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Characterization of damage during low cycle fatigue of a 304L austenitic stainless steel as a function of environment (air, PWR environment) and surface finish (polished, ground)

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Abstract

304L austenitic stainless steel is notably used to manufacture pipes in primary cooling circuits of nuclear power plants operating at a temperature close to 300°C in a specific aqueous environment. Customarily, pipes are roughly polished, however, after some interventions, a few zones might be ground. Start-ups, shutdowns and operating transients of the reactor produce Low Cycle Fatigue (LCF) loadings with different strain rates. These solicitations and the modified surface finish create specific conditions whose effects must be taken into account. In order to understand if there is a joint influence of the PWR environment and surface roughness on the successive stages of fatigue damage leading to failure, fatigue tests were conducted at 300°C under a total strain amplitude of \( \pm 0.6\% \). Two environments were used, laboratory air and simulated PWR primary aqueous environment. Two surface finishes were investigated, namely fine mechanical polishing and grinding (\(R_t\) of about 40 \(\mu\)m). The analysis of the damage process is based on data concerning crack density, crack length and striation spacing. The integration of the relation between the striation spacing and the strain intensity factor \(\Delta K_{\varepsilon}\), provides an estimation of crack propagation. It is confirmed that in PWR environment one striation can be considered as the crack advance during one fatigue cycle. Moreover, the specific crack front geometry observed in ground specimens and resulting from successive microcrack coalescences explains the reduction in fatigue life induced by grinding.

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1. Introduction

304L type austenitic stainless steels are used for manufacturing vessels and piping systems in Pressurized Water Reactors (PWR). In the primary coolant circuit of those reactors, the material is subjected to thermo-mechanical cycling caused by temperature gradients during start-ups, shutdowns or operating transients. For such conditions, computations as well as in-operation data acquisitions have evidenced the occurrence of high strain amplitude cycles at low strain rates, which indicates that low cycle fatigue could be one potential degradation process for PWR primary components. Now, it is known that cyclic stress response, damage modes and consequently fatigue life of austenitic stainless steels are highly dependent of key parameters such as temperature, strain amplitude, strain rate and environment. In particular, primary components are exposed to the PWR water, which is known to be an active environment having a strong impact on the austenitic stainless steel fatigue lifetime [1]. These effects of PWR water are commonly evaluated from a mean fatigue curve based on tests conducted in air at room temperature. However, as pointed out before, for a given strain amplitude, fatigue lifetime observed in PWR water results from the joint action of several parameters such as temperature, strain rate and environment. Thus, in order to evaluate the respective role of each parameter, an extensive study has been conducted in the last years by performing LCF tests at 300°C, in vacuum, in air and in PWR water on cylindrical fine-polished specimens. In particular fatigue lifetime, crack mechanisms and crack kinetics were investigated in each environment [2,3]. This study demonstrated that, at 300°C, compared to vacuum, air is already responsible for a large decrease in the fatigue resistance of 304L SS. This detrimental effect, previously observed in 316L SS, is particularly marked for low strain amplitudes [4]. The PWR water coolant environment appeared to be still more active than air at 300°C, especially by enhancing fatigue initiation and micro-propagation stages [3, 5, 6].

More recently, in addition to the factors considered before, it appeared that the effect of surface finish has also been taken into account in order to represent other conditions that could be encountered in primary cooling systems. Customarily, pipes are roughly polished, however, after some interventions, a few zones in the pipes might be ground. The combination of this surface finish with the thermo-mechanical conditions and the environment was therefore investigated. The approach used was the same as that previously applied for the polished samples. In order to understand the joint influence of PWR environment and surface roughness on the successive stages of fatigue damage leading to failure, namely crack initiation, micro-cracking then crack growth, fatigue tests were conducted in air, at 300°C, and in simulated primary PWR water.

