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Void swelling at low displacement rates in annealed 12X18H9T stainless steel at 4–56 dpa and 280–332 °C

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Abstract

Water-cooled fusion devices most likely will have austenitic components that operate at temperatures below the inlet temperatures characteristic of high flux fast reactors used to generate majority of data on void swelling. Many of these components will experience displacement rates of 10^{-7}–10^{-8} dpa/s that are lower than that of most in-core fast reactor experiments. One question of particular interest is how to define the lower limit of the temperature range over which void swelling can occur at such low dpa rates. This question was addressed using a flow restrictor component irradiated at 4–56 dpa and 280–332 °C in the low-flux breeder zone of the BN-350 fast reactor in Kazakhstan. This component was constructed of annealed 12X18H9T, an alloy similar to AISI 321. Extensive sectioning to produce 114 separate specimens, followed by examination of the radiation-induced microstructure showed that void swelling in the range of temperatures and dpa rates of interest occurs down to ~300 °C.

1. Introduction

For many years it was assumed that neutron-induced void formation was limited to temperatures greater than ~350 °C [1]. Recently, however, new insight and data became available showing that void formation may occur in the internal structural components of Western pressurized water reactors (PWR) and Russian design VVERs, which operate at lower temperatures (280–430 °C) and at significantly lower neutron fluxes [2–8]. Various proposed water-cooled fusion devices might also have austenitic components that experience such lower temperatures and dpa rates. While swelling must be assumed to be improbable below some lower temperature, the identification of such a limit has not previously been attained. Since most Western fast reactors have inlet coolant temperatures $\geqslant 365$ °C, there are very few data at high neutron exposure from which to extrapolate to the lower temperature limit of swelling.

This paper presents the results of a microstructural study designed to determine the lower temperature limit of swelling in type 12X18H9T austenitic stainless steel after long-term irradiation at lower damage rates in the BN-350 fast reactor in Kazakhstan at temperatures ranging from 281 to 334 °C and doses from 4 to 56 dpa.

2. Experimental details

To study the swelling of type 12X18H9T steel after low-temperature neutron irradiation, one of the out-of-core components of BN-350 was chosen. This component served as a flow restrictor to the sodium coolant in the breeder zone. The component was a hexagonal tube of 96 mm flat-to-flat size, having a central cylindrical hole 65 mm in diameter. The total length of the flow restrictor was 3.435 m.

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This flow restrictor component was made from annealed type 12X18H9T austenitic stainless steel of the following nominal specification (wt%): $C \leqslant 0.12$; Cr, 17–19; Ni, 8–9.5; $Mn \leqslant 2$; $Si \leqslant 0.8$; Ti, 0.5–0.7. The nearest Western equivalent to this steel is AISI 321 stainless steel. It is used in the countries of the former Soviet Union for reactor applications where AISI 304 would be used in Western countries.

The component was exposed without removal or rotation for 46,536 h in the breeder zone at a radial distance of 94.5 cm from the core axis. The maximum neutron fluence at the core midplane was equal to 3.3×10^{23} n/m^2 ($E > 0$) or 1.6×10^{23} n/m^2 ($E > 0.1$ MeV). This fluence in the softer neutron spectra of the out-of-core region corresponds to a neutron damage dose of 56 dpa. Hence, the maximum dose rate was 1.56×10^{-7} dpa/s, and the lowest dose regions of the restrictor reached ~4 dpa at 1.12×10^{-8} dpa/s.

The irradiation temperatures in the component were calculated to range from 281 to 334 °C (accurate within ±3 °C) in the sections examined. There is a somewhat complicated distribution of neutron fluence, dose, and irradiation temperature throughout the component. Details of the dose/temperature relationship and sectioning are contained in another paper [9].

To obtain maximum information on swelling an ambitious cutting scheme of TEM specimens was chosen. First, the flow restrictor was sectioned to produce sections 300 mm in length, (Fig. 1) and second, three of these sections were again sectioned to produce slices of ~0.6 cm thickness (Fig. 2). To prepare microscopy disks (3 mm diameter, 0.3–0.4 mm thick), several slices were cut radially from each edge of the component (seven sets of two specimens) and from the middle of each face (five sets of two specimens). The scheme of cutting of microscopy specimens shown in Fig. 2 was utilized for the three cross sections located with their centers at distances of 0, −150 and +590 mm from the core midplane. For the cross section at −670 mm, TEM specimens were cut from only three faces. A total of 114 specimens were examined by microscopy.

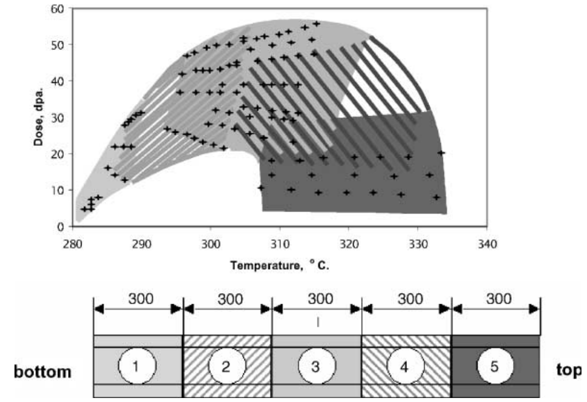

Fig. 1. Dose–temperature map of irradiation conditions and the scheme of initial cutting of the flow restrictor component. Dimensions are in mm. The middle of Section 3 corresponds to the core midplane. Crosses represent the conditions at which microscopy was performed.

