THE EVOLUTION OF THE MICROSTRUCTURE OF Cr16–Ni19 STEEL UNDER IRRADIATION IN THE LOW ENRICHMENT ZONE OF A FAST NEUTRON REACTOR. FORMATION AND DEVELOPMENT OF RADIATION POROSITY

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Abstract. Microstructural studies of samples made from various sections of fuel element shells were carried out after irradiation in the low enrichment zone of a fast neutron reactor with a sodium coolant to damaging doses of over 100 sna. The porosity characteristics of samples irradiated with different rates of generation of atomic displacements selected from sites with different irradiation temperatures are studied. Histograms of the pore size distribution are constructed for each sample, which are described by unimodal lognormal distributions. Three types of pores were identified: "small", "medium-sized" and "large", and changes in the average size and concentration of pores of each type were traced depending on the irradiation temperature and the rate of generation of atomic displacements.

Keywords: *fuel elements, neutron irradiation, porosity, austenitic steel type Cr16–Ni19 microstructure*

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INTRODUCTION

The main factors limiting the service life of a fuel assembly (FA) of a fast neutron reactor include the occurrence and development of radiation porosity and the associated swelling of the material [1]. To improve the efficiency of fast neutron reactors, it is planned to increase the service life of fuel elements until fuel burnup reaches more than 15% of t.a. (heavy atoms) and, accordingly, a damaging dose of at least 140 sleep. This task is being solved in stages, at this stage – by improving the technology for manufacturing fuel rod cladding from austenitic steel [2]. At present, four experimental fuel assemblies with fuel rod cladding made of austenitic steel type Cr16–Ni19, manufactured using the technology described in [3], have been irradiated in the BN-600 reactor. Irradiation in different zones of the reactor occurs at different rates of accumulation of the damaging dose. To determine the ultimate resource capabilities of fuel elements with Cr16-Ni19 steel cladding, it is necessary to know the regularities of the swelling process in it under irradiation in the range of temperatures and doses typical for fast reactors.

The aim of the work is to obtain experimental data on the radiation porosity of Cr16-Ni19 type austenitic steel (cold-formed) after irradiation in the low enrichment zone (LEZ) of the BN-600 reactor in the temperature range from 420°C to 630°C and to reveal the characteristic features of the process of formation and evolution of radiation pores of different types.

MATERIALS AND METHODS

The studies were conducted on samples of four fuel element claddings made of cold-deformed austenitic steel of the Cr16–Ni19 type, which had been operated in the BN-600 reactor as part of a fuel assembly in the ZMO. The samples were cut from different sections along the height of the fuel elements, irradiated at different rates of accumulation of the damaging dose.

A typical distribution pattern of neutron flux density and fuel rod cladding temperatures along the core height is shown in Fig. 1. The distribution parameters depend on the position of the fuel rod in the core and differ among different fuel rods. For studies, sections irradiated under the same narrow temperature ranges were selected from different fuel rods, within which atomic displacement rates differ for claddings of various fuel rods.

Fig. 1. Typical distribution pattern of neutron flux density and fuel rod cladding temperatures (#1, #2) along the core height.

All studied samples were divided into groups irradiated in temperature zones corresponding to seven ranges: low-temperature (420-430)°C - LT1 and (445-455)°C - LT2, medium-temperature (485-495)°C - MT1 and (515-525)°C - MT2, high-temperature (540-550)°C - HT1, (560-570)°C - HT2 and (585-630)°C - HT3. Each temperature range contained samples slightly differing in atomic displacement rates. This allowed comparing them to identify the dependence of porosity characteristics on the atomic displacement generation rate.

The studies were conducted using a high-resolution transmission scanning electron microscope Talos F200X G2, equipped with an EELS spectrometer, which allows determining the thickness of the studied foil section by the relative intensity of the zero-loss peak. During quantitative processing, this information provides the most accurate characteristics. The sample preparation method is described in [4]. Imaging for determining porosity parameters was performed on various foil sections at a magnification of 390 thousand times for calculating small pores and, depending on pore sizes, at magnifications from 14 thousand to 120 thousand times for calculating large pores. Calculation of pore parameters was performed using several images, the number of photographs ranged from 5 to 12, and the statistics included from 1000 to 3000 objects separately for small and large pores from each studied sample.

Image processing was carried out using a program for digitization and quantitative image processing - digital photo laboratory SIAMS Photolab. Based on the measurement results, histograms of pore size distribution were constructed. The histograms were presented as unimodal lognormal distributions corresponding to different types of pores by location and time of formation. After that, the median size of pores of each type, their concentration, and integral porosity were calculated according to the procedure described in [5].

