LOW CYCLE FATIGUE BEHAVIOR OF A TYPE 304L AUSTENITIC STAINLESS STEEL IN VARIOUS ENVIRONMENTAL AND TEMPERATURE CONDITIONS (AIR, VACUUM AT 20°C OR 300°C)

L. de Baglion [a,b], J. Mendez [b], JA. Le Duff [a]

a AREVA, La Défense, France

b Institut P' (LMPM_ENSMA), Poitiers, France

Abstract Primary piping of Pressurized Water Reactors "PWR" is made of 304L-type austenitic stainless steel and is used to convey water at elevated temperature under high pressure. Because of temperature gradients during start-ups, shutdowns or operating transients, this component is subjected to cyclic thermal stresses leading to high strain amplitudes at low frequencies. Consequently, the low cycle fatigue (LCF) behavior of this steel has to be considered for the fatigue design and life analysis of piping systems and other reactor components.

During a research program, in order to be aimed to evaluate the PWR water coolant environment effect on the fatigue life of a 304L-type austenitic stainless steel, a preliminary work has been conducted by performing LCF tests in a secondary vacuum, considered as a non-active environment, or in air which is currently but improperly taken as a reference to characterize the effect of reactive environments. Tests performed at various temperatures, strain amplitudes and strain rates in both environments allowed us to evaluate the intrinsic role of each parameter and the importance of coupling effects on the damage processes that already exists in air.

The main purpose of this paper is to highlight the fact that the LCF life results from complex interactions which have to be identified in order to avoid taking into account several times a test parameter effect during the fatigue design and life analysis.

1 INTRODUCTION

The 304L-type austenitic stainless steel is used for the manufacturing of vessels and piping systems in pressurized water reactors (PWR). In the primary system of those reactors, the material is subjected to a thermo-mechanical cycling caused by temperature gradients during start-ups, shutdowns or operating transients. In fact, computations and in-operation data acquisitions revealed high strain amplitudes at low frequency. Consequently, the low cycle fatigue (LCF) is considered as one of the potential degradation mechanisms affecting the life of PWR primary components. In such mechanical solicitations, the cyclic stress response (CSR) and damage modes of a metallic alloy are highly dependent of key parameters like temperature, strain amplitude or strain rate. In addition, PWR water coolant environment is known to have a strong deleterious impact on the austenitic stainless steels fatigue life [1].

During a research program devoted to this high temperature water environment effect, the LCF behavior and damage of a 304L-type austenitic stainless steel were previously investigated in vacuum or in air, at room temperature or 300°C. In particular, the tests conducted in a secondary vacuum, considered as a non-active environment with regard to fatigue processes, have permitted the identification of the respective role of fatigue test parameters as temperature, strain amplitude and strain rate.

2 EXPERIMENTS

2.1 Material and specimen

The material used in this study is a 304L stainless steel having the following chemical composition in wt%: C-0.029, Si-0.37, Mn-1.86, P-0.029, S-0.004, Ni-10, Cr-18, Mo-0.04, N-0.056 and Fe-balance. It was elaborated by Creusot Loire Industries (CLI) in the form of a 5000*2000*30 mm^3 plate obtained by rolling and then subjected to a solution-treatment at 1100°C before a water-quench. The mechanical properties are given in Table 1.

The fatigue specimens with a gage length of 13.5mm and a gage diameter of 9mm were machined in order to have the loading axis parallel to the rolling direction of the plate. The surfaces of the specimens were mechanically polished down to 1µm grade diamond paste. Figure 1 shows the specimen design which allows a control of the elongation either on the gage length or between two flanges machined on specimen shoulders.

