Cyclic softening behaviour of a P91 steel under low cycle fatigue at high temperature

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Abstract

This paper describes a model used to represent the cyclic mechanical behaviour of P91 martensitic steel. Low cycle fatigue tests were conducted at 600°C using a thermo-mechanical fatigue test machine. A unified, Chaboche viscoplasticity model, was used to model the behaviour of the steel. The microstructure of the steel at different life fractions of the tests was investigated using scanning and transmission electron microscope images. The viscoplasticity model, with two stages of softening period, has resulted in better prediction capability for the cyclic behaviour of the steel for an initially undamaged material prior to crack initiation.

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1. Introduction

P91 steel is a martensitic steel, which contains 9% chromium and 1% molybdenum, was developed in the late 1970s [1]. It has been used in power generation industry for the headers and steam piping, which involves high temperature operations for long operation periods. The steel was designed to have high creep strength. The requirement for cyclic operation of power plant requires that the steel has resistance to thermal fatigue. P91 also has high strength and low thermal expansion coefficient, so that the thickness of pipe can be reduced by comparison with the behaviour of other steels. These characteristic causes P91 to have significant advantages compared to other austenitic type steels [2].

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The behaviour of P91 steel in cyclic condition has been studied and experimental test have been performed at high temperature in order to improve the understanding of P91 behaviour under cyclic condition [3]. The results show the cyclic softening behaviour for 9-12%Cr type steel. The understanding can be further improved by simulating the power plant components using finite element method such as analyzing the creep in pressurized pipe [4]. Material constitutive models are initially developed to reproduce the stress-strain behaviour of a material. For example, the viscoplasticity model, which considers the effect of time-dependent plasticity, has been used to represent the behaviour of a nickel-based alloy used in aeroengine applications [5]. However, less effort has been put into the development of the material model for P91 steel in order to simulate the cyclic loading effect.

The aim of the work described in this paper is to describe a constitutive model to simulate the behaviour of P91 steel in cyclic loading conditions at high temperature. The material constants were determined from strain-controlled test data. These were optimized using a least-squares optimization program to improve the prediction accuracy of the model. Preliminary investigations of P91 microstructures in interrupted tests were used in order to investigate the evolution of microstructures in the material, which result in the cyclic softening behaviour.

2. Experimental procedure

The test specimens were machined from a P91 steam pipe section which was austenized at 1060°C for 45 minutes and tempered at 760°C for 2 hours during pipe manufacturing. Figure 1 shows the dimensions of the cylindrical specimens used for all of the tests. The gauge section of the specimens is 15mm in length and 6.5mm in diameter; these were finished by fine machining and polishing to an average roughness value of 0.8μm. The chemical composition of the P91 steel is given in Table 1.

Fully reversed isothermal tests were conducted at 600°C under strain-controlled loading using an Instron 8862 TMF test machine. The machine utilizes radio-frequency, induction heating and the temperature gradient along the gauge section was controlled to within ±10°C of the target temperature. A constant strain rate of 0.001s\(^{-1}\) was applied in all tests at different strain amplitudes, i.e. ±0.2%, ±0.25%, ±0.4% and ±0.5%, until failure. Two additional tests were conducted at ±0.5% strain amplitude and these tests were interrupted at 200 and 400 cycle, respectively.

| Table 1. Chemical compositions of the P91 steel (wt%) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cr | Mo | C | Si | S | P | Al | V | Nb | N | W |
| 8.60 | 1.02 | 0.12 | 0.34 | <0.002 | 0.017 | 0.007 | 0.24 | 0.070 | 0.060 | 0.03 |

The microstructure investigations were carried out on test specimens with ±0.5% strain amplitude. Scanning electron microscope (SEM) was used to look for cracks in samples taken from the longitudinal direction of specimen’s gauge section. The samples were hot mounted in conductive phenolic mounting resin and they were etched using acidic ferric chloride. Further examinations of the P91 specimens were performed using a JEOL 2000FX transmission electron microscope (TEM). The samples for TEM investigation were prepared by cutting the specimen’s gauge section perpendicularly to the loading axis and they were thinned mechanically to a thickness of less than 100μm. Finally, the samples were electropolished in a solution made with 90% ethanol and 10% perchloric acid.
3. Low cycle fatigue data

The P91 specimens showed cyclic softening behaviour in all of the tests performed at various strain amplitudes. It also exhibited the same behaviour at different temperatures and loading (e.g. cyclic strain and temperature) [6]. Fig. 2(a) shows the maximum stress evolution obtained from the test with ±0.5% strain amplitude, which can be divided into three stages. The stages of one to three represent rapid cyclic softening followed by a saturation period and finally a crack growth stage.

