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Performance of the different tungsten grades under fusion relevant power loads

A. Makhankov [a,*,1], V. Barabash [b], I. Mazul [a], D. Youchison [c]

[a] *Efremov Institute of Electrophysical Apparatus, St. Petersburg 189631, Russian Federation*
[b] *ITER Joint Central Team, Boltzmannstr. 2, Garching 85748, Germany*
[c] *Sandia National Laboratories, Albuquerque, NM 87185–5800, USA*

Abstract

The test results of several W grades at conditions typical for plasma facing component operations are summarised. These include the effects of steady-state heat fluxes (up to 43 MW/m^2), disruption simulation (up to 30 MJ/m^2 during 0.05–0.36 ms) and heat flux tests of W after disruption simulation. Representatives of the main W grades have been investigated: pure sintered W, W–Re and W–Mo cast alloys, W–1% La_2O_3, W–2% CeO_2, single crystal W, etc. The resistance to high heat fluxes strongly depends on the orientation of the W grains to incident heat flux and with proper orientation W can withstand heat fluxes up to 27 MW/m^2. After disruption simulation, intensive surface crack formation has been observed for all studied W grades except single crystal W. Severe damage after disruption and thermal fatigue loading have been observed for almost all W grades except the W–5Re–0.1ZrC alloy and W–Re single crystal. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Tungsten; Thermal load

1. Introduction

Tungsten is being considered as an armour material for plasma facing components (PFC) of the next step fusion devices such as the divertor for ITER–FEAT, [1]. The main advantages of W are low erosion, high melting point and low tritium retention. Different W grades produced by powder metallurgy, casting, plasma spray, chemical vapour depositions are currently available from industry. These materials have different thermomechanical properties and as a result their performance at expected heat flux conditions could be significantly different. For fusion application the most essential properties are thermal conductivity, ductility, structural stability at elevated temperature, stability of properties under neutron irradiation and activation, [2]. The first three properties effect the thermal fatigue behaviour and thermal shock resistance of the material.

In the various PFCs W armour will be subjected to different types of heat fluxes: steady-state fluxes 1–10 MW/m^2, and in some cases up to 20 MW/m^2, thermal transient loads (e.g., disruptions with energy density $\sim$1–30 MJ/m^2) and combined effects. There is a lack of data on the performance of the different W grades at these conditions. However, these data are key factor to be considered during the selection of the W grades.

In this paper, the results of a study of the behaviour of different W grades at representative ITER–FEAT divertor heat flux loading is presented.

2. Materials and experimental procedure

Several W grades produced by different methods (sintering of powder, casting) and single crystal W alloys have been investigated. The chemical composition of these materials is included in Table 1.

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[*] Corresponding author. Tel.: +7-812 462 7834; fax: +7-812 464 4623.

E-mail addresses: amakh@sintez.niiefa.spb.su, barabav@itereu.de (A. Makhankov).

[1] Tel.: +49-89 3299 4144; fax: +49-89 3299 4163

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Table 1
Studied tungsten grades

Material class	Tungsten grade	Chemical composition (wt%)	Material form
Single crystal (SC)	Pure W, orientation ⟨1 1 0⟩	W, 99.9%	rod
	Pure W, orientation ⟨1 1 1⟩	W, 99.9%	rod
	W–0.02Re alloy, orientation ⟨1 1 1⟩	W+0.02% Re	rod
Cast alloys	W–5Re-0.1ZrC	W+5% Re+0.1% ZrC	rod
	W–4Re-0.1HfC	W+4% Re+0.3% Mo+0.1% HfC	rod
	W–1Mo	W+0.5% Mo	rolled sheet 3 and 5 mm
	W–1Mo	W+1.3% Mo	rod
Sintered	WMP – pure sintered tungsten	W, 99.9%	rod
	WMP – pure sintered tungsten	W, 99.9%	rolled sheet 3 and 5 mm
	WL10 (Plansee AG)	W + 1% La_2O_3	rod
	WC20 (Plansee AG)	W + 2% CeO_2	rod

For ITER–FEAT PFCs W will be introduced in the form of tiles (the size and geometry depending on the specific design) which are joined to the cooled heat sink structure. Also for this study the W samples were in the form of tiles joined to a Cu heat sink. Thus the temperature distributions and thermal stresses are similar to those expected for ITER–FEAT.

