Failure analysis on 12cr1mov steel tube of high temperature reheater for 600 mw subcritical boiler

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Abstract. A 600 MW subcritical boiler high temperature reheater tube of 12Cr1MoV steel leaks after running for $11 \times 10^4$ h. Failure Analysis of the high temperature reheater is studied by optical microscope (OM), scanning electron microscopy(SEM) and energy dispersive spectroscopy(EDS), etc. The results show that under long-term service at high temperature, the alloy elements have been depleted in the matrix. The oxidation layer of the inner wall is too thick, and the micro-structure is degraded obviously. Many creep cavities and micro-cracks appear in the fire-facing side of the elbow. The micro-cracks extending along the grain boundaries are filled with oxide. In conclusion, the degradation of the microstructure caused by long term overheat is the main reason for the failure of 12Cr1MoV reheater tube, and the creep cracking causes the leak.

1. Introduction

12Cr1MoV steel has high creep rupture strength, good corrosion resistance and oxidation resistance, which is widely used for headers, pipes with steam parameters not exceeding 540°C, and superheater, reheater tube with metal wall temperatures not exceeding 580°C of the power plant boiler[1-4]. If 12Cr1MoV steel is used under high temperature and pressure environment conditions for long-term service, the high temperature and stress will increase the mobility of metal atoms and accelerate the diffusion rate, causing changes in microstructure and properties. The common structural changes of 12Cr1MoV steel are pearlite spheroidization, depletion of alloying elements in solid solution, transformation of carbide precipitation phase, precipitation and aggregation of carbides in grains and grain boundaries. The above-mentioned structural changes will adversely affect the durability and creep strength of 12Cr1MoV steel, and will cause tube explosion.

A 600 MW subcritical boiler high temperature reheater tube of 12Cr1MoV steel leaked after running for $11 \times 10^4$ h. When the high temperature reheater leaked, the unit load was 400MW, the main steam pressure was 12.86MPa, and the main steam temperature was 540°C. The failed fitting size was 63mm × 4mm. The failure tube sample was intercepted at the scene, and the failure reason was analyzed by optical microscope (OM), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), etc.

2. Experimental

During the on-site inspection, it was found that the macroscopic crack morphology appeared in the back arc of the fire-facing side of the high temperature reheater elbow, as shown in figure 1. The pipe samples
of cracked elbow were cut off and the samples were selected on the fire side and the back fire side of elbow for analysis.

The microscopic morphology of the crack and the oxide layer on the inner wall of the tube were analyzed by Leica DM2500M metallographic microscope, and the samples were analyzed by Tescon VEGA 3 LMU scanning electron microscope and Oxford x-act energy spectrometer.

3. Results and discussion

3.1. Macroscopic morphology and oxide layer analysis

The crack is located on the fire-facing side of the outer arc of the elbow and has penetrated the entire pipe wall, with a length of about 20mm. The surface of the fire-facing side is reddish-brown, and there are obvious cracks and peeling of the oxide layer. The oxide thickness of the inner wall and outer wall of the sampling position measured under the optical microscope is shown in Table 1 (the oxide layer thickness of the outer wall at the elbow cannot be measured due to the exfoliation of the oxide layer). The thickness of oxide layer on the inner wall of the elbow has reached 865.36μm, the thickness of oxide layer is too thick.

The oxide layer will reduce the effective wall thickness of the reheater tube, and well, due to the poor heat transfer ability of the oxide layer, it largely blocks the heat exchange between the steam medium and the wall metal, resulting in the rise of the wall temperature and the deterioration of the material tissue. The thinning of effective wall thickness and the increase of temperature will further deteriorate the tissue, resulting in further decrease of the load carrying capacity of the tube [5].

![Figure 1. Crack morphology appearing on the reheater elbow](image)

| Sample number | Sampling location     | the oxide thickness/μm |          |
|---------------|-----------------------|------------------------|----------|
|               |                       | the inner wall         | the outer wall |
| #1            | the fire-facing side  | 865.36                 | -        |
| #2            | the backfire side     | 298.79                 | 264.23   |

3.2. Microstructure analysis

We know that the original normalized structure of 12Cr1MoV steel is ferrite and partial lamellar pearlite mass [2]. The microstructure of the sample is shown in Figure 2. Figure 2(a) shows the microstructure of the fire-facing side of the elbow, and the pearlite area has completely disappeared. According to DL/T 773-2016, carbide aggregates grow significantly and aggregate at the ferrite grain boundaries, with a
spheroidization rating of 5. The microstructure of the backfire side of the elbow is shown in Figure 2(b). The metallographic structure is ferrite and pearlite with a spheroidization level of 3.5.

![Figure 2. Microstructure of the samples (a) the fire-facing side; (b) the backfire side](image)

![Figure 3. SEM of the sample. (a) The fire-facing side; (b) the backfire side](image)

![Figure 4. EDS analysis of precipitation carbides in the fire-facing side of sample](image)
3.3. SEM and EDS analysis
The microstructure is further analyzed by SEM. Figure 3 shows the microstructure of the inner wall section on the fire-facing side and the backfire side of the tube. It can be seen that the carbide particles on the fire-facing side and the backfire side have been spheroidized and accumulated at the grain boundary, but the dispersion degree and sizes are different. The carbide particles on the fire-facing side are obviously concentrated, and the size is obviously larger than that on the backfire side, and the area ratio is also larger than that on the backfire side. The degradation of the properties after service has a direct relationship with the transformation, average size and area ratio of carbides during spheroidization. The relationship between the number, shape, size and distribution of various carbide phases has a major impact on the properties of the material [6-8].

Figure 4 and Figure 5 are respectively the EDS diagrams of carbides precipitated from the fire-facing side tube sample and the matrix inside the crystal. The results of EDS showed that Cr, Mo and other alloying elements are in the carbide precipitate, and Fe and a small amount of C elements are left in the matrix. Literature [9] pointed out that with the increase of operating time, Cr and Mo elements were mainly precipitated into grain boundary carbides during the operation of 12Cr1MoV steel, Cr elements were precipitated after running for $5 \times 10^4$ h, Mo elements precipitated after running for $10 \times 10^4$ h, and V elements were relatively stable during the operation. It can be seen that, with the extension of the operating time, the carbide gradually precipitates, aggregates and grows, and then the flake agglomerates into a ball. Cr and Mo will continue to transfer to the carbide, and the process will be accelerated under high temperature [1].

4. Conclusion
The failure of high temperature reheater tube is caused by tissue deterioration caused by long-term service. The excessive thickness of the oxide layer on the fire-facing side of the elbow leads to long-term over-temperature operation of the tube, which resulting in serious spheroidization of the structure. The precipitation and coarsening of carbides along grain boundaries are the main causes of deterioration of material structure and properties. The precipitation and aggregation growth of carbides lead to a decrease in the content of alloying elements in the matrix and alloying element depletion in the matrix, which reduces the room temperature strength of 12Cr1MoV steel. A large number of creep holes appear on the grain boundary, and cracks form and develop along the grain boundary, which eventually lead to the failure of the tube.

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