

CHARACTERIZATION OF A TITANIUM ALLOY FOR NUCLEAR FUSION APPLICATIONS

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Riassunto.

Le leghe al titanio presentano proprietà assai interessanti, in vista del loro utilizzo come materiali strutturali per reattori a fusione termonucleare. Per selezionare una lega con proprietà adeguate, bisogna tenere in conto, in questo caso, sia delle proprietà termo-meccaniche e fisiche che di quelle nucleari. La radioattività indotta da flusso neutronico è uno dei parametri essenziali da limitare in un materiale di questo tipo: per quanto concerne la lega Ti-6Al-4V, essa si pone al di sotto dei limiti di bassa attività di cui sembra probabile l'adozione per le scorie di reattori a fusione.

Si è quindi proceduto alla caratterizzazione meccanica di due tipi di struttura della lega Ti-6Al-4V, considerando anche l'effetto della temperatura e della velocità di deformazione. Le proprietà meccaniche dei due tipi di lega si sono rivelate particolarmente interessanti, per gli elevati valori del limite elastico e a rottura. Inoltre, il comportamento a caldo (in particolare nello stato STA della lega) suggerisce l'evidente possibilità di fabbricare le complesse forme della prima parete di un reattore a fusione sfruttando la tecnica della formatura superplastica.

1. Introduction.

In some studies concerning the thermonuclear fusion systems, titanium alloys were selected on the basis of their high strength, high strength to weight ratio, excellent fatigue life, resistance to corrosion, low He production from fusion reactions, no void swelling formation, well established industry and abundant availability¹. An example of this can be found in the NUWMAK reactor study².

Taking into account these properties, and according to the new concepts related to low-activation materials, titanium alloys can also at present be considered an interesting candidate as a structural material for the next generation of fusion reactors.

Some problems are certainly to be kept present, like, for instance, the limited operating temperature (450 °C) and a low compatibility with hydrogen and its isotopes³.

In order to evaluate the suitability of the titanium alloys as structural materials for a fusion reactor, we have considered first the problems coming from neutron-induced radioactivity, and then we have characterized a Ti-6Al4V alloy from the mechanical point of view, in different conditions (temperature, strain rate, morphology).

2. Neutron-induced radioactivity in a titanium alloy.

One of the main disadvantages of the fission reactors consists, with no doubt, in their production of radioactive wastes. This is one of the real technical reasons that are obstaculating (now and in the future) a wider diffusion of this power source.

Also fusion reactors will produce radioactive wastes, even if in far lower quantities. Moreover, fusion radioactive wastes will mainly consist of structural materials, radioactivated by the exposure to neutron flux; fission wastes, on the contrary, are made by fuel and reaction products.

Neutron induced radioactivity, at a fixed flux, strongly depends on the type of irradiated material. So, with a proper selection of the materials, the amount of long-lived radioactive wastes originating from a fusion reactor can be effectively limited.

This is not possible for fission reactors, in which radioactive wastes are an unavoidable by-product. This fact is, in our opinion, one of the distinctive points for fusion power.

Most part of high radioactive waste from a fusion reactor will come from first-wall and blanket components, being these ones the most flux-exposed structures. One of the main goals of the materials research for fusion is the development and selection of alloys with good thermomechanical and physical properties, coupled with low-activation characteristics too. We mean, by low-activation, the property of a material of producing a limited quantity of dangerous radioactive nuclides, when exposed to a neutron flux.

Neutron-induced radioactivity in a first-wall alloy, in fact, is greatly influenced by the concentration of its composing elements; many authors⁴⁻⁵ have classified the chemical elements according to the different levels of induced radioactivity when exposed to a first-wall neutron flux in a fusion reactor. The most critical elements have been identified, while other ones with low activation properties have been recommended.

Titanium-based alloys, according to the most recent results, seem to be very interesting materials, due to the low induced radioactivity of their main constituent.

