

Article

Mean Stress Effect on the Fatigue Life of 304L Austenitic Steel in Air and PWR Environments Determined with Strain- and Load-Controlled Experiments

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Abstract: The mean stress effect on the fatigue life of 304L austenitic steel was evaluated at 300 °C in air and pressurized water reactor (PWR) environments. Uniaxial tests were performed in strain-control and load-control modes, with zero mean stress and a positive mean stress of 50 MPa. A specific procedure was used for the strain-controlled experiments to maintain the strain amplitude and mean stress constant. The strain-controlled data indicate that the application of positive mean stress decreases the fatigue life for a given strain amplitude in air and PWR environments. The data also show that the life reduction is independent of the environments, suggesting that no synergistic effects between the mean stress and the LWR environment occur. The load-controlled experiments confirm that the application of positive mean stress increases fatigue due to cyclic hardening processes. This observation is much less pronounced in the PWR environment. All data were analyzed using the Smith–Watson–Topper (SWT) stress–strain function, which was shown to correlate well with all strain- and load-controlled data with and without mean stress in each environment. In the SWT-life curve representation, the life reduction in the PWR environment was found fully consistent with the NUREG-CR6909 predictions.

Keywords: austenitic steel; environmentally assisted fatigue; mean stress; light water reactor environment



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1. Introduction

Austenitic stainless steels are extensively used as structural materials in light water reactor (LWR) environments where high temperature, irradiation and complex thermo-mechanical loading conditions exist [1]. Temperature variations associated with start-ups and shutdowns, power adjustments, thermal stratification and striping are responsible for thermomechanical fatigue [2,3]. While a great deal of work has been performed on the fatigue life of austenitic stainless steels, many issues remain to be addressed in the field of environmentally assisted fatigue (EAF) in LWR environments. It is now well established that the fatigue life in such environments is shorter than in air, depending in particular on the temperature, strain rate and water chemistry [3]. EAF was not explicitly considered at the time of the construction of the currently operated nuclear power plants. Following the comprehensive NUREG-CR-6909 report [4], LWR environmental effects on fatigue are quantified by an environmental factor, F_{en} , initially proposed by Kanasaki et al. [5] and defined as:

$$F_{en} = \frac{N_{f,air,RT}}{N_{f,LWR}} \quad (1)$$

However, because of the combination of moderate thermomechanical fatigue loadings and the very conservative design, fatigue damage failure in these components remains exceptional, indicating that the safety margins considered in the NUREG-CR-6909 report are likely to be too large and could be reduced to avoid excess conservatism. For this purpose, a deep understanding of the underlying mechanisms of EAF is necessary to establish careful safety assessment procedures, especially in the context of lifetime extensions beyond 50 years. A number of parameters are known to influence the fatigue life of austenitic stainless steels but have not yet been systematically studied in LWR environments. These include the effect of mean stress originating from the dead weight, internal pressure, residual stress or thermal gradient of LWR components. Indeed, in most cases, mean stress effects on austenitic steels are investigated separately from LWR environmental effects [6–11].

So far, only few investigations have been undertaken to evaluate the mean stress and LWR environmental effects on the fatigue life of austenitic steels [12–16]. Using load-controlled experiments, Solomon et al. studied the influence of a 100 MPa mean stress on the fatigue limit in air and pressurized water reactor (PWR) environments at 150 and 300 °C [14]. The effect (increase or decrease of the fatigue limit) was found to depend on the temperature and environment. This dependence was attributed to the amount of secondary hardening. Wire et al. also reported a series of tests carried out under the load-control mode, showing that the fatigue life increases with the mean stress [12]. Solomon et al. and Wire et al. performed load-controlled tests with a relatively high mean stress, 100 MPa and higher, which is not very representative of the static stress existing in pressurized pipes. For instance, it was shown by Späfig and Seifert that the hoop stresses that stem from the differential pressure (150 bar) in a pipe with an external diameter of 20 cm and a 2 cm wall thickness are lower than 100 MPa [13]. Recently, the effect of mean stress on fatigue life was investigated in a boiling water reactor and hydrogen water chemistry environment for mean stresses ranging from –20 to 50 MPa using load-controlled experiments [16,17]. All in all, the published data on the mean stress influence on the fatigue life of austenitic steels are relatively scarce and incomplete. The reason is that defining cyclic loading conditions with laboratory specimens that are representative of the real loading of components is challenging. If one uses simple uniaxial specimens (solid or hollow), the mean stress can be easily selected with load-controlled experiments. However, this type of test is rather unusual to assess the fatigue life in a LWR reactor environment, where strain-controlled experiments are considered to better mimic the thermal strains, which are the origin of fatigue in nuclear components. Strain-controlled tests with a predefined mean strain to introduce a constant mean stress are not appropriate to introduce large mean stress. Indeed, austenitic steels present a low yield stress relative to the fatigue strength, and a significant amount of plasticity occurs during cycling, even at low strain amplitudes. As a consequence, stress relaxation takes place at a rate that depends on the plastic strain amplitude. In all cases, only a small mean stress of about 10–20 MPa can be introduced with standard strain-controlled experiments.

This study was conducted to gain insight into the effect of mean stress in 304L austenitic steel by performing, on the one hand, standard load-controlled experiments and, on the other hand, nonstandard strain-controlled experiments. The latter were run using a special procedure where the strain amplitude was kept constant throughout the test while the mean strain was increased in a controlled manner to maintain the desired level of mean stress. The results and analysis of all these tests, performed in air and PWR environments at 300 °C, are reported in this paper. These results were obtained in the context of the INCEFA-PLUS project, which started in mid-2015 within the European Commission Horizon-2020 program, designed to deliver new experimental fatigue data to ultimately develop improved EAF guidelines [18–20].

