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Effect of Boron on Post Irradiation Tensile Properties of Reduced Activation Ferritic Steel (F-82H) Irradiated in HFIR

K. Shiba, M. Suzuki, A. Hishinuma, and
J. E. Pawel

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Kiyoyuki Shiba [1], Masahide Suzuki [1], Akimichi Hishinuma [1] and Janet E. Pawel [2]

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ABSTRACT: Reduced activation ferritic / martensitic steel, F-82H (Fe-8Cr-2W-V-Ta), was irradiated in the High Flux Isotope Reactor (HFIR) to doses between 11 and 34 dpa at 400 and 500 °C. Post irradiation tensile tests were performed at the nominal irradiation temperature in vacuum. Some specimens included ^{10}B or natural boron (nB) to estimate the helium effect on tensile properties.

Tensile properties including the 0.2% offset yield stress, the ultimate tensile strength, the uniform elongation and the total elongation were measured. The tensile properties were not dependent on helium content in specimens irradiated to 34 dpa, however ^{10}B-doped specimens with the highest levels of helium showed slightly higher yield strength and less ductility than boron-free specimens. Strength appears to go through a peak, and ductility through a trough at about 11 dpa. The irradiation to more than 21 dpa reduced the strength and increased the elongation to the unirradiated levels.

KEYWORDS: Reduced Activation, Ferritic / martensitic steel, HFIR irradiation, Tensile properties, Boron-10 dope, helium effect

[1] Engineer, principal research engineer and group leader, respectively, Department of Materials Science and Engineering, Japan Atomic Energy Research Institute, Tokai-mura Ibaraki-ken 319-11.

[2] Research staff member, Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6376, USA.

INTRODUCTION

Ferritic steels are one of the candidate alloys for nuclear fusion reactors because of their good thermophysical properties, their superior swelling resistance, and the low corrosion rate in contact with potential breeder and coolant materials. Another attraction of ferritic steels is the possibility of low activation. Several kinds of ferritic steels are now under investigation. The typical alloy compositions of ferritic / martensitic steels are 2.25 Cr, 7-9 Cr and 12 Cr.

Alloy F-82H was developed as a reduced activation ferritic steel by Japan Atomic Energy Research Institute (JAERI) and Nippon Kokan KK (NKK) [1]. Some characteristics have been researched in the unirradiated conditions [2-4]; however the study of the behavior under irradiation has just started [5]. The effect of helium on mechanical properties of irradiated ferritic steels has been reported [6,7]. Several techniques can be applied to generate helium during irradiation in fission reactor. The addition of ^{10}B to steel can generate helium according to the $^{10}B\ (n, \alpha)\ ^{7}Li$ reaction [8]. This technique was used in this investigation to study the effect of helium on tensile properties.

EXPERIMENTAL PROCEDURE

The alloy investigated was an 8Cr-1W-V-Ta ferritic / martensitic steel (F-82H). The same composition with boron additions was also prepared for this experiment to investigate the helium effect on tensile properties. The three alloys are standard F-82H, ^{10}B-doped F-82H and natural-boron doped F-82H; hereafter they are called as STD F-82H, ^{10}B F-82H and nB F-82H, respectively. The ^{10}B was added for the production of helium during irradiation, and nB F-82H specimens were prepared in order to study the effect of boron itself. The chemical compositions of these alloys are given in TABLE 1. The amounts of ^{10}B or nB were both about 300 appm. Pure ^{10}B was used for ^{10}B F-82H, while natural boron includes about 20 % of ^{10}B. All three alloys were cast into 25 kg ingots individually, then hot rolled to 10 mm plates at 1200 °C. The normalizing treatment for these alloys was 0.5 h at 1040 °C, and then they were tempered for 1.5 h at 720 °C. The structure after tempering was a tempered lath martensitic structure for all steels.

The steels were fabricated into SS-3 type sheet tensile specimens which are 25.4 mm in length, 4.95 mm in width and 0.76 mm in thickness. The gage section of this specimen was 7.62 mm in length and 1.52 mm in width.

