Creep rupture strength of F12 steel welded joint after long-term service

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Abstract: Creep rupture strength of F12 steel welded joint which was used as the main steam pipe and serviced 165000 hours was investigated by using high temperature creep rupture testing. Microstructure analysis results show that the microstructure of F12 steel welded joint became embrittlement significantly after long-term service. The precipitates mainly consist of M23C6 carbide and Laves phase, and the amount of M23C6 phase is more, which precipitated along the grain boundaries in bulk or chainlike with larger size. At the same time, there are larger inclusions with directional distribution, in which these inclusions have poor bonding with substrate and easily become crack source during the process of high temperature creep. The high temperature enduring strength of welded joint of F12 steel decreased significantly, it is necessary to enhance the examination of the microstructure and life assessment of pipeline in the next overhaul period.

1. Introduction

F12 standard martensitic steel which contains 12% Cr exhibits a typical high density martensite organization with some fine dispersed precipitates. The special structure of F12 steel contributes to its excellent properties such as high temperature creep strength, good obdurability, corrosion resistance and high temperature oxidation resistance and therefore expands its applications in power plant components such as the main steam pipes. [1-3].

After a long-term service on severe operating conditions such as high temperature and pressure, microstructure of F12 steel will be changed and in turn affect its performances. According to the relevant literatures [4-7], the microstructure and the properties of F12 steel will degrade significantly after its service. Specifically, the creep resistance will decrease significantly when the operating temperature exceeds 550 °C. As for the weakest link parts, the welded joints always exhibit coarse columnar grain structure due to the difficulty to achieve process conditions of the matrix when welding the steel. Moreover, the structure and properties of the HAZ will be changed obviously after one heating cycle. However, the details of the changing processes need to be investigated and whether the welded steel still meet its application requirements after these changes need to be considered. The investigated F12 steel welded joint was collected from the main steam pipe of #2 unit in a specific power plant after servicing 165000 hours at 540 ℃. High temperature creep rupture testing together with SEM analysis technology was employed to investigate the high temperature creep strength of F12 welded joint after long-term high temperature operating. The detailed creeping structure damage and the performance degradation were analyzed and the service life prediciton of F12 steel main steam pipe was conducted in order to guarantee the safety of the unit.
2. Materials and testing methods
The size of the investigated F12 steel is φ355.6mm × 40mm. SPECTROLAB quantitative spectroscopy system was employed to analyze chemical components of F12 steel after servicing. The compositions (mass ratio, %) are C 0.19, Mn 0.59, Si 0.25, Cr 12.24, Mo 1.05, V 0.22, Ni 0.67, S 0.019 and P 0.014.

F12 steel and welded joint samples were prepared according to the standard procedures [8]. High-temperature endurance tests of the samples were conducted by using RC-1130 high-temperature creep rupture testing machine, under the testing temperature of 550 ℃ and the pressures of 220Mpa, 200 Mpa, 180 Mpa, 160 Mpa and 150 Mpa, and the testing temperature of 600 ℃ and the pressures of 160Mpa, 140 Mpa, 120 Mpa. Field emission scanning electron microscope SUPRA55 combined with an EDS system were both employed to analyze the microstructure and the main alloying elements of samples.

3. Results and discussion
3.1 Creep rupture strength testing
Figure 1 shows the creep rupture strengths of F12 steel and its welded joint. There is a good linear relationship between creep rupture time and pressure. Results in Figure 1 indicate that the creep rupture strengths of F12 steel and its welded joint decrease with increasing the temperature. Moreover, the creep rupture strengths of the welded joint are lower than those of the matrix at both 550 ℃ and 600 ℃ testing temperature.

