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Swelling of improved 16Cr–15Ni–2Mo–Mn–Ti–V–B steel under dose rates from 1×10^{-8} to 1.7×10^{-6} dpa/s

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Abstract

Radiation-induced swelling negatively affects the operability of structural units of fast breeder reactor (FBR) cores. Therefore, search for new and improvement of existing steels for reducing swelling is an important task.

Since 2003, type 16Cr–15Ni–2Mo–Mn–Ti–V–B steel has shown a significant increase in radiation resistance due to its improved composition and heat treatment. Specialists of the JSC INM studied swelling of 16Cr–15Ni–2Mo–Mn–Ti–V–B steel with improved composition, data on the maximum swelling temperature, average swelling rate within typical coolant temperature ranges, as well as fast reactor dose rate were obtained.

The obtained results are based on swelling measurements using hydrostatic weighing and transmission microscopy. Errors in hydrostatic measurements were examined with involvement of metallography data and selection of immersion liquid.

It was revealed that the average swelling rate of improved 16Cr–15Ni–2Mo–Mn–Ti–V–B steel at the maximum swelling temperature is within the range of 0.04–0.14%/dpa. Shifting of this temperature from 460 to 520 °C with increase of the maximum damaging dose from 60 to 80 dpa (1.3×10^{-6} and 1.7×10^{-6} dpa/s, respectively), is observed. At doses below 10 dpa and temperatures below 400 °C the average swelling rate may reach 0.04%/dpa. At temperatures of about 600 °C and irradiation doses below 50 dpa the swelling rate does not exceed 0.01%/dpa during the whole period of observation.

Keywords: 16Cr–15Ni–2Mo–Mn–Ti–V–B steel; Average radiation-induced swelling rate; Maximum swelling temperature; Dose rate.

Introduction

Radiation swelling under irradiation with fluxes of high-energy neutrons negatively affects the properties of structural elements of FBR cores [1–5]. Implementation of new and improvement of known steels for reducing swelling is the important practical task within the framework of which investigation of characteristics such as the average swelling rate and maximum swelling temperature are important.

Starting from 2003 radiation resistance of 16Cr–15Ni–2Mo–Mn–Ti–V–B cladding steel was improved by enhancement of the composition and heat treatment [6–8]. The improvement progress of steel is hindered by extended periods of irradiation and the diversity of damaging factors involved (damage dose rate and maximum damage dose, temperature gradient, stressed-deformed state). Methodological features of post-reactor material studies are of significant importance for adequate evaluation of irradiation's results [9].

Experts from the JSC INM investigated swelling of improved 16Cr–15Ni–2Mo–Mn–Ti–V–B steel. Data array was produced containing the maximum swelling temperature (characteristic temperature) and average swelling rate within temperature range of 370–650 °C and dose accumulation rates ranging from 1×10^{-8} dpa/s to 1.7×10^{-6} dpa/s typical for FBR.

Material and experimental methodology

Swelling of samples of FBR cladding made of improved 16Cr–15Ni–2Mo–Mn–Ti–V–B steel with different heat

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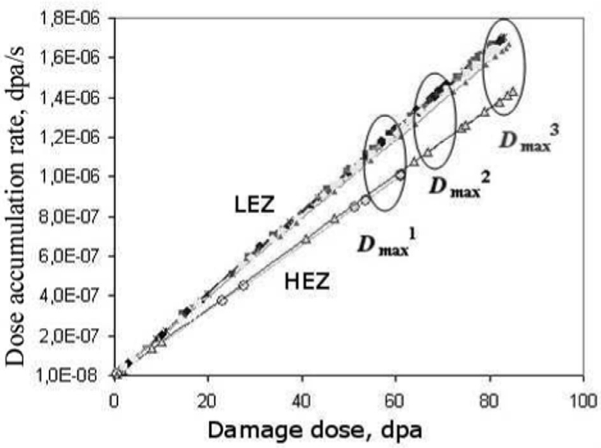

Fig. 1. Intensity of irradiation with maximum doses $D_{max}{}^1$, $D_{max}{}^2$ and $D_{max}{}^3$ within the FBR core zones of low (LEZ) and high (HEZ) enrichment.

treatment and variations of chemical composition was investigated using the methods of remote hydrostatic weighing and laboratory transmission microscopy with relative uncertainty equal to 0, 5 and 15%, respectively [10,11].

Duration of reactor irradiation of cladding materials amounted to 1.5–2 years. Maximum damage doses equal to 60–85 dpa were obtained at temperature of 520 ± 10 °C, minimum dose at the level of 0.5 dpa was obtained at 370 °C. Uncertainties of determination of average temperature of material irradiation amounted to ±10 °C, and those for the damage rate were less than 1 dpa. Intervals of dose rates for the three investigated sample array (bank) of materials with maximum damage doses equal to 60, 70 and 83 dpa, are presented in Fig. 1.

