Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Nuclear Materials 329–333 (2004) 612–616
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Experimental investigation of stress effect on swelling and microstructure of Fe–16Cr–15Ni–3Mo–Nb austenitic stainless steel under low-temperature irradiation up to high damage dose in the BOR-60 reactor

V.S. Neustroev *, Z.E. Ostrovsky, V.K. Shamardin

FSUE 'SSC RF RIAR', Dimitrovgrad-10, Ulyanovsk region 433510, Russia

Abstract

The present paper was devoted to investigation of the stress effect on swelling and microstructure evolution of the Fe–15.8Cr–15.3Ni–2.8Mo–0.6Nb steel irradiated in the BOR-60 reactor at temperatures from 395 to 410 °C and damage doses from 79 to 98 dpa. Was found out that the stress increase leads to an increase of swelling, that can be associated with a decrease in incubation period with a practically constant swelling rate. Voids concentration increases at the first stage of irradiation when the void sizes are practically constant, and then the concentration reaches some saturation and swelling increase is caused by void growth.

1. Introduction

Evolution of microstructure under low irradiation temperature, swelling and swelling-induced embrittlement of austenitic stainless steels are the topics of this investigation, because these determine the service life of reactor internal components made from these steels in many cases [1–3]. These phenomena take place in thick-walled internal components, which are of irregular shape, under temperature and neutron flux gradients [4]. Investigations devoted to study of the stress effect on swelling have been being actively undertaken in our country and abroad for the last 20 years [5–12]. The issue related to the porosity evolution and microstructure as a whole was poorly covered due to the variety of experimental conditions, different types of steels and their initial states.

In this regard, the present paper is devoted to investigation of the stress effect on swelling and microstructure evolution of the Fe–0.46C–16Cr–15Ni–3Mo–Nb annealed austenitic steel that has been irradiated in the BOR-60 reactor at temperatures and damage doses which can be reached in operation of VVER internal materials.

2. Materials, specimens and methods of testing

Gas-pressurized specimens made from annealed Fe–0.46C–16Cr–15Ni–3Mo–Nb steel irradiated in the BOR-60 reactor were selected for investigation. Each specimen was cut into four fragments with lengths of about 40 mm. The outermost specimens were used for cutting specimens for transmission electron microscopy (TEM) and central ones were used for studying the changes in material cladding density. Eight specimens were cut out at the levels of +30 and +150 mm above the center of the reactor core to perform electron microscopy. A JEM-2000FX II electron microscope was used for examination of the finished objects, which were

* Corresponding author. Tel.: +7-84235 32021; fax: +7-84235 35843.
E-mail address: fae@niiar.ru (V.S. Neustroev).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2004.04.103

prepared in accordance with the standard technique. The microstructure parameters were determined with the following relative errors: 10–15% – sizes of the voids, loops, and 30–35% for their concentration. The material density for the specimens was determined using hydrostatic weighing (HW) with the relative error of 0.4%.

3. Irradiation conditions

The specimens were irradiated in the material test assemblies in different cells of 6th row of the BOR-60 reactor. The neutron fluence with $E > 0.1$ MeV was 23.8×10^{26} m^{-2}, corresponding to the damage dose of 99 dpa. The irradiation temperature of specimens varied from 395 to 410 °C. The irradiation conditions for all specimens are given in Table 1. The damage dose rates were 4.8×10^{-7} dpa/s for the specimens with the damage dose of 99 dpa and 3.9×10^{-7} dpa/s for 79 dpa. He-generation in the BOR-60 is 0.1–0.4 appm/dpa.

4. Results of examination and their discussion

The results obtained including the measured data on volume fraction of the voids and swelling are shown graphically in Fig. 1.

The data were processed using the least-squares method on the assumption that there is a linear swelling dependence on dose. These dependences demonstrate that the swelling rate weakly depends on the stress level and it can be taken to be constant and equal to 0.14% per dpa under the given irradiation conditions. The incubation period shortens significantly with increasing stress (Fig. 2).

