EUROFUSION CP(15)04/03

M. Wirtz et al.

Thermal Shock Tests to Qualify Different Tungsten Grades as Plasma Facing Material

(18th May 2015 – 22nd May 2015)
Aix-en-Provence, France

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Thermal Shock Tests to Qualify Different Tungsten Grades as Plasma Facing Material

M Wirtz[1,*], J Linke[1], Th Loewenhoff[1], G Pintsuk[1], and I Uytdenhouwen[2]

[1]*Forschungszentrum Jülich, Institut für Energie- und Klimaforschung, 52425 Jülich, Germany*
[2]*SCK•CEN, The Belgian Nuclear Research Centre, Boeretang 200, 2400 Mol, Belgium*

E-mail: m.wirtz@fz-juelich.de

PACS: 28.52.-s, 28.52.Fa, 65.40.-b, 65.40.De

Abstract
The electron beam device JUDITH 1 was used to establish a testing procedure for the qualification of tungsten as PFM. Absorbed power densities of 0.19 GW/m² and 0.38 GW/m² for an ELM-like pulse duration of 1 ms were chosen. Furthermore, base temperatures of RT, 400 °C and 1000 °C allow investigating the thermal shock performance in the brittle, ductile and high temperature regime. Finally, applying 100 pulses under all mentioned conditions helps qualifying the general damage behaviour while with 1000 pulses for the higher power density the influence of thermal fatigue is addressed. The investigated reference material is a tungsten product produced according the ITER material specifications. The obtained results provide a general overview of the damage behaviour with quantified damage characteristics and thresholds. In particular, it is shown that the damage strongly depends on the microstructure and related thermo-mechanical properties.

1. Introduction

Plasma facing materials (PFMs) for future fusion devices like ITER and DEMO have to withstand severe environmental conditions. Especially, in the region of the divertor the steady state heat fluxes will reach values up to 10 MW/m² and during short transients even up to 20 MW/m² for ≤ 10 s. On top of these steady state heat loads PFMs will be exposed to transient events (type I edge localised modes, ELMs) with power densities of 1 – 10 GW/m² for 0.2 – 0.5 ms, which cannot be avoided during certain operational scenarios of ITER. Beside these normal operation conditions there are so called off-normal events such as vertical displacement events (VDEs) and plasma disruptions, which will deposit even higher power densities on the PFM [1-2]. These exposure conditions will induce a wide range of surface modifications and damages, which in case of resulting dust formation will influence plasma performance and stability. Therefore, it is essential to know how PFMs will perform under these conditions, i.e. what kind of damages will be induced and what are thereof the limits of the materials in terms of power density and operation time.

For an application as PFM in the divertor region tungsten is the most promising candidate due to its high melting point, high thermal conductivity, low sputtering yield etc. However, the brittle behaviour even at high temperatures and the high Z posing a severe threat in terms of plasma contamination, are disadvantages which need to be investigated [3-5]. In order to qualify tungsten as PFM high heat flux test in the electron beam device JUDITH 1 were performed at different power densities, base temperatures and pulse numbers. The investigated industrially produced reference tungsten grade was exposed to 100 and 1000 ELM-like thermal shock events on two orthogonal sides with different grain orientation with respect to the loaded surface as well as in its recrystallised state. Additionally, tensile tests were performed to characterise the mechanical properties as a function of the material's microstructure. These qualification tests and the obtained results in combination with the material properties will give an overview of the damage behaviour and development under ELM-like conditions at low pulse numbers. It will as well show how the damage behaviour is influenced by the material properties and provide quantified damage characteristics according to which other materials can be qualified.

2. Material and experimental settings

In the frame of this work a pure tungsten grade (IGP W) with a purity of 99.97 wt% was investigated. It was manufactured by the Plansee SE, Austria, according to the ITER material specification. The forged rod was produced with the dimensions 36 × 36 × 480 mm³ and was exposed to a stress relieving treatment by thermal annealing after the production process. Due to the production process the grain structure is strongly elongated with needle like grains parallel to the forging direction (diameter of 5 – 10 µm, length ca. 25 µm). Selected parts of the material were recrystallised at 1600 °C for one hour resulting in larger grains (ca 64 µm × 102 µm) without pronounced elongated grain structure anymore (see figure 3d, e, f).

