Progress on the Development of the Fabrication Technology for the ITER First Wall in Korea

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Abstract. Korea is responsible for the procurement of the ITER first wall (FW) blanket modules 1, 2 and 6, and has been developing the fabrication technology of them. Joining Be, CuCrZr and stainless steel (SS) is the most important aspect of the FW and to derive the optimum joining conditions, several mock-ups with various temperatures and pressure conditions between CuCrZr, and SS and with various interlayers between Be and CuCrZr were fabricated by using a hot isostatic pressing (HIP) bonding method. After the HIP joining, no cracks and pores were observed at the Be/CuCrZr and CuCrZr/SS joining interfaces and destructive tests showed the joining interfaces have a sufficient mechanical strength. High heat flux (HHF) tests of the mock-ups were performed to verify their integrities using e-beam facilities. All the fabricated mock-ups survived up to the expected fatigue lifetime and the measured temperatures show a good agreement with the analytical results. Fabrication of the Be/CuCrZr/SS qualification mock-ups using the developed joining technology is progressing and a high heat flux test for a mock-up qualification will be performed.

Key words: ITER, blanket, first wall, HIP joining

1. Introduction

The blanket first wall (FW) of the ITER is composed of the following three metals; beryllium (Be) armor used as a plasma facing material, Cu-alloy (CuCrZr) layer as a heat sink material, and type 316L austenitic stainless steel (SS316L) as a structural material [1]. Joining Be, CuCrZr and stainless steel is the most important aspect of the FW since it has to survive the normal and transient heat loads produced during the various ITER operating conditions. The hot isostatic pressing (HIP) bonding method has been proposed [2] to bond different metals. To find the optimum joining conditions, the HIP conditions such as the temperature, pressure, duration time, and interlayers between the Be and the CuCrZr joining interfaces have been investigated in Korea [3-6].

Several joints and mock-ups were fabricated with various joining conditions. Destructive tests such as a tensile, a Charpy impact, a four-point bend and a shear test on the CuCrZr/SS and Be/CuCrZr joints were performed to determine the mechanical strength of the joints. High heat flux (HHF) tests were performed to verify the integrity of a joint under various ITER operational conditions. Low energy electron beam accelerators were used for a heat flux test: JEBIS (JAEA Electron Beam Irradiation Stand) was used for the CuCrZr/SS mock-ups and TSEFEY-M (e-beam test facility at Efremov institute) was used for the Be/CuCrZr mock-ups. The test conditions such as the heat flux and water cooling conditions were determined by a finite element structural analysis (FEM) with the ANSYS-11 code and the fatigue lifetime was evaluated from a strain analysis. Temperature distribution for the mock-ups from the HHF test were compared with analytical results.

This paper addresses the optimum joining conditions, the result of the destructive and the HHF test of the FW mock-ups for the development of the fabrication technology.

2. Fabrication of the mock-ups

2.1. 50x100 CuCrZr/SS mock-ups

With the HIP conditions of 1050 °C and 100 MPa for 2 hours, a 50-mm x100-mm CuCrZr/SS mock-up was fabricated as shown in Fig. 1; 102-mm long, 50-mm wide, and 72-mm thick with two circular cooling tubes in the CuCrZr and two cooling holes in the SS block, respectively (10- and 15-mm ID). To install the mock-up in to the JEBIS (JAEA Electron Beam Irradiaion Test Stand), manifolds were welded to it. The specimen was fabricated with the same method as the mock-up. No defects such as cracks or pores were observed at the CuCrZr/SS joining interface, when its microstructure was observed by SEM. Tensile tests were performed on the joint specimens as well as the CuCrZr and SS base metals at room temperature. The tensile strength of the joint specimens was similar to that of the CuCrZr base metal (300 MPa). All the specimens revealed a cup-and-cone-type fracture. A fracture did not occur at the interface, but in the CuCrZr base metal. A Charpy impact test was performed on the CuCrZr/SS joint specimens together with the CuCrZr and SS base metals at room temperature. The CuCrZr/SS joint revealed a fracture with an impact energy of 22 J/cm^2. The joint specimen was fractured at the CuCrZr side of the joining interface which revealed a brittle fracture, while the CuCrZr and SS base metals revealed a ductile fracture.

