SWELLING OF HFIR-IRRADIATED F82H, F82H+^{10}B AND F82H+^{58}Ni STEELS - E.

Wakai (Japan Atomic Energy Research Institute), N. Hashimoto (Oak Ridge National Laboratory), K. Shiba, Y. Miwa (JAERI), J. P. Robertson, and R. L. Klueh(ORNL)

OBJECTIVE

The purpose of the present study is to investigate the swelling of ferritic/martensitic F82H steels following neutron irradiation in the range 200 - 500°C and the effect of dopant elements on the swelling of isotopically tailored F82H steels.

SUMMARY

Swelling of reduced-activation F82H-std and F82H steels doped with natural boron (311 appm), isotope ^{10}B (325 appm), 1.35 at% ^{58}Ni, and 1.31 at% ^{60}Ni irradiated at 300 and 400 °C to 52 dpa in the HFIR have been examined by TEM. The swelling of F82H-std irradiated at 400 °C to 52 dpa is about 0.6 % and the natural B and ^{10}B doped F82H steels is about 0.9 and 1.1 %, respectively. In the ^{58}Ni and ^{60}Ni doped F82H steels, swelling is 0.02 and 0%, respectively, even though the ^{58}Ni-doped specimen has the highest helium production. Large cavities in the F82H-std are observed in the matrix but not observed near many lath boundaries, while in the ^{10}B doped specimens, cavities are formed even near lath boundaries. While the cavities formed at 300°C to 52 dpa are observed in only the F82H+^{10}B and F82H+^{58}Ni steels, the swelling value is insignificant. The number densities of dislocation loops formed in these steels at 300°C to 52 dpa are very high(i.e., on the order of 10^{22} m^{-3}), and at 400°C to 52 dpa the number densities are very low (i.e., on the order of 10^{20} m^{-3}). A high density of precipitates is formed in the matrix of the Ni-doped F82H steels. The low swelling of Ni-doped specimens at 400 °C of 52 dpa may be caused by the formation of a high density of precipitates.

PROGRESS AND STATUS

1. Introduction

Ferritic/martensitic steels are candidate materials for the first wall and blanket structure of fusion reactors. In the D-T fusion reaction, the high-energy neutrons produced induce displacement damage and generate gas atoms (helium) in the materials from (n, p) and (n, α) reactions. The presence of these gases could lead to degradation of mechanical properties. The effect of gas atoms generated from the (n, α) reaction can be simulated by using a steel doped with ^{10}B or ^{58}Ni and irradiating with thermal neutrons in a mixed-spectrum fission reactor, such as the High Flux Isotope Reactor (HFIR). Helium is produced according to the following reactions:

^{10}B(n, α)^{7}Li,
^{58}Ni(n, γ)^{59}Ni(n,α)^{56}Fe,

The effect of neutron irradiation on the tensile deformation of F82H steel has been reported. Shiba et al. [1,2] have described the tensile data, obtained under the U.S. DOE/JAERI program, following irradiation in HFIR at 200 to 600°C for doses in the range 3-34 dpa, and the helium production effect on mechanical properties was investigated using isotope ^{10}B doping. A summary and discussion of the tensile data for 9-12Cr ferritic-martensitic steels irradiated under a variety of conditions has been presented by Rowcliffe et al. [3]. Recently, the swelling of F82H and the other 7-9Cr low-activation ferritic steels irradiated at 430°C to 67 dpa in FFTF was reported by Morimura et al. [4]; the swelling of F82H was 0.1%, and those of the other steels were 0.1-0.7%. Maziasz and Klueh[5] had investigated the swelling versus helium production rate in 9Cr-1MoVNb (-0, -2Ni) and 12Cr-1MoVW(-0, -2Ni) steels irradiated at 400°C to 47 dpa, using the efficiency of helium production rate for HFIR and FFTF, and they indicated that the swelling of 0.1 to 0.4% depended on helium production. The purpose of the present study is to investigate the swelling of F82H, for different helium production rates after irradiation in HFIR and the effect of the additional element (B and Ni) on microstructures.

