ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 308–312

journal of nuclear materials

Assessment of tungsten for use in the ITER plasma facing components [1]

J.W. Davis [a,*], V.R. Barabash [b], A. Makhankov [c], L. Plöchl [d], K.T. Slattery [a]

[a] *The Boeing Company, P.O. Box 516, St. Louis, MO 63166-0516, USA*
[b] *ITER Joint Central Team, Boltzmannstr. 2, 85748 Garching, Germany*
[c] *D.V. Efremov Institute of Electrophysical Apparatus, 189631 St. Petersburg, Russian Federation*
[d] *Plansee AG, A-6600 Reutte, Austria*

Abstract

Tungsten is one of the candidate armor materials for the plasma facing components of the International Thermonuclear Experimental Reactor (ITER). For the present reference design, tungsten has been selected as armor for the divertor upper vertical target, dome, cassette liner, and for lower baffle because of its unique resistance to ion and charge-exchange particle erosion in comparison with other materials. The issues related to the use of tungsten in ITER are described in this paper. The different tungsten grades (pure, dispersion strengthened and cast alloys) which are being considered as candidate materials are evaluated. A comparative analysis has been made of the mechanical properties of the various tungsten grades in different thermomechanical conditions, including the impact of irradiation effects. The different tungsten armor design solutions are also described.

1. Introduction

Tungsten has a high energy threshold for physical sputtering ($E_{\text{th}} \sim 200$ eV for D) and does not form hydrides or co-deposits with tritium. In addition, it has the highest melting point of all metals, the lowest vapor pressure, good thermal conductivity, and high temperature strength. This combination of physical and mechanical properties makes its use as a coating on the high heat flux components very attractive. Fig. 1 shows the regions where tungsten is currently being considered in ITER plasma facing components (PFCs). The tungsten thicknesses being considered range from 4 to 30 mm. Table 1 compares the operating conditions for tungsten in different parts of the ITER plasma facing component. From this table it can be seen that the dome and vertical target will receive the brunt of the plasma disruption and, as a result, will need to be on the order of 10 mm thick; while the liner will receive secondary energy from the disruption. The tungsten in the liner serves a dual function. First, behind the liner are the pump ducts. The liner is designed to shield these ducts from the line-of-sight flow of particles, hence the Z shape shown in Fig. 1. The second objective is to have a hot liner surface, on the order of 500–1200°C, to prevent carbon co-deposition in cold areas. Since the heat loads in this area are relatively low (<1 MW/m^2), thicker sections are used (on the order of 30 mm) to increase the ΔT through the material. During transient events the surface temperature of tungsten could approach the melting point.

In all of the components shown in Table 1, the tungsten is bonded to an actively cooled copper alloy heat sink and has no structural function. However, possible cracking and delamination could lead to the loss of the energy transfer and, therefore, both have to be avoided. Additionally, tungsten has a large mismatch in coefficient of thermal expansion with the copper heat sink. To reduce the thermal stresses, the proper selection of the tungsten armor tile geometry is needed.

---

[*] Corresponding author. Tel.: +1 314 233 6200; fax: +1 314 234 4506; e-mail: john.w.davis@boeing.com.

[1] #AC-3013 with Sandia National Laboratories.

0022-3115/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 2 8 5 - 2

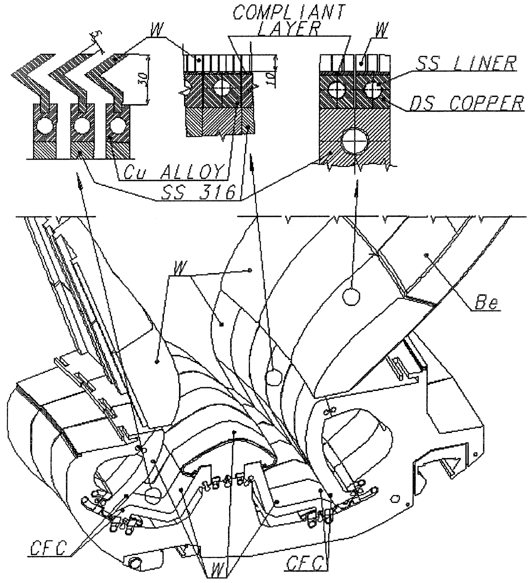

Fig. 1. General view of the lower part of ITER with W armoured components.

