Progress on the Development of Fabrication Technology for the KO HCML TBM

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Abstract. Korea has proposed and designed a Helium Cooled Molten Lithium (HCML) Test Blanket Module (TBM) to be tested in the ITER, in which Ferrite Martensite steel (FMS) and Be were used as the structural and armor materials of the first wall (FW), respectively. In order to develop the fabrication technology for a TBM structure, joining of FMS to FMS with hot isostatic pressing (HIP, 1050 ^{o}C, 100 MPa, 2 hours) has been developed including post HIP heat treatment (PHHT, normalizing at 950 ^{o}C for 2 hours and tempering at 750 ^{o}C for 2 hours). Several mock-ups were fabricated using the developed methods and one of them, three-channel mock-up, was used for performing a High Heat Flux (HHF) test to verify the joint integrity. Test conditions were determined using the commercial code, ANSYS-11, and the test was performed in the Korea Heat Load Test (KoHLT-2) facility, which was used a radiation heating with a graphite heater. The mock-up survived up to 1,000 cycles under 1.0 MW/m^2 heat flux and there is no delamination or failure during the test. Then, joining of Be to FMS has been developed with several interlayers and mock-ups were fabricated with the same method (580 ^{o}C, 100 MPa, 2 hours) by trying the different interlyers (1μm-Ti/0.5μm-Cr/5μm-Cu and 1μm-Cr/5μm-Cu). The HHF tests with a KoHLT-1 were performed with 1,000 cycles under 0.5 MW/m^2 heat flux, which is Be-compatible facility in Korea. The test conditions were determined with ANSYS-11 and the test results were compared with the preliminary analysis ones. During the test, there was no sudden increase of temperature but UT and DT results after the test showed a delamination in the case of using Ti/Cr/Cu interlayer. But the mock-up with the Cr/Cu interlayer showed a sound joining even after HHF test.

Key words: ITER, ITER Korea, breeder blanket, first wall

1. Introduction

A Korean Helium Cooled Molten Lithium (HCML) Test Blanket Module (TBM) has been designed to be tested in the International Thermonuclear Experimental Reactor (ITER) TBM. In the present design, Ferritic Martensitic Steel (FMS) was designed as a structural material [1-4] and related fabrication methods have been developed especially for joining. Since the First Wall (FW) of the HCML TBM is composed of a beryllium (Be) layer as an armor material and a FMS as a structural one, joining with Be to FMS and FMS to FMS should be developed to fabricate it. The joining of FMS to FMS was developed using a Hot Isostatic Pressing (HIP, 1050 ^{o}C, 100 MPa, 2 hours) including the post HIP heat treatment (PHHT, normalizing at 950 ^{o}C for 2 hours and tempering at 750 ^{o}C for 2 hours) [5], and several mock-ups were fabricated and tested with a high heat flux (HHF) to verify the integrity of the joints similarly to the development of the ITER blanket FW in Korea [6-8].
A Korean helium cooled molten lithium (HCML) test blanket module (TBM) has been designed to be tested in the International Thermonuclear Experimental Reactor (ITER) TBM [1-4] and related fabrication methods have been developed especially for the purpose of joining. Since the first wall (FW) of the HCML TBM is composed of a beryllium (Be) as an armor material and a FMS as a structural one, joining with Be to FMS and FMS to FMS should be developed in order to fabricate it.

In the development procedure, joining conditions were found through the fabrication of small specimens and destructive tests for confirming their joining strength. However, once one method showed feasibility, mock-ups were fabricated with this method and high heat flux (HHF) test was performed to confirm the joining integrity with the cyclic heat load, which was similar to the ITER operation conditions. Here, the mock-ups were designed considering the designed HCML TBM FW which has 60 cooling channels with 20 mm height and 10 mm width; the channel sizes remained the same as the original ones but the length was reduced to 200 mm. In the design, the structural material considered was F82H for using a reduced activated FMS but Gr91 was used in the present fabrication of the mock-ups. For Be armor, S65C (ITER graded) was used, which was proposed for ITER blanket first wall.

