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Post-irradiation mechanical properties of austenitic alloys at temperatures below 703 K

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Abstract

At temperatures below 703 K, irradiation increased flow stress and decreased elongation and fracture toughness in a 316 stainless steel. The residual ductility and fracture toughness after irradiation, however, were still high enough for structural applications. The effect of irradiation on the constitutive equation was evaluated. Results indicate that the alloy work hardens even after irradiation, and the residual work hardening capability is demonstrated to suppress flow localization. The relationship between residual fracture toughness and yield stress was examined, and irradiation effects on fatigue properties that cause channel fracture were analyzed.

1. Introduction

A type 316 austenitic stainless steel will be used for the structural material of the in-vessel components of the international thermonuclear experimental reactor (ITER). Irradiation by neutrons from a D-T plasma will produce displacement damage to a level of 10 dpa in the structural material of the first wall of the blanket, and the transmutant helium will attain levels of 100–200 appm during the life time of the machine.

The austenitic alloy will be used at temperatures ranging from 373 to 573 K. In this temperature range, irradiation damage at 10 dpa increases in yield stress to more than three times that of the alloy in solution-annealed condition at temperatures below 703 K [1–10]. Irradiation also causes reductions in the strain-hardening capability and the fracture toughness [11,12].

Because damage levels and temperatures during service vary among components, and because the dose levels and temperatures of irradiation experiments to date are limited, it may be necessary to estimate the damage and the temperature dependence of the mechanical properties by extrapolation of the test results. To get some insight for such an extrapolation, the post-irradiation test results of the mechanical properties of 316 stainless steel are reviewed here in terms of damage level, irradiation temperature and the amount of transmutant helium. Properties include strength, ductility, constitutive equation for true stress–strain relations and the residual work hardening capability. The main data source considered here are the results of the HFIR joint irradiation experiment between ORNL and JAERI.

2. Tensile properties

2.1. Temperature dependence

Neutron irradiation was carried out for a Japanese heat of 316 stainless steel in a solution annealed condition (SA-J316) to displacement damage levels of 6.7 and 19 dpa at temperatures of ~340, 473, 603 and 673 K using the spectral tailoring method in ORR and at the RB* position in HFIR [1]. The accumulated He levels in the alloy in this study were 75 and 200 appm, respectively [5]. Spectral tailoring is a method to adjust the He production rate to ~18 appm/dpa, typical of fusion neutron irradiation, by changing the ratio of fast and thermal neutron fluxes periodically throughout the irradiation period [13].

Post-irradiation tensile tests were performed at temperatures close to the irradiation temperature. The 0.2% offset yield stress (0.2% YS), ultimate tensile stress (UTS), strain-to-necking (STN) and total elongation

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(TE) values for irradiated SA-J316 tensile specimens are plotted in Fig. 1. STN is the plastic strain at the onset of neck development, and identical to uniform elongation for unirradiated austenitic alloy [2,3,5,7–9]. The results for the austenitic alloys including SA-J316 irradiated at the target position in HFIR to damage levels ranging from 5 to 50 dpa are also shown in Fig. 1, together with the results for the European Reference Heat of 316 (ERH) irradiated at HFR [4]. Only the results obtained from the tests at or near the irradiation temperature are shown in Fig. 1.

Irradiation to 6.7 dpa caused hardening and decreased elongation. The 0.2% YS increased to about three times the unirradiated value. And, the values were close to saturation, as only a slight increase of hardening and a slight decrease in elongation occurred for irradiation to 19 dpa. Temperature dependence of 0.2% YS and UTS levels was revealed to be rather small. On the other hand, STN decreased with temperature from about 22% at 298 K to 0% at 603 K and recovered to about 4% at 673 K. Despite the large decrease in STN, reduction of area was still quite large. Reduction of area attained 0.4–1.0 in natural strain (corresponding to 45–65%) for specimens after spectral tailoring irradiation to 6.7 dpa [1]. Those for specimens irradiated up to 36 dpa at the target position also attained similar levels [2].