2. Analysis of the tungsten database

Several types of tungsten are currently being considered for ITER application: pure (pressed/sintered/hot-worked), dispersion-strengthened (mechanically alloyed/pressed/sintered/hot-worked), and cast alloy.

Pure sintered tungsten produced by powder metallurgy is the most readily available and cheapest grade of tungsten but has a low recrystallization temperature in relation to the dispersion strengthened alloy W–1% La_2O_3. Dispersion strengthening is achieved by using an insoluble oxide – in this case La_2O_3. To maximize the efficiency of the La_2O_3 dispersoids, a combination of thermomechanical treatments are used to refine the microstructure and homogeneity of the dispersiods. Depending on the amount of hot work, the recrystallization temperature of W–1% La_2O_3 can be raised considerably, up to more than 1700°C in the case of thin wire. The high recrystallization temperature of W–1% La_2O_3 shown in Fig. 2 is a result of the interaction of the dispersoids and the dislocations during the thermomechanical treatment – the higher the amount of hot work, the finer dispersoid particles are formed during annealing. During recrystallization, these particles prevent secondary grain growth. Also W–1% La_2O_3 alloy has significantly higher mechanical strength in the recrystallized condition in comparison with pure W.

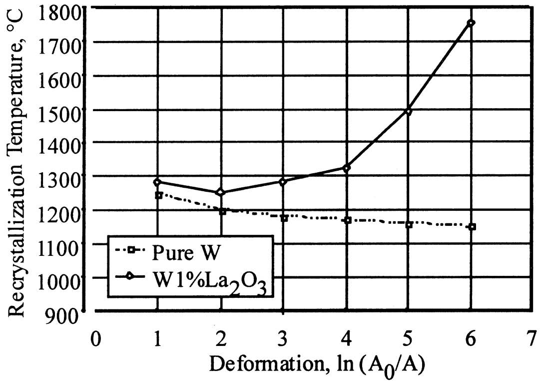

Fig. 2. Effect of cold work on the recrystallization of pure W and W–1% La_2O_3.

Cast tungsten is a relatively new product. In the past cast tungsten, because of its large grain sizes, has typically been too brittle to process into sheet or plate. However, the Russian Federation has recently developed a weakly alloyed tungsten (W–Mo–Y–Ti) designated as W-13I. This material is produced by vacuum melting and then cold deforming. The addition of reactive elements such as yttrium and titanium reduces the amount of free oxygen and carbon, resulting in improved mechanical properties.

All three of these materials show the pronounced ductile-to-brittle transition typical for tungsten and

Table 1
Operating conditions of tungsten armor in ITER PFC

Component	W form and thickness (mm)	Heat flux (MW/m^2)	Possible transient events	Fluence [a] (dpa/He appm)	Temperature (°C), Steady state/transient
Lower baffle	Macrobrush ~ 4 × 4 × 10-10 × 10 × 10, lamella	1.5–3	Disruption, VDE	~ 0.5/0.3 [b]	~ 200–600/up to MP [b]
Vertical target	Macrobrush ~ 4 × 4 × 10-10 × 10 × 10 or rods; lamella	2–5	Disruption	~ 0.3/0.2 [b]	~ 200–600/up to MP
Dome	Macrobrush ~ 4 × 4 × 10-10 × 10 × 10 or rods; lamella	2–5	Disruption, VDE	~ 0.5/0.3 [b]	~ 200–600/up to MP
Liner	Bend plate 5 × 30 × 50	0.1–1	Secondary Disruption	~ 0.1–0.3/ 0.1–0.2 [b]	~ 200–1200/up to MP

[a] ITER BPP, without any component replacement.

[b] MP – melting point.

other bcc metals. For the considered materials the ductile-to-brittle transition temperature (DBTT) is well above room temperature and ranges between 250°C and 600°C.