The definition of low-activity, however, depends on the planned management and disposal procedures for the reactor radioactive wastes. One of the most important results of the recent research in this field can be summarized as follows: the same procedures followed for the management and disposal of fission wastes will probably be adopted for fusion wastes⁶. This means the burial of the high-radioactive wastes in a Deep Geological Repository (DGR), after a period of decay in an intermediate storage within the plant, in order to eliminate the activity coming from the medium- and short-lived isotopes.

Other proposals were formulated in the past, dealing with the recycling of the materials or their burial in near-surface repositories; these appear to be not practicable for a first-wall component, as far as the European situation is concerned.

The low-activity limits that can be defined, in the case of burial in a DGR, are based on the acceptance criteria of the repository sites and on the safety precautions to follow during the transport of the component from the plant to the repository.

Acceptance criteria vary from one site to another, but they are essentially focused on the decay heat, that is, the thermal power density due to nuclear decay reactions. A maximum value of 10 W/m³ can be indicatively fixed⁷.

Safety procedures during the handling and transport of irradiated materials are mainly limiting the dose equivalent rate. According to the IAEA regulations, radioactive materials can be transported and handled for short periods in appropriate containers by the personnel

if the dose equivalent rate at the surface of the container does not exceed 2 mSv/h; this means, taking into account the standard shielding of the container, a contact dose rate at the surface of the material of 20 mSv/h. Both these limits have to be satisfied after a decay period comparable to the plant lifetime (e.g. 30-50 years).

We have simulated the irradiation in a fusion reactor of a Ti-6Al4V alloy, as a first-wall component. The length of exposure was 5 years, with a neutron wall loading of 2 MW/m². Some other alloys, among those currently proposed for the first wall, have been examined for comparison purpose: they are the austenitic steels AISI 316L and PCA, the martensitic steels MANET and FV448 and the low-activation austenitic chromium-manganese steel AMCR 0033. The vanadium alloy V-15Cr-5Ti has been considered too (see compositions in table 1).

The induced radioactivity analysis has been performed with the ANITA code⁸: some results are shown in table 2. If we compare the activation of the alloys with the previously defined low-activity limits for DGR, we see that none of the steels can be accepted. This is true even for the low-activation one AMCR 0033, which decays below the stated limits after approximately 80 years of intermediate decay. For the other steels, many centuries of decay would be necessary. In that case, of course, the component is processed for repository adopting more complicated safety procedures: a careful selection of the characteristics of the geological site could also be necessary.

As far as the non-ferrous alloys are concerned, we see that they easily fulfil the low-activity requirements. In particular, Ti-6Al-4V (see fig. 1) shows a decay heat under 10 W/m³ after less than 5 years of decay, while, to have a dose rate below 20 mSv/h, 30 years of decay are needed.

We can positively conclude that, unlike for steels, no composition adjustment is needed for our Ti-6Al-4V alloy. This material is a rather good candidate for a fusion reactor first wall, as far as its induced radioactivity is concerned.

3. Material.

The material investigated in this note is a Ti-6Al-4V alloy, made by ThyssenEdestahlwerke AG (Krefeld, Germany), under the designation "Contimet AIV64". The composition

(weight %) is shown in table 1. This is a commercial composition; with respect to the E.L.I.-grades (Extra Low Interstitial), this alloy has higher strength and lower ductility properties. Bars of 60 mm diameter were delivered in the forged and annealed condition. The micrograph of a transverse section of the bar shows the typical ($\alpha+\beta$) microstructure of the Ti-6Al-4V alloy (see fig. 2).

4. Heat treatments and microstructure.

Unmachined rough samples taken from the bar were heat-treated under argon atmosphere, to avoid the pick-up of interstitials, which would change the mechanical properties in a relevant way.

Two types of structures were obtained according to different heat-treatment conditions:

a) The fully recrystallized annealed condition (RA-type).

The structure has equiaxed α -grains with the β -phase at the grain boundaries, mainly at the triple points (fig. 3). The advantage of this structure is its stability at higher temperatures. The conditions of heat treatment are: 4 hours at 930 °C and a very slow furnace cooling.

b) The solution treated and aged condition (ST A-type).

