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Effect of chemical composition on irradiation creep of stainless steels irradiated in the BOR-60 reactor at 420 °C

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Abstract

The irradiation creep of six steels was investigated. For these steels, the Cr–Ni equivalents were calculated and the dependences of creep moduli on Ni equivalent were plotted. Pressurized tubes made from these steels were irradiated in different cells in row 6 of the BOR-60 reactor. The maximum damage doses achieved were about 60 and 100 dpa at irradiation temperature of 420 °C in various experiments. The levels of specified stresses changed from 0 to 320 MPa. The specimens were periodically removed from the reactor during refueling to measure their strain and then were returned to the reactor. The creep modulus *B* decreases with an increase of Ni equivalent over 16%. The dependence of creep modulus on Ni equivalent is similar to the dependence swelling on Ni.

1. Introduction

Irradiation creep is of the greatest importance in thick-walled elements of internals of different reactors if there are temperature and damage dose gradients over the thickness of internals. This causes swelling gradients and large stresses [1,2]. Irradiation creep in this case leads to stress relaxation and is considered as a positive radiation phenomenon causing a decrease in stress gradients and an increase in the internals service life. It results in the necessary investigation of irradiation creep at temperatures typical for internals, i.e. at 300–460 °C, and at respective damage doses up to 50–100 dpa.

Besides, at these temperatures there is radiation-induced segregation of some elements and precipitation of radiation-induced and radiation-stimulated phases that result in sharp change of Cr–Ni equivalent inside the grain and along the grain boundaries, near and far from defect sinks [3,4]. Such a change of chemical composition makes it necessary to investigate the irradiation creep versus content of some elements and, in particular, versus Cr–Ni equivalents for different steels.

Investigations of irradiation creep of austenitic steels with different content of Cr and Ni irradiated in different reactors were performed previously [5–10], but such results for steels irradiated in the BOR-60 reactor were not obtained. The present paper is devoted to investigation of effect of Ni content (Ni equivalent) on irradiation creep of six steels irradiated in the BOR-60 reactor.

2. Experimental details

The gas-pressurized specimens for irradiation creep investigation were made of steels (#1) 0.07C–12.5Cr–12.1 Ni–3.1Mo–0.11Nb–1.55Ti–0.47Si–3.0Mn, (#2) 0.05C–15.7Cr–15.3Ni–2.3Mo–0.06Nb–0.35Ti–0.33Si–1.1Mn–0.11Sc–0.004B, (#3) 0.05C–14.5Cr–23.1Ni–0.45Mo–1.35 Ti–0.65Si–0.45Al–0.88Mn–4W, (#4) 0.02C–19.3Cr–45 Ni–4.7Mo–0.63Nb–0.09Si–2Mn, (#5) 0.05C–15.7Cr–15Ni–2.3Mo–0.56Nb–0.53Si–1.1Mn, (#6) 0.12C–12.7 Cr–1.5Mo–0.44Nb–0.16Si–0.2V–0.004B. The equivalents of $[Cr]_{Eq}$ and $[Ni]_{Eq}$ measured in percentage for the investigated steels were determined using the following relationship [11] and the results are given in Table 1:

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Table 1
Cr–Ni equivalents of investigated steels

# Steels	Cr equivalent (%)	Ni equivalent (%)
1	20.6	15.9
2	20.5	17.4
3	24	25.3
4	27.7	46.6
5	20.7	17.4
6	17.1	3.6

$$[\mathrm{Cr}]_{\mathrm{Eq}} = [\mathrm{Cr}] + 5.5[\mathrm{Al}] + 5[\mathrm{V}] + 2[\mathrm{Si}] + 1.75[\mathrm{Nb}] + 1.5[\mathrm{Mo}] + 1.5[\mathrm{Ti}] + 0.75[\mathrm{W}], \quad (1)$$

$$[\mathrm{Ni}]_{\mathrm{Eq}} = [\mathrm{Ni}] + 30[\mathrm{C}] + 25[\mathrm{N}] + 0.5[\mathrm{Mn}] + [\mathrm{Co}] + 0.3[\mathrm{Cu}]. \quad (2)$$

The Cr equivalents for austenitic steels range from 20% to 28%, and the Ni equivalent covers a much wider range – from about 16% to 47%. Steels (#1)–(#5) were austenized at 1040–1050 °C for 30 min, and steel (#6) – water cooling after 1050 °C for 30 min and annealing at 770 °C for 1 h in vacuum.

The pressurized tubes were irradiated in material test assemblies in different cells in row 6 of the BOR-60 reactor at 420 °C in flowing Na. The maximum damage doses on specimens in some experiments reached about 60–100 dpa. The maximum rate of damage dose accumulation was practically the same for the investigated specimens and was about 5×10^{-7} dpa s^{-1}. The levels of specified hoop stresses at working temperatures changed from 0 to 320 MPa. The filler-gas was argon. The specimens were 60 mm long, with an outer diameter of 6.0, 6.9, 7.0 mm and a wall thickness of 0.3, 0.4, 0.3 mm, respectively. The specimens were periodically removed from the reactor during refueling to measure their length and strain in two mutually perpendicular directions and then were returned to the reactor. The length and outer diameter were measured by contact method with the accuracy of ±5 μm.

