Investigation of Irradiation Creep Fe-18Cr-10Ni-Ti Stainless Steel in Experiments with Gas-pressurized Tubes in Reactor BOR-60

Ye.I. Makarov, V.S. Neustroev, S.V. Belozerov

*JSC "State Scientific Center - Research Institute of Atomic Reactors",

Dimitrovgrad-10, Ulyanovsk region, 433510

e-mail: neustroev@niiar.ru

Keywords: stainless steel, neutron irradiation, irradiation creep, gas-pressurized tubes, creep modulus.

Abstract: The report describes the historical aspects held in JSC "SSC - NIIAR" studies of irradiation creep of austenitic stainless steels.

1. Introduction

Irradiation creep is observed in all nuclear reactor elements and structures provided that stress can occur there. Irradiation creep deformation is an important component in deformation of fuel assemblies hexagonal wrappers in fast neutron reactors at low irradiation temperatures, as well as an important component of deformation of fuel elements under standard operation conditions. Irradiation creep behavior in thick-walled elements of various reactor vessel internals in case of temperature and damage dose gradients across the thickness of products causing occurrence of high stresses is also important [1].

Irradiation creep in this case leads to stress relaxation and acts as the positive effect of radiation, leading to a decrease in the gradients of stress and improve resource of the internals. These examples are allowed to justify the need for studies of irradiation creep at temperatures of 320-400°C, characteristic for the lower parts of the hexagonal fuel assemblies and fuel rods covers fast-neutron reactors, and internals of VVER reactors and related damaging doses of 50-100 dpa.

Most studies of irradiation creep of steels and its relationship with the swelling was carried out with gas-pressurized tubes made from unstabilized or stabilized with titanium steels, austenitic AISI 316, AISI 304L, PCA [2-7] and ferritic-martensitic steels [7]. The researchers of our country in the late 70s and early 80s of the XX century have focused their efforts on the study of creep of austenitic steels stabilized with niobium [8-11]. Next experiments were carried out over a wider range of irradiation temperature and damaging doses.

In the early 80-ies, irradiation technique has been developed in experimental studies of irradiation creep based on the use of special materials science assemblies of BOR-60 that prepared for long-term experiments in reactor with intermediate measurements of the size of the gas-pressurized samples. To increase the irradiation temperature of the specimen from 330^{o}C up to 400^{o}C we used material with a high initial density (in this case tungsten) occur at the lower levels of assembly.

The resulting baseline information for non-destructive studies of gas-pressurized samples (change size in length and diameter of the sample) permitted to construct the dose dependence of the dimensional changes for each sample at a given irradiation temperature.

Based on these results, data were obtained on the magnitude of the creep modulus of the studied steels of various factors and the relationship between creep rate and the rate of swelling, see for example [9-12].

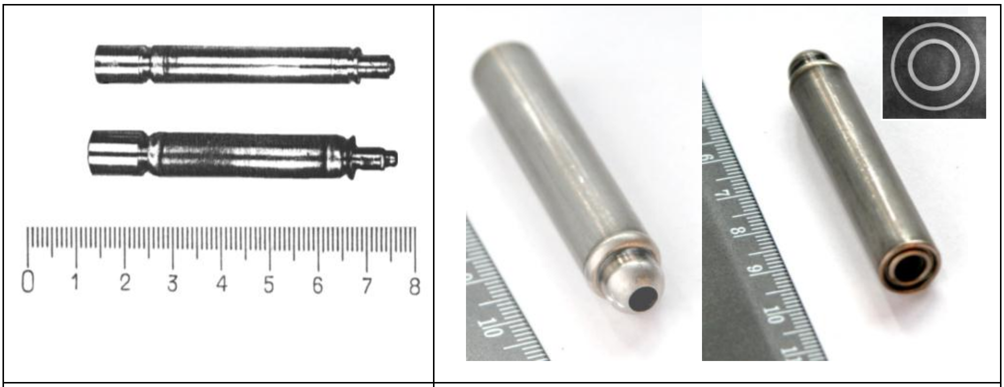
Experiments on the irradiation creep had been long enough in time from 3 to 12 years, and the number of intermediate measurements in each of the experiments varied depending on the duration of the experiment. Experiments with gas pressured tubes were held in different cells of the core and screen of BOR-60 in sectional material science packages. The rate of damage dose varied depending on the site of irradiation of samples from 4 to 17 dpa/year. The maximum fluence of neutrons with E> 0.1 MeV in 12 years of exposure for the samples in one experiment reached to 23.8×10^{26} m^{-2} (about 100 dpa). The length of the samples in different experiments ranged from 60 to 200 mm, outer diameter of 6 mm to 10 mm and wall thickness from 0.3 to 0.55 mm. Asked several levels of stress, ranging from 0 to 320 MPa at irradiation temperatures from 320 to 400^{o}C. Used different gases - argon or helium.