The two phases are primary α and a very fine ($\alpha+\beta$) mixture, which causes the strengthening effect. The latter phase is so fine to be not visible by an optical microscope (fig. 4). This structure is limited at high temperature, because it can become over-aged: the mechanical properties are however interesting.

The conditions of heat treatment are: 0.5 hours at 930 °C and quench in H₂O (solution treatment) followed by a 0.5 hours aging at 540 °C and furnace cooling.

5. Tensile testing.

Three parameters have been changed during the mechanical characterization of the alloy:

- Structure: RA and STA conditions;
- Temperature: 20°, 400° and 800 °C;
- Strain rate: $4.2 \cdot 10^{-1}$, $4.2 \cdot 10^{-3}$, $4.2 \cdot 10^{-5} \text{ s}^{-1}$.

The initial results are collected in table 3; the following quantities have been determined:

$S_{0.2}$ = Elastic offset limit stress at 0.2% plastic strain

S_u = Ultimate stress

e_{pu} = Plastic uniform elongation

e_{pb} = Plastic elongation at breaking point

It can be seen from table 3 that all the three parameters (structure, temperature and strain rate) have a great influence on the mechanical properties. We will now examine in some detail the effect of each parameter.

5.1 Influence of structure.

The ratios of the mechanical properties of the STA condition, versus the RA condition, are put in table 4. The strengthening effect and loss of ductility are already visible at 20 °C, and even more pronounced at 400 °C; for both temperatures, the effect is stronger at lower strain rates.

At 800 °C the situation is reversed, due to the superplasticity effect, especially at lower strain rates. This effect is interesting for the production of the first-wall components: their complex shapes can be produced at high temperatures and then used at far lower ones. This superplasticity effect is more important in the STA-condition.

5.2 Influence of the strain rate.

The mechanical properties, normalized with respect to the fast strain rate of $4.2 \cdot 10^{-1} \text{ s}^{-1}$, have been reported in table 5. It can be seen that a decrease of the strain rate causes, in

general, lower strength and higher strain, as expected. At 800 °C this effect becomes very marked, especially with a strain rate of $4.2 \cdot 10^{-2} \text{ s}^{-1}$, due to the superplasticity effect (see also fig. 5).

5.3 Influence of temperature.

The mechanical properties, normalized against the properties at room temperature (20°C), are listed in table 6. The effect of higher temperature, namely lower strength and higher ductility, is very relevant, both at 400 °C and 800 °C.

6. Conclusions.

Titanium alloys can be good candidates as fusion reactors structural materials, due to their interesting properties.

Neutron-induced radioactivity in a Ti-6Al-4V alloy, when exposed to the neutron flux at a fusion-reactor first wall, is low enough to permit realistic hypotheses of management and disposal of radioactive wastes from a fusion reactor. On the contrary, this is not verified with presently available steels.

The mechanical properties of two types of structure of a Ti-6Al-4V alloy were investigated: the fully recrystallized annealed condition (RA-type) and the solution treated and aged condition (STA-type); influence of strain rate and temperature has also been taken into account.

The superplasticity of the alloy has turned out to be a very interesting property, in view of the production of complex shapes for the first wall components of a fusion reactor.

References

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' Ti-6Al-4V 2 MW 5Y '

5.00 (y) (Fluxes):

