ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 967–971

journal of nuclear materials

Testing of actively cooled high heat flux mock-ups

M. Rödig [a,*], R. Duwe [a], W. Kühnlein [a], J. Linke [a], M. Scheerer [a], I. Smid [b], B. Wiechers [a]

[a] *Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany*
[b] *Forschungszentrum Seibersdorf, A-2444 Seibersdorf, Austria*

Abstract

Several un-irradiated CFC monoblock mock-ups have been loaded in thermal fatigue tests up to 1000 cycles at power densities <25 MW/m^2. No indication of failure was observed for these loading conditions. Two of the mock-ups were inspected by ultra-sonic methods before thermal cycling. It could be proved that the voids found in the post-mortem metallography existed before and had no effect on the integrity of the mock-up. For the first time, neutron-irradiated CFC monoblock mock-ups have been tested in the electron beam facility JUDITH. These mock-ups had been irradiated before in the High Flux Reactor at Petten up to 0.3 dpa at 320°C and 770°C. All samples showed a significant increase of surface temperature, due to the irradiation induced decrease in thermal conductivity of the CFC materials.

1. Introduction

High heat flux components of ITER will be exposed to heat loads of up to 5 MW/m^2 under normal and 20 MW/m^2 under transient conditions. In order to remove these high heat loads, tiles of a plasma compatible armour material must be attached to a water-cooled heat sink. Candidates for plasma facing materials are beryllium, tungsten and carbon reinforced carbon materials (CFCs). Heat sink materials are copper alloys and, as a back-up, molybdenum alloys. Several joining processes have been developed for the attachment of the plasma facing materials to the heat sinks. In order to assess these bonds, high heat flux tests with actively cooled mock-ups have been carried out in the electron beam facility JUDITH. The results for beryllium–copper modules have been reported elsewhere [1,2]; this paper deals with the high heat flux performance of CFC monoblock modules.

In former experiments, only un-irradiated mock-ups have been tested. But during the operation of ITER, the first wall and divertor components will be affected by 14 MeV-neutrons. In order to study the degradation of material properties under neutron irradiation, the irradiation experiment PARIDE has been performed in the High Flux Reactor (HFR) at Petten, The Netherlands. First mock-ups from this irradiation experiment have been tested under screening and thermal fatigue conditions in JUDITH.

2. Experimental details

2.1. Samples

Fig. 1 shows the drawing of the CFC monoblocks. Three different CFC armour materials were used: Dunlop Concept 1, SEPcarb N31 and SEPcarb N112. Heat sink tubes were made from Glidcop Al25, CuCrZr and Mo5Re. All samples were produced by Plansee AG by active metal casting (AMC®). After drilling, the CFC tiles were coated with liquid copper at 1250°C; Ti additives were used as carbide formers. Then the tubes made from the two copper alloys were brazed in by means of pure titanium [3]. The Mo5Re tubes were joint in one step with the AMC.

2.2. Test facility

The electron beam facility JUDITH in general was described in [4]. It consists of an electron gun of 60 kW

* Corresponding author. Tel.: +49-246 1616 383; fax: +49-246 1616 464; e-mail: m.roedig@fz-juelich.de.

