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Research Article

16Cr-19Ni steel swelling at dose rates from 1×10^{-8} to 1.6×10^{-6} dpa/s*

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Abstract

The article presents the first data on EK-164ID steel swelling after operational irradiation in a fast nuclear reactor in the temperature range of 370–630 °C and maximum damaging doses of 66–77 dpa. The dose accumulation rate along the cladding tubes made of this material was 1×10^{-8}–1.6×10^{-6} dpa/s. The swelling was determined by the hydrostatic weighing method with an error of no more than 0.5%. The results obtained were analyzed depending on the irradiation parameters and in comparison with the 16Cr-15Ni grade material. The objectives of the study were to estimate the characteristic values of the maximum swelling temperature and dose as well as to calculate the average material swelling rate at the working temperature of irradiation, the incubation period for the onset of swelling, and the stationary swelling rate. It was found that the tube samples, characterized with austenite grain sizes of 9–12 μm before irradiation, have an average swelling rate of 0.035–0.05 %/dpa after reaching the maximum damaging doses of 66–77 dpa (at a rate of $(1–1.5)\times10^{-6}$ dpa/s) and not more than 0.035%/dpa at doses less than 20 dpa (at a rate of 5×10^{-7} dpa/s). The characteristic maximum swelling temperature of the studied material is in the range of 430–500 °C. The characteristic maximum swelling dose is in the range of 61–72.5 dpa or 70–80% of the maximum accumulated dose. The incubation stationary swelling period for the material is 30 dpa. The stationary swelling rate is 0.1% /dpa. The radiation resistance characteristics of the studied material have an advantage over those for 16Cr-15Ni grade cladding materials under similar irradiation conditions and a similar structural state, which inherits grain sizes of 9–14 μm during the tube processing.

Keywords

16Cr-19Ni grade steel, temperature, dose rate, average radiation-induced swelling rate

Introduction

A promising material for manufacturing fuel element claddings for fast neutron reactors is EK-164ID steel with increased chromium contents of up to 19% and a complex set of alloying elements used to enhance resistance to radiation swelling (Bakanov et al. 2011; Nikitina et al. 2015). For engineering design and comparison with known 16Cr-15Ni grade materials, it is of interest to estimate this promising material by such important parameters as the characteristic values of the dose D_{ch} and temperature T_{ch} of maximum swelling as well as the swelling rate S/D depending on the temperature and the accumulation rate of the damaging radiation dose.

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Material and research methods

The first data on the ratio of these parameters were obtained in 2009 on EK-164ID steel of single heat, from which a batch of cold-worked tubes was made for separate irradiation as fuel claddings in the low enrichment zone (LEZ) and high enrichment zone (HEZ) of a fast nuclear reactor to the maximum damaging doses from 66 to 77 dpa and the temperature range of 370–630 °C. The minimum damaging dose of less than 1 dpa during irradiation was achieved at 370 °C whereas the maximum dose values were achieved at 510–550 °C. The dose accumulation rate along the length of the tubes was 1×10^{-8}–1.6×10^{-6} dpa/s (Fig. 1). The dose accumulation rate in both groups of tubes was almost identical.

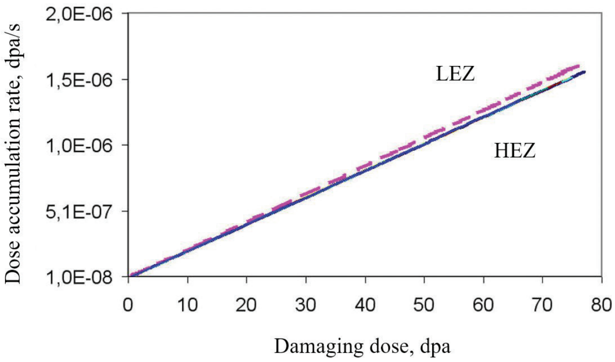

Figure 1. The damaging dose accumulation rate during reactor irradiation.

The microstructure of individual tubes of the batch at the initial stage of mastering the tube technology after finishing heat treatment at 1050 °C (Mitrofanova and Churiumova 2019) was characterized by the average nominal grain size d_g in the cross-section from 9 to 12 µm. There was no recrystallization of grains under increasing temperature along the length of the claddings during irradiation.

The steel radiation swelling S was calculated based on the generally accepted ratio of hydrostatic density ρ of each swollen sample with that ρ_0 in areas without swelling at a damaging dose of less than 1 dpa within one pipe:

$$S = \frac{(\rho_0 - \rho)}{\rho} \times 100\%.$$

The error in determining the swelling was no more than 0.5%.

