Comparative Evaluation of the Low Cycle Fatigue Behaviours of P91 and P92 Steels

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Abstract

In the present paper, low cycle fatigue (LCF) behaviour of modified 9Cr-1Mo steel (P91 steel) and tungsten alloyed 9Cr steel (P92 steel) is presented. Total axial strain controlled fatigue tests were performed in air employing a constant strain rate $3 \times 10^{-3}$ s$^{-1}$ with strain amplitudes in the range $\pm 0.25\%$ to $\pm 0.6\%$ in the temperature range 823 – 873 K. Both steels exhibited a continuous softening behaviour before the final load drop that occurred due to crack propagation. In general, P92 steel exhibited a lower stress response compared to P91 steel. At lower strain amplitudes, P92 steel showed a higher stress response than P91 steel. The softening rate of P92 steel is found to increase with increase in strain amplitude whereas the softening rate of P91 steel has remained constant with strain amplitude. Comparison of fatigue lives of the steels exhibited a mixed behaviour. Fatigue life of P92 was found to be higher at higher strain amplitude and lower at lower strain amplitudes than P91 steel.

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Keywords: Low cycle fatigue; P91 steel; P92 steel; cyclic softening

1. Introduction

The advantages that higher-chromium steels (e.g., modified 9Cr-1Mo steel) offer compared to low-alloy steels in terms of better elevated temperatures properties and increased oxidation resistance has been a driving force to constantly modify and refine the composition and microstructure to achieve better performance. Selection of these alloys is primarily based on a good combination of mechanical properties, high thermal conductivity, low thermal expansion coefficient and good resistance to stress corrosion cracking in water-steam environment systems compared to austenitic stainless steels. These alloys also exhibit good weldability and microstructural stability over a very long period of exposure to high temperature service conditions. The improvement of thermal efficiency by increasing the operating temperature and pressure of boilers has recently led to the development of new families of creep resistant steels. Replacing molybdenum with tungsten had led to the improved mechanical properties at high temperatures, in particular an increase in creep strength of 10-

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20% in $1,00,000h$ at 873 K. This makes it possible to reduce the wall thickness of the pipes and consequently improve the fatigue resistance of this alloy.

The components of the steam generators are often subjected to repeated thermal stresses as a result of temperature gradients that occur on heating and cooling during start-ups and shut-downs or during temperature transients. During hold/dwell time, under high temperature applications, creep deformation takes place, depending on stress and temperature combinations. Therefore failure mechanisms under such loading conditions are a result of complex interactions of creep and fatigue processes within low cycle fatigue (LCF) regime. Hence LCF and creep-fatigue interaction are important considerations in the design of steam generator components.

The LCF behaviour of P91 steel has been reported earlier under normalized and tempered [1-3] and thermally aged conditions [4,5] in air environment. Prolonged aging of the alloy at elevated temperatures prior to testing was found to reduce the LCF and creep-fatigue interaction lifetimes [5]. Aging resulted in the formation of Laves phase with associated reduction in the toughness and LCF lifetimes of the alloy [6]. Kannan et al [7] have reported a 5 - 20 times increase in the low cycle fatigue endurance under flowing sodium environment. The increase in fatigue life under sodium environment has been attributed to the lack of oxidation in sodium environment due to the controlled chemistry of the sodium.

J.S. Park et al [8] have studied the influence of W addition on the LCF resistance of the alloy, LCF life increases with addition of W upto 1.8 wt% and decreased with further increase in W content. An increased amount of softening was reported by Kannan et al [9] with increase in strain amplitude and temperature. Giroux et al [10] have investigated the effects of strain rate on the softening behaviour of the alloy and reported that the softening is more pronounced with decrease in strain rate. This paper attempts to compare the low cycle fatigue properties of P91 steel with P92 steel.

2. Experimental details

The chemical composition of the steels employed in this study is given in Table 1. Compared to P91 steel, in P92 steel Mo was decreased as the addition of W was increased in order to maintain the same Mo equivalent value (wt.% Mo+$1/2$ wt.% W). P91 steel was subjected to a normalizing treatment at 1313 K/1h followed by a tempering treatment at 1033 K/1 hr and P92 steel was given a normalizing treatment at 1343 K/2h followed by a tempering treatment at 1048 K/2 hr. This heat treatment yielded a tempered martensitic structure on both the steels (Fig. 1). Low Cycle Fatigue tests were performed as per ASTM E 606 standard under fully reversed total axial strain control mode employing a triangular waveform. Tests were conducted at 823 K and 873 K at a constant strain rate of $3 \times 10^{-3}s^{-1}$ with strain amplitudes varying from $\pm 0.25\%$ to $\pm 0.6\%$. The fatigue crack initiation and propagation modes under different testing conditions were studied. Samples for the optical metallography were etched using Vilella’s reagent (1g of picric acid + 5ml conc. HCl + 100ml ethyl alcohol) and examined under an optical microscope.