0022-3115/98/$19.00
PII: S0022-3115(98)00081-6

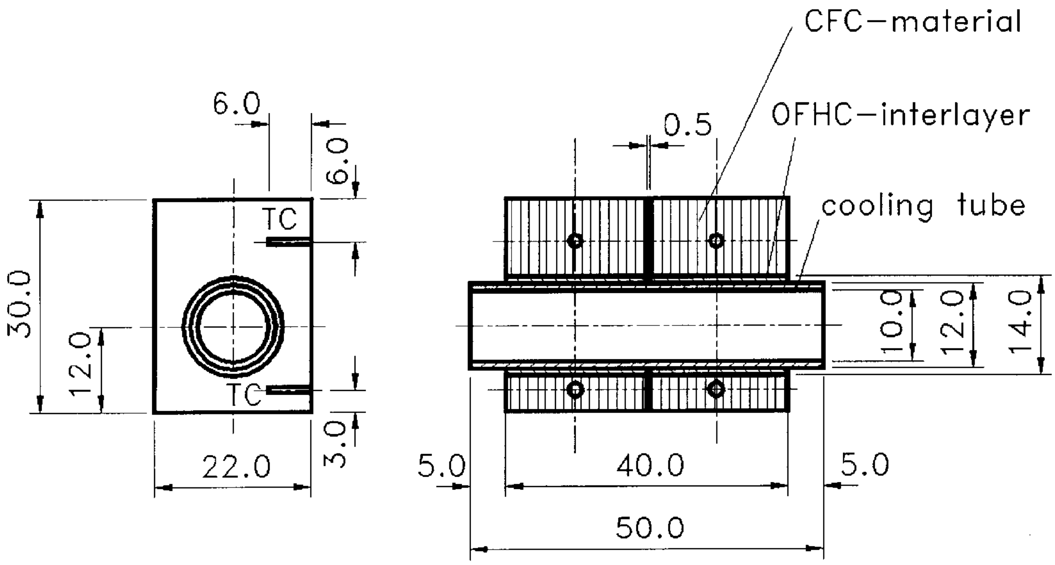


Fig. 1. Drawing of CFC monoblock mock-up.

electric power and a number of powerful diagnostic devices. The heating of the mock-ups is performed by sweeping of a focussed electron beam (≈1 mm ∅) over the sample surface at high frequencies up to 100 kHz. During the thermal heating tests, the heat sink tubes are water-cooled (water pressure: 40 bars, flow rate: 50 l/min). A swirl is mounted inside the tube to improve the burn-out behaviour. The following diagnostics have been used in the tests reported in this paper:

- infra-red camera system (RT–3000°C),
- one-colour pyrometer (200–1100°C),
- two-colour pyrometers (550–1600°C and 1000–3500°C),
- video camera,
- thermo-couples,
- instrumented cooling loop (flow rate, in/outlet temperature).

For the investigation of neutron-irradiated samples, some modification to former testing procedures were required. These modifications concerned on one hand the samples and on the other hand the testing facility.

Due to the limited space in the neutron irradiation rig, the samples had to be miniaturized. Therefore the length of the cooling tubes exceeded the length of the CFC tiles only by 5 mm on each side of the module. This was not sufficient for commercial squeezing or flange connectors, and a special clamping mechanism was developed. For installing, the radioactive samples are placed on a small tray which is transported to the clamping mechanism by manipulator. When the sample is in the correct position, the water connectors are clamped to the sample. This is performed by a motor while the force is controlled by a load cell. Sealing is achieved by special sealing adapters machined from soft copper in combination with O-ring sealings and springs. The whole clamping system is attached to the door of the vacuum chamber of JUDITH. Once the sample has been installed, the door is closed and the sample is in the correct shooting position.

For better comparison, the samples in the pre-irradiation reference tests were designed identically to those of the post-irradiation experiments.

2.3. Evaluation of data

The power absorbed by the mock-up during high heat flux loading P_{abs} can be calculated directly from the increase of cooling water temperature. If the absorbed power is compared to the incident electrical power, an absorption coefficient of 80–85% is found for CFC monoblock modules.

Therefore the absorbed power can be measured rather exactly, but the definition of power density is more complicated. During the heat loading, the area covered by the electron beam is a little smaller than the total surface. If the power density is calculated, the value depends strongly on the assumed loading area (heated area or total surface area). For the assessment of the joints, a power density which refers to the total surface area D_t is thought to be more suitable and the corresponding numbers are used in the following.

2.4. Neutron irradiation experiment PARIDE

The neutron irradiation experiment was performed in the High Flux Reactor in Petten. More than 600 samples of beryllium, CFC and tungsten alloys have been irradiated in this campaign. Nominal loading conditions were 0.5 dpa at 350°C and 700°C, respectively. The actual irradiation condition differed more or less from these nominal values according to the position of samples in the reactor. For the CFC monoblock mock-ups which are discussed in this paper, the following irradiation conditions must be assumed:

330°C, 0.30 dpa (according to $= 0.33 \times 10^{25}$ m^{-2}, $E > 0.1$ MeV), 49.6 full power days,

770°C, 0.35 dpa (according to $= 0.37 \times 10^{25}$ m^{-2}, $E > 0.1$ MeV), 23.7 full power days.