Selected intervals of the irradiation conditions in the experiments corresponded to the parameters of radiation covers hexagonal fuel assemblies of fast reactors and operating conditions of VVER internals when it can manifest itself in the process of creep deformation or stress relaxation.

Last irradiation experiment

Experiments with gas-pressurized tubes were held in different cells of the core and screen of BOR-60 in sectional material science packages. The rate of damage dose varied depending on the site of irradiation of samples from 4 to 17 dpa/year. Selected intervals of the irradiation conditions in the experiments comply with the conditions of operation of VVER internals when it can manifest itself in the process of creep deformation or stress relaxation.

We used a standard gas-pressurized samples (MP-132) and gas-pressurized samples with coaxial tubes (MP-145). Standard samples are gas-pressurized tubes, each with two plugs, conserved in a chamber under pressure. The appearance of such samples is shown in Fig. 1, a. Tube length was about 65 mm, 8 mm outer diameter and wall thickness of 0.5 mm. Another type of sample was a complex gas-pressurized samples, consisting of two coaxial tubes conserved by welding under pressure in the shells of which generates a voltage due to excessive pressure helium filling the space between the tubes (see Fig. 1 a, b) [11]. The length was about 50 mm, the initial outer diameter 10.22 mm, internal diameter 6.03 mm and the thickness of the outer or the inner wall of the complex sample 0.5-0.55 mm. Asked several levels of stress, ranging from 0 to 250 MPa at irradiation temperature not exceeding 350^{o}C. The tubes are pressurized using helium at room temperature.



a b

Fig.1. The form of gas-pressurized samples, the standard (a) and coaxial (b)

Material. Gas-pressurized specimens were made from Fe-18Cr-10Ni-Ti steel in the austenized state. The initial heat treatment of steels included heating to 1050^{o}C, exposure 15 min and cooling in air.

Gas-pressured samples from time to time taken out from reactor during the stop measure their size and return to the reactor. Measurements of length and outer diameter were carried out in a "hot" cell of the reactor BOR-60 by the contact method with an absolute accuracy of ±10 microns, ± 5 microns.

The resulting information for non-destructive studies of gas-pressurized samples (change in length and diameter of the sample) allowed to make the dose dependence of the dimensional changes for each sample at a given temperature exposure (Fig. 2-5). In the assembly of the MP-145 were irradiated with two duplicate samples for each level of applied stresses in Fig. 2 and 3 are indicated shaded and shaded markers.