These tensile specimens were irradiated in the High Flux Isotope Reactor (HFIR) target position capsules HFIR-MFE-JP-13, -16 and -14. The details of irradiation are given elsewhere [9]. The peak fluence of fast neutrons (E > 1 MeV) was about 2.0 x 10^{26} neutrons/m^2 for JP-13 and -16, and about 3.8 x 10^{26} neutrons/m^2 for JP-14. These fluences correspond to 18 and 34 dpa in atom displacement damage. The neutron flux varies in the axial direction of the capsule, so that the displacement damage of each specimen varied, depending on its position. The analyses of the flux monitors are not completed yet, therefore the irradiation information used in this paper is approximate. The high cross section of ^{10}B (n, α) ^{7}Li (4000 barns) and the low thermal flux cause complete burn up of ^{10}B in the early stages of irradiation [8]. Damage by the recoiled alphas is negligible compared to the neutron damage level investigated in this experiment. About 20% of ^{10}B is included in natural B and pure ^{10}B is used for the ^{10}B F-82H. Therefore, the amount of helium in ^{10}B F-82H is about 300 appm and that in natural B F-82H is about 60 appm after irradiation.

An Instron universal testing machine was used for tensile testing. Tensile testing was carried out at the nominal irradiation temperature in vacuum for each specimen. The strain rate was 1x10^{-3} /s. The 0.2% proof stress (YS), ultimate tensile stress (UTS), uniform elongation (Eu) and total elongation (Et) were calculated from the load-displacement chart.

TABLE 1--Chemical composition of alloys (wt%)

	Fe	Cr	W	V	Ta	Total B	^{10}B
F82H	bal.	7.44	2.0	0.20	0.04	...	...
F82H+nB	bal.	7.49	2.1	0.20	0.04	0.0060	0.0012
F82H+^{10}B	bal.	7.23	2.1	0.22	0.04	0.0058	0.0058

	C	Si	Mn	P	S	Al	N
F82H	0.100	0.14	0.49	0.001	0.001	0.019	0.002
F82H+nB	0.099	0.15	0.50	0.001	0.001	0.021	0.001
F82H+^{10}B	0.098	0.17	0.50	0.001	0.001	0.021	0.002

RESULTS AND DISCUSSIONS

Dose dependence

The tensile results before and after irradiation are listed in TABLE 2. FIG. 1 shows the yield stress and total elongation of STD F-82H irradiated at 400 and 500 °C as a function of neutron damage.

As shown in FIG. 1, all three types of alloys had some irradiation hardening after irradiation to the dose of 34 dpa at 400 °C. Only ^{10}B F-82H had the data at the dose of 11 dpa at this temperature and this was the maximum strength and minimum elongation in this experiment. The irradiation to 21 dpa reduced the change in yield strength and recovered the elongation. There was no change in yield stress between 21 dpa and 34 dpa, but there was a slight increase in elongation. STD F-82H showed the same dose dependence as ^{10}B F-82H at more than 21 dpa. However, the reduction of yield stress of ^{10}B from 11 dpa to 21 dpa seems very large, compared to the other results [6,10-12]. FIG. 2 illustrates the stress - strain diagrams of F-82H irradiated in several irradiation conditions from this experiment and others. The stress - strain curve of ^{10}B F-82H irradiated to 11 dpa at 400 °C deformed in the same manner as the specimens irradiated at lower temperatures. These specimens (3 dpa and 11 dpa) exhibited necking just after yielding, so that they did not show any work hardening. These results demonstrate much irradiation hardening occurs at lower irradiation temperatures and it appears in the relatively early stages of irradiation at 250 °C. Since ^{10}B F-82H irradiated to 11 dpa at 400 °C deformed similarly, this specimen might have been irradiated at a lower temperature than the nominal irradiation temperature.

Only results irradiated to more than 30 dpa were obtained at 500 °C. Both of the boron doped specimens and STD F-82H showed the same strength and elongation as the unirradiated values at this temperature. The stress - strain curves of STD F-82H irradiated to 34 dpa at 400 and 500 °C shown in FIG. 2 demonstrate the specimens irradiated at 400 and 500 °C deformed in the same manner and they are apparently different from the results at lower irradiation doses and temperature. The specimens irradiated to 34 dpa at 400 and 500 °C have some work hardening capacity. This means that recovery of the lath structure occurred at the higher irradiation temperatures, however some degradation of ductility occurred at 500 °C. One possible reason for this result is the coarsening of carbides or an aging effect, since helium production during irradiation in STD F-82H specimens is small. The irradiation time for both 21 and 34 dpa specimens (which were irradiated in the same irradiation capsule) was about 45 Ms, while it was 25 Ms for 11 dpa specimens. This is sufficient to cause the coarsening of carbides even in the unirradiated condition [2].

