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High heat flux performance of neutron irradiated plasma facing components

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Abstract

During the operation of ITER, the plasma facing components will undergo different kinds of thermal loadings like thermal fatigue, vertical displacement events and disruptions. In addition degradation effects due to neutron irradiations may play an important role. The electron beam facilities JUDITH and OHBIS have been designed to carry out ITER relevant simulation experiments on neutron irradiated materials and components. Carbon fiber reinforced carbon materials (CFC), Be and W alloys have been tested in thermal shock experiments. Thermal fatigue experiments have been performed with joints of these materials to Cu alloys. In thermal fatigue experiments no influence on the quality of the joints was observed whatever the testing facilities or materials combinations. But for CFC mock-ups the surface temperature is significantly increased due to the reduction in thermal conductivity. During experiments at high power densities annealing effects could be observed. Thermal shock tests show a higher erosion after neutron irradiation. The tests described above are not able to simulate the superposition of nuclear and thermal loads. In order to study the synergistic effects, in-pile thermal fatigue experiments with two CFC/Cu mock-ups and a Be–Cu mock-up have been performed in the SM-2 fission reactor in Dimitrovgrad (Russia). A first evaluation showed good performance of all three mock-ups.

1. Introduction

During the operation of ITER, the plasma facing components will undergo different kinds of thermal loadings. During normal operation the joint between plasma facing materials and the heat sink will be stressed by thermal fatigue. During off normal events like disruptions and vertical displacement events, high fluxes of energetic particles are deposited on the surface of the components and material loss or cracking may occur. In order to simulate these loading conditions, high heat flux test have been carried out in several electron beam test stands [1]. But most of these facilities are only able to test un-irradiated samples, and their experiments do not take into account the degradation effects of fast neutrons.

The electron beam facilities JUDITH at Forschungszentrum Juelich (Germany) and OHBIS at JAERI Oarai (Japan) have been designed to perform high heat flux tests on neutron irradiated materials and components in hot cells.

But electron beam experiments are not able to simulate the superposition of nuclear and thermal loads. In order to study the synergistic effects, in-pile thermal

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fatigue experiments have been performed in the SM-2 fission reactor in Dimitrovgrad (Russia).

2. Electron beam testing of neutron irradiated samples

2.1. Description of the electron beam facilities and irradiation programs

2.1.1. JUDITH

The electron beam facility JUDITH at Forschungszentrum Juelich [2] has a maximum power of 60 kW. The focused electron beam with a diameter in the order of 1 mm approximately can be swept in two directions at frequencies up to 100 kHz, and it can cover an area up to 100×100 mm^2. The machine can be operated in a short pulse mode with pulse lengths of 1–100 ms (beam rise time 130 μs), or in a long pulse mode with heating periods of 100 ms to continuous operation. The former is used for the simulation of off normal events like disruptions. The long pulse mode simulates the normal operation of components, and it is mainly used for thermal cycling experiments.

JUDITH is equipped with several kinds of diagnostics. One- and two-colour pyrometers cover the temperature range between 500 and 3000 °C, a fast pyrometer can be used to detect surface temperatures in disruption simulation tests. The sample surfaces are controlled by a video camera and an infra-red camera. The latter is a powerful tool to detect the failure of actively cooled samples. Other diagnostics are thermo couples and an instrumented cooling circuit which allows to determine the exact amount of absorbed power in the samples.

Plasma facing materials from the two irradiation campaigns PARIDE 1 and PARIDE 2 have been tested. Both irradiations have been performed in the high flux reactor (HFR) in Petten, The Netherlands. The irradiation conditions were 0.35 dpa at ~350, and ~750 °C, respectively. Thermal shock experiments (disruption simulation) and thermal fatigue experiments (normal operation) have been performed in JUDITH.

2.1.2. OHBIS

OHBIS is located at JAERI's Oarai Research Establishment. The electrons are generated by thermal emission in a 50 kW electron gun. As JUDITH, the machine can be operated in short pulse mode for simulation of disruptions and in long pulse mode for simulation of normal operations. In the latter case the beam is started on a beam dump and after reaching its full power, it is swept to the sample. The maximum scanning frequency on the sample surface is 1 kHz.