2. High heat flux test facilities

Since a HHF test is essential for investigating the thermo-mechanical performance of a FW including the integrity of the HIP bonded interfaces, the fabricated mock-ups were tested at Korea Heat Load Test (KoHLT) facilities, which were developed for ITER blanket FW [5-8]. The two facilities, KoHLT-1 and 2, have been developed and operated as follows as shown in Fig. 1:

The KoHLT-1 consists of a target assembly including a target mount and graphite heater, test chamber (0.3 m × 0.3 m × 1.2 m with cooling jackets, DC power supply, water cooling system, data acquisition system (DAS), and auxiliary system (beryllium evacuation system, helium gas feeding system, diagnostics system). This first heat load test facility was installed in the authorized laboratory equipped ventilation system with a beryllium filter to treat the beryllium toxic materials, and a ventilation system with a beryllium filter. The water cooling system can supply the coolant with 0.1 to 0.2 MPa pressure and 1 m/sec of flow rate. The target assembly was designed to mount the various mockups of different sizes, and a graphite heater was equipped in the middle of the mount between two mockups with the gap of 2 to 5 mm using the graphite grade of R8710 (SGL Carbon Group). Applied electrical power (40 kW) to the heater was adjusted by the data control system, and output power was traced by DAS. Figures 1 shows the overall operative equipment of these procedures.

The KoHLT-2 consists of the same components with KoHLT-1, two CCDs, and a pyrometer. The size of the test chamber is 1.2 m × 1.2 m × 2.4 m. Figure 2 shows the dominant components of it. The maximum electric power is 80 kW, the target area is 700 mm × 100 mm, the cooling water will be circulated in the closed loop, with 25-120 °C temperature and 3 MPa pressure. Design parameters of them were summarized as shown in Table 1.

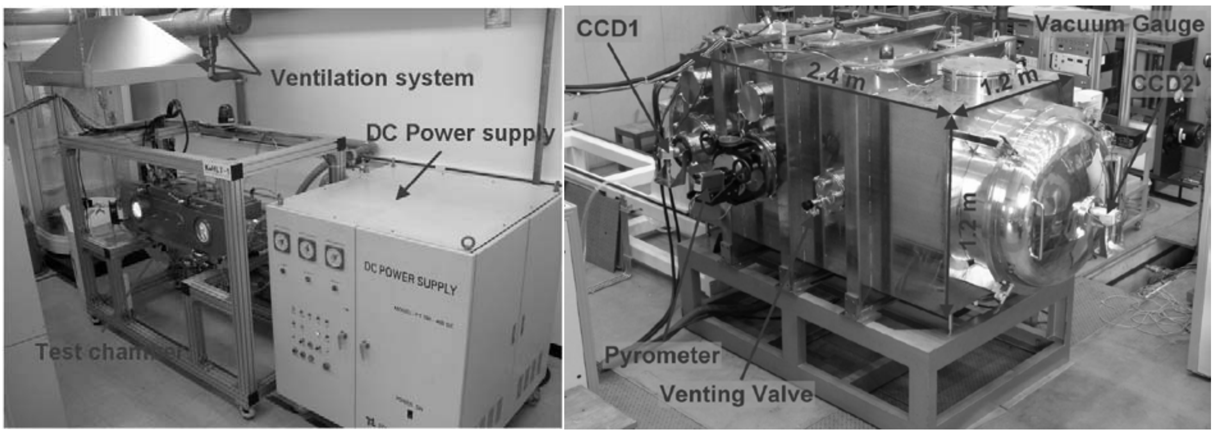

FIG. 1. Photographs of the KoHLT-1 & 2.

TABLE 1. Design parameters of KoHLT-1 & 2.

Facility	KoHLT-1	KoHLT-2
Major Target	PFC with Be	Lareg PFC
Heat flux (Target area)	0.7 MW/m^2 (244x80 mm^2) 1.5 MW/m^2 (80x80mm^2)	0.46 MW/m^2 (700x100 mm^2)
Heating elements	Gr panel (0.25Ω)	Gr panel (0.5Ω)
Power supply	40 kW (100V, 400A)	80 kW (200V, 400A)
Test chamber	0.3x0.3x1.2 m^3	1.2x1.2x2.4 m^3
Cooling water	25-120 ^oC, ~ 3MPa	25 ^oC, ~ 0.2 MPa