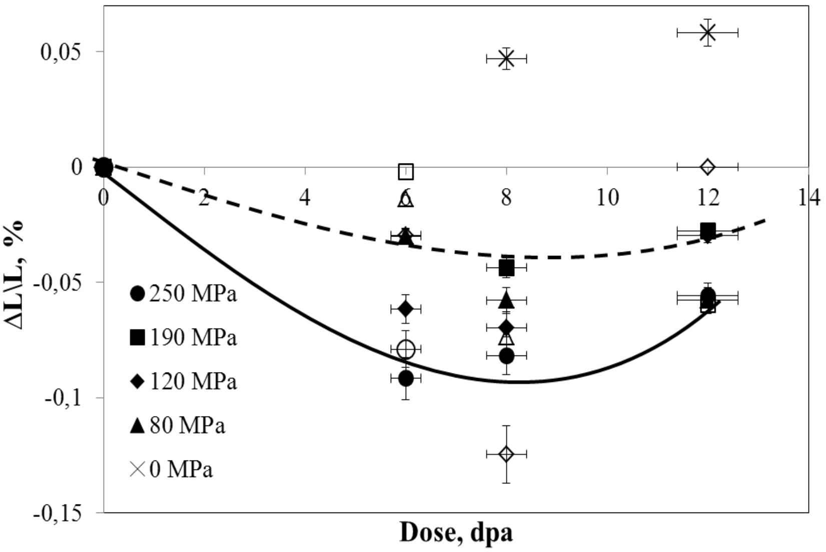


Fig. 2. Dose dependence change of length of the gas-pressurized specimens with coaxial tubes made from Fe-18Cr-10Ni-Ti steel irradiated in MP-145 in BOR-60 at 320-350°C

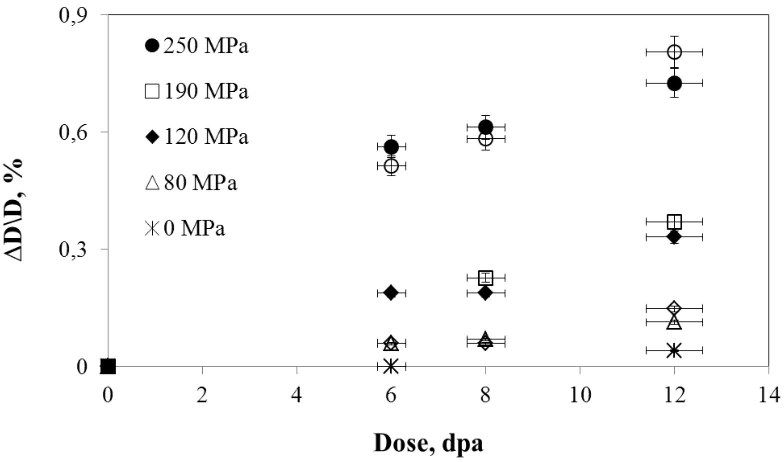


Fig. 3. Dose dependence of the diameter of the gas-pressurized specimens with coaxial tubes made from Fe-18Cr-10Ni-Ti steel irradiated in MP-145 in BOR-60 at 320-350°C

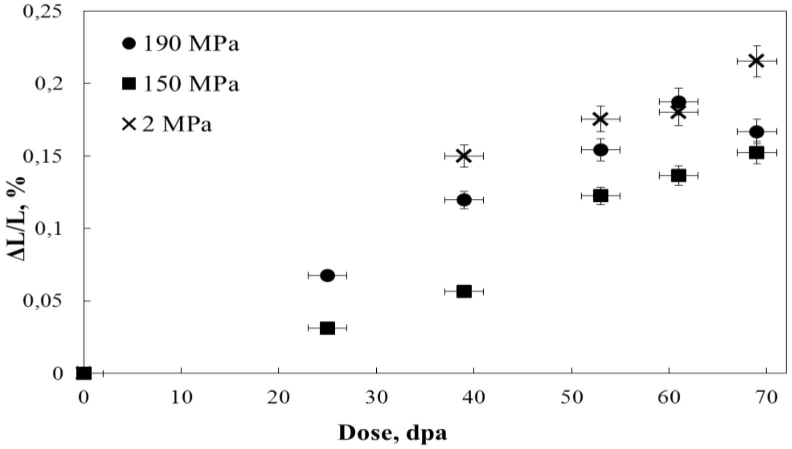


Fig. 4. Dose dependence change of length of the standard gas-pressurized specimens made from Fe-18Cr-10Ni-Ti steel irradiated in MP-132 in BOR-60 at 320-350°C

