Fusion Engineering and Design 86 (2011) 1591–1594

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

# Manufacturing, testing and post-test examination of ITER divertor vertical target W small scale mock-ups

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ARTICLE INFO

*Article history:*
Available online 31 March 2011

*Keywords:*
Tungsten mock-ups
Hot radial pressing
Joining
Non destructive testing
Thermal fatigue testing
ITER

ABSTRACT

ENEA is involved in the International Thermonuclear Experimental Reactor (ITER) R&D activities. During the last years ENEA has set up and widely tested a manufacturing process, named Hot Radial Pressing (HRP), suitable for the construction of high heat flux plasma-facing components, such as the divertor targets.

In the frame of the EFDA contract six mock-ups were manufactured by HRP in the ENEA labs using W monoblocks supplied by the Efremov Institute in St. Petersburg, Russian Federation and IG CuCrZr tubes.

According to the technical specifications the mock-ups were examined by ultrasonic technique and after their acceptance they were delivered to the Efremov Institute TSEFEY-M e-beam facility for the thermal fatigue testing. The test consisted in 3000 cycles of 15 s heating and 15 s cooling at 10 MW/m$^2$ and finally 1000 cycles at 20 MW/m$^2$.

After the testing the ultrasonic non-destructive examination was repeated and the results compared with the investigation performed before the testing.

A microstructure modification of the W monoblock material due to the overheating of the surfaces and the copper interlayer structure modification were observed in the high heat flux area.

The leakage points of the mock-ups that did not conclude the testing were localized in the middle of the monoblock while they were expected between two monoblocks.

This paper reports the manufacturing route, the thermal fatigue testing, the pre and post non destructive examination and finally the results of the destructive examination performed on the monoblock small scale mock-ups.



## 1. Introduction

This activity was aimed at investigating the feasibility of using an alternative tungsten (W) grade, manufactured in the Russian Federation, for the fabrication of the ITER divertor vertical target components.

In particular the activities included the procurement from the Efremov Institute in St. Petersburg, Russian Federation (Efremov) of the 100 monoblocks, provided with a 0.5 mm thick Oxygen Free High Conductive copper interlayer. These monoblocks had to be used for the manufacturing of six monoblock mock-ups for the high heat flux testing at the Efremov Institute. A post-testing examination was also foreseen.

The six monoblock mock-ups were manufactured by Hot Radial Pressing (HRP) technology developed by ENEA.

## 2. Description of the activities

According to the technical specifications issued by EDFA, Efremov supplied 100 (one hundred) W monoblocks provided with a pure cast Cu-OFHC interlayer together with the ultrasonic testing (UT) report and the quality documentation.

Six monoblock small scale mock-ups have been manufactured by ENEA using the HRP technology [1,2,7].

Fig. 1 shows two out of six manufactured mock-ups before the high heat flux testing.

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doi:10.1016/j.fusengdes.2011.02.079

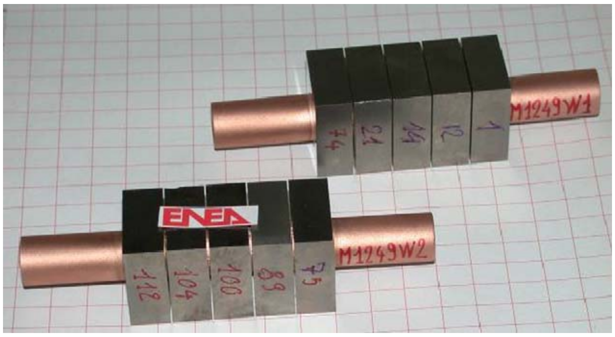


**Fig. 1.** Tungsten monoblock mock-ups before HHF testing.

The accepted mock-ups were delivered to the Efremov for the thermal fatigue high heat flux testing. After the high heat flux testing the mock-ups were shipped back to ENEA labs where a detailed investigation, where possible, was performed on the status of each mock-up, and it included the following items:

1. UT of the W to Cu joint and of the Cu to CuCrZr joint of each monoblock of each mock-up.
2. Comparison of the UT results found before and after the high heat flux testing.
3. Destructive examination of the most representative mock-ups.