2. Experimental procedure

The standard F82H steel and the F82H steel doped with ^{10}B were prepared to examine the effect of helium on the microstructures. The F82H+natural B and F82H+^{10}B steels were prepared from F82H doped with 0.0060% natural boron and 0.0058% ^{10}B with 94.37 at% purity level, respectively The F82H+^{58}Ni and F82H+^{60}Ni steels were prepared from F82H doped with isotope ^{58}Ni and ^{60}Ni, respectively. The F82H-std and these F82H+ B specimens were first normalized at 1040°C for 30 minutes in a vacuum followed by air-cooling. In the F82H+Ni specimens, the normalizing was performed at 1200°C for 2 hours. After that the F82H-std and these F82H+B specimens were tempered at 740°C for 2 hours and 1.5 hours, respectively, in a vacuum followed by air-cooling. The chemical compositions of the specimens used in this study are given in Table 1. Boron concentration in the F82H+Ni steels are now analyzing.

Table 1. Chemical compositions of the specimens used in this study(wt%)

	Cr	C	Si	V	Mn	Ta	W
F82H-std	7.44	0.1	0.14	0.20	0.49	0.04	2
F82H+natural B	7.49	0.099	0.15	0.20	0.50	0.04	2.1
F82H+^{10}B	7.23	0.098	0.17	0.22	0.50	0.04	2.1
F82H+^{58}Ni	7.8	0.04	0.2	0.2	0.4	0.04	2.1
F82H+^{60}Ni	7.8	0.04	0.2	0.2	0.4	0.04	2.1

	B (wt%)	Ni (wt%)	^{10}B (at%)	^{11}B (at%)	^{58}Ni (at%)	^{60}Ni (at%)
F82H-std	0.0004	-	0.0004	0.0017	-	-
F82H+natural B	0.0060	-	0.0064	0.0248	-	-
F82H+^{10}B	0.0058	-	0.0325	-	-	-
F82H+^{58}Ni		1.4			1.35	-
F82H+^{60}Ni		1.4			-	1.31

Table 2. Midplane fluence for HFIR JP-12

Neutron Fluence (n/cm^2)				
Total	Thermal (<0.5 eV)	0.5 eV- 0.1 MeV	> 0.1 MeV	>1 MeV
$26.3x10^{22}$	$10.9 x10^{22}$	$8.39 x10^{22}$	$7.06 x10^{22}$	$3.67 x10^{22}$

Table 3. Helium production of these steels for HFIR-JP12. α is due to impurity level of boron in the F82H+Ni steels, and β is α /52.

	F82H-Std	F82H+natural B	F82H+^{10}B	F82H+^{58}Ni	F82H+^{60}Ni
He (appm)	~26	~90	~350	~500+α	~28+α
(appm)He/dpa					
(0-54 dpa)	0.5	1.7	6	10	0.5
(0-1.4 dpa)	0.5	45	230	3.4+β	1.4+β
(1.4-54 dpa)	0.5	0.5	0.5	10	0.5

Standard 3 mm-diameter TEM disks punched from 0.25 mm-thick sheet stock were irradiated in the HFIR target in the HFIR-MFE-JP12 capsule as part of the JAERI/US collaborative program. The capsule irradiation began on July 20, 1990, at the start of HFIR fuel cycle 289 and was completed 35 cycles on April 1, 1994. The exposure was 64904 MWd at 85 MW reactor power and achieved a peak fluence of 52 dpa for the F82H-std steel in the midplane of the capsule. The dpa level is based on 0.00873 dpa/MWd in the target position. The complete description and details of the design, construction, installation of the capsule, and neutron dosimetry, and damage calculation for JP12 have been previously reported [6-10]. The midplane fluences for HFIR JP-12 are given in Table 2. The irradiation temperatures and displacement damage were 300 and 400°C and 52 dpa for the JP12 capsule. He generation in these steels at 52 dpa is given in Table 3.

Microstructures of these specimens were examined using a JEM-2000FX transmission electron microscope with a LaB_6 gun operated at 200 kV. Microstructures of unirradiated control specimens were also examined.