According to the Isothermal method, the creep rupture strengths of F12 steel and its welded joint were numerically analyzed as follows: The creep rupture strengths of F12 steel after servicing at 550 ℃ and 600 ℃ can be obtained according to equations (1) and (2), respectively. The $R^2$ are 0.989 and 0.999, respectively, indicating that excellent fittings can be obtained between the experimental and numerical data.

$$550 ℃ \quad \sigma = 290.9 \tau^{0.07} \quad (1)$$
$$600 ℃ \quad \sigma = 260.2 \tau^{0.11} \quad (2)$$

The creep rupture strengths of F12 steel welded joint after servicing at 550 ℃ and 600 ℃ can be obtained according to equations (3) and (4), respectively with $R^2$ of 0.945 and 0.983, respectively, also indicating that excellent fittings can be obtained.

$$550 ℃ \quad \sigma = 262.2 \tau^{0.07} \quad (3)$$
$$600 ℃ \quad \sigma = 244.4 \tau^{0.11} \quad (4)$$

According to DIN17175 the creep rupture strengths of F12 servicing for $10^5$ hours at 550 ℃ and 600 ℃ should be higher than 128Mpa and 59Mpa, respectively. In this study, the longest creep rupture testing time of F12 steel at 550 ℃ is approximately 5000 hours, and the testing pressure is 150 MPa, which is higher than the required value in the standard. According to equation (1), when $\tau = 5000$h, $\sigma = 136MPa$, which is also higher than 128 MPa, indicating that F12 steel can keep on working for
50000 hours at 550 °C. When the working temperature is 600 °C, the longest creep rupture testing time is approximately 780 hours and the testing pressure is 120MPa. According to equation (2), when \( \tau = 7800h, \sigma = 97MPa \), which is also higher than the required value of 59 MPa, indicating that F12 steel can keep on working for 7800 hours at 600 °C. Similarly, according to equation (3) and (4) we can observe that F12 steel welded joint can keep on working for 17000 hours and 16000 hours at 550 °C and 600 °C. However, when the working temperature is 550 °C, the strength of the welded joint is close to the limited value according to the standard.

3.2 Morphological observation
Different levels of necking occurred around the fracture. The fragments showed plastic deformation rather than entire creep deformation due to the relatively short testing time. Figure 2 shows the SEM microscopic photographs of the F12 welded joint creep fractures. The working temperature, the pressure and the working time of the analyzed samples were 550°C, 160MPa and 1621.3h, respectively. As can be seen in Figure 2, vast creep pores exist around the creep fracture. Moreover, extensive precipitates appeared in the tissue and distributed along the force direction.

3.3 Joint microstructure of F12 welded joint after servicing
As can be seen in Figure 3, F12 steel welded joint was still lath martensite structure after 165000hs’ servicing, but these martensite already decomposed into fragments, leading to the increase of the amount and size of the precipitated phases. The XRD analysis results were shown in Figure 4, showing that both F12 steel and the welded joint consist of Fe-Cr solid solution and M23C6 phase. According to the chemical compositions of F12 steel, it is also easily to know that VC phase should be existed in the matrix, but no VC phase was detected in the XRD result probably due to the lack of the VC phase.

(a) Microtopography of the creep fissure; (b) Creep pores around the creep fracture
Fig.2 Microtopography of the creep fissure of F12 welded joint after servicing

(a) F12 steel; (b) welded joint
Fig.3 Microtopography of of F12 steel and the welded joint after servicing
3.4 High temperature creep rupture property analysis

Figure 5 shows the micromorphology of F12 welded joint, Table 1 shows the EDS analysis results of the precipitation phase. Figure 5 (a) and (b) are the secondary electron image and backscattered electron images of the same region, respectively, and the results show that the grain boundary precipitates grow up together and distributed as separate particles. The EDS results show that the main alloying elements are C, Cr, Fe, Mo, V. Figure 5 together with Figure 4 show that the main precipitation phase is M$_{23}$C$_6$. According to the backscattered electron images, trace level of Laves phase exists in the precipitation phases [12]. The contrast in the back-scattered electron image appears light due to the particular structure of Laves phase.

