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Irradiation behaviour of titanium alloys for ITER blanket modules flexible attachment

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Abstract

The high strength $(\alpha+\beta)$- and α-titanium alloys are considered as a candidate materials for flexible attachments of the shield blanket modules in the ITER reactor owing to their advantageous combination of properties, i.e. low elasticity modulus, high resistance to impact loading, high strength, low density and low thermal expansion coefficient. There are limited data available on the irradiation behaviour of these materials. Neutron irradiation of $(\alpha+\beta)$ Ti–6Al–4V alloy has been performed in the framework of the ITER R&D program. Specimens from two heats of Ti–6Al–4V alloys were irradiated in the IVV-2M reactor up to a dose of 0.35–0.42 dpa at temperatures 240–260 °C. This paper describes the tensile, low cycle fatigue and fracture toughness properties of Ti–6Al–4V alloy in the unirradiated condition and after neutron irradiation.

1. Introduction

Titanium alloys are widely used in chemical and aerospace industries. As far as the applications in the fusion environment are concerned, Ti 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 alloys for application in the Tokamak physics experiment can be found in [1]. In the current design of ITER, a flexible cartridge for mechanical attachment of the shield module to the pressure vessel is recommended to be manufactured from high strength $(\alpha+\beta)$ Ti–6Al–4V alloy. The titanium alloy must operate in the temperature range of 150–260 °C and at a dose level up to about 0.1 dpa.

Ti–6Al–4V alloy is widely used in different countries and the database on physical and mechanical properties is relatively complete for the unirradiated condition [2,3]. Ti alloys are very sensitive to neutron irradiation, and even a relatively low dose of irradiation results in degradation of ductility and fracture toughness [4–7]. Most of the information about irradiation behaviour of titanium alloys is for α-titanium alloys. Data on the irradiation effects on $(\alpha+\beta)$ Ti–6Al–4V alloy are very limited [8,9].

Consequently, this study was undertaken to characterize the irradiation resistance of $(\alpha+\beta)$ Ti–6Al–4V alloy. Specimens cut from the forgings of the two heats were irradiated in the IVV-2M reactor up to a dose level

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of 0.35–0.42 dpa at a temperature range 240–260 °C. Tensile properties, fracture toughness and low cycle fatigue have been investigated before and after irradiation.

2. Experimental procedure

The chemical composition of Ti–6Al–4V alloys used in this investigation is given in Table 1.

Two forgings with a diameter of 200 and 85 mm from Heat 1 and Heat 2, respectively, were used. The billets were mil-annealed at different temperatures: Heat 2 at 700 °C for 1 h and Heat 1 at 800–825 °C for 1 h. These heat treatments resulted in different microstructures. The structure of both materials was typical for $(\alpha + \beta)$-titanium alloys, but the average grain size and the amount of transformed β-phase in Heat 1 were larger than those in Heat 2.

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 the specimens was performed by fatigue loading. Specimens for low cyclic fatigue tests were rectangular plates symmetrically thinned in the center with the ratio for gripped (28 mm^2) and gage section ($4 \times 4 = 16$ mm^2) equal to 1.75, and with a constant thinning radius in the gage section of 57 mm. The specimens were 70 mm long.

Part of the specimens from Heat 1 were hydrogen charged up to 200 ppm H_2. A Siverts-type method was used for hydrogen charging.

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

Tensile and fracture toughness tests of unirradiated and irradiated specimens were carried out on a GAMMA-1 type test machine at a crosshead speed of 1 mm/min. Tensile and fracture toughness specimens were tested in air at temperatures of 20 and 260 °C. 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 [10]. 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 [11]. *J–R* curves and $J_{0.2}$ were determined in accordance with ASTM E 1737-96 [12]. Low cycle fatigue tests were carried out in accordance with the GOST 25.502-79 standard [13]. The tests were conducted in a special low cycle fatigue facility under strain control and symmetrically sinusoidal bending. The loading frequency was 10 cycles per minute.

3. Result of tests and discussion

3.1. Tensile behaviour

The tensile tests of irradiated specimens show a change in stress–strain behaviour of material (hardening, reduction of ductility and strain hardening capability). The tensile data for both heats of Ti–6Al–4V are shown in Table 2. The effect of irradiation was more visible at the test temperature of 260 °C than at 20 °C. The strain hardening capability was decreased due to irradiation. The ratio YS to UTS can be used for characterization of materials strain hardening capability. The YS/UTS was increased due to irradiation for Heat 1 from 0.8 to 0.94 at a test temperature of 260 °C and from 0.91 to 0.92 at 20 °C. For Heat 2, the YS/UTS ratio was increased after irradiation from 0.8 to 0.95 at 20 °C and from 0.78 to 0.96 at 260 °C.

The irradiation hardening was about 30–35% at the test temperature 20 °C and approximately 40–50% at 260 °C. The reduction in elongation after irradiation was more significant at 260 °C and was equal to 70–75% for Heat 1 and about 50% for Heat 2. The value of UEL at 260 °C after irradiation was about 2–3%. Similar values of RA were observed for both alloys. The diminuation of RA was about 60–70% for Heat 1 and 50–60% for Heat 2.