The mechanical properties of tungsten are a function of the production history, alloying elements, impurities, and thermomechanical treatment. This dependence can be seen in Fig. 3 [1–3]. The values of pure tungsten in the annealed/recrystallized and in the stress-relieved conditions are the average of measurements performed on different materials with different test methods. From this figure it can be seen that there is a significant difference between the stress-relieved and recrystallized powder metallurgy tungsten. Also the strength of the W–1% La_2O_3 and W-13I fall between the two conditions. The higher value is likely due to differences in test procedures and the amount of cold work. Fig. 4 shows the data for total elongation of these materials. Pure tungsten in a cold-worked and stress-relieved condition has a higher strength and a lower ductility than recrystallized tungsten. The total elongation of W–1% La_2O_3 in the stress-relieved condition is higher than that of pure tungsten in the same condition. For temperatures above 1400°C, the differences in elongation are slightly misleading in that some of the stress-relieved materials have recrystallized while others are partially recrystallized. The important point is that they are all ductile.

In bcc metals, neutron irradiation typically causes embrittlement. In work done by Alexandrov [4], samples of sintered tungsten were irradiated at 100°C up to a dose of 4.2×10^{19} n/cm^2. As typical in low temperature irradiation, hardening and embrittlement were observed. A similar behavior was found by Steichen [5]. In this study tungsten samples were irradiated at 371–380°C up to fluence 0.5–0.9 × 10^{22} n/cm^2 (~5–9 dpa). Irradiation at this condition again increased the strength and decreased the ductility of material. The decreased ductility was also observed at T_{irr} and T_{test} equal to ~300°C [6]; the tungsten specimens had brittle fracture at stress levels 5–10 times lower than specimens tested in the unirradiated condition. Fractographic examination of the irradiated specimens indicated that embrittlement is accompanied by a tendency toward subgrain and grain boundary fracture. These data differ from the data reported in [4,5], but the difference can be explained by the different chemical compositions of tungsten alloys used.

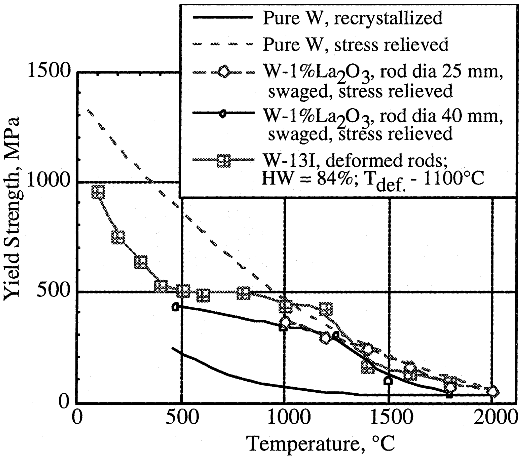

Fig. 3. Yield strength of pure W (average values) [1], W–1% La_2O_3 [2], and W-13I [3].

To summarize the data on influence of neutron irradiation on mechanical properties of tungsten, the data on DBTT could be used. The magnitude of the increase in the DBTT appears to depend on the fluence and on the irradiation temperature. A comparison of the neutron irradiation influence on pure W and W–10% Re alloy [4,5,7] shows that irradiation leads to a more rapid and severe embrittlement for the W–10% Re alloy (see Fig. 5). The results of this study are somewhat surprising: the alloying element rhenium is effective in suppressing the DBTT to around room temperature and improves the fabricability and weldability in pure tungsten. Based on this study and similar work in molybdenum, it appears that, while this alloying element is beneficial in unirradiated tungsten, it is a detriment in irradiated tungsten. This is one of the reasons why rhenium-containing alloys are not being considered for ITER.

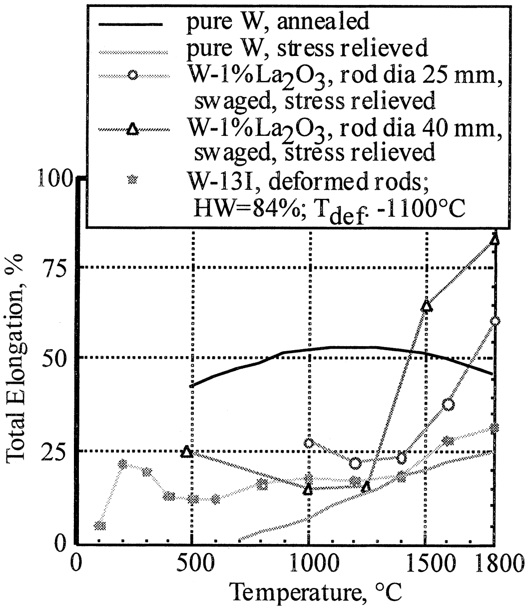

Fig. 4. Total elongation of pure W (average values) [1], W–1% La_2O_3 [2], and W-13I [3].