2. Materials and Methods

2.1. Material

The tested material was a laminated plate made of AISI 304L stainless steel manufactured by Creusot-Loire Industrie (sheet XY182), annealed at 1100 °C and quenched with water. This material has been used in various previous studies [7,8,10,21]. The mechanical properties and chemical composition are presented in Tables 1 and 2. These properties are in good agreement with the RCC-M 3307 specification requirements.

Table 1. Mechanical properties of 304L austenitic stainless steel.

		Rolling Direction	Transverse Direction
		25 °C	300 °C
Yield stress (MPa) at a 0.2% plastic strain	220	138	217
UTS (MPa)	557	403	540
Elongation (%)	67	48	67
Young's modulus	192	179	190
		300 °C	300 °C

Table 2. Chemical composition of 304L austenitic stainless steel (on product) and a comparison with the RCC-M 3307 specification (weight percentage).

Elements	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	N
RCC-M	≤0.03	≤2.00	≤1.00	≤0.03	≤0.04	9.00 ≤ 12.00	17.00 ≤ 20.00	-	≤1.00	-
304L	0.029	1.86	0.37	0.004	0.029	10.00	18.00	0.04	0.02	0.056

2.2. Procedure for the Strain Amplitude-Controlled Tests

The geometry of the specimens used for the strain-controlled tests is presented in Figure 1. For the hollow specimens, the roughness of the inner surface was $R_a = 0.2 \mu\text{m}$ and $R_t = 3.36 \mu\text{m}$. For the solid specimens, the roughness was $R_a = 0.04 \mu\text{m}$ and $R_t = 0.76 \mu\text{m}$. It was verified that, for the hollow specimens, all principal cracks led to a final rupture initiated from the inner surface. While a higher surface roughness can lead to a reduction of fatigue life in both air and PWR environments [22,23], the difference in roughness between the hollow and solid specimens is quite small. Based on the analysis from the INCEFA-PLUS project on the same material, an increase of R_t from 0.76 μm to 3.36 μm would lead to a reduction of N_f of less than 3% [24].

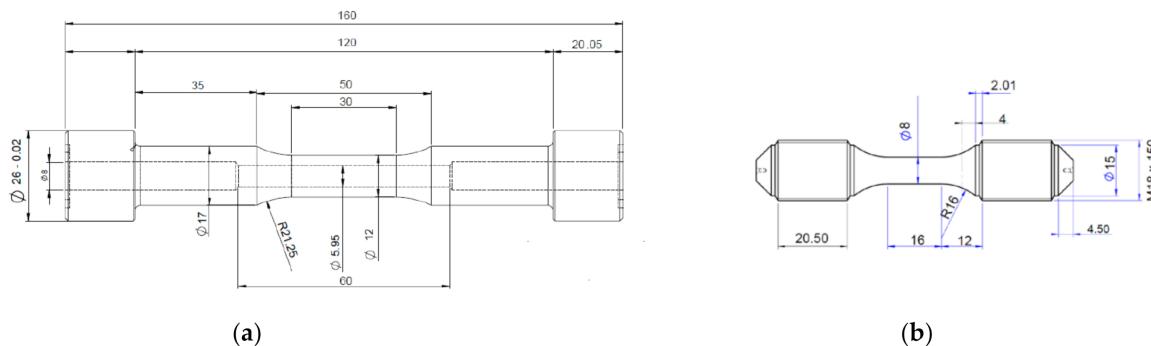


Figure 1. Specimen design of the: (a) hollow specimen; (b) solid specimen (scale in mm).

For the tests with the hollow specimens, an Instron 8862 electromechanical fatigue machine equipped with a furnace, an extensometer attached to the outer surface of the specimen and a loop, allowing the circulation of fluid in the hollow specimen during the fatigue test, were used. The simulated LWR environment corresponded to that of pressurized water reactors (PWRs) (see Section 2.4). The loop was preheated for at least 24 h before each test to ensure an isothermal condition of 300 °C for the entire rig.

The air fatigue tests were carried out on the same type of electromechanical machine (Instron 8862 with 100 KN). For the tests with the solid specimens, only the air environment was applied. The tests were also performed using a contact-type extensometer attached to the outer surface of the specimen so that they could be performed under equivalent operating conditions to the tests with the hollow specimens.

For all tests, strain control was applied using a 12.5 mm gauge length extensometer attached to the outer surface in the gauge length of the specimen (30 and 16 mm for the hollow and solid specimens, respectively). A strain rate of 0.1%/s was chosen. To impose a constant strain amplitude and constant mean stress, a specific closed control loop was developed to progressively increase the mean strain, keep the strain amplitude constant and reach and maintain the mean stress constant at the desired value [10]. A typical example of such a strain-controlled test with constant mean stress is illustrated in Figure 3.

2.3. Procedure for the Load-Controlled Tests

The geometry of the specimens used for the load-controlled tests is presented in Figure 2. The hollow specimens were used for the tests in the PWR environment, and details of the loop used can be found in [15]. The tests in air were conducted with the solid specimens. A frequency of 0.125 Hz was applied for all tests independent of the stress amplitude. The mean stress was simply adjusted by controlling the maximum and minimum stresses.

