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Progress in high heat flux testing of European DEMO divertor mock-ups

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In the framework of the DEMO divertor project of EUROfusion an extensive R&D program has been carried out to develop advanced design concepts for hot water cooled divertor targets. These plasma-facing components made of W blocks as plasma facing material and CuCrZr as cooling tubes should allow a reliable DEMO operation for 2 h long pulses and maximum heat fluxes up to 20 MW/m². Compared to ITER, the operation at the higher coolant temperature of 150 °C, the longer required lifetime, and the significantly higher neutron fluence are the design challenges exceeding the current extent of experience. In this study we present HHF test results of a total of 34 tested W monoblock mock-ups. 14 of them where tested with 20 MW/m² heat flux at DEMO hot water cooling conditions up to now. All tests were performed in the HHF test facility GLADIS from 2016 to 2018. We discuss results from the post exposure investigation of selected concepts of the first R&D phase.

Keywords: Tungsten, Divertor, Monoblock, Plasma-Facing Components, DEMO, High Heat Flux Tests

1. Introduction

In the framework of the EUROfusion DEMO divertor project (WP-DIV) an extensive R&D program has been carried out to develop advanced design concepts for hot water cooled divertor targets [1][2]. These plasma-facing components (PFCs) made of W blocks as plasma facing material (PFM) and CuCrZr as cooling tubes should allow a reliable DEMO operation for 2 h long pulses at nominal 10 MW/m² and maximum heat fluxes during slow transients events (< 10 s) up to 20 MW/m² [3].

The ITER Full-W divertor qualification program has pushed strongly the world-wide development of manufacturing technologies of W monoblock PFCs. Intensive high heat flux (HHF) tests of ITER mock-ups, up to 5000 cycles at 10MW/m² and 1000 cycles at 20 MW/m², have confirmed the achieved quality [4][6].

Compared to ITER, the operation at higher coolant temperature of 150 °C, the longer required lifetime, and the significantly higher neutron dose (4 dpa in W armour, 13 dpa in the divertor cooling tubes during two full power operation years [3]) are the design challenges exceeding the current extent of experience. The expected embrittlement of W and Cu based materials requires the development of new concepts for the specific operation in DEMO. Therefore the development and HHF assessment of six different W monoblock design concepts for the water-cooled DEMO divertor target are under investigation. Information in more detail about the design rationales, the material interfaces and the structure of the project are published elsewhere [3][7]. Further details of the design, manufacturing and testing are given in the literature, e.g. [8][9][10][11].

In general, two classes of monoblocks concepts have been tested in the HHF test facility GLADIS [12]. The so-called “ITER optimized” with W block dimensions of 28x30x12 mm³, 7 mm PFM thickness. And, secondly, so-called “DEMO” concepts with smaller dimensions to reduce temperatures and stresses. W block dimensions are: 22x24x4 mm³, 5 mm PFM thickness. The mock-ups are equipped with W blocks provided by A.L.M.T. Corp. (Japan) and AT&M (China). Most of the mockups were manufactured by hot radial pressing performed by ENEA, or brazing and hot isostatic pressing performed by different European manufacturers. Details are given in the above mentioned references.

The purpose of this paper is to present of the status of HHF testing within the WP-DIV project, not a final assessment of the tested concepts.

2. Strategy of HHF testing

The aim of the HHF tests is the evaluation of the different target concepts, the experimental validation of numerical predicted thermo-mechanical behaviour under DEMO relevant heat load and cooling conditions and finally the selection of the most promising concept(s) for further development.

A two-step procedure was applied to efficiently use the limited HHF test resources. Therefore, a first step at cold water, low pressure (20°C inlet, 1MPa static pressure, 12

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m/s axial velocity) was performed for each component as "initial quality assessment" to reduce risks & operational costs of the test facility:

- Screening from 6 to 25 MW/m², 5 cycles each step,
- 100 cycles at 10 (15) MW/m² as low cycle test.

After having passed this assessment without damage the hot water, high pressure tests (130°C inlet, 4 MPa pressure, 16 m/s axial velocity) were performed as second step.

- Screening from 6 to 20 MW/m², each component,
- 100 cycles at 20 MW/m², each component,
- 500 cycles at 20 MW/m² as low cycle fatigue, one component of each concept at least.

For selected concepts of R&D phase II it is foreseen to extend the 20 MW/m² cycling significantly.