![Typical Microstructure of P91 (a) and P92 (b) steels after normalising and tempering treatment.](image_url)
3. Results and discussion

The influence of total strain amplitude on the cyclic stress response at constant strain rate at various temperatures are depicted in Figs. 2(a) and (b) for both the steels. In general, both the alloys exhibited a continuous softening before the final load drop that occurred due to the propagation of macro fatigue cracks. The amount of softening is more at high strains wherein the plastic strain dominates compared to low strain (±0.25%) where the elastic response prevails and the plastic strain is a small fraction of total strain. This type of softening behaviour is characteristic feature of high strength materials where the initial microstructure contains high dislocation density, which redistribute to a low energy configuration [11] such as dislocation network, cell structure, slip deformation band during cyclic deformation or disappears by annihilation process [11]. In general, P92 steel exhibited higher response stresses compared to P91 steel. At the lowest strain range of investigation P91 steel showed a higher response stresses than P92. In P92 steel the half-life stress amplitude increases with decrease in strain amplitude (Table 2) and is reflected as the cross-over in the cyclic stress response curves (Fig. 2 a & b).

![Fig. 2. Comparison of Cyclic Stress Responses of P91 and P92 Steels at (a) 823 K and (b) 873 K.](image)

The softening rate (defined as the ratio of difference in first cycle stress to the cyclic stress amplitude at macrocrack initiation to the number of cycles to macrocrack initiation) increases with increase in strain amplitude for P92 steel whereas for P91 steel it remains constant with strain amplitude at high strain amplitudes (Fig. 3). Park et. al [8] have reported a decrease in the size of precipitates with increase in W content. With increase in the strain range of deformation, the precipitates can be easily cut by the dislocations and would lead to an increased amount of softening. Kruml and Polak [12] have observed a similar trend of cyclic stress response on X10CrAl24 alloy. They have attributed the two domain of cyclic softening to two different types of dislocation substructure. The dislocation substructure of samples cycled at low strain amplitudes does not differ much from that of the initial microstructure whereas a complete rearrangement of dislocation substructure was observed at higher strain amplitudes.
Table 2. Effects of Temperature on LCF Properties.

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>Total strain amplitude ($\Delta \varepsilon_t/2$) (%)</th>
<th>Half-life plastic strain amplitude ($\Delta \varepsilon_p/2$) (%)</th>
<th>First cycle stress ($\Delta \sigma/2$) MPa</th>
<th>Half-life stress amplitude ($\Delta \sigma/2$) MPa</th>
<th>Number of cycles to failure (Nf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>823</td>
<td>0.6</td>
<td>0.47</td>
<td>398</td>
<td>298</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.25</td>
<td>397</td>
<td>303</td>
<td>1070</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.13</td>
<td>368</td>
<td>293</td>
<td>3116</td>
</tr>
<tr>
<td>873</td>
<td>0.4</td>
<td>0.49</td>
<td>327</td>
<td>217</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.32</td>
<td>320</td>
<td>222</td>
<td>965</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.16</td>
<td>297</td>
<td>217</td>
<td>2615</td>
</tr>
</tbody>
</table>

![Graph](image)

Fig. 3. Comparison of Cyclic softening rate as a function of total strain amplitude and temperature.

Strain – life plots for both the steels are presented in Fig. 4 (a) and (b) at 823 and 873 K respectively. Fatigue life was found to decrease with increase in temperature and strain amplitude for both the steels. In general, the value of fatigue ductility exponent is in the range of -0.5 and -0.7 for ductile materials. But in an earlier study on the same material, the values are above the range [9]. This is ascribed to the other damage mechanisms such as creep or oxidation also operate at high temperatures which increases the overall damage on the material leading to high fatigue ductility exponent value. No evidence for creep has been found from the microstructural studies. Oxide layers were frequently observed and are considered important in reducing the LCF resistance at high temperature [9]. Oxide layers initially formed on the surface (i.e. on the surface of slip band intrusion and extrusion) can easily penetrate into specimen interior during fatigue loading. Oxide film rupture at crack tip or enhanced slip irreversibility are the possible mechanisms for the life reduction as is revealed by the higher fatigue ductility exponent values.

Comparison of fatigue lives indicate that the fatigue life of P91 steel was found to be higher at lower strain amplitude at both the temperatures and at higher strain amplitudes, P92 steel was found to yield better fatigue lives. This is ascribed to the higher response stresses developed and consequent inferior fatigue life. Effect of W addition does not influence much on the fatigue life at lower strain amplitudes in the studies conducted by Park et. al [8].
4. Conclusions

Low cycle fatigue behaviours of P91 and P92 steels are compared in the temperature range 823 – 873 K. The cyclic stress response behaviour of both alloys exhibited a continuous softening from the first cycle onwards. The amount of cyclic softening at higher strain amplitudes were higher for P92 steel and for P91 steel it remains constant. The fatigue endurance was found to be higher for P92 steel at higher strains and lower at lower strains compared to P91 steel and was attributed to the higher response stresses developed that assisted to earlier crack initiation and faster crack propagation.

References