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Irradiation creep of 11Cr–0.5Mo–2W, V, Nb ferritic–martensitic, modified 316, and 15Cr–20Ni austenitic S.S. irradiated in FFTF to 103–206 dpa

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Abstract

The irradiation creep of 11Cr–0.5Mo–2W–0.2V–0.05Nb ferritic–martensitic (PNC-FMS), modified 316 (PNC316) and 15Cr–20Ni base austenitic S.S. were determined by the gas pressurized capsule irradiation test using MOTA in FFTF. The pressurized capsules and open tubes were irradiated at 678–943 K to a peak dose of 206 dpa. The irradiation creep coefficients were derived from the diametral change differences between the capsules and open tubes, accounting for the stress-induced swelling. The creep compliance B_0 and creep-swelling coupling coefficient D for PNC-FMS were found to be $0.43–0.76 \times 10^{-6}$ MPa^{-1} dpa^{-1} and $0.85–2.5 \times 10^{-2}$ MPa^{-1} for volumetric swelling, respectively. For both PNC316 and 15Cr–20Ni base S.S. the irradiation creep properties were very similar. B_0 and D range from 0.55 to -1.5×10^{-6} MPa^{-1} dpa^{-1} and from 1.2 to -2.8×10^{-3} MPa^{-1}, respectively.

1. Introduction

Core component materials for liquid metal fast breeder reactor (LMFBR) must be highly resistant to irradiation induced swelling and creep and also have a high temperature creep strength. Ferritic or martensitic S.S. has superior swelling resistance to austenitic stainless steel. However, the high temperature strength of austenitic S.S. tends to be superior. It was on this basis that the 11Cr–0.5Mo–2W–0.2V–0.05Nb ferritic–martensitic(PNC-FMS), modified 316 (PNC316), and 15Cr–20Ni base austenitic S.S. were developed by Japan Nuclear Cycle Development Institute (JNC) as candidate materials for long-life cores in large-scale fast breeder reactors [1–3]. PNC-FMS is a martensitic stainless steel having a small amount of ferrite in which the high temperature strength was improved by a V–Nb carbonitride precipitate and by using Mo and W for solution hardening. To improve the void swelling resistance and high temperature creep properties in the PNC316 and 15Cr–20Ni base, the minor elements (such as titanium, niobium, phosphorous, and boron) and the amount of cold-work were adjusted.

The irradiation creep of the PNC-FMS, PNC316, and 15Cr–20Ni base, which were determined by using gas pressurized capsules that were irradiated using MOTA in FFTF, are presented and discussed in this paper.

2. Experimental procedure

The representative chemical compositions of PNC-FMS, PNC316, and 15Cr–20Ni base specimens used in the irradiation tests are as following: PNC-FMS 11Cr–2.1W–0.1Mo–0.2V–0.04Nb–0.11C–0.04N; PNC316 16.5 Cr–13.8Ni–2.5Mo–0.82Si–0.03P–0.003B–0.08Ti–0.08Nb; and 15Cr–20Ni base 15.1Cr–19.7Ni–2.6Mo–0.75Si–0.03 P–0.003B–0.25Ti–0.11Nb.

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Table 1
Irradiation condition for pressurized and open tubes[a]

Material	Hoop stress (MPa)	Irradiation temperature (K)					
		678	713	768	823	878	943
PNC-FMS	0, 70, 100	95 dpa[b]	–	54 dpa[c]	97 dpa[c]	89 dpa	103 dpa
PNC316	0, 70, 100	206 dpa[b,c]	79 dpa[c]	71 dpa[c]	139 dpa	133 dpa	103 dpa
15Cr–20Ni	0, 70, 100	137 dpa[b,c]	–	71 dpa[c]	138 dpa	133 dpa	103 dpa

[a] Dpa is maximum displacement damage dose.
[b] Data used for determining creep-swelling coupling coefficient D.
[c] Data used for determining creep-compliance B_0.

PNC-FMS specimens were normalized at 1333 K for 10 min and then tempered at 1023 K for 600 min. A solution heat treatment of PNC316 and 15Cr–20Ni base specimens was conducted at 1353 K for 2 min and 1353 K for 1 min, respectively. Both alloys were subsequently cold-worked to about 20%. The gas-pressurized capsules were made from tubing of these alloys, which were 6.5 mm in diameter and 28 mm in length and had a 0.47-mm wall.

