Prediction of Life Time of the First Wall under Thermal Fatigue based on Viscoplastic Deformations

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ABSTRACT

The First Wall of a fusion reactor is subjected to cyclic thermo-mechanical loading. The time history of the mechanical behavior has been analyzed using the Chaboche's viscoplastic material model. Cyclic tests and relaxation tests at 200°C and 400°C have been performed on the austenitic stainless steel SS 316 LSPH, from which the parameter sets of Chaboche's model have been determined.

1 INTRODUCTION

The First Wall of a fusion reactor is exposed to high heat flux. Cyclic operation causes thermal fatigue of the actively cooled metallic wall. Since high stresses were calculated in linear thermoelastic analyses (Ref. 1), the use of inelastic material models is necessary to address the fatigue behavior.

In this study, Chaboche's viscoplastic theory (Ref. 2, 3) is used to calculate the stress-strain field of the First Wall component. This theory is suitable to describe the behavior of metallic material under cyclic loading condition (Ref. 4) and appears to be capable of modeling a wide range of inelastic behavior characteristics (Ref. 5). The parameters of Chaboche's theory are determined parametrically on temperature based on uniaxial cyclic loading tests and relaxation tests on SS 316L SPH, which is a candidate material for the First Wall components. Using these parameters, finite element calculations are carried out to determine time-dependent stress and strain fields.

2 CHABOCHE'S CONSTITUTIVE EQUATIONS

Under uniaxial stress conditions, Chaboche's model is given by the following differential equations:

\[ \dot{\varepsilon} = \left\langle \frac{[\sigma - \gamma] - R}{K} \right\rangle \theta^{n} \text{sgn}(\sigma - \gamma) \]  

(2.1)

\[ \gamma = H \dot{\varepsilon} - D \dot{\gamma} \left| \dot{\varepsilon} \right|, \]  

(2.2)

\[ R = h \left| \dot{\varepsilon} \right| - dR \left| \dot{\varepsilon} \right|, \quad R(0) = R_{0}. \]  

(2.3)
where, $\sigma$, $\varepsilon$, $\gamma$, and $R$ denote the state variables, stress, inelastic strain, back stress and isotropic hardening, respectively. $< . >$ is zero if the value inside is negative. The parameters $K$, $n$, $H$, $D$, $h$, $d$ and the initial value of the isotropic hardening $R_0$ have to be determined from the experimental data.

3. EXPERIMENTS

Experiments were carried out on the test specimens made from SS 316L SPH. The test specimens have a cylindrical gauge length of 20 mm and a diameter of 10 mm.

The specimens were heated up to nearly constant temperature ($\pm 1^\circ C$) in a furnace with three separate heating zones. The experiments were carried out by a servohydraulic tension test device. The elongation of the cylindrical part was measured with an extensometer. From one side it grasped with two ceramic holding units into the furnace at the polished surface of the specimen. A computer allowed to program almost any arbitrary history of loading.

Cyclic tests were carried out in strain-control operation at two different temperatures, 200°C and 400°C. The hysteresis curves were used to estimate all the Chaboche's parameters. Throughout the cyclic tests strain ranges $\Delta \varepsilon$ were employed to be $0.3\%$, $0.4\%$, $0.6\%$ and $0.8\%$, and strain rates $\dot{\varepsilon}$ of $2.0 \times 10^{-4}$/sec, $2.0 \times 10^{-5}$/sec, $2.0 \times 10^{-6}$/sec and $2.0 \times 10^{-7}$/sec.

Relaxation tests were also carried out at two temperatures, 200°C and 400°C. In order to get the saturated values of isotropic hardening and the overstress, the specimens were preloaded in approximately 1000 cycles. Tests were performed with different strain ranges of $0.3\%$, $0.4\%$, $0.6\%$ and $0.8\%$, and at the constant strain rate of $2.0 \times 10^{-4}$/sec.

4. PARAMETER ESTIMATION

Parameters of Chaboche's model were determined stepwise and iteratively through the following three steps, based on the experimental results of cyclic tests and relaxation tests.

In Step 1, the parameters $K$, $n$, $H$ and $D$ were evaluated from the hysteresis loops of saturated cycles, where $R$ is constant. The stress is given by the sum of back stress, isotropic hardening and overstress as follows:

$$\sigma = \frac{H}{D} (1 - C \varepsilon^{\rho D}) + R + K \sqrt{\dot{\varepsilon}},$$

\hspace{1cm} \text{(4.1)}

where

$$\dot{\varepsilon} = \int |d| \dot{\varepsilon}|.$$

\hspace{1cm} \text{(4.2)}

The constant $C$ can be determined unambiguously on the basis of the initial condition of back stress for symmetric hysteresis loops. $P$ is the accumulated plastic strain. By means of the least-squares method, this relationship (4.1) is fitted to the experimental hysteresis curves.

However, the cyclic loop is actually almost independent of the strain rate, i.e., overstress is too small to determine reliably the parameters $K$ and $n$. On the other hand, variation of overstress is significant throughout the relaxation tests. Therefore, in Step 2, the evaluated parameters $K$ and $n$ should be confirmed by the experimental data of relaxation tests. Since all tests were performed after pre-cycling, the isotropic hardening $R$ has already been saturated. The back stress $Y$ is calculated in analogy to Step 1 (4.1). Then, only the parameters $K$ and $n$ are determined by fitting the simulated stress behavior to the experimental one, which is based on the least-squares method.