3. Joining of FMS to FMS

The joining of FMS to FMS was developed using a Hot Isostatic Pressing (HIP, 1050 ^oC, 100 MPa, 2 hours) including the post HIP heat treatment (PHHT, normalizing at 950 ^oC for 2 hours and tempering at 750 ^oC for 2 hours). In the previous work, smaller mock-ups were fabricated with 100 mm length and tested under 0.5 to 1.5 MW/m^2 heat fluxes for 20 cycles at each heat flux to investigate the joint integrity and a Critical Heat Flux (CHF) [9]. And then, in order to confirm the joining integrity between FMS and FMS with HIP, new mock-ups were fabricated. Six single channels were fabricated with a wire cutting for making a rectangular channel, which will be replaced by a cold rolling in the future in order to make longer channel and for mass production. The fabricated single channels and a back plate for each mock-up were joined by the HIP to be as one-, two-, and three-channel mock-ups. After HIP, the developed PHHT was performed with all mock-ups to recover the strength. To be installed in test facility, dummy channels and flanges were welded for one- and three-channel mock-ups, as shown in Fig. 2, in which only the three-channel mock-up was tested in the present study.

In order to install KoHLT-2, connecting flanges were welded to this mock-up and it was installed with a Cu dummy for calorimetric measurement and a graphite heater, as shown in Fig. 3. During the test, by a using a calorimeter, Cu dummy mock-up, the total power was measured and the absorbed power at the tested mock-ups was measured with a coolant temperature difference by thermocouples located at the inlet and outlet regions. Two thermocouples for the wall temperature measurement were inserted from the backside with a different depth.

The mock-up was tested according to the test conditions and they survived for 1,000 cycles for a 1.0 MW/m^2 heat flux. After evacuation of the tested mock-up, pressure test up to 3.0 MPa was performed and there was no leakage. Figure 4 shows the photograph of the tested mock-up after evacuation. Figure 5 shows the measured temperature and calculated heat fluxes during the last 30 cycles and there were no sudden increases of the measured temperature or more heat flux. The inlet water temperature increased due to the closed water supply system. The measured temperatures showed a good agreement with the analysis ones by ANSYS-11, which were used for determining the test conditions, as shown in Fig. 6.

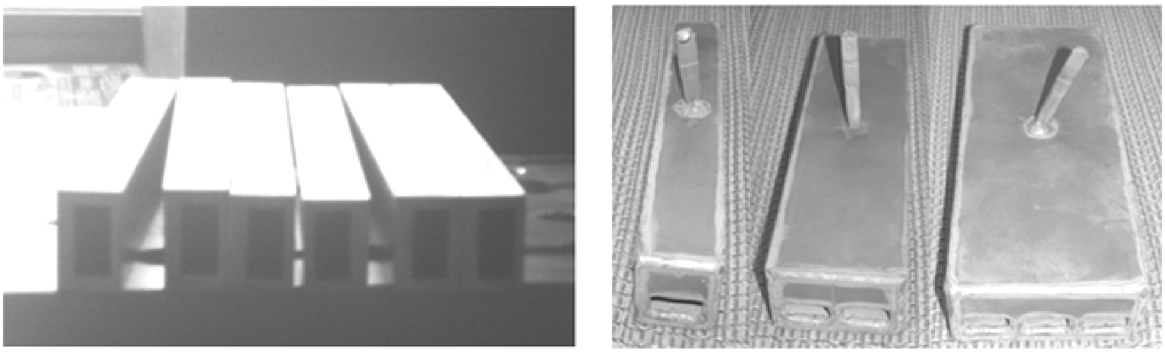

FIG. 2. Photograph of the fabricated FMS/FMs mock-ups.

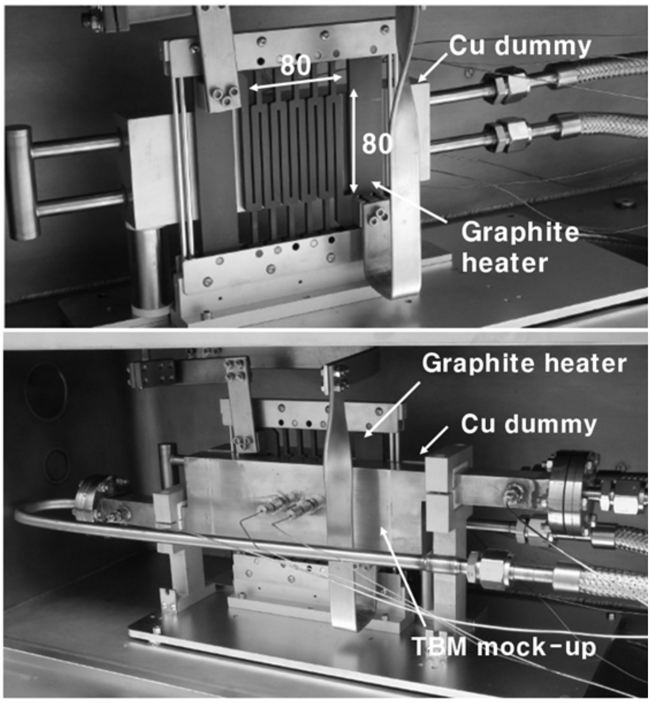

FIG. 3. Photograph of the installed FMS/FMS mock-up in KoHLT-2.