3. Results and discussion

3.1 Initial microstructures of the F82H-std, F82H+B, F82H+Ni steels

The microstructure after normalizing and tempering was a lath martensitic structure for the F82H-std, natural B, isotope ^{10}B, ^{58}Ni and ^{60}Ni doped steels as shown in Figs. 1(a)-1(e). In the F82H-std, the dislocation line density was about $1x10^{14}$ m^{-2}. $M_{23}C_6$ carbides were observed in the matrix and on grain boundaries, and the number density and mean size were $6x10^{19}$ m^{-3} and 73 nm, respectively. Only a few MC carbides were observed in the matrix, and the number density and mean size were $<1x10^{20}$ m^{-3} and 14 nm, respectively. The mean width of the lath structure was about 440 nm.

Microstructures of B-doped specimens are similar to the F82H-std. On the other hand, Ni-doped specimens have a higher MC carbide number density and no $M_{23}C_6$ carbides: a few M_6C carbides formed at lath boundaries and unidentified precipitates were sometimes observed in the matrix of some grains. The detail of the microstructures will be reported in next progress report.

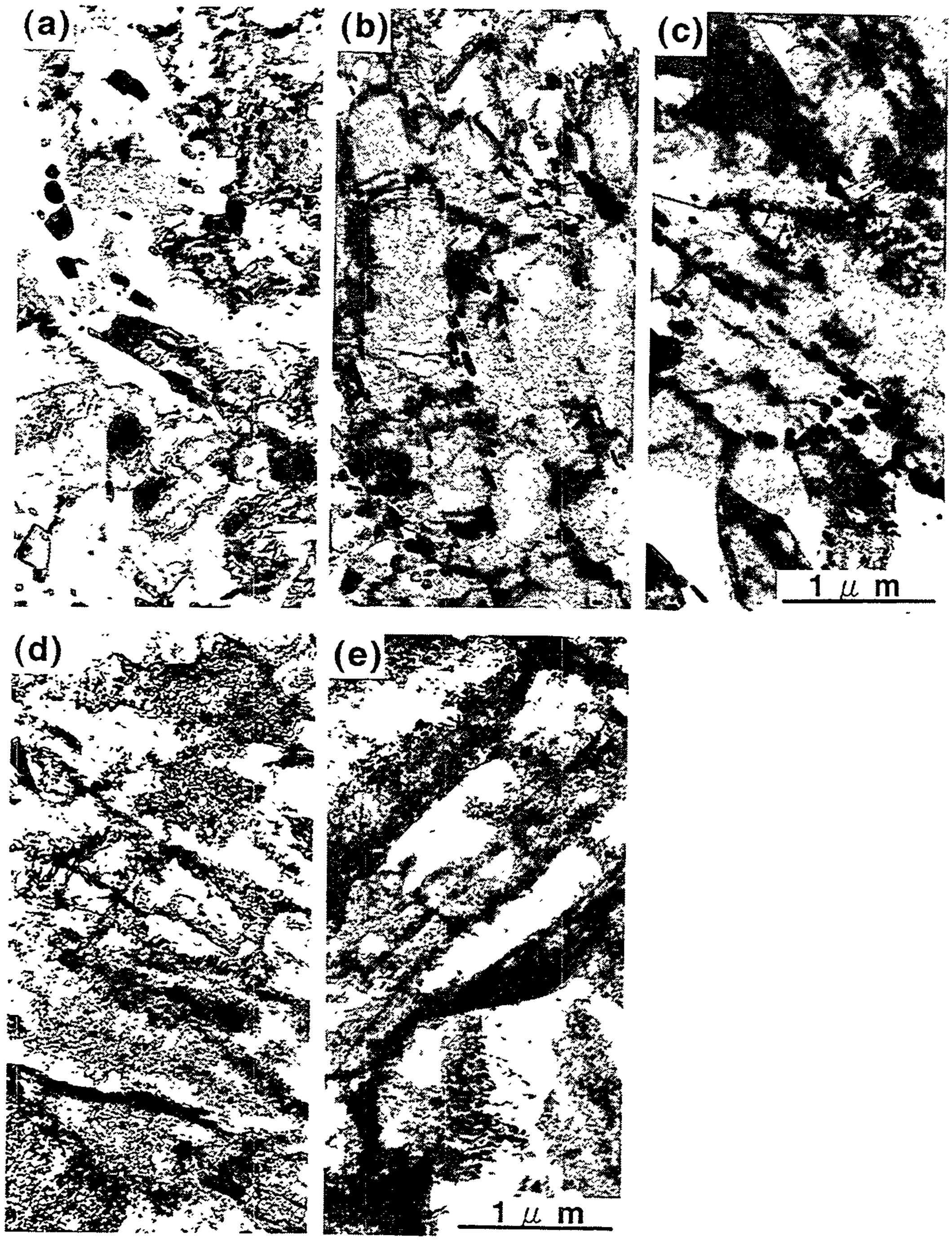

Figure 1. Pre-irradiation microstructure of (a) F82H-std, (b) F82H+natural B, (c) F82H+^{10}B, (d) F82H+^{58}Ni, and (e) F82H+^{60}Ni steels