In Step 3, the remaining parameters $d$, $h$ and $R_0$ are evaluated from the hysteresis loops of the
stress histories of cyclic tests. Since parameters $K$, $n$, $H$ and $D$ are known, correlation (4.1) contains only an unknown term of $R$. At the hysteresis tip, values of the first term and the third term can be calculated and the following relationship holds:

\[
\sigma_{\text{tip}} = Y_{\text{tip}} + \left[ R_0 + \frac{h}{d} (1 - e^{-F_0}) \right] + (K \sqrt{\dot{\varepsilon}})_{\text{tip}}
\]  

(4.3)

where $Y_{\text{tip}}$ and $(K \sqrt{\dot{\varepsilon}})_{\text{tip}}$ are known as functions of $K$, $n$, $H$ and $D$. Again, the parameters of $R_0$, $h$ and $d$ are estimated by means of the least-squares method.

After some iterations between the three steps mentioned above, the parameters were evaluated as follows:

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>K</th>
<th>n</th>
<th>H</th>
<th>D</th>
<th>h</th>
<th>R0</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>86.8</td>
<td>4.93</td>
<td>169300</td>
<td>1650</td>
<td>132.2</td>
<td>102.2</td>
<td>1.13</td>
</tr>
<tr>
<td>400</td>
<td>103.0</td>
<td>3.27</td>
<td>106448</td>
<td>1129</td>
<td>583.5</td>
<td>62.9</td>
<td>4.89</td>
</tr>
</tbody>
</table>

With these parameter sets, cyclic loading simulations and cyclic hardening simulations became possible. The results of the cyclic loading simulation for $T = 200$°C and that of the cyclic hardening simulation for $T = 400$°C are shown in Figs. 1 to 4, respectively.

5 APPLICATION TO THE FIRST WALL OF A FUSION REACTOR

5.1 Material model

The material model given in Eqs. (2.1) - (2.3) has been implemented in the ABAQUS FE-code [6]. The parameter sets for different temperatures are given in the previous section. Besides the Chaboche constitutive equations, the ORNL theory has been used to determine stress and strain fields. The ORNL material model is based on a flow rule that shows linear kinematic and isotropic hardening. The bilinear curves describing saturation cycles are included in Figs. 5 and 4.

5.2 FE-Analysis

During normal operation, the FW is periodically loaded by a surface heat flux $Q$ and internal heat generation $q$ due to neutron fluence. A cross-section of a typical FW design and its cyclic loading history is depicted in Fig. 5. The geometry is adapted from the TS1/TS2 specimens. Under the fusion program of the European Community these specimens are being examined for fatigue under thermo-mechanical conditions that are close to the loading of a next generation's fusion machine. The thermo-mechanical cycles are characterized by a burn time of 500 s with a surface heat flux of maximum 40 W/cm², volumetric heat deposition of maximum 14 kW/cm³ and an off-burn time shut down plus dwell time of 280 s. The fatigue behavior of the structure is described by the cyclic variation in stress and strain.

In a first analysis stress and strain fields have been calculated utilizing the ORNL model. Due to the model structure, it is sufficient to take into account two cycles. The second thermal period induces a saturated stress-strain cycle (if no further creep-plasticity interaction is included).

On the other hand, Chaboche's material model has been applied. As it is impossible to calculate stress and strain for several 100 cycles in order to reach saturation, the procedure is split up into two steps:
First, a small number of cycles (4) are calculated with periodic loading until with a small amount of isotropic hardening, a "first-cycle saturation" of peak stress and strain levels is reached. Second, the isotropic hardening variable $R$ is fixed by its saturation value. And again, on the basis of the fields obtained in the first step of the procedure, an analysis with a small number of cycles (5) is performed to reach stable stress-strain cycles.

Thermal and mechanical analyses have been performed with the ABAQUS FE-code. The FE-mesh shown in Fig. 6 consists of 228 2-D elements with 773 nodes. In mechanical analyses, generalized plane strain (normal to the plane of the figure) has been considered to be the most suitable boundary condition.

5.3 Results

At first sight, the calculated results look rather similar for both material models used. In Figs. 7 and 8, contour plots of the axial stress fields are traced for both material models. The diagrams show the behavior at the end of heating and at the end of dwell time. The maximum values of tensile and compressive stresses differ by up to 10%. The extreme values, however, do not occur at the same location of the structure.

Due to the non-linear hardening rule of Chaboche's model, stress and strain redistributions take place over a large number of cycles. For example, the most exposed location (which is at the heated front side), the plastic strain range is continuously reduced in terms of time. Starting at a value of 0.08% (1st cycle), it decreases to 0.32% (3rd cycle) and finally reaches a percentage of 0.321 within a saturated hysteresis loop.

For a stable cycle, the mechanical equivalent strain range is calculated to be 0.59%. For comparison, the ORNL model predicts 0.585%, and a simple plasticity model (including linear isotropic hardening) yields 1.33% of the mechanical strain range. Taking into account the fatigue curves given in the RCC-code [7] the lifetime of the component can be assessed.

Depending on the individual material model, the number of cycles up to crack initiation are predicted to be 2690 (Chaboche model), 3030 (ORNL model) and 7730 (plasticity model).

REFERENCES


Fig. 1: Hysteresis loop of 30th cycle

Fig. 2: Hysteresis loop of 30th cycle

Fig. 3: Cyclic hardening at 200°C. (Experimental data versus fit of material model)

Fig. 4: Cyclic hardening at 400°C. (Experimental data versus fit of material model)
Fig. 5: Geometry of First Wall

Fig. 6: Finite Element Mesh

Fig. 7: Axial stress fields at end of heating

Fig. 8: Axial stress fields at end of cycle