VOID SWELLING AT LOW DISPLACEMENT RATES IN ANNEALED X18H10T STAINLESS STEEL AT 4 to 56 DPA AND 280-332°C – F. A. Garner (Pacific Northwest National Laboratory)*, S. I. Porollo, A. N. Vorobjev, Yu. V. Konobeev, and A. M. Dvoriashin (Institute of Physics and Power Engineering, Russia)

ABSTRACT

Various components of pressurized water power reactors (PWRs) and some proposed fusion devices such as ITER will operate at lower temperatures and displacement rates than are encountered in many test reactors such as EBR-II, FFTF and HFIR. The question arises if the presence and magnitude of void swelling can be predicted for such irradiation environments. Data on Russian steel can be used to address part of this question. In reactor applications where Western countries typically use annealed AISI 304 stainless steel, it is the Russian practice to use annealed X18H10T, a titanium-stabilized 18Cr-10Ni stainless steel analogous to AISI 321. Using a flow restrictor component from the low-flux breeder zone of the BN-350 reactor in Kazakhstan, it was possible to examine the behavior of void swelling at relatively low temperatures and low displacement rates after 12 years of irradiation. The temperature of this component ranged from 270-340°C with a peak dose rate of 1.6 x 10^{-7} dpa/sec and a peak dose of 56 dpa. Careful sectioning of the component has yielded a large number of microscopy specimens over a ITER-relevant range of temperatures and displacement rates. Microstructural data are presented and show that void swelling at 10 to 50 dpa persists down to ~306°C for dose rates on the order of 1 x 10^{-7} dpa/sec.

Introduction

In some fusion devices such as ITER, the anticipated operating temperatures will be below the inlet temperatures of most current test reactors. The atomic displacement rates may also be much lower than found in many test reactors used in the fusion materials program. It is possible to get some idea of the anticipated swelling behavior under these conditions for fusion applications from ongoing studies in Russia directed toward the possibility of void swelling in pressurized water reactors (PWRs).

It has been predicted that void-swelling and the associated void-induced embrittlement are likely to occur in the AISI 304L and 316L steels that are used in PWR baffle-former assemblies, especially toward the end of the reactor lifetime [1-3]. These steels will receive neutron exposures producing 8 to 100 dpa (displacements per atom) at a maximum displacement rate of ~2 dpa/year over a 40-year lifetime. Temperatures will range from

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~300 to ~400°C, with the highest temperatures developing in positions closest to the core and at the highest neutron fluxes and gamma-heating rates. In such water-moderated reactors the local generation rates of helium and hydrogen in austenitic steels in the baffle-former assembly are comparable to those generated by fusion spectra [1].

Most of the baffle-former structure, however, will experience lower than maximum temperatures, lower dpa rates and thereby lower dpa levels. It is particularly fortunate that the positions experiencing the highest temperatures and highest dpa levels do not exactly coincide, since swelling of 300 series steels in the operational range of interest increases strongly with increases in both variables [4].

Unfortunately, of all easily purchased and widely used stainless steels, AISI 304 is the most swelling-prone steel available, especially when in the annealed, low-carbon condition [5]. This proclivity towards early swelling is primarily a consequence of its low nickel level and moderately high chromium content [4]. Cold-worked 316 is known to resist the onset of swelling much longer than does annealed 304L stainless steel [6,7]. It is also well known that all stainless steels eventually swell at comparable rates, however, but resist the onset of swelling differently, dependent on alloy composition, thermo-mechanical starting state, irradiation conditions, and neutron spectra. The latter determines the generation rates of helium and hydrogen, which can stabilize void nuclei [1].

Evaluation of the potential swelling behavior under ITER-relevant conditions is limited by several factors. First, essentially all data on AISI 304 and 304L were generated in the EBR-II fast reactor, which had an inlet temperature of 370°C, precluding the availability of data in the 300-370°C range that is experienced by most of the baffle-former assembly.

Second, the data on swelling of AISI 304 were generated under conditions of relatively high displacement rate and relatively low levels of helium generation compared to conditions found in PWRs [1]. Both of these factors are known to influence the duration of the incubation and transient regimes of swelling [4].

