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Qualification and post-mortem characterization of tungsten mock-ups exposed to cyclic high heat flux loading

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HIGHLIGHTS

- We characterize tungsten mono-block components after exposure to ITER relevant heat loads.
- We qualify the manufacturing technology, i.e., hot isostatic pressing and hot radial pressing, and repair technologies.
- We determine the microstructural influences, i.e., rod vs. plate material, on the damage evolution.
- Needle like microstructures increase the risk of deep crack formation due to a limited fracture strength.

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ABSTRACT

In order to evaluate the option to start the ITER operation with a full tungsten (W) divertor, high heat flux tests were performed in the electron beam facility FE200, Le Creusot, France. Thereby, in total eight small-scale and three medium-scale monoblock mock-ups produced with different manufacturing technologies and different tungsten grades were exposed to cyclic steady state heat loads. The applied power density ranges from 10 to 20 MW/m^2 with a maximum of 1000 cycles at each particular loading step. Finally, on a reduced number of tiles, critical heat flux tests in the range of 30 MW/m^2 were performed.

Besides macroscopic and microscopic images of the loaded surface areas, detailed metallographic analyses were performed in order to characterize the occurring damages, i.e., crack formation, recrystallization, and melting. Thereby, the different joining technologies, i.e., hot radial pressing (HRP) vs. hot isostatic pressing (HIP) of tungsten to the Cu-based cooling tube, were qualified showing a higher stability and reproducibility of the HIP technology also as repair technology. Finally, the material response at the loaded top surface was found to be depending on the material grade, microstructural orientation, and recrystallization state of the material. These damages might be triggered by the application of thermal shock loads during electron beam surface scanning and not by the steady state heat load only. However, the superposition of thermal fatigue loads and thermal shocks as also expected during ELMs in ITER gives a first impression of the possible severe material degradation at the surface during operational scenarios at the divertor strike point.

1. Introduction

As part of the tungsten qualification program for plasma facing materials in the divertor region, Fusion for Energy has established a task force to evaluate the option to start the ITER operation with a full tungsten divertor. Based on the related recommendation, an R&D program was launched to assess the performances of W armored plasma facing components (monoblock option) under the conditions expected in the divertor strike point region. This program consisted of the high heat flux thermal fatigue testing of small W mock-ups and prototypical components up to 20 MW/m^2 and subsequent tests to determine the critical heat flux (CHF) margin [1].

Besides in situ thermal observations and non-destructive examinations pre- and post high heat flux testing, metallographic analyses, on which the focus is set hereafter, were performed in order to characterize the occurring damages (i.e., crack formation, recrystallization, and melting). Thereby, the joining and repair technologies, i.e., hot radial pressing (HRP) and hot isostatic pressing (HIP) of tungsten to the Cu-based cooling tube, as well as the influence of the material's microstructure on the damage formation and propagation should be determined and qualified. This comprises the material's top surface due to potential interactions with the fusion plasma, e.g., by particle erosion,

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Table 1
Loading schemes for the mock-ups and VTPCs.

Loading scheme	Components	Cycles at 10 MW/m^2	Cycles at 15 MW/m^2	Cycles at 20 MW/m^2	CHF
A	Mock-ups, VTPCs	1000			
B	Mock-ups	1000		500	
C	Mock-ups	1000		1000	
D	Mock-ups	1000		1000	X
E	VTPCs	1000	1000		
F	VTPCs	1000	1000	300	

and the interface between the plasma facing material and the heat sink.

2. Components manufacturing, testing and characterization

A total of eight small tungsten mock-ups and three medium scale vertical target prototypical components (VTPCs) were manufactured by Ansaldo Ricerche, Italy (four mock-ups, one VTPC) and Plansee SE, Austria (four mock-ups, two VTPCs). The manufacturing technology consists of the casting of a pure Cu-interlayer, which aims for the reduction of thermally induced stresses originating from the thermal expansion mismatch of CuCrZr and tungsten. Subsequently, the CuCrZr cooling tube is joined to the Cu-layer by either hot radial pressing (HRP) used by Ansaldo or hot isostatic pressing (HIP) used by Plansee.

