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1 **INFLUENCE OF MEAN STRESS AND PWR ENVIRONMENT ON THE FATIGUE**
2 **BEHAVIOR OF A 304L AUSTENITIC STAINLESS STEEL**

3
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5
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10
11 **Abstract**

12
13 Uni-axial strain-controlled fatigue tests were carried out on a 304L austenitic stainless-steel
14 specimens in air at 300°C and in PWR water, without or with the application of a mean stress,
15 at different total strain amplitudes. For strain amplitude no less than 0.2%, a deleterious effect
16 of PWR water on fatigue life is observed, associated with the enhancement of both crack
17 initiation and propagation. Besides, the fatigue life is reduced by the application of a mean
18 stress for a fixed strain amplitude in a given environment. In particular, due to the acceleration
19 of crack initiation stage by an enhancement of the plastic strain accumulation, the PWR water
20 effect on fatigue life is re-activated for strain amplitude below 0.2% in the presence of a mean
21 stress. The fatigue life reduction under mean stress application is mostly related to the
22 maximum stress level and strain amplitude, rather than the generated ratcheting strain.

23
24 **Keywords:** crack initiation; crack propagation; ratcheting; environment effect; mean stress;

25
26 **Nomenclature**

27 a_0 : initial depth of the crack;

28 C, C_1, C_2 : Paris law coefficients

29 $\Delta\varepsilon_r$: ratcheting strain;

30 ΔK_ε : strain intensity factor range ;

31 $\Delta\varepsilon_t/2$: Total strain amplitude;

32 $\varepsilon_m, X\%$ of fatigue life : mean strain measured at X% of the fatigue life;

33 F_{en} : environmental factor;

34 $F_{en,theo}$: theoretical value of F_{en} ;

35 $F_{en,exp}$: experimental value of F_{en} ;

36 $F_{en,semi-exp}$: semi-experimental value of F_{en} ;

37 F_{ms} : mean stress factor;

1 m, m_1, m_2 : Paris law exponents
2 $N_{0 \text{ MPa, average}}$: average fatigue life for tests without mean stress application, for a given strain
3 amplitude and in a given environment;
4 N_5 : fatigue life defined as the number of cycles until the detection of a decrease of 5% with
5 respect to the peak stress measured at mid-life ;
6 $N_{\text{exp, air}}$: experimental fatigue life in air;
7 $N_{\text{exp, PWR}}$: experimental fatigue life in PWR environment;
8 $N_{\text{mean, air}}$: mean fatigue life in air;
9 $N_{\text{PWR, theo}}$: theoretical fatigue life in PWR water;
10 $N_{0 \rightarrow a_0}$: number of cycles required to nucleate a crack with a depth of a_0 ;
11 $N_{a_0 \rightarrow 2950 \mu\text{m}}$: number of cycles required to make a crack grow from an initial depth a_0 , to a final
12 depth of 2950 μm ;

13

14 **1. Introduction**

15 Austenitic stainless steels are extensively used in the nuclear industry, thanks to their
16 attractive combination of mechanical properties and corrosion resistance, to manufacture
17 structural components such as primary circuit pipes of Pressurized-Water Reactors (PWR).
18 Nevertheless, the impact of some specific service conditions on the performance of these steels
19 still needs to be addressed in more details in order to assess the conservatism of the design
20 approaches currently used. For instance, between start-up and shutdown operations, these
21 components are subjected to pressure and temperature transient loadings. From a design point
22 of view, such thermal transients are considered equivalent to a strain-controlled fatigue loading
23 to determine the lifetime of the component. Thus, in the ASME code ¹ and in the French RCC-
24 M design code ², the fatigue life assessment is based on a design curve derived from a broad
25 database of test results obtained under uniaxial strain-controlled cyclic loading in air. Thereafter,
26 different factors are applied to the strain amplitude and to the number of cycles to failure, in
27 order to account for the degradation in fatigue strength induced by various parameters, such as
28 the stress multiaxiality, the size, the surface finishing of the component, or the material
29 variability and the scatter in data. It is worth noticing that, when applying these factors, it is
30 assumed that these parameters influence the fatigue behavior independently from each other,
31 which may lead to a substantial over- or under-conservatism in the life prediction in presence
32 of interactions (synergy or attenuation) ³. Therefore, the investigation of the effect of these
33 parameters and their interactions is of high interest to improve the accuracy of the fatigue life
34 assessment of nuclear power-plant components.

35 As more specifically regards the effect of environment, the safety authorities such as
36 NRC in the United States, JNSC in Japan, STUK in Finland or ASN in France, so far request

1 to take into account the effect of the PWR primary water on the fatigue life of reactor
2 components. This is done on the basis of the fatigue design curve and by considering the F_{en}
3 environmental factor ⁴. This factor, defined as the ratio between the fatigue life in air and the
4 fatigue life in PWR environment, is determined by empirical equations as a function of different
5 parameters such as the strain rate, the rate of dissolved oxygen and temperature.

6 In order to critically assess this type of approach, the possible interactions between
7 environment and other influencing factors such as strain amplitude ^{5, 6}, surface treatments ⁷⁻¹⁰
8 ⁷⁻, or cold working ¹¹ have been investigated at different temperatures in the recent years.
9 However, it is noteworthy that the vast majority of these studies on the influence of the PWR
10 water were carried out with a total strain amplitude superior to 0.3%. Similar results, but with
11 a lower strain amplitude, are much less documented, albeit in this regime a potentially different
12 balance between the crack initiation stage and the crack propagation stage might justify further
13 investigation. Besides, previous studies were mainly conducted by using alternated tension-
14 compression loadings, with an almost null mean stress. In practice however, in a mixing
15 junction or near a pipe elbow, a thermal stratification of the fluid is likely to develop and to
16 promote a local increase in the mean stress. In literature, the influence of mean stress on fatigue
17 resistance has been investigated, but mainly at room temperature and on the basis of stress-
18 controlled fatigue tests ¹²⁻¹⁷. However, recently, Vincent et al. ¹⁸ successfully controlled both
19 the strain range and the mean stress to the predefined values by adjusting the mean strain during
20 fatigue tests conducted at ambient temperature. The consequences of this type of loading on the
21 fatigue strength in PWR water are not documented so far, which motivated the present work.

22 Hence, the research activities undertaken in this study were designed in order to extend
23 the assessment of the influence of PWR water on fatigue behavior of the material, at low total
24 strain amplitudes, typically inferior or equal to 0.2%, but also in presence of an applied mean
25 stress. With this aim, fatigue tests were carried out under total strain-amplitude in air and in
26 PWR environment. Some ancillary tests were interrupted at different stages of the fatigue life
27 in order to derive quantitative assessment of the damage, typically the crack depth. Finally, on
28 the basis of the experimental results, empirical equations were proposed in order to describe
29 the joint effect of total strain amplitude and applied mean stress. The present paper presents the
30 main findings of these investigations.

31

32 **2. Material, specimens, and testing facilities**

33 A plate of an AISI 304L stainless steel manufactured by Creusot-Loire Industrie (sheet
34 XY182), annealed at 1100 °C and quenched with water is used in this study. The chemical

1 composition and mechanical properties are presented in Table 1 and in Table 2, respectively.
 2 These properties are in good agreement with the RCC-M 3307 requirements ².

