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Journal of Nuclear Materials 258–263 (1998) 1600–1605

journal of nuclear materials

Section 6.4. Austenitic steels and other structural materials

The effect of hold-times on the fatigue behavior of type AISI 316L stainless steel under deuteron irradiation

R. Scholz *, R. Mueller

Institute for Advanced Materials, CEC, Joint Research Center Ispra, TP 750, 21020-Ispra (Va), Italy

Abstract

Strain controlled fatigue tests have been performed in torsion at 400°C on type 316L stainless steel samples in both 20% cold worked and annealed conditions during an irradiation with 19 MeV deuterons. A hold-time was imposed in the loading cycle. For the cold worked (cw) material, at shear strain ranges of 1.13% and 1.3%, irradiation creep induced stress relaxation led to the built up of a mean stress. The fatigue life was significantly reduced in comparison to thermal control tests. For the annealed (ann) material, tested under similar experimental conditions, irradiation creep effects were negligibly small compared to cyclic and irradiation hardening. The fatigue life was only slightly reduced. Continuous cycling tests conducted under irradiation conditions lay in the scatter band of the thermal control tests. The difference in fatigue life between continuous cycling and hold-time tests is attributed mainly to the observed difference in irradiation hardening.

1. Introduction

The next generation Tokamak reactor will have a pulsed operation at low frequency. A plasma burn time of 1000 s will be followed by a plasma off burn time of 10–100 s. The resulting temperature oscillations are causing cyclic stresses giving rise to fatigue and irradiation creep fatigue interaction of reactor structural components. Fatigue experiments conducted on 20% cold worked AISI type 316L stainless steel after an irradiation with neutrons up to 16 dpa showed that the fatigue life was reduced by a factor of 3–10 in comparison to thermal control tests on unirradiated material [1]. A similar result was obtained for other candidate materials for structural reactor applications such as MANET after light ion [2] and neutron [3] irradiation. The reduction in fatigue life was attributed to irradiation hardening and the associated loss in ductility of the material. However, post-irradiation tests were considered as an oversimplified approach since the cyclic loading is started when the irradiation hardening is completed. So, the fatigue life is determined on a material with different mechanical properties compared to in-beam/in-pile tests where the unirradiated material is exposed, simultaneously, to fatigue cycling and irradiation. So an interaction of both effects, cyclic loading and irradiation hardening may occur. In-pile continuous cycling fatigue tests conducted on the European reference material AISI type 316L showed that the number of cycles to failure, N_f, lay within the scatter band of the thermal control tests [4,5]. Again, the results were similar for MANET [6,7]. The prolonged fatigue life of the in-beam/in-pile tests was explained with the difference in irradiation hardening: there was no or a reduced irradiation hardening of the material in comparison to post-irradiation tests. However, for a plasma burn time of 1000 s, the loading conditions of the material during the irradiation are quasi static and the irradiation hardening, will be different from continuous cycling conditions. In addition, during the plasma burn period, irradiation creep occurs and may change the stress strain relationship of the loading cycle, hence, changing the loading parameters what further affects the fatigue life.

These two aspects have been studied by performing strain controlled fatigue tests with hold-times during an irradiation with 19 MeV deuterons.

* Corresponding author. Fax: +39 332 789 434; e-mail: reinhard.scholz@jrc.it.

0022-3115/98/$19.00
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2. Material and specimen preparation

The fatigue tests were conducted in torsion on hourglass shaped specimens using the creep/fatigue rig installed at the Ispra cyclotron during an irradiation with 19 MeV deuterons. The base material is processed into 20% cold-worked (cw) cylindrical bars with two intermediate annealings at 1060°C in a vacuum of 10^{-6} bar. The annealed (ann) material was obtained by keeping the (cw) bars in an inert atmosphere at 950°C for half an hour, the resulting medium grain size being approximately 10–12 μm such that about 12 grains lie across the specimen diameter. The final specimen shape is obtained by eletro-polishing a 1-cm bar segment to a minimum diameter of 140–150 μm.