3. Results and discussion

The dose dependencies of diametral deformation of the gas-pressurized tubes constructed from the different stainless steels are presented in Figs. 1 and 2. It is evident that at the indicated stresses, the strain versus dose dependence can be described by a linear dependence with a certain incubation period as well as in our other experiments at irradiation temperatures of 350 and 420 °C [7,8]. The incubation period is approximately the same for the different steels and is almost independent of stress in the stress range from 80 to 180 MPa. At larger stresses the strain begins almost without incubation period. Deformation of some specimens that lost pressure

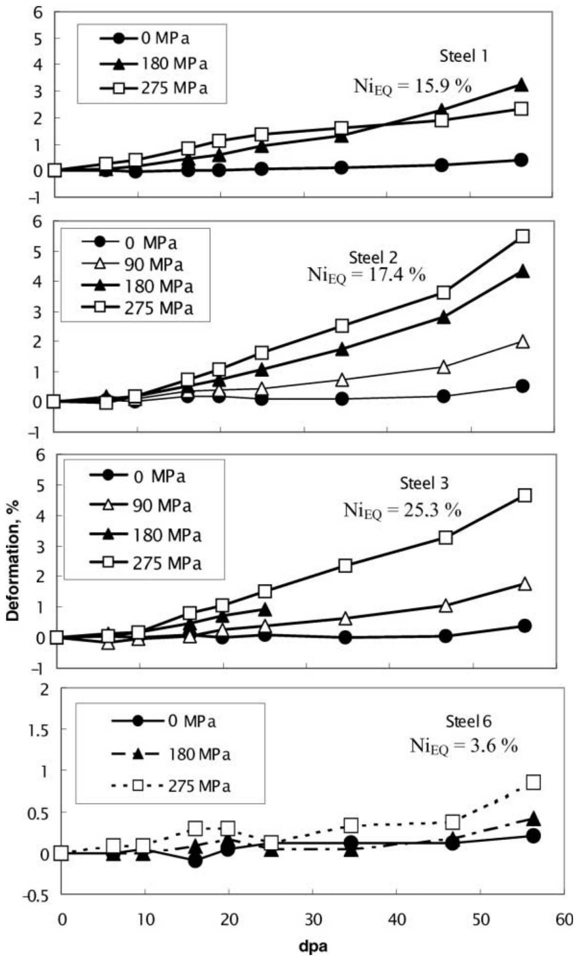

Fig. 1. Diameter change observed in gas-pressurized tubes constructed from various steels irradiated in BOR-60 reactor at 420 °C.

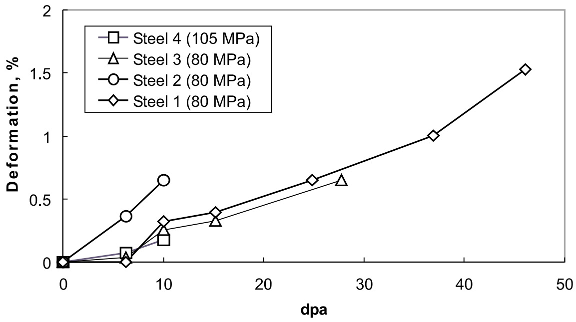

Fig. 2. Diameter change observed in gas-pressurized tubes constructed from various steels irradiated in BOR-60 reactor at 420 °C.

during irradiation (specimens of steel (#1) with a stress level of 275 MPa) changes linearly too, but at a different strain rate. Creep of the ferritic–martensitic steel is lower than that of all the austenitic steels, and even at high stresses, it does not exceed 1% at a dose level of 56 dpa (Fig. 1, steel (#6)).

To calculate the creep modulus, B, of the steels, the following relationship was used:

$$\frac{\varepsilon_{EQ}}{\sigma_{EQ}} = \frac{4}{3} \times \frac{\varepsilon_H}{\sigma_H} = B, \quad (3)$$

where ε_{EQ} is equivalent plastic strain, σ_{EQ} is the von Mises effective stress, and ε_H and σ_H are the hoop strain and stress, respectively. 'B' is called the creep modulus.

Transition from the measured diametral strain ($\Delta D/D$) to hoop strain (ε_H) was performed by the formula [10]:

$$\varepsilon_H = A\Delta D/D, \quad (4)$$

where the constant A in our experiment was equal to about 1.05.

The steel creep modulus (B_{EQ}) calculated by this method for different displacement dose levels are presented in Fig. 3. It is preferable to compare the creep moduli under equal irradiation conditions. It is possible to perform such a comparison for steels that differ in composition and Cr–Ni equivalents that were irradiated within one floor of the material test assembly. For stress levels of 80, 105, 180 MPa such comparison is given in Fig. 3, where the creep moduli of the investigated steels are presented versus Ni equivalent for different damage doses. It is obvious that this dependence follows the dependence of swelling on Ni content (Fig. 4) [12]. It is an important result that confirms the interaction of swelling and creep processes. The first observation on such linear interconnection of swelling rates and creep moduli for Russian austenitic and ferritic–martensitic steels was made in Ref. [13].