3 *Table 1. Chemical composition (wt. %) of the XY182 material as compared with the*
 4 *requirements of the RCC-M code ².*

Elements	C	Mn	Si	S	Ni	Cr	Mo	Cu
XY182 (%)	0.029	1.86	0.37	0.004	10	18	0.04	0.02
RCC-M (%) M3307	≤ 0.03	≤ 2	≤ 1	≤ 0.03	9 ~ 12	17~20	-	≤ 1

6

7 *Table 2. Mechanical properties in the rolling direction of 304L austenitic stainless steel ¹⁹*
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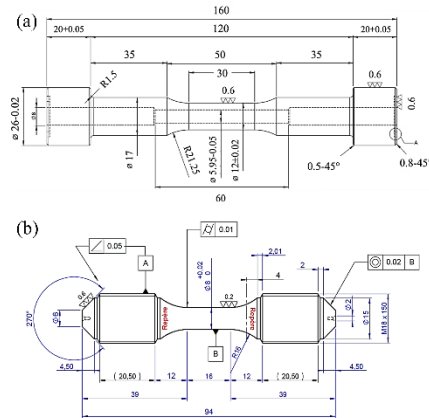
	Rolling direction		Transverse direction		RCC-M M3307 (transverse direction) ¹²	
	20°C	300°C	20°C	300°C	20°C	300°C
Yield stress (MPa)	220	138	220	136	≥175	≥105
Ultimate tensile strength (MPa)	555	401	546	402	≥490	-
Elongation (%)	68	48	68	46	≥45	-
Young's Modulus (GPa)	196	168	192	196	-	-

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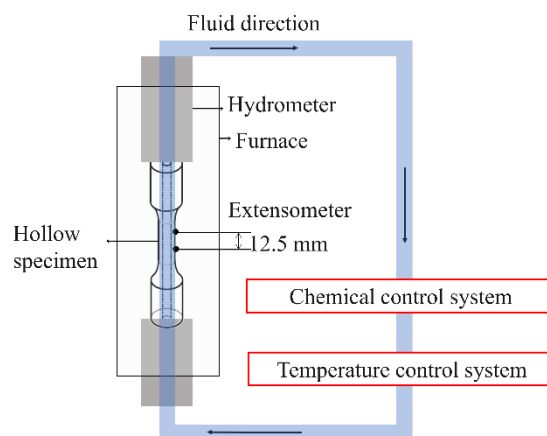
13 Two different specimen geometries were used in this study, as presented in Fig. 1,
 14 namely a tubular hollow geometry designed for tests in PWR environment but that can also be
 15 used for testing in air, and a solid cylindrical geometry only used for tests in air. For the hollow
 16 specimens, the roughness of the inner and outer surface is $R_{a,in}=0.2 \mu\text{m}$ and $R_{a,out}=0.6 \mu\text{m}$,
 17 respectively. The analysis of test results has confirmed that the fatal cracks leading to failure
 18 systematically initiated from the inner surface. For the solid cylindrical specimens, the surface
 19 roughness is $R_a=0.2 \mu\text{m}$.



1
2 *Fig. 1 : Design of the (a) hollow specimen and (b) solid bar specimen (dimensions in mm).*

3

4 The fatigue tests in PWR primary environment were carried out on an Instron 8862
5 100kN electromechanical fatigue machine. The hollow specimen is placed in a furnace
6 mounted on the loadframe, and the circulation of the PWR fluid inside the sample is insured
7 by means of a fluid loop while controlling the chemistry of this fluid all along the fatigue test,
8 as illustrated in Fig. 2. The simulated PWR primary water is characterized by 25 cm³
9 dissolved hydrogen per kilogram of water and less than 5 ppb of dissolved oxygen. The
10 conductivity of the high purity inlet and outlet water at 20 ° C is about 21 μS / cm. An
11 extensometer with a gauge length of 12.5 mm placed outside the furnace is used to control the
12 deformation applied to the specimen by means of two ceramic rods in contact with the outer
13 surface of specimen. Prior to the start of the fatigue loading, the furnace is closed, and the loop
14 is heated for at least 24 hours, to ensure an isothermal condition of 300°C in the entire rig.



15
16 *Fig. 2 : Experimental installation for fatigue test in simulated PWR water environment.*

17

18 Most of the fatigue tests in air were carried out using the same device with the hollow
19 specimen. Besides, due to constraints related to test duration, ancillary fatigue tests at low strain

1 amplitude were performed in air using solid samples on another INSTRON 8862 100kN
 2 electromechanical fatigue machine with an extensometer with a gauge length of 12.5 mm
 3 placed outside the furnace, controlling the deformation of the specimen with two ceramic rods
 4 in contact with the specimen.

5 The fatigue life N_5 is defined as the number of cycles applied until the detection of a
 6 decrease of 5% with respect to the peak stress measured at mid-fatigue life. In several tests
 7 however, such a decrease was not achieved prior to the failure of the specimen or the leak of
 8 the fluid through the tube wall. In such cases, the fatigue life was defined as the number of
 9 cycles to failure or to the leakage. Uniaxial fatigue experiments were realized under strain-
 10 control. A triangular waveshape loading with a strain rate of $0.4\% \text{ s}^{-1}$ was used. For the test
 11 reported here, the imposed total strain amplitude varied from 0.5% to 0.14%. For amplitudes
 12 that vary from 0.14% to 0.2%, a tensile mean stress of 20 MPa and 50 MPa was applied in
 13 several tests, by means of a tri-modal monitoring method, which is described in more details in
 14 section 3.2. Besides, for a strain amplitude of 0.2%, some tests were interrupted after a fixed
 15 number of cycles and then conducted to failure by high-cycle fatigue loading in laboratory air
 16 at room temperature, with a frequency of 10Hz and a load ratio of 0.2.

17

18 3. Results

19 3.1. Fatigue life without mean stress

20 The effect of PWR water on fatigue life in the absence of any applied mean stress is
 21 illustrated in Fig. 3. In this plot, the dotted blue curve represents the theoretical fatigue life in
 22 air as predicted by the mean curve in air proposed in the NUREG report ²⁰, according to
 23 Equation 1.

24 Equation 1
$$N_{\text{mean,air}} = \exp [6.891 - 1.92 \times \ln(\Delta\epsilon_t/2 - 0.112)]$$

25 Besides, the solid blue curve in Fig. 3 represents the “theoretical” fatigue life in PWR
 26 water, as predicted by Equation 2 by considering the F_{en} factor.

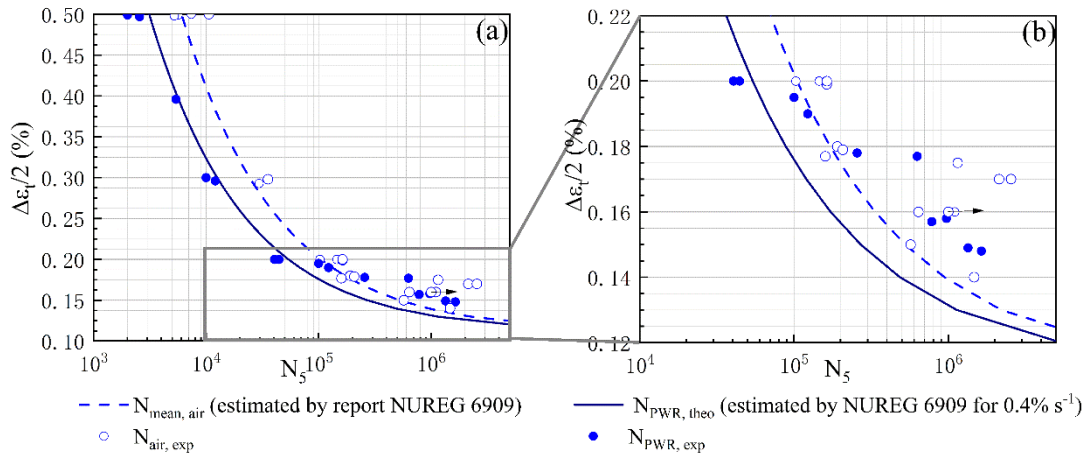
27 Equation 2
$$N_{\text{PWR, theo}} = \frac{N_{\text{mean, air}}}{F_{\text{en, theo}}} = \frac{\exp[6.891 - 1.92 \times \ln(\Delta\epsilon_t/2 - 0.112)]}{F_{\text{en, theo}}}$$

28 In this equation, $F_{\text{en, theo}}$ is the theoretical value of the abatement factor on the fatigue
 29 life in PWR water. Several empirical models based on extended experimental databases have
 30 been established to predict its value ²⁰⁻²⁴. According to the calculation method proposed in the
 31 latest NUREG report ²⁰, for a strain rate of $0.4\% \text{ s}^{-1}$ and a temperature of 300°C , the $F_{\text{en, theo}}$
 32 factor takes a value of 1.94.

