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The strong influence of displacement rate on void swelling in variants of Fe–16Cr–15Ni–3Mo austenitic stainless steel irradiated in BN-350 and BOR-60

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Abstract

Recent irradiation experiments conducted on a variety of austenitic stainless steels have shown that void swelling appears to be increased when the dpa rate is decreased, primarily by a shortening of the transient regime of swelling. This paper presents results derived from nominally similar irradiations conducted on six Russian steels, all laboratory heat variants of Fe–16Cr–15Ni–3Mo–Nb–B, with each irradiated in two fast reactors, BOR-60 and BN-350. The BN-350 irradiation proceeded at a dpa rate three times higher than that conducted in BOR-60. In all six steels, a significantly higher swelling level was attained in BOR-60, agreeing with the results of earlier studies.

1. Introduction

Earlier studies have shown that the atomic displacement rate is unexpectedly one of the most important variables in determining the onset and magnitude of swelling in austenitic stainless steels [1–11]. In general, a decrease in the dpa rate leads to an onset of swelling at a lower dose, yielding more swelling at a given dpa level than would be attained at a higher dpa rate. One recent study also suggests that a similar sensitivity to dpa rate exists in ferritic alloys [12].

Given the potential impact on the fusion swelling issue, such a surprising and counterintuitive conclusion requires additional data for confirmation, especially with respect to establishing the general applicability of this conclusion as valid for a wide variety of neutron spectra and for different austenitic steels.

This paper presents results derived from irradiations conducted on six Russian steels, each irradiated in two fast reactors. It should be noted that Russian steels used for nuclear service are in general stabilized steels, usually containing titanium or niobium, while comparable steels used for nuclear service in USA and Japan are usually unstabilized.

2. Experimental details

Two of the major test beds for high fluence irradiation in the CIS (Commonwealth of Independent States, formerly states of the Soviet Union) are BOR-60 in Dimitrovgrad, Russia and BN-350 in Aktau, Kazakhstan,

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operating at nominal power levels of 60 and 350 MW, respectively. Both BOR-60 and BN-350 are sodium-cooled fast reactors, but the latter, now decommissioned, operated at significantly higher neutron fluxes than the former.

Two experimental series are of interest to the subject of this paper. They involve comparative irradiation experiments in the two reactors that were designed primarily to explore material variables that impact swelling. However, since the irradiation conditions were largely the same except for displacement rate, these experiments also explored the competition between material variables and differences in displacement rate.

All specimens in both series were in the form of tensile specimens with a total length of 26 mm and a gauge length of 15 mm. The gauge diameter was 3 mm and that of the heads was 6 mm.

The steels investigated were all laboratory heat variants of Fe–16Cr–15Ni–3Mo–Nb–B, with compositions shown in Table 1. These steels are variations of EP-172 steel that is frequently used for nuclear applications in Russia.

Note that there were two experimental alloy series. The first four-alloy series was Fe–16Cr–15Ni–3Mo–0.6Nb–0.6Mn–0.06C–0.008P but varying in silicon content from 0.4 to 1.2 wt%. The second three-alloy series contained the 0.63% silicon variant from the first series and two other alloys where 0.15% titanium either was added to or replaced the 0.6% Nb.

After fabrication, multiple specimens of all six alloys were prepared in the fully annealed condition (50% CW/1080 °C for 30 min in argon/air cooling) and irradiated side by side in each reactor while in contact with flowing sodium coolant. In each reactor the specimens experienced similar temperature and dpa levels, but the irradiation proceeded at 5.06×10^{-7} dpa/s in BOR-60 and 1.58×10^{-6} dpa/s in BN-350, approximately a factor of three difference in rate. The fluences attained were 11.5×10^{22} and 11.9×10^{22} n/cm^2 ($E > 0.1$ MeV), respectively.

The dose reached was 52 dpa in BOR-60 and 53 dpa in BN-350, while the temperatures were 470–480 °C in BOR-60 and 490 °C in BN-350. All temperatures are calculated with an error of ±15 °C. The neutron spectra of the two reactors were very similar at ~4.5 dpa per 10^{22} n/cm^2 ($E > 0.1$ MeV), which ensures that there were no differences in helium generation or other transmutant formation rates.