Table 1: Mechanical properties in the rolling direction of 304L austenitic stainless steel

CLI plate	20°C	300°C
Elastic modulus (GPa)	192	170
Yield strength (MPa)	214	130
Ultimate tensile strength (MPa)	592	414
Elongation (%)	57	39

2.2 Test equipment and procedure

Fatigue tests were carried out using two Instron electromechanically driven closed-loop machines, Model 1362. One of these machines, used in air environment, is equipped with a lamp furnace which can control temperature within a variation of ± 1°C at steady state. The other one is equipped with a vacuum chamber in which a 3-zone resistance type furnace is placed allowing working at pressure on the order of 10^{-4} Pa at 20 or 300°C within a variation of ± 2°C at steady state.
Tests were performed in both environments at 20 or 300°C under total axial strain control using a triangular waveform at strain amplitudes of ± 0.3 or ± 0.6% and at strain rates of 4 x 10^{-3}, 1 x 10^{-4} or 1 x 10^{-5} s^{-1}.
Strain was controlled using either an extensometer directly mounted on the gage length or two Linear Variable Differential Transformers (LVDT's) measuring the displacement between flanges. This second configuration necessitated a previous correlation between shoulder displacements and gage strains. These two control means are not strictly identical because of the complex hardening and softening behavior of the material but do not lead to major variations of the CSR or LCF life.

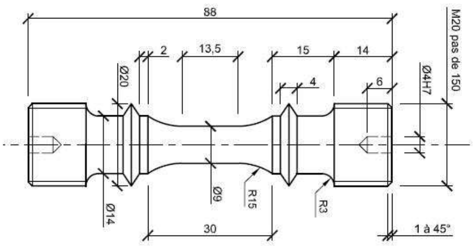


Figure 1: Schematic representation of the LCF specimen

3 RESULTS AND DISCUSSIONS

3.1 LCF intrinsic behavior

The intrinsic fatigue behavior of type 304L austenitic stainless steel at temperatures of 20 or 300°C and strain amplitudes of ± 0.3 or ± 0.6% is depicted on Figure 2 which represents the evolution of the tensile peak stress with the number of cycles in secondary vacuum. The CSR is divided into four stages (hardening, softening, stabilization and failure) which reflect the evolution of the dislocation structures and damage. In certain conditions of temperature and strain amplitude, the material exhibits a secondary hardening prior the failure. In fact, at 20°C and high strain amplitude, some TEM observations to be published elsewhere, have revealed the formation of mechanical twins and α' martensite which are responsible for strengthening the matrix. At 300°C and low strain amplitudes, a secondary hardening occurs and was already observed in a 316L-type austenitic stainless steel by Gerland et al. [2]. In that case, this phenomenon was attributed to the formation of the corduroy type dislocation structure when the cumulated cyclic plastic strain becomes significantly high, as in vacuum.

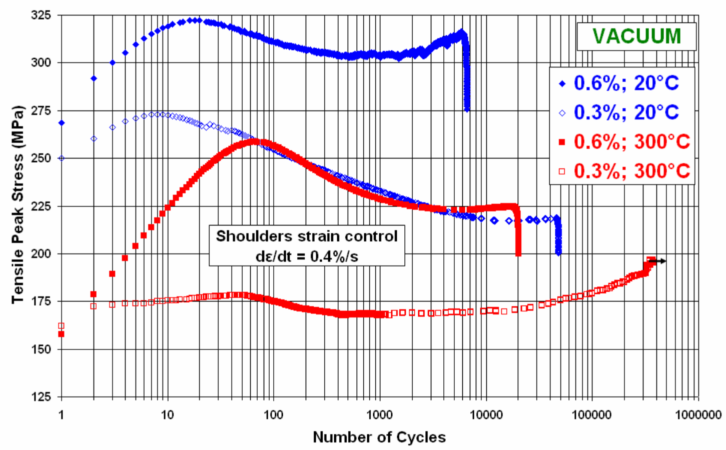


Figure 2: Tensile Peak Stress versus cycles for LCF tests in Vacuum

3.2 Temperature effect

In vacuum, the temperature of 300°C has a beneficial influence on the fatigue life at both strain amplitudes. Alain et al. [3] have obtained the same result on a 316L-type austenitic stainless steel and have explained it by a more homogeneous, planar and reversible deformation which lead mainly to a decrease of transgranular cracks initiation and propagation kinetics.

In air, we can firstly notice on Figure 3 that the CSR is similar to those in vacuum in the common life duration. In fact, the macroscopic deformation mechanisms are identical in both environments because depths of the layers concerned by environmental effects are negligible compared to the gage diameter as far as crack damage remains limited. Moreover, as evidenced in Table 2, there is no temperature influence at strain amplitude of ±0.3% and only a slight beneficial one at ±0.6%.

