Effect of W-addition on Low Cycle Fatigue Behavior of High Cr Ferritic Steels

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A study was done to investigate the effect of tungsten (W) addition on the microstructure, tensile properties and low cycle fatigue (LCF) properties of 9Cr-1Mo steels at 298K and 873K. Four steels containing different amounts of W (0W, 1.2W, 1.8W and 2.7W) were normalized at 1323K for 1 hour and tempered at 1023K for 1 hour. Microstructural analysis revealed that no significant differences were observed in their tempered martensitic microstructure of 0W, 1.2W and 1.8W alloys, but d-ferrite was observed to form at the prior austenite grain boundaries of the 2.7W alloy. With the increase in W content, yield and tensile strength increased at all temperatures. Low cycle fatigue life also increased with the W content up to 1.8%, but decreased in the 2.7W alloy, which was primarily due to the presence of soft d-ferrite acting as the crack initiation site. The fatigue life at 873K was reduced compared to that at 298K, due not only to the decrease in strength at high temperature but also to the formation of oxide layers along the slip bands, which increases slip irreversibility during cyclic deformation.

Key words: W addition, low cycle fatigue, δ ferrite, oxidation

1. INTRODUCTION

High Cr ferritic steels (9~12Cr steels) are receiving increasing interest in the power generating industry since they represent reasonably good creep strength which is comparable to that of the austenitic stainless steels [1,2,3]. Therefore, various such alloys as the 9Cr-1Mo steels that have good creep resistance have been developed to meet the requirements for improved power generating efficiency. For components operated at elevated temperatures, an accurate assessment of cyclic damage at high temperature is also an important issue to consider. Recently, it has been found that the substitution of W for Mo enhances high temperature tensile strength, fracture toughness and creep strength [4,5]. However, the effect of W addition on the low cycle fatigue (LCF) properties of 9Cr-1Mo steels has not been investigated as yet.

It is, therefore, the purpose of this investigation to study the LCF properties of 9Cr-1Mo steels at room temperature and 873K with variations in W content. Particular care was taken to determine the optimum W content representing the best LCF properties and to understand the role of W content in controlling cyclic properties. Also, the cause of fatigue life reduction at high temperature has been studied.

2. EXPERIMENTAL

The alloy compositions of four steels with various W amounts are given in Table 1. Ingots of four alloys were produced by vacuum induction melting. The alloys were subsequently rolled into 16mm thick plate at 1303K, and then, normalized at 1323K and tempered at 1023K for 1hr. A low cycle fatigue test under uniaxial tension and compression cycling was done at room temperature and 873K in air atmosphere. The fully reversed sine wave form was adopted with a constant strain rate of 0.2%/sec and the total strain amplitude was in a range between ±0.5% and ±1.5%. Fig. 1 shows the cylindrical specimen with the gage length of 6mm, which was used for the LCF tests.

3. RESULTS AND DISCUSSION

Fig. 2 shows the microstructure of four steels after nor-
Table 1. Chemical composition of steels used in this study

<table>
<thead>
<tr>
<th>Steels</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>V</th>
<th>Nb</th>
<th>B</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0W</td>
<td>0.09</td>
<td>0.07</td>
<td>0.43</td>
<td>8.90</td>
<td>1.0</td>
<td>0</td>
<td>0.21</td>
<td>0.063</td>
<td>0.004</td>
<td>0.04</td>
</tr>
<tr>
<td>1.2W</td>
<td>0.10</td>
<td>0.08</td>
<td>0.46</td>
<td>8.90</td>
<td>0.8</td>
<td>1.2</td>
<td>0.20</td>
<td>0.065</td>
<td>0.004</td>
<td>0.05</td>
</tr>
<tr>
<td>1.8W</td>
<td>0.10</td>
<td>0.08</td>
<td>0.45</td>
<td>8.86</td>
<td>0.5</td>
<td>1.8</td>
<td>0.20</td>
<td>0.064</td>
<td>0.004</td>
<td>0.05</td>
</tr>
<tr>
<td>2.7W</td>
<td>0.11</td>
<td>0.08</td>
<td>0.44</td>
<td>8.88</td>
<td>0.1</td>
<td>2.7</td>
<td>0.21</td>
<td>0.069</td>
<td>0.004</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Fig. 1. Dimension of specimen for LCF tests at 298K and 873K.

Fig. 2. TEM micrographs showing typical microstructures of 9Cr-1Mo alloys after heat treatment. (a) 0W, (b) 1.2W, (c) 1.8W and (d) 2.7W.

Fig. 3. (a) SEM and (b) TEM micrographs showing ferrite in 2.7W steel after heat treatment.

Martensite laths, but also in the grain interior. The distribution of the precipitates is shown in Fig. 4 and the size and morphology of the precipitates are summarized in Table 2. Most of the equiaxed precipitates are identified to the M$_{23}$C$_6$ type precipitates with Cr, Fe and Mo metallic elements. In addition, Nb(C,N) or V(C,N) precipitates were also identified by the energy dispersive X-ray method. It is interesting to note that the sizes of all the precipitates decreased with the addition of the W element, implying that the addition of W plays an important role in controlling the size of precipitates, i.e., retarding the growth of the precipitates. Previous work [6,7] also reports that the addition of W decreases the rate of Fe diffusion in the Fe-W binary system, which is well in accordance with the results of this investigation.

The tensile properties of the four steels are given in Table 3. It may be clearly seen that the strength and ductility decrease with increased W concentration. As to the increase in strength in the high W alloy, two major causes are considered. One is the solid solution strengthening W. The atomic size of W is about 10% larger than that of Fe, resulting in significant strengthening when deformed. The other is related to indirect effects owing to the lower self-diffusion rate of W. As shown in Table 2, the size of the precipitates decreases with increased W content resulting in increase in the strength. However, no harmful effect from the formation of δ-ferrite in the 2.7W alloy was observed in the tensile test results.

Fig. 5 shows the plastic strain amplitude ($\Delta\varepsilon_p$) versus reversals to failure (2N$_f$) curves for the four steels tested at