RESULTS

Low-temperature ranges

In the low-temperature ranges, one sample from each fuel rod was examined, the atomic displacement generation rates for different samples were $(1.0\text{-}1.1)\cdot 10^{-6}$ dpa/s for LT1 and $(1.3\text{-}1.4)\cdot 10^{-6}$ dpa/s for LT2. In the microstructure of the examined samples, pores are generally uniformly distributed throughout the volume. Pore-depleted zones are observed along some twins, primary carbonitride precipitates (Fig. 2a), and near grain boundaries. Rows of pores are observed along individual grain boundaries (Fig. 2b). A connection between pores and elements of the dislocation structure, as well as with second phase precipitates (Fig. 2b), can be traced.

Fig. 2. Microstructure of Cr16-Ni19 type steel, characteristic of low-temperature irradiation ranges. a - areas depleted of large pores near primary carbonitride precipitates; b - a row of large pores along the grain boundary (indicated by arrows).

Small pores are observed in the structure , located predominantly on elements of the dislocation structure, along grain boundaries, as well as on intragranular and grain boundary second phase precipitates (Fig. 3).

Fig. 3. Small pores in the structure of Cr16-Ni19 type steel. a - at the grain boundary; b - on intragranular precipitates.

The maximum pore size in LT1 samples does not exceed 30 nm, and in LT2 - 50 nm. A typical histogram of pore size distribution is shown in Fig. 4; mathematically, it is

correctly described by three unimodal lognormal distributions corresponding to three types of pores: small, medium-sized, and large.

Fig. 4. Typical histogram of pore size distribution in LT1 samples of fuel rod claddings made of Cr16-Ni19 type steel (atomic displacement generation rate $1.1 \cdot 10^{-6}$ dpa/s).

In the graphs (Fig. 5), the average pore diameters of each type are indicated by filled symbols and solid lines, while concentrations are shown by unfilled symbols and dashed lines. The average size of small pores (Fig. 5a) in the studied samples of both temperature ranges was ~ 1 nm.

Fig. 5. Characteristics of small (a), medium-sized (b), and large (c) pores in Cr16-Ni19 type steel samples from low-temperature irradiation ranges and integral porosity of samples (d).

The concentration of small pores in LT1 tends to decrease with increasing atomic displacement generation rate from $2.5 \cdot 10^{23}$ m^{-3} to $0.6 \cdot 10^{23}$ m^{-3}, while in LT2 there is no dependence on the atomic displacement generation rate with observed value scatter from $0.8 \cdot 10^{23}$ m^{-3} to $1.7 \cdot 10^{23}$ m^{-3} (Fig. 5a).

The diameter of medium and large pores (Fig. 5b, c) in LT1 samples does not depend on the atomic displacement generation rate within the margin of error of its determination and was ~ 3.2 nm and ~ 14 nm respectively. Meanwhile, the concentration

of pores of both sizes increases from $0.3 \cdot 10^{21}$ m^{-3} to $1.3 \cdot 10^{21}$ m^{-3} for medium-sized pores and from $2.7 \cdot 10^{21}$ m^{-3} to $5.4 \cdot 10^{21}$ m^{-3} for large pores.

In the LT2 temperature range, the pore diameter increases with increasing atomic displacement generation rate: medium-sized pores from ~ 11 to ~ 15 nm, and large pores from ~ 20 to ~ 25 nm (Fig. 5b, c). The concentration of medium-sized pores shows no dependence on the atomic displacement generation rate, with values ranging from $1.3 \cdot 10^{21}$ m^{-3} to $2.2 \cdot 10^{21}$ m^{-3}. The concentration of large pores decreases with increasing atomic displacement generation rate from $3.2 \cdot 10^{21}$ m^{-3} to $1.5 \cdot 10^{21}$ m^{-3}.

The porosity of the investigated cladding samples from various fuel rods in the NT1 temperature range is practically identical and ranges from 1.1% to 1.3%, while in the NT2 temperature range, the porosity values in samples from different fuel rods range from 1.8 % to 2.7 % (Fig. 5d).