These pressurized capsules and open tubes were irradiated under the irradiation conditions shown in Table 1. The hoop stresses in the capsules were 70 and 100 MPa and the displacement damage ranged from 54 to 206 dpa. The outer diameters of pressurized capsules and open tubes were measured during the reactor shutdown intervals with a laser profilometer. Density measurements of the capsule tubes were performed to determine the stress-induced swelling component, which was used to subtract from the total strain to correctly evaluate the swelling-driven creep component. The creep compliance B_0 and creep-swelling coupling coefficient D of these core materials were determined for various temperature and displacement damage.

3. Results

3.1. Irradiation creep of PNC-FMS

The relationship between displacement damage and diametral changes at 678 K in the PNC-FMS capsules and open tubes, where the swelling is significant, are shown in Fig. 1. The diametral strain of open tubes (0 MPa) and the density change in the capsule tubes (70 and 100 MPa) and open tubes were all very small. At about 100 dpa the void swelling was very limited and the stress-induced swelling was negligible.

The relationship between displacement damage and creep strain at 678 K for PNC-FMS is shown in Fig. 1. The hoop creep strain, ε_H, was calculated using the following correlation:

$$\varepsilon_H = (\Delta D/D_0)_t - (\Delta D/D_0)_s, \quad (1)$$

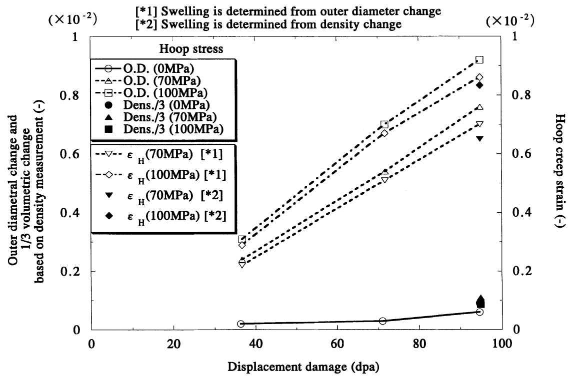

Fig. 1. Relationship between displacement damage and the diametral change and creep strain for PNC-FMS gas pressurized capsules.

where $(\Delta D/D_0)_t$ is the diameter change of the capsules (by irradiation and thermal creep and swelling) and $(\Delta D/D_0)_s$ is the swelling strain (determined by outer diameter changes in the open tubes and density changes in the capsule tubes. The hoop creep strain, ε_H, was converted to the equivalent creep strain, ε_{EQ}, using the correlation ($\varepsilon_{EQ} = 2/\sqrt{3} \times \varepsilon_H$) based on the Von Mises theory.

The hoop creep strain shown in Fig. 1 only corresponds to the irradiation creep strain at 678 K, since thermal creep is negligible in this temperature range. It shows that irradiation creep strains increase almost linearly with increasing displacement damage under hoop stress conditions of 70 and 100 MPa.

3.2. Irradiation creep of PNC316 and 15Cr–20Ni base S.S.

The relationship between displacement damage and diametral changes at 678 K for PNC316 and 15Cr–20Ni base pressurized capsules are shown in Figs. 2 and 3, respectively. The measured one-third density changes (1/3 volumetric change) in these capsule tubes were slightly higher than those for the open tubes.

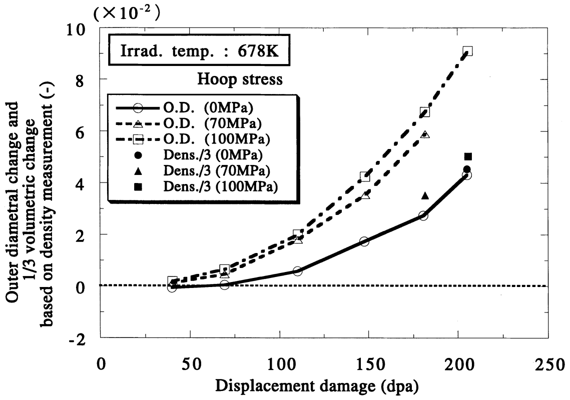

Fig. 2. Relationship between displacement damage and diametral change for PNC316 gas pressurized capsules.

