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Tensile properties of CLAM steel irradiated up to 20.1 dpa in STIP-V

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ABSTRACT

Specimens of China low activation martensitic steel (CLAM) were irradiated in the fifth experiment of SINQ Target Irradiation Program (STIP-V) up to 20.1 dpa/1499 appm He/440 °C. Tensile tests were performed at room temperature (R.T) and irradiation temperatures (T_{irr}) in the range of 25–450 °C. The tensile results demonstrated strong effect of irradiation dose and irradiation temperature on hardening and embrittlement. With T_{irr} below ~314 °C, CLAM steel specimens tested at R.T and T_{irr} showed similar evolution trend with irradiation dose, compared to other reduced activation ferritic/martensitic (RAFM) steels in similar irradiation conditions. At higher T_{irr} above ~314 °C, it is interesting that the hardening effect decreases and the ductility seems to recover, probably due to a strong effect of high irradiation temperature.

1. Introduction

In future fusion reactors, structural materials will undergo high displacement damage and transmutation helium/hydrogen production by an intense flux of high energy neutrons. As candidate structural materials, various Reduced Activation Ferritic/Martensitic (RAFM) steels [1,2] have been widely irradiated in spallation neutron source facilities to investigate irradiation effects with high transmutation production. The China low activation martensitic (CLAM) steel, one of RAFM steels, has been selected as the candidate structure material for the Chinese Test Blanket Module (TBM) for ITER [3] and the liquid blanket of the China Fusion Engineering Teat Reactor (CFETR) [2]. It exhibited equivalent mechanical properties compared to other RAFM steels, such as Eurofer97, Mod-F82H, JLF-1 and Optifer, in the unirradiated condition [4,5]. There have been several irradiation experiments carried out for the CLAM irradiated in SINQ (Swiss Spallation Neutron Source) Target Irradiation Program (STIP – V, VI, VII) [6] to investigate irradiation effects. In this work, we investigated the tensile properties of the CLAM steel after it was irradiated in STIP-V to the irradiation level of 6.6–20.1 dpa (displacement per atom) and 311–1499 appm He in a temperature range of 76–440 °C. And the effects of irradiation dose and irradiation temperature on irradiation hardening and embrittlement are also analyzed for CLAM in comparison with other RAFM steels.

2. Experimental

2.1. Material and specimen

The steel used in this study is HEAT 0408B of the CLAM steel with main chemical composition of 8.91Cr-1.44W-0.2V-0.15Ta-0.49Mn-0.11Si-0.12C. It was manufactured from a 20 kg ingot, hot-forged and rolled into a 12 mm thickness plate. The plate was normalized at 980 °C for 30 min followed by air-cooling, then tempered at 760 °C for 1.5 h and air-cooled. The detailed heat treatment conditions and composition for the CLAM steel can be found in Refs. [7–9]. Miniature flat tensile specimens (so-called 'Small tensile' in STIP [10] as shown in Fig. 1) were manufactured from the plate.

2.2. Irradiation

The CLAM specimens were irradiated in the STIP-V to reach displacement damage doses of 6.6–20.1 dpa at the temperatures of 76–440 °C. More detailed information about the irradiation of

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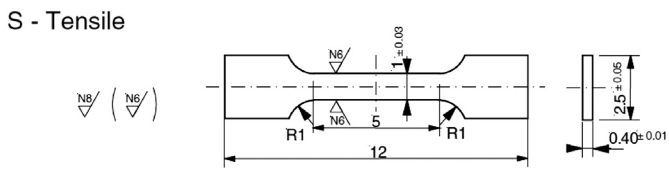

Fig. 1. Dimensions (in mm) of the small tensile specimen of CLAM steel in STIP-V.

these tensile specimens have been reported in Ref. [11]. Irradiation parameters of the specimens are given in Table 1, including calculated dose, helium concentration and irradiation temperature T_{irr}. It should be noted that the temperature is presented in the averaged values and the variation is about ±10% during irradiation in 2007 and 2008. The hydrogen content is not included because it cannot be precisely determined [12].

2.3. Tensile test and SEM observation

Tensile tests were conducted on a 2-kN screw-driven MTS mechanical testing machine equipped with a video-extensometer so that the displacement could be directly measured from the gauge section of specimen. The tests were conducted at room temperature (R.T, 25 °C) and the irradiation temperatures (T_{irr}) at a nominal strain rate of 1×10^{-3} s^{-1}. There was only one test per condition for active specimens due to limited quantity of irradiated specimens, and at least two tests per condition for unirradiated specimens. All tests were performed in an inert Ar atmosphere. Some tested specimens, as representatives, were observed with the scanning electron microscopy (SEM) technique to identify the fracture mode.