1 In Fig. 3, the experimental fatigue life in PWR water is presented in blue solid circles.
 2 An experimental value of environment factor $F_{en,exp}$ can be derived from these data according
 3 to the equation and results are shown in Fig. 4. Given the limited set of data obtained in the
 4 course of the present study and in an attempt to take into account the scatter, a so-called semi-
 5 empirical value $F_{en,semi-exp}$ was also estimated by considering the equation below. The theoretical
 6 value $F_{en,theo}$ is indicated in Fig. 4 as well for comparison purpose.

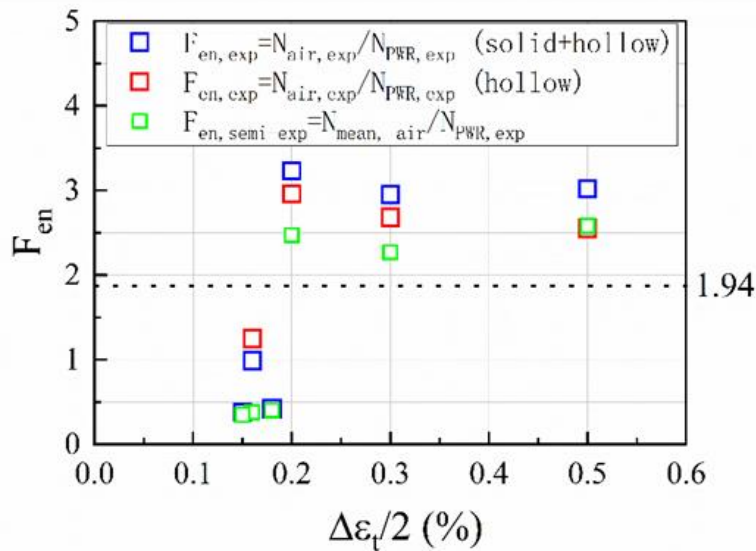
7 Equation 3
$$F_{en, semi-exp} = \frac{N_{mean, air}}{N_{exp, PWR}} = \frac{\exp[6.891-1.92 \times \ln(\Delta\epsilon/2-0.112)]}{F_{en,theo}}$$

8 It can be seen in Fig. 4 that, for a total strain amplitude ranging between 0.2% and 0.5%,
 9 the $F_{en,exp}$ value ranges between 2.27 and 3.23, that means a higher value than the $F_{en,theo}$ value
 10 equal to 1.94. A harmful effect of the PWR water on the fatigue life is hence confirmed. For a
 11 total strain amplitude less than 0.2% however, $F_{en,exp}$ varies between 0.38 and 1.25. The effect
 12 of PWR water on the fatigue life is therefore not clear in this strain amplitude interval, and the
 13 method proposed in the latest NUREG report ²⁰ tends to overestimate the deleterious effect of
 14 PWR water in this region. Furthermore, it has to be noticed that the influence of specimen
 15 geometry (solid versus hollow samples) on this tendency is extremely limited.



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Fig. 3 : Fatigue life in air and PWR water environment, without mean stress. (a) For strain amplitude between 0.1% and 0.5%. (b) Enlargement of (a) for total strain amplitudes below 0.2% (arrow: run-out test).



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Fig. 4 : Estimation of the experimental environment factor $F_{en,exp}$, and semi-experimental $F_{en,semi-exp}$ as a function of total strain amplitude without mean stress.

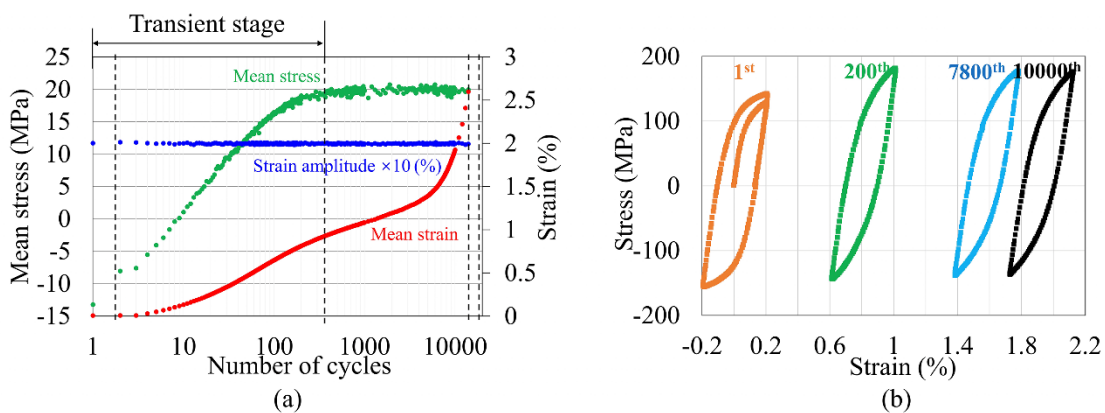
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3.2. Fatigue behavior with mean stress application

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For tests with mean stress application, a tri-modal monitoring method is applied while the strain amplitude and the strain rate are fixed. An example of such a monitoring is given in Fig. 5 for a strain amplitude of 0.2%, and a mean stress of 20 MPa: the mean strain of the material (red curve) is automatically incremented by the closed-loop system of the test machine, so as to compensate the stress relaxation resulting from cyclic loading and to gradually increase the mean stress until reaching the setpoint value (green curve). The phase during which the mean stress is progressively increasing until reaching the set point is noted in the following as the transient stage. The duration of this transient stage depends on the imposed loading (strain rate, strain amplitude and mean stress level) and the monitoring parameters (PID and tri-modal

1 gain). In a previous research on 304 THY SS, at $\Delta\varepsilon/2 = 0.18\%$, with a test frequency of 5 Hz
 2 ($3.6\%s^{-1}$), the mean stress of 50 MPa could be reached by this tri-modal monitoring in several
 3 tens of cycles ^{18, 25}, and at the end of the transient stage the mean strain is approximately zero
 4 at room temperature ¹⁸ but reached up to 2% at 300°C ²⁵, using the same test rig. In this work,
 5 after optimization of PID and tri-modal gain settings, the transient stage was controlled in order
 6 to be less than 10% of the total fatigue life, i.e. about 200 cycles for a mean stress of 20 MPa,
 7 and 1000 cycles for mean stress of 50 MPa respectively; the mean strain reached at the end of
 8 the transient stage is approximately 0.75% for 20 MPa and 4.5% for 50 MPa (Fig. 6 (b)). The
 9 large mean strain level reached is due to the enhanced ductility and reduced strain-hardening
 10 with higher temperature ²⁶⁻²⁸.



