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Irradiation behavior of Ti-stabilized 316L type steel

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ABSTRACT

Type 316L austenitic steels are widely used for the in-vessel internal structures of fission reactors (core, core support, etc.) and for experimental irradiation facilities. The modifications of 316L Type steel (316L, 316L(N), US 316, J 316, JPCA, etc.) have been considered as structural material for International Thermonuclear Experimental Reactor (ITER). The results of investigation the irradiation behaviour of Ti-stabilized 316 L type steel (0.04 C–15 Cr–11 Ni–2.5 Mo–0.5 Ti) are presented in this work. The specimens cut out from 316L-Ti steel forging were irradiated in the SM-2 reactor up to a dose ~4 and 10 dpa at 265 ± 15 °C. The tensile properties, fracture toughness and changes in resistance to intergranular stress corrosion cracking (IGSCC) have been investigated after irradiation. The results for Ti-stabilized 316L steel were compared with those for 316L(N)-IG steel irradiated at the same condition.

1. Introduction

Austenitic steels of 316L-type are widely used as the structural material of the core for the fission reactors and the structural components and facilities of the research test reactors. The modifications of 316-type steel (316, 316L, 316Ti, JPCA, 316L(N), etc.) have been considered as a structural material for the in-vessel components of International Thermonuclear Experimental Reactor (ITER) at the first stage of the designing. The paper deals with the investigation of irradiation behavior of Ti-stabilized 316L-type steel (0.04 C–15 Cr–11 Ni–2.5 Mo–0.5 Ti) which were considered as perspective material for the components of the ITER shield blanket. Irradiation was carried out in the SM-2 reactor up to doses ~4 and ~10 dpa at the temperature 265 ± 15 °C. The tensile properties, fracture toughness and susceptibility to intergranular stress corrosion cracking (IGSCC) have been investigated after irradiation.

2. Experimental procedure

The composition of the steel used in this investigation are given in Table 1. The specimens were cut off from forging after standard solution heat treatment.

Cylindrical specimens with a diameter of 1.5 mm and gauge length of 7.5 mm were used for the tensile tests. Miniature three-point bend specimens $4 \times 4 \times 32\ mm^3$ were used for the fracture toughness tests. Pre-cracking of the specimens was performed by fatigue loading.

The specimens were irradiated in the core of the SM-2 reactor. The irradiation was performed in special capsules at 265 ± 15 °C to doses of approximately 4 and 10 dpa. The activation neutron flux detectors were irradiated in combination with specimens.

Tensile and bend tests of unirradiated and irradiated specimens were carried out on a type 1794U-5 test machine at a cross-head speed of ~1 mm/min. All specimens were tested in air at a temperature corresponding to the irradiation temperature and at 20 °C. The 0.2% yield strength (YS), ultimate tensile strength (UTS), total elongation (TE), uniform elongation (UE) and reduction of area (RA) were determined as described in the standard GOST 1497 [1]. Crack-opening displacement (COD), stress-intensity factor (K_c^*) and value J-integral (J_c^*) were determined at the maximum load according to requirements of the GOST 25.506 standard [2]. After testing, the ends of the tensile specimens were used to measure the resistance to IGSCC by the Electrochemical Potentiodynamic Reactivation method (EPR, double loop), which was carried out according to the GOST 9.914 standard [3].

3. Result of test

3.1. Tensile behaviour

After irradiation the tensile tests show the significant change of the deformation behaviour and tensile properties. The smooth yielding behaviour of the unirradiated material is replaced by appearance of a yield drop and the capacity to strain hardening is decreased or eliminated. The extent of these changes depends from the dose of irradiation and the test temperature. The dose dependence of the tensile properties for the investigated steel is shown in Fig. 1(a) and (b). At the test temperature 20 °C after irradiation to a dose of ~4 dpa steel remains the strain hardening

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Table 1
Chemical composition of the investigated steel (wt.%).

Material	Fe	Ni	Cr	Mo	Si	C	P	S	Ti
316L-Ti	Bal.	10.6	15.8	2.18	1.3	0.54	0.015	0.012	0.32

capability and the shape of tensile strain–stress curves was similar to that of the unirradiated state. After irradiation to ~10 dpa the yield drop is observed in the stress–strain. The strain hardening capability practically has disappeared. However, the strain to necking was at relatively a high level. At the test temperature 265 °C the yield drop is observed after the ~4 dpa irradiation and the strain hardening capability decreases very significantly. However, the value of strain to the necking was equal 5–6%. After the ~10 dpa irradiation the strain hardening capability has disappeared and the yield drop is replaced by a softening with a very small constant rate.