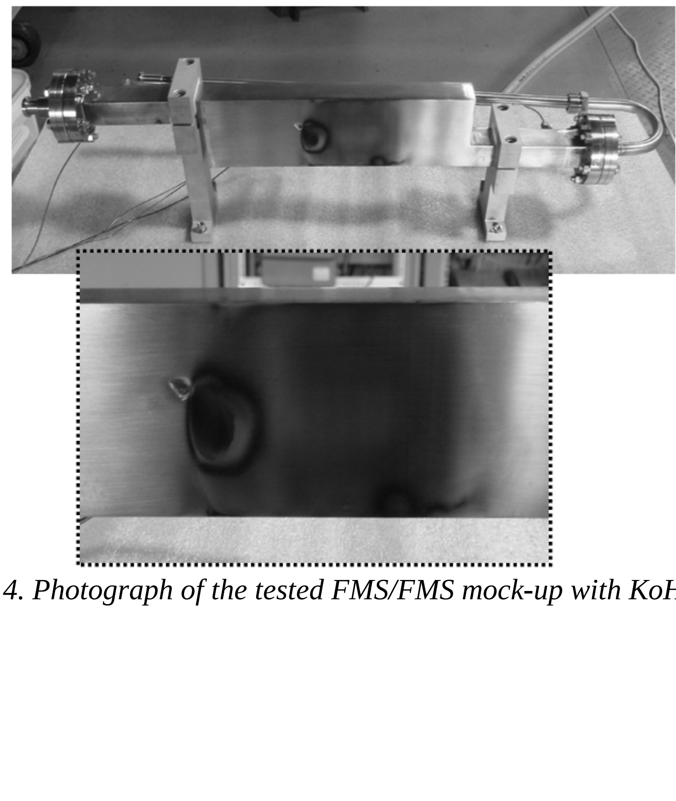

FIG. 4. Photograph of the tested FMS/FMS mock-up with KoHLT-2.

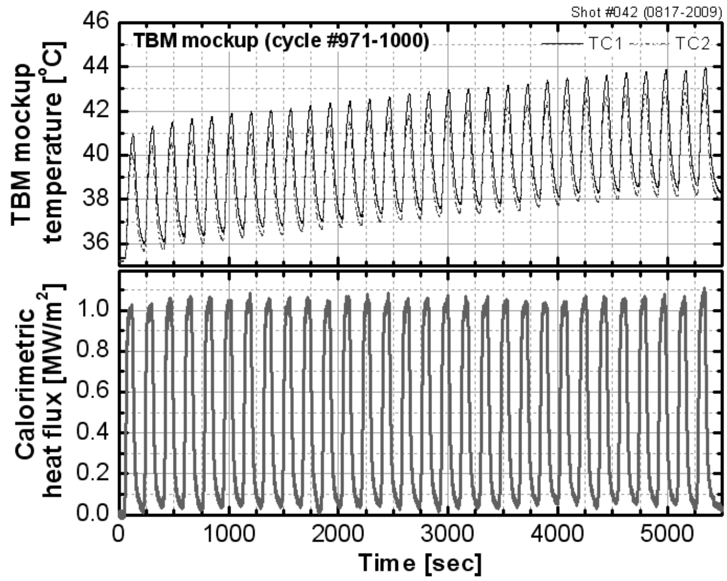

FIG. 5. Measured temperatures and heat flux of FMS/FMS mock-up.

