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Letter to the Editors

The effect of cyclic loading on the irradiation hardening of type 316L stainless steel

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Abstract

Strain controlled fatigue tests have been performed in torsion on annealed type 316L stainless steel irradiated with 19 MeV deuterons at 400°C for shear strain ranges between 0.95% and 1.4%. The irradiation hardening of the material was suppressed to a great extent for continuous cycling conditions in comparison to hold time tests.

Type 316L stainless steel has been used as a material for structural components in nuclear reactors. The effects of fast neutron irradiation on the radiation hardening and the associated embrittlement of this material and other types of steels have been investigated for a large range of irradiation conditions [1–3]. Reactor pressure vessel (RPV) steels have been studied world-wide with respect to irradiation induced microstructural changes and hardening mechanisms within reactor safety programs [4]. These studies on RPV and austenitic steels suggested that there are two principal components of irradiation hardening in these materials. The first, the so-called matrix damage component, results from point defect clustering, such as Frank loops or small voids. The second is due to irradiation-induced segregation or precipitation processes. Precipitate particles form obstacles for the free movement of dislocations, thus, contribute to material hardening.

The next generation Tokamak reactor for thermonuclear fusion will have pulsed plasma burn periods. The resulting temperature oscillations are causing cyclic stresses, giving rise to fatigue and irradiation creep fatigue interaction. Cyclic stresses may continuously change the dislocation pattern of the material and, thus, the formation kinetics of irradiation induced defect structures which contribute to strengthening of the material: dislocations which are moving under the influence of cyclic stresses may absorb point defects located in their glide plane, thus, preventing the nucleation of point defect agglomerates. The same argument may hold for the formation of radiation induced precipitations: dislocations are sinks for point defects. So, in their vicinity point defect gradients are built up during the irradiation which are causing radiation induced segregation and precipitation processes. Since these processes depend on time, the precipitate formation will be different for a moving dislocation than from a fixed one. Thermal fatigue and/or creep–fatigue interaction under high energy neutron irradiation is considered as an important mechanism which could limit the life time of a first wall element of a Tokamak fusion reactor. The effect of irradiation on the fatigue behavior of reactor materials has been studied predominantly under post-irradiation conditions. In this case, the irradiation induced microstructure is developed before the cyclic loading is started such that a possible interaction of both processes cannot be detected. The problem has been addressed in the work of Lindau and Moeslang [5] who studied the fatigue behavior of the ferritic/martensitic Cr steel MANET-I in post-irradiation conditions and during an irradiation with 104 MeV α-particles. A comparison between the two testing conditions showed that in-beam fatigue tests had a longer fatigue life, the irradiation hardening was less for equal loading conditions.

In the present work, the effect of cyclic loading on irradiation hardening has been studied by conducting strain controlled fatigue tests in torsion on 316L stainless steel specimens under thermal conditions and during an irradiation with 19 MeV deuterons. Light ion irradiations require the use of miniature specimens for damage homogeneity

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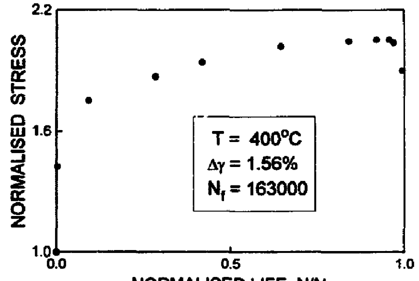

Fig. 1. The normalised torque range plotted versus the fatigue life.

and cooling reasons. Hour glass type specimens having a diameter of ~ 160 μm diameter were used in the tests. The specimens were produced from cylindrical bars by an electropolishing process. The bars were first annealed at 950°C for 1/2 h in an inert atmosphere. The resulting grain size amounted to ~ 14 μm such that about 12 grains lay across the irradiated specimen diameter. For all tests, the hysteresis loops were monitored such that the change in stress or torque range could be determined as a function of the fatigue life of the specimen. Such a plot is shown in Fig. 1 for a test conducted under thermal conditions at a specimen temperature of 400°C and a total strain range of 1.56%. It is evident that the material hardens over the major part of its fatigue life reaching a saturation value after ~ 10% of the total life. The drop in stress range at the end of the specimen life is due to formation and propagation of the failure crack. Similar curves have been measured for all tests under thermal conditions at 400°C.

Under irradiation conditions, two types of tests have been performed: (1) under continuous cycling and (2) by imposing a hold-time in the loading cycle. The test parameters are indicated in Table 1. The hold time for test (1) and (2) was imposed at the minimum strain value, i.e., under stress; for test no. 3, the stress was zero during the hold time. The tests are only partially conducted under irradiation conditions. In Table 1, the time under irradiation conditions t_{irr} divided by the total test time t_{to} of the specimen is indicated in the final column. The effect of the irradiation on the stress range for the various loading conditions imposed is illustrated in Fig. 2, where the

Table 1
Parameters imposed for the irradiation tests; Δγ stands for the total shear strain range

No.	Δγ (%)	Hold-time	dpa/s	dpa	N_f	t_{irr}/t_o
1	1.4	50 s	5×10^{-6}	0.3	46600	52%
2	1.03	50 s	5×10^{-6}	0.6	234000	33%
3	0.95	0, 1000 s	5×10^{-6}	0.32	632130	12%
4	1.23	0 s	4×10^{-6}	0.25	157330	34%

normalised torque range of the first 30 of in total 175 testing hours is shown for test no. 3: the test was started under thermal conditions (phase 1: O); thereafter the specimen was irradiated without interrupting the cyclic loading for 30000 cycles (phase 2: +). In phase 3 (*), the irradiation was continued for ~ 4 h without applying a torque. Cyclic loading was then restarted still continuing the irradiation (phase 4: +). During phase 5 (O) the specimen was subjected to cyclic loading under thermal conditions until rupture occurred. Fig. 2 shows that