The average metal swelling dose rate S/D (hereinafter referred to as ‘swelling rate’) at each irradiation temperature was calculated relative to the corresponding damaging dose D, including the incubation swelling period. The incubation dose D_0 was determined by approximating the values of the characteristic maximum swelling doses D_{ch} at the corresponding characteristic swelling temperature.

Findings

The average swelling rate of the EK-164ID steel irradiated in the LEZ of reactor, depending on the temperature and radiation dose, has a non-monotonic character (Fig. 2a). The maximum S/D is observed at a characteristic temperature of 450 °C. The swelling rate of the tube with a maximum dose of 77 dpa was 0.074%/dpa with a characteristic dose of 63 dpa ($D/D_{max} \approx 0.8$). The swelling rate of other tubes in the batch at T_{ch} = 450 °C and D_{ch} = 61–68 dpa was about 0.05%/dpa.

The maximum swelling rates of the steel under study in the LEZ are realized at a dose rate of about 1.3×10^{-6} dpa/s (Fig. 2b). At temperatures below 400 °C and a dose accumulation rate of less than 5×10^{-7} dpa/s typical of the in-vessel structures of a nuclear reactor, the swelling rate did not exceed 0.035%/dpa.

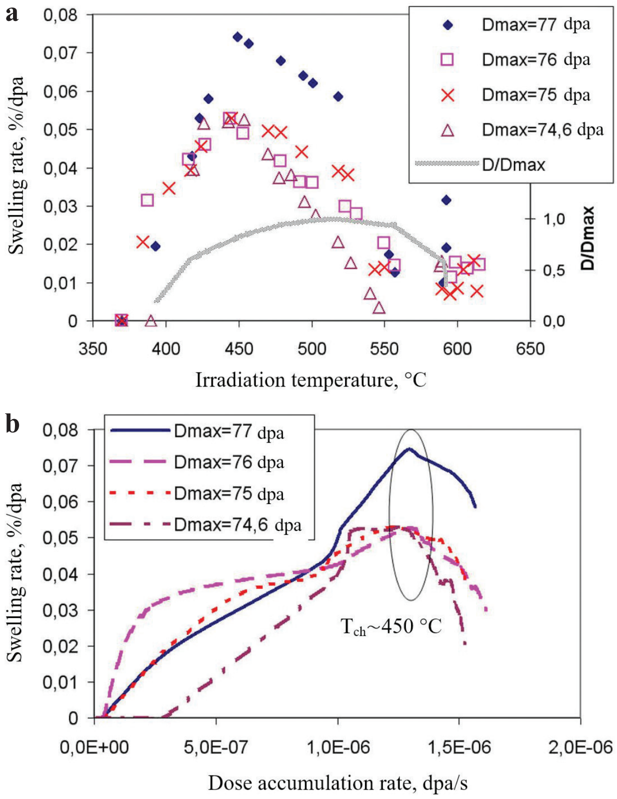

Figure 2. The swelling rate at temperature (a) and intensity (b) of irradiation in the LEZ.

The dependences of the swelling rate of the batch tubes irradiated under the conditions of the HEZ are shown in Fig. 3. A more significant scatter of data is observed here.

One tube sample with a maximum burnup of 72.5 dpa demonstrated an increased swelling rate as 0.075%/dpa at T_{ch} = 500 °C, D/D_{max} = 1 (Fig. 3a) and a dose accumulation rate of 1.47×10^{-6} dpa/s (Fig. 3b). The rest of the samples after a maximum dose of 66.5–73.5 dpa were characterized by a limiting swelling rate of 0.037 – 0.051%/dpa in a narrow range of T_{ch} = 430–450 °C at D/D_{max} ~ 0.7 and a dose rate of about 1×10^{-6} dpa/s.

The incubation dose for the maximum swelling of the considered batch of tubes made of EK-164ID steel was 30 dpa (Fig. 4). The indicated D_0 value was obtained for the initial structural state characterized by the average nominal grain size in the range from 9 to 12 µm. The statio-