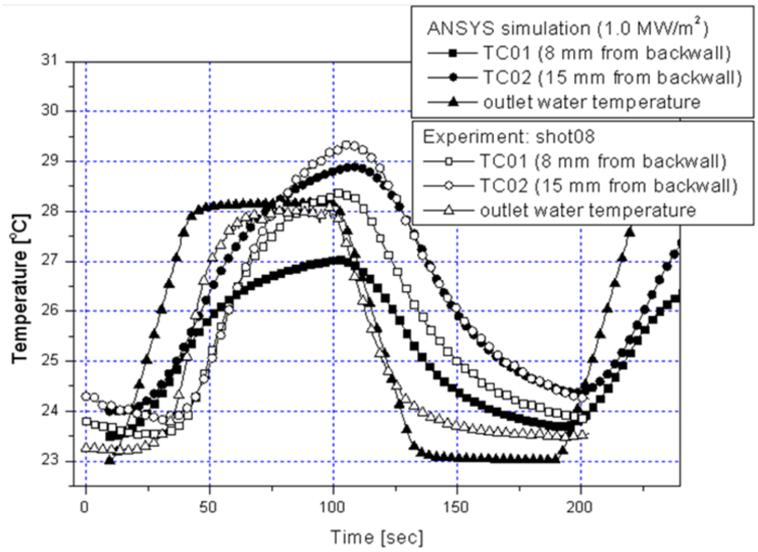

FIG. 6. Comparison the measured and predicted temperatures for FMS/FMS mock-up.

4. Joining of Be to FMS

The joining of Be to FMS were developed using the same method, HIP but the temperature and pressure conditions were different from that of FMS to FMS joining (580 ^oC, 100 MPa, 2 hours) and more, interlayer was used in Be tile side for diffusion bonding. So far, several interlayers have been tried and the following two conditions were used for fabricating the mock-ups; 1μm-Ti/0.5μm-Cr/5μm-Cu (#56) and 1μm-Cr/5μm-Cu (#57). In order for KoHLT-1 to be installed, the connecting tubes were welded to this mock-up and it was installed with a Cu dummy for calorimetric measurement and a graphite heater, as shown in Fig. 7. Differently from the previous test, no Cu dummy mock-up was used and only the coolant temperature difference by thermocouples located at the inlet and outlet regions was recorded. A thermocouple for the Be tile temperature measurement (8 mm from heated surface) was inserted.

The mock-up was tested according to the test conditions and they survived for 1,000 cycles over 0.5 MW/m^2 heat flux without any sudden increase of the mockup temperature, as shown in Fig. 8. The measured temperatures showed a good agreement with the analysis ones by ANSYS-11, which were used for determining the test conditions, as shown in Fig. 9. After evacuation of the tested mock-up, ultrasonic and destructive tests (UT and DT) were performed to find the delamination in joint interfaces. During the test there was no sudden increase of temperature but there is delamination in mock-up #56, as shown in Fig. 10. Because the thermocouple to measure the temperature was located in the sound joining region, it could not detect the delamination in the Be/FMS joint.

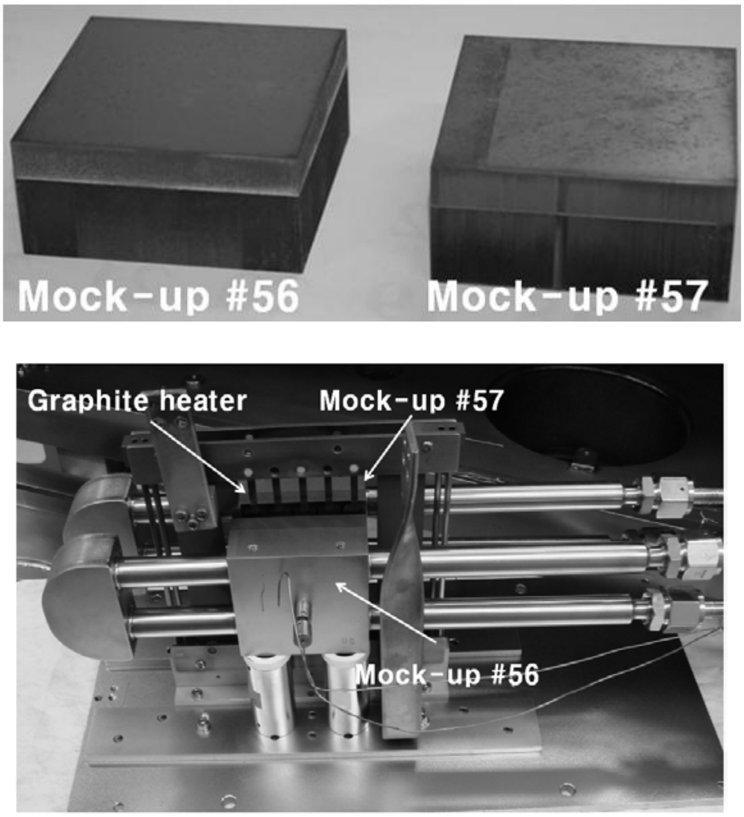

FIG. 7. Photograph of the fabricated Be/FMS mock-ups.