Before the experiments, the maximum heat flux and the heat flux profile are measured by means of a graphite calorimeter [3]. The beam profile is Gaussian and the typical full width at half maximum (FWHM) of the beam is 3 mm approximately. Diagnostics in OHBIS cover a video camera, several thermo couples and an infra-red camera.

Neutron irradiated CFCs and CFC/DSCu flat type divertor mock-ups, irradiated with 0.3 and 0.4 dpa at ~300 °C in the Japan materials testing reactor at Oarai were tested in the thermal shock and high heat load test, respectively, [4–6].

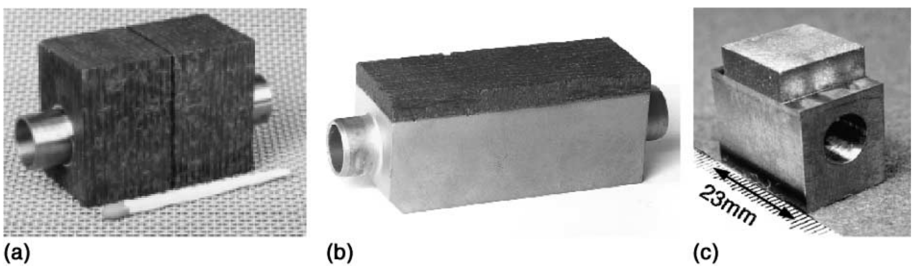
2.2. Testing of actively cooled mock-ups

2.2.1. JUDITH

Several kinds of beryllium–copper mock-ups (flat tiles with CuMn–braze and InCuSil braze), as well as CFC mock-ups (monoblock and flat tile type with different combinations of CFCs, copper alloys and Mo alloys, see Fig. 1(a) and (b)) have been irradiated up to 0.35 dpa at ~350 and ~750 °C.

Beryllium–copper mock-ups have been tested for 1000 cycles (10 s heating on/10 heating off) up to power densities of 7 MW/m^2. In all these experiments no influence on the quality of the joints concerning fatigue behaviour was observed [7].

Un-irradiated CFC copper monoblock mock-ups endured more than 1000 heating cycles at power densities up to 25 MW/m^2. After irradiation, the thermal conductivity of the carbon was reduced, and the surface temperatures were increased. Erosion due to sublima-



(a) (b) (c)

Fig. 1. Actively cooled CFC mock-ups, (a) monoblock, (b) flat tile (both EU design), (c) flat tile (Japanese design).

tion was observed on the sample surfaces beyond 15 MW/m^2. As a consequence, the thermal fatigue tests were limited to power densities of 15 MW/m^2.

In total six neutron irradiated monoblock mock-ups (similar to Fig. 1(a)) of different combinations of CFCs and copper alloys and both irradiation temperatures have been tested. Sample dimensions were $22 \times 30 \times 40$ mm^2. All samples were tested from the 'upper' side (12 mm CFC armor) and from the 'lower' side (6 mm CFC armor) first in screening tests and later in thermal fatigue tests. No degradation effects on the joints were found during these experiments up to 1000 cycles. Post-mortem metallography of the braze layers did not show any significant differences in comparison to un-irradiated samples.

An example for the influence of neutron irradiations on the heat removal efficiency is shown in Fig. 2. Armour material is the 3D-CFC Dunlop Concept 1 and the heat sink is made from Glidcop Al25. Due to the irradiation damages the thermal conductivity in carbon is reduced [8] and the surface temperatures are increased after neutron irradiation. This effect is more significant for the lower irradiation temperature of ~350 °C. For the higher irradiation temperature of ~750 °C, an annealing effect becomes effective at the higher irradiation temperature and the surface temperatures are between un-irradiated samples and those irradiated at ~350 °C.

This annealing effect was demonstrated in a screening test with a SEPcarb N112/Glidcop Al25 mock-up irradiated at ~350 °C. In this experiment, the power density was held constant at 12.4MW/m^2 (incident power density) for 20 min approximately. During ramp-up and ramp-down, short hold-times were introduced at 7.8 and 10 MW/m^2, respectively. During this test, the surface temperature was measured by two-color pyrometer. Due to the heating, annealing took place in the upper part of the CFC tiles which led to a decrease in surface temperature of 70 °C approximately (cf. Fig. 3). This was also confirmed by comparison of temperatures during the short hold-times at ramp-up and ramp-down.