3. Results and discussion

3.1. Fatigue under thermal conditions

Before starting the irradiation tests, strain controlled fatigue tests were conducted under thermal conditions at a frequency of 1 Hz on both materials (cw) and (ann). Torque twist curves were recorded such that analogous tests under irradiation conditions could show whether or not these curves are changed by the irradiation. Fig. 1 illustrates schematically the different response to cyclic loading for the two materials. The torque range, $\Delta\tau$, is plotted versus the normalized fatigue life for equal strain ranges. The curve for the (cw) material is characterized by cyclic softening over the whole fatigue life [8]. The drop in stress range occurs in three stages: there is a rapid drop in the first stage at the beginning of the cyclic loading followed by stage II where the stress decreases at a constant slope. In stage III, the material resistance declines quickly until rupture occurs. The annealed material hardens over most of its life. There is a rapid hardening after the onset of cyclic loading followed by a plateau region where the torque range increases slightly until a maximum is reached. Thereafter, $\Delta\tau$ decreases rapidly before rupture occurs. Optical observation of the samples during the fatigue cycling indicated that the decline in $\Delta\tau$ versus the end of the fatigue life coincides with the formation and propagation of the failure crack. The $\Delta\tau$ value in the plateau region of Fig. 1 is higher for the cw sample for the whole fatigue life as it is typical for metals deforming by planar slip.

3.2. Fatigue with hold-times under 19 MeV deuteron irradiation

The effect of irradiation creep was studied by imposing a hold-time at the minimum strain value of a strain controlled loading cycle during a continuous irradiation with 19 MeV deuterons. The indicated tensile equivalents of shear stress τ and shear strain γ are calculated with the formula $\epsilon/\sigma = \gamma/(3\tau)$.

3.2.1. (cw) material

Fig. 2 illustrates the effect of irradiation creep on the stress strain hysteresis loops for a test conducted on a (cw) sample for a shear strain range $\Delta\gamma = 1.13\%$ ($\epsilon = 0.66\%$): the first cycle of the test is plotted and the 1250th cycle together with the 1250th cycle of a thermal control test for which the same loading parameters were imposed. After 1250 cycles a repetitive pattern in successive cycles was reached. The plot shows that:

1. The first cycle which was equal for both samples is almost fully elastic for the strain range of 1.13%. The

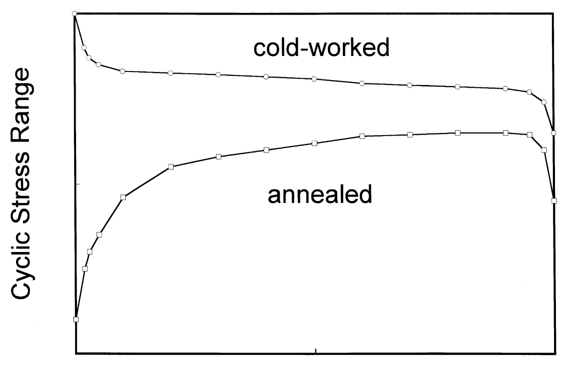

Fig. 1. Hardening and softening of annealed and 20% cold worked samples in continuous cycling at 400°C.

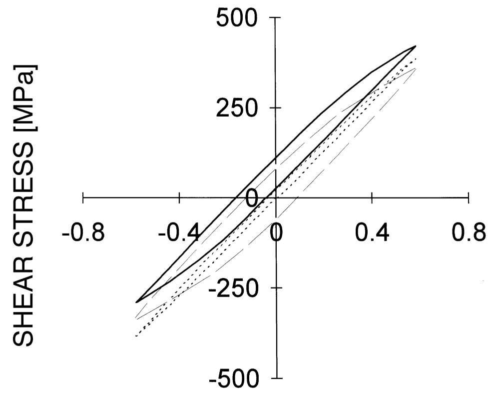

Fig. 2. Hysteresis loops of the first (...) and the 1250th cycle (—–) for a (cw) specimen during irradiation. A hold-time was imposed at minimum stress. In comparison the 1250th of a thermal control test (- -).