(a) and (c) secondary electron image; (b) and (d) backscattered electron image

Table 1 EDS analysis of microstructure of creep F12 welded joint

| NO. | C   | Si  | P/S  | Cr   | Mn | Fe   | Ni   | V    | Mo |
|-----|-----|-----|------|------|----|------|------|------|----|
| 01  | 0.85| 1.78| 0.36/ | 13.20| 0.76| 63.95| 1.36 | /    | 17.73|
| 02  | 1.03| /   | /    | 26.67| /  | 68.33| 0.69 | 0.58 | 2.71|
| 03 | 0.78 | 0.34 | 0.33 | 11.13 | 0.75 | 85.68 | 0.99 | / | / |
| 04 | 1.36 | / | / | 24.62 | / | 69.79 | 0.82 | 0.60 | 2.80 |
| 05 | 0.76 | / | / | 41.47 | 51.17 | / | 0.85 | 0.60 | 5.16 |
| 06 | 2.43 | / | / | 50.67 | / | 39.27 | / | 0.95 | 6.69 |
| 07 | 1.18 | / | / | 21.93 | / | 73.73 | 0.85 | / | 2.31 |

As can be seen in Figure 6, the amount and size of the precipitates of F12 welded joints both increased apparently, especially in the grain boundary and branch grain boundary, the M$_{23}$C$_6$ carbides nodulized, became rough and distributed along the grain boundary. The size of M$_{23}$C$_6$ carbides is large, leading to a low combination force with the matrix. When creep deformation occurred, pores were firstly formed in the boundary (as shown in Figure 6 (b)). Moreover, M$_{23}$C$_6$ with large grain size is also a main place to form pores (as shown in Figure 6 (a)).

![Figure 6 Creep deformation organization analysis of F12 welded joint](image)

(a) $\times$ 2000; (b) $\times$ 5000

Figure 6 Creep deformation organization analysis of F12 welded joint

A certain number of strip-like phases with large grain size were observed in the matrix of F12 steel HAZ and showed directional distribution. The bar-like phases should be Al and Si inclusions. The binding force between bar-like inclusions and the matrix is relatively weak, so the inclusions are likely to detach from the substrate, leading to the formation of large pores and cracks. Together these pores and cracks with the precipitates become the weak point of the organization and exist as the precursor of creep deformation.

![Figure 7 Morphology of the bar-like phase in F12 steel organization](image)

(a) metallographic structure; (b) SEM morphology

Figure 7 Morphology of the bar-like phase in F12 steel organization

4. Analysis and Discussion

When F12 steel welded joints which already served for 165000h were imposed a second high temperature creep rupture testing, their textures consist of martensite matrix and precipitate phase, and the lath structure of the martensite matrix remained clear, but the number of precipitates increased significantly and the precipitation strengthening effect increased. Due to the relatively low absolute values of molar formation of free energy of carbides (Cr, W, Mo) and the stability of carbides, M$_{23}$C$_6$ was easily to occur Ostwald ripening and prone to grow under the conditions of high temperature and creep rupture. Moreover, M$_{23}$C$_6$ precipitates out firstly near the grain boundary due to its low nucleation energy. With the continuous precipitation and growth of M$_{23}$C$_6$ during the operation, some
precipitations with fine particle size were generated and distributed in the grains of the matrix. Due to the segregation of some elements such as Cr, W, Mo and there high defect concentration near the dendritic of primary dendrite, the quantity of $\text{M}_2\text{C}_6$ is large than the matrix and $\text{M}_2\text{C}_6$ prone to precipitate and grow rapidly. Together $\text{M}_2\text{C}_6$ phase, Laves phase with the bar-like inclusions (i.e. Al, Si phases) contribute to the generation of pores due to their poor plasticity and adhesion with the matrix at high temperature and with some applied stress. These formed pores serves as precursors of cracks. The above results indicate that some detections and supervisions on the texture changes are necessary and the formation of pores and cracks in the structure need to be monitored regularly.

5. Conclusions

(1) The dominate precipitations in the creep rupture structure of F12 welded joints are $\text{M}_2\text{C}_6$ and Laves phase. The particle sizes of the precipitations are large and the adhesions between the precipitations and the matrix are low, contributing to the formation of cracks. Some Al, Si inclusions were also observed and detached during the creep rupture process, contributing to the generation of large pores and cracks. These indicate that regular detections and supervisions on the texture changes are necessary and the formation of pores and cracks in the structure also need to be monitored.

(2) By inference, F12 steel welded joint can keep on working for 17000 hours. However, when the working temperature is high, the structures and properties of the materials changed apparently, especially considering that the creep rupture strength of the welded joint is lower than that of the matrix. It indicates that thorough life evaluations need to be conducted in the next maintenance.

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