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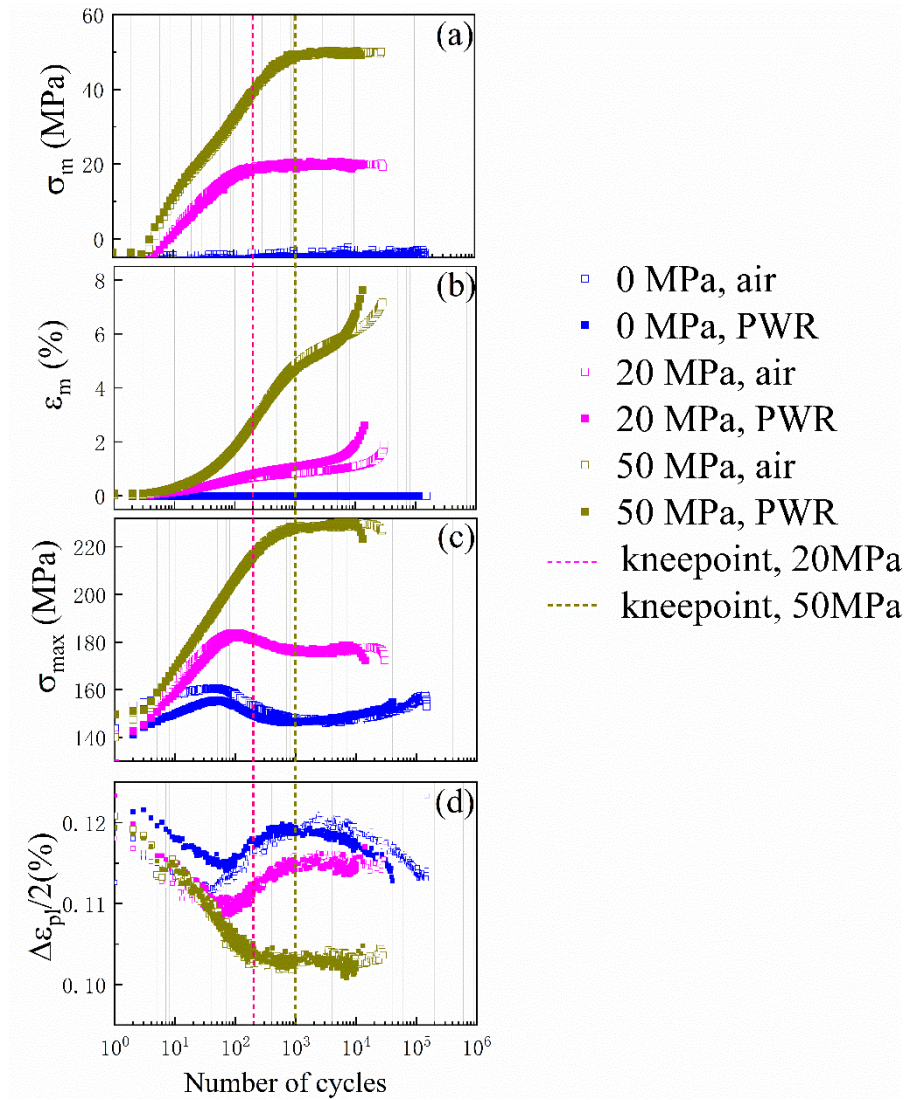
12 *Fig. 5 : Example of the fatigue behavior with mean stress application in tri-modal monitoring*
 13 *mode ($\Delta\varepsilon/2 = 0.2\%$, $\sigma_m=20$ MPa, in PWR water, fatigue life is 15600 cycles). (a) Evolution of*
 14 *the stress and strain in function of number of cycles. (b) Cyclic hysteresis loops of different*
 15 *number of cycles indicated by dotted black line in (b)*

16

17 In Fig. 6, the cyclic stress-strain response of the material for a strain amplitude of 0.2%
 18 with different mean stress levels is shown to assess the impact of applied mean stress. It is
 19 observed that this tri-modal monitoring causes as expected an increase in mean stress (Fig. 6
 20 (a)), but also in maximum stress (Fig. 6 (c)), as well as in mean strain (Fig. 6 (b)). Moreover,
 21 the amplitude of plastic strain decreases with the application of a mean stress, especially at
 22 50MPa (Fig. 6 (d)). This is related to the fact that the total strain amplitude is controlled as
 23 constant while the stress amplitude increases during the fatigue test.

24

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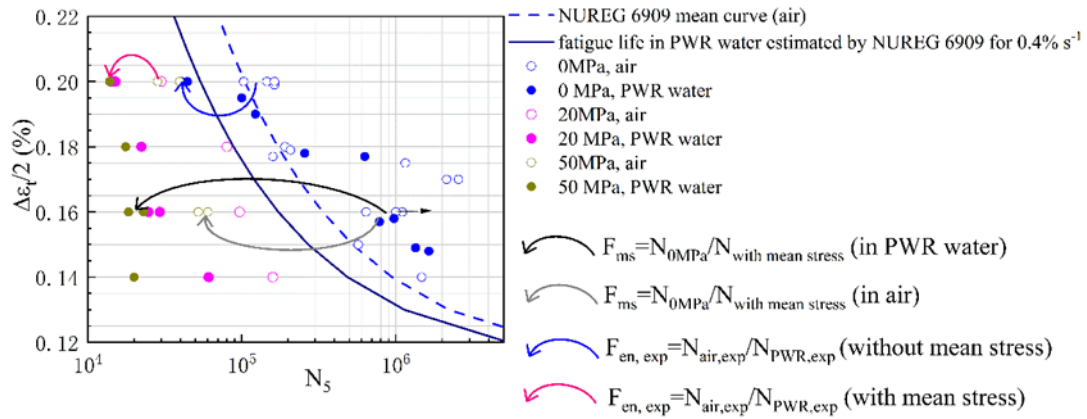


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2 *Fig. 6 : Cyclic stress-strain response in air and PWR water, $\Delta\varepsilon/2 = 0.2\%$, at $0.4\% s^{-1}$, with*
 3 *different mean stress levels. (a) Evolution of mean stress, (b) Evolution of mean strain, (c)*
 4 *Evolution of maximum stress, (d) Evolution of plastic strain amplitude.*

5

6 The effect of mean stress on fatigue life in air and in PWR water is presented in Fig. 7.
 7 For strain amplitudes varying from 0.14% to 0.2%, it can be seen that fatigue life is reduced
 8 when applying a mean stress of 20 MPa or 50 MPa as compared to tests under same conditions
 9 but without mean stress application. This reduction can be described by means of the F_{ms} factor
 10 defined as the ratio of the fatigue life without mean stress and the fatigue life with a mean stress
 11 in a given environment, as indicated in Fig. 7.



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Fig. 7 : Fatigue life in air and in PWR water environment, with or without mean stress.

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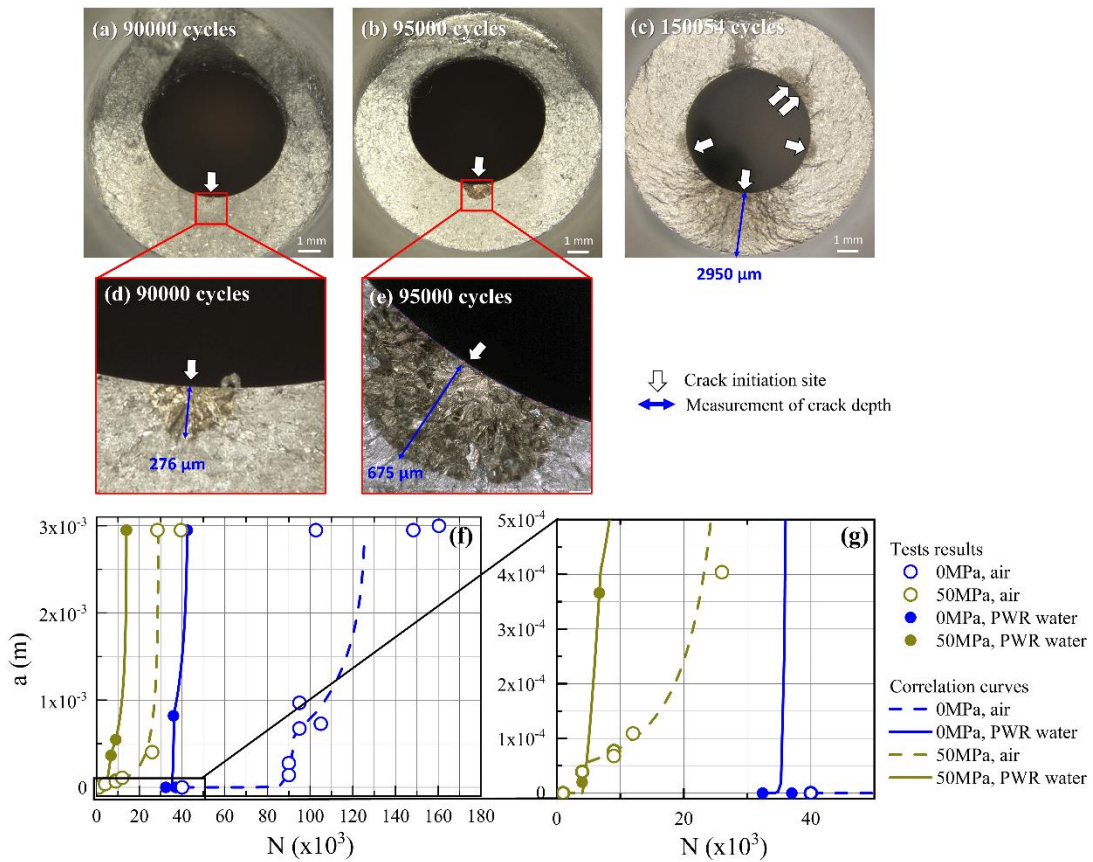
3.3 Fatigue crack initiation and growth stages at $\Delta\epsilon_t/2 = 0.2\%$

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The previous sections have presented results on the fatigue life obtained for total strain amplitudes varying from 0.14% to 0.5%. In this part, a focus is placed on the strain amplitude of 0.2% by analyzing additional data derived from interrupted tests carried out in air and in PWR water, without or with a mean stress of 50 MPa along with the results of tests conducted until failure. The objective is to evidence a possible joint effect of the mean stress application and of the exposure to PWR water on the fatigue crack growth process. With this aim, the maximum depth of the main crack observed on the fracture surface is firstly measured. Fig. 8 (a)-(e) show the measurements of crack depth for tests without mean stress application in air, at different number of cycles. The results for all tests in air and in PWR water, with and without

13

1 mean stress of 50 MPa are assembled and plotted as a function of the number of cycles in Fig.
 2 8 (f).



