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Manufacturing and Testing of ITER-like Divertor Plasma Facing Mock-ups for DEMO

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Abstract— One of the most critical parts of a high heat flux plasma facing component of a Tokamak divertor is the armour to heat sink joint. R&D activity has been launched in the frame of the EUROFUSION Power Plant Physics & Technology programme and in particular in the Divertor project area in order to investigate the possibility of using the International Thermonuclear Experimental Reactor (ITER) design and fabrication technology in an EU-DEMO tokamak.

ENEA has being involved in the R&D ITER activities since several years developing suitable joining technologies for divertor plasma facing components fabrication. In fact, Hot Radial Pressing technique was used for the manufacturing of several small and medium scale prototypes that have been successful tested by e-beam thermal fatigue testing.

A new furnace was designed and installed at ENEA labs with the objective to extend the Hot Radial Pressing manufacturing technology to EU-DEMO relevant divertor plasma facing components. This new furnace uses the pipe heat sink of these components as heater, speeding up the heating phase and allowing a better control of the pipe temperature. Considering that in EU-DEMO the thermos-hydraulic operative conditions of these components are different from ITER a FEA parametric optimization was performed and the geometry of the small mock-up to be manufactured was defined accordingly. The six manufactured mock-ups were examined by Ultrasonic and SATIR non-destructive examination methods in order to check the quality of the joining before their delivering to the high heat flux tests facility GLADIS (DE) for the thermal fatigue testing at high heat flux.

This paper reports the manufacturing procedure used to obtain mock-ups, the non-destructive check results and the final high heat flux testing results.

1. Introduction

The main objective of this activity, performed in the frame of the Divertor project of EuroFusion programme is to investigate the feasibility and the range of applicability in DEMO of a water cooled divertor based on ENEA fabrication technology developed for ITER and here named 'ITER like' concept. The technology is those currently used for the fabrication the full scale plasma facing units of the ITER Inner-vertical target prototypes by Ansaldo Nucleare. At first a suitable geometry for the monoblock type design concept was studied and optimized regarding to W armour dimensions, CuCrZr tube diameter and thickness and mainly keeping into account DEMO thermo-hydraulic operational parameters. The considered DEMO divertor target design is the tungsten (W) armoured water-cooled monoblocks concept that has to be validated for DEMO operation [1].

2. FEA geometry optimization

Main European-DEMO design parameters and requirements that impact the divertor design have been defined from the 'Work Package Divertor (WPDIV) project and the hydraulic parameters used in FEA are the following:

- Water coolant pressure 5 MPa
- operating temperature of 150°C, to work with a reasonable safety margin (50-80°C) respect to the max working temperature before reach the critical heat flux
- coolant velocity 16ms-1 in order to have a good heat transfer but keep an acceptable pressure drop
- swirl tape (thickness: 0.8 mm, twist ratio: 2)
- steady state heat flux of 10MW/m² for normal operation and up to 20MW/m² for repeated slow transients.

The parameters to be optimized taken into account were:

- coolant tube inner diameter of 10, 11, 12, 13 and 14 mm
- tube thickness from 1.5 mm to 2 mm
- pure copper interlayer from 0.5 mm to 1.5 mm
- W block side dimension from 3 to 5 mm.

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These parameters were varied in such a way that the objective function, namely, the maximum temperature in the CuCrZr tube during thermal analysis and the maximum of von Mises stress in the tube during thermo-mechanical analysis, were minimized **Errore. L'origine riferimento non è stata trovata.**.

Particular attention was payed to boundary conditions (fig. 1) that reproduce the attachment system of plasma facing unit to cassette.

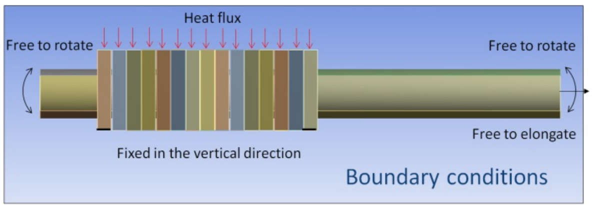

Figure 1. Boundary conditions for FEA calculations

By means of a 3D FEM analysis the geometry of the mock-up was optimized in terms of thermo-mechanical behavior by minimizing maximum stress in tube and W surface temperature [2]. Optimized mock-up geometry was identified and assessed in a 3D CAD model by 'Monoblock elastic analysis procedure' (MEAP) [9].