Microstructural observation for the same F-82H irradiated in the Fast Flux Test Facility (FFTF) by Kohno et. al [5] showed partial recovery of lath martensite at both 400 and 500 °C. This FFTF irradiation time was 29 Ms. It seems that the longer irradiation time generated much more recovery of the lath structure.

The effect of boron addition

Three types of steels were irradiated to investigate the helium effect on tensile properties. The differences between these three steels were small in all irradiation conditions in this experiment. FIG. 3 shows the yield strength and total elongation of boron-free and boron-doped F-82H irradiated to 34 dpa at 400 and 500 °C with changes of these properties. ^{10}B F-82H had slightly higher strength than STD F-82H in all conditions, and the increase of yield strength due to irradiation was also larger. The strength of nB F-82H was lower than ^{10}B F-82H, but the differences between nB and STD were not consistent with helium content even though the nB specimens have more helium than STD F-82H at 34 dpa. The helium can affect the strength as small helium bubbles. Kimura et al. found tiny voids which caused higher swelling in boron-doped 9Cr ferritic steels irradiated in FFTF at 420 °C [14]. Their boron-doped steels contained 30 wppm of natural boron. The slightly higher strength of ^{10}B specimens might be caused by these helium cavities, but the helium produced from nB was not sufficient to make a difference in strength. Lithium is also produced with helium, according to the ^{10}B (n, α) ^{7}Li reaction. This lithium could affect the tensile properties, however no useful evidence has been obtained yet. The effect of aging accelerated by irradiation overshadowed the helium effect of nB. ^{10}B F-82H had a peak of irradiation hardening at the dose of 11 dpa at 400 °C. The irradiation temperatures of 400 and 500 °C are too high to sustain the irradiation -induced dislocation loop structure. Helium cavities produced in boron-doped F-82H and the irradiation-accelerated aging effect could cause a transient hardening peak at 11 dpa.

SUMMARY

The tensile properties of 8Cr-1W-V-Ta ferritic / martensitic steel (F-82H) irradiated in the HFIR up to 34 dpa at irradiation and test temperatures of 400 and 500 °C were studied. Some of the steels investigated had ^{10}B or natural B added to the material to investigate the helium effect on the tensile properties. The following summarize the observations:

1. High irradiation hardening occurred at a dose of 11 dpa at 400 °C, but the irradiation hardening observed at higher fluence was not as large.

2. Any helium effects due to ^{10}B or natural B were small. ^{10}B F-82H, which had the most helium, had slightly higher strength than STD, but the differences between nB and STD were not consistent with helium content.

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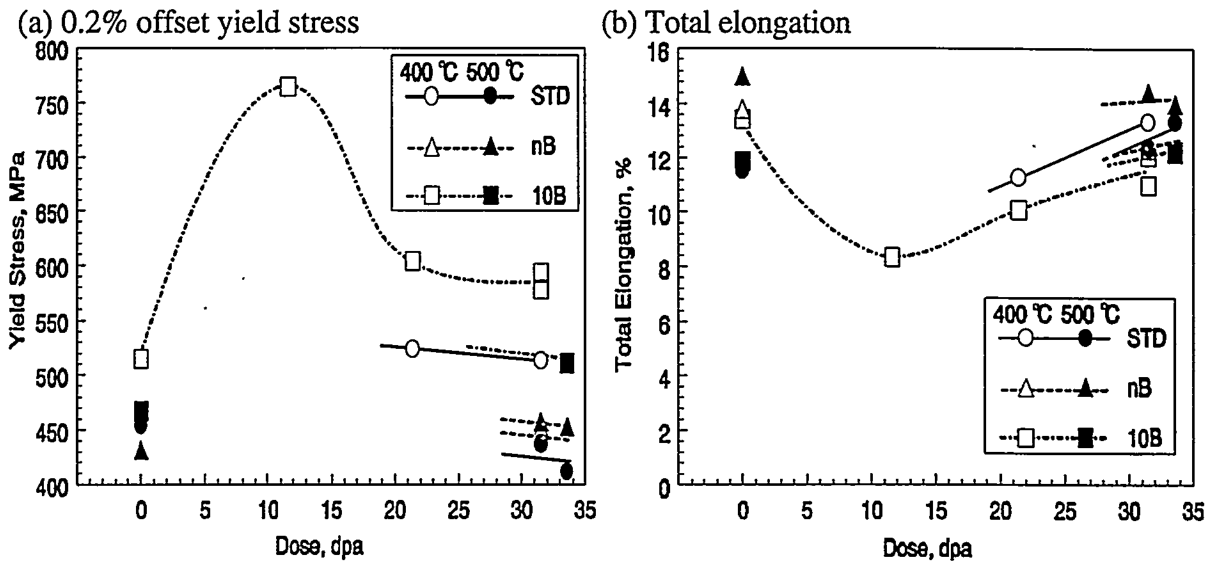