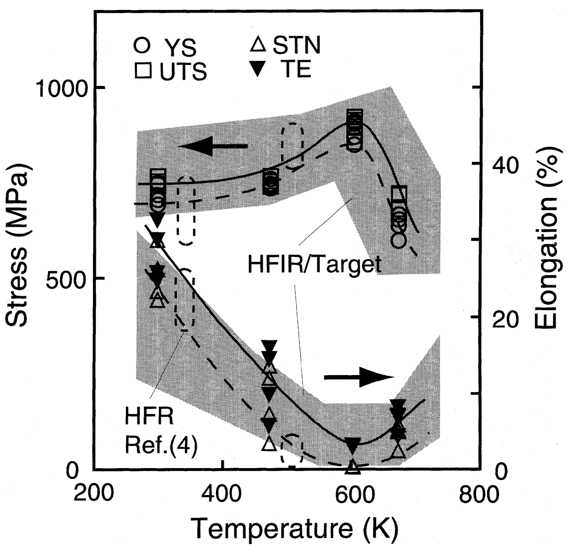

Fig. 1. Post irradiation tensile properties of SA-J316 irradiated in spectral tailored capsules to 18 dpa at temperatures ranging between 298 and 673 K. Displacement damage levels of SA-J316 are 6.9 and 18 dpa, and the accumulated He levels are about 75 and 200 appm, respectively. Changes of strength and elongation during irradiation from 6.8 to 18 dpa were not large. Results for specimens irradiated at the target position in HFIR (shaded regions) and those irradiated in HFR [4] are also shown.

Moreover, fracture stress (net section stress) obtained from reduction of area and tensile load at fracture became 1000 MPa or higher. This indicates that some work hardening was still exhibited during testing.

At damage levels higher than 3 dpa, irradiation at the target position in HFIR produced a much higher amount of He by the two step transmutation reactions in the austenitic alloys than would be expected in a fusion environment. However, the difference between the results after the spectral tailoring irradiation and those irradiated at the target position is rather small. A slightly higher stress level at 673 K was observed for alloys irradiated at the target position [2].

2.2. Constitutive equation

To evaluate the mechanical response of structures, a constitutive equation describing the relation between plastic strain and the flow stress level is essential. Eq. (1a) simulates the true-flow-stress–true-plastic-strain (TFS–TPS) relation of austenitic alloys at temperatures with small recovery (<673 K):

$$\sigma_{\text{flow}} = A(\varepsilon_0 + \varepsilon_\text{p})^n (\text{d}\varepsilon_\text{p}/\text{d}t)^m. \tag{1a}$$

For the 300 series austenitic alloys, the value of A ranges between 1000 and 1100 MPa and n ranges between 0.45 and 0.5 for unirradiated materials [2,3,14]. The value of ε_0 for the solution annealed condition is close to 0, and that for cold worked material corresponds to the plastic strain introduced by the cold work. The strain rate dependence of flow stress is rather small for austenitic alloys, and Eq. (1a) may be approximated by Eq. (1b).

$$\sigma_{\text{flow}} = A(\varepsilon_0 + \varepsilon_\text{p})^n. \tag{1b}$$

Ignoring the strain rate effect, Eq. (1b) indicates that diffuse necking initiates when plastic strain plus ε_0 becomes equal to n, the work hardening exponent. In other words, STN is calculated by subtracting ε_0 (or ε_0 calculated from YS) from n. Fig. 2 shows the relation between YS and STN. The relations obtained from unirradiated specimens (closed symbols) in solution annealed and cold worked conditions, and irradiation hardened specimens (open symbols) of J316, JPCA and EU316 at temperatures from ambient to 673 K are also plotted [2,5,9,10]. Although the scatter is rather large for the results of solution annealed specimens tested at temperatures above 473 K, STN seems to be estimated from SY by using Eq. (1b) not only for unirradiated specimens but also for irradiation hardened specimens. This indicates that TFS–TPS relations of austenitic alloy before and after irradiation are approximated by Eq. (1b) in the strain range up to n.