Tensile tests were performed on specimens with grains oriented parallel (longitudinal) and perpendicular (transversal) to the loading direction as well as on the recrystallised material. All tests were performed with a deformation speed of 0.2 mm/min (strain rate ca. 10^{-4} s^{-1}) at temperatures of 300 °C, 500 °C and 1000 °C. The stress-strains curves are shown in figure 1.

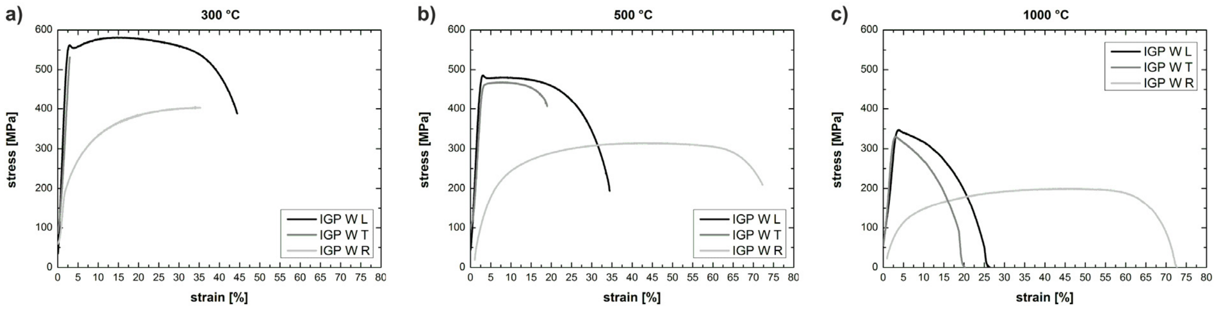

Figure 1: Stress-strain curve for the longitudinal (IGP W L), transversal (IGP W T) and recrystallised (IGP W R) material. The measurements were performed at sample temperatures of 300 °C (a), 500 °C (b) and 1000 °C (c).

The qualitative comparison of the stress strain curves shows clearly the influence of the microstructure on the mechanical properties of the material. While the material in transversal grain orientation (IGP W T) performs brittle at 300 °C and shows only a small increase in ductility with increasing test temperatures, the longitudinal (IGP W L) and the recrystallised (IGP W R) samples are ductile for all three test temperatures. In particular IGP W R is characterized by a high ductility with a maximum strain more than double the value for the other orientations. However, the mechanical strength for the recrystallized material is about a factor 2 lower. The reasons for these pronounced differences in the mechanical strength and ductility of the material are the texture strengthening for the longitudinal and transversal samples and the reduced defect density in case of the recrystallised material [6,7] which were also observed in [8]. Besides these differences, for all investigated orientations the mechanical strength decreases and the ductility increases with increasing temperature.

The simulation of transient thermal shocks was done with the electron beam device JUDITH 1 (Juelich Divertor Test Facility in Hot Cells) at Forschungszentrum Jülich [9]. Samples with the dimension 12 × 12 × 5 mm³ were cut from the tungsten rod in the longitudinal and transversal grain orientation and also in the recrystallised state. All samples were polished to a mirror finish to obtain an undamaged well-defined reference state. Based on former experiments a set of parameters was identified to give a comprehensive overview about the thermal shock performance of tungsten [3,8]. Absorbed power densities of 0.19 GW/m² and 0.38 GW/m² (electron absorption coefficient of 0.55) located above and below the expected "damage threshold" of pure tungsten with an ELM-like (edge localised mode) pulse duration of 1 ms were chosen. The tests were performed at base temperatures of RT, 400 °C and 1000 °C to investigate the thermal shock performance in the brittle, ductile and high temperature regime. While tests with 100 pulses aim on qualifying the general damage behaviour, applying 1000 pulses only at the higher power density addresses the influence of thermal fatigue and helps quantifying the damage evolution. The exposed area for all tests is 4 × 4 mm² with a focused electron beam (Ø ca. 1 mm) at very high frequencies (47 kHz in x-direction and 43 kHz in y-direction). The repetition frequency was ≥ 0.5 Hz in order to allow the sample to cool down back to base temperature.

After the exposure in JUDITH 1 the induced damages were investigated by SEM, light microscopy (LM) and laser profilometry. Subsequently, the cross sections of the samples were investigated by metallographic means to analyse the crack propagation into the bulk material.

