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Effects of helium on void swelling in boron doped V–5Fe alloys

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Abstract

The effects of helium on void swelling in V–5Fe were investigated with natural boron-doping techniques during FFTF/MOTA (Fast Flux Test Facility/Materials Open Test Assembly) irradiation. Microstructural observation was carried out to understand the swelling behavior obtained from density measurements. The cavity size distribution in V–5Fe–xB ($x = 0$, 100, and 500 appm) irradiated at temperatures lower than 713 K indicates a suppressant effect of helium on void growth, and an enhancing effect on cavity nucleation. Since the chemical effect of boron addition is competitive with the transmutation effect, the results have been compared with that of the dual ion irradiation experiments to allow separation of the effect of helium from the effect of boron.

1. Introduction

The effects of helium production through (n,α) reactions on the material performance degradation in fusion environments is one of the most important subjects for fusion reactor structural materials. Also, synergetic effects of atomic displacement and helium production is important. However, there are only a few ways to simulate that situation. Experimental techniques such as the tritium trick [1,2] and dynamic helium charging experiments (DHCE) have been utilized [3–7] to evaluate helium effects in neutron-irradiated vanadium alloys, and the boron-doping technique has also been utilized by the authors [8]. Although the addition of boron is a relatively easy method to produce helium atoms via the (n,α) reaction of ^{10}B [9–11], boron addition itself may also affect the material behavior, as well as by lithium coproduced by the ^{10}B (n,α) reaction. In [8], the complicated dependence of swelling on boron content suggests the separate and competitive actions of boron and lithium as chemical species, in addition to the action of helium as a cavity-stabilizing gas. Therefore the dual ion beam irradiation technique was utilized by the authors in order to separate the chemical effect of dopant boron from the helium effect on void swelling behavior of vanadium alloys [12,13]. The results of the dual ion irradiation experiment suggested that helium acts as cavity stabilizing gas to make cavity distribution denser and smaller than in the helium-free condition. Although the effect of boron was less significant than that of helium, boron had its own effect on swelling induced by ion irradiation.

It is known that addition of undersized atoms such as chromium and iron to vanadium leads to rather large void swelling [2,14]. In this paper, the effect of helium and boron on void swelling in V–Fe is discussed. Microstructural information was added to understand the swelling behavior measured by the immersion density technique, and the boron doping experiments using Fast Flux Test Facility (FFTF) are compared with the results of dual ion irradiation experiments.

2. Experimental

Vanadium alloys examined here were V–5wt%Fe, V–5wt.%Fe–100 appm B and V–5wt%Fe–500 appm B. Natural boron was used for the dopant. Specimens were prepared by arc-melting in an argon gas atmosphere and annealed at 1173 K for 3.6 ks in a vacuum of 10^{-4} Pa,

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followed by rapid cooling to insure that most of the boron remained in solution. Interstitial impurity contents such as carbon, oxygen and nitrogen are 36, 120, and 6 wt. ppm, respectively.

These specimens were irradiated in sealed helium-filled stainless steel packets in FFTF/MOTA (MOTA-2B) in the form of TEM disks of 3 mm in diameter. The irradiation conditions are listed in Table 1. Post irradiation experiments employed were that of density measurement using an immersion density technique and transmission electron microscopy (TEM) observation. The results of the density measurements have already been reported in Ref. [8], as shown in Fig. 1. Very large swelling (>30%) in condition E did not allow TEM images of voids. Therefore TEM observation of materials in condition E was not carried out. In addition, only silhouette-like images were obtained by TEM observation of materials in condition D (swelling >8%), so it is hard to obtain the quantitative data on void formation. Almost none of the TEM specimens were perforated in the center but in the laser-graved area because the laser graving for identification might have been too deep. Therefore the foils were quite thick even close to the edge to allow determination of reliable foil thickness using thickness fringes. Nevertheless, cavity images were taken from these specimens, although the void densities could not be accurately measured.

The helium production rates were experimentally evaluated in Ref. [8] to vary from 0.03 to 2.31 appm He/dpa in these irradiation conditions at the boron contents examined here. The softer neutron spectrum in the below-core location (condition C) makes the He/dpa ratio higher than that of a harder spectrum for an in-core location (condition A, B, D, E).

