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Tensile and low-cycle fatigue properties of solution annealed type 316L stainless steel plate and TIG-weld exposed to 5 dpa at low-temperature (42°C)

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Abstract

The austenitic stainless steel type AISI 316L was selected as the main structural material of the next-step International thermonuclear experimental reactor (ITER) fusion device, i.e., the first wall, blanket modules, and vacuum vessel components. Although this steel was extensively investigated under different aspects, most results concern irradiation temperatures above 300°C. In the present work, tensile and fatigue specimens were irradiated in the BR2 materials testing reactor at 42°C up to a maximum neutron fluence of 8×10^{21} n/cm^2 ($E > 0.1$ MeV), corresponding to 5 dpa. The European reference AISI 316L in the solution annealed condition and the TIG-metal deposit were tested in the baseline and irradiated conditions. The tensile specimens were tested at 25°C, 250°C and 450°C, while the low-cycle fatigue tests were performed at room temperature. The tensile test results obtained in this work are consistent with published data: substantial radiation hardening combined with some reduction of elongation. No specimen orientation effect could be evidenced. The amount of hardening decreases with increasing test temperature. By contrast, the low-cycle fatigue data show no or little effect of irradiation, independent from irradiation and testing conditions. No major difference was found between the plate and the weld metal.

1. Introduction

316L austenitic stainless steel in the solution annealed condition has been selected as a structural material for the first wall and blanket structures of the International thermonuclear experimental reactor (ITER). The first wall and divertor components will be exposed to a high 14 MeV neutron flux in the range 1–3 MWy/m^2 (corresponding to 10–30 dpa) in the temperature range 100–400°C [1]. These structural components will be subjected to thermo-mechanical cyclic loading as a result of cyclic strains produced during burn and off-burn periods of the plasma. Therefore, evaluation of the low-cycle fatigue properties is a very important issue as it can be the limiting lifetime parameter.

The 316L austenitic stainless steel has been extensively investigated within the fusion community. However, most of the published data are in the range 300–650°C [2–10]. By contrast, little is known of the LCF properties of this steel in the low-temperature range, in particular after irradiation.

Chung et al. [11] reported some data on the EC 316L steel in the unirradiated condition over the range 20–200°C. They found that for a total strain range $\varepsilon < 1\%$, the fatigue life is temperature independent. However, for total strain ranges above 1%, the fatigue life tends to decrease in the neighborhood of 50°C. Above this temperature, the fatigue life again becomes temperature independent. The authors [11] suggested that this is probably due to the temperature sensitivity of the mobility of interstitial carbon atoms in the crystal.

Josefsson and Bergenlid [12] have published data on the tensile and low-cycle fatigue properties of 316L plate and TIG-metal deposit weld material tested at 75°C, 250°C and 450°C, irradiated at 35°C up to 0.3 dpa to simulate the start-up of the ITER reactor life. The

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Table 1
Chemical composition of NET reference plate 316L and automatic TIG-metal deposit (wt%)

	C	Ni	Cr	Mn	Cu	Mo	Si	Co	S	P	Ta	N	B
Plate	0.019	12.2	17.2	1.75	0.07	2.3	0.35	0.08	0.0007	0.0195	0.002	0.074	0.0009
Weld[a]	0.045	9	17	2.5	0.1	2.5	0.5	0.25	0.02	0.025	–	–	–

[a] Nominal composition.

tensile properties have shown that irradiation to 0.3 dpa causes considerable material hardening.

The present work was initiated in order to provide supplementary data on tensile and low-cycle fatigue after neutron irradiation near room temperature. Tensile as well as fatigue specimens of EC 316L austenitic stainless steel (plate and TIG-metal deposit weld) were irradiated in the BR2 materials testing reactor at 42°C to a maximum neutron exposure of about 5 dpa. Tensile specimens were tested at 25°C, 250°C and 450°C, while fatigue tests were performed at room temperature. Although the above mentioned irradiation conditions are not fully representative of fusion reactors, it is interesting to know how the fatigue properties will be affected by neutron exposure at low-temperature.