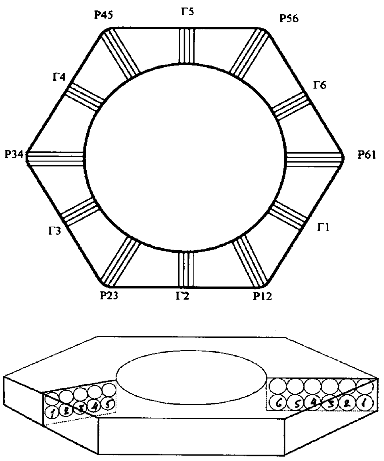

Fig. 2. Cutting scheme of microscopy specimens for component cross sections with centers located at distances of 0, −150 and +590 mm from the core midplane. *P* and *Γ* are derived from the Russian terms for corner and flat, respectively.

3. Microstructural results

Voids were observed in sections at −150, 0 and +590 mm from core center-plane, but none were detected at −670 and −450 mm. Fig. 3 shows the observed dose–temperature map of void formation. Note that voids do not form below ~305 °C at doses up to 52 dpa.

Voids, dislocation loops, dislocation segments, two types of precipitates, and deformation stacking faults characterize the microstructure of 12X18H9T steel in the specimens investigated. The dislocation structure of the irradiated steel consists of both faulted and perfect dislocation loops, and also linear dislocations. The total length of dislocations per unit volume depends only slightly on irradiation temperature in this narrow temperature interval.

In the irradiated steel two types of precipitates were observed. The first type was cubical with mean diameter of 59 nm and a rather low concentration of 5×10^{14} cm^{-3}. The volume fraction of these precipitates equals 0.72%. From electron diffraction patterns it was determined that these are TiC precipitates, which probably formed in the steel during crystallization, but a few smaller precipitates appear to have formed during irradiation. It should be noted that this precipitate was observed in all sections of the flow restrictor component regardless of temperature or damage dose.

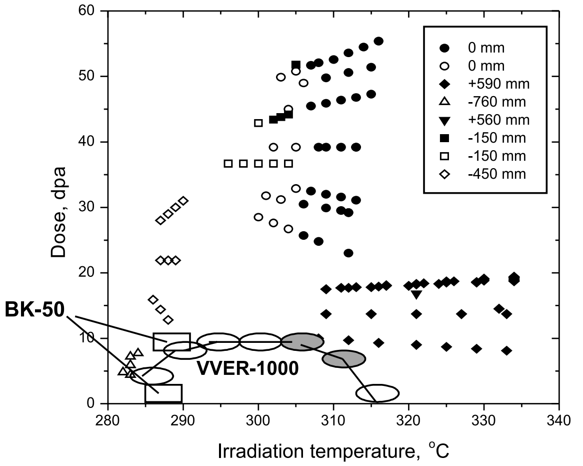

Fig. 3. The dose–irradiation temperature map of void formation in annealed 12X18H10T irradiated in BN-350. Solid symbols denote that voids were observed. Open symbols denote the absence of observable voids. Results by Neustroev et al. [10] are also shown. BK-50 is a BWR located in Dimitrovgrad, Russia, and the VVER-1000 is a PWR in Rovno, Ukraine.

The other type of precipitate consisted of very small, finely dispersed precipitates in the grain interior. An analysis has shown that these precipitates are G-phase. These did not exist prior to irradiation and are well known to be a radiation-induced phase, especially in Ti-modified stainless steels [1]. The diameter of G-phase particles increases, ranging from ~5.5 nm at 289 °C to ~15 nm at 327 °C, and the concentration decreases (3–0.6 × 10^{16} cm^{-3}) with increasing temperature.

4. Results and discussion

In Fig. 4 the temperature dependence is shown of the mean void diameter $\langle d_v \rangle$, void concentration N_v, and swelling. Despite the range of dpa and dpa rates in this dose/temperature range, it is seen that the mean void diameter increases monotonically with increase of irradiation temperature, with an activation energy of about 1 eV. In contrast to the mean void diameter, the void concentration appears to behave non-monotonically with increasing temperature. This behavior is thought to reflect primarily the shape of the dose–temperature space shown in Fig. 3, however, rather than any inherent parametric sensitivity of swelling.

Swelling shown in Figs. 3 and 4 is clearly bounded on the low-temperature side at ~300 °C over the full range of dpa rates examined. Below ~300 °C no voids were observed, even at ~50 dpa. Fig. 4 shows clearly the interplay between temperature and dpa level. The closer to the lower temperature limit, the more dpa are required to see an ever-decreasing amount of voidage.