Medium temperature ranges

In the irradiation ranges MT1 and MT2 with atomic displacement generation rates of $(1.5–1.6) \cdot 10^{-6}$ dpa/s, one sample from different fuel rods was studied. Increasing the irradiation temperature leads to an increase in the maximum pore size up to 55–70 nm in the MT1 range and up to 90–120 nm in the MT2 range in various samples. The distribution of pores with a diameter of more than 20 nm throughout the material volume becomes less uniform. Local areas where large pores are practically absent are observed, in the MT1 temperature range – up to 5% of the sample volume, and up to 8 % in the MT2 range.

Fig. 6. Microstructure of Cr16–Ni19 type steel, characteristic of medium temperature irradiation ranges with an atomic displacement generation rate of $1.6 \cdot 10^{-6}$ dpa/s; a – areas free of large pores; b – the largest pores at twin boundaries.

Areas free of large pores are more often located in deformation bands or are not associated with structural features (Fig. 6a). The largest pores (more than 120 nm) are observed at twin boundaries, sometimes forming chains (Fig. 6b). Narrow zones depleted of large pores are observed along grain boundaries, as well as the alignment of pores into rows along them.

In steel in the medium temperature regions, as in the low temperature ones, there is a high concentration of small pores up to 5 nm in size, located at the interphase boundaries of various types of second phase precipitates (G -phase, complex FCC-carbides) both intragranular and grain boundary, including phosphides formed during irradiation in these temperature ranges [4]. Small pores are also located along grain boundaries, on dislocations, in deformation bands.

Fig. 7. Typical histogram of pore size distribution in fuel rod cladding samples made of Cr16–Ni19 type steel from the MT2 irradiation range (atomic displacement generation rate $1.6 \cdot 10^{-6}$ dpa/s).

A typical histogram of pore size distribution is shown in Fig. 7; in samples from various fuel elements, the histograms are mathematically correctly described by three (in some cases four or five) unimodal lognormal distributions. In the studied samples, besides small pores, two systems of larger pores are visually clearly distinguished: medium ones (central peak in the size range of 5-25 nm) and large ones (sum of subsequent peaks). Thus, in the medium-temperature irradiation ranges, the characteristics of three pore systems were also considered: small, medium-sized, and large.

The average diameter of small pores in the studied samples of both temperature ranges MT1 and MT2 was ~ 1.3 nm, no correlation between the concentration of these pores and the atomic displacement generation rate was observed, values vary from $6.4 \cdot 10^{22}$ m^{-3} to $11.8 \cdot 10^{22}$ m^{-3} in the MT1 temperature range, and from $5.5 \cdot 10^{22}$ m^{-3} to $9.3 \cdot 10^{22}$ m^{-3} in the MT2 temperature range (Fig. 8a).

Fig. 8. Characteristics of small (a), medium-sized (b), and large (c) pores in Cr16-Ni19 type steel samples from medium-temperature irradiation ranges and the integral porosity of samples (d).

The average diameter of medium-sized pores in samples from MT1 and MT2 ranges, within the margin of error of its determination, does not depend on the atomic displacement generation rate and equals ~ 14 nm (Fig. 8b). The concentration of medium-sized pores in samples from both temperature ranges does not depend on the atomic displacement generation rate and ranges from $3.1 \cdot 10^{20}$ m^{-3} to $5.6 \cdot 10^{20}$ m^{-3} in MT1 and from $1.3 \cdot 10^{20}$ m^{-3} to $2.7 \cdot 10^{20}$ m^{-3} in MT2 (Fig. 8b).

The dependence of the average diameter of large pores in samples from both medium-temperature ranges on the atomic displacement generation rate is not evident. Within the margin of error, its value was ~ 38 nm in MT1 and ~ 54 nm in MT2 (Fig. 8c). The concentration of large pores in samples from both medium-temperature ranges does not depend on the atomic displacement generation rate, and varies from $4.2 \cdot 10^{20}$ m^{-3} to $17.9 \cdot 10^{20}$ m^{-3} in MT1 and from $3.0 \cdot 10^{20}$ m^{-3} to $5.2 \cdot 10^{20}$ m^{-3} in MT2 (Fig. 8c).

The porosity of the investigated fuel cladding samples from various fuel elements ranges from 1.4 % to 5.7 % for MT1 (differing by a factor of ~ 4), while for the temperature range MT2, the difference in porosity of samples from different fuel elements varies from 3.0 % to 6.2 % – by a factor of ~ 2 (Fig. 8d).

High-temperature ranges

In the high-temperature irradiation ranges HT1 – (540–550)°C and HT2 – (560–570)°C, one sample from different fuel elements was examined. With increasing irradiation temperature, the non-uniformity of large pore distribution in the sample volume increases (Fig. 9), the proportion of areas free from large pores , increases from 9–21% in the temperature range HT1 to 67–93% in the temperature range HT2.