Data on steels irradiated in Russian and Kazakhstan reactors have previously been used to assess the potential of void swelling at PWR-relevant dpa rates and dpa levels in the temperature range below 370°C. These data show that the Russian steels used in nuclear service exhibit void swelling at lower-than-anticipated dpa levels and irradiation temperatures [8-11], and to increase in swelling with decreasing dpa rate [12].

In order to estimate the lowest temperature at which swelling of AISI 304L might occur at ITER and PWR-relevant dpa rates, an experiment is being conducted on 12X18H10T in the annealed condition. This material was irradiated in the low flux reflector region of the BN-

350 fast reactor, located in Kazakhstan. This steel is similar to AISI 321 and is used in a wide variety of reactors of Russian design for applications where AISI 304 would be used in Western PWRs. In this experiment, however, the helium and hydrogen generation rates were significantly lower than that found in PWRs. Thus, in this case the potentially synergistic effects of dpa rate and gas generation rates can be avoided, with dpa rate effects being dominant.

Experimental Details

This steel has a composition of Fe-18.5Cr-9.5Ni-1.5Mn-0.7Si-0.65Ti-(<0.12C) in wt. %. The composition was confirmed using a "Kamebax" x-ray analyzer in scanning mode on an irradiated specimen.

The examined component was a hexagonal tube with a "flat-to-flat" distance of 96 mm and with a central hole of 65 mm in diameter. The total length of the component, including its upper and lower end units, is 3.44 m, equal to the length of driver fuel and breeder subassemblies. The component served as a flow restrictor to the sodium coolant in the reflector region.

The component was irradiated in the breeder zone of the BN-350 reactor at a radial distance of 94.5 cm from the core axis during 1939 effective power days of irradiation, beginning from November 1972 up to June 1984. At the core midplane cross-section of the component the calculated peak fluence of neutrons is 3.3×10^{23} n/cm^2 (E>0 MeV) or 1.6×10^{23} n/cm^2 (E>0.1 MeV). These peak fluences correspond to a damage dose of 56 dpa (NRT). The corresponding peak dpa rate was 1.56×10^{-7} dpa/sec. On the opposite side of the component the dpa level fell to 22 dpa at the core midplane.

Axial profiles of irradiation temperature at inner and outer surfaces of the component at the minimal radial distance from the core axis are shown in Figure 1. For opposite flats the temperatures are lower by 1-4°C. Across the central hole the temperature varies ±3°C. The irradiation temperature at the internal surface of the component in the core midplane cross-section varies along its perimeter from 299 to 302°C and the temperature at the outer surface varies from 313 to 317°C, so that the temperature decrease through the component wall is ~15°C. The irradiation temperatures depend on the reactor power level and the quoted values were averaged over the entire period of irradiation to determine the nominal temperatures, which are considered to be accurate to ±5°C over the irradiation lifetime.

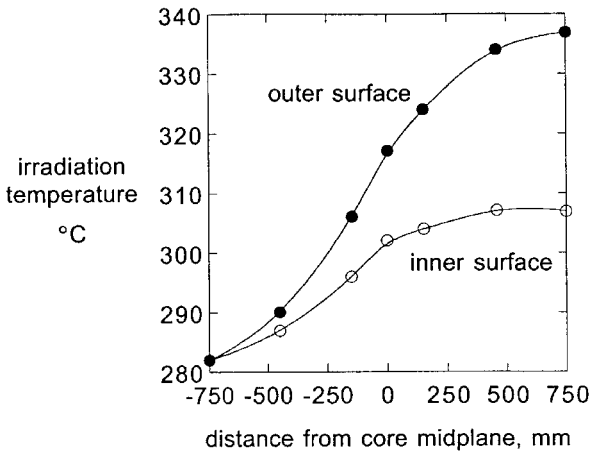

Figure 1. Temperature profiles for the inner and outer surfaces of the flow restrictor component at the position nearest to the core central axis.