3
 4 Fig. 8 : Fracture surface of the specimens after different number of cycles. 0 MPa.
 5 $\Delta\varepsilon/2=0.2\%$. In air. (a) 90000 cycles. (b) 95000 cycles. (c) 150054 cycles (until rupture). (d)
 6 and (e) are magnifications of (a) and (b). (f) Fatigue crack propagation data derived from
 7 interrupted test and fitting curves

8
 9 The fitting curves presented in Fig. 8 (f) were obtained by integrating the fatigue crack
 10 growth rates described by a Paris–Erdogan-type equation²⁹ expressed as a function of the strain
 11 intensity factor range ΔK_e (Equation 4). The use of this parameter was proposed by Kamaya et
 12 al.^{30,31} for austenitic stainless steels and was used in previous research of the same material in
 13 similar test conditions^{10,32,33}.

14 Equation 4
$$\frac{da}{dN} = C \times \Delta K_e^m$$

15 Here, C and m are parameters that depend not only on material properties, but also on
 16 additional factors such as environment, strain rate etc. Their values were here determined by a
 17 trial-and-error method, so as to fit the experimental curves obtained with hollow specimens
 18 (data obtained with solid specimens are not considered so as to eliminate any possible geometry
 19 impact on the crack propagation).

1 In order to achieve a satisfactory fitting to the experimental data, it was found necessary
 2 to consider two sets of parameters (C_1 , m_1) and (C_2 , m_2), corresponding with two regimes
 3 separated by a transition at a given number of cycles N_t , and at a transition depth of a_t . The
 4 values of C , m , N_t and a_t for each investigated condition are assembled in Table 3. This
 5 transition in crack growth rate was previously observed in 304 stainless steel on striation
 6 spacing as on crack growth rates derived from Direct Current Potential Drop (DCPD)
 7 monitoring method, at diverse strain amplitudes and strain rates and in different media ^{6, 34-36}.
 8 This can be attributed to a lower sensitivity to ΔK_ε (or crack depth) during the propagation of
 9 short cracks than the macro-crack propagation, firstly reported as a “short-crack” effect ³⁷.
 10 Except for the case with mean stress application in air, a_t is comprised from 200 μm to 900 μm ,
 11 which is consistent with the threshold crack depth for the transition from a “Physically short
 12 crack” to a “Long crack” regime as suggested by Ould Amer ³⁸ in 304 stainless steel.

13 *Table 3 : Values of the parameters of the fatigue crack growth equations and the number of*
 14 *cycles at the transition for the experimental conditions under consideration.*

Condition	C_1	m_1	N_t	a_t (μm)	C_2	m_2
0 MPa, air	1.55×10^2	2.22	91363	590	2.32×10^2	2.86
0 MPa, PWR	1.55×10^2	2.14	36000	821	1.10×10^3	2.62
50 MPa, air	7.36×10^2	2.40	3027	55	8.36×10^3	3.00
50 MPa, PWR	2.74×10^{-5}	0.55	7000	412	5.29×10^5	3.30

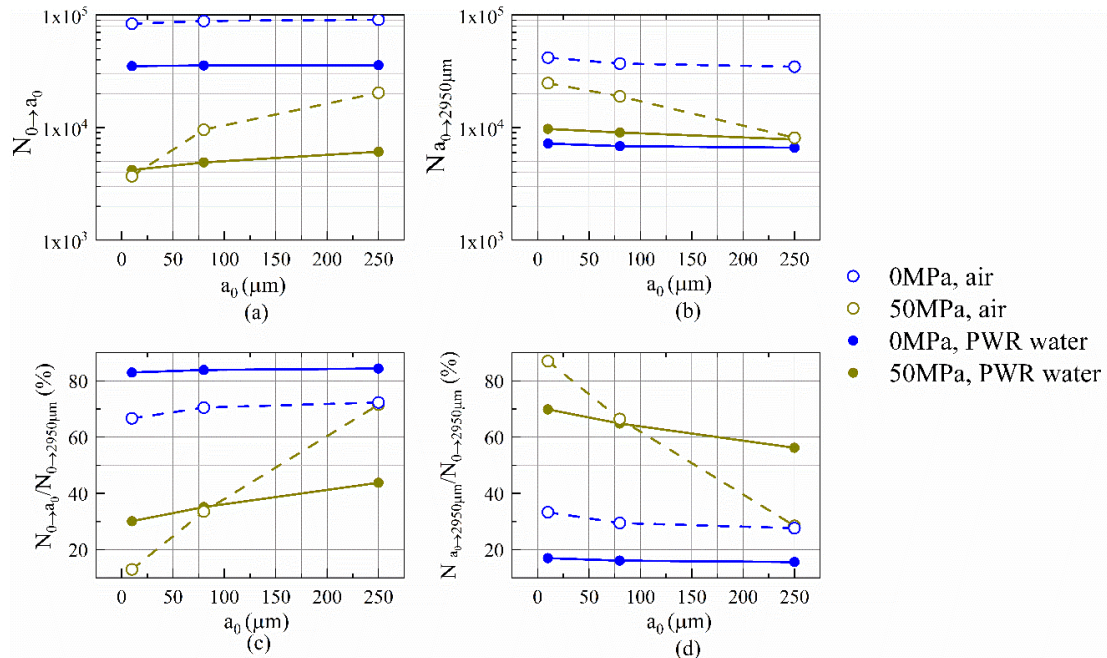
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16 The numbers of cycles required to make a surface crack grow to a certain depth are then
 17 calculated by using these values represented by the fitting curves in Fig. 8 (f). In some previous
 18 research with $\Delta\varepsilon_t/2=0.6\%$, 10-20 μm is frequently applied to define the depth of fatigue crack
 19 initiation for the 316 stainless steels ³⁹ and for the investigated material ^{6, 40}. However, at
 20 $\Delta\varepsilon_t/2=0.2\%$, even after 50% of the fatigue life, a considerable proportion of cracks can be
 21 stopped by the first grain boundaries encountered ³⁸. In fact, cracking remains sensitive to local
 22 microstructural barriers until a certain depth, known as the effect of short cracks ^{6, 32, 37, 38}. In
 23 this work, for most of observed fracture surfaces, the depth of the deepest crack, when existing,
 24 are no smaller than 77 μm , except one case showing only one crack of 39 μm . It has to be noted
 25 that the average grain size of the investigated material, measured by EBSD characterization on
 26 a statistic amounts of grains ^{6, 19, 40}, is 80 μm .

27 Hence, based on statements and observations mentioned above, values of the depth of an initial
 28 crack a_0 as 10, 80 and 250 μm was separately considered, to estimate the crack initiation life
 29 and crack propagation life. By using the fitting curves in Fig. 8 (f), $N_{a_0 \rightarrow 2950\mu\text{m}}$ is the number
 30 of cycles required to make a crack grow from a_0 , to a final depth of 2950 μm , which is the wall
 31 thickness of the hollow specimen. The number of cycles $N_{0 \rightarrow a_0}$ required to nucleate a crack of

1 a_0 is thereafter derived by subtracting to the number of cycles to failure N_5 . The result is shown
 2 in Fig. 9.

