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Tensile properties of the ferritic martensitic steel F82H after irradiation in a spallation target

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A B S T R A C T

Ferritic/Martensitic (FM) steel, F82H, was irradiated up to a displacement dose of 20 dpa (displacement per atom) at temperatures ranging from 510 to 1075 K in the third experiment of the SINQ Target Irradiation Program (STIP-III). Tensile testing was performed at 295 and 723 K. The tensile test results demonstrate that not only the specimen irradiated in the low temperature regime (<∼675 K) but also those irradiated at elevated temperatures ⩾710 K show significant hardening effect. After annealing at 873 K for 2 h the irradiated specimens still persist great hardening, which is usually not observed in FM steels after neutron irradiation at low temperatures and annealing at 873 K. The hardening observed in the specimens is believed to be due to the high-density He-bubbles formed in the specimens.

1. Introduction

Reduced-activation ferritic/martensitic steels have been developed as candidate structural materials for applications in advanced fusion [1,2] and fission reactors [3]. The F82H steel is one of such steels intensively studied in the fusion materials program because of its relatively low shifts in the ductile-to-brittle-transition temperature after neutron irradiation [4]. The F82H steel is also selected as one of main materials irradiated and studied in the SINQ (the Swiss Spallation Source) target irradiation program (STIP) [5,6] due to the promising applications of FM steels in advanced high power spallation targets [7,8]. A lot of work has been done in recent years on studying the microstructure and mechanical properties of the F82H steel after irradiation (e.g. [9–14]), mostly at low temperatures (<∼675 K). In this work the tensile properties of the F82H steel irradiated in STIP-III in a temperature range of 510 – 1075 K to displacement doses of 8 – 20 dpa have been studied.

2. Experimental

The F82H steel (IEA Heat 9741) used in this study was provided through the Fusion Technology Materials Group of CRPP-EPFL, Switzerland. Its main composition is: 7.65 Cr, 2 W, 0.16 Mn, 0.16 V, 0.02 Ta, 0.11 Si and 0.09 C in wt% and Fe for the balance. The plate was normalized at 1313 K for 38 min and tempered at 1023 K for 1 h. The specimens were miniature type with a gauge section of 5 mm × 1 mm × 0.4 mm.

The STIP-III irradiation was effectively performed for about 68 weeks during 2002 and 2003 in SINQ target-5. As shown in [5,6] the temperature history of a STIP irradiation is usually rather complicated due to a large variation of the proton beam current (about ± 15% around an averaged value) and a lot of beam trips (about 50 times per day with a duration of 1 min or longer) during two years. This results in a similar magnitude of temperature variation in the specimens, because they are mainly heated by the proton beam. In STIP-III case, the situation was even worse. The maximum temperature of the tensile specimens used in this work was about 500 K in the first week, and then increased to about 625 K in the 7 weeks that followed. In the 9th week, it increased greatly to about 1025 K due to a 15% increase of proton beam current and some unclear reasons. It remained at this level or even slightly higher (∼1075 K) afterwards for about 51 weeks. During the last 7 weeks of the irradiation it was about 940 K as the proton beam current at the target was reduced by about 20%. The temperature of each specimen was roughly proportional to the maximum value at a ratio depending on the energy deposition in the specimen. The specimens tested in this work are listed in Table 1, in which the temperature values are averaged ones calculated with the ANSYS code [5,6]. As described above it should be noted that the temperature variation is around ± 15%, plus a lot of low temperature trips.

The irradiation displacement dose of the specimens is between 8 and 20 dpa and the corresponding helium concentration is between 500 and 1800 appm, which was evaluated in the same way as described in the previous papers (e.g. [14]). The main irradiation parameters of the specimens are listed in Table 1.

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Table 1
Irradiation parameters and tensile properties of the F82H specimens. Displacement dose (*D*), yield stress (YS), ultimate tensile strength (UTS), strain-to-necking (STN) and total elongation (TE).

Specimen ID	$T_{irr.}$* (K)	*D* (dpa)	[He] (appm)	$T_{ann.}$ (K)	T_{test} (K)	YS (MPa)	UTS (MPa)	STN (%)	TE (%)
–	–	–	–	–	295	485	640	6.7	17.2
–	–	–	–	–	723	412	438	1.5	10.3
D01	510	8.8	615	–	*295*	*958*	*959*	*0.52*	*7.01*
D03	510	8.8	615	873	295	734	820	6.92	13.96
D04	700	13	985	–	295	865	920	4.43	8.91
D16	730	13	985	873	295	780	885	8.18	11.75
D09	900	17.4	1420	–	295	783	783	0.39	0.87
D21	940	17.4	1420	873	295	694	876	4.08	8.97
D12	1025	20.2	1710	–	295	701	701	0.35	0.35
D05	760	13	985	–	723	616	637	1.73	6.22
D08	930	17.4	1420	–	723	660	677	1.25	3.02
D20	1010	17.4	1420	873	723	562	562	0.61	2.7
D24	1075	20.2	1710	–	723	611	627	0.76	2.5

* Averaged temperature during the effective irradiation time period.