3.2 Swelling of F82H steels irradiated at 400°C to 52 dpa

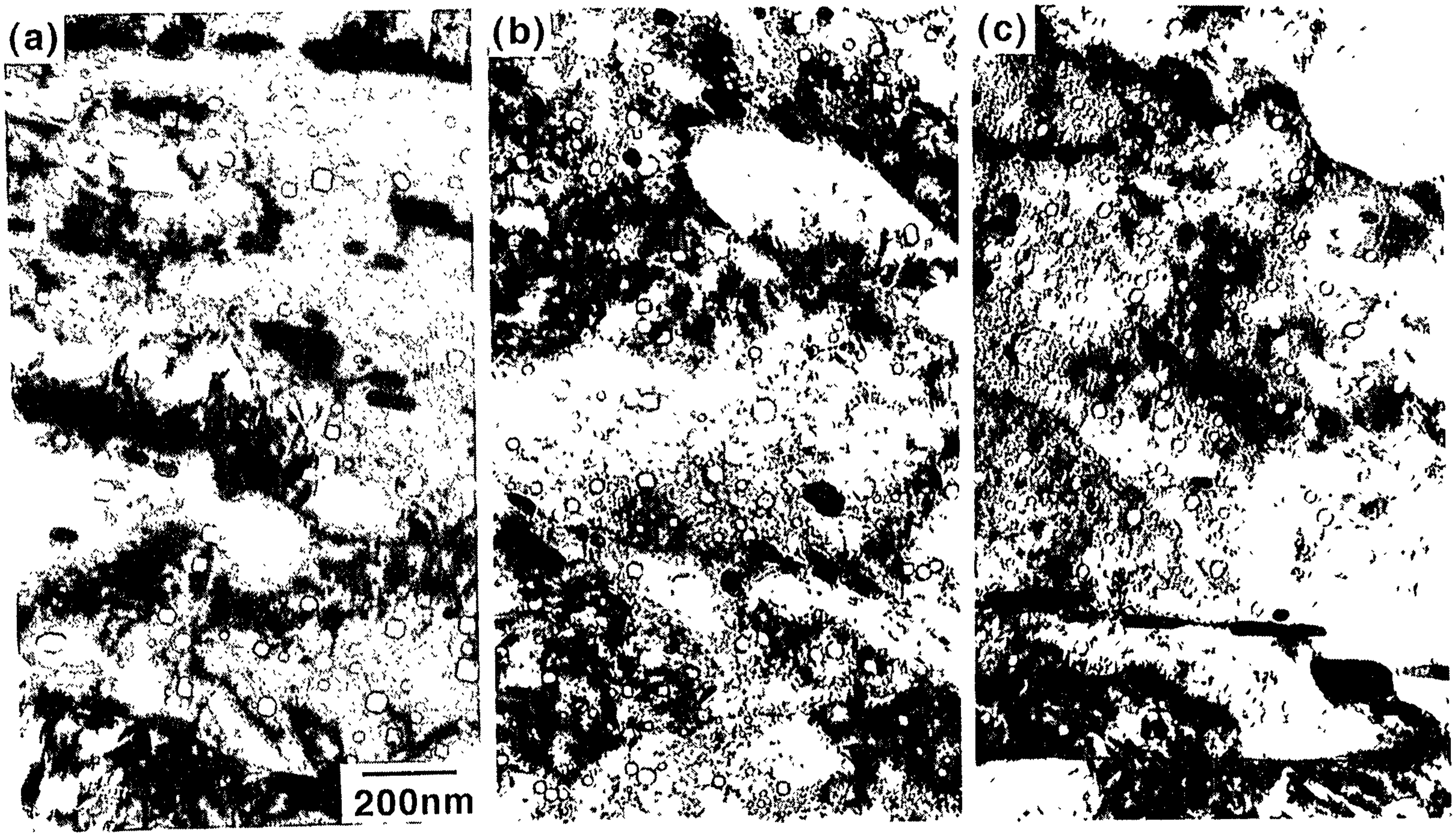

Figure 2. Cavities formed in the (a) F82H-std, (b) F82H+natural B, and (c) F82H+^{10}B steels irradiated at 400°C to 52 dpa. In the F82H-std, cavities can not be seen near the lath boundaries, while in the F82H+natural B and F82H+^{10}B steels cavities can be observed near these lath boundaries.

Figures 2(a)-2(c) show cavities observed in the F82H-std, F82H+natural B, and F82H+^{10}B steels, respectively, irradiated at 400°C to 52 dpa. Lath boundaries and many $M_{23}C_6$ precipitates can be seen in these micrographs. In Fig. 2(a), cavities can not be seen near the lath boundaries, while in Figs. 2(b) and 2(c) cavities can be observed near these lath boundaries. The swelling of the F82H-std steel was about 0.5% in average of all regions, and it was about 0.7-0.8 % in the matrix region in which cavities exist. The average swelling in all regions of F82H+natural B and F82H+^{10}B steels is about 0.9 and 1.1%, respectively. Figs. 3(a) and 3(b) show microstructures of F82H+^{60}Ni and F82H+^{58}Ni irradiated at 400°C to 52 dpa. Small cavities were observed for the F82H+^{58}Ni steel and the swelling was 0.02%, but no cavities were observed for the F82H+^{60}Ni. The number density, root mean cube radius, and swelling of cavities of these steels are summarized in Table 4. The low swelling in the Ni-doped specimens may be caused by the high density of precipitate formation as descried in the next paragraph.

The growth of $M_{23}C_6$ carbides was observed on lath boundaries at bending curves in F82H-std, F82H+natural B, and F82H+^{10}B steels. Many small M_6C precipitates were formed on the $M_{23}C_6$ carbides, and a few M_6C precipitates were formed in matrix by the irradiation. In the Ni-doped F82H+^{60}Ni and F82H+^{58}Ni steels, a high density of precipitates were formed by the irradiation as seen in Fig. 4. A low density of loops was also observed in all steels. The details of precipitates and loops will be presented in the next report.

