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Tensile and fatigue properties of two titanium alloys as candidate materials for fusion reactors

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Abstract

Titanium alloys have been identified as candidate structural materials for the first wall, the blanket and the magnetic coil structures of fusion reactors. Titanium alloys are interesting materials because of their high specific strength and low elastic modulus, their low swelling tendency and their fast induced radioactivity decay. Other attractive properties are an excellent resistance to corrosion and good weldability, even in thick sections. Furthermore titanium alloys are suitable for components exposed to heat loads since they have a low thermal stress parameter. Titanium alloys with an α structure are believed to have a good resistance against radiation embrittlement and $\alpha + \beta$ alloys should possess the best tolerance to hydrogen embrittlement. Two classical industrially available alloys in the two families, the Ti5Al2.4Sn and the Ti6Al4V alloys have been used in this study. The tensile properties between room temperature and 450°C are reported. A low cycle fatigue analysis has been performed under strain control at total strain ranges between 0.8% and 2% and at a temperature of 350°C. The microstructure of both alloys was investigated before and after both types of deformation. Both alloys exhibit excellent mechanical properties comparable to or better than those of ferritic martensitic steels.

1. Introduction

Residual radioactivity calculations show that Ti, together with V and Cr have the fastest rate of dose rate decay [1]. They present also high strength to weight ratios and an attractive combination of thermophysical and mechanical properties which result in low thermal stresses, high fatigue strength and high fracture toughness. Because of their overall corrosion resistance, they are expected to have favourable coolant compatibility. Furthermore, there exists an extensive industrial experience and properties database on a number of industrial compositions, which are extensively used in the aerospace industry.

The affinity of titanium for hydrogen delimits the two main problems associated with its use in a fusion environment: the possible hydrogen embrittlement and the increased tritium inventory. It is therefore important to develop adequate coatings as surface barriers. There is also a lack of information on the properties of the irradiated alloys.

In the present investigation, alloys in the α and $\alpha + \beta$ phase fields are investigated under conditions relevant for the application as flexible connectors between ITER blanket modules and the vacuum vessel. Results of the characterisation of the unirradiated materials are presented.

2. Experimental

2.1. Origin, structure and chemical analysis of the alloys

The Ti5Al2.4Sn alloy originates from HOWMET Mill, USA. The material obeys the AMS 4926H specification. After hot forming, it has been annealed 1 h at 815°C and then air cooled. The microstructure consists of equiaxed α grains, 20 μm in diameter. The Ti6Al4V alloy was produced by TIMET, Savoie SA in UGINE,

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Table 1
Chemical compositions: [wt%]

	Al	C	Fe	Sn
Ti 5Al2.4Sn	5.0	0.17	0.36	2.4
Ti6Al4V	6.08	0.0056	0.1399	–
H_2	N_2	O_2	V	Others
0.0036	0.010	0.179	–	
<0.0060	0.0065	0.176	3.95	<0.4

France. It was produced according to the specification WL 3.7164.1 and DIN 65040/65174 to a stock diameter of 150 mm. After hot forming in the $\alpha + \beta$ field, it was annealed for 1.5 h at 730°C and then air cooled. The structure consists of equiaxed α grains, about 20 μm in diameter surrounded by β phase and secondary α zones. The chemical specification of the alloys is given in Table 1.

2.2. Tensile tests

Tensile testing was performed using a mechanical RMC100 testing machine. The tests at elevated temperature were done in a vacuum furnace with a vacuum $\sim 10^{-4}$ Pa. Two different specimen geometries were used: the flat classical PIREX specimen with a thickness of 0.34 mm and a gauge length of 5.5 mm [2] and a comparison specimen, the DIN 50125 cylindrical specimen with a diameter of 3 mm and a gauge length of 18 mm. The PIREX specimen is a non standard specimen designed for irradiation with protons.

