Thermal fatigue testing devices for fusion-related projects

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Abstract

Paper introduces thermal fatigue testing devices, developed and operated under fusion-related projects with focus on testing of ITER First Wall (FW) mock-ups. In frame of EFDA tasks, FW mock-up testing device was developed and put into operation in Centrum Výzkumu Řež s.r.o. (CV Rez) research centre, and one testing device was modified for thermal fatigue tests in Forschungszentrum Jülich (FZJ) research centre. The FW mock-ups were tested for several parties, where the key role was played by Fusion for Energy (F4E), the European Union’s Joint Undertaking for ITER and the Development of Fusion Energy.

Keywords: ITER First Wall mock-ups; thermal fatigue testing; high heat flux; BESTH; JUDITH 2;

1. Introduction

Phase 1 of the qualification campaign for the ITER FW consisted of the fabrication and testing of small-scale mock-ups (SSMU) - 80 x 240 mm - to demonstrate the ability of the selected fabrication technology to resist to the expected thermal loads. This paper describes the activities performed in Europe to test FW SSMU for various domestic agencies (DA), produced by Hot Isostatic pressing (HIP) to bond both stainless steel to CuCrZr and then CuCrZr to Beryllium armour tiles. The tested SSMU successfully passed the required 12000 cycles at 0.625 MW/m\textsuperscript{2} fatigue tests and the 1000 cycles of the MARFE tests at 1.75 MW/m\textsuperscript{2}, and additional tests up to 2.75 MW/m\textsuperscript{2}, fully validating HIP as a robust bonding technology for the considered FW materials. The testing campaign took place at 2 locations in Europe: the Centrum Výzkumu Řež s.r.o. (CV Rez) in the Czech Republic and the Forschungszentrum Juelich (FZJ) in Germany.

As stated in the Final Report of Negotiations on ITER Joint Implementation of 1st April 2006, a prequalification will be needed for the critical procurement packages shared by multi-Parties such as the Blanket FW. Well in advance of the assumed start of the procurement, each DA shall first demonstrate its technical capability to carry out the procurement with the required quality, and in an efficient and timely manner. For the Blanket FW system, this is achieved via a two-stage qualification process: a mock-up qualification stage and a semi-prototype qualification stage.
stage. Each stage is also split into two phases: a manufacturing acceptance phase and a High Heat Flux (HHF) testing acceptance phase.

A FW panel is an actively cooled structure constituted by a 316L(N) stainless steel, a CuCrZr copper alloy and beryllium. Different industrial processes exist to manufacture such components. Among all the available processes, the diffusion welding assisted by Hot Isostatic Pressing (HIP) has been chosen in Europe as the prime candidate solution for their manufacture following an extensive R&D programme over more than 10 years where the quality of the so obtained bonding between the FW materials was well demonstrated. In the following, general approach to fabrication of SSMU is briefly mentioned and results of HHF testing of the mock-up are summarised.

2. SSMU characteristics

2.1. HIP bonding technology

The HIP technique presents several advantages to fabricate efficient and robust primary first wall panels. These advantages are:

- A perfect mechanical contact between the bounding materials over their whole surface in order to extract efficiently the heat produced by the plasma.
- Strong protection against water leakage during operations. Any welds required during the manufacture of the ITER PFW panels can be covered by similar material which, after being joined by HIP, offers a double containment to the water cooling circuit. In this way, no seal welds are directly in contact with the plasma.
- A small deformation of the materials when they fit well with each other. This point is particularly interesting in order to keep the position of the cooling circuit inside the materials as well as the size of the cooling pipes.
- The limitation of the reaction zone between dissimilar materials to obtain joints with good mechanical properties. Thermal fatigue tests performed on bi-metallic joints fabricated by HIP have led to good results [1]. CuCrZr/316LN joints tested under e-beam facility withstood 1000 cycles under 5MW/m² and then respectively 267 and 76 cycles at 7MW/m². Be/CuCrZr joints withstood 20 000 and 30 000 cycles under 0.6MW/m² without indication of failure. These results confirm that the HIP is the reference process route for the fabrication of the FW panel.

2.2. SSMU

Each SSMU consists of three layers as shown on Fig. 1:

- 316L(N) stainless steel support with cooling water pipe for additional heat removal,
- CuCrZr copper alloy heat sink with two cooling water pipes for main active heat removal,
- Beryllium armour tiles.