2. Experimental conditions

2.1. Material and specimens

The material used in this study is a 304L austenitic stainless steel plate elaborated by Creusot Loire Industries (CLI). It was obtained by rolling and subjected to a solution-treatment at 1100°C before being water-quenched. Its chemical composition is (in weight %): C-0.029, Si-0.37, Mn-1.86, P-0.029, S-0.004, Ni-10.0, Cr-18.00, Mo-0.04, N-0.056 and Fe balance. The grain size is around 80 µm.

Fatigue specimens are machined with the loading axis parallel to the rolling direction of the plate. The gauge length is 13.5 mm and the diameter is 9 mm. Precise geometry and tensile mechanical properties were described elsewhere [2, 3, 7, 8]. Flanges are machined on specimen shoulders in order to support strain measurement system, which requires a calibration to link the elongation between flanges and the strain amplitude in the gauge length.

2.2. Surface finish

Samples were turned and then mirror polished or ground. In the first case, the surfaces of the specimens were mechanically polished down to 1 µm grade diamond paste. In the second case, grinding was performed to obtain a roughness characterized by an Rt factor around 40 µm (between 35 and 50 µm). Fig. 1.a shows an optical macro view of the ground surface. This surface is characterized by the presence of facets containing the grinding scratches oriented perpendicularly to the loading axis, which can be evidenced by confocal interferometry observations as on Fig. 1.b. SEM observations of ground surface reveal chips, material pull-out and scratches.
2.3. Test procedures

LCF tests in air are performed at 300°C with an electromechanical INSTRON 1362 machine. Tests in simulated PWR primary water environment are carried out using an MTS hydraulic machine equipped with an autoclave which enables to reach a pressure of 140 bars and a temperature of 300°C. The chemical composition of this simulated PWR water environment is described elsewhere [2, 3, 7, 8]. Tests were performed under total axial strain control using a triangular waveform with strain amplitude of ± 0.6% and strain rate of $1 \times 10^{-4}$ s$^{-1}$. Strain is controlled using two Linear Variable Differential Transformers (LVDT) measuring the displacement between flanges on specimen shoulders. The fatigue life, noted $N_f$, corresponds to the number of cycles necessary to observe a decrease of 5% from the quasi-stabilized cyclic stress response. Tests were conducted to failure or stopped at different fractions of the fatigue life in order to evaluate the importance of damage (crack density, crack depth, crack geometry). For this purpose, pre-cycled specimens at 300°C were then fatigued to failure at room temperature under High Cycle Fatigue (HCF) solicitations. Observation of the fracture surfaces provides data on the largest cracks as a function of the number of cycles.

3. Results

3.1. Cyclic behavior and fatigue life

As shown in Fig. 2 the cyclic stress response is not affected in this case by the surface finish or the environment. However, tests performed in simulated PWR water lead to a fatigue life shorter than in air. Moreover, the fatigue life of ground specimens is shorter than polished ones. The factor of reduction due to the grinding is similar in both environments.
3.2. Crack initiation and early growth

Previous studies performed on polished samples have shown that there is no marked difference in crack initiation mechanisms, during early stages, between PWR environment and air. Indeed, in both environments cracks rapidly initiate, in slip bands mainly, but also at twin interfaces or grain boundaries [3, 5]. The effect of the PWR water on fatigue damage and especially on crack initiation is mainly revealed by a surface crack density twice higher than in air (after 300 cycles, density_{PWR} \approx 7 \text{ mm}^2, \text{ density}_{\text{air}} \approx 3 \text{ mm}^2).

On ground specimens, the analysis of interrupted tests show that the location and the growth of fatigue cracks in early stages are controlled by the presence and the geometry of scratches. The surface damage after only 150 cycles in air (around 5 % of fatigue life) is already important, as shown in Fig. 3. SEM observations indicate that numerous cracks initiate very quickly at the root of the micronotch constituted by the grinding scratch. Their number is more or less important according to the area considered. Furthermore, the coalescence of such cracks leads to the formation of long surface cracks some of them occupying the entire length of the scratches. The full process is illustrated by the scheme proposed in Fig. 4. So, on a ground specimen, after only 150 cycles in air, a crack of 600 \mu m of surface length is already formed while, on a polished specimen, the longest surface crack length only reaches 300 \mu m after 300 cycles and 484 \mu m after 600 cycles [3].