3. Results

3.1. Testing of un-irradiated mock-ups

Three CFC monoblock mock-ups have been exposed several times to 1000 heating cycles (10 s heating, 10 s cooling) at different power densities. Aim of these tests was on one hand to study the heat removal efficiency of the different variants and on the other hand their performance under thermal cycling conditions as they are expected in the operation of ITER. The tested materials combinations and power densities D_t were:

SEPcarb N31/ Glidcop: 7, 18 MW/m^2,

Dunlop Concept 1/ Glidcop: 7, 15, 19 MW/m^2,

Dunlop Concept 1/ CuCrZr: 7, 15, 24 MW/m^2.

A more detailed description of the loading conditions is given in [5].

The surface temperature measured by means of the infra-red camera showed strong fluctuations. Normally (e.g. in the case of Be/Cu mock-ups) this is an indication of a bad braze connection. But here strong fluctuations in the thermal conductivity of the CFC materials are responsible for this behaviour [6]. Such fluctuations lead to differences of the surface temperature of up to 200°C. In spite of this non-uniformity, the thermal fatigue behaviour of the three mock-ups was excellent. Each of the modules was loaded several times up to 1000 heating cycles at different power densities, but no failure or degradation was observed. The distribution of surface temperatures measured by the infra-red camera stayed stable during all tests, this is an indication that no failure occurred during the tests.

In the post-mortem metallography of the first mock-up (SEPcarb N31/Glidcop), small voids up to 1 mm approximately were observed in the braze layer. It was assumed that these voids were generated during the production process. In order to clarify this topic, the two other mock-ups were inspected by ultra-sonic methods before they were loaded with the last 1000 heating cycles at the highest power densities. Fig. 2 compares the result of this ultra-sonic inspection with the post-mortem metallography (mock-up Dunlop Concept 1/Glidcop). This ultra-sonic inspection is performed with a transducer inside the copper tube. The left picture shows the two-dimensional map of the intensity of reflection. Areas with a high reflectance (red) are a sign for pores, voids or detachments. By comparison of these areas with the post-mortem metallography (right picture) it becomes clear that the voids in the braze at angular positions of 210° and 310° existed before the heat cycles were applied. Nevertheless, they were stable during the thermal fatigue loading.

3.2. Post-irradiation testing

After neutron-irradiation, most of the mock-ups were optically in a good condition. In the screening tests, one mock-up showed over-heating during loading by the electron beam (SEPcarb N31/Glidcop $T_{irr} = 350°C$). But it cannot be proven that this fault was due to the neutron irradiation.

Only a limited number of mock-ups was pre-tested in screening experiments before they were irradiated in the fission reactor (mock-ups with Mo5Re heat sink tubes). The other irradiated mock-ups have to be compared with identical reference samples of the same materials combination (modules with Cu tubes).