The linear swelling dependence of stress is plotted for each damage dose for stress levels in the range from 0 to 160 MPa. It is possible to describe these dependences in the form of Eqs. (1) and (2) [4,9,13], which are used for description of the similar data in other investigations (Eq. (2) is used more often):

$$S = S_0 + B\sigma, \tag{1}$$

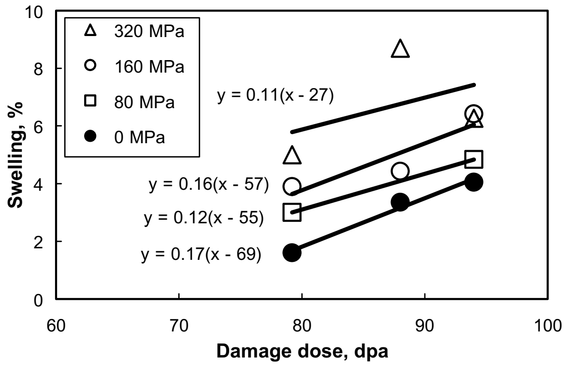

Fig. 1. Dose dependency of Fe–16Cr–15Ni–3Mo–Nb steel swelling with different levels of stress in specimens.

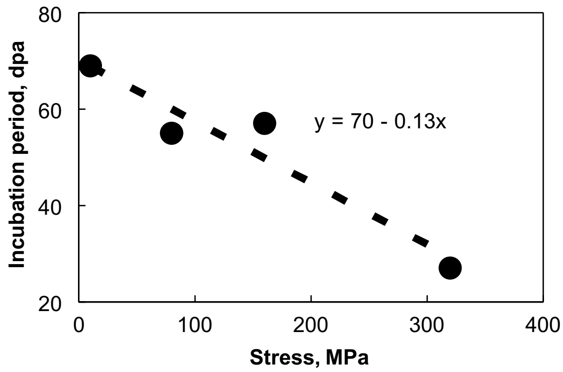

Fig. 2. Incubation period of Fe–16Cr–15Ni–3Mo–Nb steel swelling as a function of stress.

Table 1
Vacancy porosity parameters in specimens

Specimen no.	Irradiation condition			Vacancy porosity parameters		
	Dose (dpa)	T (°C)	Stresses (MPa)	Average size of voids (nm)	Concentration of voids (10^{15} cm^{-3})	Swelling (%)
13	98	395	0	21.2	3.1	2.2
9			80	20.8	3.4	2.3
1			160	22.7	4.1	3.7
5			320	25.4	2.9	3.9
16	79	410	0	20.7	2.4	1.6
12			80	22.1	3.8	3
4			160	24.4	3.8	3.9
8			320	27.3	3.2	5

$$S = S_0(1 + P\sigma), \quad (2)$$

where S – stress-induced swelling, S_0 – stress-free swelling, B and P – coefficients, σ – hoop stresses.

Fig. 3 compare two versions Eqs. (1) and (2) and shows the differences in swelling from an extrapolation of the linear dependences at lower stress levels to a stress of 320 MPa. These data allow for concluding that there is slightly different effect of higher stresses on radiation swelling of the cladding material in comparison with low stresses. Actually essentially higher strain of specimens having the stress level of 320 MPa was discovered at the beginning of irradiation in creep tests. At the same time the other specimens of lower stresses were not subjected to strain during a certain 'incubation period' [14].

This initial strain in specimens having high level of stresses can be compared with the effect of initial cold or thermal strains on steel swelling [13,15,16] in the case when the density of dislocations increases sharply because of the strain and causes the decrease in swelling.

The constant P values are in the range from 3.8×10^{-3} to 8.4×10^{-3} MPa^{-1} in the swelling-stress relationship that is described by Eq. (2). These data are in good agreement with the similar evaluation of this constant $(4–9)\times10^{-3}$ MPa^{-1} made for austenitic steels, which have been irradiated in different reactors [9,13].

