MEAN STRESS EFFECT ON FATIGUE LIFE OF 316L AUSTENITIC STEEL IN AIR AND SIMULATED BOILING WATER REACTOR HYDROGEN WATER CHEMISTRY ENVIRONMENT

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ABSTRACT

The influence of mean stress effects on the fatigue behavior of 316L austenitic stainless steel was tested in air and light water reactor (LWR) environments. Round bars and hollow specimens were used in air, while only hollow specimens with circulating high-temperature pressurized water were used for simulated LWR environment. The LWR environment was characterized by a temperature of 288 °C and high-purity, neutral water with 150 ppb dissolved hydrogen. Load-controlled experiments were performed to adjust stress amplitudes and mean stresses. The results of the fatigue tests in air showed that the application of a positive (+50 MPa) or negative mean stress (-20 MPa) leads to a clear increase in fatigue life. These results are not in line with the generally observed decrease in fatigue life with tensile means stresses. This behavior is attributed to the primary and secondary hardening stages that persist even close to the fatigue limit. The effects of the positive mean stress (+50 MPa) in the water environment are much less pronounced than in air while remaining slightly beneficial. On the contrary, negative mean stresses (-10 and -20 MPa) in the water environment induced a marked increase in the fatigue life. The comparison of the results without mean stress in water and air indicates that the fatigue life is reduced in water environment by a factor of about 2.

The effects of specimen geometry on the measured fatigue life were assessed in the air environment, and no significant difference could be discerned between the geometries. The impact of the internal pressure in the hollow specimens on fatigue life was experimentally studied by performing a series of tests with different pressures and by investigating the multiaxial stress/strain state through finite element simulations. The results showed that the internal pressure does not play an import role when varying from 80 to 200 bars in hollow specimens of 10 mm diameter with a 5 mm thick wall.

Keywords: Load-controlled fatigue behavior, mean stress, high temperature water, 316L austenitic stainless steel

1. INTRODUCTION

It is now well established that, when tested in light water reactor environment, a fatigue life reduction of the austenitic stainless steels can occur in comparison to the fatigue life in air [1,2]. The fatigue life decrease depends in particular on strain rate, temperature, strain amplitude and dissolved oxygen level, and is observed only if three threshold conditions are met simultaneously, namely when both the strain range and the temperature are above their respective threshold, and when the loading strain rate was below a minimum value [1,3]. The fatigue life in strain-controlled experiments is based on the number of cycles required to reach a
given failure criterion, often defined by a decrease (typically 25 or 50%) of the peak tensile stress or by complete failure of the specimen [4]. A 25% reduction in stress corresponds, for most fatigue specimens, to the number of cycles required to create an engineering crack of about 3 mm [5]. Shallow surface cracks of less than 10 \( \mu \text{m} \) in length appear very early in fatigue life, even at low strain amplitude. Consequently, the formation of these surface cracks is not a critical step and represents only few percent of fatigue life. Thus, the fatigue crack initiation is usually regarded as a two-step mechanism: 1) growth of microstructural cracks in stage I (cracks smaller than 200 \( \mu \text{m} \)), and 2) growth of mechanically small cracks to the engineering size in stage II. In practice, the fatigue life is composed of stage I and II, which corresponds to a crack propagation from 10 \( \mu \text{m} \) to 3 mm [6]. The reduction in fatigue crack initiation due to LWR environment was shown to arise from an enhanced growth of the small microstructural cracks in stage I and to a lesser extent by a somewhat accelerated growth rate in stage II [4].