The current consolidated process to fabricate a target divertor for ITER has been assumed: W as armour material, Cu-OFHC as interlayer joined to W by casting process, CuCrZr-IG alloy (SAA and SAA cw) as heat sink material joined to the monoblocks by HRP process **Errore. L'origine riferimento non è stata trovata.**.

The armor thickness from the surface to the interlayer was fixed at 5 mm. The influence of the varying armor thickness on the thermal and structural performance was studied elsewhere [5]. The optimized dimensions resulting from the FEA analysis are as follows :

- Tube inner diameter: 12 mm
- Tube thickness: 1.5 mm
- Interlayer thickness: 1 mm
- Armor side thickness: 3 mm

3. Plasma Facing Component mock-ups

Figure 2 and figure 3 show the reference drawings of the W blocks where the dimensions are in agreement with the results of the FEA optimization. It has to be noted that the benefit of a block smaller size of W axial thickness and side width is confirmed also from [6].

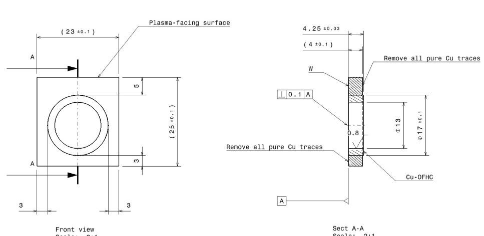

Figure 2 – W block drawing with 4 mm axial thickness

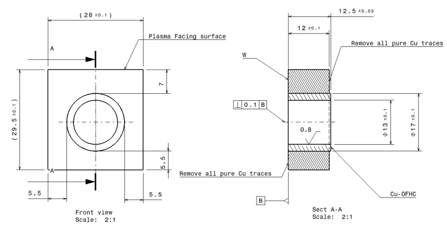

Figure 3 – W block drawing with 12 mm axial thickness

The material procurement, mainly the W blocks, where purchased from two suppliers ALMT Corp. Japan and AT&M China.

Blocks from AT&M where in the final shape and with the 1 mm thickness copper interlayer in the hole too. The copper interlayer is obtained by HIPing.

ALMT blocks where procured without copper interlayer. The interlayer was obtained by Cu-casting performed in ENEA. The quality of the interlayer was checked in ENEA by ultrasonic technique applying the same ITER acceptance criteria for W-blocks.

CuCrZr tubes were supplied by Kabel MEtal DE with the final diameters dimension (15 mm OD, 1.5 mm thickness), chemical composition and thermal-treatments in agreement with technical specification issued by WP-DIV project.

A very thin Ni coating (5 micrometre) by electrodeposition is applied onto the CuCrZr tubes to assure a good joining quality.

The drawings of the mock-ups are shown in figure 4. Drawing in the right side of the figure shows the dimension and the assembling of mock-up with optimized W blocks for DEMO while in left side of the figure is shown mock-up with ITER geometry without any optimization (W-block with 12 mm axial thickness).

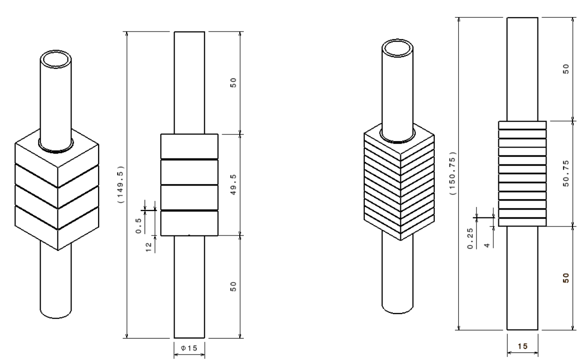

Figure 4 – Drawings of the two mock-up types

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In this way the two concept geometries are compared respect to their performance when tested under thermal fatigue in the testing facility GLADIS. Three mock-ups for each type were manufactured.