![Figure 1: SSMU fabricated under EU DA supervision](image-url)
According to [2], no exact technical specifications of joining technology are required by ITER Organization (IO) or F4E, respectively, but at least 800°C temperature shall be used for Be/CuCrZr joint remelting. Various DA supplied their SSMU with different joining technology processes, but in general minimum pressure of 100 MPa and temperature of 1000°C were used for at least 2 hours to create HIP joint between Beryllium tiles and CuCrZr heat sink.

IO requirements demand using of S-65C VHP (Vacuum Hot Pressed) grade of Beryllium, with BeO content less than 1.3% w.t.; C18150 CuCrZr alloy with 0.6-0.9% Cr, 0.07-0.15% Zn and 0.2% max of all other elements. 316L standard austenitic stainless steel is required for manufacturing of support body under CuCrZr heat sink.

3. Heat flux tests

F4E required testing of six SSMU from various DA on two independent facilities – normal operation heat load was simulated by BESTH device, operated by CV Rez, while MARFE transient heat load tests were performed on JUDITH 2 device in FZJ. The setting of heat tests was provided by IO in [3] as following:

- 12,000 shots at 0.625 MW/m² on BESTH device,
- 1,000 shots at 1.75 MW/m² on JUDITH 2 device.

Various heat fluxes on both devices were induced by different heating technologies: BESTH device is based on using of resistance heating of graphite panel, while JUDITH 2 device uses electron beam. Such technological difference also leads to various cycles duration on both devices: BESTH device’s heating cycle consists of 30 seconds power increase, 180 seconds on full power, 30 seconds of power decrease and 60 seconds of power off. JUDITH 2 device’s cycle comprises 10 seconds of full power and 90 seconds of power off.

4. Testing devices

4.1. BESTH device

The BESTH (Beryllium Sample Thermal Test) device is able to provide cyclic heat flux up to 0.625 MW/m² by means of graphite panels and measurement of temperatures on the joint between Beryllium tiles and the CuCrZr heat sink. It consists of two cooling circuits, a heating furnace, a power supply unit, a glove box and a control desk. It is operated in a Beryllium laboratory equipped with air ventilation system with HEPA filters. The cooling is provided by a small cooling tower, located outside of testing laboratory, hence all of the thermal power is released to surrounding environment. Inside BESTH, two mock-ups are accommodated in the heating furnace, facing Beryllium sides to each other. In between of them, the heating graphite panel is inserted and connected to the power supply source, as indicated on Fig. 2. The heating furnace is sealed and filled with Helium cover gas which assures low deterioration of graphite and high resistivity between mock-ups and heating panel. Heating cycles are generated by graphite panel; cooling of the mock-ups is supplied by cooling pipes.

Figure 2: Setting of heating panel in between two SSMU
Before testing in the BESTH device, each mock-up underwent non-destructive ultrasonic testing. Then, thermal fatigue testing was launched with the following parameters:

- **Beryllium surface heat flux**: 0.625 MW/m²
- **Cycle duration**: 300 seconds (30-180-30-60)
- **Inlet water coolant temperature**: ~100°C
- **Water coolant pressure**: 0.5 MPa
- **Cover gas pressure**: 80 kPa
- **Water coolant flow rate**: ~1.5 m/s

Each of six tested mock-ups reached 12,000 cycles flawlessly; with 300 seconds per cycle, total testing time was approximately 42 days. After reaching 12,000 cycles on each mock-up, BESTH device automatically turned off and was disassembled next day. According to the requirements stated in [3], all mock-ups underwent two ultrasonic NDT tests: one prior testing in BESTH device and other one after the testing in BESTH device. Beryllium contamination sweeps were taken from each mock-up to confirm Beryllium contamination is below 100 μg/m² and SSMU is suitable for transportation to FZJ for MARFE tests.

Nature of BESTH device requires two SSMU to be tested at once, which was often proved to be limiting restriction for SSMU producers: different finishing of Beryllium surfaces results in non-equivalent distribution of heat flux into the both mock-ups. Such differences are resolved by shifting of graphite panel to less utilized SSMU.