Cyclic loading on pressure boundary components of light water reactors stems from changes in the overall configuration of the mechanical and thermal loading. As a rule, the design life of components should not exceed \( 10^5 \) cycles but is usually even less than several thousand, which requires testing in the low cycle regime in strain-controlled mode. Therefore, most available data were obtained with fully reverse strain-controlled uniaxial tests of constant strain amplitude, constant temperature, constant strain rate, with well-polished specimens and without the application of a mean strain or mean stress. Such ideal conditions are evidently quite different from those experienced by components in operation in nuclear power plants. These components can undergo cyclic deformation during service due to thermal stratification that can induce thermal fatigue [7], or to flow-induced vibrations [8]. In addition, the effect of mean stress on fatigue life in water environment has been identified as one of the issue that is not sufficiently documented and that needs to be addressed. It was indeed shown that there are experimental conditions where the effect of mean stress on austenitic steel are not in line with general conventions where compressive mean stresses are usually beneficial to fatigue life and tensile ones are detrimental. This conventional behavior usually occurs in the high cycle fatigue regime (\( 10^6 - 10^8 \) cycles) when the applied stresses generate highly dominated elastic strain amplitudes. In such cases, different methods (Gerber, Goodman, Soderberg, Walker, Smith-Watson-Topper) were initially proposed to account for the mean stress effects on fatigue life [9]. The situation is different for the austenitic steels that show an elastic-plastic response even in the high cycle regime, which is believed to lead to the observed non-conventional response of the fatigue life to mean stress. For instance, the fatigue life of the 304L austenitic steel tested in stress-controlled mode at 300 °C, for both in air and LWR environments, was found to increase with a mean stress of 100 MPa [10]. In another study, Miura and Takashi showed that the Gerber and modified Goodman models did not predict correctly their high cycle fatigue results on 316 austenitic steel, which was also attributed to the elastic-plastic response observed in this regime [11]. Therefore, there are situations, dependent on temperature and environment, where mean tensile stresses on the fatigue life of austenitic steels are beneficial. This calls for further investigations, as little is known about mean stress effects in LWR environment and it would be prudent to incorporate these effects into the fatigue design code. Indeed, real loading conditions usually involve mean stresses.

The activities undertaken in this study were designed to gain insight into the influence of mean stress on fatigue life of austenitic stainless steels both in air environment and water environment referred as to BWC/HWC (boiling water reactor/hydrogen water chemistry). While the data and
analysis presented constitute the first preliminary results of an on-going project, they are numerous enough to demonstrate general trends and interpretations.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

The investigated material was from a non-stabilized 316L austenitic stainless steel pipe with an outer diameter of 219 mm and a wall thickness of 23 mm. The seamless pipe was manufactured and processed according to the requirements of the ASME BPV Code. The processing sequences of the seamless pipe material consisted of hot working, solution annealing, water quenching to room temperature, pickling and grinding. The chemical composition of the material in the as-received condition is given in Table 1. The material had an average grain size of 35 μm.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>N</th>
<th>Nb</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>0.021</td>
<td>0.26</td>
<td>1.69</td>
<td>0.033</td>
<td>0.003</td>
<td>17.5</td>
<td>2.15</td>
<td>11.14</td>
<td>0.0601</td>
<td>0.012</td>
<td>0.003</td>
</tr>
</tbody>
</table>

2.2 Test facilities and experimental conditions

The load-controlled fatigue tests were performed at 288 °C in air and in pressurized water environment characterized by high-purity, deoxygenated (nitrogen purging) water with 150 ppb dissolved hydrogen. The conductivity in the inlet and outlet water was 0.055 μS/cm and smaller than 0.07 μS/cm, respectively. Figure 1 shows a schematic of the used water loop facility, which allows the simulation of BWR and PWR water chemistry conditions. The hollow specimens are heated by the pressurized water, which circulates through them. Three different internal pressures were used: 80, 100 and 200 bars. These hollow specimens have a wall thickness of 2.5 mm and an outer diameter of 10 mm. A detailed description of the facility can be found in [12].