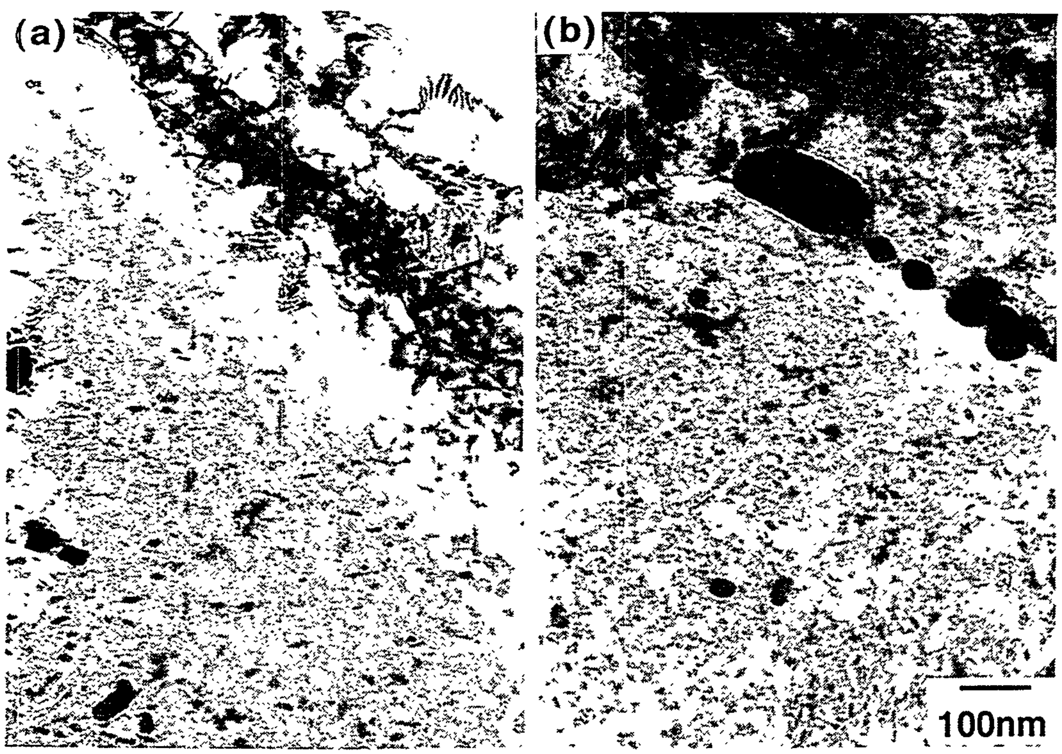

Figure 3. Microstructure of (a) F82H+^{60}Ni and (b) F82H+^{58}Ni steels irradiated at 400°C to 52 dpa. Cavities were formed in the F82H+^{58}Ni steel, but no cavities were formed in the F82H+^{60}Ni steel.

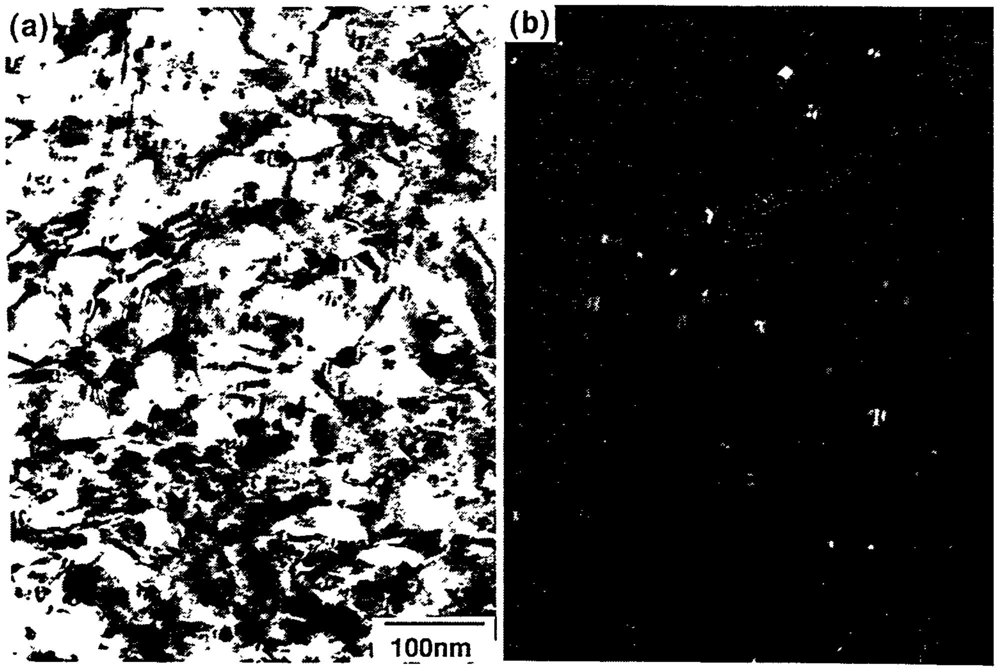

Figure 4. A high number density of precipitates formed in F82H+^{58}Ni steel irradiated at 400°C to 52 dpa

Table 4. Cavities formed at 300 and 400°C to 52 dpa in the F82H steels. RMC radius denotes root mean cube of cavity radius.

Alloy	Cavity (300°C to 52 dpa)			Cavity (400°C to 52 dpa)		
	Number Density	RMC radius	Swelling	Number Density	RMC radius	Swelling
F82H		-		$6x10^{20}$ m^{-3}	~13 nm	~0.6%
F82H+natural B		-		$2x10^{21}$ m^{-3}	~11 nm	~0.9%
F82H+^{10}B	$2x10^{21}$ m^{-3}	3 nm	0.002%	$4x10^{21}$ m^{-3}	~8 nm	~1.1%
F82H+^{58}Ni	$4x10^{21}$ m^{-3}	4 nm	0.02%	$2x10^{21}$ m^{-3}	~3 nm	~0.02%
F82H+^{60}Ni		-			-	

3.3 Swelling of these F82H steels irradiated at 300°C to 52 dpa

Figures 5(a) - 5(e) show microstructures of F82H-std, F82H+natural B, and F82H+^{10}B steels, F82H+^{60}Ni and F82H+^{58}Ni, respectively, irradiated at 300°C to 52 dpa. Cavities were observed in only the F82H+^{10}B and F82H+^{58}Ni steels, and the values of swelling were 0.02 and 0.002%, respectively.