Various axial portions of this component have been mechanically sliced to yield 0.4 mm thick plates. These plates were in turn sliced to produce 12 x 4 x 0.5 mm strips at twelve radial positions around the circumference of the component as shown in Figure 2. Microscopy disks of 3 mm diameter were then punched from the strips and thinned to 0.1-0.2 mm using sandpaper grinding. These disks were then thinned electrochemically and examined by electron microscopy at 100 keV. This work is still in progress but nearing completion.

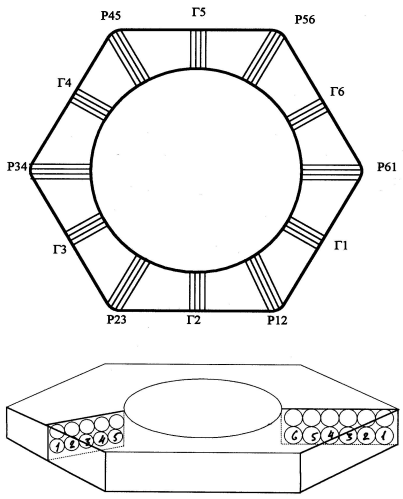

Figure 2. Diagram showing cutting location of microscopy disks for the section taken at the mid-core axial position. The core center lies along the line defined from P34 to P61. The

highest neutron exposure occurred at P61. P and Γ are derived from the Russian terms for corner and flat, respectively.

TABLE I Distribution of Normalized Neutron Fluences and Displacement Dose in Core Midplane Cross-section of the Flow Restrictor Component

Neutron Fluence Relative to Position P61	Point Number							
	P61	Γ1	Γ2	Γ3	P34	Γ4	Γ5	Γ6
E>0 MeV	1.0	0.93	0.69	0.56	0.50	0.56	0.68	0.92
E>0.1 MeV	1.0	0.91	0.60	0.47	0.42	0.47	0.59	0.90
dpa	1.0	0.90	0.57	0.44	0.39	0.44	0.56	0.89

The relative distribution of the total neutron fluence and damage dose for the core midplane cross-section of the component are given in Table I, and the positions of the microscopy specimens are shown in Figure 2. The maximum neutron fluences for E>0 and E>0.1 MeV in the core midplane position are equal to 3.3 x 10^{23} n/cm^2 and 1.6 x 10^{23} n/cm^2, respectively. This fluence corresponds to a displacement dose of 56 dpa. The neutron spectrum in this region of the reflector is relatively soft with only 3.5 dpa produced by 10^{22} n/cm^2 (E>0.1 MeV)

Results

As shown in Figure 3, voids were observed at temperatures as low as 306°C and 25.7 dpa in the slice taken at the core midplane. In the slice taken at 590 mm above the core midplane, swelling was observed as low as 308°C and 10 dpa. Thus, voids probably form at even lower dpa levels in the region just above 300°C, but cannot be observed within the limited slicing matrix employed in this experiment. It should be noted, however, that swelling does not occur below 300°C, at least for doses below ~40 dpa.

While the swelling levels are not large (<0.3%), the appearance of voids at these low temperatures was previously unexpected. The void densities are in the 10^{14}-10^{15} cm^{-3} range with mean diameters of 5 to 9 nm, except at the slices obtained at the higher elevations, where the temperature is higher and the mean diameters are >100 nm.

Typical microstructures are shown in Figures 4 and 5, showing the disappearance of voids at between 313 and 305°C at doses of 30-33 dpa. In addition to voids, the microstructures of all specimens contained dispersions of small G-phase precipitates and also plate-like

defects. These are shown in Figures 6 and 7. The plate-like defects are dislocation loops viewed edge-on.

Discussion

The swelling levels reached in this experiment are not very large in the temperature range studied, but swelling of stainless steels are known to exhibit long periods of transient swelling at low rates before the onset of accelerated swelling [4]. In a paper by Porollo and coworkers [13], it is shown that at temperatures in the range 330-342°C the end of the transient regime of both this steel and another steel is on the order of 60 dpa at higher dpa rates, with a swelling rate on the order of ~1%/dpa thereafter. Therefore, it is prudent to assume that a linear extrapolation of the data in this report to higher dpa levels will not yield a correct estimate of swelling.