The materials behaviour is attributed to differences in structure. The larger amount of β-phase resulted in larger initial strength. But this material is more sensitive to irradiation, and the ductility degradation is greater for the material having more β-phase (i.e. Heat 1).

Hydrogenation did not cause any significant change in the tensile properties both for unirradiated and irradiated materials. The amount of hydrogen in the mate-

Table 1
Chemical composition of Ti–6Al–4V alloys (wt%)

Material	Ti	Al	V	Zr	Si	Fe	O	H	N	C
Ti–6Al–4V, Heat 1	Base	6.15	4.4	0.3	0.12	0.3	0.15	0.015	0.05	0.1
Ti–6Al–4V, Heat 2	Base	6.3	4.02	–	–	0.2	0.17	0.019	0.11	0.16

Table 2
Tensile properties of unirradiated and irradiated Ti–6Al–4V alloy

Material	Dose (dpa)	T_{test} (°C)	UTS (MPa)	YS (MPa)	UEL (%)	TEL (%)	RA (%)
Heat 1	0	20	912	834	6.2	13.7	39.4
	0	260	638	510	9.0	16.6	52.0
	~0.4	20	1305	1202	3.7	12.4	14.6
	~0.4	260	1039	986	2.3	4.7	15.7
Heat 1 (200 ppm H_2)	0	20	956	842	5.7	15.6	38.7
	0	260	653	519	8.4	15.4	48.7
	~0.4	20	1325	1234	5.5	13.0	15.9
	~0.4	260	1044	986	2.2	5.7	15.1
Heat 2	0	20	981	791	7.3	14.5	37.4
	0	260	662	520	7.1	13.3	45.3
	~0.4	20	1327	1265	6.8	12.5	15.7
	~0.4	260	1067	1025	3.4	6.9	23.9

rial (200 ppm) was within the solubility limit that did not affect the deformation behaviour of material.

3.2. Fracture toughness

Both heats of Ti–6Al–4V alloy in the unirradiated condition exhibited load–displacement curves during fracture tests typical for ductile material. The appearance of the load–displacement curves after irradiation significantly changed to that one typical for less ductile materials (see Fig. 1). The *J–R* curves for unirradiated and irradiated alloys are presented in Fig. 2. Fracture toughness characteristics calculated from the load–displacement curves and *J–R* curves are also shown in Table 3.

Fracture toughness of the materials in the unirradiated condition was significantly different for different heats. The $J_{0.2}$ value for Heat 1 was approximately in 2.5 times bigger than that of Heat 2 at 260 °C. The $J_{0.2}$ value of Heat 1 decreased by a factor of 4 after irradiation. The effect of irradiation on Heat 2 was smaller and did not exceed 20–30%. As a result, the irradiated Heat 2 material had about 30% higher fracture toughness than that of irradiated Heat 1. Similar behaviour was found in the δ_c parameter. However, the effect of irradiation on δ_c was greater than for $J_{0.2}$. COD (δ_c) decreased 6–10 times due to irradiation.

Hydrogenation up to 200 ppm did not significantly affect the fracture toughness in either the irradiated or unirradiated condition.

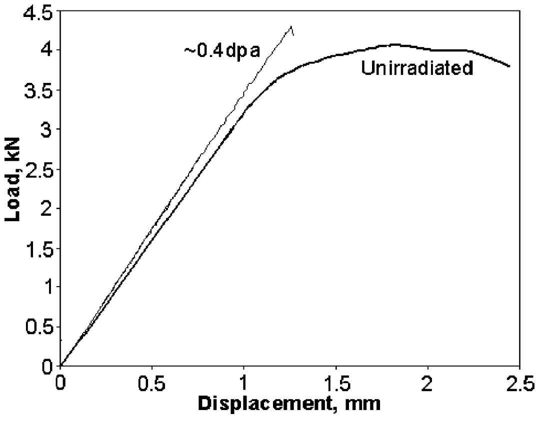


Fig. 1. Typical load–displacement curves of Ti–6Al–4V alloy at 260 °C (Heat 2).