Tensile tests were performed on a 2 kN MTS mechanical testing machine equipped with a video-extensometer so that the displacement could be directly measured from the gauge section. The tests were mostly conducted at room temperature (295 K) and 723 K at a nominal strain rate of $1 \times 10^{-3}\ s^{-1}$.

In order to study the recovery of mechanical properties after annealing and helium (He) effect on hardening, some specimens were tested after annealing at 873 K for 2 h. The fracture surfaces of some specimens tested at 295 K were observed using the scanning electron microscopy (SEM) to identify the fracture mode.

3. Results

The results of tests performed at 295 and 723 K are presented in Fig. 1(a) and (b), respectively. Both figures include results of the irradiated specimens with and without (as-irradiated) annealing at 873 K. As shown in Fig. 1(a), the tests performed at 295 K indicate that the specimens at different displacement doses having great differences in deformation behavior, although all of them showing significant hardening as compared to the unirradiated specimen. The specimen of 8.8 dpa shows prompt necking after yielding, almost without any work hardening and uniform elongation, while the 13 dpa sample obviously displays a recovery of work hardening and uniform elongation. The other two specimens of higher displacement doses, 17.4 and 20.2 dpa, are completely different from the previous two specimens of lower displacement doses, showing a very brittle fracture without any plastic deformation.

The results of tests conducted at 723 K (Fig. 1(b)) are different from that of tests at 295 K. The main differences are in the strength and more important, in the ductility of the specimens of 17.4 and 20.2 dpa.

The tensile curves of the specimens after annealing at 873 K are also included in Fig. 1. Comparing to the stress – strain curves of the as-irradiated specimens, the results illustrate a decrease in yield stress and recovery of ductility after annealing at 873 K and tested at 295 K. The single annealed specimen tested at 723 K shows a decrease in yield stress but no recovery in ductility.

The values of yield stress (YS), ultimate tensile strength (UTS), strain-to-necking (STN) and total elongation (TE) of the specimens evaluated from the corresponding tensile stress – strain curves are listed in Table 1 as well.

The fracture surfaces of the specimens at different displacement doses tested at 295 K were observed using SEM. Fig. 2(a) presents a view of the fracture surface of the 8.8 dpa specimen, which indicates a fully ductile and transgranular fracture mode. Large dimples and small secondary cracks can be observed. With displacement dose increasing to 13 dpa, a numerous of secondary cracks can be observed on the fracture surface of the specimen (Fig. 2(b)). The appearance of the fracture surface is ductile in general (Fig. 2(b)), but the dimples are very shallow, which suggests a reduced

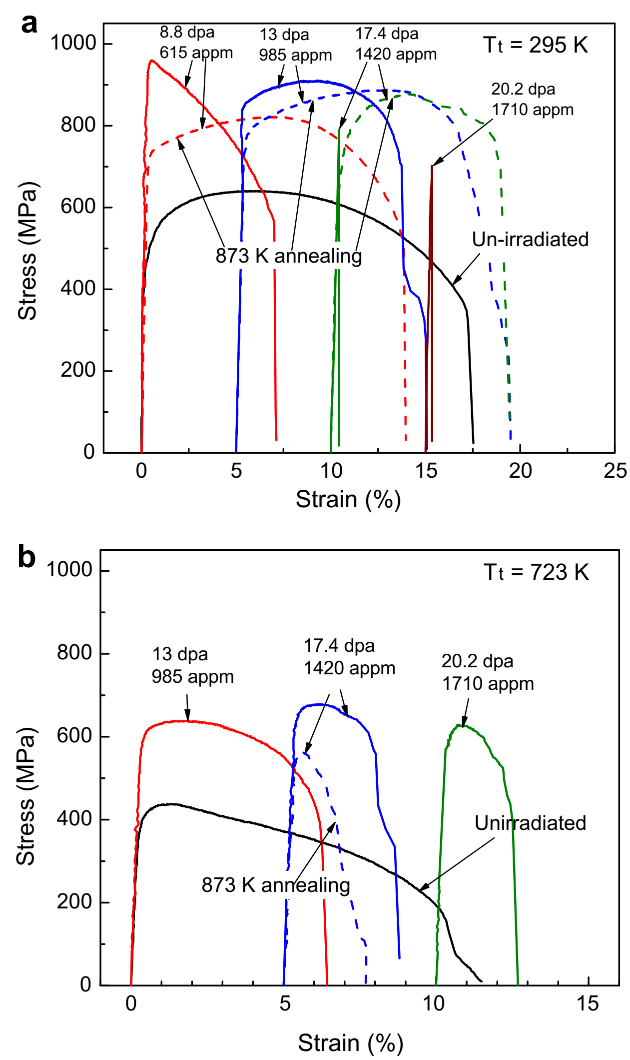

Fig. 1. Tensile stress – strain curves of the F82H specimens tested at (a) 295 K and (b) 723 K.