Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 1312–1315
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Irradiation behavior of Ti–4Al–2V (ПТ-3В) alloy for ITER blanket modules flexible attachment

B.S. Rodchenkov [a,*], A.V. Kozlov [b], Yu.G. Kuznetsov [b], G.M. Kalinin [c], Yu.S. Strebkov [a]

[a] *Research and Development Institute of Power Engineering (RDIPE), P.O. Box 788, Moscow 101000, Russian Federation*
[b] *Institute of Reactor Materials, Zarechnyi, Sverdlovsk Region 624051, Russian Federation*
[c] *Engineering Centre of Nuclear Equipment Strength (ENES), P.O. Box 788, Moscow 101100, Russian Federation*

Abstract

Titanium alloys are recommended as a material to manufacture flexible attachments of the shield blanket modules in the ITER reactor owing to their advantageous combination of properties, i.e., high resistance to impact loading, strength, density and low thermal expansion coefficient. An additional factor for selecting Ti alloys is their fast induced radioactivity decay. The (α + β)-Ti alloys have higher strength than (α)-Ti alloys but are less developed. The data base on the irradiation behavior of these materials is limited. Neutron irradiation of (α)-Ti–4Al–2V (ПТ-3В) alloy has been performed in the framework of the ITER R&D programme. Specimens from a forging of Ti–4Al–2V alloy were irradiated in the IVV-2M reactor to doses of (0.32–0.43) dpa at temperatures of (240–260) °C. This paper describes the results of tensile, low cycle fatigue and fracture toughness tests of alloy in the unirradiated and neutron irradiated conditions. The results obtained are compared with those of the (α + β)-Ti–6Al–4V alloy.

1. Introduction

Titanium alloys were considered as one of the options for manufacturing the back plate in the earlier stage of the ITER conceptual design activity (CDA). An assessment of titanium alloy properties studied within the Tokamak Physics Experiment (TPX) program can be found in [1,2]. In the current design of the ITER, a flexible cartridge for mechanical attachment of the shield module to the pressure vessel is recommended to be manufactured from high strength titanium alloys. Flexible cartridge must operate in the temperature range of 150–260 °C and at the dose level at about 0.1 dpa.

Titanium alloys are widely used in different countries in shipbuilding, chemical and airspace industries. The data base on physical and mechanical properties of titanium alloys is relatively complete for the unirradiated condition [3,4]. The available data show that Ti alloys are very sensitive to irradiation and even a low dose of irradiation results in significant degradation of ductility and fracture toughness [5–10].

* Corresponding author. Tel.: +7 095 263 74 44; fax: +7 095 264 79 34.
E-mail address: rodchen@nikiet.ru (B.S. Rodchenkov).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.03.261

This study was undertaken to characterize the irradiation resistance of high strength α-Ti–4Al–2V alloy. Specimens cut from the forging were irradiated in IVV-2M reactor to dose levels of 0.32–0.43 dpa in the temperature range of (240–260) °C. The tensile, fracture toughness and low cycle fatigue properties have been investigated before and after irradiation.

2. Experimental procedure

The tested material was Ti–4Al–2V alloy (Al: 4.26, V: 1.85; Zr: 0.3; Si: 0.12; Fe: 0.25; O: 0.15; H: 0.006; N: 0.04; C: 0.1; Ti: balance, in wt%). A forging with a diameter of 80 mm was used for cutting of specimens. The forging was annealed at 875 °C for 1.5 h. Cylindrical specimens with a diameter of 3 mm and a gage length of 12.5 mm were used for tensile tests.

Bend bar specimens with dimensions of $10 \times 5 \times 55$ mm were used for three point bend fracture toughness tests. Pre-cracking of specimens was performed by fatigue loading. Specimens for low cyclic fatigue tests were rectangular plates symmetrically thinned in the center with a ratio of gripping (28 mm^2) and gage section ($4 \times 4 = 16$ mm^2) equal to 1.75 and with a constant thinning radius of 57 mm. The specimens were 70 mm long.

The specimens were irradiated in the IVV-2M reactor at (250 ± 12) °C to damage dose levels of (0.32–0.43) dpa. The irradiations were performed in inert gas atmosphere. Fluence was monitored using an Fe^{54} activation monitor.