The first part of the testing was aimed at comparing these two specimen geometries in order to validate the results obtained with the PIREX geometry. The tensile strain rates used were 3×10^{-5} and 3×10^{-4} s^{-1}. The second part of the testing compares the properties of the two alloys using the PIREX specimen only at a strain rate of 3×10^{-4} s^{-1}.

2.3. Fatigue tests

The testing was done using the same RMC100 testing machine. The tests were carried out at 350°C in vacuum, under total strain control ($R = -1$). The strain was measured with an automatic strain extensometer, specially designed for testing radioactive specimens.

The specimen used was a cylindrical tubular specimen, 3.4×2.7 mm^2 diameter with a gauge length of 5.5 mm. This specimen was specially designed for proton irradiations [2]. The strain rate used was 0.001–0.002 s^{-1}. The extensometer was regularly calibrated at the test temperature after the specimen had separated in two pieces, using a reference extensometer on the crosshead.

2.4. Electron microscopy

TEM examinations were made on the as-received alloys and on selected tensile and fatigue specimens after fracture. Three mm disks were cut next to the fracture surface and mechanically polished to reduce the thickness down to $\sim$80 μm. The thin foils were prepared by electropolishing using a solution of 3% perchloric acid, 37% 2-butoxyethanol and 60% ethanol at 20 V and −35°C and examined in a JEOL 2010 operating at 200 kV.

3. Results and discussion

3.1. Comparison between the PIREX subsize specimen and the DIN 50125 specimen

The specimen comparison was only done with the Ti5Al2.4Sn alloy. The results of the comparison are not significantly influenced by the strain rate so they are shown in Fig. 1 only for the case of a strain rate of 3×10^{-4} s^{-1}. The stresses measured with the DIN specimen were higher than those measured with the PIREX geometry, at room temperature and at 400°C. In percentage the difference is less than 11%. But at 200°C, the differences are quite small.

Between room temperature (RT) and 400°C, uniform and total elongation are not very sensitive to temperature. Above 400°C there is an increase of the total elongation and a decrease of the uniform elongation as the temperature increases.

At room temperature, the PIREX geometry gives elongation values which are too small, by almost 50% for the total elongation and 30% for the uniform elongation. From 200°C and above, the comparison is better

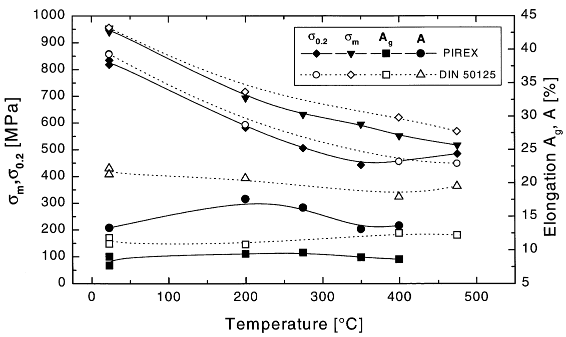

Fig. 1. Tensile properties of Ti5Al2.4Sn as a function of test temperature obtained in DIN 50125 and PIREX subsize specimens at a strain rate of 3×10^{-4} s^{-1}. $\sigma_{0.2}$ is the 0.2% offset yield stress, σ_m is the ultimate stress, A_g the uniform elongation and A the total elongation.

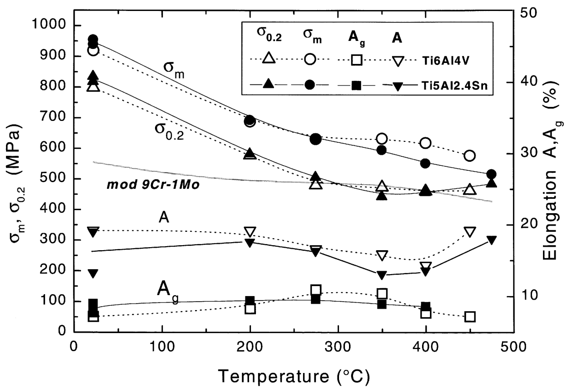

Fig. 2. Tensile properties of Ti6Al4V and Ti5Al2.4Sn alloys between RT and 475°C, at 3×10^{-4} s^{-1}. The yield stress of typical low activation FM steels [3] is shown for comparison.

although generally the values indicated by the DIN specimen are always higher.