(i) there is only a small irradiation hardening effect at the onset of the first irradiation period (+);

(ii) irradiation hardening is accelerated drastically in phase 3 when the cyclic loading is stopped. The increase in torque range is compatible with a square root relationship between hardening and irradiation dose. This relationship has been observed in related reactor irradiation tests [4];

(iii) in phase 4 (+), after restarting the cyclic loading, the material softens gradually until a saturation is reached. However, the stress range stays higher than at the beginning of phase 3, i.e., the hardening accumulated in phase 3 is not completely recovered;

(iv) In phase 5 (O), after stopping the irradiation, there is an additional softening which is followed by cyclic hardening of the material.

The experimental results shown in Fig. 2 may be explained in terms of the two-component hardening model: (1) matrix damage, such as small cavities and interstitial agglomerations, may be absorbed if they are located in the glide plane of a dislocation which is oscillating under the cyclic external forces; (2) for radiation induced precipitations (RIP), static conditions may be required to be formed at all, since RIP forms at sinks for point defects after a certain incubation dose depending on the solution limit which has to be exceeded to form the precipitation. In this sense, a mobile dislocation can hardly act as a nucleation site for RIP. So, the hardening effect which is greatly

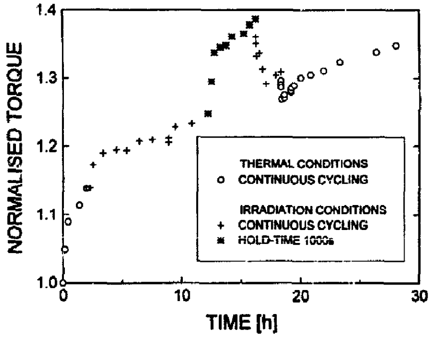

Fig. 2. The normalised torque range plotted versus the testing time for various loading and irradiation conditions imposed in test no. 3.

reduced under continuous cycling conditions increases significantly only under static conditions. The fact that the hardening formed during phase 3 is not completely recovered may be explained in a similar way: the point defect agglomerates or precipitates have reached a stable size such that they act as obstacles for moving dislocations.

Fig. 3 shows the normalised torque range response of a specimen irradiated in three occasions as a function of the normalised fatigue life N/N_f (N: number of cycles; N_f: number of cycles to failure). A hold time of 50 s was imposed at the minimum strain value in the loading cycle. Under thermal conditions, the specimen was exposed to continuous cycling at a frequency of 1 Hz. The torque range $\Delta\tau$ which increased during the irradiation periods decreased sharply at the onset of cycling loading under thermal conditions. Whereas during the first irradiation period cyclic and irradiation hardening are superimposed, the cyclic hardening has reached its saturation before the start of the second irradiation period. The increase in $\Delta\tau$ accumulated in the irradiation periods two and three is not completely recovered in the successive cyclic loading under thermal conditions. This incomplete recovery may be explained with the same arguments used above. In Fig. 4, the total strain range is plotted versus the number of cycles to failure in a double log display for tests conducted under thermal and irradiation conditions. The fatigue life of the continuous cycling tests conducted under irradiation conditions seems to be slightly reduced or, within the error limit, equal in comparison to analogous tests without irradiation. There is a noticeable reduction in fatigue life for the hold time tests. The irradiation induced hardening and

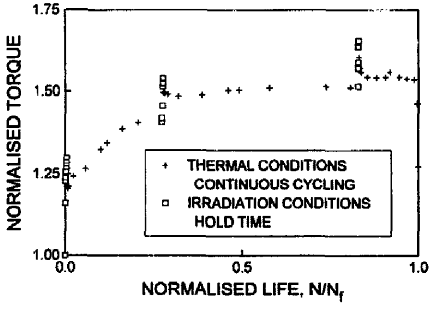

Fig. 3. The normalized torque range plotted versus the normalised life, N/N_f, for thermal (+) and irradiation conditions (O).

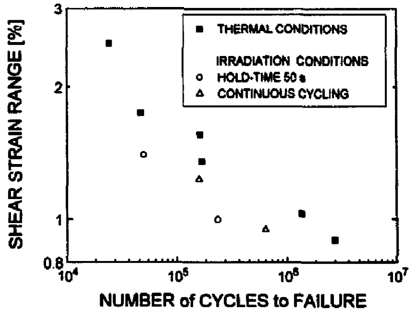

Fig. 4. Fatigue of type 316L stainless steel at 400°C.

the associated loss in ductility are the most likely causes for the reduced fatigue life. A similar argumentation has been given in Ref. [5] for the explanation of the reduced fatigue life of the MANET-1 steel for post-irradiation tests in comparison to in-beam tests. The mean stress (< 12 MPa) which was built up in the hold time tests due to the irradiation creep induced stress relaxation may further contribute to the decrease in fatigue strength of the material for the imposed testing conditions.

In conclusion, strain controlled fatigue tests were conducted on annealed type 316L stainless steel specimens exposed to an irradiation with 19 MeV deuterons for shear strain ranges between 0.95% and 1.4%. The tests show that the irradiation induced hardening of the material depends on the fatigue loading conditions. It was significantly smaller for continuous cycling conditions in comparison to hold time tests. The difference in fatigue strength under irradiation for the two testing methods may be ascribed mainly to the difference in radiation induced hardening of the material.

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