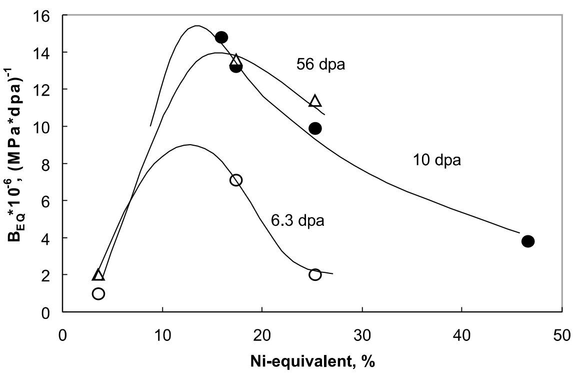

Fig. 3. Creep modulus (B_{EQ}) as a function of Ni equivalent for steels irradiated in the BOR-60 reactor at 420 °C.

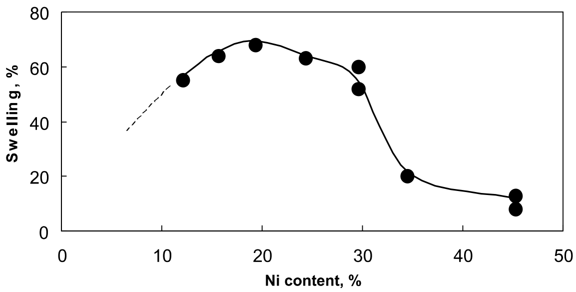

Fig. 4. Swelling of Fe–15Cr–XNi alloys observed in EBR-II at 454 °C and 45 dpa.

It was shown that the small swelling rate in the ferritic–martensitic steel corresponded to a small creep rate, and the higher creep modulus in the 16Cr–15Ni base austenitic steel also corresponded to a higher swelling rate. Similar results when comparing the creep and swelling processes of 316 stainless steel, 15Cr–20Ni austenitic steel, and HT9 ferritic–martensitic steel are obtained in Ref. [6]. Direct comparison of this kind can be conducted for creep strains in the presence of swelling at sufficiently high damage doses (over 45 dpa, Fig. 1) in the present experiment. Using the known formula connecting the creep strain rate $\dot{\varepsilon}_{EQ}$ and swelling rate $\dot{S}$

$$\frac{\dot{\varepsilon}_{EQ}}{\sigma_{EQ}} = B_O + D \times \dot{S}, \quad (5)$$

let us determine the D coefficient. This occurs at damage doses over 45 dpa (Fig. 1), which is typical for austenitic steels at such irradiation temperatures. D values for the different steels are presented in Table 2. B_O according to our results [7,8] and results of other investigators [5,6,9,10] was taken to be equal to 1×10^{-6} MPa^{-1} dpa^{-1} for austenitic steels. Modulus D can be easily determined from Eq. (5) and the current swelling rate at damage dose over 45 dpa. From the viewpoint of comparing D values, it is interesting to divide the stress range into two parts with respect to the initial yield strength of steel. The first range is when stresses are less than yield strength of this steel (80–180 MPa) and the second range is when the stress level is comparable with the initial

Table 2
D values of the investigated steels irradiated at 420 °C for different stress ranges

# Steels	$D \times 10^{-2}$ (MPa^{-1})	
	90–180 MPa	275 MPa
1	1.1	–
2	1.0–1.1	0.6–0.8
3	0.9	0.6–0.7
5	1.0 [8]	0.6 [8]
6	0.4	0.6

yield strength of the steel at these temperatures (over 180 MPa). *D* values of the steels for these stress ranges are presented in Table 2.

The table shows that at high stresses, *D* values for austenitic steels is somewhat less than the similar modulus for lower stress levels. Though for ferritic–martensitic steel this behavior is not observed. It is known that *D* decreases with an increase of the swelling rate [8,9] and an increase in the swelling rate with stress must lead to decrease of modulus *D*, which is obvious from comparison of moduli *D* at stresses of 90–180 and 275 MPa.

4. Conclusions

The irradiation creep was investigated for five austenitic stainless steels and one ferritic–martensitic steel differing in Cr–Ni equivalents and irradiated at 420 °C in the BOR-60 reactor.

The creep modulus is minimal for the ferritic–martensitic steel and maximal for the steels with Ni equivalent of 16–17%. Further increase in Ni equivalent leads to a decrease in creep modulus, just as swelling of steels decreases with an increase in Ni equivalent over 15%.

Considering the creep modulus as the sum of two items and assuming that $B_O = 1 \times 10^{-6}$ MPa^{-1} dpa^{-1} for austenitic steels, we determined that *D* for the different austenitic steels was in the range $(0.9–1.1) \times 10^{-2}$ MPa^{-1} for stresses of 90–180 MPa and $(0.6–0.8) \times 10^{-2}$ MPa^{-1} for stresses of 275 MPa.

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