The manufacturing of all mock-ups was performed by means of the same technique. HRP was used for the joining of CuCrZr tube and W-blocks with Cu interlayer. Diffusion bonding of copper to copper was achieved at a temperature of about 600 °C under vacuum with a hold time of 2 hours. During this time and inside the tube a pressure of 50 MPa by argon gas is applied.

According to WP-DIV project programme six mock-ups were manufactured in ENEA by the new DEMO-HRP equipment. This new equipment was used to reduce the heating and cooling time of the process in order to minimize properties material degradation due to the effect of temperature on thermal treated materials (i.e. CuCrZr). In fact, the heating in this furnace is achieved using the CuCrZr tube of the mock-up as heater. A high current passes in the material heating itself by Joule effect. The temperature control is achieved modulating this current with good accuracy. The new furnace assembly allow a precise measurement of the pipe temperatures during the joining process because several thermocouples are installed inside the pipe and located in the W-blocks zone. Respect to the ITER full scale vertical target units manufacturing process the internal pressure is also reduced from 60 MPa to 50 MPa.

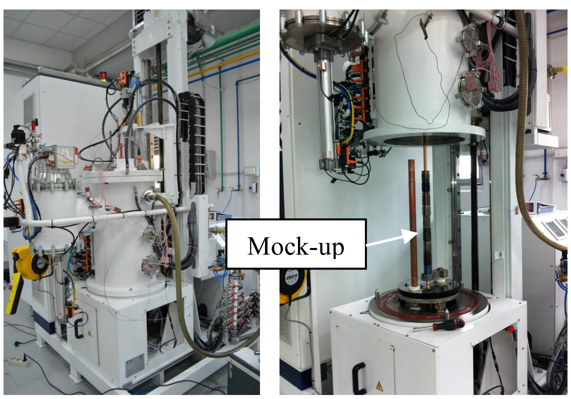

Figure 5 - New DEMO-HRP equipment during mock-up assemby

Figure 6 shows a picture of the three mock-ups named #005, #007, #008 with 4 mm thickness W blocks while figure 7 shows a picture of the three mock-ups named #009, #011, #012 with 12 mm thickness W blocks

Figure 6 - Picture of the three mock-ups named DEMO-like #005, #007 and #008 with 4 mm thickness W blocks

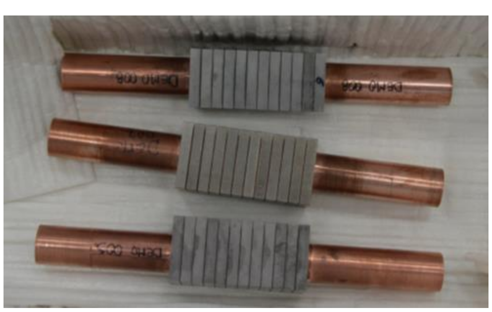

Figure 7 - Picture of the three mock-ups named ITER-like #009, #011 and #012 with 12 mm thickness W blocks.

4. Non-destructive tests

Before the foreseen thermal fatigue testing in GLADIS facility, the mock-ups were checked in the thermography test bed SATIR [8] to evaluate the overall thermal conductivity of a joint PFC by using a moderate internal heat source (i.e. hot water) for detecting bond defects of blocks and by ultrasonic technique (UT) in ENEA in order to check the quality of the materials joints.

SATIR results revealed no thermal imperfection for 86% of the blocks (no debonding at interfaces, nor degraded coefficient heat exchange in the cooling channel, nor degraded thermal conductivities of CuCrZr/tungsten). For blocks #1 and #12 (external) of mock-up #7 and three for mock-up #008 (1, 11 and 12), thermal imperfections were detected and attributed to a poor quality of interface joint.

This behaviour is in agreement with UT as shown in the figure 8 where the c-scan plot of the amplitude signal is reported. The yellow/red zones indicate reflections at the tube-to-copper interlayer joint.

