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High heat flux testing of first wall mock-ups with and without neutron irradiation

G. Pintsuk[a,*], B. Bellin[b], A. Gervash[c], J. Linke[a], N. Litunovsky[c], P. Lorenzetto[b]

[a] Forschungszentrum Jülich, 52425 Jülich, Germany
[b] Fusion for Energy, 08019 Barcelona, Spain
[c] Efremov Institute, St. Petersburg 196641, Russia

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ABSTRACT

Beryllium as the plasma facing material for the first wall of ITER will be exposed to thermal, particle and neutron loads. In the frame of the European qualification program for ITER, two HIPped beryllium small scale flat-tile mock-ups consisting of a steel support structure, a CuCrZr/Cu heat sink and two beryllium tiles on top were manufactured by CEA. One mock-up was exposed to neutron irradiation up to 0.75 dpa in beryllium in the RBT-6 fission reactor at Dimitrovgrad, Russia, while the other one was kept as reference. Furthermore, an identical mock-up was produced in Russia by manufacturing via electron beam induced rapid brazing and also exposed to the same neutron irradiation conditions.

For qualification, all three flat-tile mock-ups were exposed to cyclic steady state heat loads in the electron beam facility JUDITH-1 up to a maximum of 3.0 MW/m^2. Thereby, each tile was loaded individually as the full loading area exceeds the limits of the facility.

1. Introduction

The first wall and divertor of ITER will be exposed to high thermal, particle and neutron loads [1]. In dependence on the location in the main chamber, the material and components have to accommodate heat fluxes from 2 MW/m^2 (normal heat flux) to 4.7 MW/m^2 (enhanced heat flux) [2]. For the first wall, beryllium with all its advantageous and disadvantageous properties is chosen as plasma facing material as optimum solution with regard to plasma power handling and particle flux characteristics [3]. Thereby, the development of first wall plasma facing components is already in the qualification phase, which is done by high heat flux testing [4]. As part of the European beryllium qualification program for the use as plasma facing material on first wall components for ITER [5], two HIPped beryllium small scale flat-tile mock-ups with the normal heat flux design were manufactured by CEA [6]. The mock-ups consist of a stainless steel support structure, a CuCrZr/Cu heat sink and two beryllium tiles on top. Furthermore, an identical mock-up was produced by Efremov, Russia, by manufacturing via fast brazing [7].

The aim was to investigate synergistic effects of neutron and thermal loads in subsequent testing campaigns. Accordingly, one European mock-up and the Russian mock-up were exposed first to neutron irradiation up to 0.75 dpa in the RBT-6 fission reactor at Dimitrovgrad, Russia, while the other one was kept as reference [8]. Secondly, for qualification, all three small-scale flat-tile mock-ups were exposed to cyclic steady state heat loads in the electron beam facility JUDITH-1 at Forschungszentrum Juelich starting from screening tests at 0.5 MW/m^2 up to a maximum of 200 cycles at 3.0 MW/m^2. In total up to 1700 cycles at different power densities were applied with a maximum of 500 cycles at a particular power density. Thereby, each tile was loaded individually as the full loading area would have exceeded the limits of the facility.

Qualification criteria are not only the number of sustained cycles but also the beryllium surface temperature at a respective power density and, if existing, the failure mode.

2. Components, irradiation and testing conditions

Each of the three investigated mock-ups consists of 2 identical beryllium tiles with dimensions of ~56 × 56 × 9 mm^3 and ~56 × 56 × 10 mm^3 for the European mock-ups and the Russian mock-up, respectively, and a gap of 2 mm between these tiles. For the European mock-ups and the Russian mock-up the beryllium grades S65-C and TGP-56 were used, respectively. The tiles are

* Corresponding author.
E-mail address: g.pintsuk@fz-juelich.de (G. Pintsuk).

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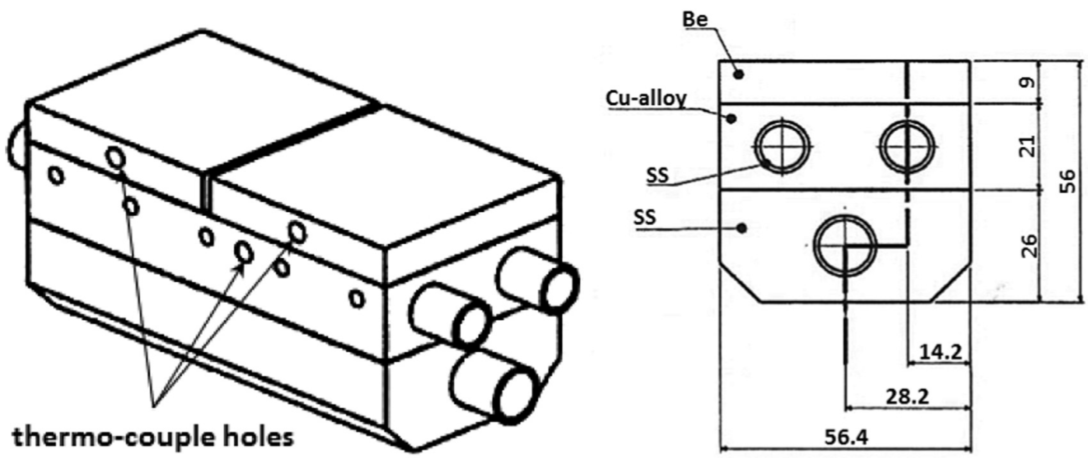

Fig. 1. Overview and cross section of the European Be mock-up including main dimensions.