Figure 1: Schematic of the high-temperature loop.
For the tests in air, round bar specimens of 8 mm diameter and 18 mm gage length were used. The technical drawings of both specimen geometries are shown in Figure 2. The tests were run in load-controlled mode using a triangular waveform at a frequency of 0.17 s\(^{-1}\). That frequency corresponds to the fastest rate that can be achieved with the electro-mechanical Instron 8862 machines used for the comparative tests in high-temperature water. With such a frequency, the testing was focused on the low-cycle regime, namely below \(N_f = 10^5\), essentially for two reasons. First, from a practical point of view, a test performed at a frequency of 0.17 s\(^{-1}\) needs one week to reach \(10^5\) cycles, which basically precludes testing at conditions leading to \(N_f >> 10^5\). Second, it is well known that for the austenitic stainless steels three concomitant threshold conditions need to be met for environmental effects on fatigue to occur. These conditions are a minimum strain range of \(\approx 0.2\% - 0.3\%\), a strain-rate lower than \(\approx 0.4\%\ s\(^{-1}\), and a testing temperature greater than 150 °C. As it will be shown below, the fatigue limit of the investigated material at 288 °C was estimated around 140 - 150 MPa. For load-controlled experiment, a stress amplitude of 150 MPa corresponds to a strain range lower than 0.25% after several thousands of cycles. Therefore, to have the strain range condition for environmental effects fulfilled, the testing was focused at stress amplitude larger than 150 MPa that were found to lead to \(N_f\) smaller than \(10^5\). Typically, the strain-rates at \(N_f/2\) were in the range 0.1 to 0.3 % s\(^{-1}\). The strain was measured with an extensometer attached to the specimens. In this exploratory study, moderate mean stresses of few tens of MPa were selected.

For the tests performed in pressurized water environment, the 200 bars internal pressure in the hollow specimens, which have to be regarded as closed end cylinders, creates a nominal axial stress of 6.7 MPa. Before starting an experiment, this stress has to be balanced by applying a compressive load of -392 N on the specimens. The electrical zero of the load signal is done only after the application of that compressive load, which actually corresponds to the zero axial stress reference level.

In this work, \(N_f\) represents the number of cycles to break the specimens in two parts. For the test in water, in few cases, the experiment was automatically stopped with the occurrence of a leakage leading to a quick pressure drop in the loop. However, for load-controlled experiments,
the number of cycles between the occurrence of leakage and the final failure is quite small, typically smaller than 100.

3. **EXPERIMENTAL RESULTS AND DISCUSSION**

3.1 **Load-controlled fatigue behavior in air and water with zero mean stress**

The tests performed in load controlled mode at 288 °C with the massive round bars and hollow specimens in air and water environment are presented in Figure 3 on a graph of the stress amplitude $\sigma_a$ versus the number of cycles to failure $N_f$. The red arrows in the figure indicate run-out tests. No striking and systematic difference was observed between the massive and hollow specimens tested in air. As far as the data obtained with the hollow specimens tested in water with 80 and 200 bars are concerned, they also fall practically all along the same curve. At $\sigma_a = 170$ MPa, three tests were carried out to assess possible effect of the internal pressure. The results are summarized in Table 2, where it is observed that $N_f$ lies within the scatter expected in fatigue experiments. The two fits in Figure 3 were respectively calculated by considering all the data in air without distinction between massive and hollow specimens, and all the data in water at 80, 100 and 200 bars.

![Figure 3: Stress-life data in air and water without mean stress at $T_{test} = 288$ °C.](image)

<table>
<thead>
<tr>
<th>$T = 288$ °C</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_a = 170$ MPa</td>
<td></td>
</tr>
<tr>
<td>80 bars</td>
<td>16354</td>
</tr>
<tr>
<td>100 bars</td>
<td>12550</td>
</tr>
<tr>
<td>200 bars</td>
<td>16802</td>
</tr>
</tbody>
</table>

Table 2: $N_f$ at different internal pressures in hollow specimens.