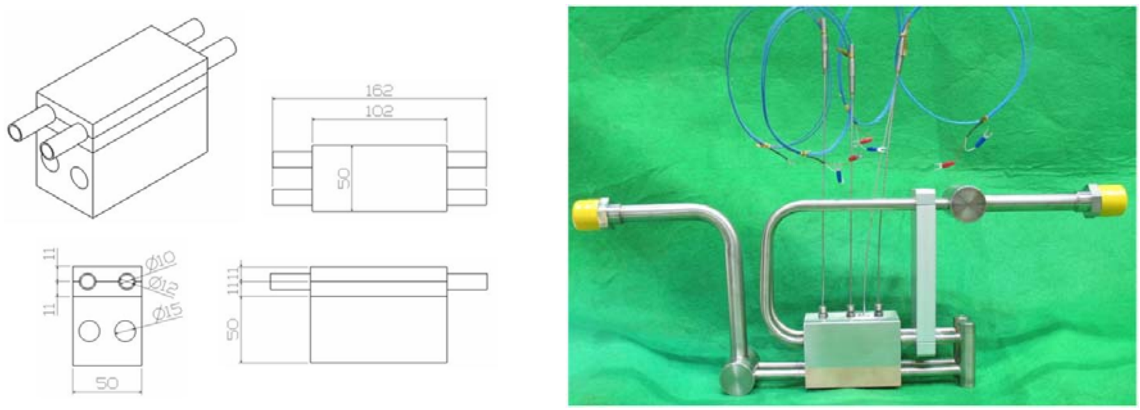


FIG.1. Schematics and a photo of the fabricated Cu/SS mock-up.

2.2. 50x50x1 Be/CuCrZr mock-ups

Two 50-mmx50-mm x1 Be/CuCrZr mock-ups were fabricated with the HIP conditions of 580/620 °C and 100 MPa for 2 hours including a post heat treatment after a HIP of a CuCrZr and SS tube with 1050 °C and 100 MPa for 2 hours. The interlayers such as a 1-µm Cr/10-µm Cu and a 10-µm Ti/10-µm Cu on a Be/CuCrZr interface were used. Figure 2 shows the schematics and a photo of the fabricated mock-ups: Be tile is 50-mm long, 50-mm wide, 10-mm thick and the Cu block is 50-mm long, 50-mm wide, 22-mm thick with two circular cooling tubes (10-mm ID, SS316L). To install the mock-up in to the TSEFEY (e-beam test facility at Efremov institute), manifolds were welded to it. With the specimen fabricated with the same conditions as the mock-ups, the microstructure of the interface was observed and no cracks and pores were observed at the Be/CuCrZr joining interface. Results of the shear tests showed a shear strength of about 169 - 181 MPa for the Cr/Cu interlayer and of about 70 - 90 MPa for the Ti/Cu interlayer. Ultrasonic test was performed with the fabricated mock-up using a probe which had a 5 MHz frequency, 0.25 inch diameter, and was a flat-type, and no defects were found in the Be/CuCrZr interfaces.

