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Effects of dose rate on microsturctural evolution and swelling in austenitic steels under irradiation

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Abstract

Effects of dose rate on microstructural evolution in a simple model austenitic ternary alloy are examined. Annealed specimens are irradiated with fast neutrons at several positions in the core and above core in FFTF/MOTA between 390°C and 435°C in a wide range of doses and dose rates. In Fe–15Cr–16Ni, swelling seems to increase linearly with dose without incubation dose. Cavities are observed even in the specimens irradiated to 0.07 dpa at 1.9×10^{-9} dpa/s. Both cavity nucleation and growth are enhanced by low dose rates. These are mainly caused by accelerated formation of dislocation loops at lower dose rates. Low dose rates enhance swelling by shortening incubation dose for the onset of steady-state swelling. In the specimens irradiated at higher dose rates to higher doses, high density of dislocation increases average cavity diameter, however decreases cavity density.

1. Introduction

Property changes in fusion materials under irradiation are usually obtained by accelerated tests with high dose rates. Even if we get the equivalent cumulative dose data, it may not be effective to predict irradiation performance of fusion materials. It has been widely recognized that dose rate or irradiation flux is one of the key parameters to influence microstructural evolution and resultant macroscopic changes [1–3]. Previous studies [4–6] show steady-state swelling rate in austenitic steels irradiated above 375°C is not strongly affected by dose rates. However, it has been found that the incubation dose to start steady-state swelling is dependent on dose rate especially above 450°C.

In this study, solution-annealed austenitic model alloys are irradiated with fast neutrons in a wide range of doses and dose rates to evaluate mechanisms of dose rates effects on microstructural evolution and swelling.

2. Experimental

Fe–15Cr–16Ni ternary alloy is prepared from high purity Fe, Cr, and Ni by arc-melting. They are rolled to sheets of 0.2 mm in thickness, cut into 3 mm disks and solution-annealed at 1050°C for 30 min in a high vacuum.

The identical samples are placed in several positions of materials open test assembly (MOTA) and irradiated with fast neutrons in the core, below core and above core of the fast flux test facility (FFTF) during the Cycle 11 for 3.61×10^{7} s. Total displacement damage ranges from 0.07 to 36.1 dpa. Dose rates have wide range of variation from 1.9×10^{-9} dpa/s to 1.0×10^{-6} dpa/s. The irradiation temperature is between 390°C and 435°C. Table 1 summarizes the irradiation conditions in the FFTF.

Microstructural evolution in the specimens irradiated at wide ranges of dose and dose rate is examined by a transmission electron microscope operated at 200 kV.

3. Results and discussion

3.1. Effects of dose rate on swelling, nucleation and growth of cavities

Cavities are observed in all the irradiated specimens. Fig. 1 shows the swelling as a function of cumulative

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Table 1
Neutron irradiation conditions in FFTF/MOTA #11

Dose rate (dpa/s)	Irradiation dose (dpa)	Temperature (°C)
1.0×10^{-6}	36.1	420
7.8×10^{-7}	28.0	390
4.1×10^{-7}	14.8	430
2.9×10^{-7}	10.5	410
3.6×10^{-8}	1.3	430
7.2×10^{-9}	0.26	435
1.9×10^{-9}	0.07	435

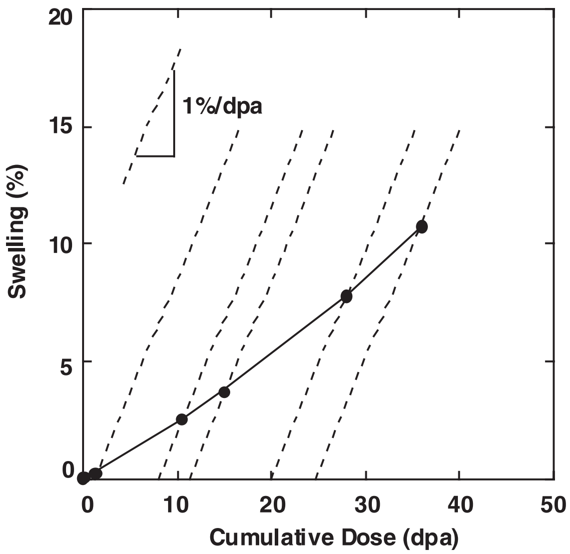

Fig. 1. Swelling of Fe–15Cr–16Ni irradiated in FFTF/MOTA as a function of cumulative dose. Each data comes from different dose rate.

dose. Note that each swelling data comes from a different dose rate. Swelling seems to increase almost linearly without any incubation dose at a swelling rate of about 0.3%/dpa.