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6 *Fig. 9 : (a) Fatigue crack initiation life $N_{0 \rightarrow a_0}$ (b) fatigue propagation life $N_{a_0 \rightarrow 2950 \mu\text{m}}$ (c)*
 7 *percentage of crack initiation life in total fatigue life. (d) percentage of crack propagation life*
 8 *in total fatigue life for different values of a_0 at $\Delta\varepsilon/2 = 0.2\%$.*

10 Fig. 9 (a) and (b) share the same axis scale. One can note that the crack initiation life is
 11 generally in the same order of, or even higher than the crack propagation life, for the various
 12 values of a_0 considered. Without any applied mean stress (blue curves in Fig. 9), the propagation
 13 stage corresponds with less than one third of the total life. With mean stress application, the
 14 crack initiation life is greatly reduced (brown curves in Fig. 9 (c)), from more than 65% of the
 15 total fatigue life to less than 30%, if considering a_0 of $10 \mu\text{m}$ and $80 \mu\text{m}$.

16 Focusing on Fig. 9, by comparing the hollow blue curve for air and the solid blue curve
 17 for PWR water, one can confirm the deleterious effect of the PWR environment in crack
 18 initiation stage and in crack propagation stage in the absence of mean stress. Besides, this effect
 19 of PWR environment during both crack initiation and propagation stage shows very little
 20 dependency on the value of a_0 considered. By comparing the blue dotted curve and the brown
 21 dotted curve, a negative effect of mean stress application in air for the crack initiation and
 22 propagation stage can be noticed. This negative effect during the crack initiation stage is

1 particularly pronounced while considering a_0 as 10 μm . However, when these two deleterious
2 parameters co-exist, an interesting point is observed, indicated by brown solid curves in Fig.
3 9: the crack initiation life in PWR water with mean stress application is closed to that in air
4 with mean stress application, if considering $a_0 = 10\mu\text{m}$; the crack propagation life in PWR water
5 with mean stress application is, on the other hand, slightly longer than the crack propagation
6 life in PWR water but without applied mean stress, for all the considered values of the initial
7 crack depth a_0 .

8

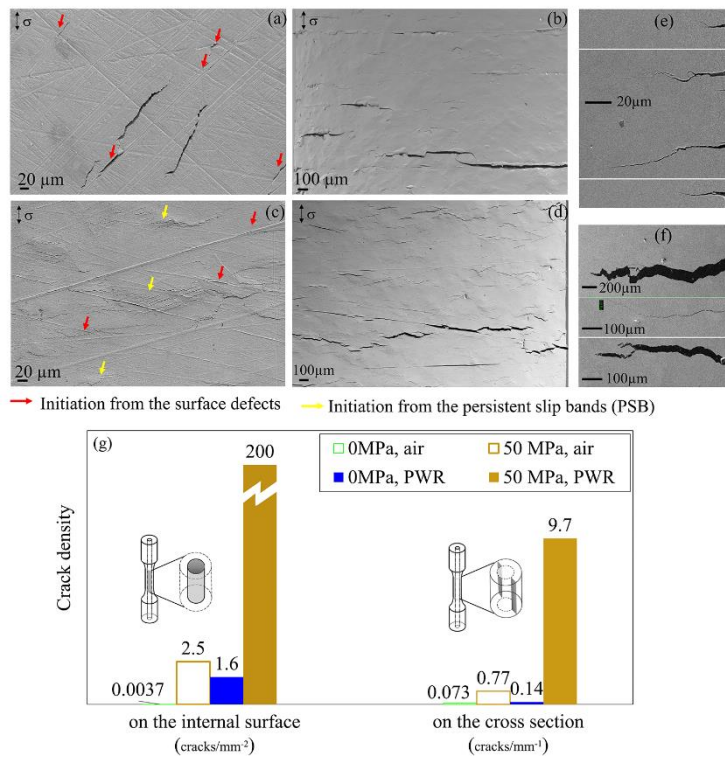
9 **4. Discussion**

10 **4.1. Effect of PWR water on fatigue life**

11 From Fig. 8 (f) and Fig. 9 (a), it is revealed that this crack initiation life is much lower in PWR
12 water than in air. This detrimental effect of PWR water on the crack initiation stage is in
13 agreement with previous research⁴⁰⁻⁴².

14 Despite this enhancement of fatigue crack initiation in PWR water, the crack initiation
15 stages in air and in PWR present some similarities. The first one is the predominance of the
16 crack initiation life within the entire fatigue life in both environments in the absence of mean
17 stress, as mentioned above. In fact, $N_{0 \rightarrow a_0}$ detains approximately 70% and 83% of the fatigue
18 life, in air and in PWR water respectively, as shown in Fig. 9. It is worth noticing that the higher
19 fraction in PWR water results from higher fatigue crack growth rates, and consequently a
20 relatively shorter crack propagation stage, as it will be explained in the next section. The second
21 similarity between the two environments lies in the nature of the crack initiation sites, which
22 are generally related to surface defects introduced during specimen machining, as illustrated in
23 Fig. 10 (a) to (d). In fact, Persistent Slip Bands (PSBs) are rarely observed on the surface, even
24 at the end of the fatigue test, which can be at least partly attributed to the low values of plastic
25 strain encountered in this domain. The third similarity is the limited number of crack initiation
26 sites in both environments. The crack density, measured on the specimen internal surface (Fig.
27 10 (a) to (d)) and expressed in cracks/ mm^2 , and on cross sections of the sample (Fig. 10 (e) and
28 (f)) and expressed in cracks/ mm , are assembled in Fig. 10 (g). Only the specimens fatigued to
29 failure are included in this plot, as the specimens from interrupted tests show only a very limited
30 number of cracks: for instance, in air, only one crack is observed after 95000 cycles (69% of
31 the fatigue life); in PWR water, only one crack is noticed after 36000 cycles (84% of the fatigue
32 life); for another specimen tested to 37000 cycles in PWR water, no crack is detected. With a
33 strain amplitude of 0.2%, crack density on the specimens tested to failure is low, in air as well

1 as in PWR water, while with a strain amplitude of 0.6%, the crack initiation site density is
 2 doubled in PWR water and reaches 23 mm⁻² after just 600 cycles⁶.



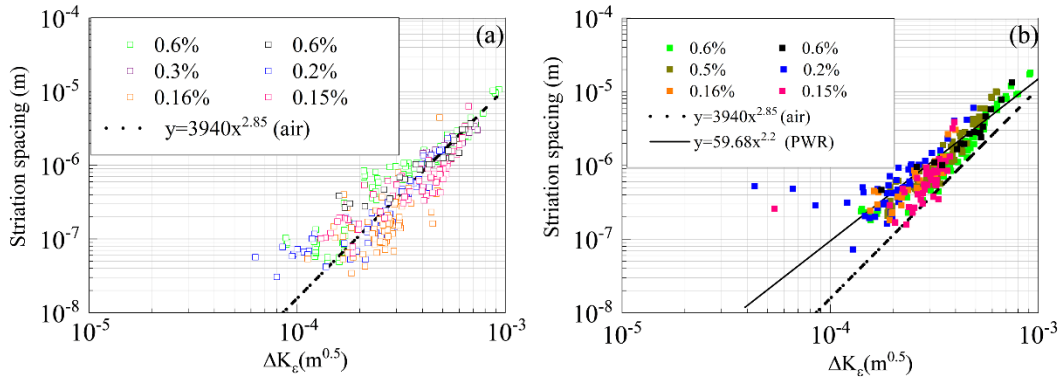
3
 4 **Fig. 10 : Observations of the cracks in the hollow specimens with a strain amplitude**
 5 **$\Delta\epsilon_r/2=0.2\%$ after fatigue tests of different numbers of cycles. (a) 40731 cycles, without mean**
 6 **stress, in PWR water, on the internal surface. (b) 9000 cycles, 50 MPa, in air, on the internal**
 7 **surface. (c) (d) 9000 cycles, with a mean stress of 50 MPa, in PWR water, on the internal**
 8 **surface. (e) 40731 cycles, without mean stress, in PWR water, on cross section. (f) 15534**
 9 **cycles, with a mean stress of 50 MPa, in PWR water, on cross section. (g) Crack density on**
 10 **the internal surface and on the cross section at the end of the fatigue test.**

11

12 These similarities between the two environments suggest that, under a strain amplitude
 13 of 0.2%, and without any applied mean stress, the cyclic plastic strain accumulation represents
 14 the key factor controlling crack initiation. In air, a previous study carried out at higher strain
 15 amplitudes pointed out that cracks principally initiate from the extrusion/intrusions on the
 16 surface due to emergence of persistent slip bands^{6, 19, 43}. In the present study however, due to
 17 the low strain amplitudes considered, the plastic strain accumulation is extremely slow, so that
 18 only very few slip bands are activated and emerged on the free surface. As a consequence,
 19 cracks preferably initiate in the vicinity of surface defects, where a local concentration of stress
 20 and/or deformation develops due to the geometry singularity. The PWR water environment can
 21 facilitate the crack initiation by successive repetition of oxidation of the strain concentration
 22 site, and rupture of the oxide film formed on the crack tip, as previously pointed out^{19, 44}.
 23 Nevertheless, it is worth noticing that these interactions are based on the assumption of a

1 sufficient accumulation of plastic strain required to promote preferential oxidation^{19, 43, 45} and
2 to conduct to the failure of the oxide layer by shearing^{43, 44}.