The number of cycles to failure, Nf, is defined according to BS7270:2006 standard as the cycle during which the maximum stress has decreased by 10% from that predicted by extrapolation of the saturation curve (stage 2), as shown in Figure 2(a). The low cycle fatigue data can be represented by a Coffin-Manson relationship, as follow:

\[
\frac{\Delta \varepsilon_p}{2} = \varepsilon_f' (2N_f)^c
\]

where \(\Delta \varepsilon_p/2\) is the plastic strain amplitude, \(2N_f\) is the number of reversals to failure, \(\varepsilon_f'\) is the fatigue ductility coefficient and \(c\) is the fatigue ductility exponent. Based on experimental data, the plastic strain ranges in P91 specimens, in strain-controlled tests, increase nonlinearly from beginning up to the end of stage 1 and it slightly linearly increases in stage 2 to the fracture cycle. Thus, the plastic strain range, at half number of cycles to failure, was used to determine the fatigue constants, as shown in Fig. 2(b). The value of \(\varepsilon_f'\) and \(c\) are 0.225 and -0.577 respectively.

4. Isothermal cyclic behaviour modelling

4.1. Material behaviour model

The Chaboche unified viscoplasticity model [7] was chosen to model the behaviour of the P91 steel. The main parameter is the viscoplastic strain rate as defined by the following equations:

\[
\dot{\varepsilon}_p = \left( \frac{f}{Z} \right)^n \text{sgn}(\sigma - \chi)
\]

4.2. Numerical model

The experimental data was used to determine the fatigue constants as shown in Eq. (1). The value of \(\varepsilon_f'\) and \(c\) were 0.225 and -0.577 respectively. The Coffin-Manson relationship was fitted to the experimental data using the least square method with R² = 0.9606.
where
\[\text{sgn}(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}, \quad \chi = \frac{R - k}{R + k} \]

The evolutions of the various parameters in the model are given by:
\[
\begin{align*}
\dot{\chi}_i &= C_i (a_i \dot{\varepsilon}_p - \chi_i \dot{p}) \\
\chi &= \chi_1 + \chi_2 \\
R &= Q (1 - e^{-b \sigma_p}) \\
\sigma_v &= Z p^{1/n} \\
\dot{p} &= \dot{\varepsilon}_p
\end{align*}
\]

where \(\sigma_v\) is the viscous stress; \(p\) is the accumulated viscoplastic strain; \(a_i\) and \(C_i\) (i=1,2) represent the stationary values of \(\chi_i\) and the speed to reach the stationary values, respectively; \(Q\) is the asymptotic value of the isotropic variable, \(R\), at the stabilized cyclic condition and \(b\) governs the stabilization rate. The applied stress can be decomposed as
\[
\sigma = \chi + (R + k + \sigma_v) \text{sgn}(\sigma - \chi) = E(\varepsilon - \varepsilon_p)
\]

The equations described above, which are the uniaxial form of the viscoplasticity equations, were used to determine the material constants, using data from tests at 600°C, with strain amplitude of ±0.5%.

4.2. Identification of material constants

The approximate constants of the viscoplasticity model can be initially determined by using a step-by-step procedure on the first quarter cycle of an isothermal cyclic test, as explained in [8]. These constants can be used to reasonably accurately predict the stress-strain behaviour of P91 steel [6]. However, the way in which the initial material constants have been determined does not take into account the interactions which take place between the various aspects of the model. Thus, an optimisation procedure was used to improve the constants and hence improve the stress-strain predictions. An optimisation program, developed by Gong et al [8], based on a least squares algorithm, was used for this purpose.