These results reflect that the beneficial influence on the LCF life obtained with a temperature of 300°C in vacuum is partially or totally hidden in air because of a pronounced environmental effect at this temperature.

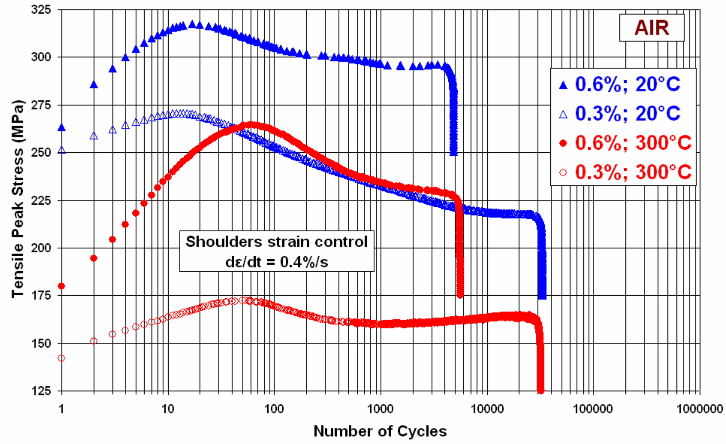


Figure 3: Tensile Peak Stress versus cycles for LCF tests in Air

Table 2: Temperature influence depending on strain amplitude and environment

Temperature influence: $N_{300°C} / N_{20°C}$	Air	Vacuum
$\Delta\varepsilon t/2 = \pm 0.3\%$	0.95	> 7.7
$\Delta\varepsilon t/2 = \pm 0.6\%$	1.2	3.1

3.3 Air environment effect at 300°C

As shown in Table 3 at 20°C, the fatigue lives are a bit decreased in air compared to vacuum indicating a small air environment effect at ambient temperature. On the contrary, we can observe a deleterious air environment effect at 300°C with significantly lower fatigue lives in air than in vacuum, especially at the lowest strain amplitude.

The same fatigue behavior was previously observed in a type 316L austenitic stainless steel [3].
In this temperature range, such an air environment effect is attributed, for several metallic alloys (Ti, Al or Fe alloys), to the effect of water vapor as shown by Petit, Hénaff et al. [4-7] for example. In fact, a Rehbinder effect followed by Hydrogen – plasticity interactions are presumably responsible for an acceleration of both crack initiation and propagation phases as explained notably by Murakami et al. [8, 9]; McEvily and Velazquez [10] or Davidson and Lankford [11].

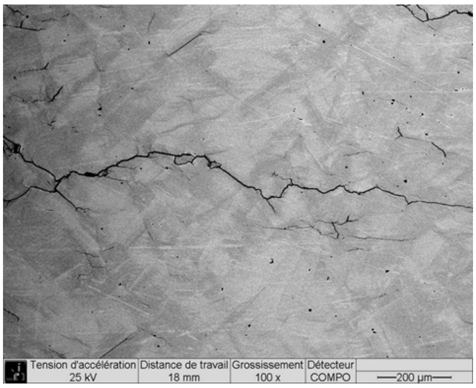
Table 3: Environmental effect depending on strain amplitude and temperature

Environmental effect: N_{Vacuum} / N_{Air}	20°C	300°C
$\Delta\varepsilon t/2 = \pm 0.3\%$	1.5	> 11,8
$\Delta\varepsilon t/2 = \pm 0.6\%$	1.25	3.3

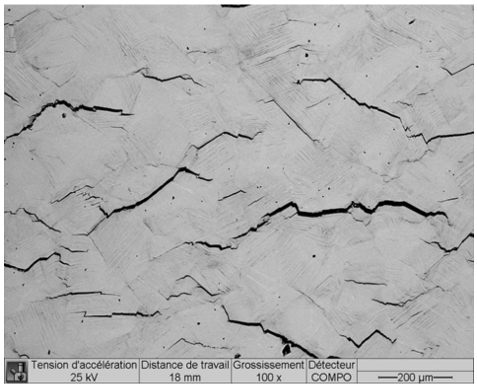
3.4 Damage analysis

Numerous SEM examinations of surface cracks were achieved depending on the tests conditions. From these observations, we can infer that whatever the environment, the cracks initiate in stage I mode II, mainly on slip bands but also on grain or twin boundaries. Moreover, the cracks propagate in stage II mode I with a slight dependence on the microstructure, especially in vacuum.