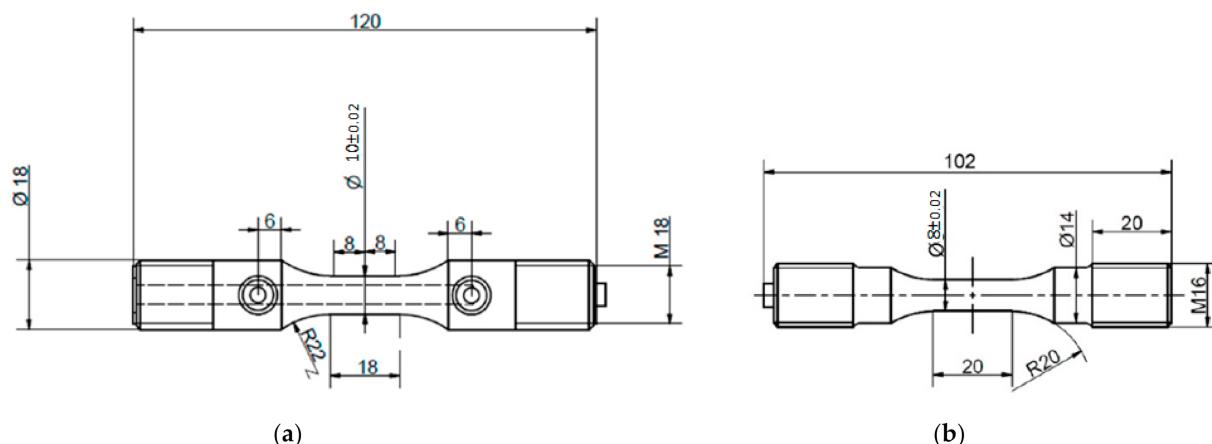


Figure 2. Specimen design of the: (a) hollow specimen; (b) solid specimen (scale in mm).

For the hollow specimens, the roughness of the inner surface is $R_a = 0.2 \mu\text{m}$. For solid specimens, the roughness is $R_a = 0.04 \mu\text{m}$. In this case, all principal cracks that led to a final rupture were initiated from the inner surface.

2.4. LWR Environment in the Fatigue Tests

The LWR environment selected corresponded to that of the PWR environment, characterized by $25 \text{ cm}^3/\text{kg}$ of dissolved hydrogen and less than 5 ppb of dissolved oxygen. The B and Li contents were in the range $1000 \text{ ppm} \pm 100 \text{ ppm}$ and $2 \text{ ppm} \pm 0.2 \text{ ppm}$, respectively. The resulting pH value at 300°C was around 6.95. The tests were performed in the same conditions (air and PWR) as the INCEFA-PLUS tests except for the strain rate $\dot{\epsilon}$. Indeed, $\dot{\epsilon}$ was chosen at $0.1\%/\text{s}$ to reduce the time of testing. This corresponded to a frequency of 0.125 Hz for a 0.2% strain amplitude, which was the frequency selected for the load-controlled tests. The F_{en} calculated with the NUREG/CR-6909 formula corresponding to $0.1\%/\text{s}$ was equal to 2.68, which was well defined for the strain-controlled tests carried out by EDF. For the load-controlled tests, the F_{en} values were estimated after the tests, based on the average strain rate over all the cycles of the experiments. This led to a rather modest range of F_{en} from 2.59 to 3.05 or, equivalently, an estimated F_{en} of 2.82 ± 0.23 .

3. Results

All data of the INCEFA-PLUS mean stress program are summarized in Appendix A Table A1. Some additional data of the main INCEFA-PLUS program used for comparison purposes are reported in Appendix A Table A2 [25]. Below, we successively present the strain-controlled (ε -controlled) test data and the load-controlled (L-controlled) data along with a synthesis and an analysis of all the data put together. Note the strategy adopted in this study was to investigate the mean stress effect at a relatively low strain amplitude corresponding to a fatigue life of about 10^5 . The main reason for this choice was to avoid as much ratcheting as possible during the load-controlled experiments as well as during the strain-controlled experiment with mean stress. For the strain-controlled and load-controlled experiments without mean stress, this corresponded, respectively, to a strain amplitude of about 0.2% and a stress amplitude of about 160 MPa.

3.1. Strain-Controlled Test Results

The fatigue life of austenitic stainless steels is typically characterized by the succession of: (1) primary cyclic hardening, (2) softening and (3) stabilization or secondary hardening. The details of the hardening/softening sequence depend in particular on the strain amplitude, strain rate and temperature so that the hardening/softening/hardening can occur at different stages of the fatigue life. In strain-controlled experiments, cyclic hardening and softening are simply manifested by an increase or a decrease of the stress amplitude during the fatigue life. Hardening followed by softening occurs between 10 and 100 cycles, as we can observe in Figure 3a, which corresponds to a test without mean stress in the strain-controlled mode. For the test with a 50 MPa mean stress, due to the Bauschinger effect of the material, the desired value of the mean stress can only be reached after around 5000 cycles, as illustrated in Figure 3b. This is possible due to a continuous increase of the mean strain, which reaches around 8% for the tests at a 0.2% strain amplitude and 7.5% for 0.18%. It should be noted that there are no notable differences in mechanical behavior in water in comparison to air. This is in good agreement with what has been observed by many authors for tests performed in the strain-control [22,26] as well as in the load-control modes [15].