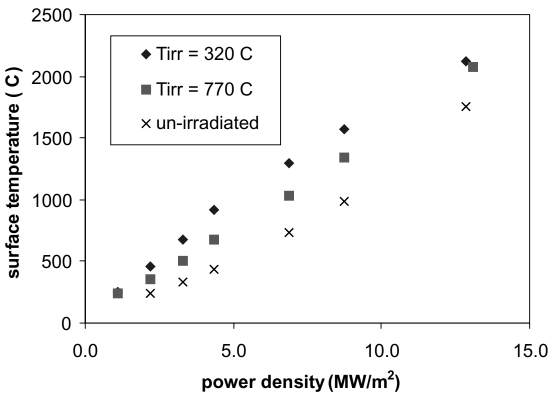


Fig. 2. Heat removal efficiency for neutron irradiated and un-irradiated CFC monoblock mock-ups (Dunlop concept 1/ Glidcop Al25, 12 mm CFC armour).

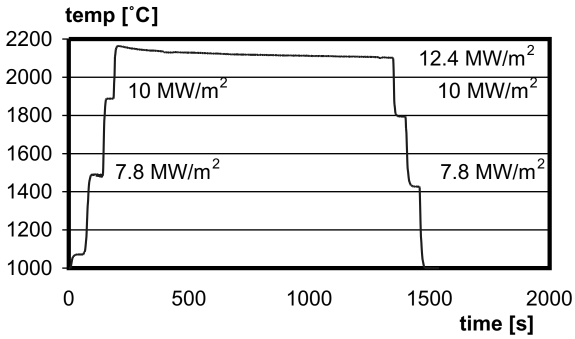


Fig. 3. Demonstration of the annealing effect in a neutron irradiated CFC mock-up (SEPcarb N112/Glidcop Al25, irradiation condition: 0.35 dpa, 350 °C.

2.2.2. *OHBIS*

Actively cooled samples were miniaturized divertor mock-ups of the flat tile type (Fig. 1(c)). Armour tiles were made from the CFC CX2002U and the heat sink from DS–Cu (Glidcop Al 15). The dimensions of the CFC tile and Cu heat sink are $15 \times 15 \times 5$ mm^3 and $23 \times 15 \times 17$ mm^3, respectively. The heat sink has a hole of 8 mm diameter as a cooling water channel. The armor is brazed onto the heat sink with a 1 mm thick OFHC–Cu interlayer by a Cu–Ti–Ag braze.

Heat removal and thermal cycling tests were carried out in order to investigate the thermal performance and durability of the joining interface between the armor and heat sink. An example of the results for the heat removal tests is shown in Fig. 4. At a power density of 5 MW/m^2, surface temperatures of the un-irradiated, 0.3 and 0.4 dpa mock-ups were about 300, 700 and 1200 °C, respectively. The increase of surface temperature is caused by the degradation of CFC's thermal conductivity due to the neutron irradiation.

As in the case of the lower irradiation temperature in the JUDITH experiments (Fig. 2), the curve corresponding to the poorest thermal conductivity (here the 0.4 dpa data) shows a non-linearity as a function of heat flux. This is presumably caused by the annealing effect at the higher temperatures [9].

Thermal cycling tests were carried out at a power density of 5 MW/m^2. Heating and cooling periods were 10 s each; this was enough to bring the sample to thermal equilibrium. The result of thermal fatigue tests up to 1000 cycles at 5 MW/m^2 is shown in Fig. 5. No damage could be observed in the mock-ups up to 1000 cycles.