2. Materials and irradiation conditions

Two materials were investigated here, plate and weld. The plate material was the CEC reference AISI 316L-167 SPH stainless steel, heat 12879. It was solution annealed at 1100°C for 30 min, followed by a water quench. The chemical composition of the 316L performed by Creusot–Loire [13] is given in Table 1.

The metal deposit blocks NET 805-19 and NET 805-21 were produced at the Danish Welding Institute with an automatic TIG-welding machine and provided to SCK-CEN for testing. The nominal chemical composition of the metal deposit is given in Table 1.

Fatigue and tensile specimens (plate and weld) were neutron irradiated in the BR2 reactor (SCK-CEN) in the rigs LOTION 1 and 2, respectively. The specimens were cooled by the BR2 primary water ($\sim$ 42°C). The accumulated maximum neutron exposure is 5.4 dpa, which corresponds to a maximum fluence of 8×10^{21} n/cm^2 ($E > 0.1$ MeV) for the fatigue specimens and 5.2 dpa (7.7×10^{21} n/cm^2, $E > 0.1$ MeV) for the tensile specimens. Helium production was estimated to be 88.6 and 82.5 at. ppm, respectively.

3. Experimental

3.1. Tensile tests

Details on the tensile tests are given elsewhere [14,15].

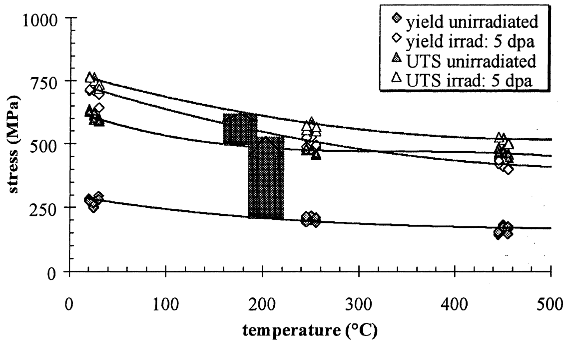

Fig. 1. Irradiation effects on the yield strength and UTS of the CEC reference AISI 316L plate material.

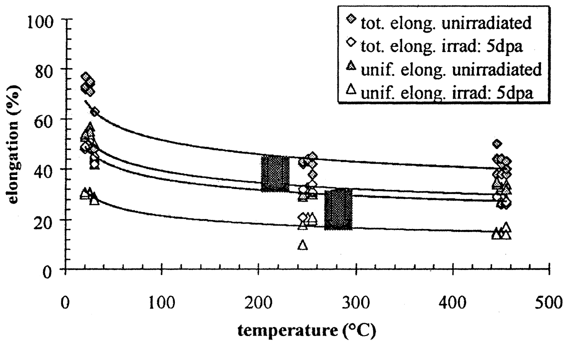

Fig. 2. Effect of irradiation on the uniform and total elongations of the 316L plate material.

3.1.1. Plate material

Analysis of the tensile properties has shown that, within the experimental scatter [1], there is no major difference between the three orientations. Therefore, similar symbols are used in Figs. 1 and 2 for the three orientations. In Fig. 1, the yield strength and ultimate tensile strength (UTS) in both unirradiated and irradiated conditions are compared. After irradiation, a drastic increase of the yield strength is observed associated with a significant decrease of strain hardening

[1] Note that if any effect exists, it should be consistently observed on the various parameters at the three test temperatures.

capacity. The elongation is also affected by irradiation. Fig. 2 shows the uniform and total elongation as a function of test temperature. As for stresses, no major difference in elongation was found between the three orientations.

3.1.2. TIG-weld

As before, no specimen orientation effect was found. Therefore, no symbol distinction is made in Fig. 3, which shows the yield strength and UTS as a function of test temperature. The increase of the yield strength is modest in comparison to the plate material. However, in the baseline condition, the weld material exhibits higher stresses than the plate.