3 Secondly, as concerns the crack propagation life as quantified by the $N_{a0 \rightarrow 2950\mu m}$
4 parameter, the PWR water evidently reduces the crack propagation life, as indicated in Fig. 9
5 (b). This is furthermore consistent with the variation observed in fatigue striation spacing on
6 the crack propagation area of the fracture surface, and, as presented in Fig. 11 as a function of
7 ΔK_{ϵ} . In Fig. 11, the results for strain amplitudes equal to and lower than 0.2% are compared
8 with results previously obtained for the same material and under the same strain rate, but at
9 significantly higher strain amplitudes (0.6%^{6, 40}, 0.5%¹⁹, and 0.3%⁴⁰). It is found that, for a
10 given environment (air or PWR water), the effect of strain amplitude on fatigue crack growth
11 rates is extremely limited, and that the fatigue crack growth rate in air is always smaller than in
12 PWR water. This suggests that, as long as the crack propagates in a stage-II mode along with
13 the formation of fatigue striations, the harmful effect of PWR water is similar, regardless the
14 applied strain amplitude varying from 0.14% to 0.6%. The fatigue crack growth equations
15 established by Kamaya et al.^{46, 47} (curves in Fig. 11) present a fair estimation of the fatigue crack
16 growth rates in air and especially in PWR water. However, it has to be pointed out that the
17 positive mean stress and the associated progressive mean strain are expected to influence crack
18 closure effects, but also the magnitude of environmental effect. Indeed, in a previous study, it
19 was established that the crack is fully open with a slightly negative strain during the rising load
20 part of a push-pull loading ($R_{\epsilon}=-1$)³³. As the magnitude of environmental enhancement of
21 fatigue crack growth rate is controlled by the duration of exposure to environment, it is partly
22 controlled by the opening strain. This effect is particularly marked at very slow strain rates. In
23 the present study, the experimental conditions considered do not vary enough to distinguish any
24 potential effect of the variation of the opening strain on fatigue crack growth rate enhancement
25 in PWR environment. Indeed, the maximum factor on exposure duration is two.



1

2 *Fig. 11 : Striation spacing in function of ΔK_{ϵ} , without mean stress, at $0.4\%s^{-1}$ in comparison*
 3 *with results at strain amplitudes of 0.6%^{6, 40}, 0.5%¹⁹, and 0.3%⁴⁰. (a) In air. (b) In PWR*
 4 *water.*

5 The analysis developed in the two previous paragraphs, on crack initiation and crack
 6 propagation respectively, explains the drop in fatigue life noticed in PWR water at $\Delta\epsilon/2=0.2\%$
 7 without mean stress application, as shown by the pink arrow in Fig. 7. Besides, it provides a
 8 possible explanation for the disappearance of the negative effect of PWR water on fatigue life
 9 noticed in Fig. 3 and Fig. 4 for strain amplitude smaller than 0.2%. During the major part of the
 10 fatigue life at low strain amplitudes, the oxide layer on the specimen surface might not fail and
 11 the underlying metal is probably not exposed to the PWR water. As a consequence, during this
 12 period, the PWR environment might not significantly contribute to the crack initiation process.
 13 However, once the fatigue crack grows deep enough to form observable fatigue striations, the
 14 PWR effect is activated. However, as the crack propagation stage is relatively short compared
 15 to the initiation stage, the impact of PWR environment on the total fatigue life, which is
 16 represented by the $F_{en,exp}$ parameter, is very limited. Therefore, for such strain amplitudes
 17 typically lower than 0.2%, the $F_{en,exp}$ value is approximately equal to 1, while it is above 2 for
 18 strain amplitudes higher than 0.2%.

19 Besides, a negative effect of PWR water on the fatigue life is observed in Fig. 7 even
 20 for strain amplitudes varying from 0.14% to 0.2%. The threshold value of 0.2% for the strain
 21 amplitude established in the absence of mean stress application does no longer hold. A possible
 22 explanation for this is given in section 4.2.

23

24 **4.2. Effect of mean stress on fatigue life**

25 As shown in Fig. 6, the application of a mean stress greatly modifies the cyclic stress-
 26 strain response of the material, which in turn results in changes in the crack initiation
 27 mechanism. Firstly, the application of a mean stress leads to a sharp increase in crack density.
 28 Indeed the SEM observations of the internal surface of specimens indicate that, with a mean

1 stress of 50 MPa, a large quantity of PSBs are already formed on the internal surface of the
2 specimens fatigued after 9000 cycles (Fig. 10 (c) (d)). The crack density measured on the
3 internal surface and the cross section is significantly higher than the case without mean stress
4 application, as shown in Fig. 10 (d). In contrast to the case without mean stress application, the
5 defects initially present at the surface do no longer constitute the main crack initiation sites.
6 Meanwhile, it can be seen from Fig. 9 (a) that the crack initiation stage is greatly reduced to
7 about 35% of the total fatigue life, i. e. a much lower fraction compared to the case without
8 mean stress application (about 80%). It is deduced that, for strain amplitudes smaller than 0.2%,
9 the predominance of the crack initiation stage on the fatigue life does no longer hold with the
10 application of mean stress. The mean stress application would thus favor the initiation of surface
11 cracks, which are then exposed to the PWR water earlier during the fatigue life. This may be
12 the reason for the negative effect of PWR water noticed with mean stress application for strain
13 amplitudes lower than 0.2%.

14 The sharp increase in the number of PSBs indicates that the application of a mean stress
15 under a given strain amplitude enhances the accumulation of plastic strain. It should be noted
16 however that, in this study, the plastic strain amplitude decreases as a mean stress is applied
17 (Fig. 6 (d)). Therefore, this enhancement of plastic strain accumulation should be attributed to
18 the increase of maximum stress or the mean strain (Fig. 6 (a)-(c)). Further discussion on that
19 point is provided in sections 4.5 and 4.6.

20 Besides, as regards the crack propagation stage, as indicated in in Fig. 9 (b), the harmful
21 effect of the mean stress application in air is confirmed. In PWR water however, the mean stress
22 application even shows a slightly beneficial impact. Considering the scatter in data, it is likely
23 that, in PWR water, the mean stress application effect on crack propagation is either neutral or
24 slightly positive. An in-depth investigation of the crack propagation micro-mechanism would
25 be necessary to explain the disappearance of the mean stress effect in PWR water during the
26 crack propagation stage.

27 28 **4.3. Influence of mean strain on the fatigue life**

29 In this study, the trimodal monitoring method induces an increase of the maximum stress,
30 the minimum stress, the stress amplitude, and the mean strain. More particularly, the variation
31 of the mean strain can be extremely important, typically up to 8% at the end of the tests with a
32 mean stress of 50MPa and a strain amplitude of 0.2%. The potential role of such a mean strain
33 in the reduction of fatigue life under mean stress application is discussed in the following lines.