Many small M_6C precipitates were also formed on the $M_{23}C_6$ carbides. The size of $M_{23}C_6$ carbides in the F82H-std was smaller than that in the F82H+B steels. Many dislocation loops were formed in all steels. A summary of the results for the microstructures of these irradiated steels is given in Table 5. Further details of precipitates and loops will be described in the next progress report.

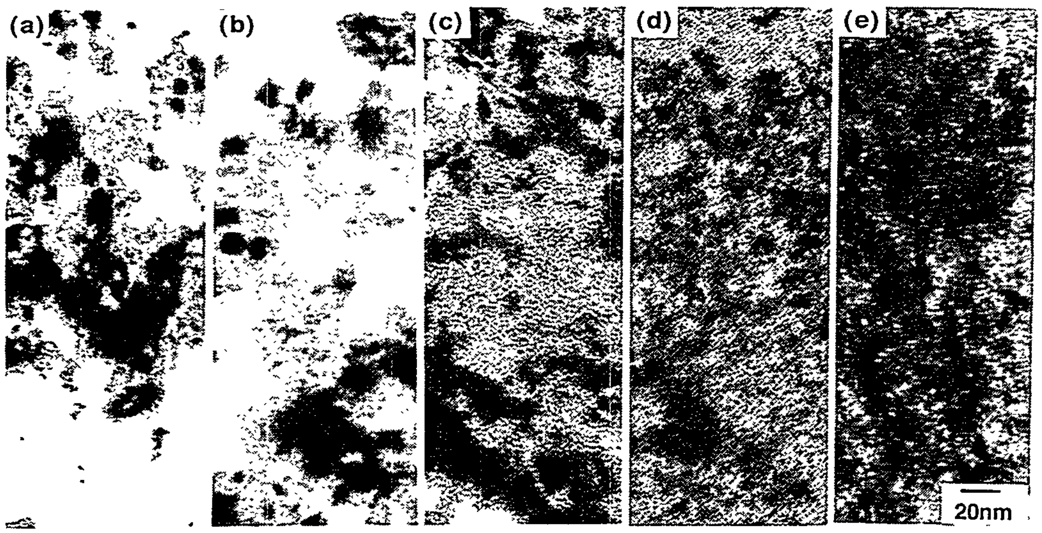

Figure 5. Microstructure of (a) F82H-std, (b) F82H+natural B, and (c) F82H+^{10}B , (d) F82H+^{60}Ni, and (e) F82H+^{58}Ni steels irradiated at 300°C to 52 dpa. Small cavities were observed in only the F82H+^{10}B and F82H+^{60}Ni steels.

Table 5. Summary of radiation-induced defect clusters formed at 300 and 400°C to 52 dpa in the F82H steels

Alloy	300°C to 52 dpa			400°C to 52 dpa		
	Loop	Cavity (swelling)	Precipitate	Loop	Cavity (swelling)	Precipitate
F82H	high	No	M_6C on $M_{23}C_6$	low	large (~0.6%)	M_6C on $M_{23}C_6$ few M_6C in matrix ($M_{23}C_6$ growth)
F82H+natural B	high	No	M_6C on $M_{23}C_6$	low	large (~0.9%)	M_6C on $M_{23}C_6$ few M_6C in matrix ($M_{23}C_6$ growth)
F82H+^{10}B	high	small (0.002%)	M_6C on $M_{23}C_6$	low	large (~1.1%)	M_6C on $M_{23}C_6$ few M_6C in matrix ($M_{23}C_6$ growth)
F82H+^{58}Ni	high	small (0.02%)	MC in matrix	low	small (0.02%)	M_6C in matrix others
F82H+^{60}Ni	high	No	MC in matrix	low	No	M_6C in matrix others

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