3.1.3. Discussion

As other laboratories also investigated this plate, it is interesting to compare the tensile properties obtained in this work with those found in the literature [7,12,13,16–18]. Fig. 4 compares the data in terms of yield and ultimate stresses as a function of test temperature. A very good agreement between the various data is found. Similar consistency is found on the TIG-weld material in

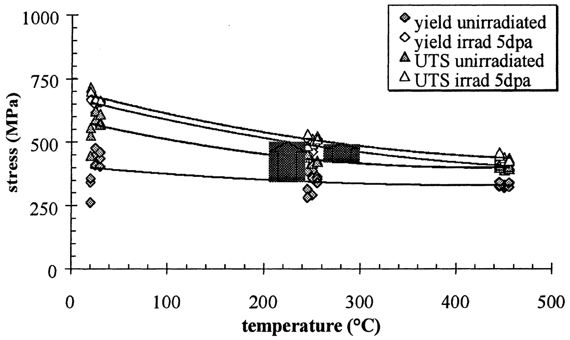

Fig. 3. Yield strength and UTS of the TIG weld material in the baseline and irradiated conditions.

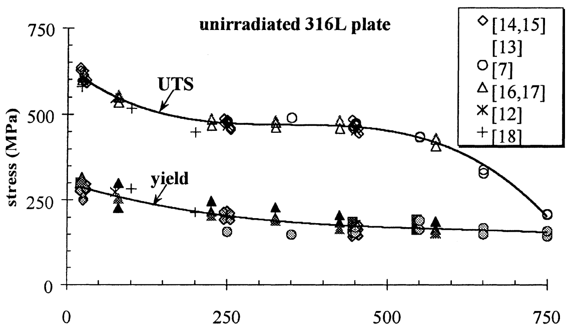

Fig. 4. Comparison of tensile strength properties of the AISI 316L plate material in the baseline condition.

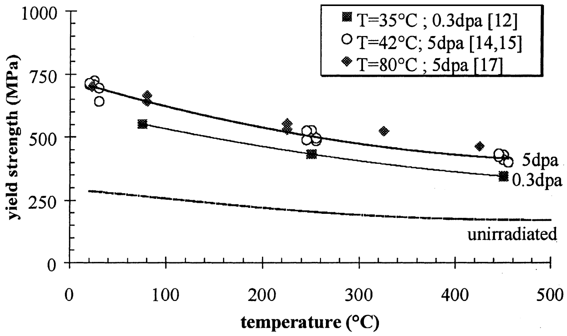

Fig. 5. Yield strength of AISI 316L plate material irradiated at $T < 100°C$

comparison with the STUDSVIK data [12] in the test temperature range up to 450°C.

In the irradiated condition, Fig. 5 compares our results with the few data found in the literature. Of course, much more data were published, but the conditions of irradiation were very different. At 5 dpa, there is a good agreement between our data and ECN data [17]. Note that the most of the hardening occurs at a very low neutron dose level, as found by other investigators [19–22].

The increase in yield strength induced by irradiation decreases with increasing test temperature. A similar trend was reported by Wiffen and Maziasz [22]. Although irradiated in identical conditions, the increase in yield strength is higher in the plate than in the weld. This can be associated with the strain hardening capacity of the materials. Indeed, if the yield strength increase is plotted as a function of the difference between the UTS and the yield strength in the baseline condition, the strengthening is found to correlate very well with the initial strain hardening capacity. In other words, the yield strength increase is limited by the initial work hardening capacity of the material. This is also observed with cold-worked stainless steels for which the yield increase becomes almost negligible for high cold-working levels [5,22]. This is also consistent with the saturation of yield strength [19]. Note that an appropriate parameter reflecting the irradiation damage would be the strain hardening capacity but expressed in terms of stress rather than uniform elongation.

