Isothermal and Thermal Mechanical Low Cycle Fatigue of 316 L Steel

C. KORN and G. PLUVINAGE
Laboratoire de Fiabilité Mécanique, Université de Metz, Faculté des Sciences, Ile du Saulcy, 57045 Metz, France

ABSTRACT

Isothermal and thermomechanical low cycle fatigue tests were conducted on 316 L steel to determine the behaviour of this material under strain cycling including dwell times in a total strain range of 1 % and in a temperature range of 150° C to 500° C. Some models of life prediction were used and discussed on the results of the different kind of tests.

KEYWORDS

316 L steel, isothermal test, Thermomechanical test, modelisation of life time.

Introduction :

Isothermal and thermomechanical low cycle fatigue tests are performed to study the behaviour of materials used in mechanical equipment and structural components which are submitted to cyclic straining at elevated temperatures.

This paper describes the results of a study on a 316 L steel used in nuclear plant, submitted to complex strain and temperature cycling and discusses on the results of predicted life time from different models of life time prediction.

Experimental procedure :

All the tests were performed on a servocontrolled electrohydraulic machine driven by computer. The strain was measured and controlled by using an uniaxial high temperature extensometer with return sticks, and the temperature was obtained with an infra-red heating chamber connected to the computer. The thermal and mechanical cycles are described Figure 1. The total strain range is about : $\Delta \varepsilon_1 = 1 \%$ and the two extreme temperatures of the thermal cycle are : $T_{\text{min}} = 150°$ and $T_{\text{max}} = 500°$ C. The duration of one cycle is about 4 minutes, including dwell times of 10 and 30 seconds.
The chemical composition of the material is described in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>Co</th>
<th>S</th>
<th>P</th>
<th>Fe</th>
<th>N</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.012</td>
<td>12</td>
<td>17</td>
<td>2.5</td>
<td>1.8</td>
<td>1.5</td>
<td>1.2</td>
<td>2.5</td>
<td>&lt;0.01</td>
<td>0.035</td>
<td>&lt;0.15</td>
<td>0.06</td>
<td>&lt;15 ppm</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of the 316 L steel.

Experimental Results:

Three kinds of tests on 316 L steel were performed: One isothermal fatigue test at 150°C, one at 500°C, with the mechanical cycle shown in Figure 1, and one thermomechanical test with the thermal and mechanical cycles shown in Figure 1. The results of life time Nf of these tests are summarized in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Nf cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal 150°C</td>
<td>2515</td>
</tr>
<tr>
<td>Isothermal 500°C</td>
<td>971</td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>792</td>
</tr>
</tbody>
</table>

Table 2: Number of cycles to failure for the different tests.

Stabilized hysteresis loops for each test are shown in Figure 2. Figure 3 describes the evolution of the maximal and minimal loads obtained on different points of the mechanical cycle: at the start and the end of each dwell time, for each kind of test. The evolution of the plastic strain $\Delta e_p$ versus the number of cycles is shown in Figure 4.

Discussion:

The evolution of the maximal and minimal loads is quite the same during each test. Figure 3 shows three different stages: hardening of the material, stabilisation in load and crack growth before rupture. The duration of each stage is shown in Table 3.

<table>
<thead>
<tr>
<th>Test</th>
<th>Duration of hardening</th>
<th>Duration of stabilisation</th>
<th>Duration of crack growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal 150°C</td>
<td>7% of Nf</td>
<td>73% of Nf</td>
<td>20% of Nf</td>
</tr>
<tr>
<td>Isothermal 500°C</td>
<td>7% of Nf</td>
<td>67% of Nf</td>
<td>6% of Nf</td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>8% of Nf</td>
<td>67% of Nf</td>
<td>25% of Nf</td>
</tr>
</tbody>
</table>

Table 3: Duration of the three stages.

At 500°C the hardening of 316 L steel is more important than at 150°C. In the two cases, the load relaxation is greater in compression than in traction. In the three tests, the duration of hardening (in % of number of cycles to failure) is quite the same. The great difference is on the duration of crack growth: at 500°C the duration of this stage is shorter than at 150°C or in thermomechanical fatigue test, and the number of cycles for hardening is shorter at 500°C because the speed of cells creation increases when the temperature increases. In thermomechanical fatigue test, the duration of crack growth is greater than in isothermal conditions because the maximal strain in traction is obtained at the minimal temperature and we combine the effects of temperature and mechanical cycling.

On the curves of the evolution of the plastic strain versus the number of cycles, we also see three different stages: decreasing, stabilisation and final decreasing before rupture; the plastic strain range is greater at 150°C than at 500°C due to the fact that the influence of temperature is greater in this last case. In thermomechanical fatigue test, the plastic strain range is greater than at 500°C but lower than at 150°C.