3.2. The tensile behaviour of Ti5Al2.4Sn and Ti6Al4V alloys

The behaviour of the yield stress and ultimate stress as a function of the temperature is reported in Fig. 2 for both alloys, tested at 3×10^{-4} s^{-1}. Depending on the temperature, they show tensile strengths higher or similar to those observed in low activation ferritic martensitic steels [3]. At low temperatures (up to 150°C) the α alloy Ti5Al2.4Sn is slightly superior in strength to the $\alpha + \beta$ alloy Ti6Al4V whereas at higher temperatures (from 300°C) the $\alpha + \beta$ alloy seems to overtake the α alloy. The tensile tests have demonstrated good ductilities for both alloys (Fig. 2). The uniform elongation is slightly lower in the $\alpha + \beta$ alloy as compared to the α alloy. Correspondingly, the situation is reversed in terms of total elongation.

3.3. Fatigue tests results

3.3.1. General behaviour

The fatigue testing presented in this work was done under total strain range control. Since titanium alloys are very elastic ($E = 120\,000$ MPa) and very strong, the elastic contribution of the total strain is much larger than the plastic contribution. Because low cycle fatigue (LCF) requires plastic deformation, the testing of titanium alloys demands very high total strain ranges. The lower limit of the total strain range measured corresponds to fatigue lives around 10 000 cycles and the upper bound was limited by the stability of the fatigue specimen used. For the alloys studied, the practical range of the total imposed strain was found to be between 1% and 2%.

The behaviour of the total stress range and the plastic strain range as a function of the number of cycles to failure for both alloys, tested at a high imposed strain is as follows. In the case of the Ti6Al4V alloy stress and strain are almost constant over the number of cycles. But for the Ti5Al2.4Sn, the stress diminishes and the plastic strain increases as a function of the cycles, thus indicating that some softening is taking place.

Fig. 3 shows the behaviour of both alloys when they are tested at a low imposed strain. Up to about 800 cycles, both alloys show cyclic softening. The softening is higher in the α alloy. Above 800 cycles, cyclic hardening is observed. The cyclic hardening is higher in the $\alpha + \beta$ alloy than in the α alloy. In the Ti 6Al 4V the stress at the end of life reaches the level it had at the first cycle.

The total stress range is shown in Fig. 4 as a function of the imposed strain, at first cycle and at half life for both alloys. The difference between both curves represents the softening at half life. In the α alloy the softening increases slightly as the imposed strain increases.

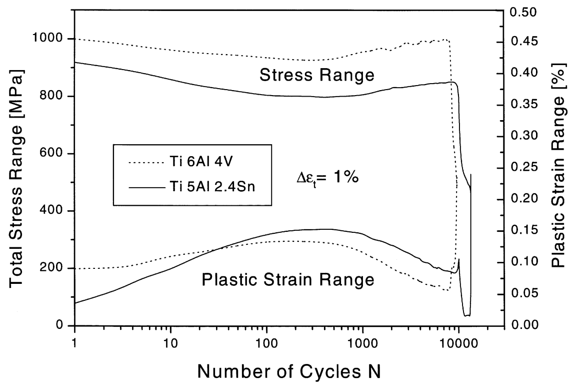

Fig. 3. Softening behaviour at a low imposed strain. $T = 350$°C, vacuum.