The following experiments have been performed:

- Thermocycling tests have been carried out in the Efremov Institute at the TSEFEY e-beam facility and in Sandia National Laboratory, Albuquerque, at the EBTS facility. The heat flux was in range 20–43 MW/m^2.
- Disruption simulations have been performed in the VIKA plasma gun facility, Efremov Institute, and in the 2MK-200 plasma accelerator TRINITY. The conditions were the following: VIKA facility – pulse duration – 0.09–0.36 ms, incident energy density – 7.5–30 MJ/m^2; 2MK-200 facility – pulse duration 0.05 ms, incident energy density – 15 MJ/m^2.
- Thermocycling tests after disruption simulation have been performed in the TSEFEY e-beam facility at heat flux of 15–20 MW/m^2.

After the tests an extensive microstructural analysis of the W materials was performed.

3. Results and discussion

3.1. Behaviour of the W grades at thermocycling tests

Several mock-ups with different W grades have been manufactured and tested:

(a) Mock-ups with pure sintered and rolled W, tile's size 44 × 44 × 5 and 20 × 20 × 5 mm^3. The grain orientation in the W was parallel to the surface of the W/Cu joint and perpendicular to the applied heat flux. These mock-ups have been tested at a heat flux up to 5 MW/m^2 and for 1000 cycles. No damage was observed at this condition. However, at higher heat flux (~7.5 MW/m^2) and after 100 cycles, the delamination cracks frequently appeared inside the W tiles, which caused the surface overheating (Fig. 1(a)).

(b) A mock-up with pure sintered W, tiles 20 × 20 × 5 mm^3 has been manufactured from rod. In spite of an unfavourable orientation of the grains (perpendicular to heat flow direction), the tiles survived 2150 cycles at 16 MW/m^2 with only surface cracks of <0.5 mm on the loaded tile surface, (Fig. 1(b)).

(c) A mock-up with cast rolled W + 1.3% Mo alloy, tiles 20 × 5 × 10 mm^3 (thickness), with the grain structure orientation is parallel to incident heat flux. No damage has been detected in the W after 900 cycles at 15 MW/m^2.

(d) A mock-up with pure sintered tungsten (produced from rod), single crystal W with orientation ⟨1 1 0⟩ and W–5Re–0.1ZrC cast alloy, tiles 9.7 × 9.7 × 10 mm^3 has been tested. The grain orientation was parallel to the applied heat flux. The test condition was 16 MW/m^2, 2000 cycles. Surface cracks in the pure and single crystal W have been detected (crack length ~ 100 μm), but they did not propagate into the bulk of the material. W–5Re–0.1ZrC has no visible cracks on its surface in spite of much higher (~300–400 K) surface temperature due to lower thermal conductivity. Sintered tungsten recrystallised up to the depth of 3–4 mm from the surface but W–5Re–0.1ZrC only to a depth of 200 μm (Fig. 2). The higher resistance of W–5Re–0.1ZrC alloy against recrystallization and surface crack formation can be explained by stabilisation of the grain structure by the fine ZrC particles and by the high ductility due the presence of Re.

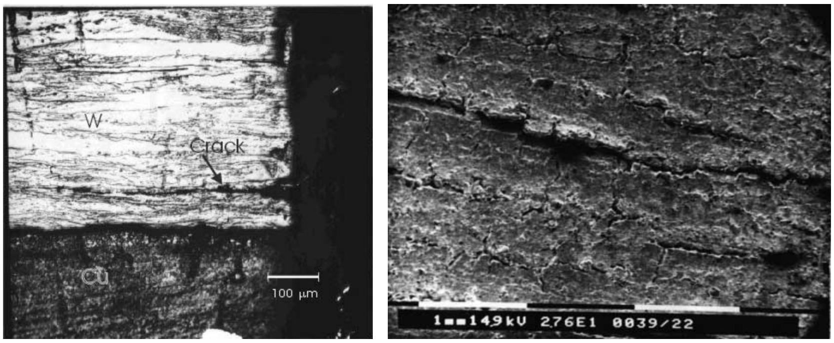

Fig. 1. Delamination of the rolled pure sintered W (a), surface cracks in pure sintered W (b).