Tensile and fracture toughness tests of unirradiated and irradiated specimens were carried out on a GAMMA-1 type test machine at the crosshead speed of 1 mm/min. Tensile and fracture toughness specimens were tested in air at 20 °C and 260 °C corresponding to the irradiation temperature. Fatigue specimens were tested only at 20 °C.

The 0.2% yield strength (YS), ultimate tensile strength (UTS), total elongation (TEL), uniform elongation (UEL) and reduction of area (RA) were obtained in accordance with the GOST 1497 standard [11]. Three parameters, δ_c, J_c and $J_{0,2}$ were used for characterization of fracture toughness. Crack opening displacement (COD), δ_c, and J_c were determined at the maximum load in accordance with the GOST 25.506 standard [12]. J–R curves and $J_{0,2}$ were determined in accordance with ASTM E 1737-96 [13]. Low cycle fatigue tests were carried out in accordance with the GOST 25.502-79 standard [14]. The tests were carried out in a special low cycle fatigue facility under strain control and symmetrically sinusoidal bending. The loading frequency was 10 cycles per minute. The statistical treatment of fatigue experimental data has been performed in accordance with ASTM E739-91.

3. Result of tests and discussion

3.1. Tensile behavior

The tensile tests of irradiated specimens show a change in stress–strain behavior of the material (hardening, reduction of ductility and strain hardening capability). The tensile data of Ti–4Al–2V alloy are shown in Table 1. The effects of irradiation were more visible at the test temperature 260 °C compared with that one at 20 °C. The typical tensile curves before and after irradiation are presented in Fig. 1.

The strain hardening capability of the alloy was decreased due to irradiation. The ratio YS to UTS can be used for characterization of the materials strain hardening capability. The YS/UTS was increased due to irradiation from 0.8 to 0.96 at the test temperature 260 °C and from 0.85 to 0.98 at 20 °C.

The ratio $\frac{N_{\mathrm{irr}}-N_{\mathrm{in}}}{N_{\mathrm{in}}} = K_{\mathrm{ir}}$, where N_{irr} and N_{in} are values YS for irradiated and initial condition accordingly are using to estimate the irradiation hardening or UEL for irradiated and initial condition accordingly to estimate irradiation embrittlement. The irradiation hardening of the investigated alloy was 1.13–1.40 at a test tempera-

Table 1
Tensile properties of unirradiated and irradiated Ti–4Al–2V alloy

Dose (dpa)	T_{test} (°C)	UTS (MPa)	YS (MPa)	UEL (%)	TEL (%)	RA (%)
0	20	740–760	620–660	4.7–6.8	12.5–19.4	38.5–50
	260	440–470	345–370	4.9–7.2	16.3–17.8	67–75
0.39–0.43	20	1100–1120	1070–1090	5.5–6.8	13–15.5	15–18
	260	810–870	790–830	2.5–2.8	7.6–9.6	31.5–38.5

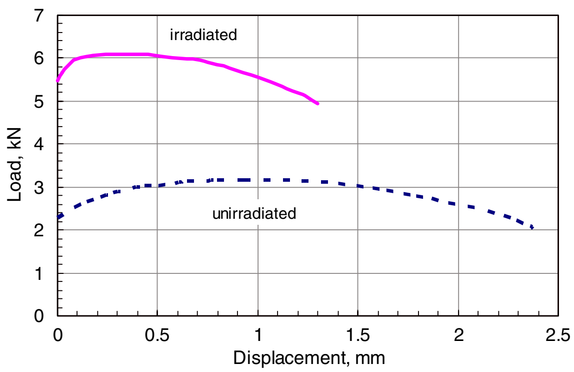

Fig. 1. Typical tensile curves of Ti–4Al–2V alloy at the temperature 260 °C.

ture of 260 °C and 0.62–0.75 at 20 °C. The irradiation embrittlement was equal 0.43–0.65 at 260 °C and 0.17–0.45 at 20 °C. The value of UEL at 260 °C after irradiation was equal 2.5–2.8% and 5.5–6.8% at 20 °C. The reduction of RA after irradiation was about 60% at 20 °C and 50% at 260 °C. The value of RA after irradiation did not decreased lower than to 31.5% at 260 °C.