Following irradiation the specimens were cleaned and their density measured using a CCl_4 immersion technique. Measurements were performed on two (BN-350) to six (BOR-60) nominally similar specimens for each heat. Each specimen was weighed three times to determine the average density. Measurement accuracy was ±0.2% before irradiation and ±0.5% in the hot cell after irradiation. In general, there was a rather limited range of swelling variation for nominally identical

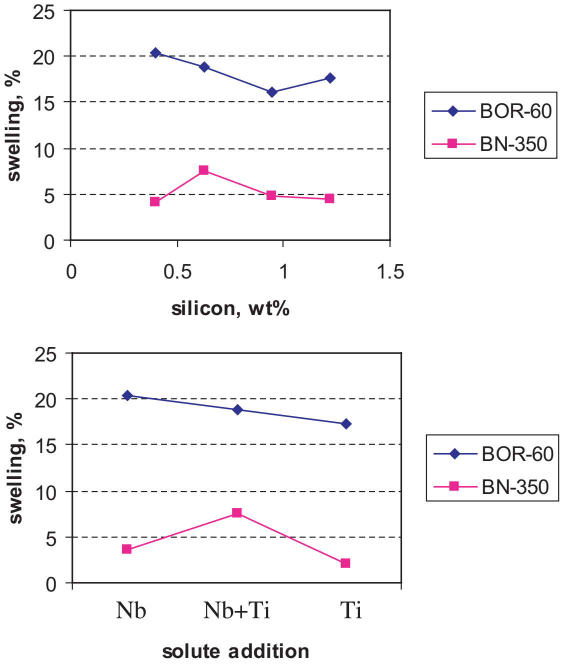

Fig. 1. Comparison of swelling measured by density change for the two experimental series irradiated in BOR-60 (470–480 °C, 52 dpa, 5×10^{-7} dpa/s) and BN-350 (490 °C, 53 dpa, 15.6×10^{-7} dpa/s).

Table 1
Chemical composition in wt% of the EP-172-type steels irradiated in both BOR-60 and BN-350

Steel #		C	Mn	Si	S	P	Cr	Ni	Mo	Nb	Ti	B
16Cr–15Ni–3Mo–B	1	0.060	0.7	0.40	⩽0.015	⩽0.015	16.00	15.00	2.90	0.65	–	0.007
	2	0.063	0.7	0.63	⩽0.015	⩽0.015	16.20	15.20	2.98	0.65	–	0.008
	3	0.062	0.6	0.95	⩽0.015	⩽0.015	15.50	14.50	2.90	0.65	–	0.008
	4	0.064	0.6	1.22	⩽0.015	⩽0.015	16.25	15.30	3.00	0.60	–	0.008
	5	0.060	0.5	0.64	⩽0.015	⩽0.015	16.03	15.06	3.00	0.06	0.15	0.006
	6	0.060	0.6	0.63	⩽0.015	⩽0.015	16.05	15.08	2.93	0.60	0.15	0.008

Nitrogen contents of all steels lie in the range 0.02–0.03 wt%.

specimens. Each data point in Fig. 1 represents the average of six (BN-350) or 18 (BOR-60) measurements. For example the swelling of the 0.04% Si specimen in BOR-60 ranged from 19.3% to 22.5%, showing rather good agreement for six nominally identical specimens.

3. Results

Fig. 1 shows that in each case there was a clear effect of composition on the swelling in both series of alloys, but there was more swelling (16–20%) in the BOR-60 experiment conducted at the lower displacement rate, while only 2–7% was reached in the BN-350 experiment at the higher displacement rate.

Another observation is that the relative behavior with composition of each alloy series is somewhat different in the two reactors, indicating that the onset of swelling in response to a given compositional variable can change as competitive and synergistic influences of other environmental variables, such as dpa rate, come into play.

4. Discussion

Considering that the two irradiations were conducted in separate reactors, even with nominally similar conditions of temperature, temperature history, neutron spectra and helium generation rate, one can not firmly state based on these data alone that the different dpa rates were the only variable operating to produce the large difference in swelling. However, the very large difference in response between the two irradiations is strongly supportive of an interpretation based on flux-dependent swelling, especially when viewed in the context of the earlier quoted studies [1–11].

While the level of swelling in these experiments appears to be affected by the dpa rate, it is not clear in what stage of the swelling evolution the effect is manifested.

The ‘flux-effect’ studies led by Okita et al. [4,6,7] show that, at least in simple model austenitic alloys, the post-transient steady-state swelling rate is not affected by differences in dpa rate, with the flux sensitivity confined to the transient regime. Okita presents microstructural evidence to support the flux dependency arising primarily from the flux sensitivity of Frank loop evolution and its subsequent transition to a network dislocation.

5. Conclusions

As data continue to accumulate it appears that austenitic stainless steels irradiated in various fast reactors develop void swelling at accelerated rates as the atomic displacement rate decreases. Synergisms between compositional and irradiation variables operate to produce the observed swelling behavior.

Acknowledgements

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