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Irradiation creep and stress-enhanced swelling of Fe–16Cr–15Ni–Nb austenitic stainless steel in BN-350

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Abstract

A pressurized tube expeiment was conducted on a Russian Fe–16Cr–15Ni–Nb stainless steel in the BN-350 reactor in Kazakhstan. Strain data are reported on annealed tubes irradiated to 60 dpa at 480°C and to 20 dpa at 520°C, both at hoop stress levels ranging from 0 to 200 MPa. The strains observed were linear with applied stress, and the void swelling derived from density measurements was clearly enhanced by stress, an observation confirmed by electron microscopy examination. The derived creep coefficients agree well with those found in Western studies on stainless steels.

1. Introduction

Irradiation creep and void swelling will be important damage processes for stainless steels when subjected to fusion neutron irradiation at elevated temperatures. The absence of an irradiation device with fusion-relevant neutron spectra requires that data on these processes be collected in surrogate irradiation devices such as fast reactors.

To date, most data published of this type have been derived from steels prepared by various Western nations and Japan [1]. A smaller amount of such data have been published on steels used in the countries of the former Soviet Union. Whereas most of the non-Soviet steels are variants of type 316 stainless steel, the comparable Russian steel is a niobium-stabilized steel.

This paper describes the results of an experiment involving irradiation of gas-pressurized tubes constructed from this steel in the low enrichment zone of the BN-350 fast reactor located in Kazakhstan.

2. Experimental details

The steel used in this experiment was Fe–15.74Cr–15.32Ni–2.95Mo–0.78Mn–0.54Nb–0.29Si–0.05C (wt%) with 0.009S, 0.011P and 0.035N. The specimens were in the form of argon-pressurized thin wall tubes, as shown in Fig. 1, with the argon purity at 99.998%. The end plugs of the tube were welded in place. Before pressurization, the tubes were annealed at 1040°C for 3 min. The larger plug contained an axial cylindrical, threaded hole. Hoop stress levels ranging from 0 to 196 MPa were used. After pressurizing in a high pressure chamber, the hole in the end plug was mechanically sealed with a threaded needle value while still in the chamber. After removal from the chamber, the butt-end of the plug was welded.

The tubes were irradiated in a duct of the same size as the fuel driver assemblies of BN-350, and were contained in perforated cylindrical baskets of 76 mm diameter, allowing direct contact with flowing sodium. The normalized flux profile and the temperature profile are shown in Fig. 2. The tubes discussed in this paper were irradiated in basket #4 (0–100 mm from the core midplane) and basket #15 (650–750 mm). This yielded 60 dpa at ∼480 ± 10°C, and 20 dpa at ∼520 ± 10°C, respectively, using the standard NRT model. The

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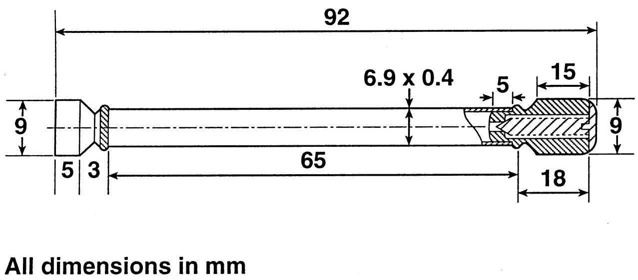

Fig. 1. Argon-pressurized creep tubes irradiated in BN-350.

maximum dose of 60 dpa resulted from a fast neutron fluence of 1.36×10^{23} n/cm^2 ($E > 0.1$ MeV) and a total neutron fluence of 1.9×10^{23} n/cm^2 over an irradiation time of 9430 h. The doses correspond to those at the middle of the tubes. At 480°C there is very little flux variation, and at 520°C there was some flux gradient along the length of the tube. Tubes at a given dose and temperature, but with different hoop stresses, were irradiated side-by-side without change in location during the experiment.