The surface temperatures for the un-irradiated and 0.3 dpa mock-up were stable during the thermal fatigue test. However for the 0.4 dpa mock-up, it decreased from about 1200 °C to about 1000 °C during the first

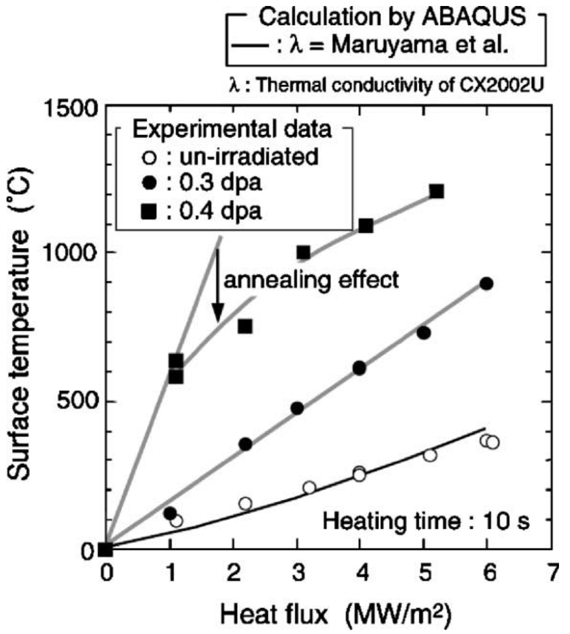


Fig. 4. Result of heat removal tests of the flat type divertor mock-up.

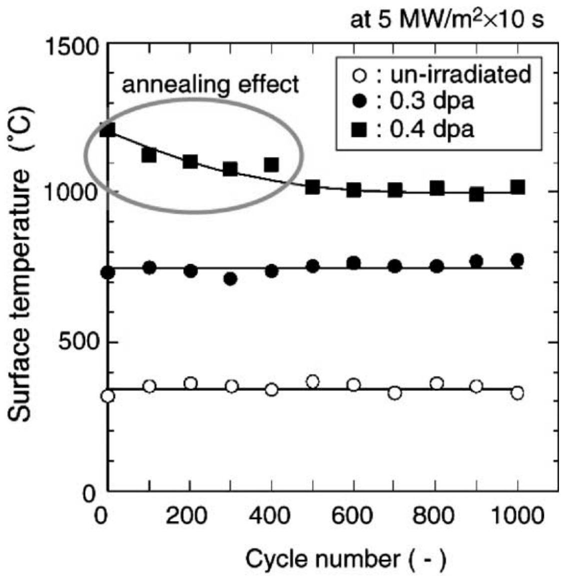


Fig. 5. Result of thermal cycle tests of the flat type divertor mock-up.

500 cycles. This phenomenon is also thought to be a result of the annealing effect.

The degradation and recovery of the thermal conductivity of CFC materials due to neutron irradiation and temperature induced annealing is an important effect for the evaluation of the performance for plasma facing components.

2.3. Thermal shock testing

2.3.1. OHBIS

Weight loss of each specimen during thermal shock test was determined by means of an electronic balance. Eroded surface profiles along the center line of the craters were measured by laser profilometry. In addition, the eroded surfaces were observed with a scanning electron microscope.

Examples of the results for the thermal shock tests are reported below. Specimens were made from the 2-directional CFC material CX2002U. The sample dimensions were $11.5 \times 11 \times 7.5$ mm^3. The heating time of the thermal shock tests was 40 ms, and the heat flux was 500 MW/m^2 (according to an energy density of 20 MJ/m^2).

CFCs show a rather rough erosion profile with many spikes. Therefore the measured profiles were fitted to a Gaussian curve. From surface profilometry it was found that the crater depth is not affected by the neutron irradiation (Fig. 6). But surface morphologies and erosion profiles show that the eroded areas and the FWHM of erosion craters increase with neutron radiation [4].

Weight loss of CX2002U as a function of radiation damage is shown in Fig. 7. With neutron irradiation an increasing weight loss was observed. This confirms the results of the profilometry measurement.

The higher erosion after neutron irradiation is attributed to a loss of thermal conductivity with neutron fluence due to radiation damage.

