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Low-temperature irradiation effects on tensile and Charpy properties of low-activation ferritic steels

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Abstract

Tensile and Charpy properties of low-activation ferritic steel, F82H irradiated up to 0.8 dpa at low temperature below 300°C were investigated. The helium effect on these properties was also investigated using the boron isotope doping method. Neutron irradiation increased yield stress accompanied with ductility loss, and it also shifted the ductile-to-brittle transition temperature (DBTT) from −50°C to 0°C. Boron-doped F82H showed larger degradation in DBTT and ductility than boron-free F82H, while they had the same yield stress before and after irradiation. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Low-activation ferritic/martensitic steel has been investigated as a primary candidate material for the first wall/blanket (FW/B) structure of a fusion reactor [1,2]. Though the service condition of the FW/B is not defined clearly, it is planned to be used in a temperature range between 250°C and 450°C for the Steady State Tokamak Reactor (SSTR) designed by Japan Atomic Energy Research Institute (JAERI). The low-activation ferritic/martensitic steels considered as FW/B material are mostly martensitic steels containing 7–9% Cr and 1–2% W [3]. Previous irradiation results have indicated that this type of steel does not show much irradiation hardening after irradiation to about 30 dpa at temperatures above 400°C. However, irradiation below 350°C causes large irradiation hardening [4–8]. Since the SSTR is designed to use a high-pressure water cooling system, the FW/B material is exposed to neutron irradiation around 250°C in the low-temperature section. This low-temperature irradiation causes large hardening and embrittlement. Furthermore, high-energy neutron irradiation generates transmutant helium, which reduces the toughness of the material [9,10]. Therefore, low-temperature irradiation induces severe irradiation embrittlement due to multiple effects of lattice damage and helium generation. In this paper, both low-temperature irradiation and helium effects on tensile and Charpy impact properties after neutron irradiation up to 0.8 dpa were investigated on low-activation martensitic steel F82H (Fe–8Cr–2W–0.1VTa) and boron-doped F82H (120 appm-^{10}B, 360 appm-total B).

2. Experimental procedure

Material used for the present study is low-activation martensitic steel F82H. Boron-doped F82H was also used for the irradiation experiment to investigate the effect of helium produced from ^{10}B irradiation. The chemical compositions of boron-free F82H (F82H original) and boron-doped F82H (^{10}B-F82H) specimens are listed in Table 1. These alloys were heat treated after hot-rolling at 1200°C. F82H original was normalized at 1040°C for 40 min, then tempered at 740°C for 2 h. Boron-doped F82H was normalized at 1040°C for 0.5 h, then tempered at 740°C for 1.5 h. The thermal treatment condition of boron-doped F82H was chosen to obtain the same ductile-to-brittle transition temperature (DBTT) as that of F82H original. Boron-doped F82H includes about 360 appm of boron in total, and 1/3 of the total boron is ^{10}B, i.e., 120 appm of ^{10}B.

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Table 1
Chemical composition of alloys (wt%)

	Fe	Cr	W	V	Ta	^{10}B	Total B
F82H original	Bal.	7.46	2.1	0.18	0.03	Trace	0.0004
F82H+^{10}B	Bal.	7.53	2.1	0.21	0.04	0.0023	0.0059
	C	**Si**	**Mn**	**P**	**S**	**Al**	**N**
F82H original	0.097	0.09	0.07	0.002	0.003	0.025	0.002
F82H+^{10}B	0.098	0.15	0.50	0.001	0.001	0.021	0.002

These materials were fabricated to round-bar tensile specimens with a diameter of 4 mm and a length of 22 mm in the gauge section and full size Charpy specimens with a 2 mm deep 45° V-notch. Neutron irradiation was carried out using the Japan Material Testing Reactor (JMTR) in the Japan Atomic Energy Research Institute (JAERI). Tensile specimens were irradiated to 0.8 dpa at temperatures ranging from 250°C to 265°C and Charpy specimens were irradiated to 0.3–0.7 dpa at temperatures ranging from 230°C to 290°C. The 120 appm-^{10}B in boron-doped F82H generates about 100 appm of helium during irradiation and about 0.02 dpa of displacement damage from He and Li recoils is included in the displacement damage described above.

Tensile specimens were tested at strain rate of 1.7×10^{-4} s^{-1} at temperatures ranging from room temperature to 400°C in vacuum, except for room temperature tests. Yield stress, ultimate tensile stress, fracture stress, uniform elongation and total elongation were measured from the load–crosshead displacement chart. Reduction of area was also measured. The 0.2% offset proof stress was measured as yield stress, and fracture stress was calculated with fracture load divided by fracture area.

Charpy impact tests were performed with a hammer type testing machine at temperatures between −70°C and room temperature to obtain ductile-to-brittle transition behavior.

Scanning electron microscopy observation of fracture surfaces was carried out on both tensile and Charpy specimens after testing.

3. Results and discussions

3.1. Tensile properties

The test results of neutron irradiated round-bar tensile specimens tested at temperatures ranging from room temperature to 400°C are plotted in Fig. 1. F82H and boron-doped F82H had almost the same tensile properties before irradiation. Therefore, unirradiated tensile properties of both alloys are indicated as a hatched band in Fig. 1.