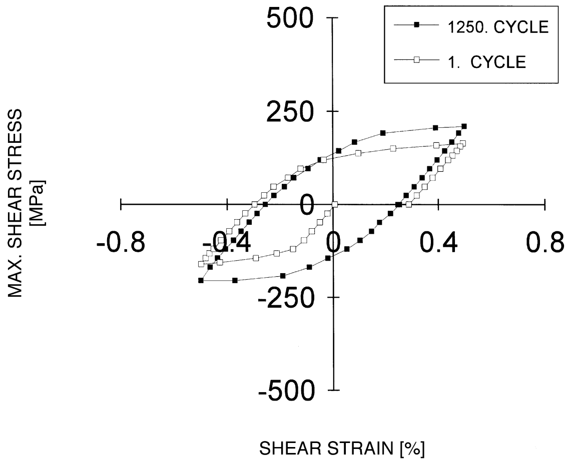

Fig. 3. Hysteresis loops of the first and the 1250th cycle for an annealed specimen for the same conditions as those in Fig. 3.

maximum shear stress $\tau_H = 355$ MPa during the hold-time.

2. After 1250 cycles, the hysteresis loop of the non-irradiated sample has widened by cyclic softening, it stayed symmetric in stress.
3. For the irradiated sample, the irradiation creep induced stress relaxation led to a decrease in the absolute magnitude of stress, τ_H, maintained during the hold-time. The hysteresis loop is shifted on the stress axis and a positive mean stress is built up.
4. The stress relaxation during the hold-time changes the loading parameters: as the magnitude of τ_H decreases the irradiation creep induced stress relaxation decreases, on the other hand, if the maximum stress is shifted over the yield stress, plastic flow occurs and the shifting of the hysteresis loop is stopped.
5. The magnitude of the plastic strain component is smaller for the irradiated sample due to irradiation hardening.

3.2.2. (ann) material

The (ann) material was subjected to the same loading and irradiation conditions as the (cw) material. Fig. 3 shows the first and the 1250th cycle of an irradiated sample, the strain range $\Delta\gamma = 1.03$ ($\Delta\epsilon = 0.6\%$).

(i) In the first cycle, due to the low yield stress of the (ann) material, plastic flow occurs during the first half cycle and the stress acting during the hold-time is less than half that of the cw material. Therefore, irradiation creep effects are, in comparison, much smaller, at the beginning of the irradiation.

(ii) The 1250th cycle is still symmetric in stress. The magnitude of stress maintained during the hold-time, τ_H, has grown by about 30%, despite the hold-time imposed, due to irradiation and cyclic hardening.