The fits through the experimental data were determined with a power law equation of the type:

$$\sigma_a = B(N_f)^{-b} + A$$ (1)

The two datasets are not large enough to determine the three parameters of the equation accurately. However, a rough, albeit reasonable estimate of the fatigue limit, can be done from the existing data points. Decreasing the stress amplitude below 150 MPa would raise the number of cycles to failure in the range $10^6$ or even higher. Hence, the fits were calculated by arbitrarily fixing the parameter $A$ to 150 MPa and by adjusting $B$ and $b$ only. Clearly fatigue failure occurred in fewer cycles in water environment than in air. There is reduction in fatigue life by a factor of about 2 within the stress amplitude range 170-190 MPa. Additional tests in air are
required to better estimate the fatigue endurance in order to investigate the influence of the water environment on this last property.

From numerous earlier investigations of fatigue behavior in strain-controlled mode, it is well known that the fatigue life of austenitic stainless steels is often characterized by the succession of: 1) primary hardening, 2) softening, and 3) secondary hardening. As a matter of fact, the hardening/softening sequence depends in particular on the strain-amplitude, strain-rate, and temperature so that it can occur at different stages of the fatigue life [13,14]. In strain-controlled experiments, hardening and softening are simply manifested by an increase or a decrease of the stress amplitude during the fatigue life. In load-controlled experiments however, the hardening and softening sequence appears as a variation of the strain amplitude, where a decrease of the strain amplitude evidently represents the hardening behavior, while an increase reflects the softening. The sequence of hardening/softening for some of our experiments is illustrated in Figure 4 to Figure 7. In water and in air with zero mean stress, the tests are characterized by a primary hardening during the initial stage of cycling up to several tens of cycles. Some softening takes place afterwards, which in the case of stress amplitude smaller than 190 MPa is followed by secondary hardening up to failure. These three different stages are indicated in Figure 4. The secondary hardening regime is less marked or even quasi-nonexistent at $\sigma_a = 190$ MPa as can be seen in Figure 5, where the test at 80 bars does not exhibit secondary hardening while the test at 200 bars displays a small decrease in strain amplitude in the last stage of the fatigue life. Figure 6 and Figure 7 compare the tests in air and water at $\sigma_a = 170$ MPa and $\sigma_a = 190$ MPa respectively. The cyclic plasticity in both environments appears identical.

![Figure 4: Cycle hardening/softening response at $\sigma_a=170$ MPa in water, 80 and 200 bars.](image)

![Figure 5: Cycle hardening/softening response at $\sigma_a=190$ MPa in water, 80 and 200 bars.](image)
3.2 Load-controlled fatigue behavior in air with mean stress

The influence of mean stress in air was determined with round bar specimens. The results are plotted in Figure 8. The application of relatively modest positive mean stresses, 20 and 50 MPa, increases the fatigue life, in opposition to most proposed standard models characterizing the effect of mean stress. The effect of a positive mean stress of 20 MPa is relatively small and within the usual scatter observed in fatigue results. Nonetheless, the trend appears systematic and is confirmed by the data with a 50 MPa mean stress that shifts the fatigue life to even higher $N_f$. Thus, it is concluded that the application of tensile mean stresses at 288 °C increases the fatigue life. This finding is in line with results reported by Solomon et al. on 304L austenitic steel, where they showed that the application of a 100 MPa mean stress increases both the fatigue life and the fatigue limit at $10^7$ cycles for tests performed at 300 °C [10]. The run-out at $\sigma_a = 170$ MPa and $\sigma_m = 50$ MPa suggests that the application of a positive mean stress increases the fatigue limit by few tens of MPa. Confirming this point would require increasing the frequency of the testing significantly to keep the duration of the tests reasonable. A strong effect of a compressive mean stress was also shown from a single test run with $\sigma_a = 190$ MPa and $\sigma_m = -20$ MPa, where an increase of the fatigue life by one order of magnitude was found. The hardening/softening behavior of the material for positive and negative mean stress, with $\sigma_a = 190$ MPa is shown in Figure 9. The unusual response of this material to a positive mean stress can be rationalized in terms of the primary and second hardening on the one hand, and on the softening on the other hand. For all the mean stress considered, one observes a strong reduction of the strain amplitude during the first 20-30 cycles, followed by a softening whose amplitude is much smaller than that of the specimen tested with a zero mean stress.
Figure 8: Stress-life data in air with and without mean stress at $T_{\text{test}} = 288 \, ^{\circ}\text{C}$.