An increase in yield stress was observed at all test temperatures. The tensile test at 400°C, which is higher than the irradiation temperature, also had the same increase in yield stress as at the lower test temperatures. This means that the obstacle causing hardening induced by low-temperature irradiation is relatively stable. Since boron-doped F82H has the same or smaller yield stress as the boron-free one, 100 appm of helium does not appear to affect the strength. However, boron-doped F82H exhibited less ductility than in F82H. Boron-doped F82H showed about 2–4% less total elongation than boron-free F82H. The most apparent difference was observed in reduction of area. Boron-free F82H had the same value of reduction of area before and after irradiation. On the other hand, boron-doped F82H after irradiation showed a significant decrease in reduction of area, but no particular defects could not be found in boron-doped F82H by SEM observation of the fracture surface.

Fig. 2 shows a comparison of present yield stress data with previous results [4–6]. Yield stresses in this figure are obtained from the tensile tests at irradiation temperatures. Experimentally, yield stress increases logarithmically with irradiation damage [11]. Present data is on a trend line obtained from the HFIR (High Flux Isotope Reactor in Oak Ridge National Laboratory), JMTR and JRR-2 (Japan Research Reactor 2) irradiation test results at 300°C. A trend line obtained from these test results can be explained experimentally by the following equation:

$$\text{Yield stress (MPa)} = 665 + 59\ln(\text{dpa}),\quad \text{where dpa} > 0.1. \tag{1}$$

This trend line gives an estimated yield stress after 100 dpa of about 1000 MPa. The fracture stress of F82H obtained from fracture load and fracture area is about 1200 MPa. When the yield stress increases to this level, it is possible that fracture occurs without elongation. In the present experiment, the fracture stress of boron-doped F82H was about 1000 MPa, while that of boron-free F82H was 1200 MPa. Low reduction of area of boron-doped F82H seems to be caused by this reduction of fracture stress that may be caused by helium generation during irradiation. This decrease in fracture stress

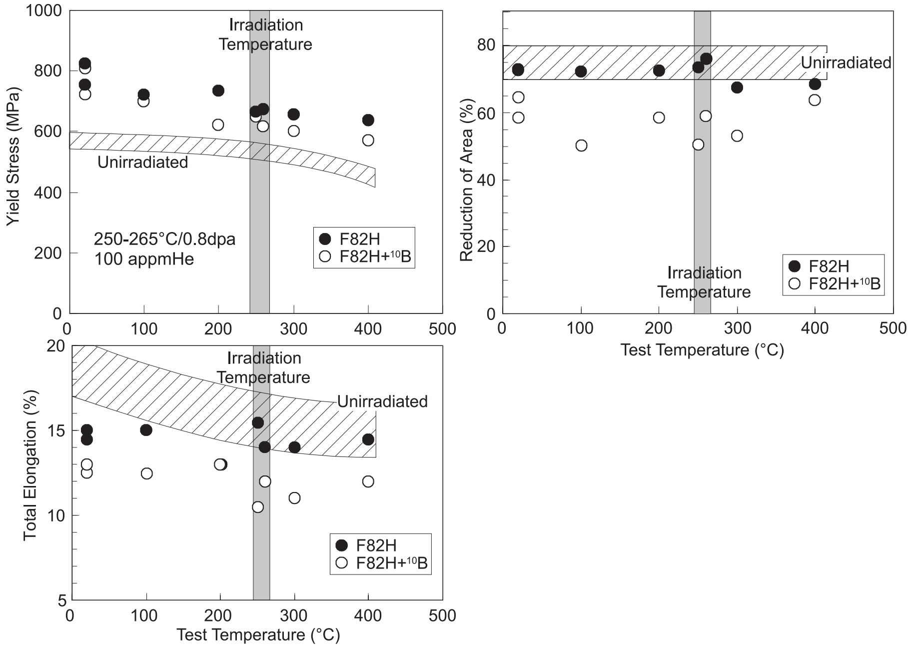

Fig. 1. Post-irradiation tensile test results of F82H and boron-doped F82H.

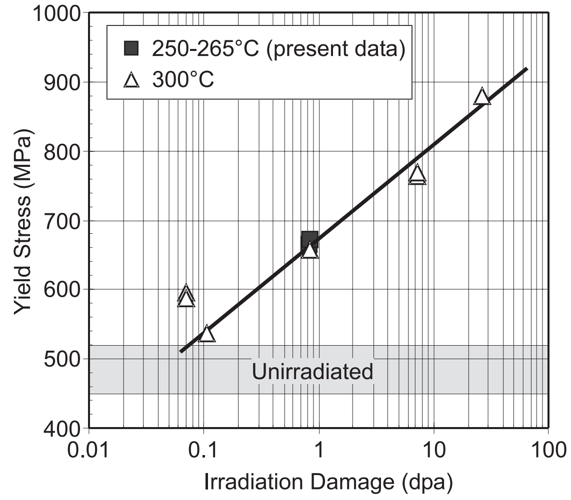

Fig. 2. Irradiation temperature dependence of yield stress tested at the irradiation temperature after neutron irradiation.

possibly causes brittle fracture at a lower increase in yield stress or damage level.