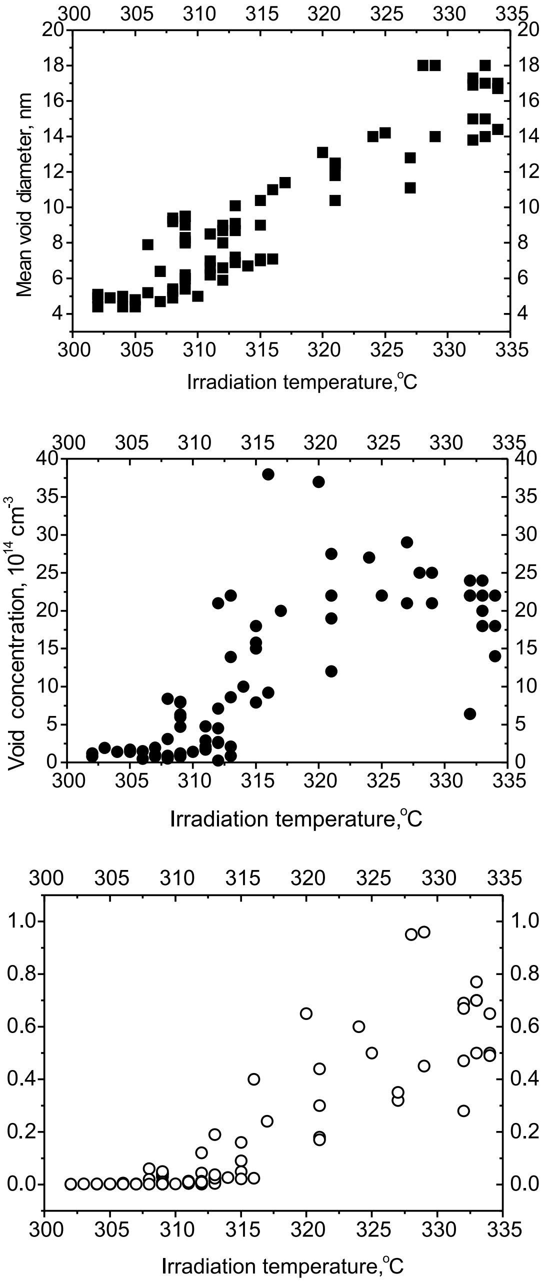

Fig. 4. Temperature dependence of mean void diameter, concentration and swelling.

At a temperature of ~330 °C and doses ranging from 8 to 20 dpa the swelling level ranges from ~0.3% to 1.0%, depending on both the dpa and dpa rate. At the highest temperature examined, ~334 °C, the swelling ranged from 0.5% to 0.8% at ~19 dpa. Most significantly, swelling below ~300 °C did not occur even for doses on the order of 50 dpa, indicating that some thermal barrier exists to void nucleation that can not be easily overcome by continued irradiation.

Neustroev and co-workers have recently published swelling data on this same steel from several light water reactors (LWRs), with all data derived at comparably low dpa rates [10]. Fig. 3 shows a comparison of these data with those of the current study. In general, the two data sets are very consistent, especially in defining ~300 °C as the swelling boundary at lower dpa levels.

Once again it appears that ~300 °C is the lower limit of void formation for this steel at doses of 10 dpa or greater, and that voids can form at doses perhaps as low as 7 dpa at temperatures above 305 °C. It is important to note, however, that in the LWRs the generation rates of helium and hydrogen are much larger than in fast reactors [3]. In spite of this difference the ~300 °C limit appears to be unaffected.

Neustroev et al. have also published data on the 12X18H9T steel after irradiation at 1.3×10^{-7} dpa/s in the reflector region of the BOR-60 fast reactor [7]. At ~345 °C, 1.4% swelling was reached at only 38 dpa, with a significantly smaller incubation dose than observed in comparable irradiations conducted in-core in BOR-60 at higher dpa rates.

As shown by Edwards et al., voids are already forming in some PWR baffle bolts made with cold-worked 316 stainless steel irradiated to only 8–12 dpa at temperatures in the range 330–345 °C [11]. At 19.5 dpa and ~320 °C swelling was an order of magnitude smaller, indicating the strong influence of irradiation temperature on swelling in the low-temperature regime. This steel is normally considered to be rather swelling resistant, especially when compared to annealed 304 stainless steel.

5. Conclusions

Voids in type 12X18H9T austenitic steel irradiated in the BN-350 fast reactor at dose rates ranging from 1.1×10^{-8} to 1.6×10^{-7} dpa/s are observed in the temperature range of 305–334 °C at doses ranging from 8 to 56 dpa. At irradiation temperatures below ~300 °C voids resolvable in an electron microscope were not found.

The ~305 °C lower boundary of swelling appears to be relatively insensitive to dpa rate and gas generation rates in the range examined, and also insensitive to differences in neutron spectra between fast reactors and water-moderated reactors.

The ~305 °C boundary also appears to be consistent with observations on other Russian steels, providing confidence in predicting that such a boundary may also apply to the AISI 304 and 316 steels employed in PWRs of Western design and in various proposed water-cooled fusion devices.

Acknowledgements

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