3. High heat flux loading

3.1. Heat transfer conditions and critical heat flux of cold and hot water cooling

This section describes shortly the differences between 20°C cold- and 130°C hot water cooling related to the 150°C design water temperature of DEMO. It is easy to understand that the heat flux concentration at the inner wall of the cooling tube of a one-side heated monoblock component is crucial for its thermal performance. The so-called peaking describes the concentration of heat flux at the inner cooling tube compared to the heat flux incident on the loaded surface of the component. The peaking factor depends on the component design e.g. ratio of width and cooling tube diameter, thermal conductivity of materials and thickness of the component. For the W monoblock components investigated in WP-DIV we can assume a peaking factor of 1.5 – 1.8. This means, during operation at 20 MW/m² surface load the resulting local heat flux at the inner cooling tube of 30 – 36 MW/m² requires a safe heat transfer. Taking into account a design safety margin of 1.4 [7] to the critical heat flux (CHF) calculated according to TONG75-CEA [13], the cold water cooling conditions applied in GLADIS allow HHF test up to about 28 MW/m² component load (45 MW/m² at inner tube). The heat flux limit of the hot water test is reduced to ≤22 MW/m² component load (35 MW/m² at inner tube). Due to the higher water velocity of 16 m/s in GLADIS compared to 15 m/s in the DEMO design, the heat transfer and the CHF are equal despite the slightly lower static pressure.

2.2. Loading and surface temperature measurement

The actively water cooled mock-ups reached thermal equilibrium after ~7 s meaning a constant temperature and stress profile across the sample. Therefore, all cycle tests were performed with 10 s loading followed by 50 or 80 s cooling, respectively. The applied hydrogen neutral beam (150 mm FWHM) ensures a simultaneous and homogeneous heating of all monoblocks of the mockups as shown in Fig. 1.The outer monoblocks are loaded with 95% of the central heat flux. The comparison between the calorimetrically measured absorbed power and the calculated incident power is in an agreement within ±5%. The central surface temperature of the exposed mock-ups was measured with one- and two-colour pyrometers as well as monitored by an infrared camera Infratec VARIOCAM HD. The two-colour pyrometer (Ø8mm focus, λ=1.4-1.75µm, temperature range 500-1700 °C) was used as reference for the emissivity determination of the one-colour pyrometer (Ø22mm focus, λ=2.0 – 2.2 µm, temperature range 350 – 3500°C) and the IR camera. A crucial point of reliable surface temperature measurements of such W components is the surface modification during HHF cyclic loading and of course, the pyrometer spot sizes compared to the monoblock dimensions. All presented temperatures are IR camera measured average values over the loading campaign due to the change of the emissivity during loading and fluctuations of the beam power. Only for measurements during screening the obtained pyrometer data are reliable within an accuracy of ±5% of due to the change of the emissivity during cyclic loading and fluctuations of the beam power.

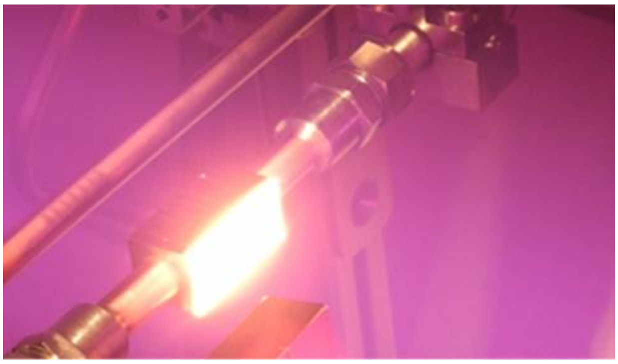

Fig. 1: Arrangement of the mock-ups in GLADIS. The image shows a DEMO type mockup with 12 W blocks at 20 MW/m² loading. The mock-ups were fully loaded in the neutral beam. The water connectors are protected by beam scrapers. The scraper of the water outlet (lower left in the image) is visible.

3. Results and discussion

We applied 3300 cycles at 10 MW/m² cold water cooling and 4200 cycles at 20 MW/m² hot water cooling up to now. No unexpected serious defect occurred during cyclic testing of the various target concepts in total equipped with 244 monoblocks.

Fig.2 shows for seven different concepts the equilibrium surface temperatures versus applied heat flux up to 20 MW/m² at 130 °C water temperature. The observed temperature of beginning of recrystallization is marked at 1200 °C (more details are given below in section 3.1.) because recrystallization processes affect both the surface modification and crack formation, and therefore, the lifetime of the component. It should be noted, that the recrystallization temperature of W materials strongly depends on the manufacturing and the material composition. At heat fluxes up to 10 MW/m² the surface temperature is clearly lower than 1000 °C and no recrystallization should occur during long-term loading. At 15 MW/m² loading the surface region is close to the recrystallization temperature. Loading at 20MW/m² results in surface temperatures of 1600 – 2000 °C.