Another feature of these data is that irradiation temperature appears to be a more important variable than the displacement level in the low temperature regime. Otherwise one would expect the data shown in Figure 3 to tend to show more swelling at lower temperatures as the dpa level increased, rather than to stop swelling at ~300ºC at all doses. This perception is biased, however, by the direct coupling of dpa and dpa rate in these data, such that swelling decreases with dpa rate but increases with dpa level.

Since the composition of this Russian steel is somewhat different from that of AISI 304L, especially in their titanium and carbon contents, one cannot use these data to predict the swelling of AISI 304L. However, based on these results and those of the experiments cited earlier, it is reasonable to expect that swelling of 304L and 316 stainless steels can occur to temperatures approaching 300°C for displacement rates on the order of ~10^{-7} dpa/sec.

It is known that the swelling of 304 and 304L stainless steels at 370-390°C are sensitive to displacement rate, however, with swelling increasing as the displacement rate decreases [13-17]. If this sensitivity also applies at temperatures below 370°C, it is not unreasonable to expect that swelling of AISI 304L will also extend down to ~300°C.

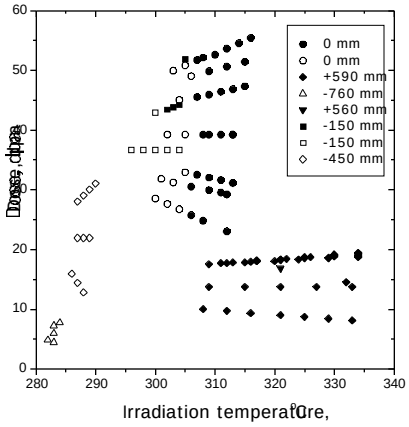

Figure 3. Dose-temperature map of void observations in annealed X18H10T austenitic stainless steel after irradiation in the BN-350 reactor near the core midplane. Elevations where slices were cut are indicated by shape of symbol. Irradiation conditions for midplane flats Γ2 and Γ5 are identical, yielding an overlap of some data, since the microstructures were essentially similar. Solid symbols indicate voids observed; open symbols indicate no voids found.

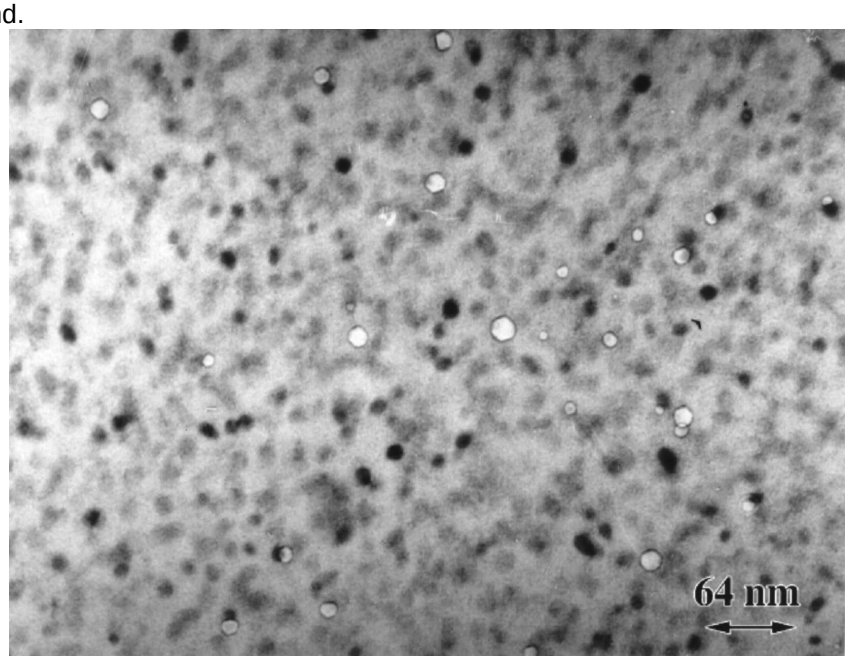

Figure 4. Microstructure of neutron irradiated 12X18H10T at 313°C and 30.2 dpa showing void and precipitate formation. Swelling of 0.05% was produced at 0.84 x 10^{-7} dpa/sec.