The W monoblocks have a total height of 25 mm on the mock-ups and 28 mm on the VTPCs. For the latter, different material grades were used, i.e., sheet (Ansaldo, $d = 13$ mm) and rod material (Plansee, $\varnothing = 35$ mm) while the mock-ups were manufactured in both cases from the sheet material. Furthermore, the width and axial length of the tungsten tiles are 28 and 12 mm, respectively. The tungsten tile thickness from top surface to cooling tube for the mock-ups and the VTPC manufactured by Ansaldo is 5 mm and 5.5 mm, respectively. For the mock-ups and VTPCs manufactured by Plansee this thickness is 6 mm and 6.5 mm, respectively. The pure Cu interlayer thickness varies between 1 mm (Ansaldo) and 0.5 mm (Plansee). The dimensions of the CuCrZr cooling tube are kept constant with an inner and outer diameter of 12 and 15 mm, respectively. This means, that the overall distance from the top-surface to the inner wall of the coolant channel is 0.5 mm larger for the components manufactured by Plansee. Additionally, for each manufacturer, two mock-ups and one VTPC have a repaired monoblock.

The hydraulic arrangements ($p = 3.3$ MPa, $v = 12$ m/s, $T = 120\,°$C), the testing protocols (10 s power on, 10 s dwell time) [1] and the pre and post-test non-destructive infrared examinations by SATIR [2,3] were carried out by CEA Cadarache, France. Summarizing, the mock-ups and the loading of individual tiles are divided into 4 different loading schemes for the mock-ups (Table 1). Based on these results, the loading scheme of the VTPCs, also shown in Table 1, was modified to 3 different loading types of which the first is identical to those for the mock-ups described above, which were investigated in [4].

Non-destructive examination by SATIR [4], in situ thermal observation during thermal fatigue testing ($T_{surf} \sim 1400\,°$C at 15 MW/m^2 and $\sim 1900\,°$C at 20 MW/m^2) [1] and visual inspection of the individual tiles, allowed the identification of particular tiles (Figs. 1 and 2) to be investigated by metallographic means. This aims for determining damage characteristics like cracking, recrystallization and melting at particular loads.

3. Results and discussion

The microstructural analyses show, that all small scale mock-ups are produced from tungsten sheet material without any preferential orientation perpendicular to the loaded surface. Therefore, the main focus herein is on the qualification of the joining technology only. However, also the different distance from the loaded surface to the coolant channel and of the pure Cu-interlayer has to be taken into account in the evaluation of the results since different surface temperatures are to be expected due to this geometrical variation.

For loading scheme "A" (Table 1) no visible damage was observed. This means that neither recrystallization nor cracking thresholds (in tungsten and at the tungsten/heat sink interface) were exceeded during thermal loading. For loading scheme "B", first longitudinal cracks that are more or less centered above the cooling tube were observed as well as recrystallization and grain growth occurred on up to 70% of the tile surface, in particular for the components made by HRP. At these locations, also surface roughening and the loss of grains were observed (Fig. 3). In contrast, for the HIPed mock-ups no indication of grain growth or crack formation was found. However, surface roughening and potential grain loss is observed on the whole loaded area. This change in surface morphology might be on the one hand related to a change in mechanical properties in a surface near layer, e.g., due to recrystallization. On the other hand, similar surface morphologies were observed after thermal shock loads via electron beam loading in dependence on the base temperature. Therefore, this kind of damage might also be an artifact. However, in ITER, the superposition of thermal fatigue and thermal shock loads seems to be inevitable. Therefore, these results seem to give a first impression on the interaction of steady state and transient thermal loads, e.g., ELMs. Here in this case, the HIPed mock-ups seemed to be more affected, which might be related to a larger armor thickness and an overall 0.5 mm larger distance to the coolant channel.

For loading condition "C", which means a continuation of 500 more cycles at 20 MW/m^2 compared to loading condition "B", a further increase in roughening and particle erosion was observed as well as strong surface melting at the tile edges (Fig. 4). While particle erosion and melting may be a hazard to safe plasma operation, the interface between tungsten and pure Cu is still intact and related to this the heat removal capability of the component.

Finally, the application of the CHF on the modules led to partial melting and vaporization of the copper-alloy coolant channel. Melting at the top surface affects about 2–3 mm in both cases, i.e., HRP and HIP manufactured mock-ups. Similar to the previously described cases recrystallization or more precisely grain growth only takes place in the mock-ups produced via HRP as well as longitudinal crack formation. Based on the results obtained for the small scale mock-ups, both fabrication technologies seem to be able to provide the required thermal fatigue stability. However, the HIP technology used by Plansee seems to offer a preferential performance when taking the larger distance between surface and inner coolant channel wall as well as the lack of crack formation into account.

For the VTPCs, similar to the mock-ups, no damage or degradation was observed during thermal fatigue loading according to loading scheme "A", which corresponds with the metallographic observations. For loading scheme "E" first longitudinal cracks were found for the rod material with a depth of several mm. Hence,