3. Results and discussion

The induced surface modifications and damages after the ELM-like thermal shock tests were colour and shape coded and depicted in so-called damage mappings which are shown in figure 2. Symbols with a black central part stand for the 1000 thermal shock pulses while the plain-coloured ones represent the induced damages after 100 pulses Based on these damage mappings it can be stated that the longitudinal material shows the best thermal shock behaviour. It stays undamaged at power densities of 0.19 GW/m² while there are small cracks visible at RT for the transversal material and surface modifications due to plastic deformation are induced on the recrystallised one at elevated temperatures. In contrast to that the samples show a very similar damage response in terms of damage categories at 0.38 GW/m² after 100 and 1000 ELM-like thermal shock events.

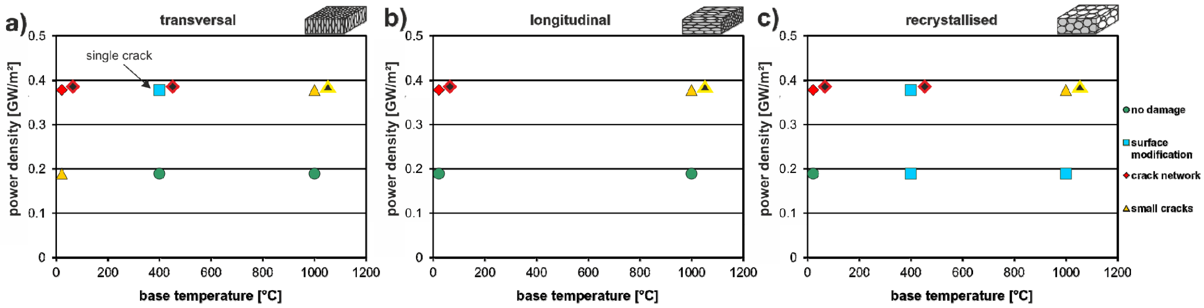

Figure 2: Damage mapping of tungsten samples exposed to ELM-like thermal shocks with transversal (a), longitudinal (b) and recrystallised (c) grain structure. Plain-coloured symbols stand for samples with 100 thermal shock pulses. Symbols with a black centre stand for samples exposed to 1000 pulses.

A more detailed analysis of the induced damages shows that there are differences in terms of surface roughness (table 1). While the transversal and longitudinal samples show a very similar increase of the surface roughness (R_a) with power density and pulse number, the R_a values for the recrystallised samples are generally a factor 1.5 to 2, in one extreme case even a factor 10, higher.

Table 1: Overview of the arithmetic mean roughness (R_a) of all tested samples.

R_a [µm]	**RT**			**400 °C**			**1000 °C**			
grain structure	**T**	**L**	**R**	**T**	**L**	**R**	**T**	**L**	**R**	
0.19 GW/m²	0.05.	0.15	0.08	0.03	-	0.09	0.07	0.19	0.13	**100 pulses**
0.38 GW/m²	0.15	0.13	0.27	0.41	-	0.62	0.46	0.51	0.66	**100 pulses**
0.38 GW/m²	0.22	0.40	0.89	0.52	-	4.90	0.65	0.62	1.33	**1000 pulses**

The differences in crack formation of the three grain structures are exemplary shown in figure 3. For the transversal (figure 3a) and recrystallised (figure 3c) samples the cracks are randomly distributed and show no preferential direction. In contrast, thermal shock cracks on longitudinal samples follow clearly the grain orientation and are oriented parallel to each other without any interconnecting crack formation. The crack density at RT is for all three grain structures very similar and shows no change with increasing pulse number, which is an indication for brittle crack formation. In contrast to that the crack width for the recrystallised samples is much larger than for the transversal or longitudinal. The reason for that is the agglomeration of lattice defects at the grain boundaries and a resulting lower cohesion between single grains after recrystallisation [10]. Cross sections (figure 3d, e, f) show that the cracks propagate perpendicular to the loaded surface and achieve a depth of 150 µm to 300 µm. For transversal and longitudinal samples no crack propagation parallel to the surface was observed. Only the recrystallised samples show parallel crack propagation and cracking around single grains which lead to a severe reduction of the heat dissipation and can lead to overheating and melting of the loaded surface. Additionally, grain loss at the surface takes place for the transversal and recrystallised samples. This happened during the metallographic preparation of the cross section and not during the thermal shock exposure. However, it is a sign for a combination between thermal shock induced de-cohesion between single grains and the low mechanical strength in the plane with parallel grain orientation. In view of high expected numbers of ELM pulses proceeding damage may lead to erosion of complete areas of the surface and/or surface near grains. Longitudinal samples show delamination of surface near grains, which is a potential source for dust formation.