Methodological uncertainties of remote hydrostatic measurements were analyzed using results of optical microscopical metallography, transmission electron microscopy and selection of immersion liquid (distilled water with addition of surfactant and kerosene). Effects associated with changes of structural and phase state of steel under irradiation were not taken into account.

Results and discussion

Array of average rates of radiation swelling of improved 16Cr–15Ni–2Mo–Mn–Ti–V–B steel during the early stages of testing (bank $D_{max}{}^1$ with maximum damage doses of ~60 dpa) is presented in Fig. 2a. Within the ranges of low (<400 °C) and high (>580 °C) temperatures for doses below 25 and 55 dpa, respectively, swelling rate remains below 0.01%/dpa. Peak of swelling rate of ~0,04%/dpa is reached at characteristic temperature at the level of 450–460 °C and doses of the order of 50 dpa.

Extension of testing duration of steel for the purpose of achieving maximum damage doses of the order of 70 dpa (bank $D_{max}{}^2$) induces increase of average swelling rate within the whole temperature range (Fig. 2b). Below 400 °C and with doses up to 30 dpa, as well as temperatures above

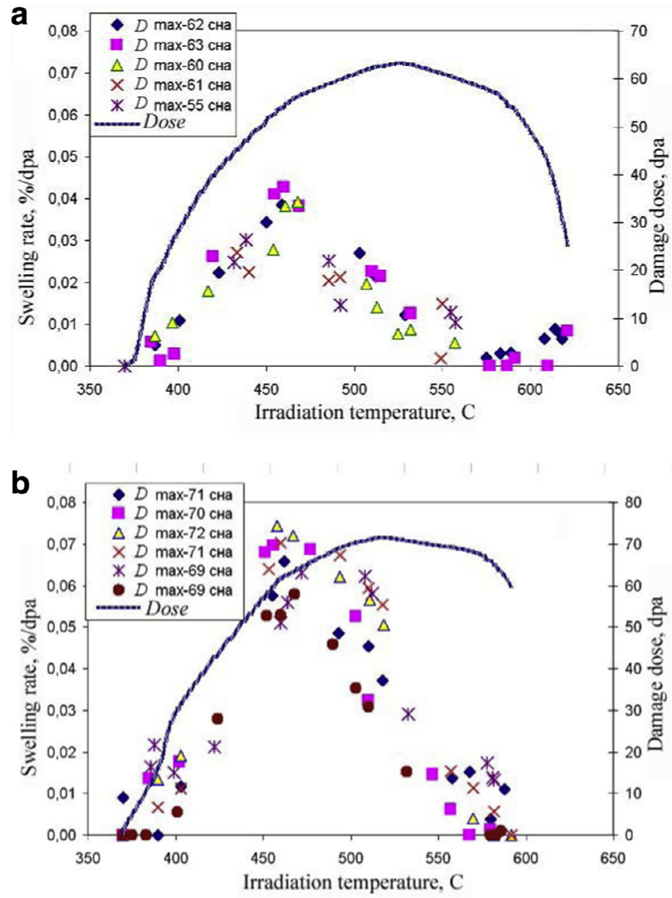

Fig. 2. Swelling rates of steel in the conditions of reactor irradiation implemented for banks $D_{max}{}^1$ (a) and $D_{max}{}^2$ (b).

580 °C and doses below 65 dpa swelling rate amounts to 0.01–0.02%/dpa. Rate of maximum swelling at characteristic temperatures equal to 460–470 °C and doses of ~65 dpa reaches 0.06–0.075%/dpa.

Array of results on the swelling of batches of steel with maximum doses of 80–83 dpa (bank $D_{max}{}^3$) is the most representative and is conventionally divided into stages associated with improvement of tube technology during the periods of 2003–2006 and from 2007 until 2009 (Fig. 3). The array demonstrates the increase of characteristic temperature of maximum swelling (up to 480–520 °C) with tendency of shifting of the peak of swelling rate in the area of maximum damage doses. The rate range of maximum swelling rates for steel amounts from 0.08 to 0.20%/dpa.

During the most recent years of its manufacturing 16Cr–15Ni–2Mo–Mn–Ti–V–B steel is predominantly characterized with rates of its swelling below 0.13%/dpa (Fig. 3b). Higher values of this indicator obtained during all years of testing must be regarded as not promising, while the best results (less than 0.10%/dpa) are accepted as the realistic possibility for ensuring workability of 16Cr–15Ni–2Mo–Mn–Ti–V–B steel at doses of 110–140 dpa.

Low temperature behavior of improved steel at doses below 40 dpa for bank $D_{max}{}^3$ is characterized with swelling rate