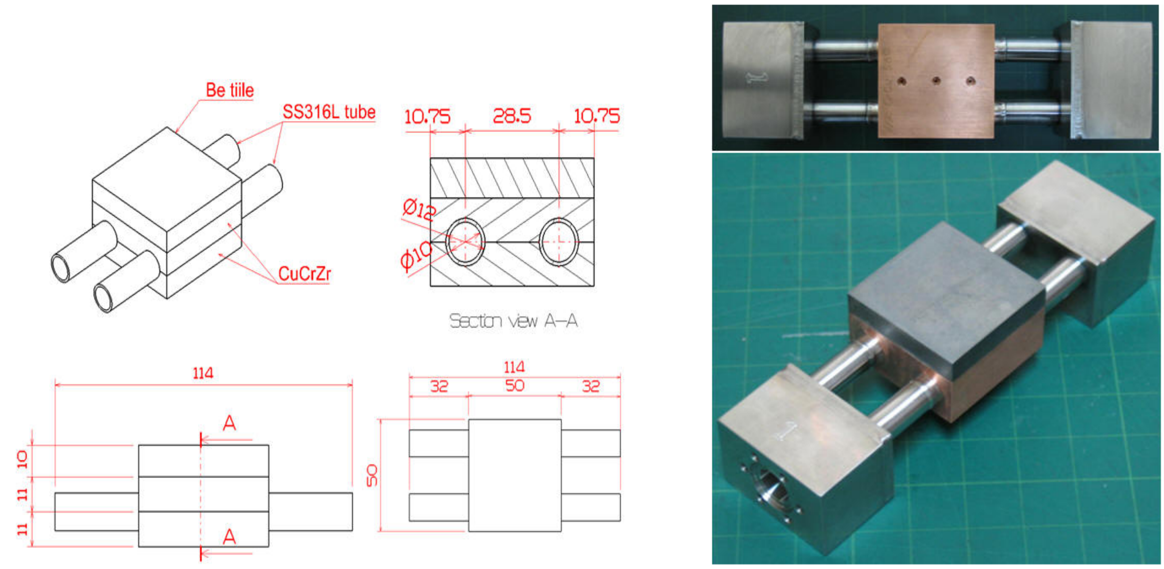


FIG.2. Schematics and a photo of the fabricated Be/Cu mock-up.

2.3. 80x80x3 Be/CuCrZr/SS mock-ups

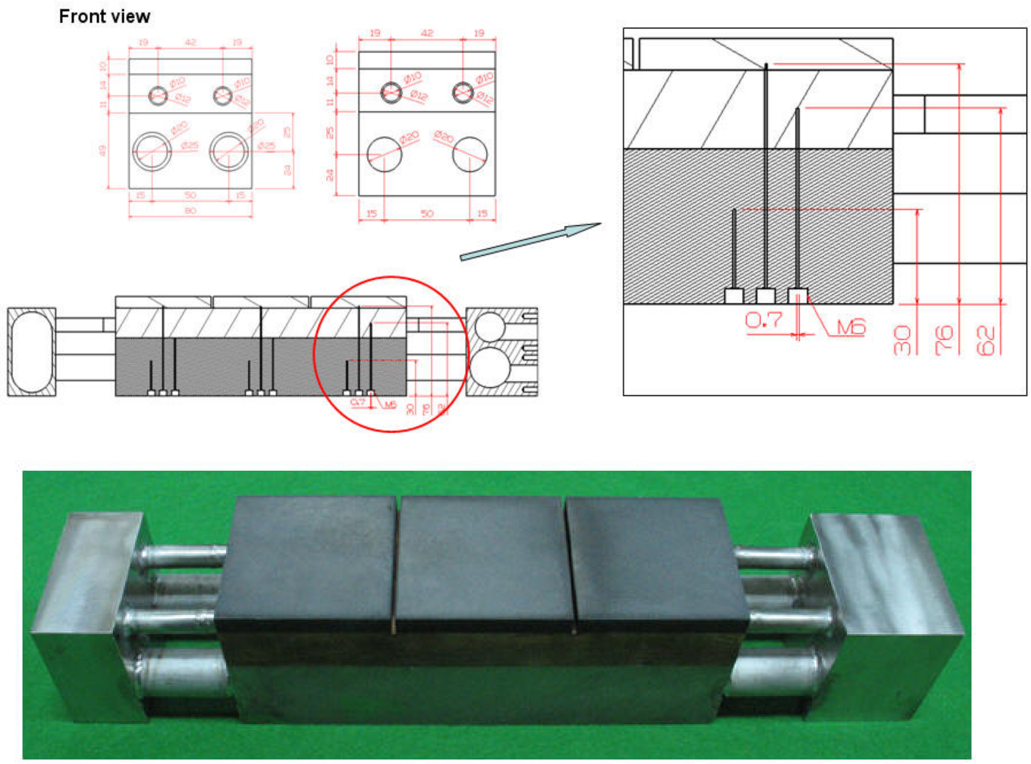


FIG. 3. Schematisc and a photo of the Be/Cu/SS mock-ups.

