non-destructive technique [11]. We measured the cavity density in the 12Cr1MoVG steel within a certain area. The results in Figure 2a indicate that the cavity density decreased from around 3700 to around 100 per square millimeters when the distance from the notch tip increased to 4 mm. This suggests that cavities start to appear in vicinity of the edge of a sample. Thereafter, more cavities are produced, both in the vicinity of the edge and in the area away from the edge. As indicated in Figure 2b, the average cavity size over the area measured fluctuated within a certain range from around 2.8 to 4.4 \( \mu m \). These cavities gradually grew to larger sizes, coalescing into larger cavities or cracks, and finally formed macroscopic cracks that would lead to rupture of the steel.

It was the formation and evolution of cavities in the 12Cr1MoVG steel that resulted in deteriorated mechanical properties during the long-term creep at a high temperature. Compared with 15CrMoG steel reported in our previous work [12], the density of cavities in the 12Cr1MoVG steel was lower under similar creep conditions. The average cavity diameter was close to that of the 15CrMoG steel. These results indicate that the 12Cr1MoVG steel has higher creep resistance at its service temperatures.

![Figure 2](image-url)

**Figure 2.** (a) Cavity density and (b) average diameter of cavities in the 12Cr1MoVG steel with a size of 4.5×3 mm\(^2\). The quantity of cavities was measured along the tensile direction. The data in plot b are presented as the average ± standard deviation.

In order to further investigate the changes in microstructure of the 12Cr1MoVG steel subjected to the long-term creep, metallographic images of an untreated sample and a sample experiencing creep at 600 °C over 20000 h were obtained, as shown in Figure 3. For the untreated sample (Figure 3a), the dark regions denote unspheroidized pearlite, where the carbide exists in lamellar form. For the sample after long-term creep (Figure 3b), the light regions denote the pearlite and ferrite. The carbide was distributed at the grain boundaries, suggesting that pearlite spheroidization took place in the sample subjected to the creep tests at the selected temperature.
4. Conclusions

To sum up, the 12Cr1MoVG steel has been subjected to long-term creep tests at selected temperatures, based on which the creep rupture strength at 20000 h was obtained. According to the long-term creep rupture data, appropriate work conditions for the 12Cr1MoVG steel as a key material for boilers can be determined. The structural changes of the 12Cr1MoVG steel during the long-term creep were studied by analyzing the evolution of cavities in the steel and observing the metallographic changes. The cavitation evolution including migration and growth of cavities with the time account for the reduced mechanical performance of the steel. Subjected to the creep, the 12Cr1MoVG steel showed the phenomenon of pearlite spheroidization, as reflected by the distribution of carbide at the grain boundaries. The findings of this work provide useful information on the creep properties at high temperatures of 12Cr1MoVG steel and can guide the safe service of the boilers using 12Cr1MoVG steel as the material.

Acknowledgment

This work is financially supported by the Jiaxing Science and Technology Project (2019AD32016).

References

[1] Roy K, Ting T C H, Lau H H, Lim J B P 2019 Experimental and numerical investigations on the axial capacity of cold-formed steel built-up box sections. J. Constr. Steel. Res. 160 411-427
[2] Ting T C H, Roy K, Lau H H, Lim J B P 2018 Effect of screw spacing on behavior of axially loaded back-to-back cold-formed steel built-up channel sections. Adv. Struct. Eng. 21 474-487
[3] Aghajani A, Somsen Ch and Eggeler G 2009 On the effect of long-term creep on the microstructure of a 12% chromium tempered martensite ferritic steel. Acta Mater. 57 5093-5106
[4] Rojas D, Garcia J, Prata O, Carrascoc C, Sauthoffa G, Kaysser-Pyzalla A R 2010 Design and characterization of microstructure evolution during creep of 12% Cr heat resistant steels. Mater. Sci. Eng. A 527 3864-3876
[5] Guo L, Sui Y-h, Zhang X-Z (2018) High-temperature creep constitutional model of Q460E steel and effect of creep on bulging deformation of continuous casting slab. J. Iron Steel Res. Int. 25 1123-1130
[6] Pan J P, Tu S H, Sun G L, Zhu X W, Tan L J, Hu B 2018 High-temperature creep properties and life predictions for T91 and T92 steels. IOP Conference Series: Materials Science and Engineering 292 012098
[7] Peng Y-Q, Chen T-C, Chung T-J, Jeng S-L, Huang R-T, Tsay L-W 2017 Creep Rupture of the
simulated HAZ of T92 steel compared to that of a T91 steel. Materials 8 139

[8] Fedoseeva A, Dudova N, Kaibyshev R 2016 Creep strength breakdown and microstructure evolution in a 3%Co modified P92 steel. Mater. Sci. Eng. A. 654 1-12

[9] Vallant J C, Vandenbergh B, Hahn B, Heuser H and Jochum C 2008 T/P23, 24, 911 and 92: New grades for advanced coal-fired power plants-properties and experience. Int. J. Pres. Ves. Pip. 85 38-46

[10] Cerjak H, Hofer P and Schaffernak B 1999 The influence of microstructural aspects on the service behaviour of advanced power plant steels. ISIJ Int. 39 874-888

[11] Auerkari P, Holmström S, Veivo J and Salonen J 2007 Creep damage and expected creep life for welded 9-11% Cr steels. Int. J. Pres. Ves. Pip. 84 69-74

[12] Pan J, Tu S, Zhu X, Tan L 2019 Creep behaviour and cavitation evolution of 15CrMoG steel at high temperatures. Adv. Mech. Eng. 11 1-7