Figure 9: Cycle hardening/softening response at $\sigma_a = 190$ MPa in air, with tensile and compressive mean stress.

3.3 Load-controlled fatigue behavior in water with mean stress

The whole set of fatigue data obtained in high-temperature pressurized water environment are presented in Figure 10. The open circles correspond to the baseline with zero mean stress. Like the data in air, a fit through these data was calculated using a power law. For this dataset, one test with a stress amplitude of 150 MPa was run up to $10^6$ cycles before being interrupted. That last stress amplitude can also be considered very close to the fatigue limit, so that only $B$ and $b$ parameters were adjusted for the fit. For the sake of clarity, only the dataset with zero mean stress was considered to calculate the fit. In Figure 10, all the data points with $\sigma_m \geq 0$ are represented with dots while those with $\sigma_m < 0$ are triangles. To better separate the data with positive mean stress from those with a negative one, two dotted curves are plotted that demarcate a band in the $(\sigma_a-N_f)$ plane within which all the data with $\sigma_m \geq 0$ fall. It is clear that the effect of the positive mean stresses considered is moderate. Keeping in mind that there is an intrinsic scatter in fatigue data, it could be argued that these positive mean stresses practically do not influence the fatigue behavior. Nonetheless, the datasets with $\sigma_m = 10$ and 50 MPa show some trends: the fatigue life seems to be reduced by the application of $\sigma_m = 10$ MPa while it increases for $\sigma_m = 50$ MPa. Note that for $\sigma_m = 20$ MPa, the only data point obtained indicates that the fatigue life is also reduced. Therefore, the response of the material tested in water environment to the mean stress might be slightly different from that determined with the massive specimens tested in air where the fatigue life was found to increase for all mean stresses studied, either positive or negative. The overall fatigue behavior in water with $\sigma_a = 190$ MPa is presented in Figure 11, where four curves with different mean stress are drawn. These curves can be compared with those in air in Figure 9. The general trend is quite similar: the succession of hardening-softening-hardening is also observed with a softening that decreases with positive and negative mean stress. It is noted that a relatively small compressive stress of $\sigma_m = -10$ MPa results in a large fatigue life increase while a tensile stress of $\sigma_m = 10$ MPa has little influence on the fatigue response.
After having discarded the run-outs, all the fatigue life data for the tests with a non-zero mean stress $N_f(\sigma_m)$ in air and water environment were normalized by the fatigue life with zero mean stress $N_f(\sigma_m=0)$. These normalized fatigue lives are reported in Figure 12. It appears that the material responds quite similarly in air and water with a beneficial effect of the mean stress on the fatigue behavior. The few data points that exhibit a relatively small life reduction in water environment corresponds to $\sigma_m = 10$ MPa and $\sigma_m = 20$ MPa. While the reason of this observation remains to be investigated, it is quite plausible that some effects resulting from the multiaxial stress state in the hollow specimens induce a "hidden" contribution of few MPa to $\sigma_m$, which is not taken into account in the plot in Figure 12. This point is qualitatively discussed in the next section.