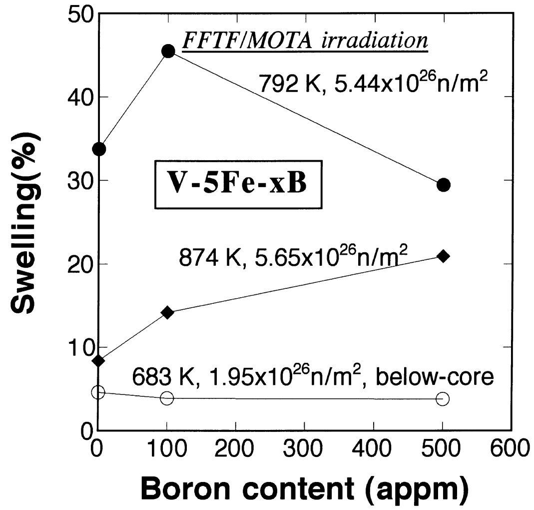

Fig. 1. Effect of boron content on swelling in V–5Fe–B alloys measured by immersion density technique [8].

3. Results

Fig. 2 shows the cavity microstructure of the three alloys irradiated in conditions A (0.29 dpa, 710 K), B (1.5 dpa, 704 K), and C (10.2 dpa, 683 K, below core). Cavities are distributed almost uniformly in the matrix in these alloys. Inhomogeneous cavity formation near grain boundaries was not seen in each alloy, while denuded zones were seen near grain boundaries in several specimens. In spite of the lowest fluence at somewhat higher irradiation temperature, the average cavity size in condition A was comparable to the other conditions of higher fluences at somewhat lower irradiation temperatures.

In condition B, each alloy contains some larger cavities among many smaller ones. The cavity size distribution in condition B is plotted in Fig. 3, in which bimodal cavity size distribution is seen in each of these alloys. Boron addition increases the size of the larger void class. In condition C, large-grown voids are less significant than in condition B, and the cavity size distribution seems to be almost single-modal (Fig. 4). Fig. 5 plots the average cavity size as a function of boron content in each irradiation condition together with the swelling in condition C measured by immersion density technique. Although the cavity size is smaller for 500 appm boron than in 100 appm boron, swelling values are comparable between 100 and 500 appm boron in condition C. This suggests that cavity number density should be higher in V–5Fe–500 appm B than in V–5Fe–100 appm B. In the other two conditions, the average cavity size of V–5Fe–100 appm B is larger than the other alloys.

Table 1
Irradiation conditions in FFTF–MOTA

Condition ID	Temperature (K)	Neutron fluence, $E > 0.1$ MeV (n/m^2)	dpa	Position in FFTF	Measurement
A	710	6.75×10^{24}	0.29	In-core (level 7)	TEM
B	704	3.63×10^{25}	1.5	In-core (level 6)	TEM
C	683	1.95×10^{26}	10.2	Below core basket	Density, TEM
D	874	5.65×10^{26}	30.5	In-core (level 3)	Density, TEM
E	792	5.44×10^{26}	29.5	In-core (level 4)	Density