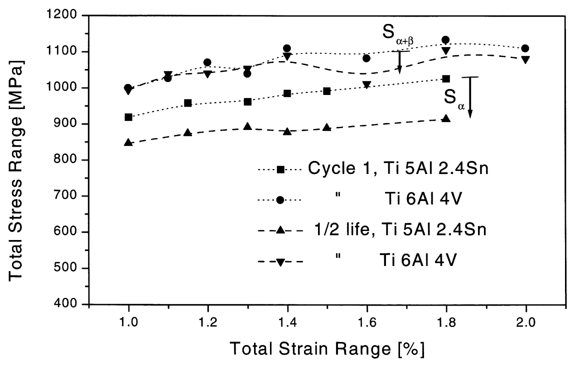

Fig. 4. The total stress range as a function of the imposed strain range at first cycle and at half life. The arrow indicates the magnitude of the softening in both alloys, respectively.

The softening is relatively important and is of the order of 80–100 MPa. In the $\alpha + \beta$ alloy the softening at half life is absent at low imposed strains but a value of 75 MPa is measured at 1.6%.

The softening is more important in the α alloy as compared with the $\alpha + \beta$ alloy.

Fig. 4 shows also that the cyclic stresses are about 15% higher in the $\alpha + \beta$ alloy.

Another general feature observed in the fatigue testing of both alloys, is the fact that the compressive stress of the hysteresis loop is always higher than the tensile stress.

The difference of the tensile and compressive stresses is constant during the life.

This characteristic seems to be typical for titanium alloys, since it was observed in both alloys and at all the test conditions used in this study (see also [4,5]).

3.3.2. Fatigue endurance

The imposed total strain $\Delta\varepsilon_t$, the total elastic strain $\Delta\varepsilon_e$ and the total plastic strain $\Delta\varepsilon_P$ taken at half life, were plotted as a function of the number of cycles to failure N_f, for both materials. The plot enables then the calculation of the coefficients of the fatigue life equation

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = C_p N_f^{k_p} + C_e N_f^{k_e}.$$

The following strain life equations were established:

For Ti 5Al 2.4Sn

$$\Delta\varepsilon_t = 260 N_f^{-0.84} + 1.24 N_f^{-0.03}.$$

For Ti 6Al 4V

$$\Delta\varepsilon_t = 64 N_f^{-0.71} + 1.4 N_f^{-0.04}.$$

Finally in Fig. 5, the imposed total strain is represented as a function of N_f for both alloys. The fatigue resistance appears to be higher in the α alloy. This is in accordance with the behaviour shown in Fig. 3. The higher cyclic stresses in the $\alpha + \beta$ alloy are inducing a higher crack growth rate.

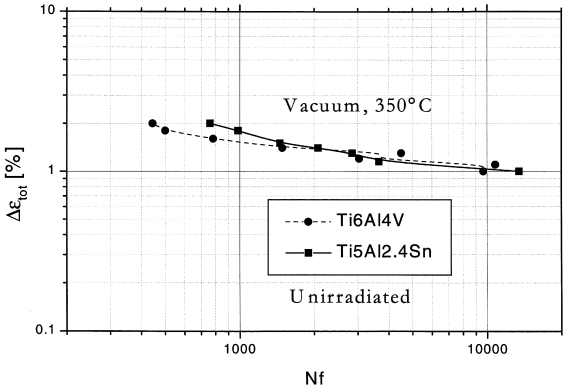

Fig. 5. Strain life data for Ti5Al2.4Sn and Ti6Al4V alloys tested at 350°C in vacuum. Strain rate: 0.0015 s^{-1}.

3.4. Electron microscopy

The initial microstructure of both alloys shows irregular arrays of a-type dislocations, $b = 1/3\langle 1\,1\,\bar{2}\,0\rangle$ and traces of deformation bands. Tensile specimens of Ti–5Al–2.4Sn tested at RT and 350°C exhibit a very high density of a-type straight screw dislocations, together with parallel arrays of shorter c-component dislocations. Formation of subgrains and deformation bands is also observed.

Ti–5Al–2.4Sn samples fatigued up to fracture at 350°C show strong damage and a different structure appears, consisting of parallel deformation cell walls, see Fig. 6(a). Dislocation debris is also observed, Fig. 6(b), composed mainly of residues of a-type dislocations and small dislocation loops.