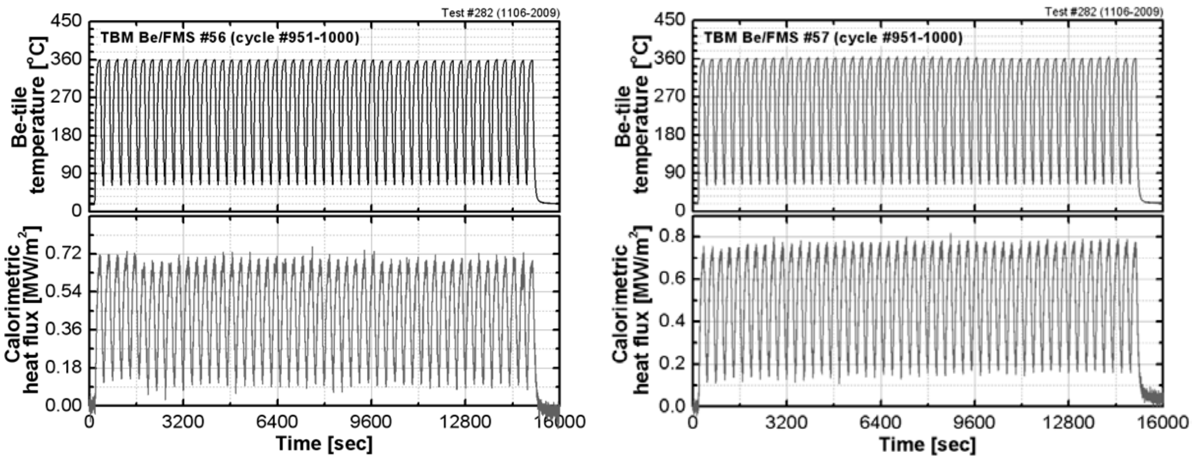

FIG. 8. Measured temperatures and heat flux for Be/FMS mock-ups.

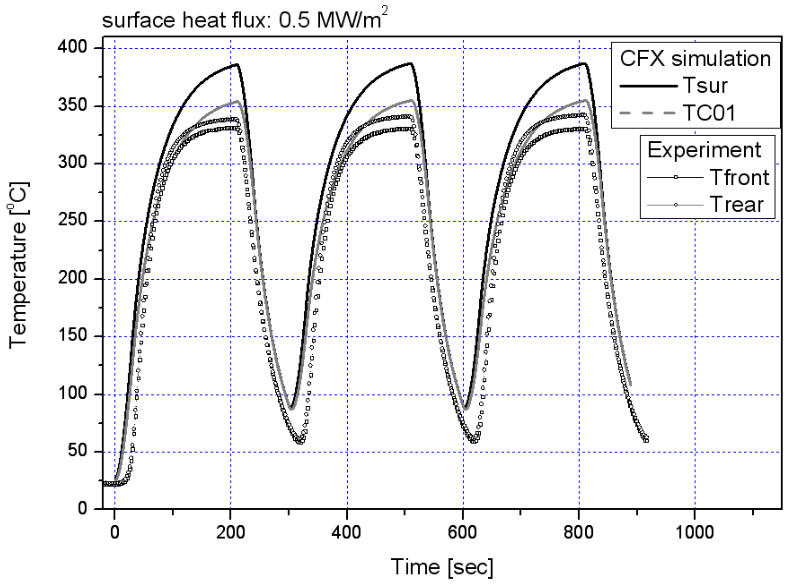

FIG. 9. Comparison the measured and predicted temperatures for be/FMS mock-ups.