After irradiation, the specimens were cleaned with a 50/50 mixture of ethyl alcohol and water, and then subjected to both non-destructive and destructive measurements. The diameters were first measured by a direct contact method at the tube middle and also at positions 15 mm from each end. Measurements were taken at two orientations across the tube circumference, 90° from each other. Destructive examination followed to remove the end caps to produce the central 50 mm tube section, and later to produce rings of 4 mm width for microscopy. Density measurements were performed on both the full tube length and the rings, using a hydrostatic technique in air and in carbon tetrachloride. The accuracy of the density measurements is ±0.5%. Standard microscopy specimens were then punched from the rings, mechanically reduced in cross-section by grinding to remove the specimen curvature, and then electrolytically thinned with an electrolyte consisting of 5 vol% of perchloric acid in acetic acid. Microscopy was performed on a JEM-100 CX electron microscope.

3. Results

For the specimens irradiated at 480°C to 60 dpa, none of the tubes failed or displayed any brittleness as a consequence of the large swelling levels attained. The swelling measured by microscopy agreed very well with that obtained by density, ranging from 20% to 30%. Since there was very little flux gradient along the tube length, the density of the ring section used for microscopy agreed well with the density obtained earlier using the entire tube after the end sections had been removed. As shown in Fig. 3, the swelling level was very clearly

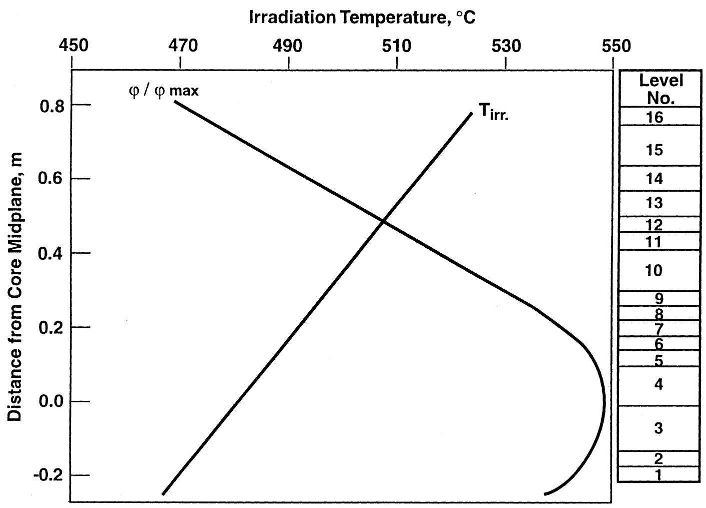

Fig. 2. Profiles of temperature and normalized neutron flux ($E > 0.1$ MeV) in the irradiation creep experiment conducted in BN-350.

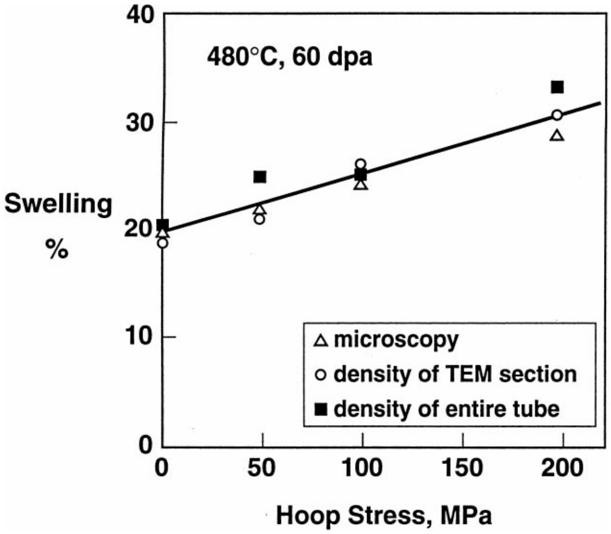

Fig. 3. Swelling measured by three methods in tubes irradiated at ∼480°C to 60 dpa.

enhanced by stress. Fig. 4 demonstrates that the dislocation density and mean void size are relatively insensitive to the stress level, with the stress-enhancement of swelling reflected only in the void number density.

When the swelling-induced component of diametral deformation (determined from 1/3 of the swelling calculated from density change) is subtracted from the total deformation, the irradiation creep component is shown to be linear with stress over the range 0–196 MPa, as shown in Fig. 5.

For the tubes irradiated at 520°C to 20 dpa, density was measured only on the rings which were cut from the center of the tubes. Only the 0, 49 and 98 MPa specimens were measured by density, however. Microscopy was not performed on these specimens. As shown in Fig. 6, swelling is again shown to be stress-sensitive, and the irradiation creep strain is again linear with stress. Since the dose level at 520°C is only 20 dpa, the strains are much smaller than those observed at 480°C and 60 dpa.