As shown in Fig. 5, the yield strength is significantly increased at very low neutron dose levels. It is known that the yield strength after irradiation saturates with increasing fluence at a value independent of the initial condition of the alloy [19]. In Fig. 6, tensile test data at low-irradiation and test temperature (25–80°C) show clearly the decreasing hardening with neutron exposure. It also clearly shows the loss of hardening capacity with increasing neutron dose. This is also reflected by the TIG-metal deposit, which shows less hardening than the

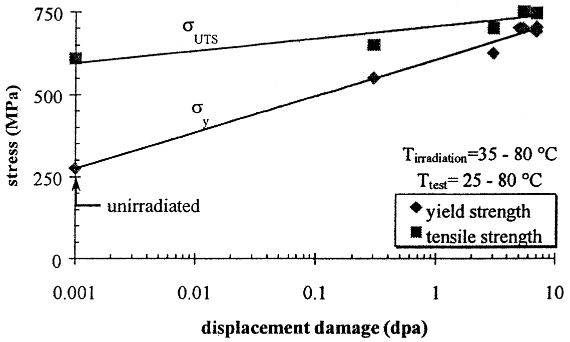

Fig. 6. Hardening saturation. Some of the data are taken from the literature [12,18,21].

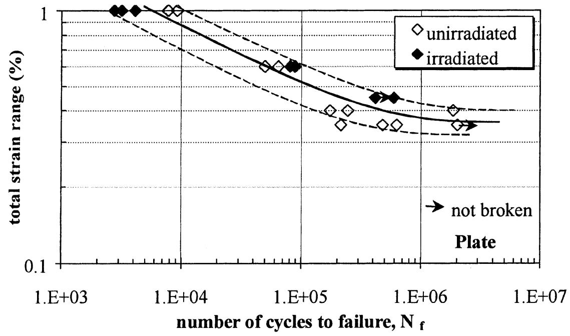

Fig. 7. Low-cycle fatigue behavior of the 316L plate material.

plate, the yield strength values before irradiation being higher for the weld. This suggests that the yield increase (irradiation hardening) is proportional to the difference between the tensile and yield strength (work hardening).

3.2. Low-cycle fatigue tests

Since tensile properties did not show any major influence of specimen orientation, only the T orientation was selected for the plate material for fatigue testing. For the TIG-weld, specimens available in the two orientations L and T were tested.

The fatigue test specimen was cylindrical with a cross-section of 3 mm diameter and 7.5 mm gauge length.

Testing was conducted in total axial strain control by a means of an axial extensometer. Specimens were alternatively loaded in tension and compression using a rigid load line. A sinusoidal strain waveform was applied, starting in tension. The tension/compression loading line was carefully aligned to avoid any bending. Before testing, each specimen was loaded/unloaded twice in the elastic domain in order to check the strain measurement.

The following testing procedures were used:

- For the unirradiated samples, a constant frequency of 0.5 Hz was applied for $N < 40\,000$ and 2.5 Hz above.
- For the irradiated samples, the frequency was successively increased with the number of cycles: 1.5 Hz up to 1000 cycles, 2.5 Hz up to 10^4 cycles, 5 Hz up to 10^5 cycles and 10 Hz above.

The stress vs total strain hysteresis loops were recorded in logarithmic increments of fatigue life, i.e., 1 to 10, 100, 1000, 10 000 and 100 000th cycle. The minimum and maximum load reached during cycling as a function of time was continuously recorded. Throughout the tests, the R-ratio ($\sigma_{\min}/\sigma_{\max}$) was taken equal to −1 (mean strain = 0). Where possible, the tests were conducted until failure occured. Details on the test results can be found in the SCK-CEN report [15]. Here, only a summary of the test results will be given.

3.2.1. Plate material

The LCF test results on unirradiated and irradiated plate materials are reported elsewhere [15]. Three diagrams of the LCF tests have been extracted: the strain range vs number of cycles to rupture ($\Delta\varepsilon$–N_f) diagram, the stress range vs number of cycles (σ–N) for different strain ranges and the stress range vs strain range (σ–ε) at two different stages of fatigue life ($N = 1$ and $N = 1000$).

Fig. 7 shows the LCF curve ($\Delta\varepsilon$–N_f) of the unirradiated and irradiated samples. At 1% strain range, a decrease of the fatigue life is observed (by a factor of 2–3) but the reverse occurs for lower strain ranges. However, within the experimental and statistical uncertainties, there is no or little effect of irradiation on the low-cycle fatigue life.