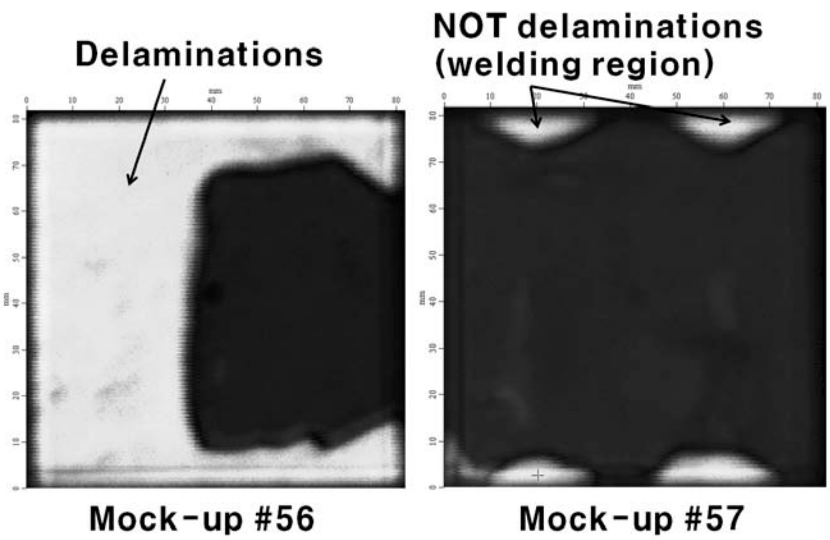

FIG. 10. UT results after HHF tests.

5. Summary

Korea has proposed and designed the HCML TBM to be tested in the ITER and the fabrication methods such as HIP for TBM FW has been developed. For FMS to FMS joining, mock-ups were successfully fabricated with a HIP (1050 °C, 100 MPa, 2 hours) and the following PHHT (normalizing at 950 °C for 2 hours and tempering at 750 °C for 2 hours). HHF tests with a KoHLT-2 were successfully performed with the mock-up of up to 1,000 cycles under 1.0 MW/m^2 heat flux without any delamination or failure. For Be to FMS joining, mock-ups were successfully fabricated with a HIP (580 °C, 100 MPa, 2 hours) by trying the different interlyers (1μm-Ti/0.5μm-Cr/5μm-Cu and 1μm-Cr/5μm-Cu). In the same way, HHF tests with a KoHLT-1 were performed with 1,000 cycles under 1.0 MW/m^2 heat flux. During the test, there was no sudden increase of temperature but UT and DT results after the test showed a delamination in the case of using Ti/Cr/Cu interlayer. But the mock-up with the Cr/Cu interlayer showed a sound joining even after HHF test.

Acknowledgement

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References

[1] D. W. Lee, et al., "Current status and R&D plan on ITER TBMs of Korea," J. of Korean Phys. Soc. 49, (2006) S340-S344.
[2] D. W. Lee, et al., "Preliminary design of a helium cooled molten lithium test blanket module for the ITER test in Korea," Fusion Eng. Des. 82 (2007) 381-388.
[3] D. W. Lee, et al., "Helium cooled molten lithium TBM for the ITER in Korea," Fusion Sci. Tech. 52 (2007) 844-848.
[4] D. W. Lee, et al., "Design and preliminary safety analysis of a helium cooled molten lithium test blanket module for the ITER in Korea," Fusion Eng. Des. 83 (2008) 1217-1221.
[5] Y. D. Bae, et al., "Development of a high heat flux test facility for plasma facing component," Fusion Sci. and Tech. 56 (2009) 91-95
[6] J. Y. Park, et al., Optimization of joining condition for ITER first wall fabrication, J. Korean Phys. Soc. 49, (2006) S442-S446.
[7] D. W. Lee, et al., "Development of Fabrication and Qualification Methods for the First Wall of the International Thermonuclear Experimental Reactor (ITER)," J. Korean Phys. Soc. 51, (2007) 1210-1215.
[8] D. W. Lee, et al., "High heat flux test with HIP bonded Cu/SS mock-ups for the ITER first wall," Fusion Eng. Des. 83 (2008) 1038-1043.
[9] D. W. Lee, et al., "Fabrication and high heat flux test of the first wall mock-ups for the Korean He Cooled Test Blanket (KO HCML TBM)," Fusion Eng. Des. 84 (2009) 1164-1169.
[10] A. Cardella, et al, Technical Basis for the ITER EDA plasma facing components, Fusion Eng. Des. 39-40 (1998) 377-384.
[11] ITER Material Properties Handbook, File code: ITER-AA02-2402.
[12] R. L. Klueh, D. L. Harries, High Chromium Ferritic and Martensitic Steels for Nuclear Applications, West Conshohocken, PA: American Society for Testing and Materials, 2001. (ISBN: 0-8031-2090-7)