After irradiation to a dose of ~4 dpa the YS steel increases about ~180% relative to the YS of the unirradiated material at test temperature 20 °C and about ~160% at 265 °C. After irradiation at a dose of about 10 dpa the increase of YS achieved ~200% at 20 °C and 225% at 265 °C. Relation YS/UTS of unirradiated steel was equal 0.43–0.45. Irradiation results in essential increase of this parameter at the both test temperatures to 0.95–0.96 after a dose ~4 dpa and to 0.99 after a dose ~10 dpa.

The change of relation UE/TE of steel after irradiation depends on the test temperature. This parameter practically do not changes at 20 °C (although the absolute values of the both characteristics are decreasing). At 265 °C it diminishes by a factor of approximately two after a dose ~4 dpa and from 0.8 to 0.04 – after the ~10 dpa irradiation.

3.2. Fracture toughness

Fracture toughness of unirradiated steel was high. The value of the δ_c (COD) exceeded 0.4 mm and K_c^* was higher than ~400 MPa m$^{1/2}$. Irradiation produced a significant decrease in parameters of fracture toughness, Table 2. At the test temperature 265 °C after irradiation to a dose ~4 dpa the value of K_c^* diminished to 46–48 MPa m$^{1/2}$ and the value of δ_c decreased to ~0.003 mm. After increase a dose to ~10 dpa the values of these parameters practically did not changed, that can consider as the achievement of the saturation state, see Table 2. At the tests temperature 20 °C the effect of irradiation at the parameters of fracture toughness was significantly lower.

3.3. Resistance to IGSCC

The unirradiated steel shows high resistance to IGSCC estimated using the Electrochemical Potentiodynamic Reactivation (EPR) method. There was no evident the susceptibility to IGSCC of investigated steel after irradiation to a dose up to 10 dpa.

4. Discussion

The influence of neutron irradiation on the deformation behaviour and the tensile properties of type 304 and 316 type austenitic steels is relatively well studied in Refs. [4–17]. The mechanical properties of 316 type steels as structural materials for using in