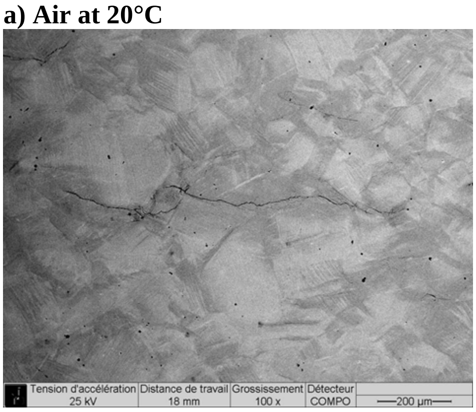
As shown in Figure 4, for tests conducted till failure, the crack density is lower in vacuum than in air environment. Moreover, the number of cracks is higher at 300°C than at 20°C independently of the environment, which is coherent with the observations previously made on a 316L-type austenitic stainless steel [3]. Thus, we can not say that the crack density is always a relevant parameter to predict the fatigue life. In fact, in spite of a crack density higher in vacuum at 300°C than in vacuum at 20°C, the fatigue life is increased by a factor of 3,1 and on the contrary, in spite of a crack density higher in air at 300°C than in vacuum at 300°C, the fatigue life is decreased by a factor of 3,3.



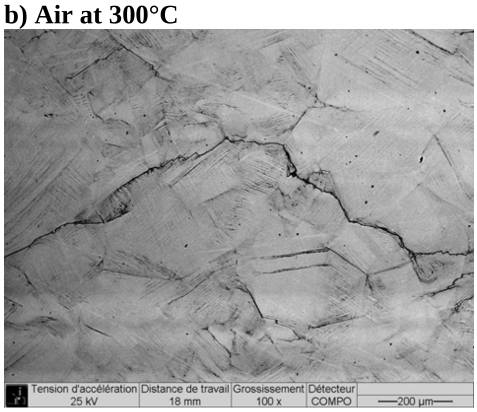
a) Air at 20°C



b) Air at 300°C



c) Vacuum at 20°C



d) Vacuum at 300°C

Figure 4: Surface cracks SEM examinations of failed specimens tested in air or in vacuum at 300°C, $\Delta\varepsilon t/2 = \pm 0.6\%$ and $d\varepsilon/dt = 4 \times 10^{-3} s^{-1}$; a) Air at 20°C; b) Air at 300°C; c) Vacuum at 20°C; d) Vacuum at 300°C

3.5 Strain rate effect at 300°C

As shown on Figure 5, whereas a positive strain rate dependence of stress response is observed at 20°C, a negative one appears at 300°C. In fact, at high temperature, the cyclic stress is increased when the strain rate is decreased for example, from 4×10^{-3} to 1×10^{-5} s^{-1}. This unusual behavior is explained by the occurrence of dynamic strain aging (DSA) which is a thermally activated and time-dependant phenomenon corresponding to the interactions between diffusing solute atoms and mobile dislocations during plastic deformation at elevated temperature. It depends on the deformation rate and temperature which respectively govern the velocities of mobile dislocations and diffusing solute atoms. For austenitic stainless steels, the temperature range is [200-800°C] and the strain rate range is $[10^{-2}\text{-}10^{-6} s^{-1}]$ as shown for example by Jenkins and Smith [12]; De Almeida and Monteiro [13] or Hong and Lee [14].