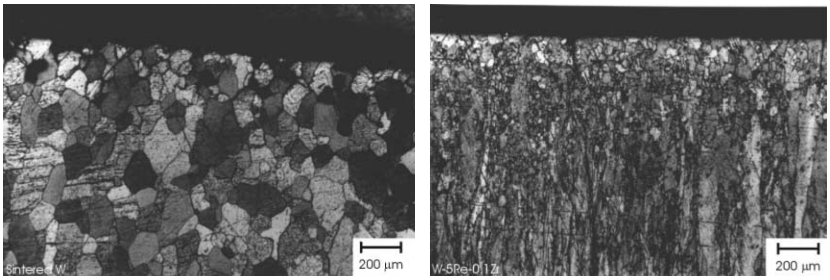

Fig. 2. Microstructure of the pure sintered W and W–5Re–0.1Zr cast alloy after 2000 cycles at 16 MW/m^2.

(e) Mock-ups with single crystal W–0.02Re alloy, orientation $\langle 1\,1\,1 \rangle$, tiles $9.7 \times 9.7 \times 10$ mm^3 were tested. Some tiles have been subjected to a heat flux of 20–43 MW/m^2 causing surface melting. The number of cycles at heat fluxes of $\sim$27 MW/m^2 were 1500. Significant creep deformation of tiles was detected and a new grain structure was produced. More detail information on the results of this test will be presented in [3].

Summarising these results, it can be concluded that all tested tungsten grades with correct grain structure orientation relative to applied heat flux direction show a rather good high heat flux performance. The more favourable orientation of grains is parallel to applied heat flux. The best tungsten grades from the thermal fatigue performance point of view are W–5Re–0.1ZrC and single crystal W–0.02 Re alloy.

3.2. Behaviour of the W grades at disruption simulation conditions

Several W grades (single crystal, W–4Re–0.1HfC cast alloy, W–1Mo cast alloy, recrystallised sintered tungsten) in form of the tiles (size $10 \times 10 \times 5$ mm^3) joined to a Cu heat sink have been tested in the VIKA facility. The texture of W tiles has been selected parallel to the plasma flow. Tungsten assemblies were subjected to 10 shots of energy density 15 MJ/m^2 and a pulse duration of 0.36 ms. The preheating temperature was chosen as 200°C (below ductile- to brittle-transition temperature, (DBTT), for most of the tungsten grades) and 600°C (above DBTT for most of the tungsten grades). Later it was turned out that the damage of the W grades does not depend on the preheating temperature.

For all tested tungsten grades, except of single crystal tungsten, surface cracking has been observed similar to results in [4,5]. For W–1Mo and W–4Re-0.1HfC the depth of the surface cracks was in the range 30–150 μm, but in the recrystallised sintered tungsten cracks have propagated through the whole thickness (5 mm) of the sample, Figs. 3 and 4(a). All the cracks found in the samples are of intergranular nature and oriented perpendicular to the loaded surface (even for recrystallised W) which reflects the stress field. Such cracks seem not to be dangerous, as they do not lead to the fracture of the armour.

The surface of the W-4Re-HfC tile has a quite different structure from other grades with a wavy surface texture (Fig. 4(b)).

The higher resistance of single crystal tungsten is explained by higher ductility in comparison with other grades (ductile at RT) and the absence of grain boundaries. Under disruption loading the tile surface layer remains as a single crystal.

Several tests have been performed in the 2MK-200 facility. Mock-ups with W tiles (size – $44 \times 44 \times 3$ mm^3)

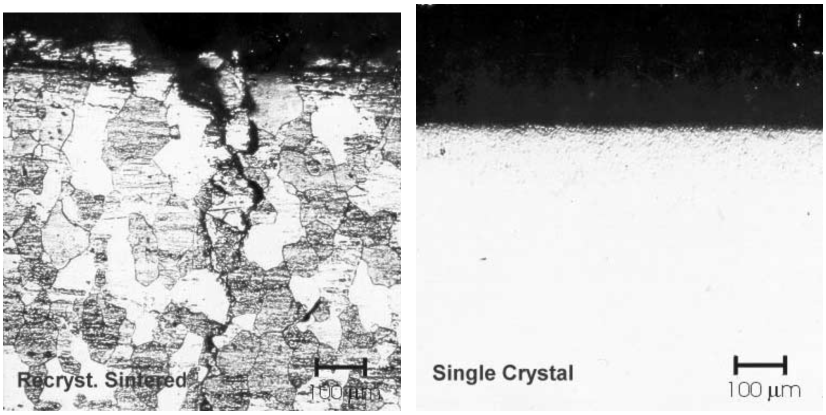

Fig. 3. Microstructure of the recrystallised sintered W (a) and single crystal W (b) and after 10 shots at 15 MJ/m^2.