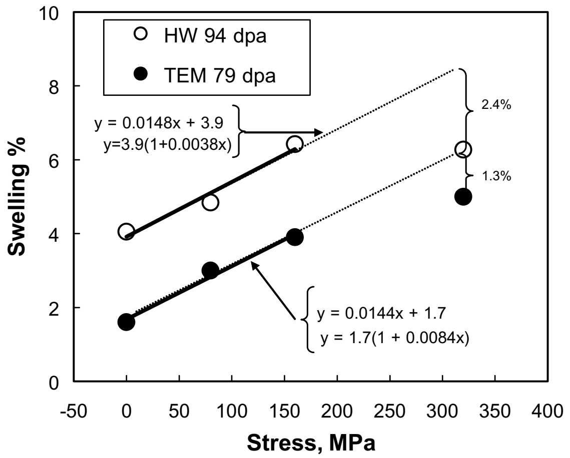

Fig. 3. Swelling as a function of stresses for Fe–16Cr–15Ni–3Mo–Nb steel. Figure also shows the deviations from linear dependences of the swelling at a stress of 320 MPa (%).

5. Transmission electron microscopy

The structure of irradiated gas-pressurized specimens made from annealed Fe–16Cr–15Ni–3Mo–Nb steel was subjected to TEM examination. Eight specimens were used for examination. The irradiation conditions and parameters of vacancy porosity of these specimens are given in Table 1.

The given parameters of vacancy porosity indicate that the swelling increase caused by stress increasing is mainly associated with grow of the average size of voids but at the same time their concentration changes insignificantly.

The measurements of dislocation loop sizes and density did not reveal a considerable dependence on irradiation parameters (temperature and dose) and stress value in cladding. The average diameter of loops is estimated as 9.5 nm with the measurement error of 20% and density is estimated as 5×10^{16} cm^{-3} with the error

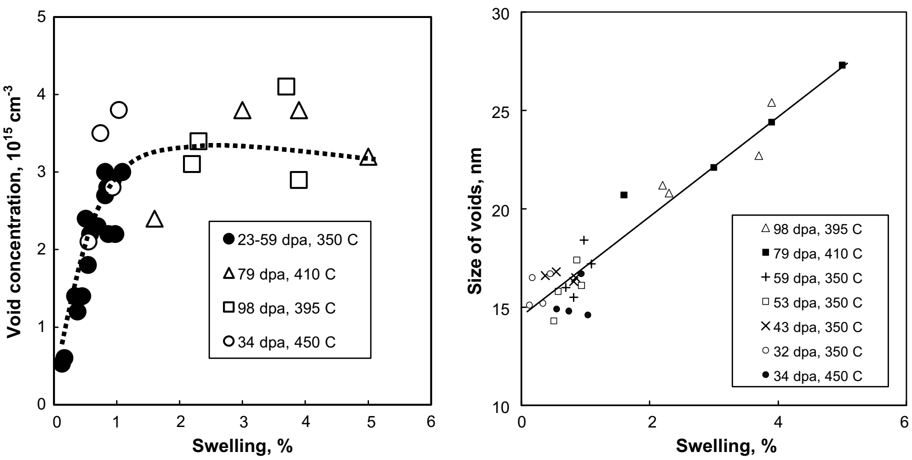

Fig. 4. Concentration and size of voids as a function of swelling in Fe–16Cr–15Ni–3Mo–Nb steel irradiated in BOR-60 at the 350–450 °C up to different damage doses under the stresses and without them.

of 30%. Analysis of line directions of zero contrast in foils having different orientations revealed the loops with habit planes of {1 1 0} and {1 2 0} in the examined specimens. No regularity in reorientation of loops under the effect of stress in the cladding was revealed.

It is interesting to carry out the joint analysis of all results related to microstructure examination of annealed Fe–16Cr–15Ni–3Mo–Nb steel, which has been irradiated in the BOR-60 reactor in experiments with gas-pressurized fuel pins and tubes. There were four of such experiments [10–12 and the present work]. Sizes of voids did not change at low damage doses with the stress. But the size of voids increased when the stresses increased at slightly higher temperatures. It is safe to say that the concentration of voids increased with increasing stress at low swelling. This conclusion is more evident if we analyze the porosity parameters as a function of swelling.

The concentration and size of voids as a function of swelling are shown in Fig. 4. The data on porosity, which have been obtained in all four experiments, are combined here irrespective of the stress level, damage dose and irradiation temperature.

This figure suggests that the ensemble of voids has got the same stages in its development at irradiation temperatures of 350–450 °C: the first stage – incubation period, when sizes of voids change insignificantly but their concentration increases. The second stage begins when the concentration of voids reaches the saturation point and a decrease in void concentration can be observed because of their coalescence. Swelling grows at this stage because of void increase in size. The transition from one stage to another one can take place under these irradiation conditions when swelling makes up 1.5–3%.