4. Discussion

The stress enhancement of swelling is a well-known phenomenon [1–3] and its observation here is consistent with that of other studies. Swelling enhancement appears to be linear with stress level over the range studied. The linearity of irradiation creep strain with stress is also well-known. Of more current interest is a recent observation by Toloczko and Garner [1,4] that there exists a feedback between swelling and irradiation creep such that irradiation creep is first accelerated by void swelling,

$$\overline{B} = \frac{\dot{\bar{\epsilon}}}{\overline{\sigma}} = B_0 + D\dot{S}.$$

where $\overline{B}$ is the observed creep rate, $\dot{\bar{\epsilon}}$ is the equivalent strain rate per dpa, $\overline{\sigma}$ is the equivalent stress, B_0 is the creep compliance, D is the creep-swelling coupling coefficient, and $\dot{S}$ is the instantaneous swelling rate per dpa. Initially, the D coefficient is about 0.6×10^{-2} MPa^{-1}, but Toloczko and Garner have shown that the D coefficient falls from this value as $\dot{S}$ increases. This process has been described as "creep disappearance"

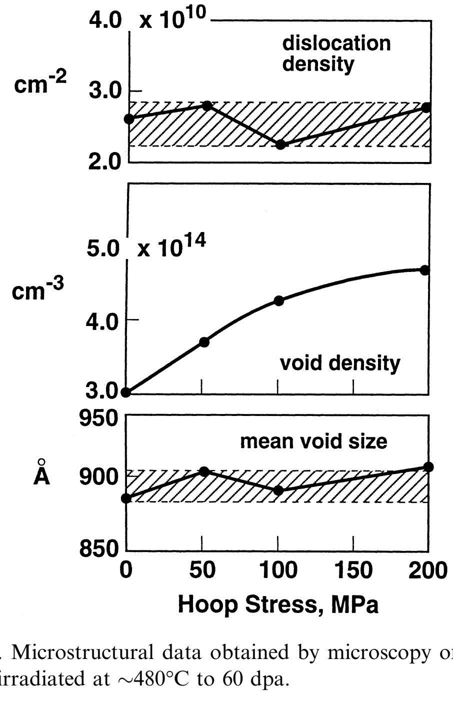

Fig. 4. Microstructural data obtained by microscopy of specimens irradiated at ∼480°C to 60 dpa.

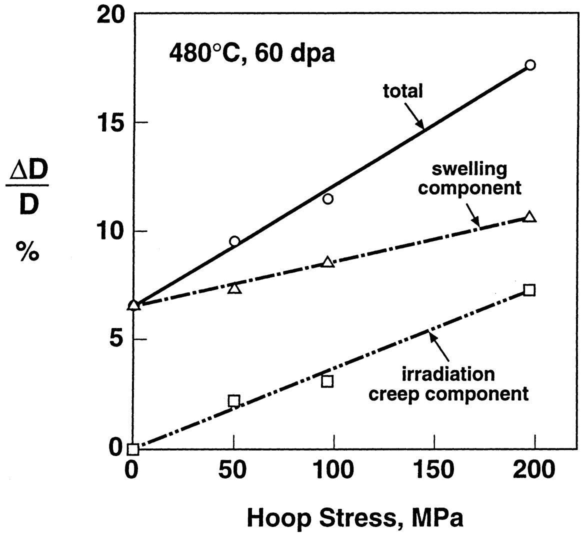

Fig. 5. Total strain, irradiation creep, and swelling strains observed at ~480°C and 60 dpa.

[1,5,6]. These researchers also demonstrated that if only the stress-free swelling rate is employed to derive the creep coefficients, the fall in the D coefficient is hidden by the stress-enhancement of swelling, and D appears to be independent of the swelling rate.

If it is assumed that $B_0 \approx 1 \times 10^{-6}$MPa^{-1} dpa^{-1}, which is a very typical value for austenitic stainless steels, we can calculate for the data at 480°C the estimated values of D that would result from using either the stress-free swelling or the actual swelling. Since there is only one fluence level, however, in each case the swelling rate employed will not be an instantaneous rate, but will be an average swelling rate defined as S/dpa. As shown in Table 1, the derived average D-values range from 0.28×10^{-2} to 0.17×10^{-2}MPa^{-1} as the actual swelling increases with stress. When the stress-free swelling values are used, however, D ranges 0.60×10^{-2} to 0.45×10^{-2}MPa^{-1}. This behavior is very consistent with that demonstrated by Garner and Toloczko in analyses of various US and French stainless steels [1].