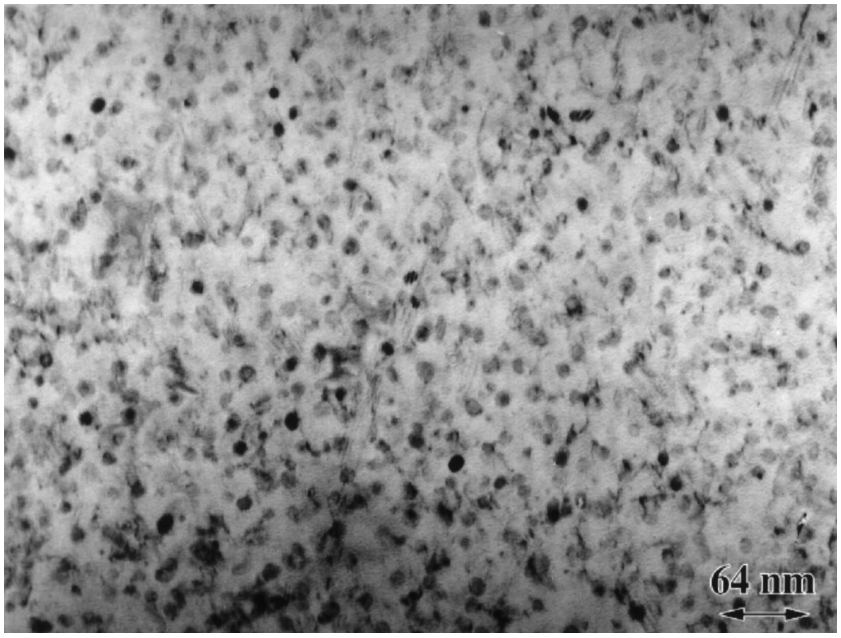

Figure 5. Microstructure at 305°C and 33.0 dpa showing precipitates but no voids at 0.92 x 10^{-7} dpa/sec.

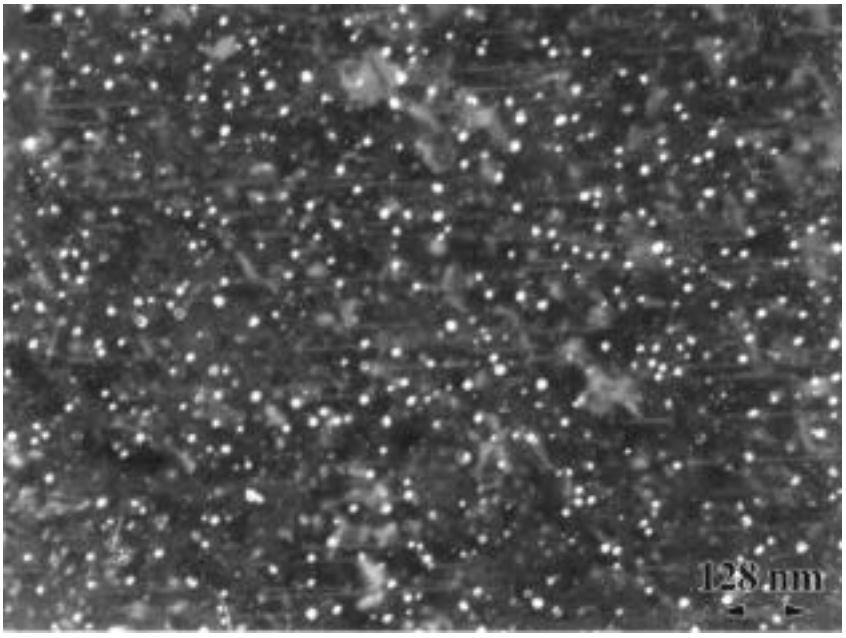

Figure 6. Dark-field micrograph showing G-phase precipitates at 309°C and 31.9 dpa.