In this study, the isotropic hardening model as shown in equation (7) is further modified by adding a linear term [9] as given by following equation:
\[
R = H p + Q (1 - e^{-b \sigma_p})
\]

where \(H p\) is the linear term. \(H\) is a constant and the linear term is the slope for stage 2 of cyclic softening, as shown in Fig. 2(a). The constants previously determined by the optimisation programme can remain the same except constants \(Q\) and \(b\) which represent stage 1 of the cyclic softening. \(Q\) can be estimated as the difference between point X and maximum stress at first cycle in Fig. 2(a) while \(b\) is the speed to reach the maximum stress at the end of stage 1. The viscoplasticity constants, with the nonlinear (NR) and linear nonlinear (NLR) isotropic hardening, versions of the model are given in Table 2.
Table 2. The viscoplasticity model constants for P91 steel at 600°C with nonlinear (NR) and linear-nonlinear (LNR) isotropic hardening model

<table>
<thead>
<tr>
<th>Model</th>
<th>E (MPa)</th>
<th>k (MPa)</th>
<th>H (MPa)</th>
<th>Q (MPa)</th>
<th>b</th>
<th>a_1 (MPa)</th>
<th>C_1 (MPa)</th>
<th>a_2 (MPa)</th>
<th>C_2 (MPa)</th>
<th>Z (MPa.s^{1/n})</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>140000</td>
<td>90</td>
<td>-</td>
<td>-70</td>
<td>1.1</td>
<td>70</td>
<td>900</td>
<td>100</td>
<td>50</td>
<td>1000</td>
<td>3.482</td>
</tr>
<tr>
<td>LNR</td>
<td>140000</td>
<td>90</td>
<td>-2.9</td>
<td>-52</td>
<td>1.9</td>
<td>70</td>
<td>900</td>
<td>100</td>
<td>50</td>
<td>1000</td>
<td>3.482</td>
</tr>
</tbody>
</table>

4.3. Modelling of cyclic behaviour

Figure 3(a) shows the predictions obtained for a strain-controlled situation, using Abaqus FE software, for both sets of viscoplasticity model constants. In general, both models give accurate prediction when compared with the experimental data. However, the linear nonlinear model predicts better predictions of the maximum stress value, from beginning up to the end of stage 2. The problem with the nonlinear isotropic hardening model for the P91 specimen is that the model predicts a constant peak stress after certain number of cycles, while the test data shows gradual linear decrease in stage 2. The model also gives good stress-strain predictions for simulation during the lower strain amplitude regions, as shown in Fig. 3(b).

5. Preliminary microstructure investigation

The application of mechanical loading, either constant or cyclic, of P91 steel is reported [3] to cause a coarsening of laths and subgrains and to decrease the dislocation density. The microstructural evolution occurs on a subgrain scale and hence a transmission electron microscope is required to investigate this. Fig. 4 (a) to (d) show the bright field TEM images for different life fractions, i.e. (a) as received material, (b) cycle 200\textsuperscript{th}, (c) cycle 400\textsuperscript{th} and (d) cycle 656\textsuperscript{th} respectively. By using the line intersection technique, the subgrain sizes for Fig. 4 (a) to (d) are 0.383, 0.507, 0.551 and 0.604 µm respectively. It can be seen that the subgrains are coarsened, as the cycles increase. Although it is difficult to clearly identify the subgrain evolution, at different life fractions, using SEM, the SEM images show that a small number of cracks start develop at about the end of stage 2 of cyclic softening, as shown in Fig. 4(e). During this period, the microcracks do not significantly damage the material, as shown by the value of the cyclic Young’s modulus, which is similar to the initial Young’s modulus. The modulus value is capable of giving an indirect measurement of damage [9]. Fig. 4(f) shows a typical crack which exists in a fractured specimen (cycle 656) at which point there was an approximate 30 percent decrease in the Young’s modulus value.

![Fig. 3. (a) Comparison predictions obtained for NR and LNR models of isotropic hardening and (b) stress-strain predictions using the LNR model at half the number of cycles to failure, for two different strain-controlled loading cases](image-url)
Fig. 4. Bright field TEM images for (a) the as-received material, and the subgrain evolution which occurs in ±0.5% strain-controlled test at cycle (b) 200th, (c) 400th and (d) 656th. Also, SEM images of the cracks initiated on the specimen’s surface at (e) cycle 400th and (f) cycle 656th.

6. Conclusions

The viscoplasticity model developed in this study gives accurate correlations with the experimental data. The linear nonlinear model performs better than the nonlinear model. The softening behaviour of stage 1 and 2 is mainly related to the evolution of microstructure while the propagation of cracks affects the third stage.

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