Fig. 9. Microstructure of Cr16–Ni19 type steel, characteristic of high-temperature irradiation ranges HT1, HT2; a – temperature range (540–550)°C, atomic displacement generation rate $1.6 \cdot 10^{-6}$ dpa/s; b – temperature range (560–570)°C, atomic displacement generation rate $1.5 \cdot 10^{-6}$ dpa/s.

In samples from the temperature range HT3 – (585–630)°C, no statistically significant number of large pores was observed except for the sample irradiated at an atomic displacement generation rate of $1.4 \cdot 10^{-6}$ dpa/s, where the volume free from large pores was 88%.

As in the previous temperature ranges of irradiation, a system of small pores is clearly visible, uniformly distributed throughout the volume of the material of the studied samples and located both on elements of the dislocation structure, along grain boundaries, and on intragranular and grain boundary precipitates of various types of second phases (*G* -phase, complex FCC carbides, Laves phase, phosphides) [4].

Histograms of pore size distribution in fuel cladding samples from temperature ranges HT1 and HT2 were described by the number of peaks from three to five (Fig. 10), and as in the case of the medium temperature range, the characteristics of three pore systems were considered. The maximum pore size with increasing irradiation temperature increased to 140 nm in the temperature range HT1 and to 350 nm in HT2.

Fig. 10. Typical histogram of pore size distribution in fuel cladding samples from Cr16–Ni19 type steel from the high-temperature irradiation range HT1 (atomic displacement generation rate $1.6 \cdot 10^{-6}$ dpa/s).

No dependence of the concentration of small pores on the atomic displacement generation rate is observed in all high-temperature ranges, the values vary from $2.8 \cdot 10^{22}$ m^{-3} to $6.3 \cdot 10^{22}$ m^{-3} in the HT1 range, from $2.3 \cdot 10^{22}$ m^{-3} to $6.1 \cdot 10^{22}$ m^{-3} in the HT2 range and from $1.3 \cdot 10^{22}$ m^{-3} to $5.0 \cdot 10^{22}$ m^{-3} in the HT3 range (Fig. 11a).

The average size of small pores in the studied samples of high-temperature ranges does not depend on the atomic displacement generation rate, in the temperature range HT1 it was ~ 1.3 nm, and in the temperature ranges HT2 and HT3 ~ 1.8 nm (Fig. 11a).

Fig. 11. Characteristics of small (a), medium-sized (b) and large (c) pores in Cr16–Ni19 type steel samples from high-temperature irradiation ranges and integral porosity of samples (d).

The average diameter of medium-sized pores in samples from temperature ranges HT1 and HT2 is independent of the atomic displacement generation rate within the margin of error and equals ~ 13–

14 nm. The concentration of medium-sized pores in samples from temperature ranges HT1 and HT2 is independent of the atomic displacement generation rate, and varies from 3.4·10 19 m -3 to 11.6·10 19 m -3 in the HT1 range and from 8.6·10 19 m -3 to 11.8·10 19 m -3 in the HT2 range (Fig. 11b). No medium-sized pores were observed in the HT3 irradiation temperature range.

The average diameter of large pores in samples from ranges HT1 and HT2 is independent of the atomic displacement generation rate within the margin of error and equals ~ 63 nm in the HT1 range and ~ 75 nm in the HT2 range, while in the sample from the HT3 range it is ~ 57 nm (Fig. 11c).

The concentrations of large pores in samples from ranges HT1 and HT2 tend to increase with increasing atomic displacement generation rate, from 1.0·10 20 m -3 to 1.6·10 20 m -3 in the HT1 range and from 0.1·10 19 m -3 to 2.1·10 19 m -3 in the HT2 range, while the concentration of large pores in the sample from the HT3 range was 0.9·10 19 m -3 (Fig. 11c).

The porosity of the investigated fuel rod cladding samples from the HT1 range is between 1.5 % and 3.9 %, with differences up to 2.6 times. The porosity of the investigated fuel rod cladding samples from other high-temperature ranges does not exceed 0.8 % (Fig. 11d).

DISCUSSION OF RESULTS

Analysis of results shows that the average size of small, medium, and large pores in each of the studied temperature ranges does not depend on the atomic displacement generation rate within the measurement error. We can only note a tendency toward an increase in the diameter of medium and large pores in samples after low-temperature (445–455)°C irradiation. The concentrations of small and medium pores at irradiation temperatures above (445–455)°C have large variations within each temperature range, and no dependencies on the atomic displacement generation rate are observed. The dependencies of the average size and concentration of various types of pores on the irradiation temperature were constructed (Fig. 12–14).