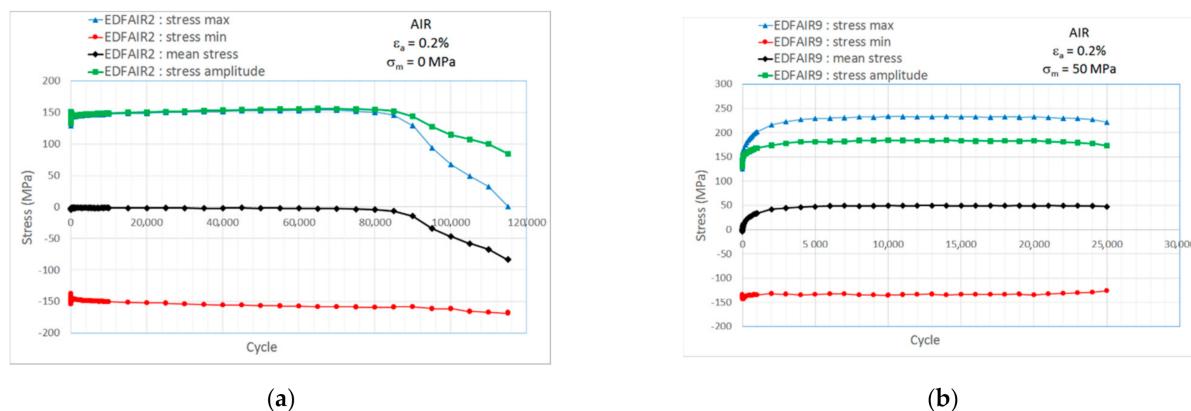


Figure 3. Stresses (min, max and amplitude) and the mean stress evolution versus cycle at (a) a nominal strain amplitude of 0.2% in air with $\sigma_m = 0 \text{ MPa}$; (b) $\sigma_m = 50 \text{ MPa}$ (right); ε -control mode.

The results of the ε -controlled tests on the effect of the environment on fatigue life are illustrated in Figure 4. The mean curve (NUREG/CR-6909) was calculated using Equation (4), and the mean curve in the PWR environment was shifted to the left by a factor of 2.68 (see Section 2.4). As expected, the PWR environment has a detrimental effect on the fatigue life of 304L austenitic stainless steel at a 0.2% strain amplitude. In addition, the decrease of the fatigue life is well predicted by the environmental factor F_{en} given by NUREG/CR-6909 for the strain rate tested, i.e., 0.1%/s. This is true for the tests

without mean stress and for the tests with a 50 MPa mean stress. One can also observe from this figure that a mean stress has a detrimental effect on the fatigue life both in air and water environments, whatever the strain amplitude is (0.2% or 0.18%). The three tests performed at a 0.18% strain amplitude without mean stress are not sufficient to conclude on the effect of the environment. It seems that no environmental effect occurs on the mean stress effect in these temperature conditions and at a strain rate at this level of strain amplitude. On the contrary, when a mean stress is applied, the fatigue life in the water environment is again lower than that in air, and the difference can be well estimated by the NUREG/CR-6909 prediction.

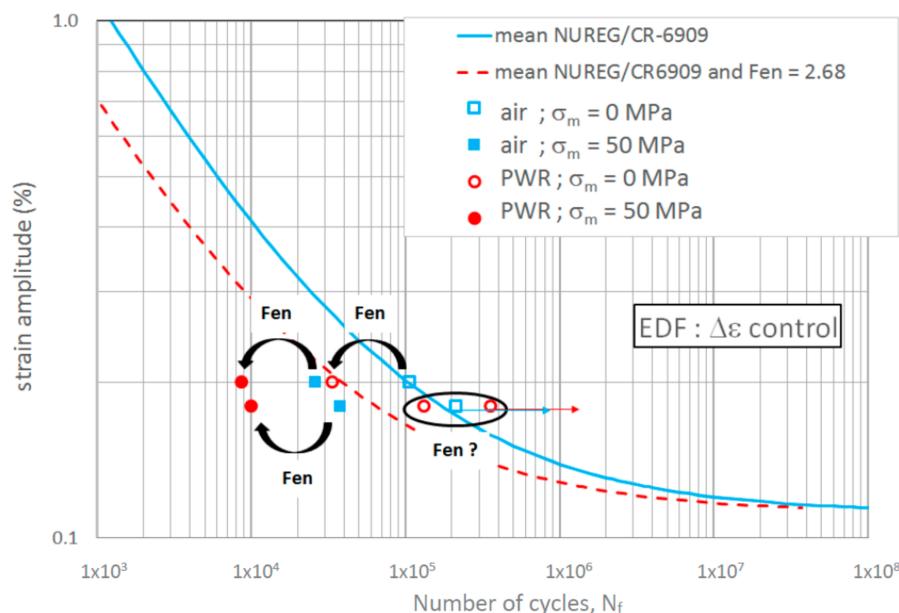


Figure 4. Strain–life data obtained from the ε -controlled tests.

3.2. Load-Controlled Test Results

In the load-controlled experiments, the cyclic 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 evolution of the strain amplitude and mean strain for some of our experiments is illustrated in Figures 5 and 6. We can clearly see in Figure 5a for the tests without mean stress that the strain amplitude decreases slightly during most of the fatigue life, reflecting a persistent cyclic hardening. It also has to be emphasized that, for a similar stress amplitude, the tests with $\sigma_m = 50$ MPa have a smaller strain amplitude than those with zero mean stress. The behavior is specific to austenitic steel and explains the increase of the fatigue life with mean stress at a given stress amplitude (compare the plots in Figure 5a,b and Figure 6a,b). Note also the difference in the mean strain evolution during the fatigue life. As can be seen, the mean strain is of the order of a few percent in the stabilized region, and the ratcheting remains limited. The mean strain is constant after several cycles at the beginning of the experiment to reach the imposed σ_{max} value.