![Figure 10: Stress-life curve in water at 288 °C with mean stress, hollow specimens.](image1)

![Figure 11: Cycle hardening/softening response at $\sigma_a=190$ MPa, water at 288 °C, with tensile and compressive mean stress.](image2)

![Figure 12: Normalized fatigue life versus mean stress in air and water.](image3)
3.4 Finite element analysis of hollow specimens

In Section 3.1, it was shown that the geometry of the specimens, round bars against hollow specimens, does not modify the fatigue life significantly in air environment. Neither does the variation of the internal pressure in hollow specimens, from 80 bars to 200 bars, in water environment. These conclusions were drawn from the experimental results. Nonetheless, some authors also reported moderate difference (between hollow and bar specimens) in the low cycle regime of an austenitic steel tested in strain-controlled mode, which was attributed to a difference in the internal plastic strain [15]. Generally, hollow specimens are used in testing facilities where rapid temperature variations are of interest, such as in thermo-mechanical fatigue studies. If the hollow specimens are pressurized, like in this study, a multiaxial stress state exists in the cylindrical wall of the hollow specimens. It must be recalled here that the stress triaxiality depends not only on the internal pressure but also on the specimen geometry, in particular on the outer and inner radii. It is therefore interesting to gain some insight into the influence of stress triaxiality on the cyclic plastic flow. Thus, finite element simulations of the pressurized tube were undertaken to study the stress/strain state in pressurized hollow specimens and to compare this state with that developed in non-pressurized tube, or round bars, as a function of the applied axial stresses. So, an axisymmetric model of the tubular specimen was developed with ABAQUS 6.14-1. The specimen was meshed with 2266 elements of the type 4-node bilinear axisymmetric quadrilateral, reduced integration. The model, including the specimen and the boundary conditions, is shown in Figure 13.

The steps of the model were implemented in a way that mimics the experimental procedure. First, the pressure in the internal part of the specimen is raised up to 20 MPa (200 bars), a small compressive load of -390N is then applied on the specimen head to balance the internal pressure that creates an axial tensile stress of about 6 MPa, and finally the specimen is loaded to a prescribed load (either in tension or compression). In our case the specimens were loaded up to a nominal tensile stress $\sigma_{yy} = 190$ MPa, defined as the experimental value by $\sigma_{yy} = L/S_o$, where $L$ is the load and $S_o$ is the specimen cross-section. Since the fatigue cracks initiate inside of the specimens, in the following we focus our attention on the stresses and strains averaged over the so-called internal gage length (see Figure 13). In order to study the evolution of the stress/strain state during the fatigue life, two simulations were performed: one at the beginning of the fatigue life (2nd cycle) and one at the end of the primary hardening stage (50th cycle). The plastic flow properties (true stress versus true plastic strain) given as input for the simulations were extracted from the loading part of the cycles, corresponding to the red segments shown in Figure 14.
Figure 13: The axisymmetric finite element model of the hollow specimen.

Figure 14: Plastic flow properties of the 2nd and 50th cycle used in the simulations.

We note that essentially three components of the stress tensor act within the entire gage length of the specimen, namely $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$. The simulation shows that only the shear component $\sigma_{yy}$ is different from zero but its amplitude remains below 1 MPa, and can be neglected. In other words, $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$ can be assimilated to the principal stresses in good approximation. During a fatigue experiment with a pressurized specimen, the stress state on the internal gage length is triaxial with $\sigma_{xx}$ and $\sigma_{zz}$ being practically constant, while $\sigma_{yy}$ is cycled. $\sigma_{xx}$ and $\sigma_{zz}$ are about -20 MPa and 33 MPa respectively on the internal face.

Owing to the triaxial stress state, the accumulation of equivalent plastic strain is not symmetric with respect to the change of sign of the axial component $\sigma_{yy}$. This directly results from the definition of von Mises stress $\sigma_{Mises}$, which in terms of the principal stress component reads:

$$\sigma_{Mises} = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{xx}-\sigma_{zz})^2}{2}} \quad (2)$$