Fig. 12. Dependencies of the average size (a) and concentration (b) of small pores on the irradiation temperature in fuel rod cladding samples made of Cr16–Ni19 steel.

The average size of small pores increases with increasing irradiation temperature from ~ 1 nm at temperatures of (420–450)°C to ~ 1.8 nm at temperatures of (560–630)°C, while their concentration decreases almost linearly with increasing temperature from ~ 450°C to ~ 600°C (Fig. 12).

The average size of medium-sized pores increases when the temperature changes from (420–430)°C to (445–455)°C and does not change within the determination error up to temperatures of (560–570)°C; at higher irradiation temperatures, medium-sized pores are not observed (Fig. 13a). The concentration of medium-sized pores increases with increasing irradiation temperature from (420–430)°C to (445–455)°C, where it reaches its maximum; increasing the irradiation temperature to (485–495)°C leads to a decrease in the concentration of medium-sized pores by almost five times. With an increase in irradiation temperature above (485–495)°C, a slight decrease in the concentration of medium-sized pores is observed with increasing temperature (Fig. 13b).

Fig. 13. Dependencies of the average size (a) and concentration (b) of medium-sized pores on the irradiation temperature in fuel rod cladding samples made of Cr16–Ni19 steel.

The average size of large pores increases almost linearly with the increase in irradiation temperature from (420-430)°C to (560-570)°C (Fig. 14a). At the same time, the concentration of large pores decreases sharply when the temperature changes from (420-430)°C to (485-495)°C, further increase in irradiation temperature leads to a weak monotonic decrease in the concentration of large pores (Fig. 14b).

Fig. 14. Dependence of average size (a) and concentration (b) of large pores on irradiation temperature in fuel rod cladding samples made of Cr16-Ni19 type steel.

The analysis of the obtained data was carried out based on the following premises. A necessary condition for the formation and growth of a pore is that the influx of vacancies exceeds the flow of interstitial atoms [6, 7].

Due to the higher binding energy of interstitials compared to vacancies, already at the kinetic stage of cascade formation, a larger number of interstitial complexes are formed and, as a consequence, more single vacancies than interstitials remain in the solid solution. The energy of interaction between a vacancy and a pore is calculated as the difference between the energy of the system when the vacancy is in the matrix - E_v , and when it has entered the pore E_{vV} (the energy of interaction between a vacancy and a pore), which led to a change (increase) in the surface energy of the pore by ΔE_{sv} : $E_{vV} = E_v - \Delta E_{Sv}$. Similarly, the energy of interaction between an interstitial and a pore is calculated: $E_{iV} = E_i - \Delta E_{Si}$ (where E_i , - interstitial is in the matrix, ΔE_{si} - change in the surface energy of the pore due to the interstitial). When an interstitial enters the pore surface, its volume and surface area decrease. Therefore, the energy of interaction of interstitials with pores is higher than that of vacancies. The difference decreases with pore growth and, upon reaching a critical diameter, the pore begins to grow by the mechanism of unbalanced vacancy flux into it [6, 7].

But to achieve this, a gas-vacancy bubble must form and grow [8]. The role of such gas in steels is played by transmutation helium, formed mainly in nuclear reactions of neutrons with certain gas impurities and nickel [9, 10]. The rate of helium generation in Cr16-Ni19 type steel in BN reactors is six orders of magnitude lower than the rate of vacancy generation [11]. Therefore, the concentration of helium in the matrix is small, and the probability of homogeneous formation of helium bubbles is very low. It is more likely for a helium atom to reach some sink: dislocation, grain boundaries, twins, or phases. Then, for a certain time depending on the binding energy with the sink and temperature, helium migrates along the sink. During this time, it can meet another helium atom, as well as a vacancy, and form a complex that transforms into a bubble as it grows, the growth of which is regulated by the effective surface tension of its boundary (specific surface energy and He pressure from inside on the bubble wall) and is controlled by the helium supply [12].