The role of stress in this case assumes the displacement of the void ensemble toward larger size leading to greater swelling. So it is possible to conclude that stress accelerates the void ensemble evolution. The incubation period shortens in this case as was proved with the study of material density change.

6. Conclusions

1. The results of examinations performed on gas-pressurized specimens made from annealed Fe–16Cr–15Ni–3Mo–Nb steel irradiated in BOR-60 in the temperature range of 395–410 °C and damage dose up to 98 dpa revealed that the increase of stress results in radiation swelling increase.
2. The proportionality constants derived to describe the linear dependence of swelling on stress are in good agreement with similar values determined for other austenitic steels irradiated in different reactors under similar irradiation conditions.
3. Swelling increase with increasing stress can be associated with a reduction in the swelling incubation period required to obtained steady swelling rate and with an increase of the average void diameter under the given irradiation conditions.
4. Summarization of all data on examination of microstructure in experiments with gas-pressurized specimens made from annealed Fe–16Cr–15Ni–3Mo–Nb steel which were performed in RIAR allowed that concentration of voids increases in the first stage of irradiation when the size of voids is practically constant, then the concentration of voids reaches saturation and swelling increases with void increase in size.

References

[1] F.A. Garner, L.R. Greenwood, D.L. Harrod, in: Sixth International Symposium on Environment Degradation of Materials in Nuclear Power Systems – Water Reactors, The Minerals, Metals, and Materials Society, 1993, p. 783.
[2] V.S. Neustroev, V.K. Shamardin, Ostrovsky et al, in: Proceedings of Fourth International Symposium on Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, Fontenvraud, France, vol. 1, 1998, p. 261.
[3] S.I. Porollo, A.N. Vorobjev, Yu.V. Konobeev, et al., J. Nucl. Mater. 258–263 (1998) 1613.
[4] V.M. Troyanov, Yu.I. Likhachev, M.Ya. Khmelevsky, et al., in: Proceedings of the 5th Russia Conference on Reactor Material Science, Dimitrovgrad, vol. 2, 1998 p. 3 (in Russian).
[5] J.F. Bates, E.R. Gilbert, J. Nucl. Mater. 71 (1978) 286.
[6] D.L. Porter, F.A. Garner, ASTM STP 870, American Society for Testing and Materials, Philadelphia, 1985, p. 233.
[7] G. Arnand et al., in: Proceedings of the Conference on Irradiation Behavior of Metallic Materials for Fast Reactor Core Components, Ajaccio, Corsica, France (1979), Gif-sur-Ivette, 1979, p. 367.
[8] K. Herschbach, W. Schneider, H.J. Bergmann, ASTM STP 1046, American Society for Testing and Materials, Philadelphia, vol. 2, 1990, p. 570.
[9] R. Hubner, K. Ehrlich, ASTM STP 1366, American Society for Testing and Materials, West Conshohocken, PA, 2000, p. 778.
[10] V.A. Krasnoselov, A.N. Kolesnikov, V.I. Prokhorov et al., RIAR Preprint-16 (469) – Dimitrovgrad, 1981 (in Russian).
[11] V.K. Shamardin, V.S. Neustroev, V.N. Golovanov et al., ASTM STP 1046, American Society for Testing and Materials, Philadelphia, 1990, p. 753.
[12] V.S. Neustroev, Z.E. Ostrovsky, V.K. Shamardin, The Physics of Metals and Metallography 86 (1) (1998) 79.
[13] F.A. Garner, in: Materials Science and Technology: A Comprehensive Treatment, vol. 10A, VCH, 1994, p. 419.

[14] V.S. Neustroev, V.K. Shamardin, IAEA-TECDOC-1039, Vienna, 1998, p. 179.
[15] V.S. Neustroev, T.M. Bulanova, Ostrovsky et al., RIAR Proceedings, Dimitrovgrad, 1997, vol. 1 p. 15 (in Russian).
[16] V.S. Neustroev, M.G. Bogolepov, V.N. Golovanov, et al., Voprosy atomnoy nauki I tehniki. Ser.: Atomnoe materialovedenie, 1 (24) (1987) 17 (in Russian).