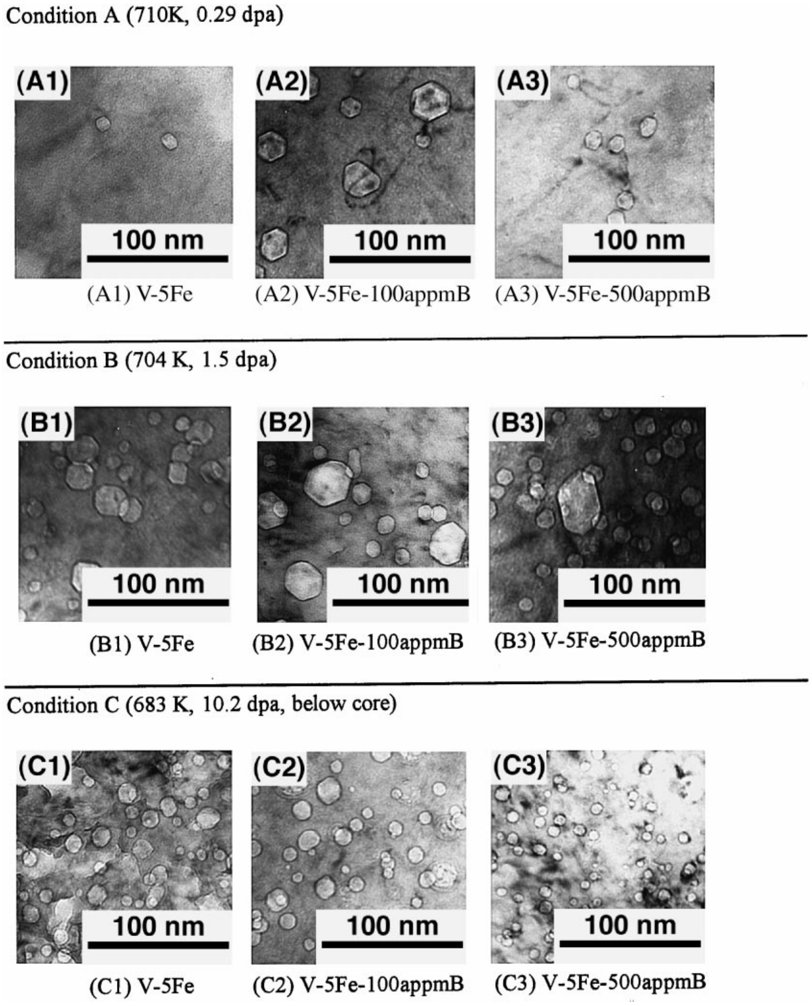

Fig. 2. Cavity microstructures of V–5Fe, V–5Fe–100 appm B and V–5Fe–500 appm B irradiated in FFTF/MOTA. (Upper) condition A: 710 K, 0.29 dpa, (middle) condition B: 704 K, 1.5 dpa, (lower) condition C: 683 K, 10.2 dpa, below-core.

4. Discussion

The previous work of dual ion irradiation on V–5Fe [12,13] was intended to separate the effects of helium from the effects of the other elements, especially boron. The influence of simultaneous helium implantation on cavity formation was very significant, with enhanced cavity nucleation and suppressed cavity growth. The latter effect was less significant at higher irradiation temperature (873 K). In the FFTF irradiation examined here, the suppressant effect is also seen in the cavity size distribution shown in Figs. 3 and 4. In particular, it is significant in V–5Fe–500 appm B irradiated in the below-core location, in which helium production rate per dpa is highest among the conditions examined here. Therefore it is convincing that the enhanced cavity nucleation by helium suppresses cavity growth in the neutron-irradiated V–Fe alloys at the irradiation temperature around 683 K. This is consistent with the reported suppressant effect of helium produced by tritium trick method at 673 K [2]. The similar swelling values between V–5Fe–100 appm B and V–5Fe–500 appm B in condition C can be attributed to the enhancement effect on cavity nucleation of helium.

In addition, the effects of boron and lithium have to be considered to understand the results. Since there are few data on the effect of lithium on swelling in vanadium alloys, only the effect of boron is discussed here. Addition of 100 appm boron to V–5Fe enhances either the swelling value as measured by immersion density technique (see Fig. 1) or the cavity size in all irradiations at in-core locations, and further addition up to 500 appm reduces them, except during irradiation at the highest temperature (874 K). According to the ion irradiation

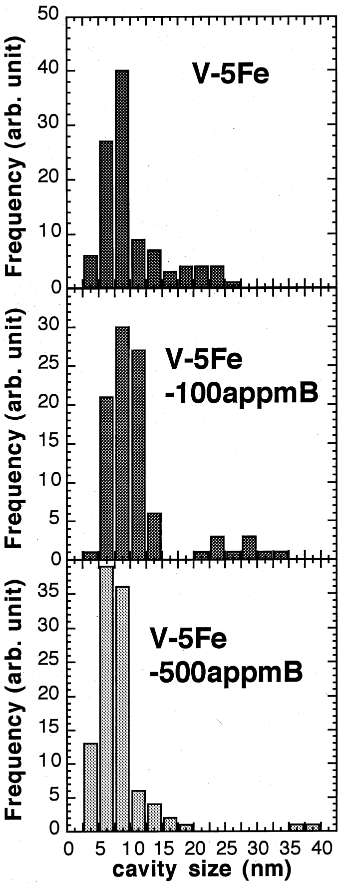

Fig. 3. Cavity size distribution in V–5Fe–B alloys irradiated at in-core location to 1.5 dpa at 704 K.