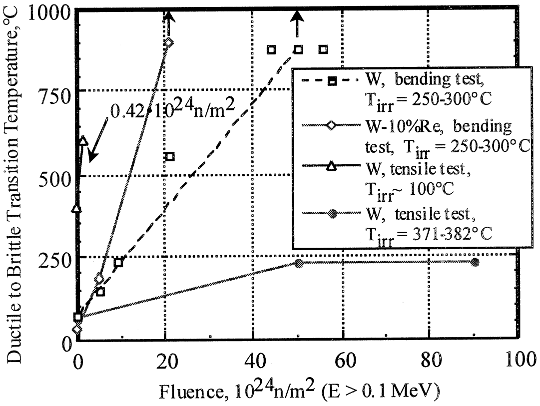

Fig. 5. Influence of neutron irradiation on the DBTT of pure W and W–Re alloy, [4,5,7].

3. Unique protection schemes

As discussed earlier, tungsten is bonded to an actively cooled copper substrate. The water inlet temperature to the copper is nominally 140°C. Depending on the heat flux, the interface temperature between the copper and the tungsten can be on the order of 160–200°C, while the surface of the tungsten can be between 200 and 1200°C (see Table 1). This large variation in temperature can lead to large stresses in the tungsten as a result of differences in the thermal expansion (4×10^{-6}/°C for tungsten versus 18×10^{-6}/°C for copper) between the two materials. To reduce these stresses, a variety of fabrication approaches are being investigated.

The first of these methods, referred to as the macrobrush, is being developed by Plansee AG [8]. This approach uses small pieces (4.5 × 4.5 × 10 mm) of tungsten with pure copper cast around them. After the pure copper is cast around the tungsten, the copper side of the combination is electron beam-welded to CuCrZr or DS copper substrates. The combination of the small size of tungsten brush and the surrounding soft-cast copper, which yields easily, lowers the residual stresses at the bond line and in the brittle tungsten. This concept has been tested in the CEA-Le Creusot high heat flux facility at both 9 and 16 MW/m^2 for up to 1000 cycles [8]. During the heat flux test of the EU/Plansee small-scale divertor mock-up [8], it was observed that the W–1% La_2O_3 macrobrush cubes did not recrystallize after 1000 cycles at 18 MW/m^2, leading to surface melting and a tungsten-copper interface temperature of 800–900°C. Cracks in the tungsten between heating periods have not been observed either. A similar approach but with tungsten tile dimensions of 10 × 10 × 10 mm has been applied in Efremov Institute. A small size mock-up with four tiles has survived as many as 2000 cycles at 16 MW/m^2 without damage.

A second approach is to use a lamella-type structure being developed by the Efremov Institute [9]. This approach (shown in Fig. 6) uses 5-mm-thick plates, again with pure copper cast around tungsten plates. The cast combination is then brazed to the copper alloy heat sink using a CuInSnNi filler metal. Again the residual stresses at the bond line are lowered by surrounding the tungsten with a thin layer of soft cast copper. Additionally, casting the copper to the large tab on the tungsten greatly increases the bond surface area. This combination was tested at 15 MW/m^2 and 2150 cycles. Small surface cracks were observed in the tungsten, and the soft copper experienced excessive creep as a result of overheating; however, there was still a good bond at the joint.