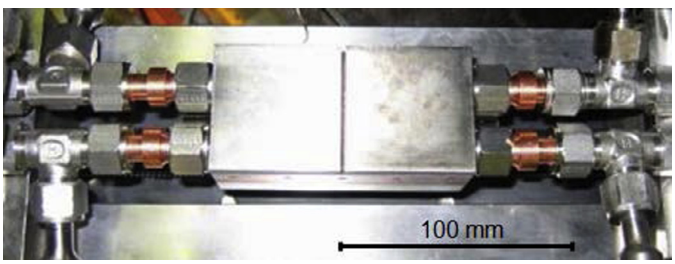

Fig. 2. Installation of the Be mock-ups in JUDITH-1 by the specially developed clamping device also for handling via manipulators.

HIPped to a 21 mm high CuCrZr heat sink containing two symmetrically positioned stainless steel cooling channels with 10 mm inner diameter and 1 mm wall thickness. As supporting structure a 26 mm stainless steel back plate is joined to CuCrZr. This support structure contains an additional cooling tube of 12 mm inner diameter (Fig. 1).

Neutron irradiation of one European mock-up and the Russian mock-up was performed in the RBT-6 reactor at Dimitrovgrad. Inpile thermal cycling (3720 thermal cycles at 60 °C coolant temperature and a surface heat flux of 0.5 MW/m^2) of the mock-ups was performed to a damage level of 0.11 dpa (Be) / 0.15 dpa (CuCrZr and SS). This was followed by irradiation in the non-cycling regime up to an average fluence of fast neutrons ($E > 0.1$ MeV) of 1.4×10^{21} n/cm^2 still at 60 °C coolant temperature. This resulted for Be and CuCrZr/stainless steel in a volume averaged damage level of 0.75 ± 0.05 dpa and 1.05 ± 0.05 dpa, respectively. For the thermal monitoring during neutron irradiation, thermo-couple holes were inserted at the side of the component in beryllium and CuCrZr (Fig. 1).

The high heat flux (HHF) testing was done at the electron beam facility JUDITH-1 at Forschungszentrum Juelich, which is located in a hot cell [9]. For the installation of the irradiated mock-ups and the required remote handling via manipulators, a new clamping device was developed (Fig. 2). The connection between cooling circuit and mock-up was established via conical adaptors made from pure Cu. Thereby, due to the limited manageability via manipulators, cooling was only performed via the two stainless steel cooling tubes in CuCrZr while the stainless steel support structure had to be left uncooled. However, based on experience the influence of cooling the stainless steel support structure on the overall temperature field was assumed to be marginal.

Table 1
High heat flux testing parameters in JUDITH-1.

$A_{loading}$	~56 × 56 mm^2
Scanning frequency	40 × 31 kHz
v (water)	~2.8 m/s
p_{in} (water)	~0.4 MPa
T_{in} (water)	RT
t @ cycling	50 / 50 s

Table 2
Planned loading conditions for the qualification of the mock-ups.

# of cycles	P [MW/m^2]
500	1.8
500	2.4
500	2.75
200	3.0
200	3.25, 3.5, 3.75, …

Each tile (A and B) was loaded individually as the full loading area would have exceeded the limits of the facility. Furthermore, the electron beam has a beam diameter at full width half maximum of 1 mm, requiring high frequency scanning across the surface in a triangular scanning mode. The chosen frequencies and all other parameters are shown in Table 1. Thereby, for the cooling circuit of JUDITH-1 a linear dependence of water velocity and pressure exists resulting in a relatively low inlet pressure due to the required low flow rate of ~2.8 m/s. The chosen cycling time of 50 s on and 50 s off allows the component to reach steady state in the loading but also in the cooling regime.

For allowing the qualification of the component in a first step the initial performance of the mock-ups and in particular the joints was investigated by various screening cycles from 0.5 to 1.8 MW/m^2. In a second step, several cycling steps were performed applying up to 500 cycles at a particular loading condition (Table 2) until failure of the component occurred or the temperature limit of the facility, i.e. 700 °C, was reached.

3. Results and discussion

During HHF-testing of the non-irradiated European mock-up, both tiles, although loaded individually, started overheating at one outer corner of the loaded area (Fig. 3) during cycling at 2.75 MW/m^2. However, even up to 200 cycles at 3 MW/m^2 the tiles