Austenitic alloys often hardened by irradiation at around 600 K to a level where STN becomes zero. As indicated earlier, austenitic alloys even with no STN

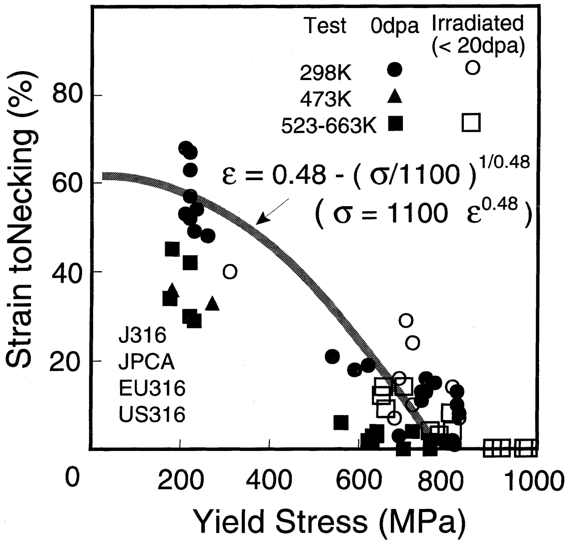

Fig. 2. Relation between strain to necking and yield stress levels for the solution annealed, cold worked and irradiated specimens of J316, JPCA, EU316 and US316. No large difference was seen between the STN of the specimens hardened by cold working and irradiation with similar YS levels.

exhibit considerable reduction of area. Moreover, the flow stress level increased during the test. YS and true fracture stress (FS) of irradiated specimens are plotted at ε_0 and at $\varepsilon_0+\varepsilon_p$ in Fig. 3, where ε_f is true plastic strain at fracture. FS was determined from net section stress at the minimum cross section at fracture and ε_f was obtained from $\ln(A_0/A_f)$, where A_0 and A_f are the minimum area at gage section before and after the tensile test. The plots fit a line by Eq. (1b) with A of 1100 MPa and n of 0.48 (strain rate effect is ignored again). This indicates that Eq. (1b) represents TFS–TPS relation of austenitic alloys before and after irradiation with appropriate ε_0 in the strain range to fracture. This also suggests that short term mechanical properties of irradiated austenitic alloys may be approximated by that of alloys in cold worked condition, as far as irradiation does not introduce significant change in fracture mechanism (e.g., irradiation may cause channel fracture indicated later in Section 4).

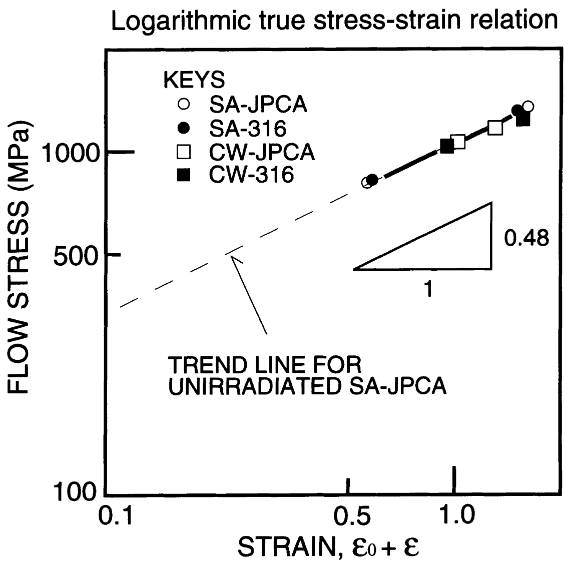

Fig. 3. True stress strain relation of Eq. (1b) and the flow stress levels of irradiated austenitic alloys at yield point and at fracture. Yield stress values were plotted at ε_0 of equivalent strain for irradiation hardening. True stress and strain at fracture were obtained from the reduction of area and fracture stress of nominal stress strain relation.

2.3. Residual ductility and work hardening capability

Residual ductility acts as a margin for the fracture of the structure. Residual work hardening ability often reduces flow localization to enlarge the margin. Deformation of a thin plate with a circular hole was estimated by finite element method using the ABAQUS code. Fig. 4(b)–(d) show the results of the numerical calculations with constitutive equations of elastic–perfectly plastic (with no work hardening), Eq. (1b) with ε_0 of 0.5 (and $n = 0.48$) and that with ε_0 of 0 (close to the solution annealed condition, and $n = 0.48$), respectively. Again, a strain rate sensitivity m of zero was assumed. The results clearly show that work hardening ability reduces the flow localization, which appeared in the model without work hardening (Fig. 4(b)) at an angle of about 50° to the tensile direction. It should be noted that the absence of the flow localization in the plate with ε_0 of 0.5 and n of 0.48 is qualitatively similar to that for the plate in solution annealed condition (with $n = 0.48$).