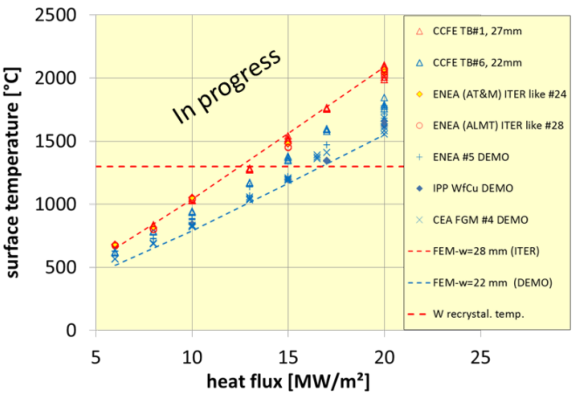

Fig. 2. Surface temperature of selected concepts depending on heat flux at 130°C, 4 MPa, v=16 m/s cooling. The temperature was pyrometrically measured in the centre of mock-ups.

The loading limits of the thermal break concept can be concluded from Fig.2. The concept mitigates the local heat flux and stress concentration at the cooling tube by inserting of an additional thermal resistor. The reduced thermal transfer in the centre increases the W/Cu interface and surface temperature significantly. The results of two tested mockups subjected to 20 MW/m² cyclic loads at hot water cooling illustrates the limit of the thermal performance. One of them (27 mm width of W blocks) shows the first visible damage after 150 cycles. The other one (22 mm width of W blocks) survived 500 cycles, however the first overheating of individual blocks occurred after 350 cycles. Further design details and HHF tests results are presented in reference [5][7].

Microscopic examination

We have performed a microscopic examination of two mock-ups loaded with 500 cycles at 20 MW/m² hot water cooling. The first one, ITER optimized, manufactured by ENEA and equipped with W blocks made by AT&M, shows strong surface modifications and swelling of the W blocks. It is noted for the following text, that the term “swelling” does not mean a nuclear radiation effect but an inelastic effect. First indications of swelling were visible after 100 cycles only. The manufacturing gap of 0.5 mm between blocks is nearly closed in the centre between the blocks as visible in Fig. 3. The effect increases with the thickness of recrystallized material as can be seen in Fig.4. The beginning of recrystallization measured in the micrograph corresponds to a finite element method (FEM) calculated temperature of 1170°C. The remaining 3 – 3.5 mm thickness of unaffected W material above the cooling tube is similar for all tested concepts, except the thermal break concept of CCFE. During long-term operation swelling could lead to damage of the component. In the past, we observed swelling of the same W material of other monoblock components with similar geometry tested at 500 cycles at 20 MW/m² in GLADIS. Swelling of Japanese ITER mockups loaded with 1000 cycles at 20 MW/m² in the electron beam facility IDTF is reported in the literature [6]. The swelling could mostly be interpreted as accumulation of a cyclic accumulation of creep strain and creep-plasticity interaction as described in reference [14]. In this publication, a numerical thermo-mechanical analysis of structural impact of creep in tungsten monoblocks (ITER like geometry) was performed. The structural impact of creep at 20 MW/m² heat loading was analyzed quantitatively with the aid of FEM. It turned out that creep of tungsten plays an important role for the structural behavior of tungsten targets. The numerical simulations have revealed that creep results in an increase of inelastic strain accumulation. With increasing armor thickness, the tensile surface stress along the width of the monoblock at the plasma-facing surface reduces, while the surface stress along axial direction of the cooling tube changes from tensile to compressive. Creep will accelerate this change.

However, the observed swelling during cyclic heat loading needs further investigation to mitigate the effect during long-term operation of DEMO.

In comparison to the swelling described above we do not observe noticeable swelling of DEMO geometry mockups (equipped with W made by A.L.M.T. Corp.) as can be seen in Fig. 5. The smaller W block dimensions and the lower temperatures during loading do not lead to swelling. The reduced thickness of the recrystallized material layer of 1.5 mm as shown in Fig.5 is based mainly on the smaller geometrical dimensions. According to FEM results the recrystallization of this W block started at 1150°C.

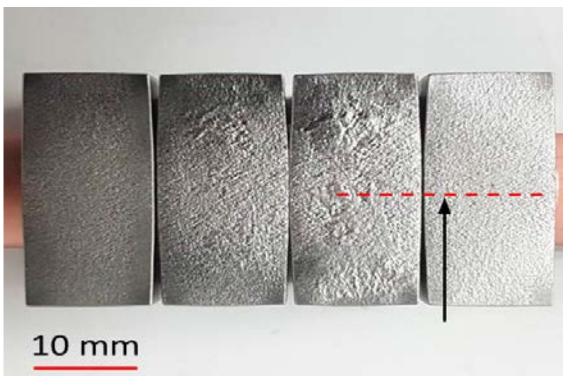

Fig. 3. Surface view on ENEA ITER like #11 after 500 cycles 20 MW/m² loading at hot water cooling.