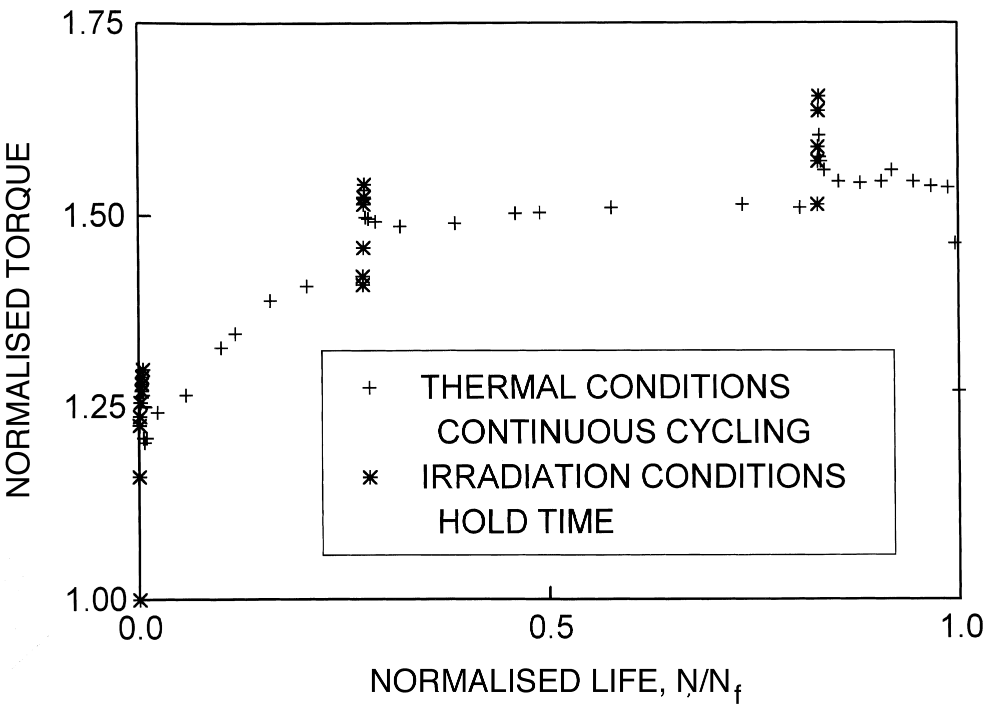

Fig. 4. Hardening and softening under irradiation and thermal conditions.

After the first irradiation period, the specimen was subjected to irradiation two more times, still imposing the same loading cycle with a hold-time of 50 s. Between the irradiation, continuous cycling was applied under thermal conditions at 400°C and a frequency of 1 Hz. In Fig. 4, the normalized torque range, $\Delta\tau/\Delta\tau_{in}$, recorded for this test, is plotted versus the normalized fatigue life, N/N_f, where $\Delta\tau_{in}$ is the torque range of the first cycle. The $\Delta\tau/\Delta\tau_{in}$-values grow during each irradiation period and reach 230 MPa at the end of the third irradiation, the hysteresis loops staying almost symmetric in stress. So, the effect of irradiation creep on the stress strain relationship in the loading cycle is small in comparison to cyclic and irradiation hardening. Fig. 4 illustrates that the hardening of the material depends on both, loading and irradiation conditions: the hardening of the material accumulated during irradiation under quasi-static conditions (hold-time of 50 s) is recovered to a great extent during the continuous cyclic loading under thermal conditions. After the last irradiation period, the accumulated irradiation hardening recovered to 78%. The recovery occurred within about 200 cycles. Note that during the irradiation phases (*), the number of cycles, N, amounts to 70 /h (hold-time of 50 s), whereas during the continuous cycling phase $N = 3600$. Therefore, the sharp increase in $\Delta\tau$ in Fig. 4 for the irradiation periods.

3.3. Hardening under cyclic loading conditions

In an attempt to study further the effect of cyclic loading on the irradiation hardening, continuous cycling tests have been performed under irradiation conditions combined with hold-times imposed at zero stress. So, irradiation creep effects are excluded. Fig. 5 shows an example for a shear strain range $\Delta\gamma = 1\%$. The normalized torque range, $\Delta\tau/\Delta\tau_{in}$ is plotted versus the testing time. It is evident that the material softens at a transition from irradiation to thermal conditions, it hardens at a transition from thermal to irradiation conditions. However, the difference in hardening between thermal and irradiation conditions is small if the sample is subjected to continuous cycling. The hardening is accelerated drastically when a hold-time of 1000 s is maintained. However, the hardening accumulated during the hold time phase disappears to a great extend during the continuous cycling period (see Fig. 5). This difference in hardening between the hold-time phase and continuous cycling conditions may be explained in terms of the two component hardening model which assumes that there are two principal components of irradiation hardening in austenitic and other types of steels [9]: the first one, the so-called matrix damage component is the result of point defect clustering, such as Frank loops and small voids, the second one is due to radiation induced