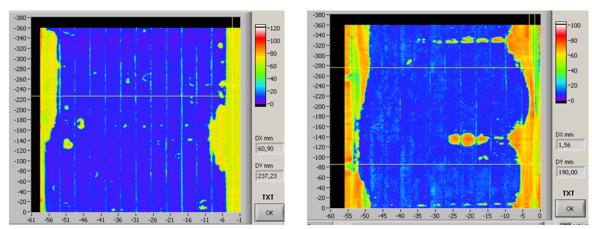

Figure 8: UT C-scans results for #007 and #008 mockups

Figure 9 shows instead the UT C-scan for mock-up #005 where a perfect tube joining is evident.

The ultrasonic check for #009,#0011and #0012 mock-ups did not show any joining defects.

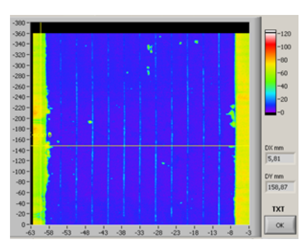

Figure 9: UT C-scan results for #005 mockup

All mock-ups where sent to GLADIS HHF testing including mock-ups #007 and #008. These two mock-ups can give information on acceptance criteria of such

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component by studying the defect evolution when subject to high thermal loads.

5. High Heat Flux testing

As foreseen in the WP-DIV programme, the first phase of development of plasma facing units for DEMO-divertor finishes with the high heat flux testing in GLADIS test bed [5]. The cyclic HHF testing, after a screening test up to 20 MW/m², starts with a first phase where the cooling is performed by cold water (11 m/s water velocity, 15 °C inlet temperature and 1 MPa static pressure and follows with hot water cooling condition (16 m/s water velocity, 130 °C inlet temperature and 4 MPa static pressure) similar to the expected DEMO divertor operation. The applied cooling conditions ensure the safe heat transfer in the regime of sub-cooled boiling. HHF loading with 100 cycles at 10 MW/m², 10 s loading following by 50 s cooling down, on each W monoblock was performed. Mock-ups that pass this loading step were further tested at 20 MW/m². The typical W surface temperature during 10 MW/m² loading is about 900–1000 °C.

The hot water testing was currently performed on one component for each concept. For ENEA the chosen mock-ups were #005 and #0011 respectively. They passed 100 cycles at 20 MW/m² with hot water cooling.. Figure 9 and 10 show from the surface temperature distribution during loading recorded by an IR camera. The homogenous temperature distribution, no local hot spots, did not indicate any defects of the component. Figure 10 and 11 show a screen show acquired from GLADIS thermocamera at 100th shot at 20 MW/m².

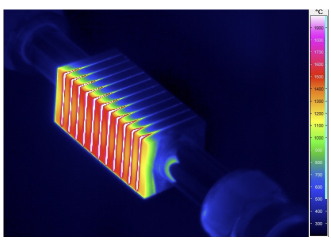

Figure 10: Mock-up #005 - 100th cycle at 20 MW/m² loading, water cooling 130°C

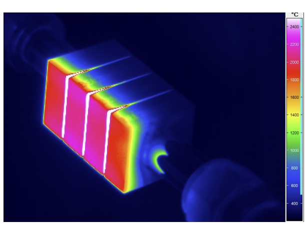

Figure 11: Mock-up #011 - 100th cycle at 20 MW/m² loading, water cooling 130°C

The same good result was achieved for mock-up #007. Mock-up #011 showed during the cycling a slight increase of block centre temperature that could indicate a joint degradation to be confirmed by further ultrasonic and metallographic investigations.

6. Conclusions

The manufacturing route used for the fabrication of both 4 mm and 12 mm W block thickness mock-ups with ITER-like geometry optimized for DEMO operation conditions was assessed. Also the new DEMO-HRP furnace, after a proper setting up can be currently used for mock-up fabrication. The good performances respect to thermal fatigue testing of the manufactured mock-ups confirmed the reliability of the HRP manufacturing process but also that the ITER design concept can be used in a DEMO divertor where hydraulic condition could be different. Investigation on performance influence of different W grades and suppliers is part of the next activity.

Acknowledgements

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