2.3.2. JUDITH

The erosion in the JUDITH tests was significantly lower than in the OHBIS experiments. This is ascribed

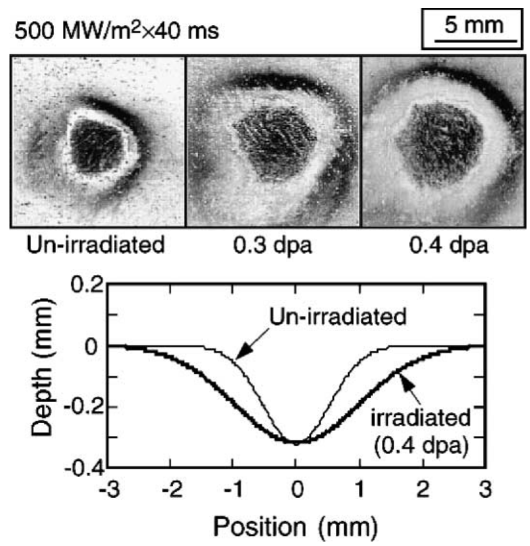


Fig. 6. Surface morphologies and erosion profiles of CX2002U.

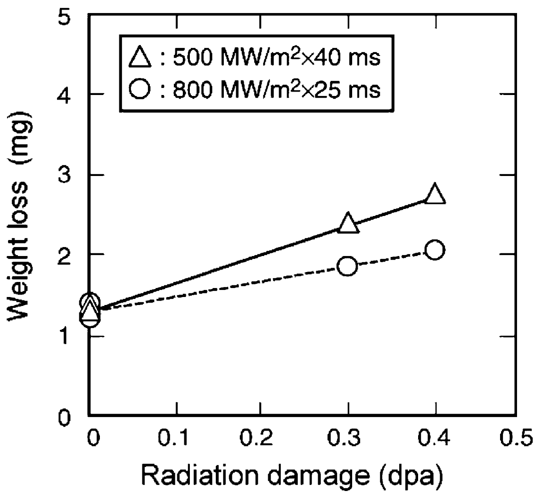


Fig. 7. Weight loss of CX2002U as a function of radiation damage.

to different heat load parameters and to differences in the scanning mode (JUDITH: swept focused beam, OHBIS: static un-focused beam), which may lead to a different temperature history on the sample.

Thermal shock tests with un-irradiated and irradiated carbon materials have been carried out with 5 ms pulses at 8.4 MJ/m^2 (absorbed energy density). Materials under investigation were several 3D- and 2D-CFCs. In order to minimize surface conditioning effects, all samples were loaded by five shots. Un-irradiated and irradiated samples were tested in the same testing campaign. Before and after the thermal shock experiments, all samples were weighed and the weight loss of un-irradiated and irradiated samples was determined.

Very little erosion was observed under the specific loading conditions and the weight losses were only little above the resolution of the micro balance [10]. With respect to these uncertainties and to the low sample numbers, no quantitative statements should be taken from these results. But there seems to be a tendency for higher erosion at materials irradiated at ~350°. This is ascribed to the reduction of thermal conductivity in carbon materials irradiated at low temperatures. At 750 °C annealing becomes effective and the thermal conductivity comes near to the one of un-irradiated samples [8].

For beryllium a similar effect, i.e. an increased erosion after neutron irradiation (up to 100%) has been observed. This process cannot be attributed to a decrease in the thermal conductivity of the bulk beryllium. However, a clear pore formation has been observed in the melt layer of all neutron irradiated test coupons after electron beam loading (Fig. 8). The tritium and helium production due to neutron irradiation in the HFR reactor at 700 °C has been calculated to be 3.6×10^{18}

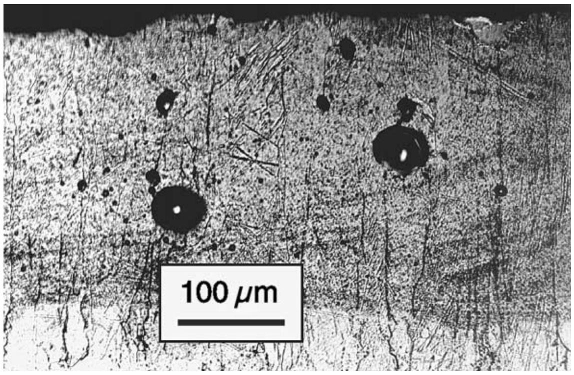


Fig. 8. Pore formation during electron beam loading of neutron irradiated beryllium (DShG 200, 0.35 dpa at 700 °C).

atoms/g Be, which corresponds to a concentration of 55 ppm. During disruptions these gases will form bubbles in the melt layer. In Be the neutron induced embrittlement and brittle destruction during electron beam loading with transient heat pulses may also play a non-negligible role.