Because of the conservatism for evaluating the strength of the structure after irradiation, the constitutive equation of the material is often supposed to be elastic–perfectly-plastic. Although irradiation hardening reduces work hardening capability ($d\sigma/d\varepsilon$) and reduces the margin for flow localization, such an approximation seems be too conservative, as demonstrated in Fig. 4.

3. Fracture toughness

3.1. Reduction of fracture toughness by irradiation

Pawel et al. and Alexander et al. reported fracture toughness of SA-J316 after irradiation to 3 dpa at the target position in HFIR [11,12]. The results are shown in Fig. 5. Irradiation caused a decrease of the fracture toughness. The residual fracture toughness, however, was higher than 100 kJ/m^2, indicating the alloys are still

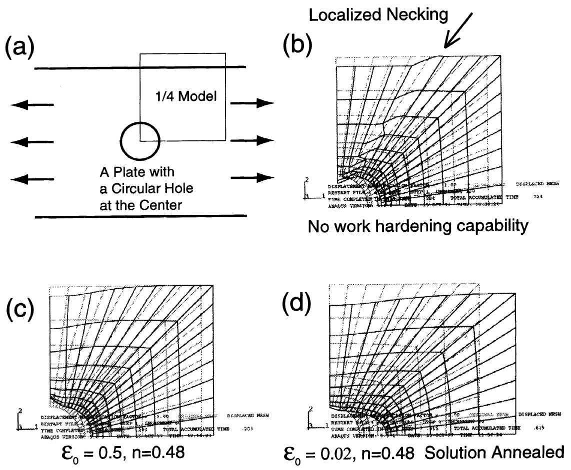

Fig. 4. Effect of residual work hardening capability after irradiation (a simulation). (a) Deformation of a plate with a circular hole was calculated with finite element method using constitutive equations of; (b) elastic perfectly plastic (with no work hardening); (c) Eq. (1b) with $\varepsilon_0 = 0.5$ and $n = 0.48$; and (d) Eq. (1b) with $\varepsilon_0 = 0.02$ and $n = 0.48$ (simulating the behavior in solution annealed condition).

quite tough even after the irradiation. The toughness was too high to satisfy the size requirement of ASTM E813 for the specimens used [15].

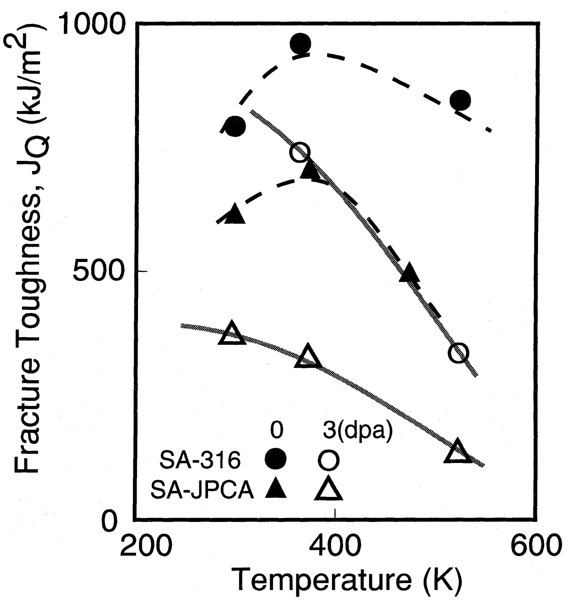

Fig. 5. Temperature dependence of fracture toughness before and after irradiation to 3 dpa (from Refs. [11,12]). 0.18 DCT specimens of SA-J316 and SA-JPCA were irradiated to 3 dpa. Irradiation caused a decrease in fracture toughness. Residual fracture toughness levels are, however, still quite large (>100 kJ/m^2).