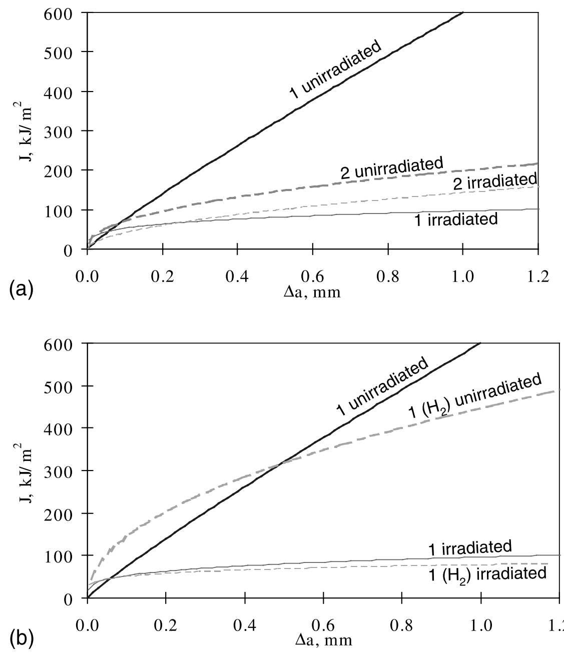
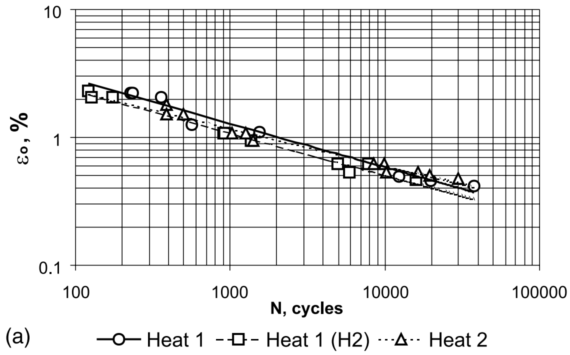


Fig. 2. Influence of irradiation on *J–R* curves of Ti–6Al–4V alloy in initial (a) and hydrogenated (b) conditions at 260 °C (1 – Heat 1, 2 – Heat 2).

Table 3
Fracture toughness characteristics of unirradiated and irradiated Ti–6Al–4V alloy

Material	Dose (dpa)	T_{test} (°C)	COD (δ_c) (mm)	J_c (kJ/m^2)	$J_{0.2}$ (kJ/m^2)
Heat 1	0	20	0.040	78	90
	0	260	0.144	240	293
	~0.4	20	0.002	16	–
	~0.4	260	0.014	75	66
Heat 1 (200 ppm H_2)	0	20	0.031	77	63
	0	260	0.115	212	252
	~0.4	20	0.010	25	26
	~0.4	260	0.015	64	61
Heat 2	0	20	0.018	65	95
	0	260	0.110	184	115
	~0.4	20	0.002	38	–
	~0.4	260	0.019	73	89



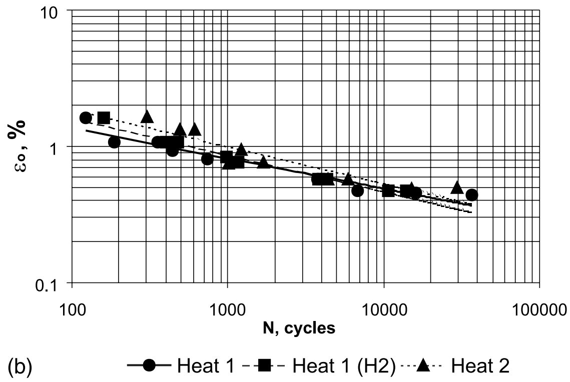


Fig. 3. Fatigue curves of unirradiated (a) and irradiated (b) Ti–6Al–4V alloy.

3.3. Low cycle fatigue

Results of low cycle fatigue test are presented in Fig. 3. The fatigue resistance of both heats in the unirradiated condition was similar. 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 a strain amplitude reduction, the cyclic strength of the irradiated specimens was approximately the same as in initial state. The observed deterioration of fatigue resistance at high strains was more obvious for the Heat 1 material.

Hydrogenation up to 200 ppm did not affect to the fatigue behaviour of Ti–6Al–4V alloy.

4. Conclusions

Irradiation to a dose level of about 0.4 dpa resulted in changes in the mechanical properties of a Ti–6Al–4V alloy. The effects of irradiation depend on test temperature and material structure.

At 20 °C the changes in tensile properties due to irradiation were less significant than those at 260 °C. Radiation hardening reached 60–90% and reduction of ductility was found equal to 50–70% at 260 °C. Both investigated heats of the Ti–6Al–4V alloy showed some strain hardening capability and values of UEL did not drop below 2–4% in the irradiated condition.

The irradiation caused significant reduction in fracture toughness of the Ti–6Al–4V alloy. The value of $J_{0.2}$ was reduced by a factor of 4 and 20–30% for the materials of Heat 1 and Heat 2, respectively, when tested at 260 °C.

Irradiation resulted in a slight decrease of low cycle fatigue, in the range of large strain amplitudes. The number of cycles to failure did not decrease during strain controlled fatigue tests for the strain amplitudes less than 0.5–0.7%.

There is a different value of mechanical properties changes (tensile, fracture toughness and fatigue) due to irradiation for the different material structures. The anneal of Ti–6Al–4V alloy at lower temperature (700 °C) resulted in smaller grain size and β-phase formation, and this led to better radiation resistance (smaller property changes due to irradiation) in comparison with material annealed at the higher temperature (800–825 °C).

Hydrogenation to 200 ppm did not significantly change the mechanical and fracture behaviour of Ti–6Al–4V alloy in either the unirradiated or irradiated conditions.

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