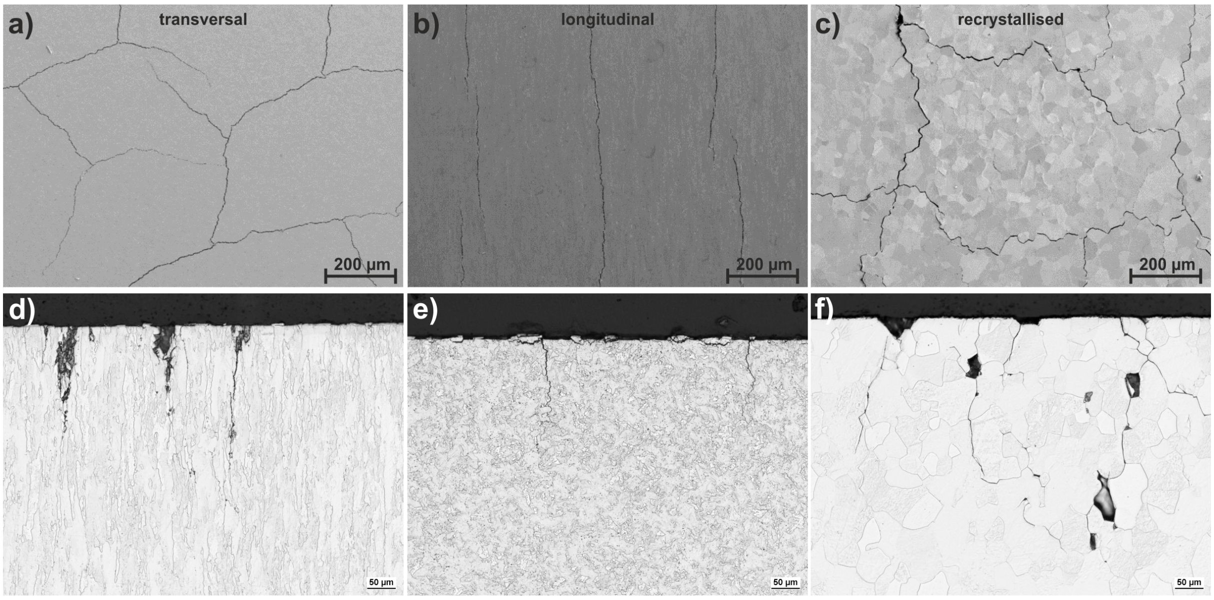

Figure 3: SEM and LM images of induced crack networks on the loaded surface (a, b, c) and the crack propagation into the sample material (d, e, f) after the exposure to 100 pulses with an absorbed power density of 0.38 GW/m² at RT for transversal (a, d), longitudinal (b, e) and recrystallised samples (c, f).

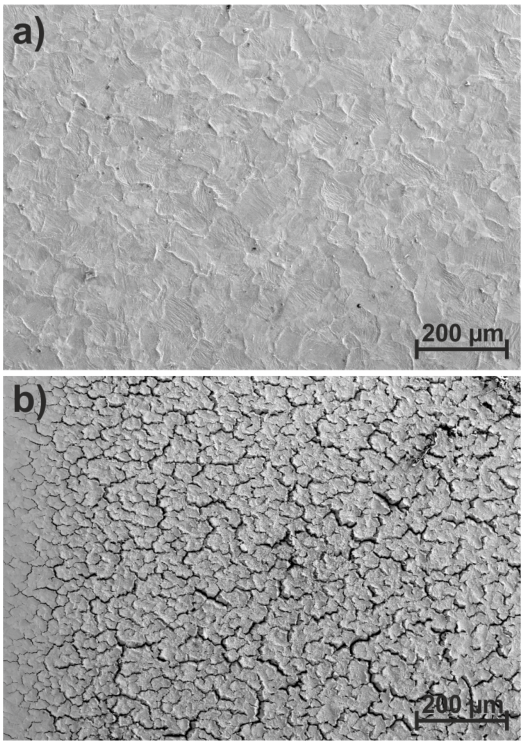

Figure 4: SEM-images of a recrystallised sample exposed to 100 (a) and 1000 (b) ELM-like thermal shock events with an absorbed power densities of 0.38 GW/m² at 400 °C.