Since $\sigma_{xx}$ and $\sigma_{zz}$ are practically constant on the internal surface of the specimen during the fatigue experiment with small strain amplitude, $\sigma_{Mises}$ can be regarded as a unique function of $\sigma_{yy}$ but is not an even function: $\sigma_{Mises}(\sigma_{yy}) \neq \sigma_{Mises}(-\sigma_{yy})$. Taking $\sigma_{xx} = -20$ MPa and $\sigma_{zz} = 33$ MPa
and using the previous equation, one finds a difference, which is little dependent on \( \sigma_{yy} \), of about 12 MPa between \( \sigma_{\text{Mises}}(\sigma_{yy}) \) and \( \sigma_{\text{Mises}}(-\sigma_{yy}) \). This was confirmed by the finite element calculations. As a consequence, the amounts of equivalent plastic strain (\( \varepsilon_{p/q} \)) accumulated during the loading in tension and compression are different from one another, even if the specimen is loaded completely symmetrically.

The difference in \( \varepsilon_{p/q} \) reached at maximum and minimum stress is illustrated in Figure 15. \( \varepsilon_{p/q} \) (average value over the internal gage length) is plotted against the stress amplitude. The plastic flow properties for the calculations were deduced from the 2\(^{nd} \) cycle of a fatigue experiment with \( \sigma_a = 190 \) MPa. The dashed and solid red curves refer to \( \varepsilon_{p/q} \) in tensile and compressive loading respectively. One can see that there is indeed a tension/compression bias, which increases with stress amplitude. Hence, cycling between \(+\sigma_a\) and \(-\sigma_a\) on pressurized hollow specimens corresponds to cycling between two different \( \varepsilon_{p/q} \). In Figure 15, the blue curve represents the symmetric response of a non-pressurized specimen. In principle, the fatigue behavior comparison between pressurized and non-pressurized hollow specimens should take into account this \( \varepsilon_{p/q} \) bias. For instance, from the plot in Figure 15 one can deduce that the strain-amplitude (\( \varepsilon_a \)) of the 2\(^{nd} \) cycle a non-pressurized specimen at \( \sigma_a = 180 \) MPa is equal to 0.381 % and the mean strain (\( \varepsilon_m \)) is equal to 0%. However, the same exercise done for the pressurized specimen indicate that \( \varepsilon_a = 0.466 \% \) and \( \varepsilon_m = -0.085\% \).

![Figure 15: \( \varepsilon_{p/q} \) at \( \sigma_{\text{max}} \) (tensile) and \( \sigma_{\text{min}} \) (compression) versus \( \sigma_a \) for the 2\(^{nd} \) cycle.](image)

![Figure 16: \( \varepsilon_{p/q} \) at \( \sigma_{\text{max}} \) (tensile) and \( \sigma_{\text{min}} \) (compression) versus \( \sigma_a \) for the 50\(^{th} \) cycle.](image)

Qualitatively, this analysis shows that, for the pressurized hollow specimen, the strain amplitude is larger and that a slightly negative mean strain exists. However, owing to the hardening and softening occurring during the fatigue life, it is not straightforward to set up a procedure to transfer the data between pressurized and non-pressurized specimens. For instance, the same analysis of \( \varepsilon_{p/q} \) done at the end of the primary hardening stage by considering the plastic flow properties after the 50\(^{th} \) cycle shows that the amplitude of the bias decreases, see Figure 16. In any case, this analysis demonstrates that, for pressurized specimens, load-controlled fatigue experiments with zero-mean stress induce a negative mean strain. Nevertheless, it has to be emphasized that, for our experimental condition, the amplitude of the \( \varepsilon_{p/q} \) bias remains relatively small in agreement with the experimental data.