Moreover, at 300°C and whatever the strain amplitude, the LCF life decreases with the strain rate as shown in Figure 6. This strain rate effect on the CSR and fatigue life was also obtained with another 304L-type austenitic stainless steel plate, as shown in a previous paper [15]. This life reduction was explained in the works of Srinivasan et al. [16] or Hong et al. [17], by an enhancement of surface crack initiation and by an increase of the stress intensity factor at the crack tip accelerating crack growth.
In order to investigate the evolution of surface damage in terms of crack density and crack length with decreasing strain rates, fatigue tests conducted in air at 300°C, $d\varepsilon/dt = 4 \times 10^{-3}$, 1×10^{-4} or 1×10^{-5} s^{-1} and $\Delta\varepsilon t/2 = \pm 0.6\%$ were interrupted after 300 then 600 cycles. Cracks quantifications on the gage surfaces, performed by SEM examinations after each interruption, confirmed that DSA leads to an acceleration of crack initiation and growth with decreasing strain rates, as we have shown in a previous paper [15].

In addition, the role of DSA on stainless steel behavior during strain-controlled fatigue tests has been intensively studied by Mannan et al. [18] who showed that the plastic deformation is not uniformly distributed within the grain but heterogeneously localized in few intensive slip bands. This heterogeneity of plastic deformation is also considered to be responsible for the damage kinetics enhancement which leads to a reduction in fatigue life.
Thus, few TEM analyses, of the dislocation structures and deformation modes were achieved on specimens cycled 600 times in air at 300°C, $\Delta\varepsilon t/2 = \pm 0.6\%$ and $d\varepsilon/dt = 4 \times 10^{-3}$, 1×10^{-4} or 1×10^{-5} s^{-1} (work to be published elsewhere). In accordance with the CSR, we have observed an increased dislocation density at low strain rate and as expected for this kind of alloy, we have confirmed that the main deformation mode is dislocations glide.
However, other deformation modes were observed at low strain rate (1×10^{-4} or 1×10^{-5} s^{-1}) with a small amount of ε martensite at the intersections of micro-twins. Considering the literature, the formation of mechanical twins and ε martensite is unexpected, especially at high temperature and low strain rate. This indicate surely that the plastic deformation is hardly accommodated at low strain rate because of dislocations interactions occurred by DSA phenomenon, having certainly a deleterious impact on the fatigue damage resistance of this stainless steel.

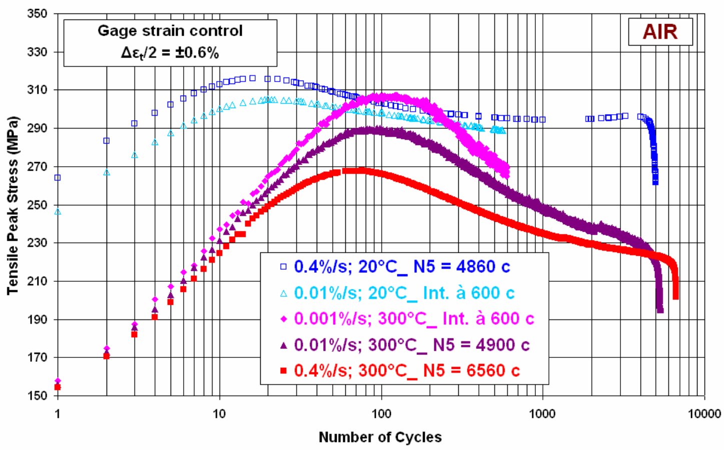


Figure 5: Negative strain rate dependence of stress response at 300°C

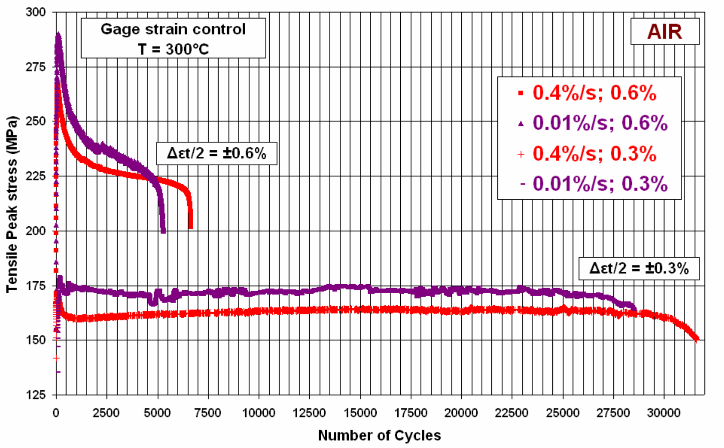


Figure 6: Fatigue life reduction in air at 300°C with decreasing strain rate at strain amplitudes of 0.3 or 0.6%