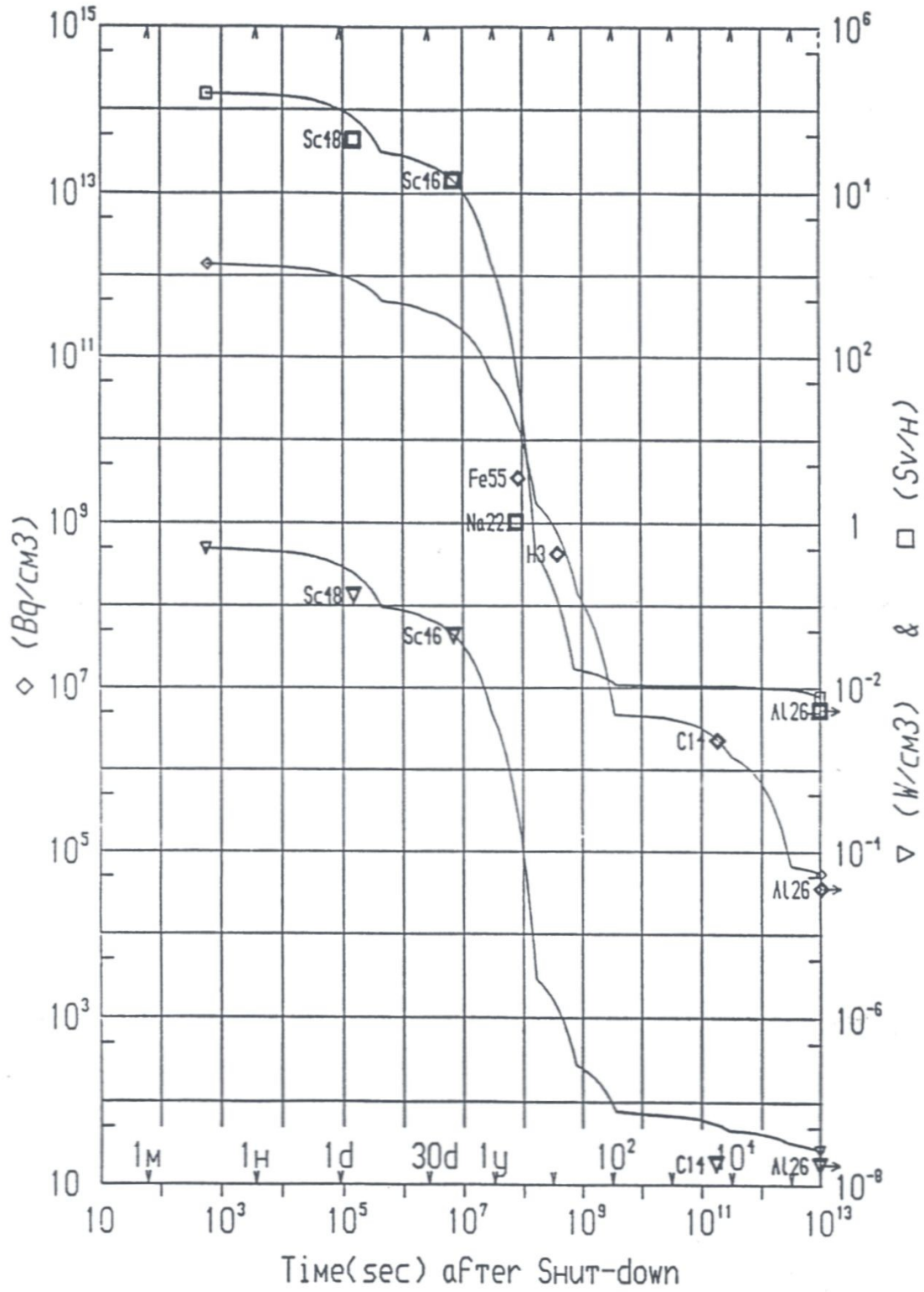


Figure 1: Induced radioactivity in a Ti-6Al-4V alloy after 5 years of exposure in a fusion reactor first wall.



Figure 2
Microstructure in the forged and annealed condition (as delivered state). (x 500)

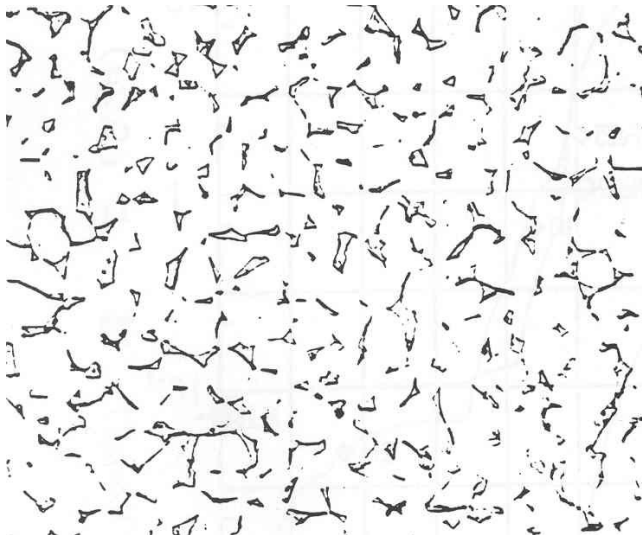


Figure3
Microstructure in the fully recrystallized annealed condition (RA-type). (x 500)
Alpha phase is white
Beta phase is dark