### 4.2. JUDITH 2 device

The electron beam facility JUDITH-2 is placed in a hot materials laboratory in the restricted area of FZJ. The facility consists of an electron beam gun, a process chamber with vacuum system and cooling circuits and is equipped with an Electron Beam (EB) generator with a maximum beam power of 200 kW. A system of two magnetic lenses is used to focus the beam to a diameter of not smaller than 4 mm. The maximum heated area is 500 x 500 mm². Active cooling of mock-ups is carried out with water of 100°C, inlet water pressure of 3 MPa and a flow rate of 4 m/s. The following diagnostics were installed for the tests:

- Digital infrared camera (IR camera Flir SC6000),
- Two-colour pyrometer,
- Three thermocouples inside the three beryllium tiles of the mock-up.

The following parameters were recorded electronically: temperatures of thermocouples and pyrometer, cooling water conditions (water flow rate, inlet/outlet temperature, pressure) and IR images. The IR images were taken at the end of each heating cycle (at maximum temperature). The vacuum pressure was registered manually.

The heat flux tests in the JUDITH 2 facility were performed in two steps, with loading conditions as follows: the surface heat load was 1.75 MW/m² (incident power density including effect of electron reflection effects) with a heating period of 10 s and a cool-down time of 90 s (this duration is necessary to achieve acceptable cool-down of the mock-up). 1000 cycles were performed with inlet cooling water temperature of 100°C and inlet water pressure of 3 MPa +/- 5% and a flow rate of 4 m/s +/- 5%. In order to check all systems of JUDITH 2, four heating up cycles with increased power densities at 0.5 MW/m², 1.0 MW/m², 1.5 MW/m² and 1.75 MW/m² (10 s heating period, 60 s cooling time) were performed.

### 5. Results

Six SSMU from EU DA, US DA, CN DA, RF DA and KO DA were successfully tested in both BESTH and JUDITH 2 devices. Due to various natures of both devices, different measurement techniques were applied on each device.

#### 5.1. BESTH device

The heat flux is computed from water flow rate and inlet and outlet water temperature, with respecting of heat losses. Each beryllium tile is equipped with one thermocouple, giving three measuring points on each mock-up. Both records of Beryllium tile temperatures and ultrasonic inspection can be used for determination of potential Beryllium tile detachments, which indicates failure of Be/CuCrZr HIP joint.
Comparing of ultrasonic screens made before and after heat flux test shows formation of gas gaps, produced by Beryllium detachments.

Record of Beryllium temperature can also indicate tile detachment – rapid increase of temperature (more than 5°C per day) is result of aggravated heat removal, induced by failure of Be/CuCrZr joint.

On the other hand, slow increase of Beryllium temperature (less than 1°C per day) is caused by Beryllium surface deterioration, as the shiny and polished Beryllium surface gradually loses its reflectance and continually absorbs more heat, which was earlier reflected. Such behavior was observed on all six tested SSMU and changes of Beryllium surface reflectance were also witnessed after maintenance outages, when BESTH device was stopped in operation and mock-ups were dismantled from inner installation.

5.2. JUDITH 2 device

The behavior of each tested mock-up was documented by temperature measurements and optical inspections before and after testing. The evolution of temperatures measured by the thermocamera on the surface of the three beryllium tiles and three thermocouples during the 1000 cycles of the MARFE tests was recorded for each mock-up. The flawless performance of mock-up resulted in constant temperatures during the MARFE test. After finishing the MARFE tests some additional tests at higher absorbed power density (2.25 MW/m²) were also done on selected mock-ups. After the completion of the tests at higher power densities the mock-ups were inspected again and sent back to CV Rez for last ultrasonic inspection.

6. Conclusion

The EU DA has been successful with Stage 1 of the ITER FW qualification programme by passing fabrication acceptance tests and subsequent high heat flux acceptance tests on the two required FW qualification mock-ups and high heat flux tests on four more FW qualification mock-ups from US DA, KO DA, RF DA and CN DA. Both EU DA mock-ups were fabricated by HIP, the selected fabrication technology in the EU, and were tested up to 2.75 MW/m², i.e. well above the original ITER FW requirements of 0.5 MW/m². This shows the robustness of the proposed fabrication route, which is the achievement of an extensive R&D programme performed in the EU over more than 10 years. Discussions are on-going with the IO for the preparation of Stage 2 of this FW qualification programme which consists in manufacturing and testing larger scale FW panel semi-prototypes. The successful achievement of this Stage 2 by a DA is the prerequisite to be eligible for the procurement of the ITER FW.

References