Figure 7 presents the fatigue life of the load-controlled experiments. One observes a clear increase of the fatigue life with mean stress for the tests performed in air. On the contrary, the effect, if any, is much less marked in the PWR environment. This observation is in agreement with the results of Chen et al., who showed a clear beneficial effect of mean stress in air in the low- and high-cycle fatigue regime while, in the LWR environment, the positive effect of mean stress is obvious only for $N_f < 10^4$ [16,17]. The reason for this is still unclear, but the oxide-induced crack closure effect is a possible reason to explain the difference between the behavior in air and LWR environments.

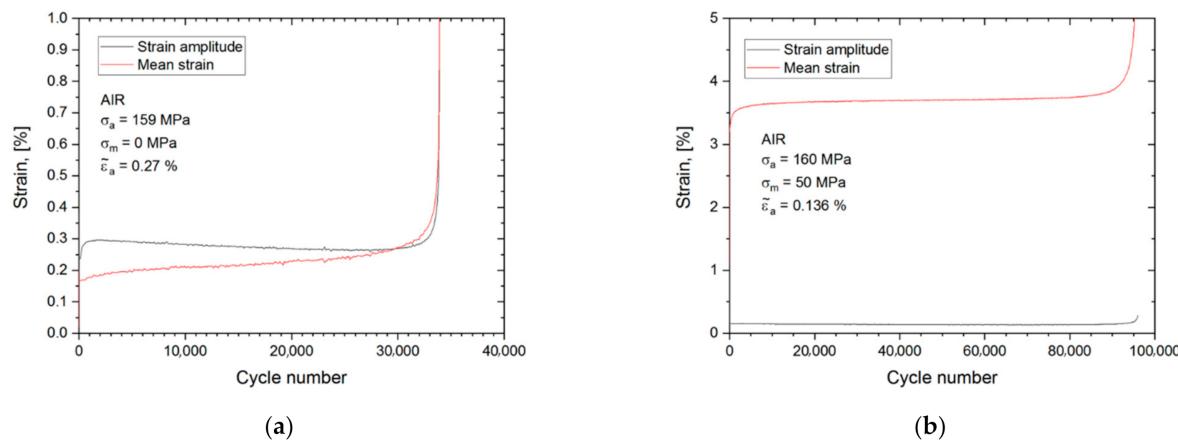


Figure 5. Strain amplitude and mean strain evolution versus cycle at a nominal stress amplitude of 160 MPa in air with: (a) $\sigma_m = 0 \text{ MPa}$ (left); (b) $\sigma_m = 50 \text{ MPa}$ (right).

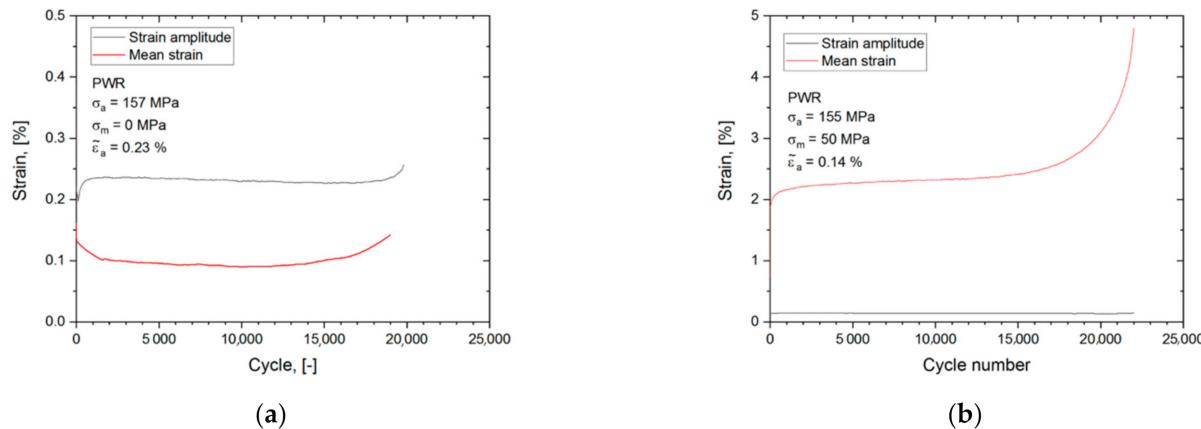


Figure 6. Strain amplitude and mean strain evolution versus cycle at a nominal stress amplitude of 160 MPa in the pressurized water reactor (PWR) with: (a) $\sigma_m = 0 \text{ MPa}$ (left); (b) $\sigma_m = 50 \text{ MPa}$ (right).

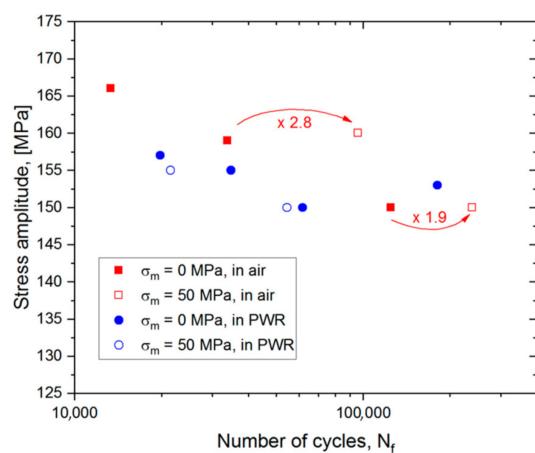


Figure 7. Stress–life data obtained from the load-controlled tests.