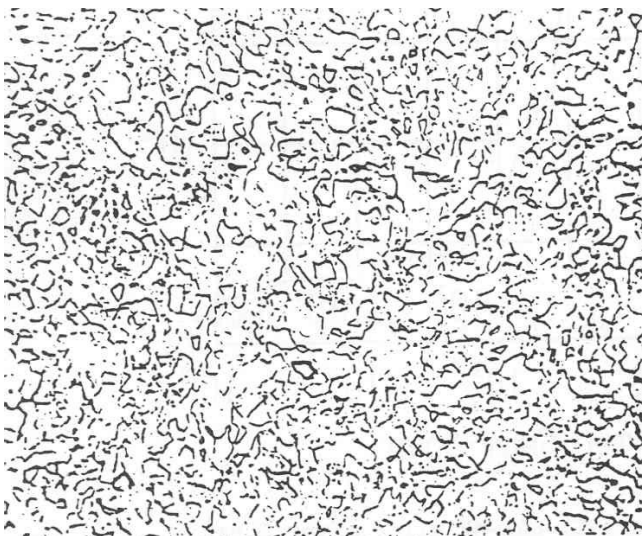


Figure 4
Microstructure in the solution treated and aged condition (STA-type). (x 500)

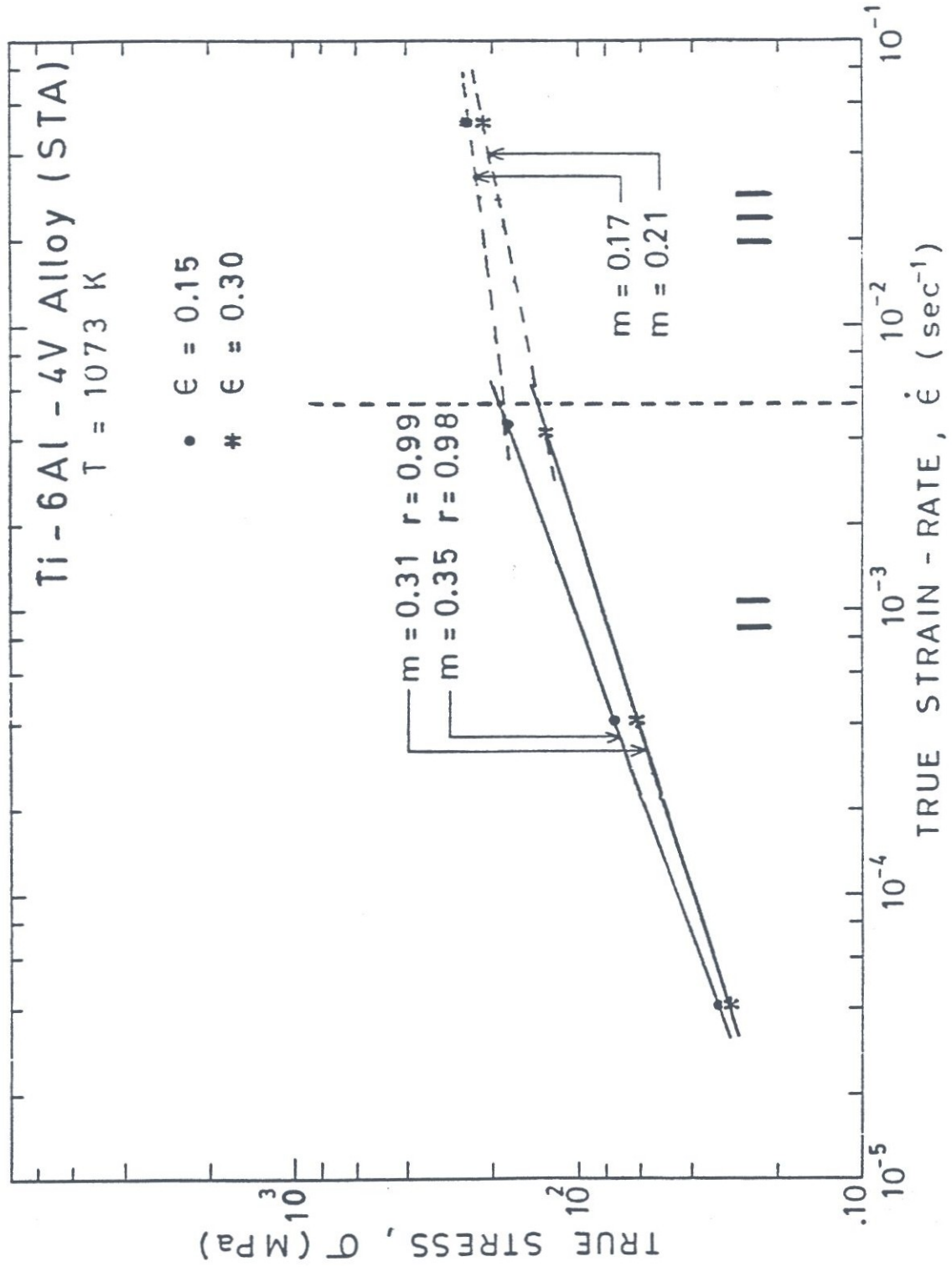


Fig. 5: Stress-strain diagram for the ti-6Al-4V alloy.

Table 1- Composition of some fusion reactor structural materials (mass%)

ELEM.	AISI316L	PCA	MANET	FV448	AMCR 0033	Ti6Al4V	V15Cr5Ti
Fe	bal.	bal.	bal.	bal.	bal.	0.25	--
C	0.024	0.05	0.12	0.15	0.1	0.08	--
Cr	17.44	14.0	10.3	11.3	10.12	--	15.0
Ni	12.32	12.2	0.60	0.75	0.1	--	--
Mn	1.81	1.8	1.15	0.8	17.5	--	--
S	0.002	0.009	0.005	0.01	0.008	--	--
P	0.027	0.027	0.005	0.01	0.016	--	--
Mo	2.5	0.05	0.65	0.66	0.06	--	--
Al	--	0.001	--	0.005	0.0025	6.0	--
Ti	--	0.24	--	--	--	bal.	5.0
Cu	0.2	--	0.02	0.01	0.06	--	--
V	--	0.04	0.20	0.25	0.02	4.0	bal.
Si	0.46	0.09	0.005	0.4	0.55	--	--
N	0.06	0.01	0.03	0.06	0.19	0.05	--
Sn	--	0.05	--	--	--	--	--
Nb	0.01	--	0.15	--	--	--	--
O	--	--	--	--	--	0.20	--
Co	0.17	--	0.02	--	--	--	--
W	--	--	--	0.02	--	--	--

Table 2 – Neutron induced radioactivity in first-wall alloys for fusion reactors.

ALLOY	DECAY HEAT after 50 years of decay (W/m ³)	DOSE RATE after 50 years of decay (mSv/h)	DECAY TIME needed to fulfill both the activity limits (years)
AISI 316L	71.9	12200	> > 10 ³
P.C.A.	18.0	3700	> 10 ³
MANET	8.0	1340	10 ³
FV 448	2.7	321	> 10 ³
AMCR 0033	0.96	82	80
Ti-6Al-4V	0.20	12.2	30
V-15Cr-5Ti	0.15	5.8	30
Low-Activity Waste	< 10	20	< 30 - 50