3. In-pile thermal fatigue testing

3.1. Experimental details

The superposition of nuclear and thermal loads on actively cooled mock-ups was achieved in the SM-2 experimental reactor at Dimitrovgrad (Russia). The high heat loads are generated by nuclear heaters made from massive tungsten blocks.

Fig. 9 shows a scheme of the irradiation rig. The tungsten heaters are pressed by a system of springs to the armour material. In order to avoid bending stresses, an individual tungsten heater was used for each tile of the mock-ups. In order to improve the heat transfer to

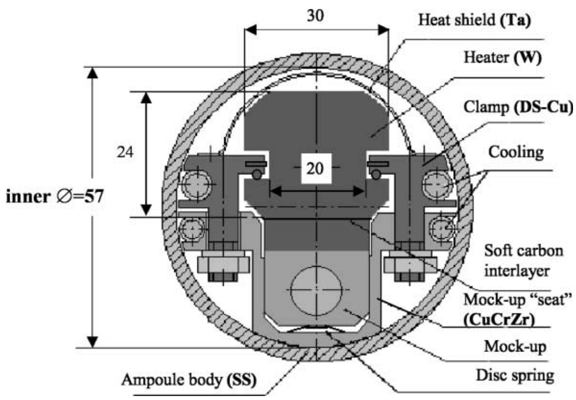


Fig. 9. Cross section of the test rig.

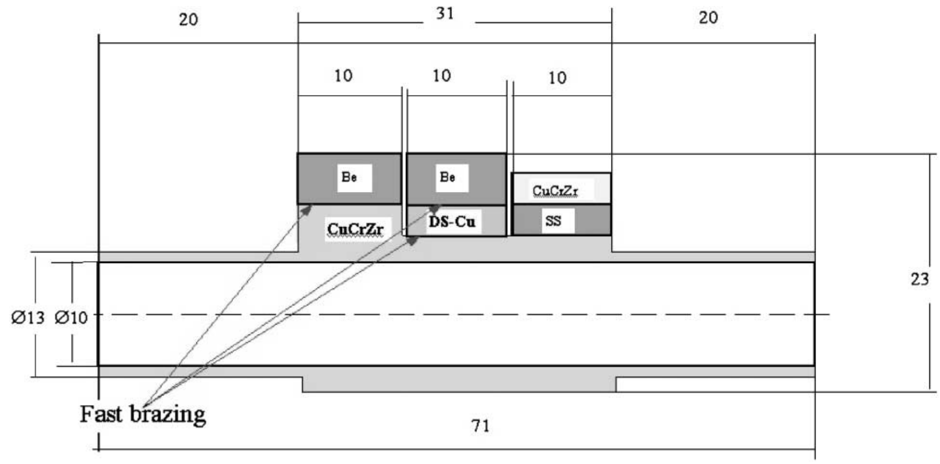


Fig. 10. Beryllium–copper sample for in-pile test.

the mock-up, soft carbon sheets (Papyex) of 0.3 mm thickness were placed between heater and sample surface. Calculations showed that the tungsten heaters reached temperatures up to 2300 °C, and additional measures had to be taken against radiation heat losses. Therefore a tantalum heat shield was installed around the open edges of the heaters. By this measures the radiation heat escape was reduced from 15% down to 5–7%.

The environment of the samples was helium on the outside, and cooling was performed by means of the water from the reactor tank (inlet temperature: ~70 °C, velocity: ~8 m/s, pressure: ~5.2 MPa).

Cycling of thermal and neutronic loads has been provided by simple periodical pulling of the rig from the high flux regime of the reactor.

All necessary parameters such as fast neutron flux, its distribution along the core height, heat release for different materials were repeatedly tested and well known before the experiments. On the base of these data, thermal and mechanical working modes, including estimated heat fluxes have been calculated by finite element methods. During the in-pile experiments, power meters equipped with thermo couples have been installed in a line next to the tested mock-ups. From the measurement it was possible to get the ratio of calculated and real heat loads.

