Influence of surface finish in fatigue design of nuclear power plant components

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Abstract

The fatigue design of nuclear components is based on an S-N curve established in air at 20°C. To this curve, different penalty factors, representative of various effects (scale effect, material variability, surface finish, environmental effect, etc), are then applied. This method considers that these effects are independent from each other.

This paper is focused on the interactions between surface finish effects and environmental effects in the Low Cycle Fatigue (LCF) domain of an austenitic stainless steel type 304L. The aim of this work is to determine whether the effects of these two parameters are really independent or coupled. To better understand the environmental influence, high vacuum is used as reference. Tests were realized with a triangular waveform signal at a total strain amplitude of ±0.6% in different environments: vacuum, air and simulated Pressurized Water Reactor (PWR) water, at 300°C. Two surface finishes were considered: ground and polished.

Experimental results obtained on ground samples are here compared with results obtained on polished samples in a previous study. It appears that, while the cyclic stress response of the material is not affected by the surface finish, a ground surface finish decreases the fatigue life. Moreover, this surface finish effect seems to be less pronounced when the environmental effect is important, which indicates the presence of a coupling between surface finish influence and environmental effects.

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1. Introduction

The 304L austenitic stainless steel is notably used to manufacture pipes in primary circuit of nuclear power plants. Start-ups, shutdowns and operating transients of the reactor cause temperature gradients and the components are subjected to thermo-mechanical solicitations. These Low Cycle Fatigue (LCF) loadings are furthermore applied in presence of the Pressurized Water Reactor (PWR) environment. This exposure is expected to cause a degradation of the fatigue resistance of the components.

The fatigue design of nuclear components is established on the basis of a mean curve derived from uniaxial strain controlled fatigue tests completed at $R_e = -1$ in air at room temperature on polished specimens. Additional effects like environmental influence, size effect or material variability are then taken into account.

To obtain the design curve in air, the mean curve is divided by a factor of 2 on the strain amplitude and a factor of 12 on the number of cycles to failure, then the most conservative result is selected [1], cf Figure 1 (a). The factor of 12 is divided in four safety factors, $A \times B \times C \times D$, as shown in Figure 1 (b), which represent, the effects of material variability, specimen size, surface finish and loading history, respectively. This method considers that each factor is independent from each other, that is to say that no coupling takes place between the various processes.

In addition, in order to account for environmental effects, the Fen penalty factor is defined as follows [1]:

$$Fen = \frac{N_{300^\circ C}^{\text{air}}}{N_{300^\circ C}^{\text{PWR}}} \times \exp(0.734 - O^* \times T^* \times \varepsilon^*) \tag{1}$$

The Fen is a function of the temperature $T^*$, strain rate $\varepsilon^*$ and dissolved oxygen content $O^*$.

Previous studies undertaken to estimate the influence of each individual effect and to improve the understanding of the mechanisms behind each safety factor, have analyzed the influence of environment on the low cycle fatigue behaviour of the 304L austenitic stainless steel, and more particularly the influence of the PWR water environment on damage and cracking processes on polished samples [2-4]. Furthermore, Areva has initiated studies on the fatigue life of ground surface finish specimens in PWR environment [5-7].

In this framework, this paper is focused on the influence of a ground surface finish on the fatigue life of the 304L austenitic stainless steel in different environments. In particular, the aim of this study is to determine whether these two effects are really independent one from each other or they are coupled, and if need be, to evaluate the degree of coupling.
In the sake of improving the understanding of these mechanisms by isolating the individual effects, a high vacuum environment, considered as non-active environment, is used to determine the intrinsic influence of grinding on fatigue resistance in the absence of environmental effects. Afterwards, the influence of surface finish is analysed in several environmental conditions (Air and PWR environment).

2. Experiments

2.1. Material

The 304L austenitic stainless steel used in this study was elaborated by Creusot Loire Industrie (CLI) by rolling. Its chemical composition is presented in Table 1. The plate was subjected to a solution-treatment at 1100 °C before a water-quench. The same material was used in various previous studies [2, 8, 9].

Table 1. Chemical composition of 304L stainless steel (CLI).

| Elements | C   | Mn  | Si  | S   | P   | Ni  | Cr   | Mo  | N   | Fe  |
|----------|-----|-----|-----|-----|-----|-----|------|-----|-----|-----|
| Composition (wt %) | 0.029 | 1.86 | 0.37 | 0.004 | 0.029 | 10.00 | 18.00 | 0.04 | 0.056 | Balance |

2.2. Sample preparation

Samples are turned to obtain the geometry presented in Figure 2 (a). Then, they are either mechanically polished with emery papers up to #4000 and afterwards with diamond paste 3 and 1 μm, or they are ground to obtain a roughness characterised by Rt factor around 40 μm. The two surface finishes are illustrated in Figure 2 (b).