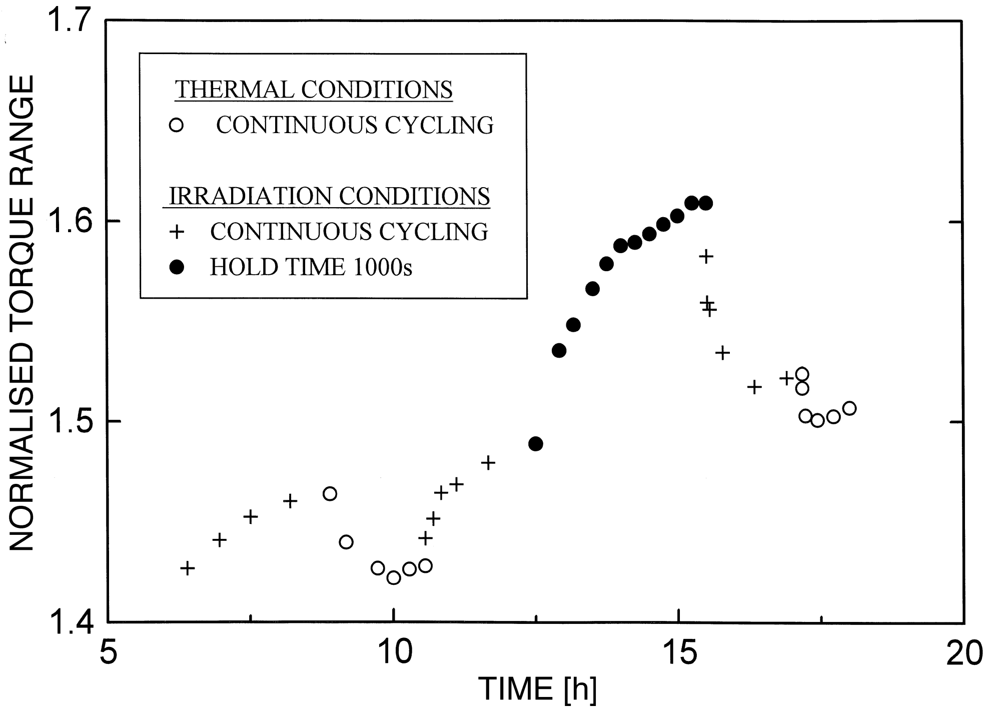

Fig. 5. Hardening and softening under continuous cycling and during a hold-time of 1000 s.

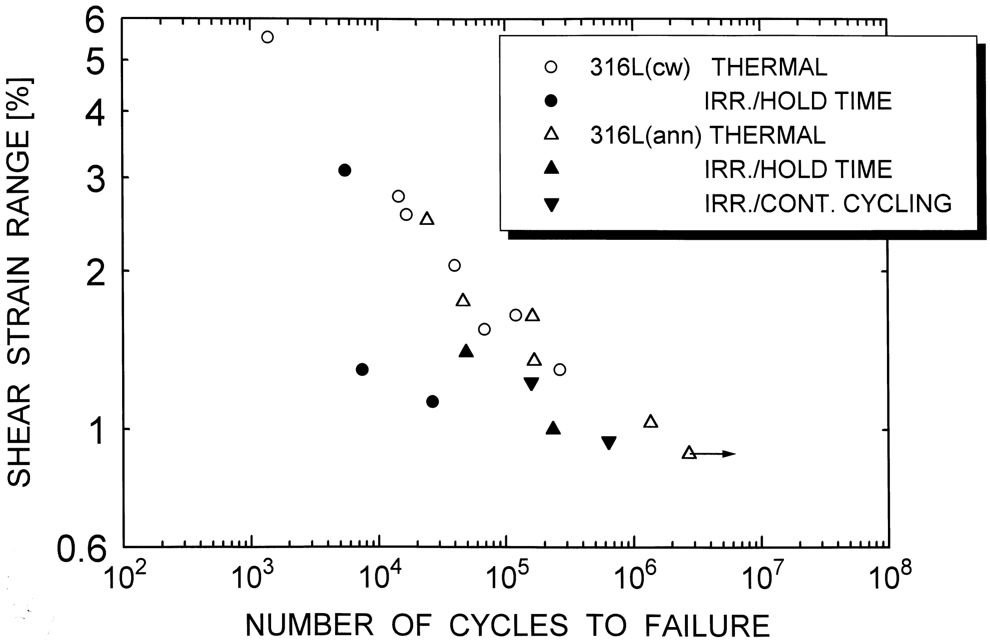

Fig. 6. Fatigue of 316L stainless steel at 400°C under thermal and irradiation conditions.