3. Results and discussion

3.1. Tensile properties

The engineering tensile stress–strain curves of the irradiated and unirradiated CLAM specimens tested at room temperature are shown in Fig. 2. It is indicated that a significant hardening and embrittlement effect was induced by irradiation at the temperature lower than ~314 °C. Specimens with different displacement doses and He concentrations exhibit different deformation behavior. The specimens irradiated to ≤11 dpa/658 appm He at temperatures ≤144 °C show a total elongation of ~8% and a prompt necking after yielding without any uniform elongation. The specimen irradiated to 20.1 dpa/1499 appm He at 313 °C exhibits a very small total elongation and a small uniform elongation of ~2.2%.

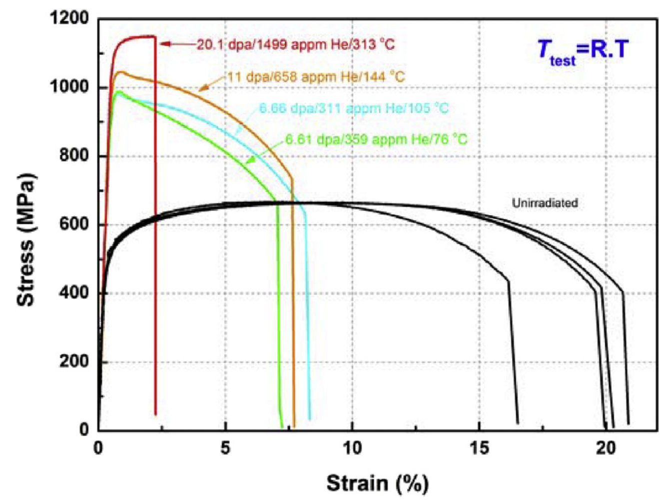

Fig. 2. Engineering tensile stress–strain curves measured at room temperature of CLAM irradiated in STIP-V.

Tensile stress–strain curves of the specimens tested at the irradiation temperatures are shown in Fig. 3. The specimens irradiated at low temperatures between 75 °C and 313 °C, similar to those of the specimens tested at room temperature, showed little or no work hardening capabilities. However, the specimens irradiated at high temperatures between 314 °C and 440 °C exhibit recovery of work hardening and uniform elongation.

The tensile results of the CLAM specimens are listed in Table 1

Table 1
Irradiation parameters and tensile test results of CLAM specimens in STIP-V.

Specimen id	Dose (dpa)	He (appm)	T_{irr} (°C)	T_{test} (°C)	YS (MPa)	UTS (MPa)	STN (%)	TE (%)
UnR-J01	–	–	–	R.T	527	667	6.96	16.15
UnR-J02	–	–	–	R.T	508	666	8.36	19.82
UnR-J03	–	–	–	R.T	505	666	9.38	19.59
UnR-J04	–	–	–	R.T	495	664	8.69	20.66
UnR-J05	–	–	–	150	478	595	6.58	14.85
UnR-J06	–	–	–	150	476	597	6.75	15.66
UnR-J07	–	–	–	250	451	561	5.61	13.44
UnR-J08	–	–	–	250	457	562	5.73	13.96
UnR-J09	–	–	–	350	435	526	4.32	12.03
UnR-J10	–	–	–	350	436	532	5.03	12.80
UnR-J11	–	–	–	450	421	469	2.71	11.46
UnR-J12	–	–	–	450	409	469	3.00	12.35
5-ST-J01	6.6	359	76	R.T	978	989	0.37	6.75
5-ST-J05	6.7	311	105	R.T	977	984	0.31	7.86
5-ST-J04	11	658	144	R.T	1036	1046	0.46	7.28
5-ST-J13	20.1	1499	313	R.T	1113	1150	1.62	1.70
5-ST-J11	6.6	359	75	150	834	841	0.37	6.26
5-ST-J08	11	658	144	150	962	965	0.28	6.11
5-ST-J07	10.1	613	192	250	914	916	0.30	4.88
5-ST-J09	16.2	1085	235	250	948	967	0.64	5.78
5-ST-J14	15.3	1012	314	350	734	799	4.06	8.57
5-ST-J17	20.1	1499	313	350	967	992	0.53	4.64
5-ST-J16	20.1	1482	440	450	625	698	3.55	4.03
5-ST-J15	20.1	1499	378	450	662	707	1.58	2.02

Note: YS: yield stress, UTS: ultimate tensile strength, STN: strain-to-necking, TE: total elongation.