Table 3 – Tensile properties of Ti-6Al-4V Alloy

Temp. °C	Cross head velocity mm/min	Strain rate sec ⁻¹	Recrystallized Annealed (RA)				Solution Treated + Aged (STA)			
			S _{0.2} MPa	σ _u MPa	ε _{pu} %	ε _{pb} %	S _{0.2} MPa	S _u MPa	ε _{pu} %	ε _{pb} %
20	50	4,2.10 ⁻¹	981	1002	2.2	11.6	1248	1304	1.9	9.7
	0.5	4,2.10 ⁻³	889	929	5.7	16.4	1126	1196	2.9	10.6
	0.005	4,2.10 ⁻⁵	822	895	10.1	18.8	1107	1207	4.3	11.1
400	50	4,2.10 ⁻¹	542	619	11.5	20.7	773	883	4.4	12.8
	0.5	4,2.10 ⁻³	458	581	15.8	23.0	687	886	5.2	15.6
	0.005	4,2.10 ⁻⁵	467	633	16.7	24.4	706	913	5.7	17.8
800	50	4,2.10 ⁻¹	272	288	7.1	55.0	303	313	4.2	55.5
	0.5	4,2.10 ⁻³	151	167	1.0	95.0	137	162	2.0	165
	0.005	4,2.10 ⁻⁵	47	59	1.3	372	20	28	3.4	605

Table 4 – Ratio of STA-condition / RA-condition

Temp. °C	Gross head velocity (cm/min)	$s_{0.2}$	s_u	e_{pu}	e_{ph}
20	50	1.27	1.30	0.86	0.84
	0.5	1.27	1.29	0.51	0.65
	0.005	1.35	1.35	0.43	0.59
400	50	1.43	1.43	0.38	0.62
	0.5	1.50	1.52	0.33	0.68
	0.005	1.51	1.44	0.34	0.73
800	50	1.11	1.09	0.59	1.01
	0.5	0.91	0.97	2.00	1.74
	0.005	0.43	0.47	2.62	1.63

Table 5 – Strain-rate sensitivity (Properties normalised with respect to $\dot{\epsilon}' = 4,2 \cdot 10^{-1} \text{ s}^{-1}$)

Temp. °C	Decrease of $\dot{\epsilon}$	Recrystallised Annealed (RA)				Solution Treated, Aged (STA)			
		$s_{0.2}$	s_u	e_{pu}	e_{pb}	$s_{0.2}$	s_u	e_{pu}	e_{pb}
20	10^{-2}	0.91	0.93	2.59	1.41	0.90	0.92	1.53	1.09
	10^{-4}	0.84	0.89	4.59	1.62	0.89	0.93	2.26	1.14
400	10^{-2}	0.85	0.94	1.37	1.11	0.89	1.00	1.18	1.22
	10^{-4}	0.86	1.09	1.45	1.18	0.91	1.03	1.30	1.39
800	10^{-2}	0.56	0.58	0.14	1.73	0.45	0.52	0.48	2.97
	10^{-4}	0.17	0.20	0.18	6.76	0.07	0.09	0.81	10.9

Table 6 – Influence of temperature (Properties normalised with respect to T = 20°C)

Influence temper. at T (°C)	cross head velocity		Strain rate $\dot{\epsilon}$	Recrystallised Annealed (RA)				Solution Treated Aged (STA)			
	cm/min	sec ⁻¹		$s_{0.2}$	s_u	e_{pu}	e_{pb}	$s_{0.2}$	s_u	e_{pu}	e_{pb}
400	50	$4,2 \cdot 10^{-1}$	0.55	0.62	5.23	1.78	0.62	0.68	2.32	1.32	
	0.5	$4,2 \cdot 10^{-3}$	0.52	0.63	2.77	1.40	0.61	0.74	1.79	1.47	
	0.005	$4,2 \cdot 10^{-5}$	0.57	0.71	1.65	1.30	0.64	0.76	1.33	1.60	
800	50	$4,2 \cdot 10^{-1}$	0.28	0.29	3.23	4.74	0.24	0.24	2.21	5.72	
	0.5	$4,2 \cdot 10^{-3}$	0.17	0.18	0.18	5.79	0.12	0.14	0.69	15.57	
	0.005	$4,2 \cdot 10^{-5}$	0.06	0.07	0.13	19.79	0.02	0.02	0.79	54.5	