3.2.2. TIG-weld

The fatigue test results on the unirradiated and irradiated TIG-weld materials are reported in [15]. Similar to the plate, Fig. 8 shows that no statistically significant effect of irradiation can be discerned. The scatter, indicated with dashed lines, seems slightly larger than the

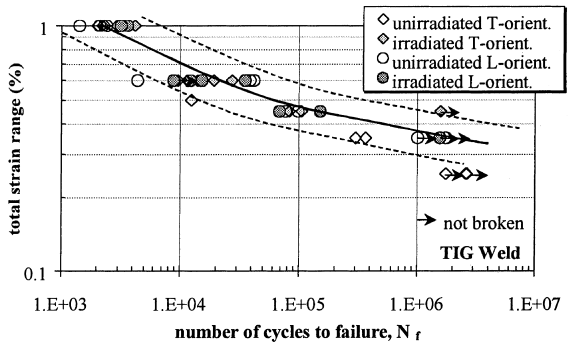

Fig. 8. Low-cycle fatigue behavior of the TIG metal deposit.

plate material. Consistent with the tensile data, no orientation effect could be detected.

3.3. Discussion

Other investigators reported little or no effect of irradiation on LCF properties. However, the number of specimens is usually very limited. Therefore, it is interesting to combine the experimental data presented here to those found in the literature. First, in the unirradiated condition, a large number of experimental data on LCF of type 316L steel were found, but at various test temperatures, ranging from 75°C to 550°C. These are shown in Fig. 9, where one additional data set on type 316 steel tested at 625°C is added [23]. It is obvious that test temperature plays a very small role on the LCF properties. However, one can distinguish two trend curves corresponding to temperature ranges of 25–430°C and 450–625°C. Another curve (Langer equation) proposed by Tavassoli [24] is also shown. The overall agreement between the various data is very good. Note however that, for strain ranges >1%, there might be a more significant temperature effect, as reported by Chung et al. [11].

There are limited data on irradiated materials. This is complicated by the additional important parameters that should be taken into account, i.e., irradiation temperature, neutron flux and fluence. Therefore, in most cases, the available data for specific test temperature and irradiation conditions are not statistically representative. However, by gathering the available data in one single (ε–N) diagram, it is very hard to clearly distinguish between the various data sets in terms of test temperature, irradiation temperature or neutron dose (Fig. 10). Therefore, irradiation has little or no effect on the fatigue life of the 316L plate.

The test results obtained here contrast with the effects of irradiation on the tensile properties. Indeed, the flow properties of the materials were drastically affected by

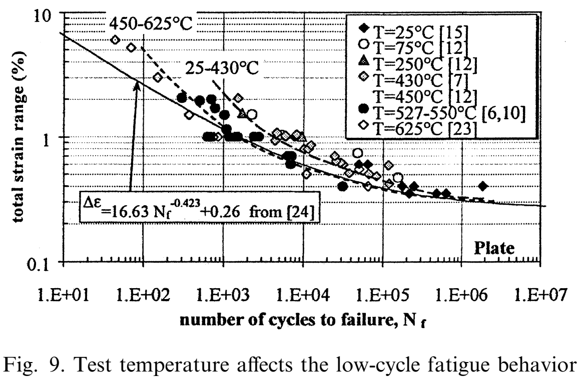

Fig. 9. Test temperature affects the low-cycle fatigue behavior of the plate material (unbroken specimens are removed for clarity).