FIG. 1--0.2% offset yield stress (a) and total elongation (b) of F82H (STD, natural B doped and ^{10}B doped) irradiated in HFIR target position at 400 and 500 °C.

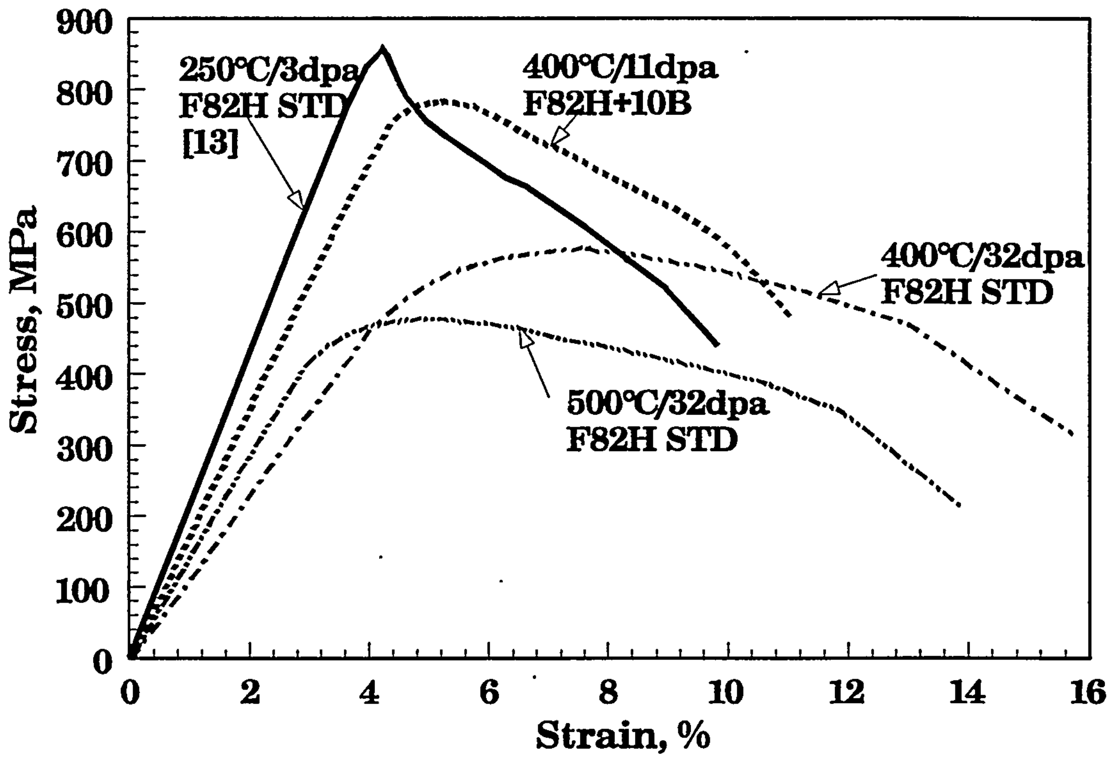

FIG. 2--Stress - strain diagram of F-82H irradiated in HFIR target position.[13]