On a dislocation, the probability of such an encounter and the rate of helium supply to the bubble (one-dimensional movement) are higher than at boundaries (grains and twins). Therefore, the first bubbles form on dislocations, which are the first to grow into voids, forming the first maximum. In addition, silicon and nickel arrive at the dislocation, which is detected by TEM methods and creates favorable conditions for the formation of high-nickel intermetallic phases (γ', *G*) [4]. All observed large voids are associated with precipitates of second phases. Over time, the dislocation structure evolves - new dislocations form (particularly due to the coalescence of growing interstitial dislocation loops), on which the next generation of medium-sized voids can form, creating a second maximum on the histogram.

The microstructure shows that all small voids at all irradiation temperatures are associated either with dislocations , or with boundaries (grains, second phases). These voids are gas-vacancy nuclei of the last generation voids, which formed on the structure developed during the irradiation process.

Bubbles slowly accumulate and grow. As this happens, the distance between them decreases, and upon reaching a certain distance, they begin to merge, which leads to an increase in size and a pause in the growth of bubble concentrations. The peak of the bubble size distribution splits, and the bubbles that have grown during coalescence, after reaching a critical size, transition into the class of pores. The increase in temperature to values optimal for the implementation of the described process leads to an increase in size and a decrease in the concentration of small pores, which are gas-vacancy bubbles, as shown in Fig. 12a, b.

An increase in irradiation temperature leads to a decrease in the lifetime of helium (as well as vacancies) at sinks, particularly at dislocations, which causes a decrease in the concentration of medium and, especially, large pores (Fig. 13b, 14b).

Comparison of the results shows that in the temperature range of (450-570)°C, large pores grow, while medium pores practically do not change in size (Fig. 13a, 14a). This is related to the combination of interstitial and vacancy fluxes. At temperatures of (450-570)°C, the mobility of interstitials increases by 1.4 times, and that of vacancies by almost three times, which promotes an increase in the vacancy flux into pores.

At the same time, the increased mobility of point defects (PD) causes a decrease in their concentration in the matrix, which reduces the fluxes. The influx of PD into small pores is determined by their concentration at dislocations. The unbalanced vacancy flux into pores located on dislocations consists of the flux of PD migrating along the dislocation and the flux of PD from the matrix through the pore surface.

The vacancy flux into pores (bubbles) from dislocations j_b is determined by the expression [13, 14]:

$$j_{\mathrm{b}} = 2 \cdot a_1 \cdot \frac{c_{\mathrm{lb}}}{\rho_{\mathrm{d}}} \cdot \nu \cdot \exp(-E_{\mathrm{m}} / kT) \cdot \omega_{\mathrm{b+}} , \qquad (1)$$

where a_1 is the radius of the first coordination sphere; c_{lb} is the linear concentration of vacancies on the dislocation; ⟩ d is the dislocation density; v is the Debye frequency; E_m is the vacancy migration energy; k is the Boltzmann constant; T is the temperature, K; ⟨ b + is the probability that a vacancy approaching the boundary of a pore (bubble) will enter it at the next jump.

At the same time, a flow of point defects enters through the pore surface [13, 14]:

$$j_{\mathrm{s}} = 6\pi \cdot d^2 \cdot a_1 \cdot c_{\mathrm{ib}} \cdot \nu \cdot \exp(-E_{\mathrm{m}} / kT) \cdot \omega_{\mathrm{b+}} , \quad (2)$$

where d is the diameter of the pore (bubble); c_{ib} is the concentration of vacancies in the matrix.

Note that the flow of PD into pores from the matrix does not change their concentration, but only increases their size. Using the experimental results shown in Fig. 12-14, let's compare the PD flows into pores through various channels at different irradiation temperatures. When the temperature increases above ~ 450°C, the concentration of helium and vacancies on dislocations decreases, resulting in a lower concentration of small and medium pores. Further temperature increase reduces the rate of PD flows from dislocations to pores (due to the decrease in vacancy concentration on dislocations), but increases flows from the matrix. In total, the PD flows remain constant, and the size of medium pores changes little. For large pores, the influx from the matrix significantly exceeds the flows from dislocations. We can only note a tendency toward growth in the diameter of medium and large pores in samples after low-temperature irradiation. This is associated with increased flows of point defects, leading to an earlier transition of bubbles into pores, so that by the end of irradiation they have time to grow more.

According to Fig. 12-14, clear dependencies of average sizes and concentrations of small, medium-sized, and large pores on irradiation temperature can be traced throughout the entire investigated temperature range.

Using formulas (1) and (2) and the experimental results of changes in pore concentrations and sizes, we can compare the total number of PDs in pores. The specific volume occupied by pores whose size corresponds to the selected histogram section can be estimated as

$$\delta v = \frac{n_v \cdot \pi \cdot d_v^{\,3}}{6}, \qquad (3)$$

where n_v is the concentration of pores; d_v is the average size of pores in the considered histogram section.