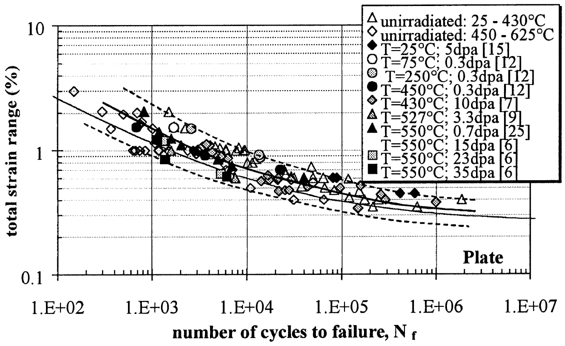

Fig. 10. Irradiation effects on the low-cycle fatigue behavior of the 316L plate material (unbroken specimens are removed for clarity).

irradiation. As a consequence, it was expected that this would be reflected on the low-cycle fatigue properties as well. However, throughout a literature review, it was found that low-cycle fatigue properties are little if any affected by irradiation. The only published data showing some effect are those of Grossbeck and Liu [3], Tanaka et al. [5] and Vandermeulen et al. [4]. In all these cases, the irradiation and testing temperature is 430°C. On the other hand, no effect was found at 550°C for dose levels of 0–15 dpa [2,9,10,23,25]. However, the effect on the LCF life reported by Grossbeck and Liu [2] and Takana et al. [5] remains small. Note that the range of dose levels that was covered by the comparisons performed here is quite large, 0.3–35 dpa. As irradiation does not significantly affects the LCF behavior of 316L material, it is not surprising that test temperature would also not play a role. It should be mentioned, however, that the environmental conditions of testing could affect the LCF behavior. Indeed, as shown by Wood [23], testing in air reduces by a factor of about 5 the LCF life of 316 steel in comparison to inert gas environment.

Comparison to data on 316L TIG-weld material found in the literature are reproduced in Fig. 11 which clearly indicate a very good agreement despite the various irradiation and testing conditions. This is also consistent with the comparison made on the plate material. A very good agreement is found with the Langer equation curve proposed by Tavassoli [24] except at high-strain ranges, where the experimental data are scarce.

At this stage, it is interesting to compare the unirradiated to the irradiated condition by considering the stress–strain behavior. In the unirradiated condition, the stress increases slowly during the first 20–30 cycles followed by a gradual decrease until fracture occurs. In the irradiated condition, up to a strain range of 0.45%, the stress does not vary much. At higher-strain ranges (>0.5%), the stress decreases continuously. The (σ–ε) diagram shows that, before irradiation, the evolution of the stress in the material is nearly the same at all strain

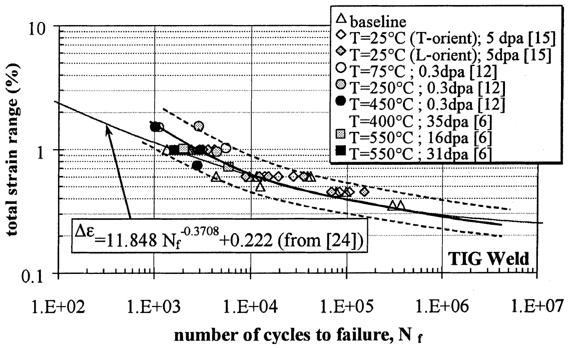

Fig. 11. Comparison of low-cycle fatigue data of TIG metal deposit with literature. Good agreement is found despite the various irradiation and testing conditions (nominal composition).

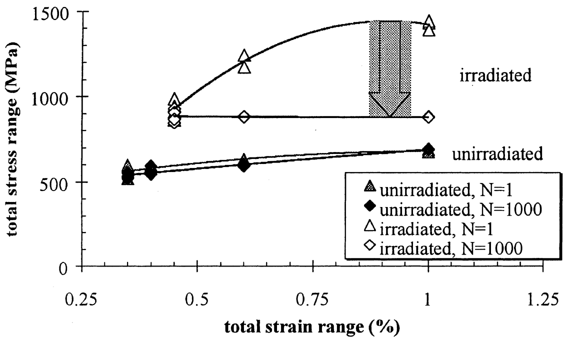

Fig. 13. Effect of irradiation on the total stress range $\Delta\sigma$ (MPa) vs total strain range $\Delta\varepsilon$ (%) at $N = 1$ and $N = 1000$.

ranges. On the other hand, in the irradiated condition, the fatigue process tends to recover the hardening induced by irradiation resulting in a softening of the material. Fig. 12 shows the evolution of the stress–strain loop of irradiated TIG-weld sample under an applied strain of 1% with the number of cycles. In Fig. 13, the (σ, ε) curve evolution is shown for two different stages of fatigue life, $N = 1$ and 1000, respectively. It can be seen that the higher the applied strain range, the larger the softening of the irradiated plate material. Similar behavior is found with the TIG-weld material.