These come from enhanced swelling at lower dose rate. When one assumes steady-state swelling rate of 1%/dpa as was frequently observed in neutron-irradiated austenitic steels with fixed dose rates [7,8], lower dose rate is considered to shorten incubation dose for the onset of steady-state swelling as schematically indicated in Fig. 1.

Fig. 2 shows the cavity density and average cavity diameter as a function of cumulative dose. At lower dose rates, cavity nucleation is clearly enhanced from very low dose region. It is also found that lower dose rates also enhance cavity growth especially at 3.6×10^{-8} dpa/s and lower dose rate. At 15 dpa and lower doses, enhanced swelling at low dose rates is caused by both cavity nucleation and growth. Cavity density has a peak at 10.5 dpa and decreases with dose at higher dose. However, cavities grow continuously after very rapid growth at lower dose and dose rate region. Although cavity nucleation and growth dependence on dose and dose rate is complicated, swelling during one cycle of irradiation increases linearly with dose as shown in Fig. 1.

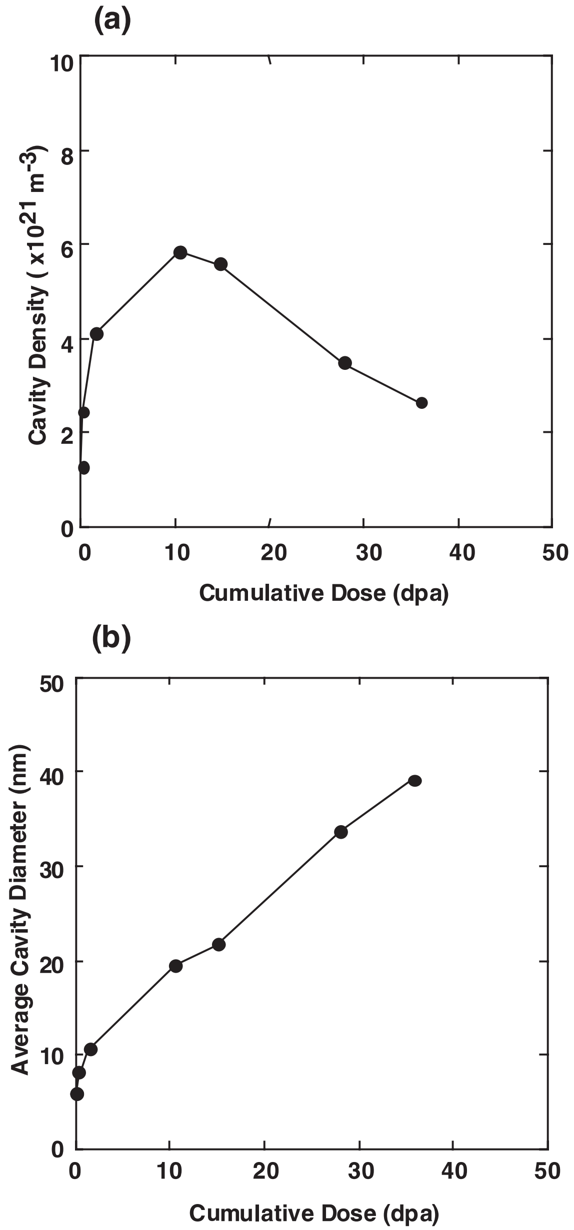

Fig. 2. (a) Cavity density and (b) average cavity diameter in Fe–15Cr–16Ni irradiated in FFTF/MOTA as a function of cumulative dose. Each data comes from different dose rate.

3.2. Effects of dose rates on dislocation sink strength and swelling incubation dose

Total dislocation density is shown in Fig. 3. High density of loops are observed in the specimens irradiated at low dose rates. Lower dose rates are considered to enhance interstitial clustering and, therefore, increases dislocation density. This is the major factor to enhance cavity nucleation and growth at low dose rate.

Lower irradiation temperature by 20–40°C increases dislocation density. Total dislocation densities at 10.5 dpa with 2.9×10^{-7} dpa/s at 410°C and at 28.0 dpa with 7.8×10^{-7} dpa/s at 390°C are relatively larger compared with those from other specimens irradiated around 430°C. Swelling, however, is not found to be strongly affected by this irradiation temperature difference.

Fig. 4 shows estimated ratios of cavity sink strength and dislocation density as biased sink for all the irradiation conditions with very wide range of dose rate. In all the cases including very low dose irradiation, this ratio is found to be near 1, which indicates swelling can increase almost linearly with dose [9,10].