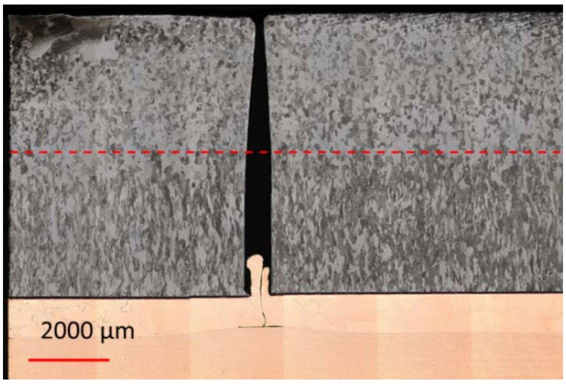

Fig 4. ENEA#11 axial cross-section 500 x 20 MW/m². The red dashed line marks the beginning of recrystallization. The total thickness of the W block is 7 mm.

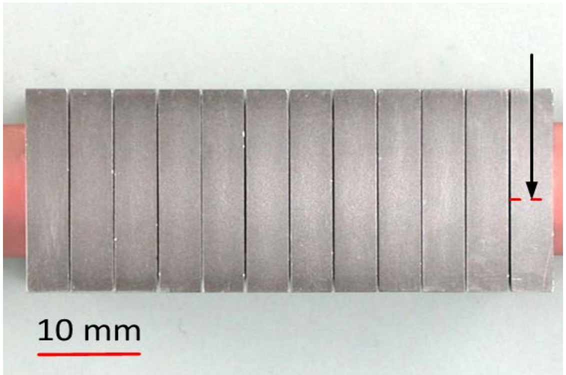

Fig 5. Surface view on ENEA DEMO #5 after 500 cycles 20 MW/m² loading at hot water cooling. The arrow marks the micrograph shown in Fig.4. The total thickness of the W block is 5 mm.

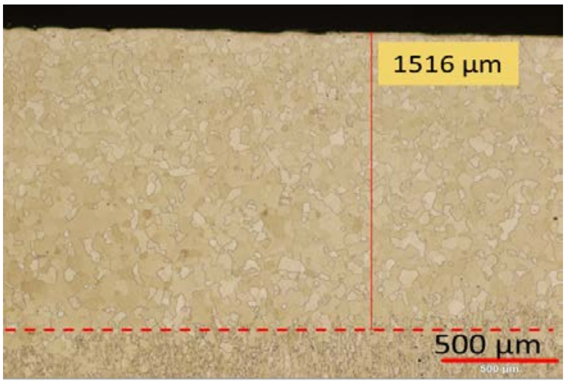

Fig 6. ENEA DEMO#5, tile 12 centre 500 x 20 MW/m²

4. Summary and conclusion

As mentioned in the introduction, this paper does not give a final assessment of the HHF tests performed on the newly developed DEMO divertor target concepts. Up to now, we applied 3300 cycles at 10 MW/m² cold water cooling and 4200 cycles at 20 MW/m² hot water cooling on XX mockups with the following results:

- No unexpected serious defect occurred during cyclic testing of the various target concepts.
- We do not see any surface cracks of the W monoblocks.
- The beginning of recrystallization started at 1150-1200°C for W blocks delivered by both manufacturers, AT&M and A.L.M.T.
- We could experimentally confirm the performed FEM predictions.
- We observed swelling and surface roughening of ITER like geometry W blocks tested with 500 cycles at 20 MW/m², 130°C cooling water.
- On W blocks of DEMO geometry tested at the same conditions, the swelling and the change of surface morphology is strongly suppressed.
- The hot radial pressing, performed by ENEA, is a reliable bonding process.

On the basis of our experiences we can conclude:

A number of European manufacturers are able to produce advanced W divertor PFCs for DEMO application. These water-cooled components are able to withstand 20 MW/m² cyclic heat load. The WP-DIV program achieved an important R&D progress in the development of DEMO divertor targets made of W monoblock PFCs. Further activities are necessary to develop HHF assessment criteria applicable to a series production.

From an engineering point of view, an optimized size of the W blocks should be developed taking into account the thermo-mechanical behavior under cyclic heat loading, the component behavior under high neutron fluxes, the expected erosion of W and of course, costs of a future reliable production of a high number of components in the order of 500.000 – 1.500.000 W monoblocks.

Acknowledgments

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