Nevertheless, most of tests found in literature with varying strain rates or temperatures were conducted in air. Those results therefore combine deformation and environment interactions which impede the evaluation of the intrinsic influence of strain rate on type 304L fatigue life.
Thus, few LCF tests were conducted in vacuum at 300°C, $\Delta\varepsilon t/2 = 0.6\%$ and $d\varepsilon/dt = 4 \times 10^{-3}$ or 1×10^{-4} s^{-1}. After 6000 cycles, these tests were interrupted and SEM examinations of the gage surfaces for cracks quantifications were performed.

As illustrated on Figure 7, the strain rate influence on CSR and fatigue life is of the same order in vacuum than those observed in air. Moreover, the cracks densities and lengths presented in our previous paper [15] underline that also in vacuum, with a highly limited environmental effect, reducing strain rate leads to an acceleration of cracks initiation and propagation.
This result is in accordance with the fact that changes in deformation modes could be at the origin of the observed damage acceleration at low strain rate.

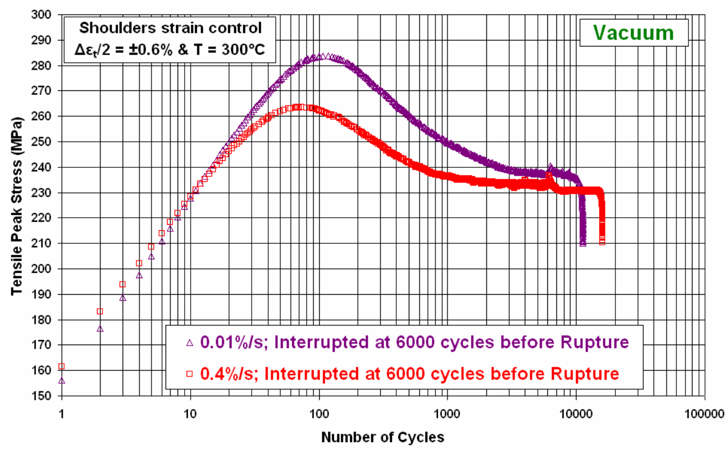


Figure 7: Tensile Peak Stress versus cycles for LCF tests conducted in vacuum at 300°C, $\Delta\varepsilon t/2$ = 0.6% and $d\varepsilon/dt$ = 4 x 10^{-3} or 1 x 10^{-4} s^{-1}; Interrupted at 6000 cycles and conducted to fracture

4 DISCUSSION

Firstly, we have shown at 300°C that the LCF lives are higher in vacuum than those in air indicating a deleterious air environment effect at this temperature. Then, in air and especially in vacuum, we have evidenced at 300°C that the LCF lives are decreased when the strain rate is decreased below 10^{-3} s^{-1} highlighting a detrimental intrinsic strain rate effect.

Consequently, we could expect an increased air environment effect at 300°C and low strain rate. However, as we can see on Figure 8 and Table 4, this is not the case and we rather observe a contradictory tendency. These results underline the complex competition existing between air environment effect and strain rate influence.