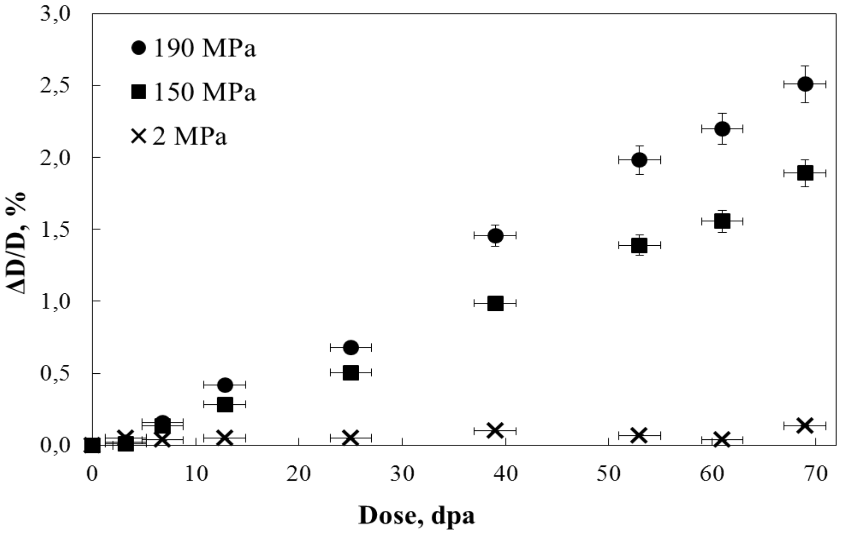


Fig. 5. Dose dependence of the diameter of the standard gas-pressurized specimens made from Fe-18Cr-10Ni-Ti steel irradiated in MP-132 in BOR-60 at 320-350^{o}C

Fig. 2 shows that the relative change of the length for the gas-pressurized samples with coaxial tubes decreases in the initial stage of irradiation for different levels of applied stresses. Fig.4 illustrates a well known fact that with increasing damage dose increase the relative length change for the gas-pressurized samples and the greater the level of the applied stress, the greater the increase.

Fig. 3 and 5 shown that with increasing damage dose proportional increases the diameter of the gas-pressurized samples at different applied stress. Relative growth of the diameter of the gas-pressurized samples were Fe-18Cr-10Ni-T from stress and damage dose is close to linear.

In the overall change in the diameter of the samples affect two factors. The first factor is associated with the deformation due to creep and depends on the stress and the second is associated with the deformation of swelling. Both of these factors have a positive impact on increasing the diameter changes, that is, lead to increase in diameter due to each factor.

The total change in length is a more complex process. The change in the length of the gas-pressurized samples is influenced by at least three factors: a factor associated with the deformation due to creep, a factor associated with the deformation of swelling, both of these factors lead to an increase in the length of the sample. But there is a third factor, the so-called form factor. This factor reduces the length of the sample with an increase in diametral strain and can lead to a decrease in the length of the gas-pressurized specimens under irradiation. With the introduction of this factor can be associated decrease in the length of the samples in an experiment with complex samples (see Fig. 2) and a negative elongation values at the initial stage of irradiation of gas-pressurized samples in some experiments with standard samples [3]. Data obtained in this work are in good agreement with the known laws of irradiation creep.

The equations calculate the creep modulus

To calculate the creep modules of the investigated steel in [2,3,13-15] used the known relations based on the theory of Von Mises, connecting the transition from hoop strains (ε_H) and stress (σ_H) to equivalent strains (ε_{EQ}) and stress (σ_{EQ}):

$$\frac{\varepsilon_{EQ}}{\sigma_{EQ}} = \frac{4}{3} \times \frac{\varepsilon_H}{\sigma_H} = B. \tag{1}$$

The transition from the measured diametral strain ($\Delta D/D$) to the district strains (ε_H) was performed according to the formula [15]:

$$\varepsilon_H = A \cdot \frac{\Delta D}{D}, \tag{2}$$

where the constant A in the experiment was approximately 1.05.

The study of the relationship of creep and swelling in the experiments carried out at temperatures of 400-420^{o}C when there is significant swelling (higher than 1%).

In studies devoted to the study of irradiation creep in the temperature range of existence of swelling, it is accepted (K. Erlih, F.A. Garner, V.S. Neustroev and others [2, 3, 8-9, 12]) to describe the deformation of samples under pressure from the equation:

$$\frac{\dot{\varepsilon}_{EQ}}{\sigma_{EQ}} = B = B_O + D \times \dot{S}, \tag{3}$$

where $\acute{\varepsilon}$ – unsteady (current) creep rate, $\%\cdot\mathrm{dpa}^{-1}$;
σ – the equivalent stress, MPa;
B – transient (current) rate of creep, $(\mathrm{MPa}\cdot\mathrm{dpa})^{-1}$;
B_0 – independent of the swelling ratio of creep, $(\mathrm{MPa}\cdot\mathrm{dpa})^{-1}$;
D – the pair correlation coefficient of swelling and creep, MPa^{-1};
$\acute{S}$ – the current rate of swelling, $\%\cdot\mathrm{dpa}^{-1}$.