Figure 15 shows the graph of the dependence of the specific volume occupied by different types of pores on the irradiation temperature. The graph shows that at all irradiation temperatures, the specific volume of vacancies in small pores is ~ $1 \cdot 10^{-4}$. At temperatures above 520°C, the specific volume of vacancies in medium-sized pores ranges from $2.7 \cdot 10^{-4}$ to $1.1 \cdot 10^{-4}$, which is of the same order of magnitude as the volume of small pores. While in large pores at a temperature of ~ 520°C, the estimation gives ~ $3.2 \cdot 10^{-2}$ (which exceeds the result for medium-sized pores by more than an order of magnitude). With increasing irradiation temperature, the concentration of small pores decreases, and at temperatures above ~ 450°C, it decreases almost linearly (Fig. 12). The reason for this dependence pattern is that with increasing temperature, the lifetime of helium at sinks decreases, which reduces the probability of bubble formation and leads to a decrease in their concentration.

Fig. 15. Dependence of the specific volume occupied by different types of pores on the irradiation temperature in Cr16-Ni19 type steel.

One of the main characteristics of porosity affecting the swelling rate is the specific surface area of pores [15, 16]. The dependences of this parameter on porosity for the studied irradiation temperature ranges are shown in Fig. 16. The symbols indicate values obtained for the austenitic steel samples of Cr16-Ni19 type studied in this work. The lines show the trend dependencies obtained.

Fig. 16. Dependence of the specific surface area of pores on porosity in fuel rod cladding samples made of Cr16-Ni19 type steel for different irradiation temperature ranges.

As shown in our previous works [15, 16, 17], the specific surface area of pores reaches saturation with increasing porosity, and the surface area of pores corresponding to the saturation stage decreases with increasing irradiation temperature. In the studied samples, the specific surface area of pores did not reach saturation except for the temperature ranges of (515–525)°C and (540–550)°C, where its values were $48.9 \cdot 10^{5}$ m $^{-1}$ and $26.3 \cdot 10^{5}$ m $^{-1}$ respectively. The characteristic of the specific surface area of pores is a geometric factor affecting swelling, inherent in any kind of materials.

The total porosity determines swelling, which limits the service life of the fuel element according to the criterion of exhaustion of the minimum flow section for sodium coolant. In addition, porosity characteristics affect changes in mechanical properties, which can lead to cladding failure. The results presented in this work can be used to determine the residual and ultimate service life of fuel elements in fast neutron reactors.

CONCLUSION

Studies of radiation porosity formed in fuel cladding samples made of cold-worked Cr16–Ni19 type steel after irradiation in the BN-600 reactor at different temperatures and atomic displacement generation rates showed:

1. In Cr16–Ni19 type steel, the pore size distributions are multimodal in all studied irradiation temperature ranges, with distinct pore systems: small – helium-vacancy pore nuclei, and medium-sized and large pores growing due to vacancy influx.

2. In samples irradiated under similar conditions, large variations in porosity characteristics are observed.

3. It was not possible to identify unambiguous dependencies of the average size and concentration of small, medium-sized, and large pores on the atomic displacement generation rate in fuel cladding samples made of Cr16–Ni19 type steel.

4. The average size of small and large pores increases with irradiation temperature. The average size of medium pores at an irradiation temperature of ~450°C is more than four times larger than the average size at an irradiation temperature of ~425°C. The average size of medium pores does not change in the irradiation temperature range from ~450°C to ~570°C; at higher irradiation temperatures, medium-sized pores are not observed.

5. The concentration of small and large pores decreases with increasing irradiation temperature. Maximum concentrations of medium-sized pores are observed in samples irradiated at a temperature of ~450°C.

6. The surface area of pores in Cr16–Ni19 type steel increases with porosity in all irradiation temperature ranges, tending toward saturation.

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CONFLICT OF INTERESTS

The authors of this work declare that they have no conflict of interest.