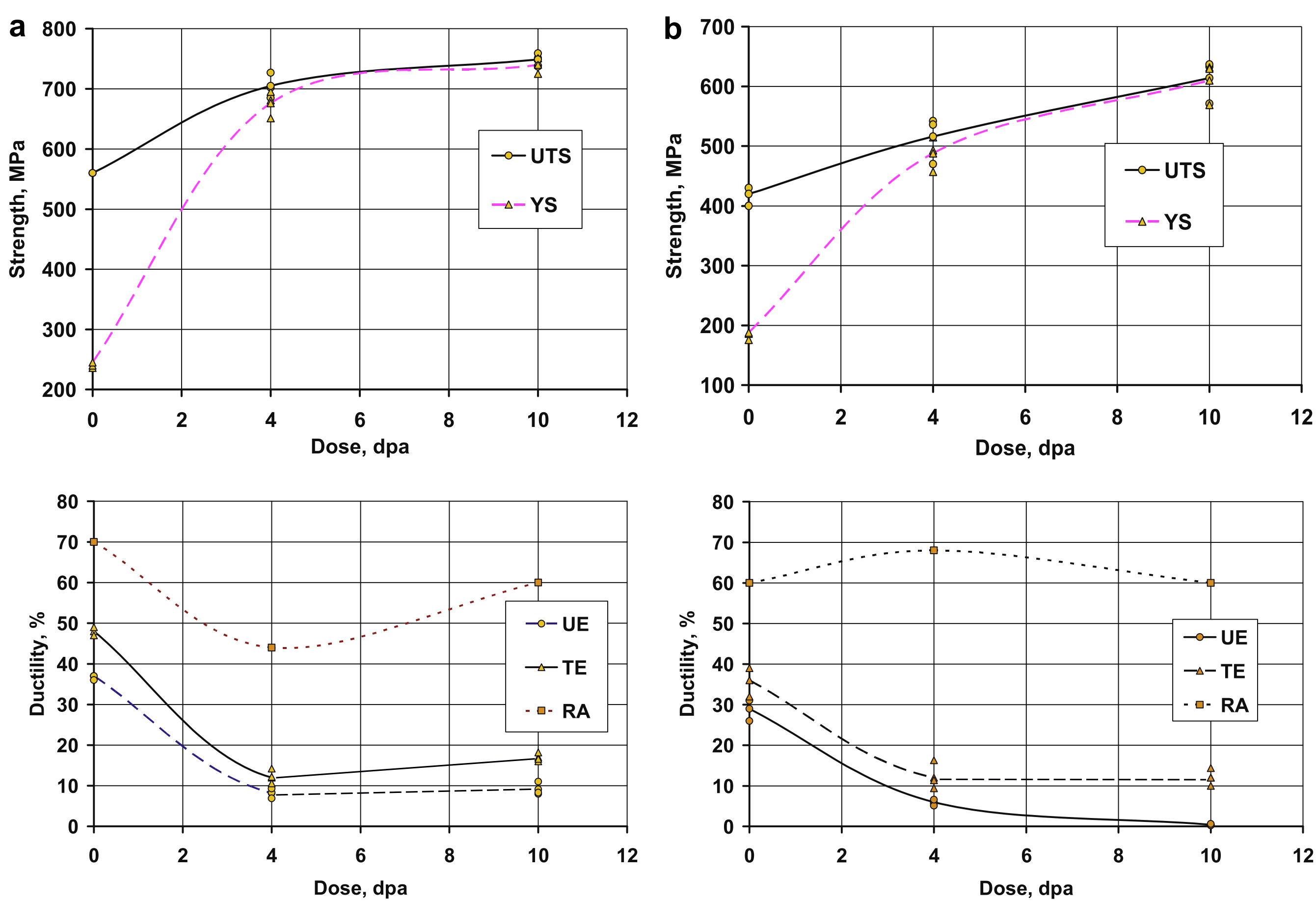

Fig. 1. (a) Irradiation effect on the tensile properties of 316L-Ti stainless steel at 20 °C. (b) Irradiation effect on the tensile properties of 316L-Ti stainless steel at 265 °C.

Table 2
Parameters of the fracture toughness investigated steel after irradiation.

Test temperature (°C)	Dose (dpa)	Fracture toughness		
		K_c^* (MPa m$^{1/2}$)	COD (δ_c) (mm)	J_c^* (MPa m)
20	∼4	73–74	0.19–0.21	143–81
	∼10	106	0.38	93
265	∼4	46–48	0.0021–0.0039	6–57
	∼10	46–49	0.0027–0.0031	9

Table 3
Irradiation effect at the properties of 316L-Ti and 316L(N) steels.

Steel	Dose (dpa)	T_{test} (°C)	UTS (MPa)	K_{ir}	YS (MPa)	K_{ir}	UE (%)	K_{ir}	TE (%)	K_{ir}	STN (%)	COD (mm)	K_c^* (MPa m$^{1/2}$)	J_c^* (MPa m)
316L-Ti	0	20	560		245		37		54					
		265	420		188		29		36			0.4		
	∼4	20	705	0.26	676	1.83	8	0.78	12	0.78		0.2	74	110
		265	516	0.23	488	1.6	5–6	0.82	12	0.65	5–6	0.003	47	32
	∼10	20	749	0.34	740	2.02	9	0.76	16	0.78		0.38	106	93
		265	614	0.46	610	2.25	0.4	0.98	12	0.64	4–7	0.003	47	9
316L(N)	0	20	608		405		30		48					
		265	437		240		21.5		25.5			0.4		
	∼4	20	898	0.48	854	1.1	8.4	0.72	17	0.64		0.24	78	429
		265	718	0.64	704	1.93	0.75	0.96	18	0.29	3–5	0.076	46	225
	∼10	20	827	0.36	814	1.0	1.5	0.95	11	0.77		0.17	60	228
		265	738	0.68	726	2.02	0.6	0.97	12.7	0.5	4.8	0.05	37	120