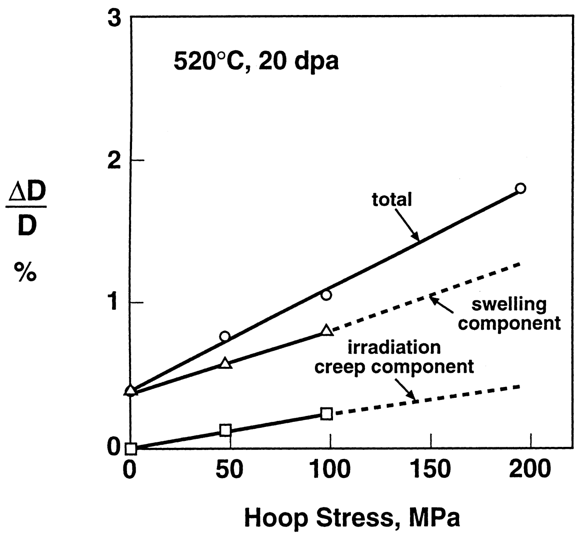

Fig. 6. Total strain, irradiation creep, and swelling (1/3 of swelling calculated from density change) strains observed at ~520°C and 20 dpa.

In the case of the data at 520°C and 20 dpa, the swelling levels at 20 dpa are much lower, and were probably zero for much of the 20 dpa exposure. If it is assumed that all creep strains arose from B_0 only, this would imply that B_0 is $\sim 1.7 \times 10^{-6}$ MPa^{-1}, very close to the usually assumed value of $\approx 1.0 \times 10^{-6}$ MPa^{-1}. Therefore, a value of D cannot be confidently extracted from these data, since the $D\dot{S}$ contribution is very small and the average swelling rate is probably not very close to the final instantaneous value.

In another experiment conducted at both 350°C and 420°C in the BOR-60 fast reactor in Dimitrovgrad, Russia, it was shown by Neustroev and Shamardin [7] that another heat of this steel also had values of B_0 and D (for the stress-free swelling case) of 1×10^{-6} MPa^{-1} dpa^{-1} and 0.6×10^{-2} MPa^{-1}, respectively. This implies that the creep coefficients for this steel are relatively independent of temperature over the range 350–520°C.

Table 1
Derived creep-swelling coupling coefficient at 480°C, assuming $B_0 = 1.0 \times 10^{-6}$ MPa^{-1} dpa^{-1}

Hoop stress (MPa)	Assuming stress-free swelling	Assuming stress- affected swelling
49	0.60×10^{-2} MPa^{-1}	0.28×10^{-2} MPa^{-1}
98	0.45×10^{-2} MPa^{-1}	0.17×10^{-2} MPa^{-1}
196	0.47×10^{-2} MPa^{-1}	0.18×10^{-2} MPa^{-1}

5. Conclusions

The swelling and irradiation creep behavior of a Russian variant of niobium-stabilized stainless steel derived from an irradiation experiment conducted in the BN-350 reactor are very similar to the behavior observed in non-Russian steels. Void swelling is enhanced by applied stresses and irradiation creep strains are linear in stress,with creep arising from two major components, one related to swelling and one independent of swelling. The derived values of creep rate $\overline{B}$ and estimates of the creep-swelling coupling coefficient D are also comparable to those of non-Russian steels.

When creep coefficients are derived using stress-free swelling values, it is known from other studies by Toloczko and Garner the onset of "creep disappearance" is masked by the stress-enhancement of swelling. When actual swelling values are employed, the creep-swelling coupling coefficient derived in this study at 480°C and 60 dpa falls from the usual "stress-free swelling" value of $\sim 0.6 \times 10^{-2}$ MPa^{-1} to $\sim 0.2 \times 10^{-2}$ in the "stress-affected swelling" case, consistent with the results of various earlier studies by Toloczko and Garner.

Acknowledgements

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