Arrhenius plots of yield stress show two separate temperature regime as shown in Fig. 3. The transition temperature is about 450°C, above which yield stress decreases rapidly. The low temperature trend line can be described by the following equation in the temperature range between −80°C and 400°C

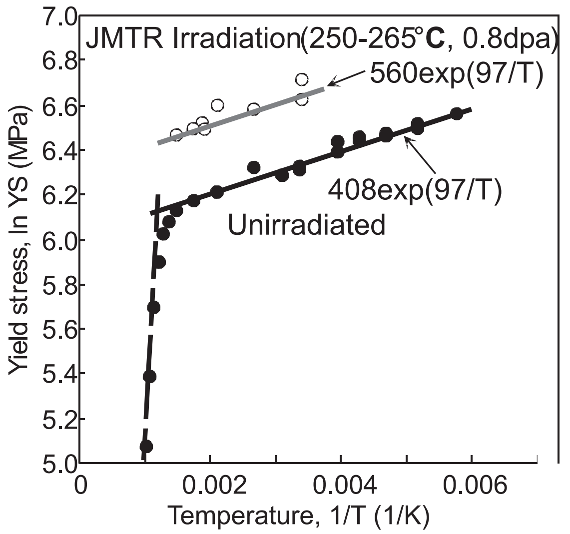

Fig. 3. Test temperature dependence of the yield stress of F82H before and after JMTR irradiation.

$$\text{Yield stress (MPa)} = 407.5\exp(69.9/T), \quad \text{where } T \text{ is temperature in K.} \qquad (2)$$

As shown in Fig. 3, results on F82H tested at temperatures ranging from room temperature to 400°C exhibit the same temperature dependence as unirradiated material. It indicates irradiated and unirradiated yield

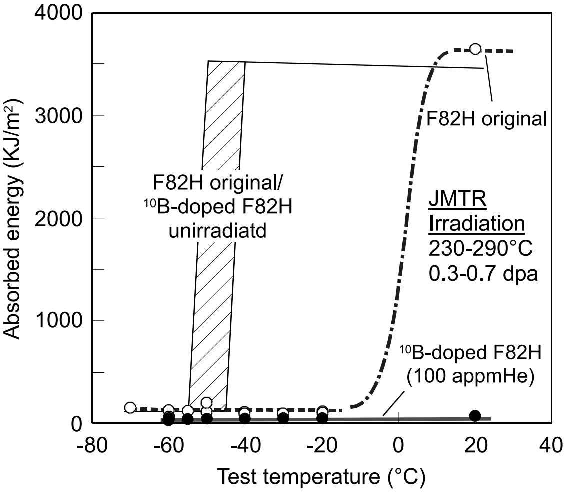

Fig. 4. Charpy test results of F82H and boron-doped F82H after JMTR irradiation.

stresses have the same temperature dependence, so that yield stress at other temperatures can be estimated.

3.2. Charpy impact properties

Charpy specimens irradiated with tensile specimens in the same capsule were tested to obtain absorbed energy transition behavior with test temperature. Charpy test results are plotted in Fig. 4. In irradiated undoped specimens, a DBTT was about 0°C. Though DBTT increased about 50°C, the upper-shelf energy (USE) retained the same. Previous irradiation experiments carried out in the JMTR up to 0.9 dpa above 350°C showed a slight reduction in USE, but the DBTT was not changed by neutron irradiation [5]. Only low-temperature irradiation below 300°C effected significant change in the DBTT after low-dose irradiation.

Boron-doped F82H was also tested after irradiation. Unfortunately, specimens were tested in a temperature range only up to room temperature, and all of the specimens fractured in a brittle manner. Therefore, the DBTT of boron-doped F82H can not be defined, but it must be above room temperature. The USE of boron-doped F82H could not be obtained either. Previous irradiations at higher temperatures showed a wider transition temperature range in boron-doped F82H, but the lower end of the transition temperature range was not changed by irradiation [5]. On the other hand, the effect of helium seems much larger at lower irradiation temperatures. Additional irradiation using the JMTR to obtain a full transition curve on boron-doped F82H is in progress.

4. Summary

Low-activation martensitic steel F82H and boron-doped F82H were irradiated in the JMTR. Tensile specimens were irradiated to 0.8 dpa at temperatures ranging from 250°C to 265°C and Charpy specimens were irradiated to 0.3–0.7 dpa at temperatures ranging from 230°C to 290°C.

1. The yield stress of F82H increased to 850 MPa, consistent with the trend obtained previously under various irradiation conditions.
2. About 100 appm of helium generated from ^{10}B in boron-doped F82H degraded the ductility and the fracture stress of the alloy, while boron-doped F82H had the same or slightly smaller irradiation hardening.
3. About a 50°C increase in DBTT was observed in F82H, but the USE was not changed by irradiation.

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