The differences in the observed surface modifications and damages induced by the ELM-like thermal shock exposure can be explained by the inhomogeneities in the crystallographic structures and the consequential difference in mechanical strength and ductility. In contrast to earlier investigations [8] of transversal and longitudinal grain structures with disk like shaped grains as a result of a unidirectional single forging process, the needle like grain structure seems to improve the mechanical strength and ductility of the transversal grain orientation. The detailed analysis of the induced thermal shock damages has shown that a decrease of the mechanical strength and a reduced cohesion between single grains, e.g. due to recrystallisation, leads to a much faster deterioration of the thermal shock performance and a much faster damage evolution with increasing number of thermal shock pulses.

4. Conclusion

Thermal shock experiments with Plansee tungsten (IGP) produced according to ITER specifications at different power densities and base temperatures were performed. The obtained results cover induced surface modifications and damages and have shown that the above defined set of parameters provides a good overview of the thermal shock response of tungsten. Additionally, the comparison of the surface modifications after 100 and 1000 pulses indicates the damage evolution to be expected during the operation of fusion devices like ITER and DEMO.

The inhomogeneity in the as-produced state and the recrystallisation of the crystallographic structure has a strong influence on the mechanical properties of the material and, as a result thereof, also on the thermal shock performance. The material has the highest mechanical strength in the direction parallel to the elongated grains and shows for specimens with this direction parallel to the loaded surface the best thermal shock performance in terms of damage formation and evolution. The recrystallised material shows the worst performance due to its significantly reduced mechanical strength, which cannot be compensated by the higher ductility of the material. All materials showed evidences of grain erosion, which originated in this study from the preparation of metallographic cross sections. However, it shows clearly that the risk of surface near grain erosion increases during the operation as PFM in a fusion device under such loading conditions.

The obtained results are only valid for 100 and 1000 thermal shock events and take only the pure heat loading into account. However, they provide a good benchmark towards the fast qualification of other tungsten grades that are, e.g. developed in the EUROfusion WPMAT program.

Besides the fast qualification, for the life time analysis of the PFM also high pulse number tests and experiments with combined heat and particle exposure are necessary to investigate thermal fatigue and synergistic effects.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was done within the EUROfusion work program MAT.

References

[1] Federici G, Zhitlukhin A, Arkhipov N, Giniyatulin R, Klimov N, Landman I, Podkovyrov V, Safronov V, Loarte A and Merola M 2005 *Journal of Nuclear Materials* **337-339** 684-90

[2]Pitts R, Carpentier S, Escourbiac F, Hirai T, Komarov V, Kukushkin A, Lisgo S, Loarte A, Merola, M, Mitteau R, Raffray A, Shimada M and Stangeby P 2011 Physics basis and design of the ITER plasma-facing components *Journal of Nuclear Materials* **415** S957 - S964

[3] Pintsuk G, Prokhodtseva A and Uytdenhouwen I 2011 Thermal shock characterization of tungsten deformed in two orthogonal directions *Journal of Nuclear Materials* **417** 481-486

[4] Linke J 2006 High heat flux performance of plasma facing materials and components under service conditions on future fusion reactors *Fusion Science and Technology* **49** 455-464

[5] Philipps V 2011 Tungsten as material for plasma-facing components in fusion devices *Journal of Nuclear Materials* **415** S2-S9

[6] Lassner E and Schubert W-D 1999 Tungsten: Properties, Chemistry, Technology of the Element, Alloys, and Chemical Compounds Kluwer Academic /Plenum Plub-lishers, New York

[7] Martienssen W and Warlimont H 2005 Springer Handbook of Condensed Matter and Materials Data, Springer, Berlin

[8]Wirtz M, Cempura G, Linke J, Pintsuk G and Uytdenhouwen I 2013 Thermal shock response of deformed and recrystallised tungsten *Fusion Engineering and Design* **88** 1768-1772

[9] Duwe R, Kuehnlein W, Muenstermann H 1995 The new electron beam facility for materials testing in hot cells, *Fusion Technology* 356–358

[10] Humphreys F J and Hatherly M 2003 Recrystallization and Related Annealing Phenomena *Pergamon*, 2 edition