Effect of the aging treatment on the precipitates and Vickers hardness of friction welded T92 joint

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Abstract: In this paper, the precipitates and vickers hardness of the friction welded T92 joints were studied after aging at 600°C for different time. Cr23C6 carbides and MX carbonitrides were denoted precipitated phases in the X-ray diffraction profiles. Precipitation, growth and aggregation of the Cr23C6 carbides and MX carbonitrides were the main precipitated phase evolution mechanism. The vickers hardness of the joints increased firstly, than decreased when after aged for 500 h, this is attributed to the aggregation and growth of the Cr23C6 carbides.

Introduction

In the current century, energy shortage and environmental pollution are two main challenges that all countries must face. The best choice is to build high-capacity ultra-super critical power units. However, the development of the ultra-supercritical technology would no doubt bring lots of problems, especially fabrication and safe reliability assessment of the new-style steel weld joints. Consequently, heat-resistant steels, mainly referring to martensitic steels, have been pursued simultaneously since the emergence of ultra-supercritical boilers for applications. Subsequently, a wealth of research has been carried out on these heat-resistant steels such as T91, to investigate characteristics of their performance deterioration after long-term services. Among them, the T92 approximately similar to T91 but with a little modification in chemical compositions for preferable high temperature properties, and will certainly have a broad application prospect in forth coming ultra-super boilers[1,2]. However, in this situation, a question is how to join the new martensitic steel together. The conventional fusion welding joints of martensitic steel exhibit inferior mechanical properties due to the formation of intermetallic compounds at the joint interface, and the excessive residual stresses. The friction welding can be more suitable than fusion ones since many problems associated with melting are eliminated or reduced [3-5]. In order to use friction welded T92 joints widely in higher temperature environment, the effect of aging time on the precipitates and vickers hardness of the joints is investigated. It provides the more fundamentals for wide application of the friction welded T92 joints at higher temperatures.

Experimental procedures

The pipes of T92 martensitic steel were used as base metals. Friction welding was carried out using a continuous drive friction welding machine. During the friction welding operations, the friction welding parameters were set to the following combinations: a friction speed of 1200 rpm, a friction pressure of 120 MPa, an upset pressure of 150 MPa and a friction time of 5s. These specimens were heated respectively in a tube furnace at 600°C for 500h, 1000h, 1500h, 2000h, 2500h, and 3000 h, respectively. The microstructures of the aged samples were observed and analyzed by using a scanning electron microscopy (SEM) equipped with an energy dispersive spectroscopy (EDS) system. Vickers hardness values of the joints were tested using a vickers hardness testing instrument with a loading of 5 kg and an enduring time of 15 s.
Results and Discussion

Fig. 1 shows the X-ray diffraction profiles of the welding joints aged for 1000h, 2000h and 3000h respectively. It can be sure that the peaks with the highest intensity correspond to the $\alpha$-Fe phase and the precipitated phases for all the samples. It was known that $\text{M}_2\text{C}_6$ ($\text{M} = \text{Fe}, \text{Cr}, \text{W}$) carbides, $\text{M}\text{X}$($\text{M} = \text{Nb}, \text{V}$ and $\text{X} = \text{C}, \text{N}$) carbonitrides and the Laves phase were three main second-phases in the high-temperature aged T92 martensitic steel. The $\text{M}_2\text{C}_6$ mainly distributes along the prior austenite grains boundaries and the martensite lath boundaries, while $\text{M}\text{X}$ carbonitrides and Laves phases distribute inside the prior austenite grains. With the increasing of aging time, the lattice parameter and the amount of the precipitated phases is increasing. The X-ray result indicated that the precipitated phases included the Cr and Fe elements, and the Cr element is the major metal element. The Cr element has a tendency to form carbides, some C element and Cr element precipitated from supersaturated martensite and formed the precipitated phases $\text{Cr}_2\text{C}_6$ at the grain boundary preferentially. Because there are some trace elements of Nb and V in the T92 martensitic steel. So the MX carbonitrides containing Nb and V should be precipitated theoretically. It is difficult to index the MX carbonitrides and the Laves phase due to their lower intensities peaks. Therefore, the welded joints after the aging treatment, the main phase is the $\alpha$-Fe phase and the precipitated phases are $\text{Cr}_2\text{C}_6$ carbides, MX carbonitrides and Laves phases.

Fig. 1 XRD patterns of the welding joint after aging for different time(a)1000h; (b)2000h; (c)3000h;