However, for real components like tubes that operate under internal pressure, the role of the internal pressure on fatigue life might not be negligible. We believe that there is a need to gain
insight into this issue. As an example, let us consider a long tube of 20 cm diameter with a 2 cm wall thickness that operates under an internal pressure of 150 bars. Within the framework of elasticity, the radial stress \( \sigma_r \) and the hoop stress \( \sigma_\theta \) of a pressurized tube can be easily calculated through the tube thickness. Actually, \( \sigma_r \) and \( \sigma_\theta \) do not depend on the amplitude of the axial stress but they depend on each other through the radial equilibrium equation. On the internal surface of the tube, \( \sigma_r \) equals the pressure \( P \) independently of the tube geometry, but \( \sigma_\theta \) depends on the ratio of the internal radius \( R_i \) to the external one \( R_o \), as:

\[
\sigma_\theta = P \left( \frac{1 + \left( \frac{R_i}{R_o} \right)^2}{1 - \left( \frac{R_i}{R_o} \right)^2} \right)^{1/2}
\]

which in this example yields \( \sigma_\theta = 68 \) MPa. With \( \sigma_r = 15 \) MPa, one can then calculate von Mises stress in tension and/or compression for any given axial stress \( \sigma_z \). As discussed above, one also finds different values of von Mises stress in tension and compression. Typically, if the amplitude of the axial stress component is taken at 150 MPa (i.e. close to the fatigue limit), then von Mises stress in compression is about 50 MPa higher than in tension. It appears that for the \( R/R_o \) ratio of the pipe considered, the plastic flow asymmetry in load controlled experiments is even more pronounced in comparison to the tubular specimens we used in this study. As a general rule, the effective effect of stress triaxiality on fatigue life of pressurized pipes is expected to play a role whose importance is related to the complex solicitation mode of real components: stress versus strain controlled, mean stress or mean strain, hold time, cyclic thermal stresses, etc. Many of these issues can be addressed by well-designed experiments where the internal pressure and specimen geometry \( (R/R_o) \) are varied in a systematic manner.

**CONCLUSIONS**

A series of load-controlled fatigue experiments was conducted on a non-stabilized 316L austenitic stainless steel to investigate mean stress effects on fatigue life in air and LWR environments. The fatigue tests were performed at 288 °C, in air with round bar and hollow specimens, and in simulated boiling water (hydrogenated water with 150 ppb dissolved hydrogen) with pressurized hollow specimens only. Load-controlled experiments were selected to fully control the mean stress level in both environments. The fatigue data with zero-mean stress of the round bars and hollow specimens were found to be in very good agreement in air. Two internal pressures were chosen (80 and 200 bars) for the hollow specimens in water and, for this case too, no significant difference was found, suggesting that the influence of the internal pressure for the specimen geometry used remains limited for the tests with zero mean stress. The comparison of the results obtained in air and in water with zero mean stress indicated that, in simulated boiling water environment and for the selected testing conditions close to the strain rate threshold, the environmental effect decreases the fatigue life by a factor of about 2.

Interestingly, it was found that at 288 °C in air, positive and negative mean stresses increase the fatigue life notably. This rather unusual effect of tensile mean stress was attributed to a primary and secondary hardening effect. The tests run in water with pressurized tubular specimens revealed a somewhat different behavior, where positive stresses of 20 MPa or less, reduced the fatigue life moderately, while an increase was observed for a mean stress of 50 MPa, as well as for compressive mean stress. Again, the mean stress influence on the fatigue life is essentially beneficial, except for the tests in water with a positive mean stress of 20 MPa or less. However,
it was mentioned that a small effect of the internal pressure in the hollow specimens could modify the mean stress by several MPa, and therefore explains the reduction of $N_f$ for those specimens.

To gain some insight into the possible effects of the internal pressure on the cyclic plastic behavior, finite element simulations were performed on pressurized hollow specimens at 200 bars. A difference in the accumulation of plastic strain on the internal face between the tensile and compressive loading part of a cycle was established. This difference was shown to stem from an asymmetry of the von Mises yield criterion by inverting the sign of the axial stress component while maintaining the radial and hoop stresses constant. The main conclusion was that this asymmetry is responsible for the occurrence of a small internal mean strain when cycling with a non-zero mean stress, whose influence remains moderate as suggested by the experimental results.

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