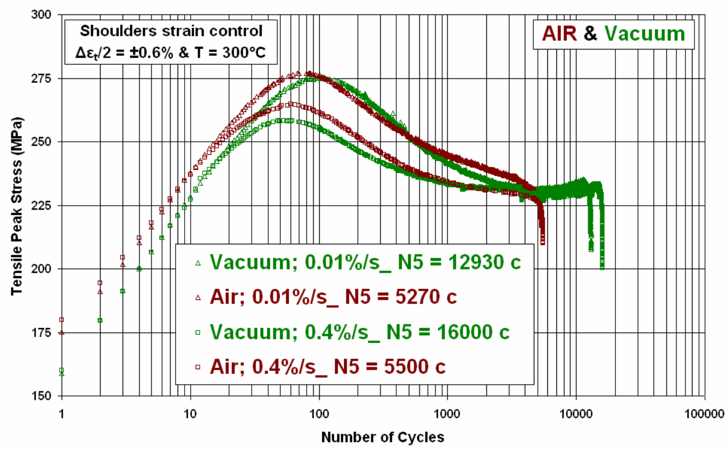


Figure 8: Tensile Peak Stress versus cycles for LCF tests conducted in air or in vacuum at 300°C, $\Delta\varepsilon t/2$ = 0.6% and $d\varepsilon/dt$ = 4 x 10^{-3} or 1 x 10^{-4} s^{-1}; Competition between air environment and strain rate effects

Table 4: Environmental effect depending on strain rate at 300°C

Environmental effect at 300°C: N_{Vacuum}/N_{Air}	
$d\varepsilon/dt$ = 4 x 10^{-3} s^{-1}	2.8
$d\varepsilon/dt$ = 1 x 10^{-4} s^{-1}	2,3

Finally, in order to illustrate the deleterious PWR water environment effect, we have reported in Figure 9, a comparison between the LCF lives obtained in vacuum, in air or in PWR water for tests conducted at T = 300°C, $d\varepsilon/dt$ = 0,4%/s and $\Delta\varepsilon_t/2$ = ±0.6%. Despite a similar CSR of the material in each environment in the common life duration, the LCF life in PWR water is decreased by a factor of 3 when compared to air and by a factor of 9 in comparison with vacuum. The LCF tests results obtained in PWR water and their analysis will also be published elsewhere.

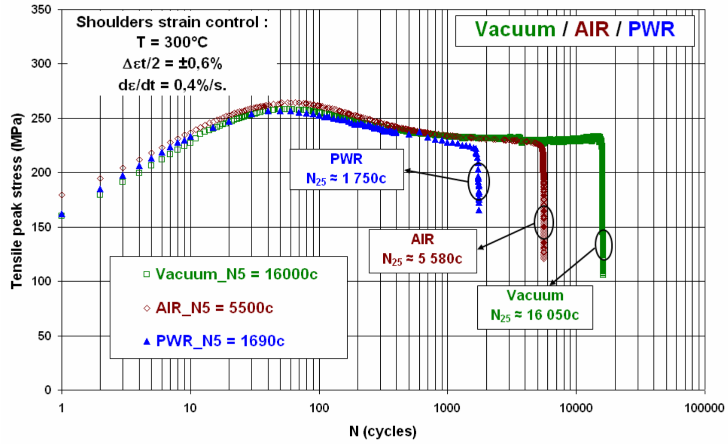


Figure 9: Tensile Peak Stress versus cycles for LCF tests conducted at T = 300°C, dε/dt = 0,4%/s and $\Delta\varepsilon_t/2$ = ±0.6%; Comparison between Vacuum, Air and PWR water

5 CONCLUSIONS

Whatever the environment, the CSR as well as the damage modes are very similar in the same life duration and differences are only visible on damage kinetics (higher number of surface cracks, faster crack initiation and growth).
In vacuum, a beneficial influence of the temperature of 300°C is observed on the LCF life notably at low strain amplitude.
However, this beneficial temperature influence is partially or totally hidden in air because of a strong deleterious environmental effect.
At 300°C and whatever the environment, a decrease in strain rate leads to a decrease in LCF life which seems to be mainly linked with deformation mode changes, accelerating crack initiation and crack propagation phases. Thus, by a relative comparison with vacuum test results, the air environment effect, already important at 300°C and high strain rates, is not increased by a reduction of the strain rate which increases the time exposure.
Considering all these complex interactions, a simple additive or multiplicative factor approach can not be used in air to take into account at the same time, the environmental and strain rate effects for example.

The first LCF test result obtained in PWR water coolant environment exhibits a larger decrease in fatigue life than the one obtained in air environment. To conclude, the analysis of the fatigue tests conducted in such an active environment would have to determine and consider the competitions or couplings existing between the environmental effect and other loading or deformation parameters effects.

6 ACKNOWLEDGEMENTS

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