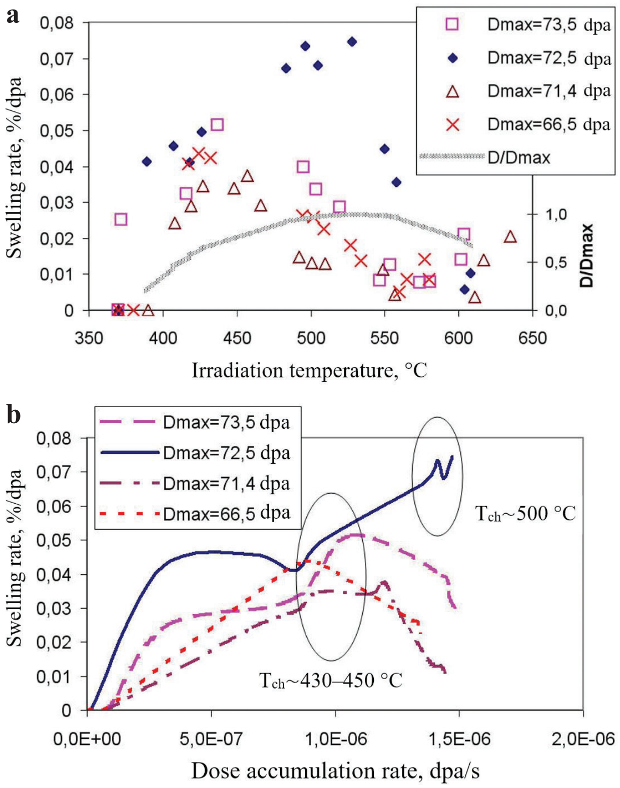

Figure 3. The swelling rate at temperature (a) and intensity (b) of irradiation in the HEZ.

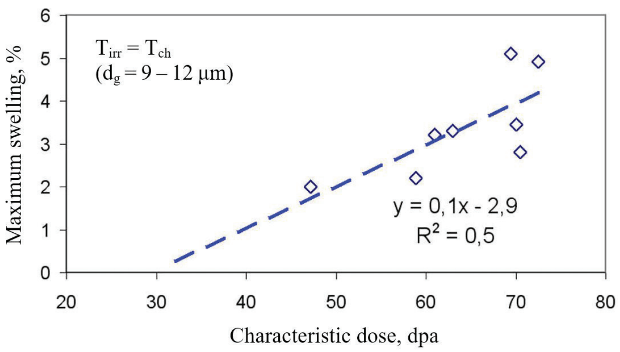

Figure 4. Dependence of the swelling of the investigated batch of tubes at characteristic radiation doses.

nary steel swelling rate in the range of 30–75 dpa was at the level of 0.1 dpa/s.

Discussion

The first experience of reactor irradiation of EK-164ID steel as a material for manufacturing fuel element claddings, despite the above scatter of the investigated swelling characteristics, shows the prospect of increasing the radiation resistance of the 16Cr-19Ni grade steel as compared to the 16Cr-15Ni grade steel. This conclusion is based on a comparison of the data presented in this work with the previously obtained results (Bakanov et al. 2011a; Kinev and Panchenko 2017; Kinev 2019). The generalized data for analysis are given in Tab. 1 to characterize tubes having similar irradiation parameters

Table 1. Comparison of the swelling characteristics of the 16Cr-19Ni and 16Cr-15Ni grade samples (Kinev and Panchenko 2017, Kinev 2019).

Steel grade	D_{max}, dpa	D_{ch}, dpa	D_0, dpa	T_{ch}, °C	S/D, %/dpa	Dose accumulation rate, dpa/s
16Cr-19Ni	66–75	61–72.5	30	430–500	0.035–0.075	$(1–1.47)\times10^{-6}$
16Cr-15Ni	69–76	60–75	55	460–480	0.06–0.1	$(1–1.55)\times10^{-6}$

with an initial austenite grain size of no more than 14 μm. The grain size is an indicator of the limiting temperature conditions for the tube processing of steels having similar chemical composition.

The table shows that the average swelling rate of the 16Cr-19Ni grade steel for the entire irradiation period is noticeably lower than that of the reference object. This is due to the fact that, despite a decrease in the incubation period for the onset of intense swelling, the rate of stationary swelling decreases six times as compared to that for steels with lower nickel contents (Kinev and Panchenko 2017). Therefore, when the maximum damaging dose of about 75 dpa is reached, the total swelling of the promising EK-164ID steel turns out to be lower than that of the 16Cr-15Ni grade steels.

In addition, it should be noted that, in isolated cases of accelerated (*S/D* ≈ 0.075 dpa/s) swelling of the EK-164ID steel in the LEZ and HEZ, there were no obvious metallographic differences (grain size, micro-hardness) or operational factors (dose, temperature), highlighting specimens of tubes with abnormally high swelling from the main group with an average swelling rate of less than 0.05 dpa/s.

A similar situation was repeatedly observed for the 16Cr-15Ni grade steels due to the inhomogeneity of the tube processing technology (Tselishchev et al. 2010; Shemyakin et al. 2019), which is still being improved for both steel classes (Bakanov et al. 2005). In this aspect, it is logical to consider the 16Cr-19Ni grade samples with an increased swelling rate as a deviation from the 'standard' achieved by the technology and not take them into account when analyzing the radiation resistance of the entire group of tubes at the initial stage of development.