3.2. Fracture toughness

Ti–4Al–2V alloy in the unirradiated condition exhibited load–displacement behavior typical for ductile material during fracture tests. The appearance of load–displacement curves after irradiation changed, but were typical for less ductile materials. The *J–R* curves for unirradiated and irradiated Ti–4Al–2V alloy are presented in Fig. 2. Fracture toughness characteristics calculated from the load–displacement curves and *J–R* curves are shown in Table 2.

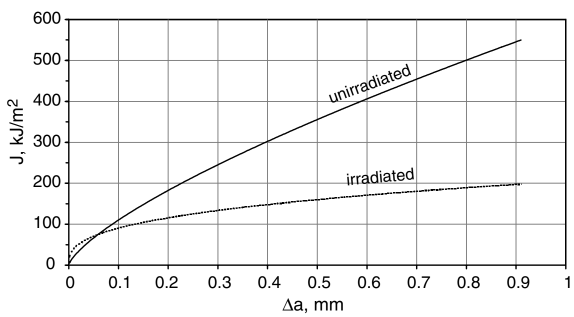

Fig. 2. Influence of irradiation on *J–R* curves of Ti–4Al–2V alloy at the temperature 260 °C.

Table 2
Fracture toughness characteristics of unirradiated and irradiated Ti–4Al–2V alloy

Dose (dpa)	T_{test} (°C)	COD (δ_c) (mm)	J_c (kJ/m^2)	$J_{0,2}$ (kJ/m^2)
0	20	0.078	122	227
	260	0.26 ± 0.014	240 ± 10	515
0.32–0.4	20	0.008	48	–
	260	0.036 ± 0.005	102 ± 8	126

A strong temperature dependence of fracture toughness was observed in the unirradiated condition. The COD, J_c and $J_{0,2}$ values were higher at 260 °C than those at 20 °C.

The irradiation significantly decreased the fracture toughness of Ti–4Al–2V alloy. The COD value after irradiation diminished by a factor of 10 at 20 °C and approximately 4.5 times at 260 °C. The effect of irradiation on J_c and $J_{0,2}$ values was smaller. After irradiation the J_c values decreased by a factors of 2.5 and 2.35 at 20 °C and 260 °C, respectively. The $J_{0,2}$ value at 260 °C reduced due to irradiation by a factor about 4, from 515 kJ/m^2 to 126 kJ/m^2.

3.3. Low cycle fatigue

Results of low cycle fatigue test are presented in Fig. 3. Minor deterioration of fatigue resistance due to irradiation has been observed in the high strain range (the irradiated specimens failed at a smaller number of cycles). At lower strain amplitudes, the cyclic strength of the irradiated specimens was approximately the same as in the initial state.

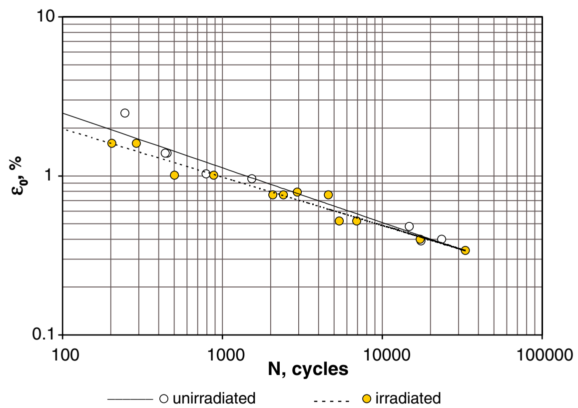

Fig. 3. Fatigue curves of unirradiated and irradiated Ti–4Al–2V alloy.

Table 3
Influence of irradiation on properties of (α)-Ti–4Al–2V and (α + β)-Ti–6Al–4V alloys

Material	Dose	UTS (MPa)	K_{irr}	YS (MPa)	K_{irr}	UEL (MPa)	K_{irr}	TEL (%)	K_{irr}	COD (mm)	K_{irr}	$J_{0,2}$ (kJ/m^2)	K_{irr}
Ti–4Al–2V	0	455		360		6		17		0.21		515	
	∼0.4	840	0.84	810	1.25	2.5	0.58	9	0.47	0.047	0.78	126	0.75
Ti–6Al–4V	0	638		510		9		16.6		0.14		293	
	∼0.4	1039	0.63	986	0.93	2.3	0.74	4.7	0.72	0.014	0.9	66	0.77

The fatigue curves are described with sufficient accuracy by equation $\lg(\varepsilon_0) = k \cdot \lg N + c$, where $k = -0.34$; $c = -0.92$ for the initial state and $k = -0.3$; $c = -1.1$ – after irradiation.