In the Ti6Al4V alloy, the deformed microstructure of the primary α grains present the same characteristics as in the case of the Ti5Al2.4Sn alloy, i.e. long parallel arrays of a-type dislocations for tensile and dislocation debris for fatigue. As shown in Fig. 6(c), for the Ti6Al4V

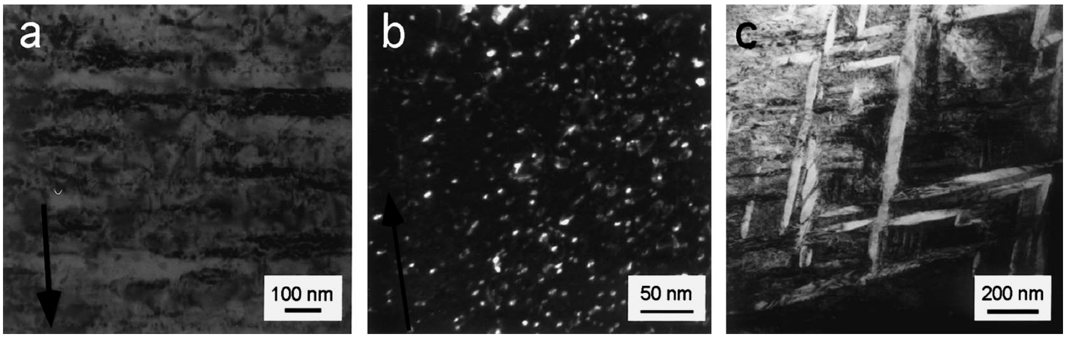

Fig. 6. (a) Dislocation walls in fatigued Ti5Al2.4Sn, $g = (2\,\overline{1}\,\overline{1}\,0)$ (arrow). (b) Dislocation debris in fatigued Ti6Al4V α grains, $g = (0\,\bar{1}\,1\,1)$ (arrow), weak beam $g(4g)$. (c) Deformation-induced martensite in fatigued Ti6Al4V β grains.

alloy, deformation-induced martensite appears clearly in the β grains. The quantity of this transformed phase is higher in the samples tested in fatigue than in tension.

4. Conclusions

- The comparison between subsize and the DIN normal-sized specimens shows that the measured stresses in the subsize specimen are smaller by less than 11% and that the differences observed are temperature dependent, while the elongations observed in the DIN specimen are higher, specially at room temperature.
- The tensile strength of both studied alloys is very similar and comparable or larger than that found in ferritic-martensitic steels. At temperatures up to 150°C, the α alloy Ti5Al2.4Sn is slightly superior to the $\alpha + \beta$ alloy. The reverse takes place at higher temperatures. The uniform elongation is slightly lower in the $\alpha + \beta$ alloy as compared to the α alloy.
- Two different regimes have been observed in the behaviour under cyclic stresses. At a high imposed strain, softening is almost absent in the Ti 6Al 4V and is small in the Ti5Al2.4 Sn. At a low imposed strain, for both alloys, during the first period of life, cyclic softening takes place (up to about 800 cycles). But then a transition occurs after which a regime of cyclic hardening appears.
- The fatigue resistance of the Ti5Al2.4Sn alloy is higher than that of the Ti6Al4V alloy.

Acknowledgements

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References

[1] O.N. Jarvis, Selection of low-activity elements for inclusion in structural materials for fusion reactors, Report AERE-R 10496, June 1982.
[2] P. Marmy, Ruan Yuzhen, M. Victoria, J. Nucl. Mater. 179–181 (1991) 697.
[3] A.A.F. Tavassoli, J. Nucl. Mater. 258–263 (1998) 85.
[4] T. Bui-Quoc, R. Gomuc, A. Biron, J. Eng. Mater. Technol. Transactions of the ASME 114 (1992) 390.
[5] A.S. Beranger, X. Feaugas, M. Clavel, Mater. Sci. Eng. A 172 (1993) 31.