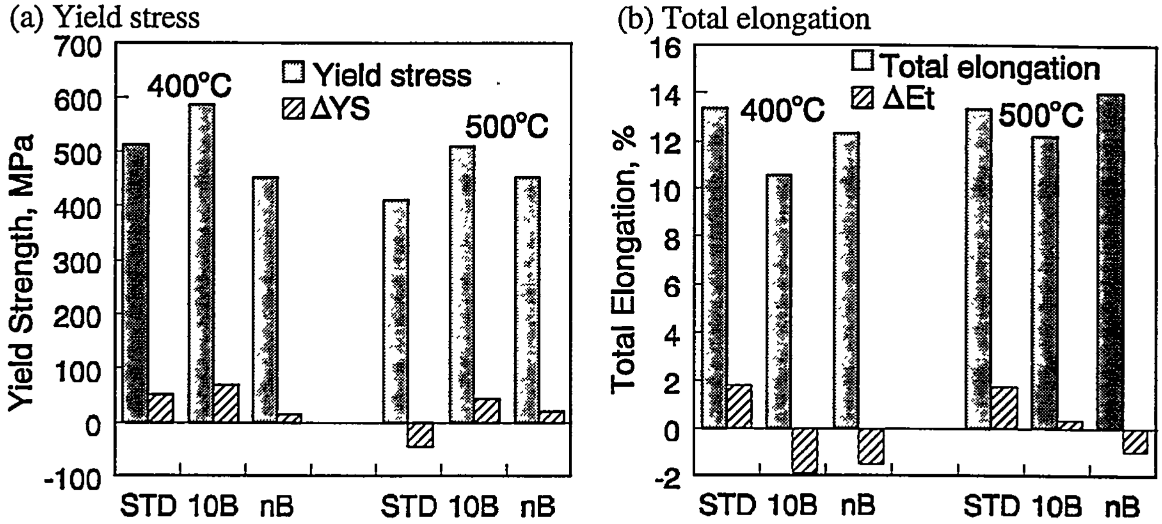

FIG. 3-- Comparison of tensile properties between STD F-82H and boron doped specimens irradiated in HFIR target position. (a) yield stress and (b) total elongation. The changes of yield stress and total elongation due to irradiation are also displayed.

TABLE 2--The tensile test results of F-82H irradiated in HFIR target position

Alloy	Irradiation			Test	Strength		Elongation		Increase			
	Temp. °C	Damage dpa	Helium appm He	Temp. °C	YS MPa	UTS MPa	Uniform %	Total %	YS MPa	UTS MPa	Uniform %	Total %
STD F-82H	...	0	0	250	507	578	3.2	13.3	...	...	...	...
	250	3	1	250	853	856	0.3	7.8	346	278	-2.9	-5.5
	...	0	0	400	460	534	2.5	11.5	...	...	...	...
	400	21	6	400	524	570	2.1	11.3	64	36	-0.4	-0.2
	400	32	9	400	513	580	3.0	13.3	53	46	0.5	1.8
	...	0	0	500	455	503	2.0	11.6	...	...	...	...
	500	32	9	500	437	478	1.8	12.4	-18	-25	-0.2	0.8
	500	34	9	500	411	494	2.6	13.3	-44	-9	0.6	1.7
F-82H + ^{10}B	...	0	0	400	515	600	3.3	13.4	...	...	...	...
	400	12	303	400	764	783	1.0	8.3	249	183	-2.3	-5.1
	400	21	306	400	604	642	2.0	10.1	89	42	-1.3	-3.3
	400	32	309	400	593	655	3.3	12.1	78	55	0	-1.3
	400	32	309	400	578	636	3.3	11.0	63	36	0	-2.4
	...	0	0	500	467	514	1.9	11.9	...	...	...	...
	500	34	309	500	510	543	2.3	12.2	43	29	0.4	0.3
	500	34	309	500	512	557	2.8	12.3	45	43	0.9	0.4
F-82H + nB	...	0	0	400	467	539	3.5	13.8	...	...	...	...
	400	32	69	400	451	555	2.7	12.3	-16	16	-0.8	-1.5
	...	0	0	500	432	509	3.7	15.0	...	...	...	...
	500	32	69	500	457	520	2.9	14.4	25	11	-0.8	-0.6
	500	34	69	500	453	504	2.7	14.0	21	-5	-1.0	-1.0