Modelisation of Life Time:

- According to TAIRA [1], plastic strain in thermomechanical fatigue, $\Delta e_{p,m}$ is defined by the relation:

$$\Delta e_{p,m} = \Delta e_1 ^{-v/(\gamma/E)}T_2 ^{-v/(\gamma/E)}T_1$$

with $T_1$ the minimal temperature and $T_2$ the maximal one.

The author has also suggested the use of the concept of an equivalent temperature for correlating thermal fatigue behaviour with isothermal one. This concept states that, regarding thermal fatigue cycling between two temperatures, the same fatigue life will be developed by isothermal cycling at the equivalent temperature defined as follows:

$$T_e = (T_{max} + T_{min})/2$$

if the difference between $T_{max}$ and $T_{min}$ is small

$$T_e = T_{max}$$

if this difference is great

- COFFIN [2] proposed a concept which takes account of the frequency of cycling in traction:

$$\Delta e_p = C_1 [N_f (\nu_f/2)^k-1]^\beta$$

which $C_1$, $k$, $\beta$ constants, $\nu_f$ the frequency in traction and $\Delta e_p$ the plastic strain.

- DEGALLAIX [3] considers that the life time $N_f$ is a function of plastic strain:

$$1/N_f = A_1 (\Delta e_p)^{B_1} . e^{Q/R T} + A_2 (\Delta e_p)^{B_2}$$

where $A_1$, $B_1$, $A_2$, $B_2$, are material constants, $Q$ is an apparent activation energy, $T$ the temperature. ($Q = 4.795$ Kcal/mol/K for 316 L steel).
- Taira also introduced the concept of "Spanning Factor" which permits the calculation of the number of cycles to failure \( N_f \) in thermomechanical fatigue with results obtained under isothermal conditions at the two temperatures of the thermal cycles \( T_1 \) and \( T_2 \).

\[
N_f = \frac{(2 [N_f(T_1)/N_f(T_2)]^{1/2} + 1 + [N_f(T_1)/N_f(T_2)]) \times N_f(T_2)}{2/3 \beta(T_2)}
\]

with \( \beta(T_2) \) is the absolute value of the slope of the plastic curve of Manson at the temperature \( T_2 \); \( N_f(T_2) \) is the life time of the material, for a same total strain, in isothermal cycling at the temperature \( T_2 \) and \( N_f(T_1) \) at the temperature \( T_1 \).

Table 4 summarizes the different values of the coefficients for modelisation, and table 5 the calculated life time obtained with the different models compared to the experimental ones.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \Delta \text{plm} )</th>
<th>C1</th>
<th>k</th>
<th>( \beta )</th>
<th>A1</th>
<th>B1</th>
<th>A2</th>
<th>B2</th>
<th>K Kcal/mol/K</th>
<th>( \Delta \text{ep} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal 150°C</td>
<td>69 %</td>
<td>155</td>
<td>7.35</td>
<td>6.4450x10^5</td>
<td>5.1246</td>
<td>6.9049x10^-1</td>
<td>1.792</td>
<td>2x10^-5</td>
<td>69 %</td>
<td></td>
</tr>
<tr>
<td>Isothermal 500°C</td>
<td>60 %</td>
<td>151</td>
<td>5.86</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>675 %</td>
<td>358</td>
<td>4.576</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>66 %</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Values for modelisation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Isothermal 150°C</th>
<th>Isothermal 500°C</th>
<th>Thermomechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_f ) calc</td>
<td>( N_f ) exp</td>
<td>Error</td>
</tr>
<tr>
<td>Taira</td>
<td>3134</td>
<td>2515</td>
<td>25%</td>
</tr>
<tr>
<td>Frequency</td>
<td>1403</td>
<td>2515</td>
<td>44%</td>
</tr>
<tr>
<td>Separation</td>
<td>2786</td>
<td>2515</td>
<td>11%</td>
</tr>
<tr>
<td>Spanning factor</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Life time predictions obtained in calculation with the different models.

The fatigue life values obtained from experiments are lower than the ones predicted from the models of Taira and Degallaix. The frequency separation concept gives, in each case, fatigue life values greater than the experimental ones. The best results are obtained with Degallaix's model under isothermal conditions, and with the concept of spanning factor in thermomechanical fatigue test; the other models seem not to be accurate for predicting life time in such kind of tests.

REFERENCES


ACKNOWLEDGMENTS

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Figure 1: Thermal and Mechanical cycles

Figure 2: Stabilized hysteresis loops obtained in each test

Figure 3: Evolution of the loads versus the number of cycles in each test
Figure 4: Evolution of the plastic strain versus the number of cycles

Figure 5: Main crack on 316L steel at 150°C