Fig. 2 shows the precipitated phase of the welding joints aged for different times with EDS to show the elements of the precipitated phases. Table 1 shows the EDS analysis results of the precipitated phases at positions shown in Fig. 2. Fig. 2 (a) shows the shape of precipitated phases of welded joints aged for 1000h, the precipitated phase A is $\text{Cr}_2\text{C}_6$ carbides and the precipitated phase B is MX carbonitrides. Fig. 2 (b) shows the shape of precipitated phases of welded joints aged for 2000h, the precipitated phase A is $\text{Cr}_2\text{C}_6$ carbides and the precipitated phase B is MX carbonitrides. Fig. 2(c) shows the shape of precipitated phases of welded joints aged for 3000h, the precipitated phase A is $\text{Cr}_2\text{C}_6$ and the precipitated phase B is the Laves phases. The $\text{Cr}_2\text{C}_6$ carbides has a face-centered cubic structure and consists of Fe and Cr as well as small amount of Mo and W. The shape of the $\text{Cr}_2\text{C}_6$ carbides are rod-like particles and round-like particles. The rod-like $\text{Cr}_2\text{C}_6$ carbides mainly distributes inside the martensite lath and the round-like $\text{Cr}_2\text{C}_6$ carbides distributes along the prior austenite grains boundaries. Because of the squeezing effect between the martensite lath during the process of the rod-like $\text{Cr}_2\text{C}_6$ carbides growth, the growth direction of the rod-like $\text{Cr}_2\text{C}_6$ carbides is parallel to the direction of the slats martensite lath. The MX carbonitrides has a higher melting point and is precipitated from the matrix during the normalizing treatment. The particles size of the MX carbonitrides is small and is mainly distributed inside the martensite lath and along the martensite lath boundaries. The MX carbonitrides has a face-centered cubic structure
and consists of V, Nb, C and N as well as small amount of Si and W. Because the bonding strength of carbides is stronger than the bonding strength of carbonitrides, most of the carbon elements are combined with alloying elements at higher temperature. The content of nitrogen in the matrix is small and it is difficult to form the carbonitrides. The content of Nb and V in the carbonitrides is less than other alloying elements. Because that the poor solid solution ability of Nb and V in the matrix, the coarsening of carbonitrides is difficult. The coarsening of carbonitride is not obvious because that the carbonitrides is difficult to grow and aggregate in the aging process.

The T92 martensitic steel welded joints show the excellent creep rupture strength, and the martensitic matrix still keep the fine microstructure. This could be attributed to the dispersively distributed of the strengthening phase MX carbonitrides, which can effectively pin dislocations and grains boundaries, than impede the movement of dislocations and grains boundaries[6]. The Laves phases has a hexagonal close packed structure and consists of Fe and Cr as well as small amount of Mo and W. Because the constituent elements of the Laves phase are easily precipitated from the matrix at high temperatures, the coarsening process of the Laves phases is faster and is easy to grow and aggregate. Therefore, the Laves phase is not conducive to the higher temperature performance of welded joints. So, the Laves phase is harmful to the higher temperature performance of T92 martensitic steel.

![Fig.2 The precipitated phases of the welding joints: (a)1000h, (b) 2000h, (c) 3000h](a) (b) (c)

**Table 1** The energy spectrum analysis of the precipitated phase

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>V</th>
<th>Cr</th>
<th>Fe</th>
<th>Nb</th>
<th>Mo</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>The precipitated phase A (aged for 1000h)</td>
<td>6.64/23.24</td>
<td>2.84/8.54</td>
<td>-</td>
<td>-</td>
<td>10.77/9.22</td>
<td>77.38/58.29</td>
<td>-</td>
<td>0.79/0.35</td>
<td>1.58/0.36</td>
</tr>
<tr>
<td>The precipitated phase B (aged for 1000h)</td>
<td>8.77/29.04</td>
<td>8.93/26.51</td>
<td>-</td>
<td>3.8/2.42</td>
<td>9.85/7.14</td>
<td>26.11/17.62</td>
<td>42.54/17.27</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The precipitated phase A (aged for 2000h)</td>
<td>20.23/54.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.72/6.0</td>
<td>66.56/38.95</td>
<td>-</td>
<td>0.68/0.23</td>
<td>2.8/0.49</td>
</tr>
<tr>
<td>The precipitated phase B (aged for 2000h)</td>
<td>10.47/33.93</td>
<td>7.55/25.01</td>
<td>-</td>
<td>2.47/1.7</td>
<td>6.11/4.62</td>
<td>13.26/9.33</td>
<td>60.14/25.42</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The precipitated phase A (aged for 3000h)</td>
<td>7.57/27.53</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.19/12.44</td>
<td>75.55/59.08</td>
<td>-</td>
<td>1.43/0.65</td>
<td>1.26/0.3</td>
</tr>
<tr>
<td>The precipitated phase B (aged for 3000h)</td>
<td>7.43/30.49</td>
<td>0.63/2.22</td>
<td>7.09/12.45</td>
<td>-</td>
<td>7.21/6.83</td>
<td>41.66/36.67</td>
<td>0.29/0.16</td>
<td>6.59/3.39</td>
<td>29.10/7.8</td>
</tr>
</tbody>
</table>
Fig. 3 depicts the Vickers hardness as a function of the aging time. As the aging time increased, the Vickers hardness of the joints increases sharply (<500 h), and then decreases (500-3000 h). In the aging process, the Vickers hardness change of the welding joints is certainly corresponding to the microstructure evolution. Precipitation, aggregation and growth of the precipitated phases are main reasons of the microstructure evolution of the welding joints. In the early aging stage, the strain hardening effect of the Cr$_{23}$C$_6$ carbides and MX carbonitrides may be overwhelming, the Vickers hardness of the joints increased. As the aging time increased continuously, aggregation and growth of the Cr$_{23}$C$_6$ takes place, the hardening effect of the precipitated phases decreases simultaneously, resulting in the apparent drop of the Vickers hardness.

Conclusions

In the aging process, the precipitated phase evolution of the friction welded joints was exhibited. Cr$_{23}$C$_6$ carbides and MX carbonitrides is denoted precipitated phases in the X-ray diffraction profiles. Precipitation, growth and aggregation of the Cr$_{23}$C$_6$ were the main precipitated phase evolution mechanism. The welded joints shows the excellent creep rupture strength, it could be attributed to the dispersively distributed of the strengthening phase MX carbonitrides, which can effectively pin dislocations and grains boundaries. As the aging time increased, the Vickers hardness of the joints increased in the initial stage, than decreased after aged for 500 h.

References