34 Firstly, previous researches on polished specimen made from pre-hardened austenitic
35 stainless steel show that, for a given strain amplitude, the mean strain level does not lead to

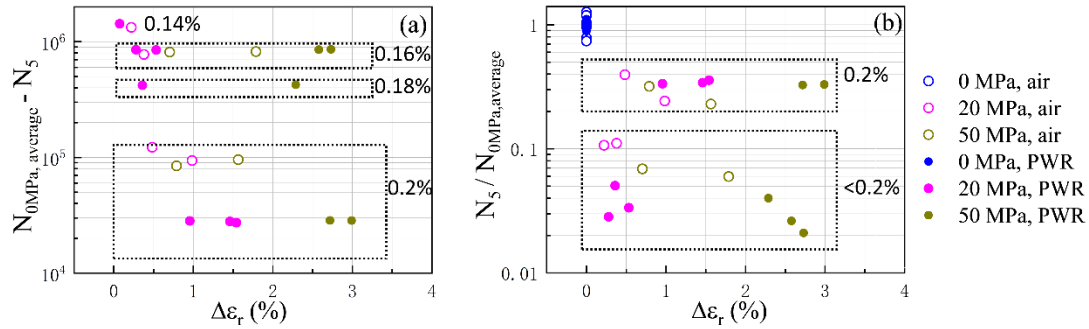
1 reduction of fatigue life in air ^{14, 48} nor in PWR water ^{15, 49}. These studies however concerned
2 pre-straining from 10% to 40%, that means largely higher than the mean strain values achieved
3 here. Therefore, it can be deduced that, in the tests presented here, the mean strain by itself is
4 not responsible for the fatigue life reduction. It is the modification of the mean strain,
5 characterized by the ratcheting strain, or the modification in surface roughness that may have
6 potential negative effect on the fatigue life.

7 In stress-controlled tests carried out on a non-prestrained 316L austenitic stainless steel
8 ⁴⁹, even though the ratcheting strain increases, it was observed that the fatigue life was improved
9 with the applied mean stress. This indicates that the cyclic hardening outweighs the possible
10 detrimental effect of positive ratcheting strain on fatigue life. However, the analysis of
11 ratcheting strain as generated by the trimodal control used in this study was not examined in
12 previous studies.

13 In this study, the ratcheting strain $\Delta\epsilon_r$ is defined as the difference between the mean strain
14 measured at 10% of the fatigue life and the one measured at 95% of the fatigue life, as expressed
15 in *Equation 5*. The mean strain variation prior to crack initiation and the one occurring near the
16 final rupture are therefore excluded in this definition. The choice of the 10% of the fatigue life
17 as a lower bound for this parameter is furthermore consistent with the transient regime shown
18 in Fig. 5 corresponding to the establishment of the imposed mean stress.

19 *Equation 5*
$$\Delta\epsilon_r = \epsilon_{m, 95\% \text{ of the fatigue life}} - \epsilon_{m, 10\% \text{ of the fatigue life}}$$

20 In Fig. 12 (a), the decrease in fatigue life due to the application of mean stress, expressed
21 as the difference between the reference fatigue life in absence of mean stress $N_{0MPa,average}$ and
22 the fatigue life resulting from the application of a mean stress N : $N_{0MPa,average} - N_5$, is plotted as a
23 function of $\Delta\epsilon_r$. $N_{0MPa,average}$ was determined for each environment and strain amplitude, by
24 averaging all the obtained reference fatigue tests results. It comes out that, for a fixed strain
25 amplitude, the decrease in fatigue life induced by the application of a mean stress can be
26 considered as independent of the ratcheting strain value. In Fig. 12 (b), the reduction of fatigue
27 life is described by the ratio $N_5/N_{0MPa,average}$. Without mean stress application, $N_5/N_{0MPa,average}$ in
28 PWR water varies from 0.7 to 1.3, which represents an index of the scatter in the fatigue lives
29 in the absence of mean stress. The reference value of the ratio $N_5/N_{0MPa,average}$ is expected to be
30 around 1 but as it can be seen in Fig. 12 (b) it is characterized by a relatively large scatter,
31 especially in air. Nevertheless, it is shown that in the presence of a mean stress, the ratio
32 $N_5/N_{0MPa,average}$ is significantly lower than 1, but does not seem to be affected by the ratcheting
33 strain nor by the environment. Hence, a mean value around 0.3 is obtained with a strain
34 amplitude of 0.2%, and less than 0.1 at lower amplitudes, almost regardless of the test
35 environment.



1

2 *Fig. 12 (a) decrease of fatigue life due to the application of a mean stress $N_{0MPa,average} - N_5$ in*
3 *function of the ratcheting strain $\Delta\epsilon_r$ (2) Normalized fatigue life with or without mean stress*
4 *$N_5 / N_{0MPa,average}$ as a function of the ratcheting strain $\Delta\epsilon_r$*

5

6 Kamaya and Kawakubo⁴⁸ carried out fatigue tests with a mean stress application on a
7 316L austenitic stainless steel in air at room temperature and calculated a normalized fatigue
8 life by considering the life determined by the effective strain range, that means the range during
9 which the crack is fully open, as a function of the ratcheting strain. The inverse correlation
10 between these two parameters was explained by the authors by the fact that a high value
11 ratcheting strain favors the crack opening and therefore enhances the crack growth rates.
12 However, in another research on 316L SS in air but at 300°C¹⁵, the relation between this
13 normalized life and the ratcheting strain is no longer obvious, but is characterized by a
14 considerable scatter, in agreement with the tendency presented here. It is therefore likely that
15 ratcheting does contribute to the reduction in fatigue life in presence of a mean stress application,
16 for example by enhancing the crack opening as explained in^{14, 15, 48}, but at high temperature,
17 this influence tends to saturate when a small ratcheting value, typically less than 0.5% in the
18 present study, is achieved. This is probably why a similar weak dependence on the ratcheting
19 strain is observed in PWR water in this study. Further investigation of this suggestion is
20 nevertheless required.

21 Given that, it can be concluded that ratcheting, despite of the high mean strain value that
22 can be achieved at the end of test, is of limited contribution in the fatigue life reduction due to
23 mean stress application, particularly in PWR water.

24

25 **5. Conclusions**

26 This paper reported on experimental results of uniaxial strain amplitude-controlled
27 fatigue tests carried out to get insight into the joint influence of the exposure to PWR water and
28 of the application of a mean stress on the fatigue strength of a 304L austenitic stainless steel,

1 with a special attention paid to the strain amplitudes equal or smaller than 0.2%. The main
2 findings can be summarized as follows.

- 3 1. In the absence of mean stress application, for a strain amplitude ranging between 0.2%
4 and 0.5%, the fatigue life in PWR water is reduced as compared to air. The experimental
5 environmental factor F_{en} in this regime lies between 2.27 and 3.23, that means slightly
6 higher than the theoretical value of 1.94 derived from the NUREG/CR-6909 report ²⁰
7 for this condition.
- 8 2. Furthermore, it is shown that the reduction in fatigue life induced by PWR water is
9 related to the acceleration of the crack initiation stage, as well as of the crack
10 propagation stage. For a strain amplitude smaller than 0.2%, the PWR water effect on
11 fatigue life is negligible, as the crack initiation stage predominates the entire fatigue life
12 under such loading conditions and as the PWR water has only a limited impact during
13 this stage. However, additional fatigue tests at small strain amplitudes below 0.2%, and
14 with other strain rate below $0.4\%s^{-1}$ are still necessary to definitively assess this point.
- 15 3. With a given strain amplitude lying between 0.14% and 0.2%, the application of a tensile
16 mean stress reduces the fatigue life by accelerating the crack initiation stage and the
17 crack propagation stage in air, but merely by accelerating the crack initiation stage in
18 PWR water. An in-depth investigation of the crack propagation micro-mechanism
19 would be necessary to explain the disappearance of the mean stress effect in PWR water
20 during the crack propagation stage.
- 21 4. Due to the enhancement of the plastic strain accumulation induced by the mean stress
22 application, the crack initiation stage is accelerated and the PWR water effect on fatigue
23 life is re-activated for strain amplitude below 0.2%, in the presence of a mean stress.

24 25 **Declaration of Competing Interest**

26 The authors declare that they have no known competing financial interests or personal
27 relationships that could have appeared to influence the work reported in this paper.

28 **CRedit authorship contribution statement**

29 Z. Peng: Investigation, writing original draft & editing. G. Henaff: Supervision,
30 discussion, writing review & editing. J-C. Le Roux: Investigation, writing - review & editing.
31 R. Verlet: Investigation, writing - review & editing.

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3

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