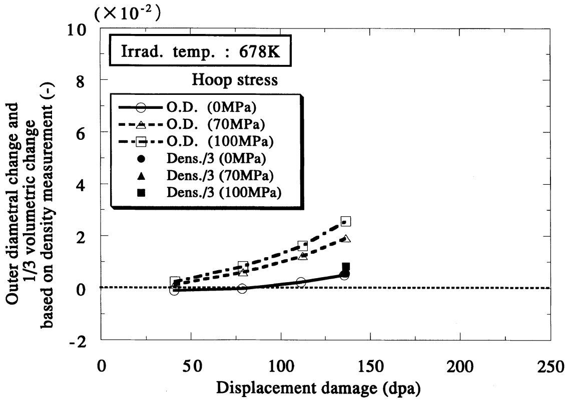

Fig. 3. Relationship between displacement damage and diametral change for 15Cr–20Ni base S.S. gas pressurized capsules.

The stress-induced swelling occurred at both 70 and 100 MPa.

The relationship between displacement damage and equivalent creep strain at 678 K for PNC316 is shown in Fig. 4. The irradiation creep strain, based on swelling determined from density changes in the capsule tubes, was smaller than outer diameter changes. For 15Cr–20Ni base tubes the behavior was similar. This is because the stress-induced swelling is not negligible in PNC316 and 15Cr–20Ni base tubes. The creep-swelling coupling coefficient was derived by using the density measurement data correctly to determine the amount of void swelling in pressurized capsules. The irradiation creep strains in both PNC316 and 15Cr–20Ni base tubes increase almost linearly with increasing displacement damage in the low displacement damage levels. But at high displacement damage level, where swelling occurs, the irradiation creep strain increases non-linear with an increase in displacement damage.

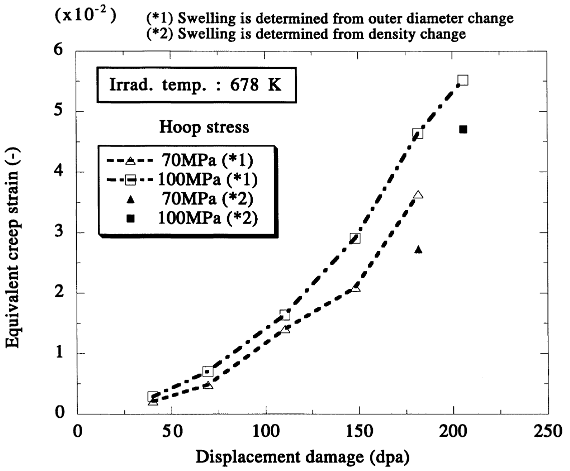

Fig. 4. Relationship between displacement damage and creep strain for PNC316.

4. Discussion

The irradiation creep can be expressed in the general form [4]:

$$\varepsilon_{EQ}/\sigma_{EQ} = B_0\phi_t + DS, \tag{2}$$

where ε_{EQ} and σ_{EQ} are the equivalent strain and stress, ϕ_t the displacement damage in dpa, S corresponds to the volumetric swelling, B_0 the creep compliance of irradiation creep deformation, and D is the creep-swelling coupling coefficient for irradiation creep deformation.

The creep compliance B_0 was determined based on the following correlation using the creep data at the appropriate range of displacement damage and temperature, as shown in Table 1, where the strain caused by swelling and thermal creep was negligible:

$$B_0 = \varepsilon_{EQ}/(\sigma_{EQ}\ \phi_t), \tag{3}$$

where the B_0 values determined for PNC-FMS, PNC316 and 15Cr–20Ni base are shown in Fig. 5. B_0 of PNC-FMS is 0.43–0.76 $\times 10^{-6}$ MPa^{-1} dpa^{-1}, which is almost the same as 0.44–1.0 $\times 10^{-6}$ MPa^{-1} dpa^{-1} for martensitic steel EM10, HT9 and 9Cr–1Mo and ferritic–martensitic steel EM12 [5–8]. PNC316 and 15Cr–20Ni base show similar irradiation creep behavior. Their range of B_0 is 0.55–1.5 $\times 10^{-6}$ MPa^{-1} dpa^{-1}, which is the typical value for 20% CW316 and CW316Ti [6,9–11]. B_0 tends to decrease with increasing irradiation temperature, which suggests the possibility of temperature dependence, as shown in Fig. 5.