Analysis of the results of the study of creep of austenitic and ferritic steels in various initial state [8-9, 12] showed that in spite of the rather complicated nature of the change of the current coefficient B of creep damage dose, the creep process is described by equation (1) with a system of weakly varying coefficients B_0 and D. For example, the coefficient B_0 for class of austenitic steels is $1\cdot10^{-6}$ $(\mathrm{MPa}\cdot\mathrm{dpa})^{-1}$, and the coefficient D varies in the range of $(0.3\text{-}1.0)\cdot10^{-2}$ MPa^{-1}.

3. Summary

We use method of conducting experiments on irradiation creep of materials for nuclear technology in the BOR-60 reactor with special material science assemblies;

Currently, experiments on irradiation creep of steel Fe-18Cr-10Ni-Ti are held in reactor BOR-60 for the study of radiation properties of VVER reactors internal materials.

Examples of the use of this method in the study of gas-pressurized irradiation creep specimens of austenitic steels in the BOR-60.

References

[1] F.A. Garner, L.R. Greenwood, D.L. Harrod: 6th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, The Minerals, Metals, and Materials Society, Sun Diego (1993), p. 783-790.
[2] K. Erlich: Journal of Nuclear Materials, V. 100 (1981), p. 149-166.
[3] F.A. Garner: Materials Science and Technology: A Comprehensive Treatment, Vol. 10A (1994), VCH Publishers, p. 419-543.
[4] R.J. Puigh, E.R. Gilbert, B.A. Chin: Effects of Irradiation on Materials. 11th Conference, ASTM STP 782, Philadelphia, Pa, American Society for Testing and Materials (1982), p. 108-121.
[5] M.B. Toloczko, F.A. Garner: Journal of Nuclear Materials, Vol. 212-215 (1994), p. 509-513.
[6] D.L. Porter, G.D. Hudman, F.A. Garner: Journal of Nuclear Materials, Vol. 179-181 (1991), p. 581.

[7] M.B. Toloczko, F.A. Garner: 21st International Symposium, ASTM STP 1447, ASTM International, West Conshohocken PA (2004), p. 454-467.

[8] V.K. Shamardin, V.S. Neustroev, V.N. Golovanov et al: 14th International Symposium (V.2), ASTM STP 1046, American Society for Testing and Materials, Philadelphia (1990), p. 753-765.

[9] V.S. Neustroev, V.K. Shamardin: Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175, American Society for Testing and Materials, Philadelphia (1993), p. 816-823.

[10] V.S. Neustroev, V.K. Shamardin: Effects of Radiation on Materials: 19th International Symposium, ASTM STP 1366, American Society for Testing and Materials, West Conshohocken, PA (2000), p. 645-654.

[11] V.S. Neustroev, V.K. Shamardin: Journal of Nuclear Materials, Vol. 307-311 (2002), p. 343-346.

[12] F.A. Garner, D.L. Porter: Journal of Nuclear Materials, Vol. 212-215 (1994), p. 604-607.

[13] D.G. Morris: Acta Metallurgica, Vol. 26 (1978), p. 1143-1151.

[14] M.B. Toloczko, F.A. Garner: Journal of Nuclear Materials, Vol. 212-215 (1994), p. 509-513.

[15] M.B. Toloczko, B.R. Grambau, F.A. Garner and K. Abe: Effects of Radiation on Materials: 20th International Symposium, ASTM STP 1405, American Society for Testing and Materials, West Conshohocken, PA (2001), p. 557-569.

[16] V.S. Neustroev, S.V. Belozerov, Ye.I. Makarov, Z.Ye. Ostrovsky, The Physics of Metals and Metallography Vol. 110 (2010), №4, p. 412-416.