## 3. Material specifications

The W monoblocks, provided of a copper interlayer, were supplied by Efremov. The technical specifications for these monoblocks were the following:

- Machined from hot-rolled sheets with a pickled surface and in the annealed stress-relieved condition.
- From sheets free of impurities, splits, fractures and inclusions.
- Grain orientation perpendicular to the surface subject to heat flux loading.
- The W monoblocks must be supplied in the final shape and equipped with a copper (Cu-OFHC EN10204) cast interlayer.

The cooling tube used for the mock-ups manufacturing was of CuCrZr (Elbrodur IG).

## 4. Tungsten monoblock interlayer casting

EFREMOV has successfully supplied the required 100 W monoblocks provided of the Cu OFE interlayer.

The thickness of the Cu interlayer is 0.5 mm.

The W to Cu joint of each monoblock was ultrasonically inspected by EFREMOV before their delivering to ENEA. The acceptance criteria reported below from (a) through (c) have been checked for the W/Cu joint for each monoblocks:

(a) No defect shall have one dimension greater than 3 mm;
(b) The total defect area shall not exceed the 5% of the total joint area of each tile;
(c) Two or more imperfections smaller than described above shall be unacceptable unless separated by a minimum distance equal to the greatest dimension of the largest imperfection.

According to the UT report issued by EFREMOV all supplied monoblocks fulfill the acceptance criteria requirements.

The UT has been also repeated in the ENEA lab on some of the supplied monoblocks and no monoblock presented debonding on the Cu//W interface.

## 5. Manufacturing of the six mock-ups

The prototypes consist of a straight high heat flux unit made of five W monoblocks. The external dimension of the monoblocks was 28 mm × 30 mm × 12 mm. The W thickness in the heat flux direction was 6.5 mm and the final Cu-OFHC thickness was 0.5 mm. It results in a distance from the top heated surface to the center of the cooling tube of 14 mm.

The 0.5 mm gap between two adjacent monoblocks was respected during the manufacturing. The overall mock-up length was about 142 mm.

A tube connection zone was left free and it was of 40 mm on both sides.

The mock-ups were manufactured by HRP [7] according to the following process parameters:

- Vacuum environment with a pressure better than $10^{-5}$ mbar.
- Bonding internal tube pressure of 60 MPa.
- Bonding temperature of 580 °C.
- Pressure holding time of 120 min.

After the manufacturing all mock-ups were controlled by UT. The acceptance criteria required in the technical specifications for mock-ups were the following:

(a) No defect shall have one dimension greater than 4 mm.
(b) The total defect area shall not exceed the 10% of the total joint area of each tile.
(c) Two or more imperfections smaller than described above shall be unacceptable unless separated by a minimum distance equal to the greatest dimension of the largest imperfection.

Two of them were not accepted (1249-03 and 1249-04) because they presented some joining defects exceeding the acceptability limits.

The six mock-ups accepted, after the leak test, were delivered to Efremov for the thermal fatigue testing.

In four mock-ups were also installed a swirl tape in order to promote turbulence.

## 6. High heat flux testing

The performance of the W monoblocks were planned to be assessed via cyclic high heat flux loading (4000 cycles per mock-up) and performed in the TSEFEY facility at EFREMOV.

The TSEFEY beam parameters were the following: typical diameter of $D = 10$ mm, acceleration voltage $U = 40$ kV, beam current $I \sim 1.06$ A at $q = 10$ MW/m$^2$ and $\sim$2.2 A at $q = 20$ MW/m$^2$. The average specific power of non-scanning beam was $UI/S = 53$ kW/cm$^2$ at $q = 10$ MW/m$^2$ and about twice at $q = 20$ MW/m$^2$. The beam raster consisted of 816 beam steps with exposition in each stop of 10 μs. So the period of raster repetition was 816 × 10 = 8160 μs.

Reflection of beam power from tungsten is about 35%.

E-beam in the gaps was not hindered. It touched the cooling cannel there.

The high flux testing consisted in an alternative heating done by the electron beam sweeping in A–B mode: two mockups were irradiated in one set. The e-beam raster was moved from surface of one mockup to surface of the second. So, thermal loading cycle onto one mockup was corresponding by time to cycle-to-cycle pause of the second mockup. The water cooling of the mockups couple