4. Discussion

An attempt to correlate all the fatigue data with zero stress and nonzero mean stress in the air and PWR environments and for both testing modes was made. For austenitic steels, it has already been shown that the fatigue life can be predicted with the Smith–Watson–Topper (SWT) approach, based on a maximum stress–strain amplitude function [27]. The

SWT function between strain amplitude, maximum stress, mean stress and fatigue life has the form:

$$\text{SWT} = \sqrt{(\sigma_a + \sigma_{\text{mean}})\varepsilon_a E} = \sqrt{\sigma_{\text{max}}\varepsilon_a E} \quad (2)$$

where E is the Young's modulus, and σ_{max} is the value determined at half-life. In the original paper by SWT, various forms, albeit similar, of the stress–strain function were suggested. In our analysis, we selected the values at half-life ($N_f/2$) for σ_{max} and ε_a and noted them $\tilde{\sigma}_{\text{max}}$ and $\tilde{\varepsilon}_a$. Thus, in the following, SWT is calculated as:

$$\text{SWT} = \sqrt{\tilde{\sigma}_{\text{max}} \tilde{\varepsilon}_a E} \quad (3)$$

SWT is calculated with the data summarized in Appendix A Table A1, and the data are plotted in Figure 8. Clearly, all load- and strain-controlled data fall along the same curve independently of the mean stress, as can be observed in Figure 8. It was not possible to improve the statistical reliability by repeating the tests for each condition. However, there is a fair number of data to validate the applicability and usefulness of the SWT function.

The SWT stress correlates well with almost all the data, even though an opposite mean stress effect on the fatigue life is observed between the ε -controlled and L-controlled experiments. Again, a positive mean stress at constant strain amplitude in the ε -controlled tests reduces N_f while it tends to increase N_f in the L-controlled tests. In ε -controlled tests, the SWT-stress increases with the mean stress (or equivalently with the maximum stress) leading to a reduction of N_f (see Equation (3)). Increasing the mean stress in the L-controlled experiments also increases the SWT stress, but this is usually accompanied by a reduction of the strain amplitude, which, in turn, decreases the SWT stress. In the L-controlled experiments, the interaction between the variation of the mean stress and the strain amplitude can then lead to an increase or decrease of N_f , which depends on the stress amplitude and mean stress selected. Furthermore, the fact that almost all data are well correlated indicates that the level of ratcheting occurring in our experiment probably plays a minor role, at least for the testing conditions considered in this study.

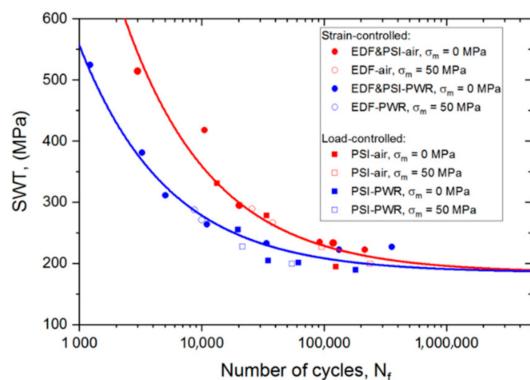


Figure 8. Smith–Watson–Topper (SWT)–life curve calculated with the specific 304L mean curve coefficients.

In order to use the SWT parameter in a practical way for fatigue life predictions, we need to find an expression for $\text{SWT} = \text{SWT}(N_f)$ that can be easily derived from the ε -controlled data without mean stress and to check a posteriori if this calculated SWT function predicts the fatigue life of the tests with mean stress correctly. In other words, we first consider the mean NUREG/CR-6909 air curve, which is a Langer equation represented by the relation between ε_a and N_f as [28]:

$$\tilde{\varepsilon}_a = P(N_f)^{-\beta} + C \text{ or equivalently } N_f = \left(\frac{P}{\tilde{\varepsilon}_a - C} \right)^{1/\beta} \quad (4)$$

The values of these coefficients for the NUREG/CR-6909 mean air curve (austenitic stainless steels) are: $P = 36.2$, $C = 0.112$ and $\beta = 0.5208$. Note that mean stress is not considered in the derivation in Equation (4). We can then calculate the SWT function for the tests without mean stress by considering a relationship between $\tilde{\sigma}_{\max}$ and $\tilde{\varepsilon}_a$ (or N_f), which we established empirically by plotting $\tilde{\sigma}_{\max}$ against $\tilde{\varepsilon}_a$ (see Figure 9a) for all our tests obtained in the air and PWR environments. No big difference between the two environments can be seen. A power law between $\tilde{\sigma}_{\max}$ and $\tilde{\varepsilon}_a$ was considered to fit the data.

$$\tilde{\sigma}_{\max} = G + H \tilde{\varepsilon}_a^n \quad (5)$$

The previous relation allows writing SWT as a function of $\tilde{\varepsilon}_a$:

$$SWT = \sqrt{(G + H \tilde{\varepsilon}_a^n) \tilde{\varepsilon}_a E} \quad (6)$$

Using Equation (4), SWT can be written as a function of N_f to derive a SWT-life curve:

$$SWT = \sqrt{(G + H(P(N_f)^{-\beta} + C)^n)(P(N_f)^{-\beta} + C)E} \quad (7)$$

Using the numerical values of the NUREG/CR-6909 mean curve for P , C and β , and the fitted values G and H , we can calculate the SWT-life curve to check if our experimental data in air are consistent with the predictions in Equation (7). The results are shown in Figure 8, where one can clearly see that, globally, all data with and without mean stress, independently of the deformation mode, are well described by Equation (7).