3.2. Testing of mock-ups

Two CFC/Cu mock-ups (similar to the ones shown in Fig. 1(a) and (b)) and a Be/Cu mock-up have been irradiated in different testing campaigns.

One of the CFC mock-ups was of monoblock type the other one of flat tile design (similar to the ones shown in Fig. 1(a) and (b), respectively). In both cases SEPcarb NB31 was used as armour material and CuCrZr as heat sink. The monoblock was joint by hot isostatic pressing, and the flat tile mock-up by active metal casting and electron beam welding [11]. Before the in-pile testing, the mock-ups were checked through screening tests in the JUDITH facility.

For the beryllium – copper mock-up the Russian beryllium grade TGP-56 was used as an armour material, and CuCrZr as well as DS–Cu were used for the heat sink. A schematic drawing of the Be/Cu mock-up is shown in Fig. 10. [1]

To provide ITER relevant temperature gradients, both Be/CuCrZr and Be/DS–Cu joints were actively cooled during the in-pile test. Russian fast brazing technique [12] with STEMET 1108 amorphous alloy ($T_{braz} = 780$ °C, soak time 5 s) was used to join the armour to the heat sink. All joints were brazed simultaneously.

All three mock-ups were loaded up to 1000 cycles. The maximum neutron flux ($E > 0.1$ MeV) was 4.9×10^{14} $n\,cm^{-2}\,s^{-1}$, leading to a damage rate of 0.2 dpa in CFC or 0.15 dpa in beryllium. The effective test duration was ~186 h, with ~600 s per cycle in full power position.

Heat flux for all three mock-ups during the experiments was estimated as 7.5–8 MW/m^2. Post irradiation inspection of the samples showed them in good condition. None of them was detached, destroyed or melted. The clamping mechanism between heaters and mock-ups kept good elasticity and pressing ability; hence the heat transfer was guaranteed during the whole irradiation experiment.

[1] The segment of the mock-up with CuCrZr/SS joint was not part of the thermal cycling experiment, as no tungsten heater was installed on this part of the mock-up.

In order to get information on any degradation effects during the neutron irradiation, the screening tests in JUDITH will be repeated at the two CFC mock-ups after re-transport from Dimitrovgrad. All samples will be inspected by hot metallography.

4. Summary and conclusions

High heat flux tests with neutron irradiated samples have been carried out in the electron beam facilities JUDITH and OHBIS. The aim of these tests was to simulate ITER relevant loading conditions on plasma facing materials and their joints.

In JUDITH, plasma facing materials irradiated up to 0.35 dpa at 350 and 700 °C have been tested. Plasma facing materials were CFC, beryllium and tungsten and heat sinks were made from copper alloys. In OHBIS, neutron irradiated CFCs and CFC/DSCu mock-ups, irradiated with 0.3–0.4 dpa at 300 °C, were tested in thermal shock and thermal fatigue experiments, respectively.

After neutron irradiation, all actively cooled samples showed a good reliability of their joints during thermal fatigue tests. For beryllium–copper mock-ups no change of the heat removal efficiency was observed. But for CFC mock-ups the degradation and recovery of the thermal conductivity, due to neutron irradiation and temperature induced annealing, is an important effect for the evaluation of the performance for plasma facing components.

In thermal shock experiments with CFC materials, a slightly increased erosion is observed after neutron irradiation. This again is attributed to the reduced thermal conductivity. For beryllium a pore formation is observed in the melt layer due to the helium and tritium production under neutron irradiation.

Electron beam tests of irradiated samples are not able to simulate the superposition of nuclear and thermal loads. In order to study the synergistic effects, in-pile thermal fatigue experiments have been performed in the SM2 fission reactor in Dimitrovgrad (Russia). Two CFC/Cu mock-ups (monoblock and flat tile design) and one Be/Cu mock-up have been tested up to 1000 cycles and 0.2 dpa approximately at power densities of 7.5–8 MW/m^2. A first evaluation showed good performance of all three mock-ups.

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