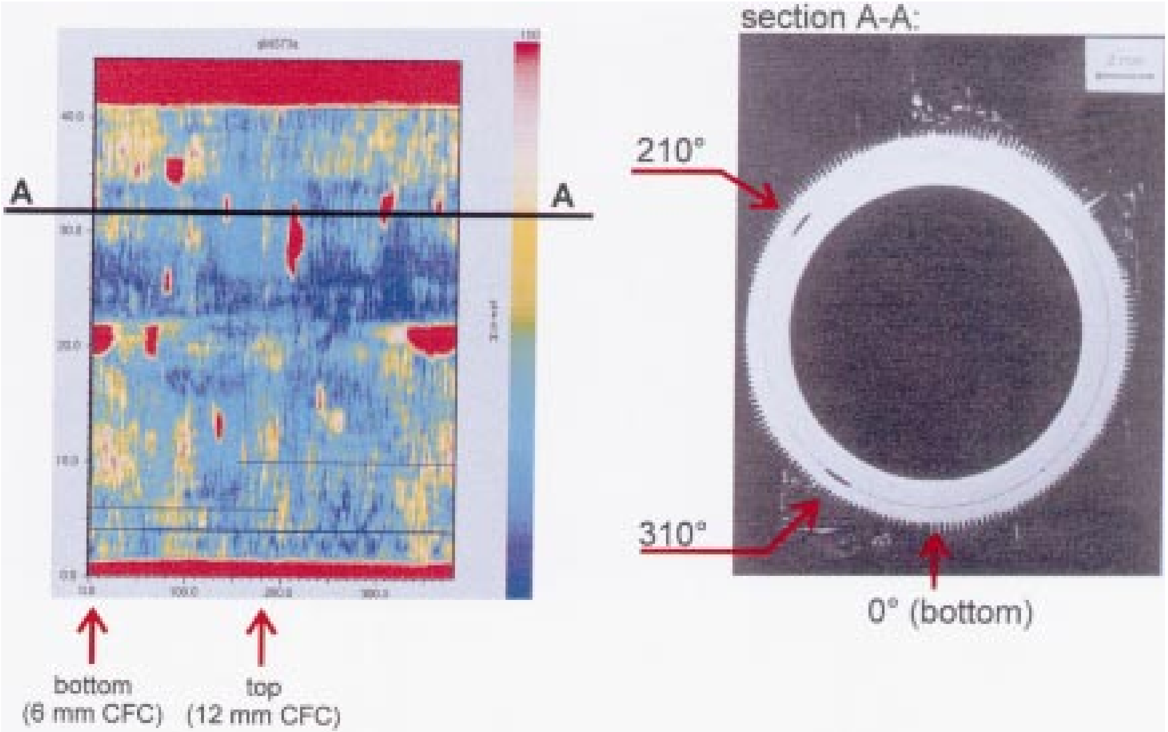
3.2.1. Mock-ups with Mo5Re tubes

Identical monoblock mock-ups with Mo5Re heat sink tubes were compared in the electron beam facility at constant power densities before and after neutron-irradiation ($T_{irr} = 770°C$). Fig. 3 gives an example for such a comparison for a mock-up made from Dunlop Concept 1. The distribution of surface temperatures measured by the infra-red camera did not change after neutron irradiation, but the surface temperature increased significantly. In Fig. 4 for three mock-ups with different CFC armor the surface temperatures (measured by pyrometer) are plotted versus the absorbed power density. In all cases a significant increase of temperature after exposure to neutrons is observed. This is due to a decrease in thermal conductivity which was reported before for the CFC material SEPcarb N112 [7], and which is expected for the other CFC materials too [8]. The exact values of thermal conductivity will be available later from samples which had been included in the irradiation experiment PARIDE.

Dunlop Concept 1 which before irradiation had the best thermal conductivity of all three CFCs, was more influenced by the neutron irradiation than SEPcarb N31 and shows a higher increase of surface temperature than the latter. SEPcarb N112 shows the lowest thermal conductivity of the three CFCs before and after neutron irradiation.

3.2.2. Mock-ups with copper tubes

In a second test series, CFC monoblock mock-ups with copper heat sink tubes were loaded under screening



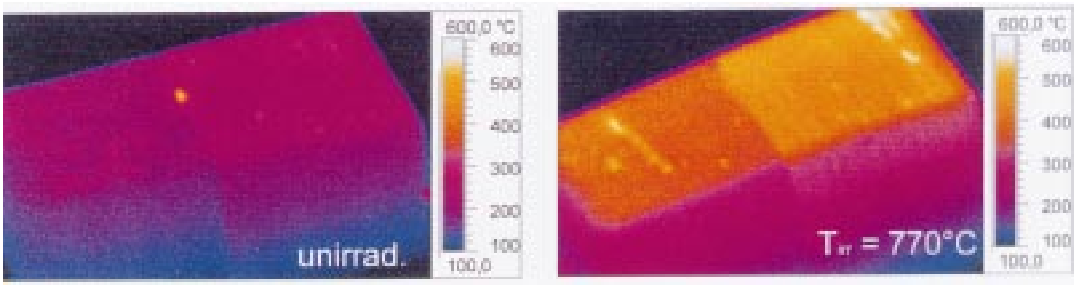


Fig. 2. Comparison of ultrasonic inspection (left) and post mortem metallography (right).

Fig. 3. Infra-red image of a monoblock mock-up made from Dunlop Concept 1 and Mo5Re, power density $D_t = 2$ MW/m^2.

conditions (steady state) from the top (12 mm CFC) and from the bottom (6 mm CFC) side. The tests were limited to surface temperatures below 2200°C, according to power densities of 10 and 15 MW/m^2 approximately. After screening, all samples were loaded by 100 heating cycles at power densities between 8 and 15 MW/m^2 and one sample (Dunlop Concept 1/Glidcop) up to 1000 cycles at 15 MW/m^2. None of these samples showed failure or any instabilities.