Finally, as the unirradiated and irradiated materials exhibit very different flow properties, it is interesting to examine how the applied total strain is distributed in terms of elastic vs plastic strain. Most of comparative illustrations on the irradiation effects on the LCF properties are based on the total applied strain. Fig. 14 shows the plastic component of the strain as a function of the number of cycles to rupture for both unirradiated and irradiated plate material. While all unirradiated samples were loaded in the plastic regime, only irradiated samples loaded to 1% total strain exhibit measurable plastic deformation. However, it is difficult to extract the irradiation effect alone from such an analysis as far as the effect of cyclic plastic strain on crack initiation and the effect of irradiation crack growth rate are unknown [7].

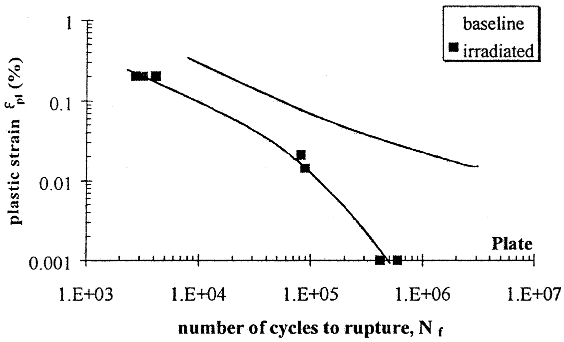

Fig. 14. Plastic strain vs number of cycles to rupture for the 316L plate material.

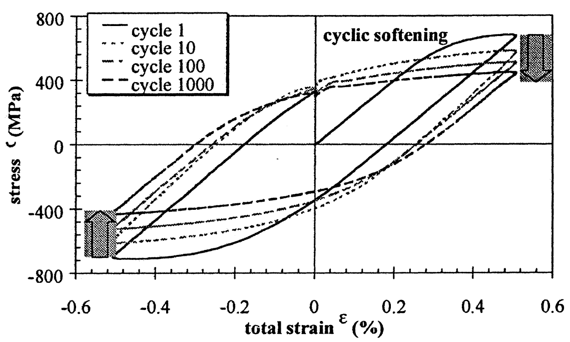

Fig. 12. Evolution of the hysteresis loop during the fatigue test under strain control. Irradiated specimen tested with a strain range of 1% exhibiting cyclic softening.

4. Conclusions

Tensile and low-cycle fatigue properties of type 316L austenitic stainless steel (plate and TIG-weld) were investigated in the baseline and irradiated condition (dose = 5 dpa, $T_{\mathrm{irradiation}} = 42°C$). The main results obtained are:

- No major difference was found in the flow properties in the three orientations, *L*, *S* and *T*.
- The tensile test data were in very good agreement with the literature data on similar plate and weld materials.
- Neutron irradiation induces a substantial hardening and loss of ductility but without reduction of fatigue life of both plate and weld materials.

- Comparison to literature data on similar materials shows that the effect of test temperature on LCF is small up to about 430°C; above this temperature, oxidation effects may reduce (slightly) the fatigue life.
- For unirradiated materials, the stress range remains unchanged, independent of the applied strain range.
- By contrast, in the irradiated condition, cyclic softening is observed which increases with the applied strain, and the stress component of the inelastic deformation tends to vanish.
- No major difference was found between plate and weld behavior except that the TIG-weld exhibits larger initial stresses than the plate and the LCF properties are slightly better for the plate.
- An overall comparison of LCF data over a wide range of irradiation conditions (irradiation temperature and fluence) and test temperatures shows no or little effect of irradiation on the LCF properties of 316L steel.

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