REFERENCES

1. *Porollo S.I., Konobeev Yu.V., Shulepin S.V.* Analysis of the behavior of BN-600 fuel rod claddings made of 0Kh16N15M3BR steel at high fuel burnup // Atomic Energy. 2009. Vol. 106. No. 4. P. 188–194.
2. *Tselishchev A.V., Ageev V.S., Budanov Yu.P., Ioltukhovskiy A.G., Mitrofanova N.M., Leontyeva-Smirnova M.V., Shkabura I.A., Zabudko L.M., Kozlov A.V., Maltsev V.V., Povstyanko A.V.* Development of structural steel for fuel rods and fuel assemblies of fast sodium reactors // Atomic Energy. 2010. Vol. 108. No. 4. P. 217–221.
3. *Mitrofanova N.M., Churyumova T.A.* EK164 steel – structural material for fuel rod claddings of BN reactors // VANT. 2019. No. 2(98). P. 100–109.
4. *Panchenko V.L., Portnykh I.A., Ustinov A.E.* Evolution of microstructure of Cr16–Ni19 type steel during irradiation in the low-enrichment zone of a fast neutron reactor. Influence of neutron irradiation conditions on the structural-phase state // FMM. 2025. Vol. 126. Issue 1. P.
5. *Portnykh I.A., Kozlov A.V., Skryabin L.A.* Dimensional characteristics of the ensemble of radiation pores in cold-deformed Kh16N15M2G steel irradiated with high neutron fluences // Advanced Materials. 2002. No. 2. P. 50–55.
6. *Katz J., Wiedersich H., Chem J.* Nucleation of voids in materials supersaturated with vacancies and interstitials // Phys. 1971. V. 55. P. 1414–1425.

7. *Kozlov A.V., Portnykh I.A., Blokhin A.I., Blokhin D.A., Demin N.A.* The dependence of critical diameter of void nuclei in ChS68 austenitic steel on temperature of neutron irradiation in the model of formation of helium-vacancy bubbles // Inorganic Mater. Appl. Research. 2013. V. 4. № 3. P. 183–188.
8. *Trinkaus H.* Energetics and formation kinetics of helium bubbles in metals // Radiat. Effects. 1983. V. 78. P. 189–211.
9. *Stoller R.E., Odette G.R., Garner F.A., Packan N.H., Kumar A.S. (Eds.)* A comparison of the relative importance of helium and vacancy accumulation in void nucleation, in Radiation-Induced Changes in Microstructure // 13th International Symposium, West Conshohocken, PA: ASTM International, 1987. P. 358–370.
10. *Glushkova N.V., Portnykh I.A., Kozlov A.V.* Mechanism of the effect of transmutation helium produced in fuel element claddings made of austenitic steel ChS-68 under neutron irradiation on void formation // FMM. 2009. V. 108. № 3. P. 276–282.
11. *Blokhin A.I., Demin N.A., Manokhin V.N., Sipachev I.V., Blokhin D.A., Chernov V.M.* Computational complex ACDAM-2.0 for studying nuclear physical properties of materials under neutron irradiation // VANT, ser. "MiNM". 2015. Issue 3(82). P. 81–109.
12. *Mansur L.K., Lee E.H., Maziasz P.J. and Rowcliffe A.P.* Control of helium effects in irradiated materials based on the theory and experiments // J. Nuclear Mater. 1986. V. 141–143. P. 633–646.
13. *Kozlov A.V., Portnykh I.A.* Vacancy Void Growth Rate as a Function of the Neutron Irradiation Parameters at the Initial Stage of Transient Swelling // Russian Metallurgy (Metally). 2019. V. 2019. № 3. P. 261–267.
14. *Kozlov A.V., Kozlov K.A., Portnykh I.A.* The evolution of helium-vacancy bubbles in austenitic steels under neutron irradiation // J. Nuclear Mater. 2021. V. 549. P. 152915.
15. *Kozlov A.V., Portnykh I.A., Isinbaev A.R.* Model of the final stage of the transient radiation swelling of metals // FMM. 2020. V. 121. № 7. P. 675–681.
16. *Portnykh I.A., Kozlov A.V., Isinbaev A.R.* Prediction of radiation porosity development in austenitic steel 07C-16Cr-19Ni-2Mo-Ti-Si-V-P-B, irradiated at temperatures of 715-815 K to damage doses of 72-92 dpa // Proceedings of the XXIX International Conference "Radiation Physics of Solid State" (Sevastopol, July 08-13, 2019), edited by Honored Scientist of the Russian Federation, Doctor of Physical and Mathematical Sciences, Prof. Bondarenko G.G., Moscow: FGBNU "NII PMT", 2019. P. 233-244.
17. *Kozlov A.V., Portnykh I.A.* Conditions for achieving the stage of steady-state radiation swelling // FMM. 2007. Vol. 103. No. 1. P. 108-112.