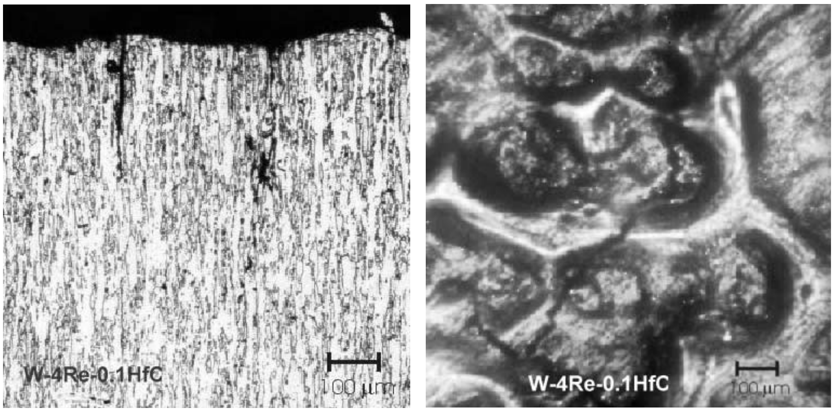

Fig. 4. Microstructure of the W–4Re-0.1HfC after 10 shots at 15 MJ/m^2.

of rolled pure sintered W and W + 0.5% Mo cast alloy have been subjected to 10 shots of 15 MJ/m^2 and for a plasma pulse duration of 0.05 ms in the presence of 5 T magnetic field. The behaviour of both grades was very similar: a lot of surface cracks perpendicular to the loaded surface and many cracks parallel to surface (along the material structure), Fig. 5. A high level of residual stresses due to large tile dimension and the tendency of rolled tungsten to delaminate could explain such a behaviour. The melt layer depth in this case was about 50 µm what is much higher than in experiments in the VIKA facility.

A few mock-ups with tiles 9.8 × 9.8 × 10 mm^3 made of pure single crystal, single crystal W–0.02Re, W–5Re–0.1ZrC cast alloy, pure sintered tungsten, W + 1.3% Mo cast alloy in cold worked and recrystallised states, WL10 $(W + 1\%\ La_2O_3)$, WC20 $(W + 2\%\ CeO_2)$ have been tested at the same conditions. Generally the behaviour of the grades was similar to the behaviour observed in previous tests: no cracks for single crystal W samples, fine mesh of the intergranular surface cracks for all other grades. The surface of the WC20 alloy looks like a solidified boiled surface. This could be explained by the presence of the CeO_2 particles, which have a lower melting temperature in comparison with pure W and these particles could be a centre of boiling.

The main conclusions from these tests are:

- All tungsten grades except for single crystal showed intergranular crack formation.
- Recrystallised sintered W has the lowest crack resistance.
- Cracks are mainly oriented perpendicular to the loaded surface and seem not to be dangerous for armour operation with proper orientation of the W grains.
- As in the thermocycling experiments, grain orientation perpendicular to the heat flow results in delamination of the rolled W.
- Dispersion strengthened W grades with the HfC, La_2O_3, CeO_2 particles typically have the wave surface structure which is caused by the lower melting temperature of these particles.

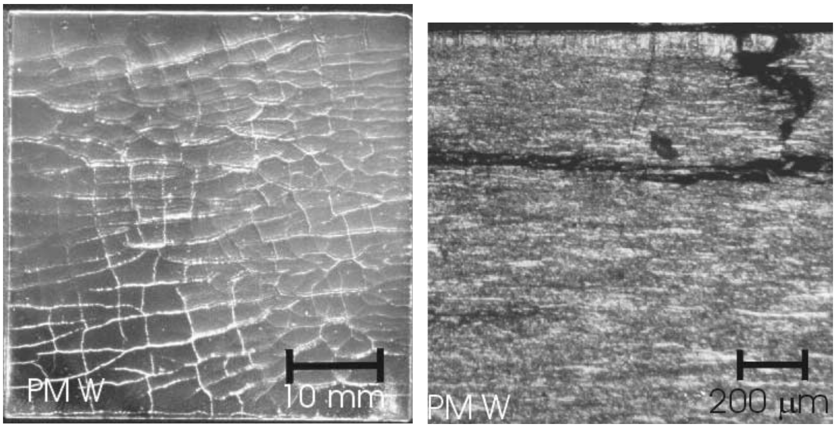

Fig. 5. Microstructure of the sintered W after 10 shots at 15 MJ/m^2.