Fig. 5 shows estimated incubation dose as a function of dose rate. Here it is assumed that swelling in all the specimens increases with 1%/dpa. It is very striking that incubation dose increases linearly with dose rate including the lowest dose case. However, this simple correlation is considered to be effective when the sink strength ratio for cavities and dislocation is within the narrow band near 1. Accelerated nucleation of dislocation loops enhances cavity nucleation at low dose rates. Nucleated low density of cavities can grow larger, because high density of dislocation sink provides enough vacancy supersaturation for these cavities. This balance is considered to increase swelling rapidly from very low dose region.

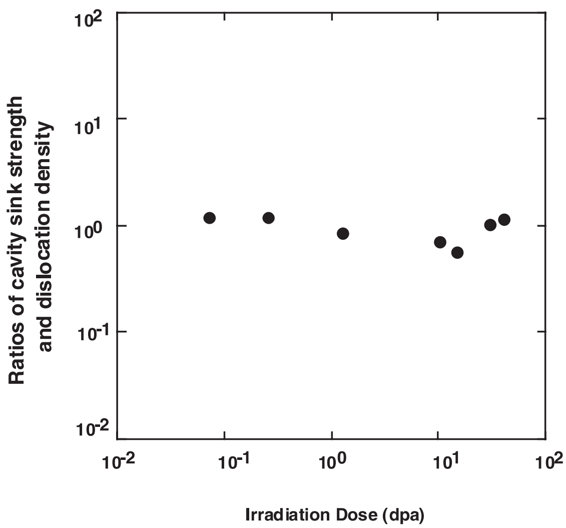

Fig. 4. Ratios of cavity sink strength and dislocation density as a function of cumulative dose. Each data comes from different dose rate.

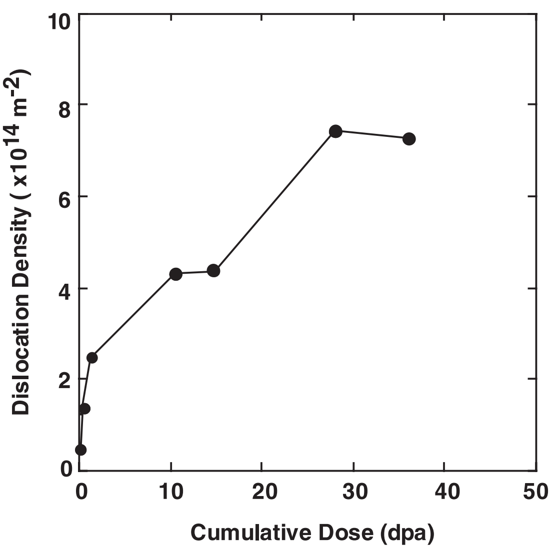

Fig. 3. Total dislocation density in Fe–15Cr–16Ni irradiated in FFTF/MOTA as a function of cumulative dose. Each data comes from different dose rate.

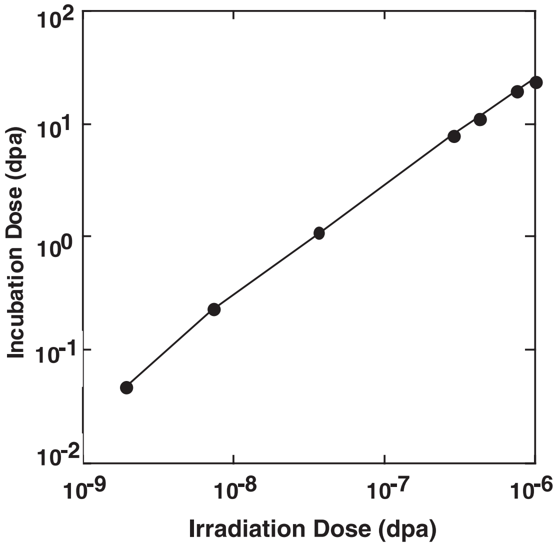

Fig. 5. Estimated incubation dose as a function of dose rate.

4. Summary

Solution-annealed austenitic model alloys are irradiated in FFTF/MOTA with the wide range of dose rates, and effects of dose rates on microstructural evolution are estimated. Lower dose rates enhance swelling by shortening incubation dose, which is estimated to be proportional to dose rates. At lower dose rates, accelerated loop formation enhances cavity nucleation and growth from the very low doses. At higher doses and dose rates, cavity density is low despite large cavity diameter and high dislocation density.

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