A third approach, which is being pursued in the US, is tungsten brush structure (patent pending), which uses small (1.58–3.16 mm diameter) tungsten welding electrodes and soft copper [10]. The tungsten is held in place using a welded honeycomb core and is joined to the copper alloy heat sink using low temperature (450–550°C) diffusion bonding of copper to copper (see Fig. 7). In addition to the small size of the tungsten rods

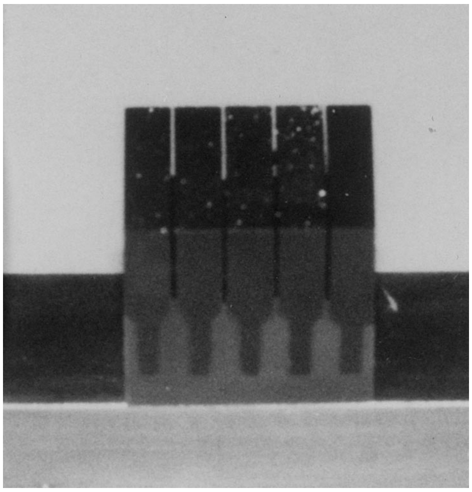

Fig. 6. Lamellar W/Cu mock-up [9].

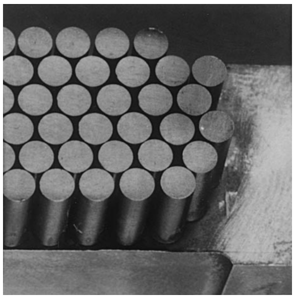

Fig. 7. US/Boeing direct diffusion bond brush.

and the use of soft pure copper, the low bonding temperature further reduces the residual stresses. Mock-ups of the plasma-sprayed and direct diffusion-bonded techniques have been fabricated and are currently undergoing high heat flux testing in the Electron Beam Test Stand at Sandia National Laboratories in Albuquerque, NM, USA.

4. Conclusions

Three different tungsten grades have been evaluated for possible use in ITER plasma facing components. Key in material selection are the features of the operational conditions and design requirements for ITER. Generally, there is a very limited database for the tungsten grades within the temperature range of interest to ITER. Therefore, the material selection must be based mainly on limited information. Among the different tungsten grades, W–1% La_2O_3, W-13I, and pure W in the cold-worked condition are all considered candidates. For the final selection, additional R&D is needed. Tungsten in the recrystallized condition could not be used because of its low strength, low thermal shock resistance, and high DBTT. Since tungsten grades are brittle in the low temperature ranges of armor operation (unirradiated and irradiated), it seems reasonable to use a form without any possible crack initiators. To avoid loss of material due to delamination, the orientation of the texture (rolling or extrusion direction) needs to be perpendicular to the surface of the tungsten/copper joints.

Three different plasma facing concepts using tungsten have been proposed by the ITER Home Teams with different forms of tungsten (rod, bar, and plate). Each appears capable of reducing the thermal stresses in the tungsten/copper joints. Very preliminary results indicate no delamination of the tungsten during testing and adequate thermal performance of tungsten/copper joints.

References

[1] J.W. Davis, ITER Material Properties Handbook, Publication Package 3, S74RE1 97-08-01W1.6, International Atomic Energy Agency, 1997.

[2] Plansee AG Product Specification for Tungsten 1% La_2O_3 Rods, 39.39.40-GR130, Part 7, Rev. 0.

[3] L. Kosachev, A. Makhankov, private communication, 1997.

[4] I. Alexandrov, I.V. Gorynin, Metallovedenie 22 (1979) 35.

[5] J.M. Steichen, J. Nucl. Mater. 60 (1976) 13.

[6] I.V. Gorynin, V.V. Rybin, V.R. Barabash et al., J. Nucl. Mater. 191–194 (1992) 421.

[7] P. Krautwasser, H. Derz, E. Kny, Influence of Fast Neutron Fluence on the DBTT of W, W10Re and W3.4Ni1.6Fe, Refractory Metals 77, p. 673.

[8] G. Vieider et al., Fusion Technology 1996, North-Holland, Amsterdam, 1997, p. 275.

[9] V.A, Belyakov, O.G. Filatov, I.V. Mazul, Development of Plasma Facing Components for ITER in Efremov Institute, to be published in: Proceedings of the 17th Symposium on Fusion Engineering, San Diego, CA USA, October 6–10, 1997.

[10] K.T. Slattery, T.N. McKechnie, Development of Tungsten Brush Structures for PFC Armor Applications, to be published in: Proceedings of the 17th Symposium on Fusion Engineering, San Diego, CA, USA, October 6–10, 1997.