Due to the better annealing effects of irradiation damages with increasing temperature, the decrease of thermal conductivity for the samples irradiated at 770°C was found to be less distinctive. This is shown in Fig. 5 for the materials combination Dunlop Concept 1/Glidcop.

4. Summary

No indication of failure was observed for CFC monoblock mock-ups loaded under thermal fatigue condition up to 1000 cycles at power densities $\leqslant 25$ MW/m^2. Two of the mock-ups were inspected by ultrasonic methods before the last campaign of thermal cy-

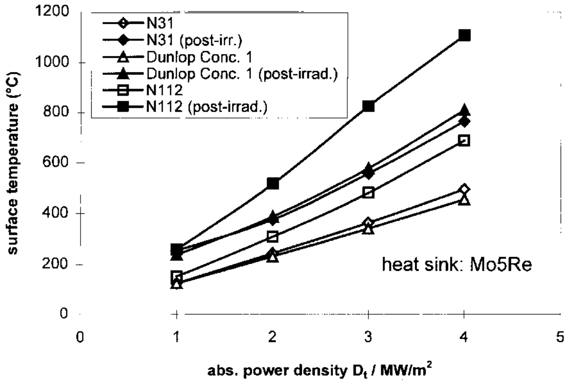


Fig. 4. Surface temperature during electron beam loading before and after neutron irradiation for three CFC materials brazed to Mo5Re tubes.

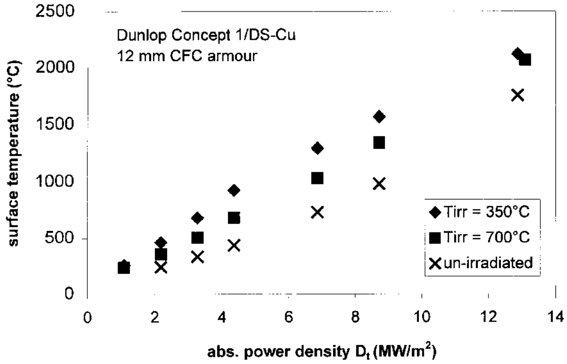


Fig. 5. Surface temperature during electron beam loading for three CFC mock-ups (unirradiated, $T_{irr} = 350°C$ and $T_{irr} = 700°C$).

cling. It could be proved that the voids found in the post-mortem metallography existed before and had no effect on the integrity of the mock-up.

First neutron-irradiated CFC monoblocks have been tested in the electron beam facility JUDITH. These mock-ups had been irradiated in the High Flux Reactor in Petten up to 0.3 dpa at 320°C and 770°C. All samples showed a significant increase of surface temperature, due to the decrease in thermal conductivity of the CFC materials. This effect is less distinctive for those samples irradiated at the higher temperature of 770°C. During short thermal fatigue tests (100 cycles at 8–15 MW/m^2) no failure or instability occurred at any of the mock-ups.

Acknowledgements

The authors would like to acknowledge the help of F. Meuser in the preparation of the neutron-irradiation experiment. H. Klöcker and H. Münstermann assisted in the electron beam experiments. In addition V. Gutzeit and H. Hoven assisted in the metallographic examination.

References

[1] M. Rödig, R. Duwe, J. Linke, A. Schuster, B. Wiechers, Proceedings of the 3rd IEA International Workshop on Beryllium Technology for Fusion, Mito City, Japan, 22–24 October 1997.
[2] M. Rödig, R. Duwe, J. Linke, A. Schuster, Fusion Eng. Design 37 (1997) 317.
[3] G. Vieider et al., in: C. Varandas, F. Serra (Eds.), Fusion Technology 1996, Elsevier, Amsterdam, 1997, p. 275.
[4] R. Duwe, W. Kühnlein, H. Münstermann, Proceedings of the 18th Symposium on Fusion Technology (SOFT), Karlsruhe, Germany, 22–26 October 1994, p. 355.
[5] M. Rödig et al., Proceedings of the 4th International Symposium on Nuclear Fusion Technology (ISFNT-4), Tokyo, to be published.
[6] M. Rödig, R. Duwe, A. Gervash, J. Linke, A. Schuster, Phy. Scripta 64 (1996) 60–66.
[7] D. Moulinier, PhD thesis, Conservatoire National des Arts et Metiers, Paris, 1996.
[8] V. Barabash et al., these Proceedings.