The same analysis was done with the data obtained in the PWR environment. To take into account the LWR environment effect, we consider the approach based on the environmental factor F_{en} that we apply on the SWT-life curve. Since F_{en} is defined as

$$F_{en} = \frac{N_{f,air}}{N_{f,water}} \quad (8)$$

and since it is a constant for a given testing condition (T , $\dot{\varepsilon}$ and dissolved oxygen content) and the fatigue limit C is unaffected by the environment, it can be simply written as:

$$F_{en} = \left(\frac{P_{air}}{P_{water}} \right)^{1/\beta} \text{ or equivalently } P_{water} = \frac{P_{air}}{(F_{en})^\beta} \quad (9)$$

For our test conditions, the F_{en} is about 2.7, and P_{water} is equal to 21.6. With that value, we recalculated the SWT-life curve in the PWR environment and found that the PWR data are also in reasonable agreement with the SWT predictions, as can be observed in Figure 9. The analysis shows that converting the standard NUREG/CR-6909 strain-life curve into a SWT-life appears as a powerful method to account for the mean stress effect in air and PWR environments. However, it must be recognized that the fitted curves slightly overpredict the measured fatigue lives in the PWR environment. This suggests that the relation between $\tilde{\sigma}_{\max}$ and $\tilde{\varepsilon}_a$ (Equation (5)) might be slightly different for the tests in LWR environments compared with the tests in air, leading to a less accurate life prediction in LWR environments.

Therefore, instead of using the SWT function given by Equation (7), one can empirically fit the SWT data with a simple Langer equation [28] to avoid establishing a relation between $\tilde{\sigma}_{\max}$ and $\tilde{\varepsilon}_a$:

$$SWT = X(N_f)^{-n} + Y \quad (10)$$

keeping the power exponent n and SWT fatigue limit Y the same in both environments to make use of the F_{en} concept (in our case $n = 0.6$ and $Y = 185$ MPa). The Langer fits the yield somewhat better than the predictions, as can be seen in Figure 10. Furthermore, the F_{en}

factor associated with these Langer fits was found equal to 2.8, which is consistent with the expected F_{en} estimated with the NUREG/CR6909 formula for the testing conditions.

Note finally that the main advantage of the SWT(N_f) approach with respect to the strain life $\varepsilon_a(N_f)$ representation resides in the fact that all critical factors, namely ε_a , σ_m and σ_{max} , are considered and lumped together in a single parameter that allows correlating data obtained with any combination of these parameters.

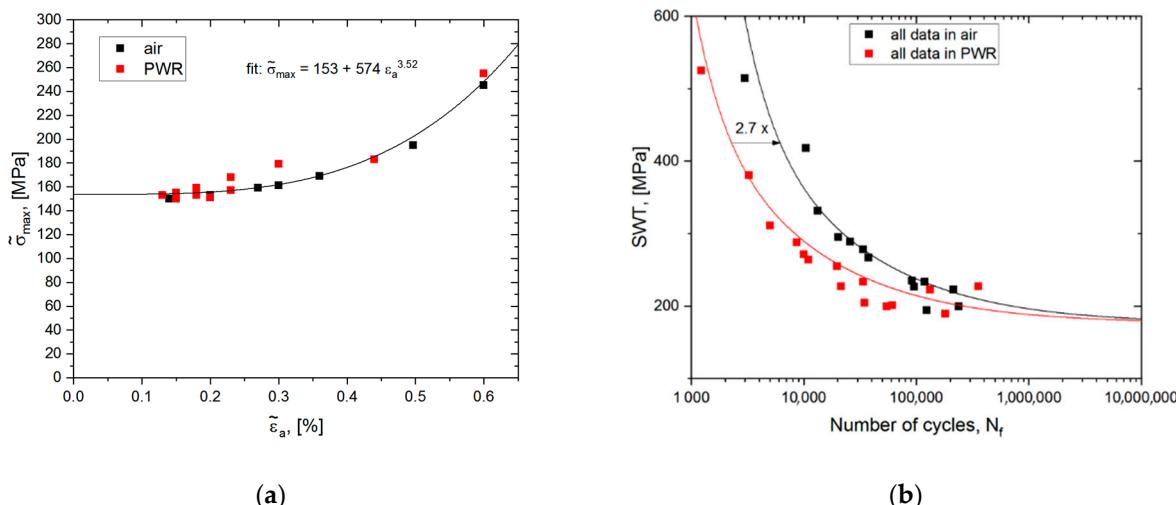


Figure 9. (a) Empirical relation between $\tilde{\sigma}_{max}$ and $\tilde{\varepsilon}_a$; (b) SWT-life curve calculated with NUREG-CR6909 mean curve coefficients.