![Fig. 3. SEM observations of surface damage after 150 cycles in air on a ground specimen. The red arrow indicates the solicitation axis.](image)

![Fig. 4. Schematic view of crack evolution in a grinding scratch.](image)

Fig. 5.a illustrates the fact that, for ground specimens the crack growth in depth is continuous, whereas the evolution of surface crack length is strongly influenced by grinding scratches favoring coalescence in the near surface layer and leading to a more discontinuous growth process. This evolution is clearly illustrated in Fig. 5.b with pictures of the fracture surfaces at different stages of the fatigue life. For the different conditions investigated here, cracks are always very elongated near the surface with a small value of the depth/surface length ratio.
On the other hand, Fig. 6 shows that, in polished samples, the crack front evolves towards a semi-circular shape from the initiation site even if, in later stages, coalescence between this kind of cracks can also be encountered. Similar features are observed on ground specimens tested in PWR water. Such differences in crack morphology between polished and ground samples are observed in both environments, air and PWR water.

Fig. 6. SEM observations of fracture surface. Polished specimen. Air.

3.3. Crack propagation law in air and in simulated PWR primary water environment

With test conditions considered here, the crack initiation stage is very short in both environments. Fatigue damage is quickly important, as previously detailed on polished and ground surface finishes tested in air. Therefore, the crack propagation stage corresponds to the major part of the fatigue life.

In both environments, the crack growth mode is essentially transgranular and deep striations, perpendicular to the crack growth direction, are observed on fracture surfaces as previously reported [1, 3, 5]. However, spacing between striations is greater and have a higher planar aspect in the specimen tested in simulated PWR water than that in air. In both cases striation spacing increases with crack depth showing a crack growth acceleration.
Moreover, several authors have shown, on polished samples, that in PWR water, the striation spacing can be considered as representative of the crack advance per cycle. Therefore, the measurement of the striation spacing gives a good evaluation of the crack growth rate evolution as a function of the crack size [3, 5, 6]. The increase of the striation spacing in this environment is consistent with the decrease in fatigue life.

The above results concerning differences in crack morphology would suggest that the decrease in fatigue lifetime observed on ground samples, in comparison to polished ones, could be explained by differences in the crack tip stress state caused by differences in the crack front geometry. Thus, the integration of a unique crack propagation law, specific to each environment and strain rate, and expressed as a function of a crack intensity factor, depending on the mechanical loading and crack geometry, should allow to evaluate the number of cycles to propagation.

Kamaya has shown that the strain intensity factor, $\Delta K_c = F(a).\Delta \varepsilon_t.\left(\pi.a\right)^{1/2}$, can be considered as the crack driving force for this material in the LCF conditions considered here [9]. The striation spacing versus the crack depth was measured on samples tested in PWR and in air. In order to estimate the $\Delta K_c$ value, the geometrical correction factor $F(a)$ is determined by considering the $a/b$ ratio, experimentally measured in both type of specimens, as a function of the crack depth $a$. $a$ and $b$ are the half value of, respectively, the minor and major axis of an elliptical surface crack. The value of the $F(a)$ function is then calculated using the Carpinteri equations for the each $a/b$ value under consideration [10].