3.2. Relation between irradiation hardening and fracture toughness

As indicated earlier, plastic behavior of the irradiated alloys is approximated well by the materials in cold worked condition with the same YS level. This indicates that the strain distribution around the crack tip in irradiated specimen is similar to that in cold worked specimen until crack extension occurs. Fracture toughness mainly depends on the work done for plastic deformation prior to the crack extension. Therefore, fracture toughness of the irradiated specimen may be similar to that of cold worked specimens with the almost same flow stress level, as long as the fracture mechanisms at the crack tip are not affected by irradiation [16].

Fracture toughness values of the specimens prepared from cold worked plates to different amounts were obtained, and J_Q values are plotted against YS of the material in Fig. 6. Tests were performed using 0.18DCT specimens, 10 and 25 mm thick compact tension specimens. The size dependence of J_Q was not large, however. Although the data for irradiated specimens are sparse, their J_Q values are reasonably close to those for the cold worked specimens, as seen in Fig. 6. If transmutation-produced He reduces fracture stress and strain at the crack tip, the relation obtained from the cold worked specimens may indicate an upper bound of fracture toughness at a YS level for materials irradiated in a fusion environment. Also if the irradiation hardening

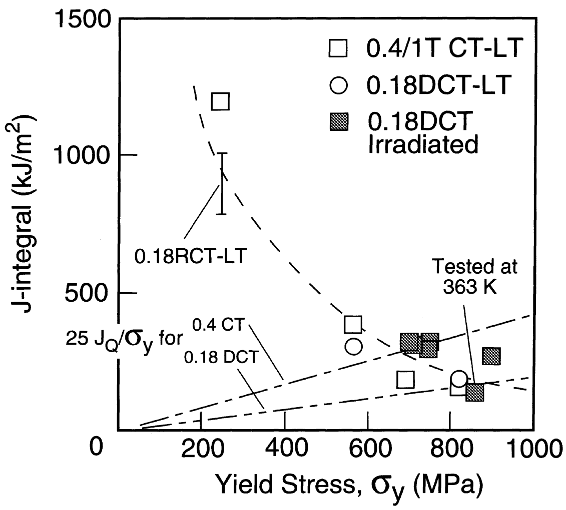

Fig. 6. Relation between fracture toughness and yield stress level of JPCA in solution annealed, cold worked and irradiated conditions. Because irradiation does not seem to introduce a large change in the constitutive equation of Eq. (1b), plastic deformation is expected to be identical for both irradiated and cold worked specimens with the same yield stress level, suggesting that the fracture toughness values are also in the same level.

becomes high enough to cause flow localization around the crack tip, fracture toughness and tearing modulus may severely reduce (this has been indicated by Lucas and Gelles [17]) to make the deviation from the relation even larger.

4. Fatigue and fatigue crack growth

The fatigue crack growth (FCG) rate of an irradiated CW-316 stainless steel is shown in Fig. 7 [18]. The specimens were fabricated from a duct used in the core of a fast breeder reactor JOYO at 683 K. The damage level for the duct material was 15 dpa. The test was carried out at 573 K.

Irradiation caused an increase in FCG rate at ΔKs above 15 $MPam^{1/2}$. Fractography revealed that the acceleration was accompanied by a change in crack growth mechanism from striation mechanism to channel fracture mechanism.

The effect of irradiation on the relation between total strain range and the number of cycles to failure is rather small. On the other hand, the effect on the relation between plastic strain range and fatigue life is rather strong, as indicated by Boutard [19]. Fig. 8 shows the irradiation effect on this relation for limited data on SA-J316 stainless steel irradiated to about 40 dpa and tested at 703 K [20].