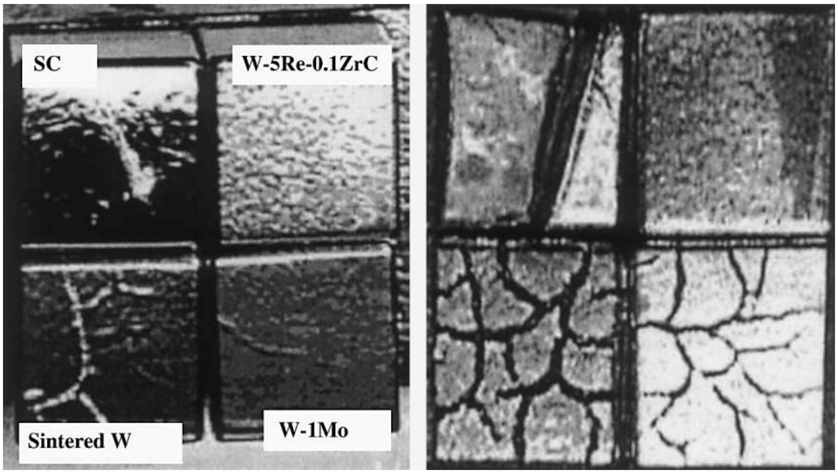

Fig. 6. Surface structure of the several W grades after disruption shorts (a) and after following thermocycling (b).

3.3. Behaviour of W grades at thermocycling after disruption

A few mock-ups with the $9.8 \times 9.8 \times 10$ mm^3 tiles (which have been subject to thermal shocks in the 2MK-200 facility) have been exposed to high heat flux up to 20 MW/m^2 at the TSEFEY facility. Generally after a few cycles at 20 MW/m^2 without disruption shots no damage in the W tiles is observed. However, after the disruption shots (which produce the significant surface damage in the materials) and after thermocycling, the behaviour of some grades was very unusual:

- For pure sintered W, pure single crystal W, W–1Mo, WL10 and WC20 alloys after these tests the severe cracks were formed (up to 10 mm through the thickness of tiles), Fig. 6;
- For single crystal W–0.02Re alloy and W–5Re–0.1ZrC cast alloy no visible cracks have been observed. The possible explanation for W–5Re–0.1ZrC cast alloy is that addition of Re, improves the ductility and fracture toughness. For W–0.02Re alloy the orientation $\langle 1\,1\,1 \rangle$ is most favourable for stress accommodation.

These results are different from the result reported in [6], where it was concluded that damage after disruption is not so crucial. The present study used higher heat fluxes, which could explain this difference.

4. Conclusion

These results show that the performance of the W grades depends on the operational conditions with be significant differences.

The proper design of the W armour (size of tiles, grain orientation) is very important for the high heat flux performance. For accommodation of the high heat flux the recommended grain orientation is parallel to the direction of the heat flow. However for this orientation surface cracks appeared on the surface of all tungsten grades at heat fluxes of about 15 MW/m^2 in thermal fatigue test, except W–5Re–0.1ZrC alloy and W–0.02 Re single crystal alloy. Rolled tungsten with texture orientation perpendicular to the heat flow direction shows the tendency of delamination at heat fluxes higher than about 5 MW/m^2.

Disruption simulation tests show that nearly all tungsten grades suffer from surface cracking except for single crystal tungsten with proper orientation. However, for grain orientation parallel to the heat flow, the cracks propagate in the same direction and are not so dangerous as they do not lead to complete fracture. Disruption loads also leads to the delamination of the rolled W tungsten with grain orientation perpendicular to the applied heat flux.

Thermal fatigue test at 20 MW/m^2 of mock-up after disruption simulation demonstrated that there is severe crack formation in almost all materials except for W–5Re–0.1ZrC alloy and W–0.02 Re single crystal alloy.

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