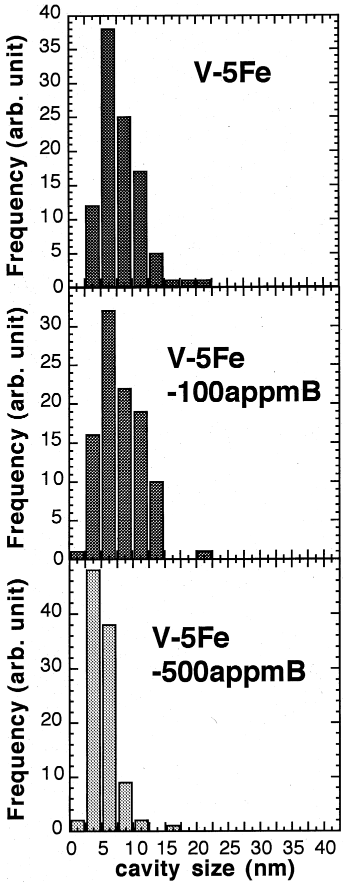

Fig. 4. Cavity size distribution in V–5Fe–B alloys irradiated at a below-core location to 10.2 dpa at 683 K.

experiment, addition of 500 appm boron to V–5Fe seemed to enhance cavity growth at 793 K [13]. Since the effect of boron is presumed to be due to chemical processes, it is possible that the tendency holds in the conditions of fast neutron irradiation examined here. If it is assumed that this tendency holds in the conditions of fast neutron irradiation examined here, it appears that the observed dependence on boron content results from the competing effects of boron and helium. Under this assumption, the enhancement effect of boron is presumed to be dominant at 100 appm boron in the in-core irradiation conditions, while the suppressant effect of helium should be dominant at 500 appm boron. At 874 K where addition of 500 appm boron enhances swelling, helium should not suppress swelling due to its irradiation temperature being high enough to promote void growth, but to enhance swelling by assisting cavity nucleation. Simultaneous helium implantation during heavy ion irradiation also had little influence on cavity size, but increased the cavity density at 873 K while it suppressed cavity growth at 793 K [12,13]. On the other hand, no enhancement effect of boron was observed in specimens irradiated at below-core location at 683 K. This is presumed to be due to approximately four times larger helium production rate per dpa than in the in-core irradiation, comparable to the helium production rate in V–5Fe–500 appm B irradiated at in-core locations.

5. Conclusion

The effect of helium on void swelling in V–5Fe was investigated using boron doping technique together with dual ion irradiation experiments that help separate the effect of helium and dopant boron itself. These results are reasonably understood in terms of the competing effects of helium and boron. Cavity stabilization by helium is dominant at 500 appm boron where the He/dpa ratio is no less than 0.5 appm He/dpa. Boron primarily appears to enhance swelling at smaller He/dpa ratios.

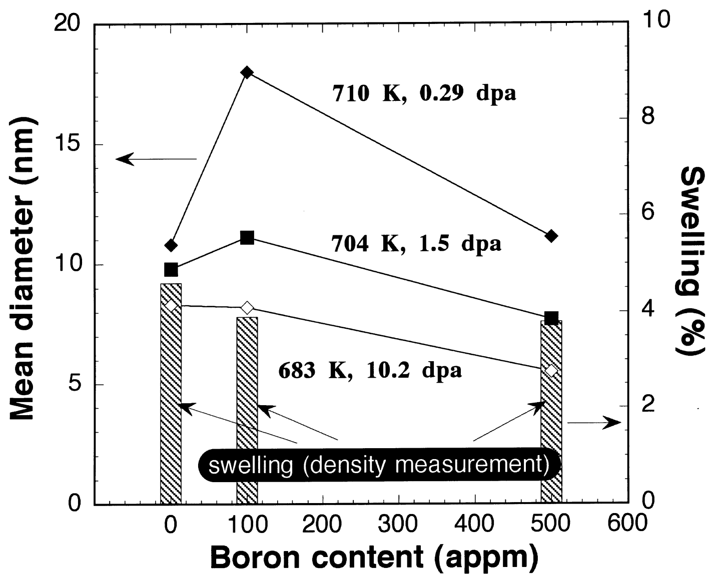

Fig. 5. Average cavity size as a function of boron content in each irradiation condition together with the swelling in condition C (10.2 dpa at 683 K, below-core) measured by the immersion density technique.

Acknowledgements

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