No significant differences are observed in the evolution of $a/b$ ratio in both environments. The curves plotted in Fig. 7 were established on the basis of numerous measurements made on fracture surfaces of specimens submitted to different number of cycles. They illustrate substantial differences of $a/b$ ratio with regard to the surface finish. It follows that for a given value of the crack depth, $F(a)$ and thus $\Delta K_c$ are higher for a straight shaped crack than for a semicircular one. Fig. 8 shows that the striation spacing versus $\Delta K_c$ curves for polished and ground samples cycled in simulated PWR water, are very similar. The continuous red line has been drawn to take into account all of the results. It was decided to use two power laws to describe the entire relation between striation spacing evolution with $\Delta K_c$, as indicated in Fig. 8, in order to account for the behavior of short cracks (below 800 µm). Indeed, for these short cracks the crack growth rates exhibit a lower sensitivity to $\Delta K_c$ than the macro-cracks. It can be noted that, while these results are not included in this paper, this change in the power coefficient of the experimental crack propagation law is even more pronounced in the case of tests performed at lower strain rates [8, 11].

![Fig. 7. Mean evolution of $a/b$ ratio versus crack depth. Polished and ground specimens. Air or PWR water.](image_url)
Moreover, the integration of the above \( \frac{da}{dN} - \Delta K_e \) relations from an initial crack depth of 15 µm for polished samples and 40 µm for ground ones has been done. This calculation, leads to an estimation of the fatigue life in good agreement with experimental results (see Table 1). This confirms that the decrease in fatigue life produced by grinding is primarily due to the peculiar morphology of the fatigue cracks which initiate and coalesce rapidly from the root of the scratches leading to the formation of long surface cracks.

Therefore, the use of striation spacing evolution as a macroscopic fatigue crack growth rate is efficient to assess the fatigue life in simulated PWR environment. Moreover, to correctly perform this assessment depending on the specimen surface finish, the \( \Delta K_e \) mechanical parameter has to be used because of its ability to account for different crack front evolutions.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Fatigue life (cycles)</th>
<th>Calculated life (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polished</td>
<td>Ground</td>
</tr>
<tr>
<td>PWR env.</td>
<td>930</td>
<td>620</td>
</tr>
<tr>
<td>Air</td>
<td>5300</td>
<td>3200</td>
</tr>
</tbody>
</table>

It must be pointed out that the same measurement procedure can be applied to the fatigue striations observed in air experiments. However, in this case, the integration of the corresponding apparent \( \frac{da}{dN} - \Delta K_e \) curve does not lead to a fatigue life consistent with the experimental results. Table 1 reports the propagation cycles estimated by integrating the striation spacing evolution relation (for polished samples only). This number of cycles is much lower than the fatigue life, 3015 cycles compared to 5300 cycles. Such a difference cannot be explained by a long crack initiation period in air. Indeed, as reported above, after only 300 cycles on polished specimens cycled in air, fatigue damage is already important. That means that in air, each striation cannot be attributed to a single fatigue cycle. The use of the striation spacing evolution tends to over-estimate the crack growth rate. Other procedures to establish the \( \frac{da}{dN} - \Delta K_e \) curve in this environment are thus required.

4. Conclusions

LCF tests were conducted on a 304L stainless steel under a total axial strain of ± 0.6% and a strain rate of 1.10^{-4} s^{-1}. They were performed in air at 300°C or in simulated PWR primary water using specimens with two surface finishes, fine mechanical polishing and grinding.
It was shown that the cyclic behavior is similar for all testing and surface preparation conditions while fatigue life in PWR water is significantly shorter than in air. Similarly, grinding operation reduces the fatigue life of a same factor in both environments with respect to polishing.

A detailed analysis of damage indicates that crack initiation and first stages of growth occur very early in the life in both environments and more especially on ground specimens in which multicracking and coalescences very rapidly lead to the formation of long surface cracks at the root of micronotches constituted by the grinding scratches. Observations performed at different fractions of the fatigue life revealed the particular crack front geometry due to numerous successive crack coalescences that occur near the surface layer.

A fatigue crack growth law was established using a relation between the striation spacing versus the strain intensity factor $\Delta K_e$. The integration of this relation provides a fair evaluation of the fatigue life for polished and also for ground specimens cycled in PWR water. A similar approach cannot be developed for tests performed in air because the non-equivalence between one striation spacing and the crack advance produced during one cycle.

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References