segregation/precipitation processes. Point defect or precipitate particles form obstacles for the free movement of dislocations and, hence, contribute to material hardening. Under cyclic loading, these particles may be absorbed if they are located on the glide plane of a dislocation oscillating due to cyclic external forces. Under static conditions, point defect agglomerates or precipitates have time enough to reach a stable size such that they can act as obstacles for a moving dislocation and a hardening of the (ann) material is suppressed to a great extent for simultaneous irradiation and cyclic loading. The hardening of the material observed for a hold-time of 1000 s is compatible with a square root relationship between hardening and irradiation dose. This relationship has been determined for reactor irradiations under static conditions [9]. So, with respect to irradiation hardening 1000 s hold-time tests are close or equal to static conditions for the beam intensities applied.

3.4. The effect of irradiation on the fatigue life

In Fig. 6, the shear strain range is plotted against the number of cycles to failure, N_f, for tests under thermal and irradiation conditions. The experimental parameters are listed in Table 1. The tests are only partly conducted under irradiation conditions. The irradiation time, t_{irr}, divided by the total test time, t_0, is indicated in the last row. There is a big difference in beam duty time for the various tests, mainly due to the fact that, for relevant

Table 1
Parameters imposed for the irradiation tests

No	$\Delta\gamma$ (%)	hold-time	dpa/s	dpa	N_{irr}	t_{irr}/t_0
20% cold-worked material						
1	5.5	20 s	1×10^{-6}	0.15	6700	100%
2	1.3	20 s	6×10^{-6}	0.9	7200	100%
3	1.13	50 s	6×10^{-6}	0.8	26400	85%
Annealed material						
4	1.4	50 s	5×10^{-6}	0.3	46600	52%
5	1.03	50 s	5×10^{-6}	0.6	234000	33%
6	0.95	0, 1000 s	5×10^{-6}	0.32	632130	12%
7	1.23	0	4×10^{-6}	0.25	157330	34%

$\Delta\gamma$ stands for the total shear strain range.

strain ranges, the fatigue life exceeds the available beam time. So, the data plotted in Fig. 6 indicate a trend how the various testing conditions may affect the fatigue life: the continuous cycling tests conducted under irradiation lie within the scatter band of the thermal control tests. For the hold-time tests, there is a significant reduction in N_f for the (cw) material and a small reduction for the (ann) material. The reduction in N_f may be attributed to the irradiation induced hardening and the associated loss in ductility for both materials. Irradiation creep induced built up of a mean stress further contributes to a reduction in N_f for (cw) samples, whereas, for (ann) samples irradiation creep effects are negligibly small compared to cyclic and irradiation hardening of the material.

4. Conclusions

Strain control fatigue tests have been performed on AISI type 316L stainless steel in both, cold worked and annealed conditions during an irradiation with 19 MeV deuterons at 400°C. The hold-time was imposed in the loading cycle in two positions; (1) at maximum stress such that irradiation creep could take place; (2) at zero stress in order to study the effect of cyclic loading on the irradiation hardening of the material. The tests performed for a shear stress range between 1% and 1.4% (tensile equivalents 0.54% and 0.82%) show that:

(A) For the cold worked material, irradiation creep may lead to the built up of a mean stress which contributes to the significant reduction in fatigue life in addition to irradiation induced hardening and the associated loss in ductility.

(B) For the annealed material:

1. Irradiation creep induced stress relaxation is small in comparison to cyclic and irradiation hardening.
2. The irradiation hardening is suppressed to a great extent, by continuous cyclic loading, but is similar or equal to static conditions for 1000 s hold-time fatigue tests.
3. The small reduction in fatigue life observed for the hold-time tests may be attributed, as in the case of the (cw) material, to irradiation induced hardening and loss in ductility.
4. Continuous cycling in-beam/in-pile fatigue tests may not be suitable to simulate the hardening of type 316L stainless steel which will occur under 1000 s pulsed reactor conditions. Since hardening/ductility is life determining for low cycle fatigue, post-irradiation fatigue data seem to be more appropriate for the next step reactor design.

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