![Figure 2 (a). LCF sample ; (b) Polished and ground surface finish.](image)

2.3. Test equipments

In PWR water, tests were performed with a MTS hydraulic machine equipped with an autoclave, which enables to reach a pressure of 140 bars and a temperature of 300°C. Fatigue tests in air and secondary vacuum (around \(10^{-3}\) Pa) were performed using two electromechanical INSTRON 1362 machines. Tests were conducted at 300°C under fully reversed total axial strain control using a triangular waveform at strain amplitude of ±0.6 % and a strain rate of \(1 \times 10^{-4}\) s\(^{-1}\). Strain was controlled using two Linear Variable Differential Transformers (LVDT) measuring the displacement between flanges as it was done in previous work [2]. This strain control has necessitated a correlation between the strain amplitude on the specimen gauge length and the displacement between sample shoulders.
3. Results

3.1. Intrinsic influence of ground surface finish

The intrinsic fatigue behaviour of type 304L austenitic stainless steel at 300°C determined in vacuum on polished and ground surface finishes is presented in Figure 3 (a).

The cyclic stress response (CSR) is composed of four stages: an initial hardening stage, followed by a softening, a stabilization and finally a secondary hardening. This last stage was firstly observed at 300°C and low strain amplitudes in a type 316L austenitic stainless steel by Gerland and al. [10]. In these conditions, the secondary hardening is attributed to the formation of the corduroy type dislocation structure which appears in temperature when planar slip mode is predominant and the cumulated cyclic plastic strain becomes significantly high. In 304L at high strain amplitudes, the secondary hardening could be related to deformation-induced martensite transformation.

Figure 3. (a) Max stress versus cycles for LCF tests in vacuum at 300°C at 1.10^8 s^{-1} ; (b) Cyclic behaviour at 10th cycle, comparison of ground and polished surface finish

The CSR, presented in Figure 3 (a) and Figure 3 (b), is very similar for polished and ground surface finish at the same number of applied cycles. The ground surface finish decreases the fatigue life by a factor of about two. In fact, the crack growth kinetics are enhanced in this case, especially in the crack initiation and early growth stages.

Figure 4. SEM examination on broken specimens (vacuum, 300°C, ±0.6% and 1.10^{-4} s^{-1}): (a) Polished surface finish ; (b) Ground surface finish
SEM examinations show, as exemplified in Figure 4, that grounding scratches favor cracks initiation and propagation along the scratches. Complementary examinations on ground samples are in progress to get further insights in the crack initiation process and the development of the crack front during early stages of propagation.

3.2. Influence of ground surface finish in different environments

We can notice in Figure 5. (a) and Figure 5. (b) that the CSR is not influenced by the surface finish, regardless of the environment.

A decrease of the fatigue life is observed from vacuum to air environment, and a still larger decrease from vacuum to PWR environment. These results can be explained by the increase of the damage rates when the environment becomes more active. This tendency is observed both for polished and ground surface finish.

Concerning the grinding influence, the fatigue life reduction is of the same order of magnitude in all the environments.

4. Discussion

The results presented here have shown the intrinsic influence of surface finish, Figure 3, the environmental effects, Figure 4 (a), and the combination of these two effects, Figure 4 (b). In this section we will discuss about the possible existence of a coupling effect between surface integrity and environmental effects.

The comparison of fatigue lives in vacuum and PWR environment shown in Table 2 reveals interactions between the environmental and surface finish effects. On one hand, the influence of the PWR water environment appears to be more pronounced on polished specimens (fourth column). On the other hand, the influence of the ground surface finish is more marked in vacuum than in PWR environment (last line). Indeed the joint influence of ground surface finish and PWR environment is lower than the combination of the two separate effects.

Table 2. Fatigue lives and allowance factors for different conditions

| Fatigue life : $N_{25}$ | Vacuum | PWR environment | $N_{\text{Vacuum}} / N_{\text{PWR}}$ |
|------------------------|--------|-----------------|-----------------------------------|
| Polished               | 13100  | 975             | 13.4                              |
| Ground                 | 6250   | 600             | 10.4                              |
| $N_{\text{Polished}} / N_{\text{Ground}}$ | 2.1    | 1.6             |
Otherwise, the NUREG CR-6909 [1] defined a safety factor to account for the surface finish effect with a value of 2 to 3.5. This value does not depend on the considered environment.

![Graph showing fatigue life for polished and ground surface finish in Vacuum and PWR environment.](image)

Figure 6: Fatigue life for polished and ground surface finish in Vacuum and PWR environment at ± 0.6 % and 0.01 %/s

Figure 6 shows the fatigue lives obtained with polished and ground surface finish in Vacuum and PWR environment. The polished fatigue lives reduced by a factor of 2 and of 3.5 are also indicated for both environments by dashed lines. It can be seen that a reduction of 3.5 of polished fatigue life is somehow conservative in both environments. From polished to ground surface finish, the fatigue life reduction is approximately 2 in Vacuum and lower than 2 in PWR environment. The impact of a ground surface finish is reduced in the presence of PWR water environment. Complementary studies are in progress in order to confirm these results in particular at other amplitude levels or for other strain rates.

5. Conclusion

In the present study, it has been shown that while the CSR is not affected by the surface finish, ground surface finish increases the damage and leads to a non-negligible fatigue life reduction.

Environmental effects cause a reduction in the fatigue life without changing the CSR.

The fatigue design of nuclear components takes into account surface finish and environmental effects with different factors. First experimental results show the presence of a coupling between surface finish influence and environmental effects. The fatigue lives reductions observed in this study are lower than the product: 

environmental effects x surface finish effect

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