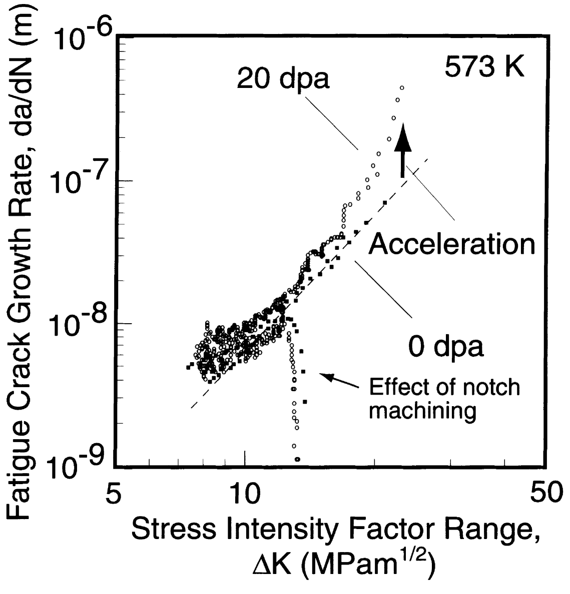

Fig. 7. Acceleration of fatigue crack growth rate (da/dN) by neutron irradiation to 20 dpa. da/dN–ΔK relations before (open symbols) and after irradiation (closed symbols) are plotted. da/dN in a CW-316 stainless steel was increased by irradiation to 20 dpa at 683 K in the ΔK range higher than 15 $MPam^{1/2}$. Fractography revealed that the acceleration was accompanied by a change in the crack growth mechanism.

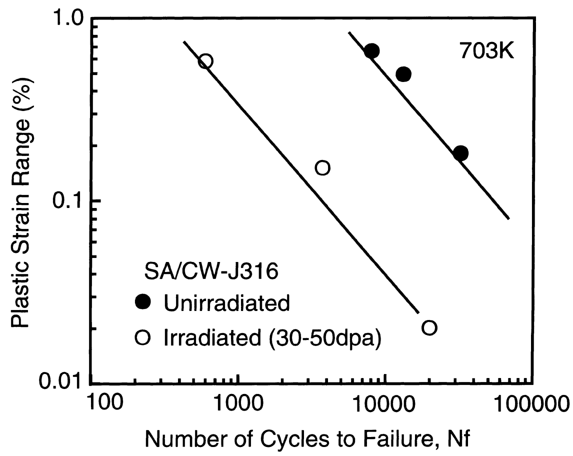

Fig. 8. Relation between the plastic strain range ($\Delta\epsilon_p$) and the number of cycles to failure (N_f) of J316. The effect of irradiation on the total strain range–N_f relation is not large, while the $\Delta\varepsilon_p$–N_f relation was rather susceptible to irradiation. Constant B in Eq. (2) for unirradiated specimens was about five times larger than that for the irradiated specimens.

It has been indicated that the number of cycles to failure (N_f) may be estimated from plastic strain range at the cycle of $N_f/2$ and tensile ductility by using Coffin–Manson relation of the form

$$\Delta\varepsilon_p N^p = B\varepsilon_f. \qquad (2)$$

The relation was applied to the results of unirradiated and irradiated specimens, and the B values for unirradiated specimens in both solution annealed and cold worked conditions were revealed to be five times as much as that for irradiated specimens.

5. Conclusions

(1) Specimens of SA-J316 stainless steel were irradiated up to about 50 dpa at temperatures below 703 K and tested to obtain a variety of mechanical properties. At temperatures below 673 K, irradiation caused hardening and reduction of ductility. The ratio of helium generation rate to displacement damage production did not appear to cause a significant effect on the post-irradiation tensile properties.

(2) Except for the effect on ε_0, irradiation introduces little change on the constitutive equation of the form; $\sigma_{flow} = A\,(\varepsilon_0+\varepsilon_p)^n$. This indicates that the true flow stress and true plastic strain relation of an irradiated austenitic alloy is simulated well with that of the alloy in cold worked condition with similar yield stress level. It should be noted, however, that irradiation hardening

reduces work hardening capability ($d\sigma/d\varepsilon$) and reduces the margin for flow localization.

(3) Residual work hardening capability of the irradiation hardened material is estimated to be high enough to suppress flow localization.

(4) Elastic–plastic fracture toughness of the irradiated specimen to 3 dpa agreed with J_Q values of cold worked specimens with similar yield stress level. This and (2) suggest that the mechanical response of an irradiated structure with an austenitic alloy may be approximated by a model structure with the alloy in cold worked condition, as far as irradiation does not introduce significant changes in fracture mechanism.

(5) Fatigue crack growth rate was increased by irradiation at temperatures of 573 and 673 K. This was accompanied by a change in the crack growth mechanism. The relation between plastic strain range and the number of cycles to failure in fatigue testing was affected after irradiation to about 20 dpa at 700 K.

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