Taking into account the criterion of permissible shape change and maximum swelling of 15% (Bakanov et al. 2011a), the use of the lower swelling rate limit gives a predictive estimate of the possibility of operating steels with increased nickel contents in fast reactors up to the level of 119 dpa (Isinbaev et al. 2019). Therefore, the experience of optimizing the chemical composition of the 16Cr-19Ni grade steel and the implemented technology for manufacturing nuclear fuel claddings should be recognized as positive, and we should expect the results of materials science studies of irradiated tubes at the next production stages with a larger austenite grain size.

Conclusion

The article investigated the radiation swelling of EK-164ID steel samples (16Cr-19Ni grade) at the initial stage of tube production after neutron irradiation in a fast nuclear reactor at temperatures of 370–630 °C.

It was found that the tube samples with grain sizes of 6–12 μm have average swelling rates of 0.035–0.05%/dpa after reaching the maximum damaging doses of 66–77 dpa (at a rate of $(1–1.5)\times10^{-6}$ dpa/s) and not more than 0.035%/dpa at doses less than 20 dpa (at a rate of 5×10^{-7} dpa/s).

The characteristic temperature of maximum swelling of the studied material is in the range of 430–500 °C.

The characteristic dose of maximal swelling is in the range of 61–72.5 dpa or 70–80% of the maximum dose.

The incubation period for stationary swelling is 30 dpa.

The stationary swelling rate is 0.1%/dpa.

The radiation resistance characteristics of the studied material have an advantage over those for Cr16Ni15 grade cladding materials under similar irradiation conditions and a similar structural state, which inherits a grain size of 9–12 μm during the tube processing.

References

- Bakanov MV, Chuev VV, Kriukov OV, Lukin AV, Bychkov SA, Budanov YuP, Korostin OS, Tselishchev AV, Tarasyuk VB (2005) Optimization of structural state of cladding tube material made of ЧС-68 steel in cold-worked state. Izvestia Vysshikh Uchebnykh Zawedeniy. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Energy] 1: 139–145. [in Russian]
- Bakanov MV, Maltsev VV, Oshkanov NN, Chuyev VV (2011) The main results of operation of structural materials in the BN-600 reactor core. Izvestia Vysshikh Uchebnykh Zawedeniy. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Energy] 1: 177–186. [in Russian]
- Bakanov MV, Maltsev VV, Oshkanov NN, Chuyev VV (2011a) The main results of workability control of fuel rods with new generation austenitic steel claddings. Izvestia Vysshikh Uchebnykh Zawedeniy. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Energy] 1: 187–195. [in Russian]
- Isinbaev AR, Kozlov AV, Portnykh IA (2019) Forecasting of a residual resource of pin with a cover from EK164 steel after operation in BN-600 reactor with achievement of the maximum damaging dose 99 dpa. VANT. Ser. Materialovedenie i Novye Materialy [VANT. Series: Material Science and New Materials] 5 (101): 75–82. [in Russian]
- Kinev EA (2019) Correlation of high-dose radiation swelling of 16Cr-15Ni steel grade with grain size. Perspektivnye Materialy [Advanced Materials] 3: 39–46. [in Russian]
- Kinev EA, Panchenko VL (2017) Swelling of 16Cr-15Ni improved steel at a speed of a dose rate from $1,0\times10^{-8}$ to 1.7×10^{-6} dpa/s. Izvestia Vysshikh Uchebnykh Zawedeniy. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Energy] 1: 63–70. [in Russian] https://doi.org/10.26583/npe.2017.1.06
- Mitrofanova NM, Churiumova TA (2019) EK164 steel–a structural material of fuel rod claddings of fast nuclear reactors. VANT. Ser. Materialovedenie i Novye Materialy [VANT. Series: Material Science and New Materials] 2 (98): 100–109. [in Russian]
- Nikitina AA, Ageev VS, Leontyeva-Smirnova MV, Mitrofanova NM, Naumenko IA, Tselishchev AV, Chernov VM (2015) Development of works on structural materials of fast reactor cores. Atomnaya Energiya [Atomic Energy] 119 (5): 292–300. [in Russian] https://doi.org/10.1007/s10512-016-0074-2
- Shemyakin VN, Kinev EA, Kozlov AV, Portnykh IA, Panchenko VL, Yevseev MV (2019) The dispersion reasons analysis of spent pin claddings properties of the fast reactor. Izvestia Vysshikh Uchebnykh Zawedeniy. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Energy] 3: 96–107. [in Russian] https://doi.org/10.26583/npe.2019.3.09
- Tselishchev AV, Ageev VS, Budanov YuP, Ioltukhovskii AG, Mitrofanova NM, Leontyeva-Smirnova MV, Shkabura IA, Zabudko LM, Kozlov AV, Maltsev VV, Povstianko AV (2010) Development of construction steel for fuel rod claddings and sodium fast reactors fuel assemblies. Atomnaya Energiya [Atomic Energy]119 (4): 217–222. [in Russian]