The creep-swelling coupling coefficient D was determined using the displacement damage and temperature data in Table 1 (where swelling occurred) in the following correlation:

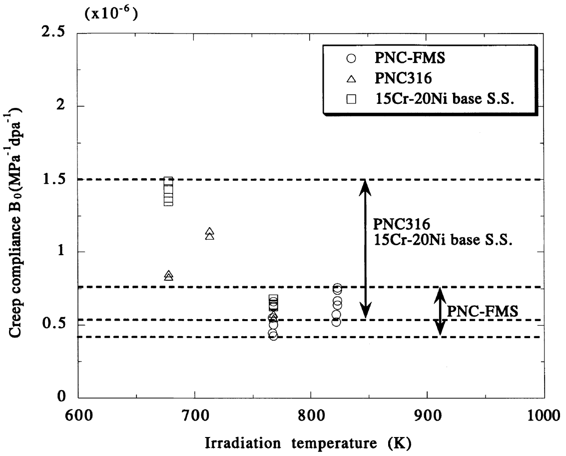

Fig. 5. Creep compliance B_0 for PNC-FMS, PNC316 and 15Cr–20Ni base S.S.

$$D = (\varepsilon_{EQ}/\sigma_{EQ} - B_0\phi_t)/S. \quad (4)$$

For PNC-FMS, D was determined using the average value of B_0 because the temperature range used to determine D was different from that for B_0. In the case of PNC316 and 15Cr–20Ni base, D was determined using B_0 of the irradiated specimens under the same temperature and pressure conditions and using the density change measurement data of the pressurized capsules, because the stress-induced swelling was not negligible. The D values for PNC-FMS, PNC316 and 15Cr–20Ni base are shown in Fig. 6. For PNC-FMS tubes D was 0.85–2.5 $\times 10^{-2}$ MPa^{-1}, which is slightly larger than those of other martensitic steels such as HT9 and 9Cr–1Mo, 0.6–1.4 $\times 10^{-2}$ MPa^{-1} [6–8,12]. D was similar for

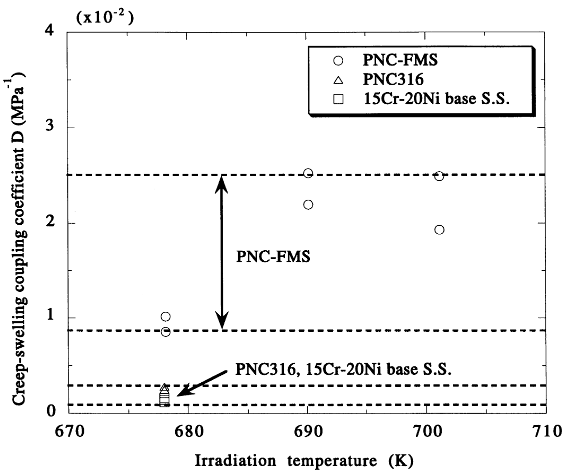

Fig. 6. Creep-swelling coupling coefficient for PNC-FMS, PNC316 and 15Cr–20Ni base S.S.

both PNC316 and 15Cr–20Ni base, 1.2–2.8 $\times 10^{-3}$ MPa^{-1}, which is similar to CW316 and CW316Ti [6,10,11]. It is difficult to determine D values accurately at higher temperature because the swelling level is low at high temperature. The dependence of D on the irradiation temperature is uncertain.

5. Conclusions

In this study, the irradiation creep of PNC-FMS, PNC316 and 15Cr–20Ni base S.S. were determined by means of gas pressurized capsules and open tubes irradiated in the MOTA of FFTF. The results are summarized as follows:

1. The PNC-FMS swelling was very low, so the stress-induced swelling was negligible. The preciously derived creep compliance B_0 and creep-swelling coupling coefficient D value are 0.43–0.76 $\times 10^{-6}$ MPa^{-1} dpa^{-1} and 0.85–2.5 $\times 10^{-2}$ MPa^{-1} for volumetric swelling, respectively.
2. Irradiation creep properties for both PNC316 and 15Cr–20Ni base are very similar. Their B_0 and D values were found to be 0.55–1.5 $\times 10^{-6}$ MPa^{-1} dpa^{-1} and 1.2–2.8 $\times 10^{-3}$ MPa^{-1}, respectively, by accounting for the stress-induced swelling in the pressurized capsules.

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