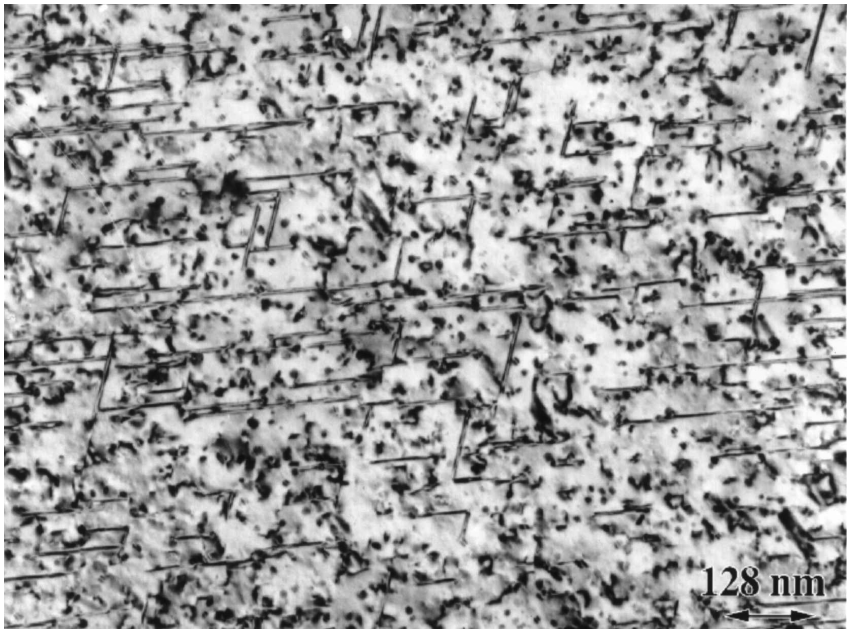

Figure 7. Bright field micrograph of specimen in Figure 6, imaged to show dislocations, precipitates, and a few very small voids, producing ~0.02% swelling at 0.89 x 10^{-7} dpa/sec

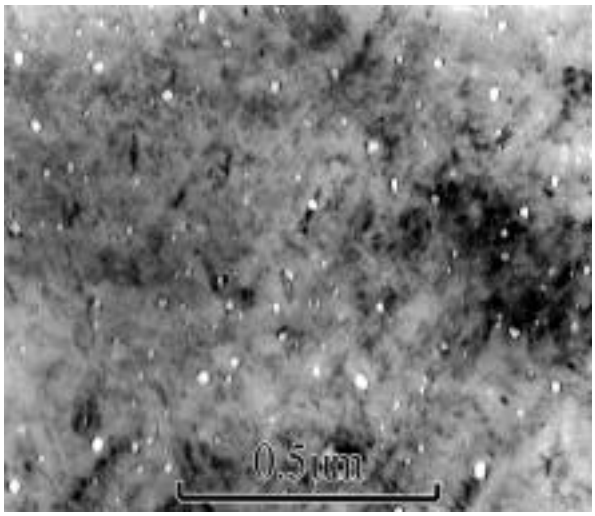

Figure 8. Swelling at ~0.2% observed in annealed 12X18H10T stainless steel at 16.8 dpa and 321°C after irradiation at ~4 x 10^{-8} dpa/sec in the BN-350 fast reactor [8].

One issue not addressed in this report is the possible acceleration of swelling due to higher levels of both helium and hydrogen found in PWR and fusion neutron spectra. In this study voids were found at 25-35 dpa, but in PWR reactor spectra and other even more thermalized

spectra, voids appear to form in stainless steels at 1-10 dpa [8, 18-20]. Several recent studies have shown that hydrogen, probably in molecular form, appears to collect in and pressurize voids nucleated by helium [18,21]. It has been proposed that helium-assisted storage of hydrogen will accelerate the onset of void swelling [22].

Conclusions

Until recently it was thought that austenitic stainless steels would not exhibit void swelling at ITER and PWR-relevant temperatures and displacement rates. It has been shown, however, that void swelling in annealed X18H10T appears to develop at temperatures as low as 306°C when irradiated in a Kazakhstan fast reactor at ITER and PWR-relevant damage rates on the order of 1×10^{-7} dpa/sec. This indicates the possibility that similar swelling can occur in 300 series stainless steels in ITER and other fusion devices.

ACKNOWLEDGEMENTS

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