ITER in-vessel components were investigated in Refs. [11–17]. Analysis of the deformation behaviour and tensile properties for investigated 316L-Ti shows that these well correlates with known data. In Refs. [17,20], the irradiation behaviour of the 316L(N)-IG steel was studied at the temperature-dose condition coincided with those of present work. The comparison of these data are presented in Table 3. The comparison shows, that the YS of unirradiated steel 316L-Ti lower at 25–40%, than that for 316L(N)-IG steel, but the TE of 316L-Ti steel is higher at 11–29%. After irradiation at a dose ∼4 dpa YS are increasing at the 160% for 316L-Ti and approximately at 195% – for 316L(N)-IG steel. After irradiation up to a doses ∼10 dpa the rate of radiation hardening increases to 225% for 316L-Ti steel and only to ∼200% – for 316L(N)-IG steel. The both steels remained the TE at the level 12–18% after dose 10 dpa and the decrease of TE was equal approximately 50–78%. The change of UE was more higher. After dose 4 dpa the UE of 316L-Ti steel is diminished at ∼82% and was equal ∼5%. The change of UE for 316L(N)-IG steel was more higher and achieved approximately 96%. After dose 10 dpa the UE of the both steel was practically the same and was at a low level, 0.4–0.6%.

Horsten and de Vries [16–18] have shown that the onset of necking takes place at a characteristic value of the load decrease that occurs after reaching the UTS, the so-called strain-to-necking (STN). STN are proposed to use as the value of UEL for irradiated austenitic steel components of ITER [19,21]. The values of STN for 316L-Ti steel and 316L(N) are presented in Table 3. The estimated values STN for the both steels were practically the same. After irradiation to a doses 4–10 dpa STN were equal 4–7% that good agreed with data [16].

The values K_c^* for irradiated steels 316L-Ti and 316L(N)-IG are very similar. However, the values J_c^* and in particular δ_c at 265 °C for 316L-Ti are significantly lower than for 316L(N)-IG steel. The reason of this may be in essential difference of load–displacement curves. The comparison of the load–displacement curves for 316L(N)-IG steels are shown at Fig. 2. The yield drop are observed at the load–displacement curves for 316-Ti steel but are absent at the curves of 316L(N)-IG steel. According GOST 25.506 fracture toughness were determined for the maximum load and accounted the plastic component of δ_c and J_c for 316L-Ti was low, although in fact the growth of the crack was continued after the maximum of the load. The appearance of the fractures is well correlates with this explanation: was ductile, although estimated values δ_c and J_c corresponded for the brittle material.

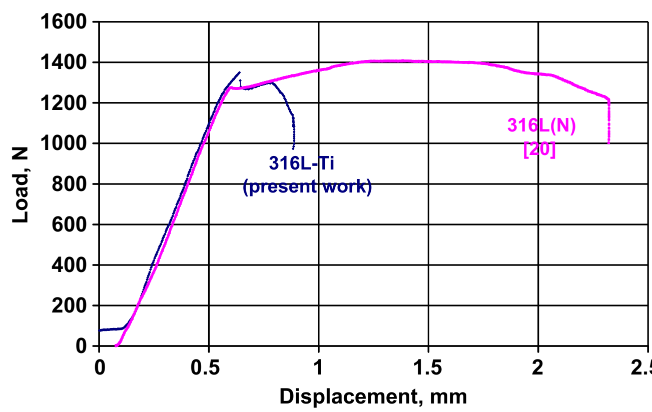

Fig. 2. Load–displacement curves for irradiated 316L-Ti and 316L(N) steels.

5. Conclusion

Steel 316L type stabilized Ti have been irradiated in SM-2 reactor up to about 10 dpa at 265 °C. The tensile properties, fracture toughness and resistance to IGSCC by EPR method were determined.

Radiation hardening at ∼160% is observed after irradiation to a dose ∼4 dpa and approximately ∼225% – after dose ∼10 dpa. After dose ∼4 dpa the steel lost essentially the capability to strain hardening. However, uniform plastic deformation remained relatively high (UE = 5–6%). After the ∼10 dpa irradiation the strain hardening capability has disappeared completely, the values of yield strength and ultimate tensile strength were practically the same and uniform elongation was below ∼0.5%. However, the value of the total elongation are remained at ∼12%.

The fracture toughness, K_c^* of 316L-Ti steel, decreased to 46–48 MPa $m^{1/2}$ after a dose ~4 dpa and practically did not-changed after ~10 dpa.

After irradiation to ~10 dpa the steel 316L-Ti remained the resistance to IGSCC.

The comparison of the irradiation effect at properties 316L-Ti and 316L(N) steels showed after dose 4 dpa somewhat lesser decrease of the ductility for 316-Ti steel, but after dose 10 dpa the ductility of the both steels were practically the same.

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