Neutron irradiation of (α + β)-Ti–6Al–4V alloy has been performed in the framework of the ITER R&D program [15]. The comparison data for irradiated and unirradiated (α)-Ti–4Al–2V alloy obtained in this work and (α + β)-Ti–6Al–4V alloy [15] are presented in Table 3. The average values of results at 260 °C were used in Table 3.

The absolute values of results and their reduction/increase coefficient due to irradiation, K_{irr}, were used for analysis of the irradiation effect. K_{irr} equals to the ratio of results of irradiated alloy to that for the unirradiated alloy. The (α + β)-Ti–6Al–4V alloy indicated higher strength and practically the same ductility and significantly lower fracture toughness in the initial condition than those of the Ti–4Al–2V alloy. Radiation hardening of the (α)-Ti–4Al–2V alloy was higher than that of the (α + β)-Ti–6Al–4V alloy and values of K_{irr} were equal to 0.84–1.25. On the contrary radiation embrittlement estimated by K_{irr} for ductility and fracture toughness was higher for the (α + β)-Ti alloy.

4. Conclusions

Irradiation to a dose level of about 0.4 dpa resulted in changes of mechanical properties of the Ti–4Al–2V alloy. The effects of irradiation depend on test temperature.

At 20 °C the changes in tensile properties due to irradiation were less significant than those at 260 °C. Radiation hardening reached 140% and irradiation embrittlement was found equal to 43–65% at 260 °C. The Ti–4Al–2V alloy kept strain hardening capability and UEL did not drop below 2.5% in the irradiated condition.

The irradiation caused a significant reduction of fracture toughness of Ti–4Al–2V alloy. The value of $J_{0,2}$ at 260 °C was reduced by a factor of 4 due to irradiation.

Radiation hardening of the (α)-Ti–4Al–2V alloy was higher than that for the (α + β)-Ti–6Al–4V alloy and values of K_{irr} were equal 0.84–1.25. On the contrary radiation embrittlement estimated by K_{irr} for ductility and fracture toughness was higher for the (α + β)-Ti alloy.

References

[1] J.W. Davis, M.A. Ulrikson, R.A. Causey, J. Nucl. Mater. 212–215 (1994) 813.
[2] J.W. Davis, G.W. Wille, P. Heitzenroeder, J. Nucl. Mater. 233–237 (1996) 592.
[3] Titanium Alloys, ASM Hand book, vol. 2, 1979, p. 483.
[4] G.I. Kopirin (Ed.), Titanium Alloys in Mechanical Engineering, Leningrad, 1977, p. 230 (in Russian).
[5] I.V. Gorinin, V.F. Vinokurov, O.A. Kojjevnikov, V.V. Rybin, I.I. Yarmolovitch, Plasma Dev. Oper. 4 (1996) 235.
[6] D.R. Duncan, R.J. Puigh, E.K. Opperman, J. Nucl. Mater. 103&104 (1981) 919.
[7] S. Tähtinen, P. Moilanen, B.N. Singh, D.G. Edwards, J. Nucl. Mater. 307–311 (2002) 416.
[8] A. Kohyama, K. Asaho, N. Igata, J. Nucl. Mater. 141–143 (1986) 987.
[9] R.E. Nygren, J. Nucl. Mater. 85&86 (1979) 861.
[10] S. Sastry et al., Comparison of Titanium Alloy Ti–6Al–4V and 5621S Microstructure after EBR-II Irradiation, ADIP Quarterly Report DOE/ET-0058/1, 1978.
[11] Metals Method of Tension Tests. Standard GOST 1497-73 (in Russian).
[12] Method of Mechanical Testing of Metals. Determination of Fracture Toughness Characteristics under Static Loading. Standard GOST 25.506 (in Russian).
[13] ASTM Standard E 1737-96. Standard Test Method for J-integral Characterization of Fracture Toughness, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 1998.
[14] Methods of Mechanical Testing of Metals. Methods Fatigue Tests. Standard GOST 25.502-79 (in Russian).
[15] B.S. Rodchenkov, A.V. Kozlov, et al., J. Nucl. Mater. 307–311 (2002) 421.