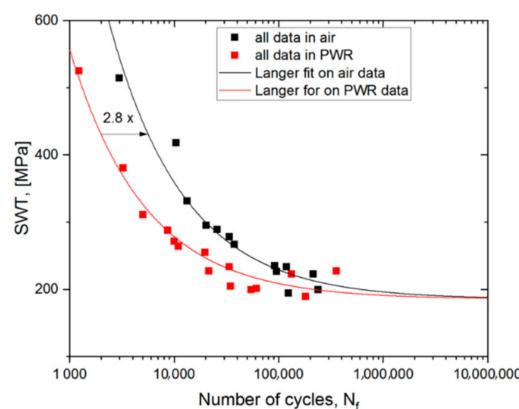


Figure 10. Langer fits on the SWT data.

5. Conclusions

The mean stress (+50 MPa) effects on fatigue life and possible interactions with a PWR environment were investigated with ε -controlled and L-controlled experiments. For the ε -controlled experiments and for $N_f < 10^5$, a clear reduction of fatigue life in the PWR environment was found independent of the mean stress level and in good agreement with the predictions based on the F_{en} calculations with the NUREG/CR-6909 equation. This indicates that there is no synergistic effect between the mean stress and PWR environments. A reduction of fatigue life in the PWR environment was also found for the L-controlled tests and $N_f < 10^5$.

The large scatter and uncertainty in the fatigue life for all tests performed with a smaller strain or stress amplitude leading to $N_f > 10^5$ do not allow drawing firm conclusions on the conjugate effect of mean stress and the PWR environment in the HCF regime. However, it seems that environmental effects on the fatigue life disappear for the lowest

amplitudes (stress or strain) tested in this study without mean stress, becoming effective again when a nonzero mean stress is applied.

An analysis based on the Smith–Watson–Topper parameter was considered. The NUREG/CR 6909 air curve was converted into a SWT-life curve using an empirical calibration between the maximum stress and strain amplitude at half-life. The SWT parameter was calculated for all tests of the program. The results obtained in air show that the NUREG/CR-6909-converted SWT-life curve correlates all the data with and without mean stress well. Similarly, the data obtained in the PWR environment fall reasonably close to the SWT-life curve, shifted by the appropriate F_{en} . This observation also confirms that for the conditions tested in this program, mean stress does not amplify the PWR environment effect.

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Data Availability Statement: Requests to access the data presented in this study can be submitted to the data owner(s). The data are stored in a database and traceable through DOIs [25] but are not publicly available due to the data policy of the project.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Fatigue data of the INCEFA-PLUS mean stress program obtained with different control modes and mean stresses.

Specimen Code	Testing Mode	N _f (Cycles)	ε _a (%)	̃ε _a =̃ε _a (N _f /2) (%)	σ _{mean} (MPa)	̃σ _{max} =σ _{max} (N _f /2) MPa	σ _a (MPa)
1563 XDAL14	ε-control air	10500	0.497	0.497	0	195	-
EDF-AIR-2	ε-control air	92000	0.2	0.2	0	153	-
EDF-AIR-12	ε-control air	215000 (runout)	0.18	0.18	0	153	-
EDF-AIR-9	ε-control air	25864	0.2	0.2	50	232	-
EDF-AIR-17	ε-control air	37872	0.18	0.18	50	219	-
EDF-REP-22	ε-control PWR	132850	0.18	0.18	0	153	-
EDF-REP-23	ε-control PWR	358019 (runout)	0.18	0.18	0	159	-
EDF-REP-17	ε-control PWR	33752	0.2	0.2	0	151	-
EDF-REP-21	ε-control PWR	10015	0.18	0.18	50	227	-
2090-A-2	ε-control PWR	8724	0.2	0.2	50	230	-
PSIair4	L-control air	13336	-	0.36	0	169	169
PSIair11	L-control air	124613	-	0.14	0	150	150
PSIair13	L-control air	33801	-	0.27	0	159	159
PSIair14	L-control air	238439	-	0.11	50	200	150

Table A1. Cont.

Specimen Code	Testing Mode	N _f (Cycles)	ε _a (%)	˜ε _a =˜ε _a (N _f /2) (%)	σ _{mean} (MPa)	˜σ _{max} =σ _{max} (N _f /2) MPa	σ _a (MPa)
PSIair12	L-control air	95900	-	0.136	50	210	160
PSIwater10	L-control PWR	61632	-	0.15	0	150	150
PSIwater13	L-control PWR (runout)	180760	-	0.13	0	153	153
PSIwater14	L-control PWR	34800	-	0.15	0	155	155
PSIwater17	L-control PWR	19800	-	0.23	0	157	157
PSIwater16	L-control PWR	21500	-	0.14	50	205	155
PSIwater11	L-control PWR	54500	-	0.11	50	200	150

Table A2. Fatigue data of the INCEFA-PLUS main program used in this study.

Specimen Code	Testing Mode	N _f (Cycles)	ε _a (%)	˜ε _a =˜ε _a (N _f /2) (%)	σ _{mean} (MPa)	˜σ _{max} =σ _{max} (N _f /2) MPa	σ _a (MPa)
PSIair6	ε-control air	20337	0.3	0.3	-	161	-
PSIair7	ε-control air	2997	0.6	0.6	-	245	-
LEI19	ε-control air	118800	0.2	0.2	-	151	-
PSIwater2	ε-control PWR	5041	0.3	0.3	-	179	-
PSIwater6	ε-control PWR	1225	0.6	0.6	-	255	-
JRC31	ε-control PWR	3244	0.44	0.44	-	183	-
CIEMAT12	ε-control PWR	10996	0.23	0.23	-	168	-

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