Two 80-mmx80-mmx3 Be/CuCrZr/SS mock-ups for the HHF test were fabricated on the basis of the following joining conditions; Be/CuCrZr joints were successfully fabricated by a HIP at 580 ^{o}C and 100 MPa for 2 hours including a post heat treatment after a HIP of the CuCrZr and SS tube with 1050 ^{o}C and 100 MPa for 2 hours. The 1-µm Cr/10-µm Cu interlayer was used at Be/ CuCrZr joining interface. After a HIP joining, no cracks and pores were observed at the joining interfaces. Three Be tiles, 80-mm long, 80-mm wide, 10-mm thick were used: the CuCrZr block is 244-mm long, 80-mm wide, 25-mm thick with two circular cooling tubes (10-mm ID, SS316L): SS block is 244-mm long, 80-mm wide, 49-mm thick with two holes for coolant (20-mm D). Nine thermocouples were installed at each mock-up to measure the temperature at an inner part of a mock-up and additional coolant pipes and manifolds were welded to the mock-ups in order to install it at TSEFEY, as shown in Fig. 3. The shear specimen which is 50-mm long and 10-mm wide, and the other conditions which followed ASTM B432, ASTM A265, and JIS G0601 were fabricated with the same conditions as the mock-ups for the shear tests. The loading speed was 0.5 mm/min and the shear strength was about 200 MPa. Ultrasonic test was performed with the fabricated mock-up using a probe which had a 5 MHz frequency, 0.25 inch diameter, and was a flat-type, and no defect was found in the Be/ CuCrZr interfaces.

3. High Heat Flux Test

Finite element structural analyses were carried out to determine the test conditions and to predict the fatigue lifetime of the mock-ups according to the various ITER operation conditions. In order to reduce the test time, an acceleration test was performed by increasing the heat flux up to 3.2 MW/m^2 for the CuCrZr/SS mock-ups, 2.5 MW/m^2 for the Be/CuCrZr mock-ups, and 1.5 to 2.0 MW/m^2, for the Be/CuCrZr /SS mock-ups where the heat fluxes were determined to avoid the evaporating temperature of a Be tile. In the 3-dimensional FEM analysis with ANSYS-11, a uniform heat flux was applied to the Be tiles at the heating phase and the coolant flows continuously during the heating and cooling phases. The simulation and test conditions for each test are summarized in Table 1.

TABLE 1. Summary of the simulation and high heat flux tests.

Items		50x100 CuCrZr/SS MU	50x50x1 Be/CuCrZr MU	80x80x3 Be/CuCrZr/SS MU	
Loaded heat flux [MW/m^2]		3.2	2.5	1.5	2.0
Water flow rate [kg/sec]		0.471	1.57	0.738	
Velocity [m/sec]	SS tube	3.0	10	4.7	
	SS hole	1.33	-	1.2	
Duration time		30 sec heating 60 sec cooling	40 sec heating 40 sec heating	100 sec heating 100 sec cooling	
Inlet water conditions		0.1 MPa, 25 ^{o}C	0.1 MPa, 25 ^{o}C	0.1 MPa, 25 ^{o}C	
Max. surface temperature [^{o}C]		412	478.3	403.5	543.2
Max. deformation [mm]		0.75	0.276	0.868	1.2
Max. strain [%]	SS tube	0.66	0.44	0.94	1.31
	Cu block	0.47	0.43	0.85	1.17
Number of cycles to a failure		1350	1900	220	<100
Tested cycles		1530	1000	1000	268

Temperature distributions at a heating phase and the temperature evolutions of the mock-ups were calculated. Among them, the case of the 80x80x3 Be/CuCrZr /Su mock-up is shown in Fig. 4. Deformation and strain distributions at a heating phase are shown in Fig. 5 for the case of the 80x80x3 Be/ CuCrZr/SS mock-up. The maximum deformations at a Be tile, the maximum total strains, and the estimated numbers of cycles to a failure are also summarized in Table 1.

In the HHF test, a pre-determined heat flux was used for each mock-up. During the heating by e-beam, the surface temperature of a mock-up was measured by an IR camera and a pyrometer to monitor a sudden increase of the temperature by a delamination or irregular heat flux. The HHF tests were performed up to the cycles shown in Table 1 without any sudden increase of the temperature, and no delamination, nor failure was found after the tests. Figure 6 shows the comparison of the temperature between the measured and analytical results for the CuCrZr/SS and Be/CuCrZr mock-ups. Some thermocouples were detached from their original location and delayed responses were observed. But most of the measured temperatures show a good agreement with the analytical results.

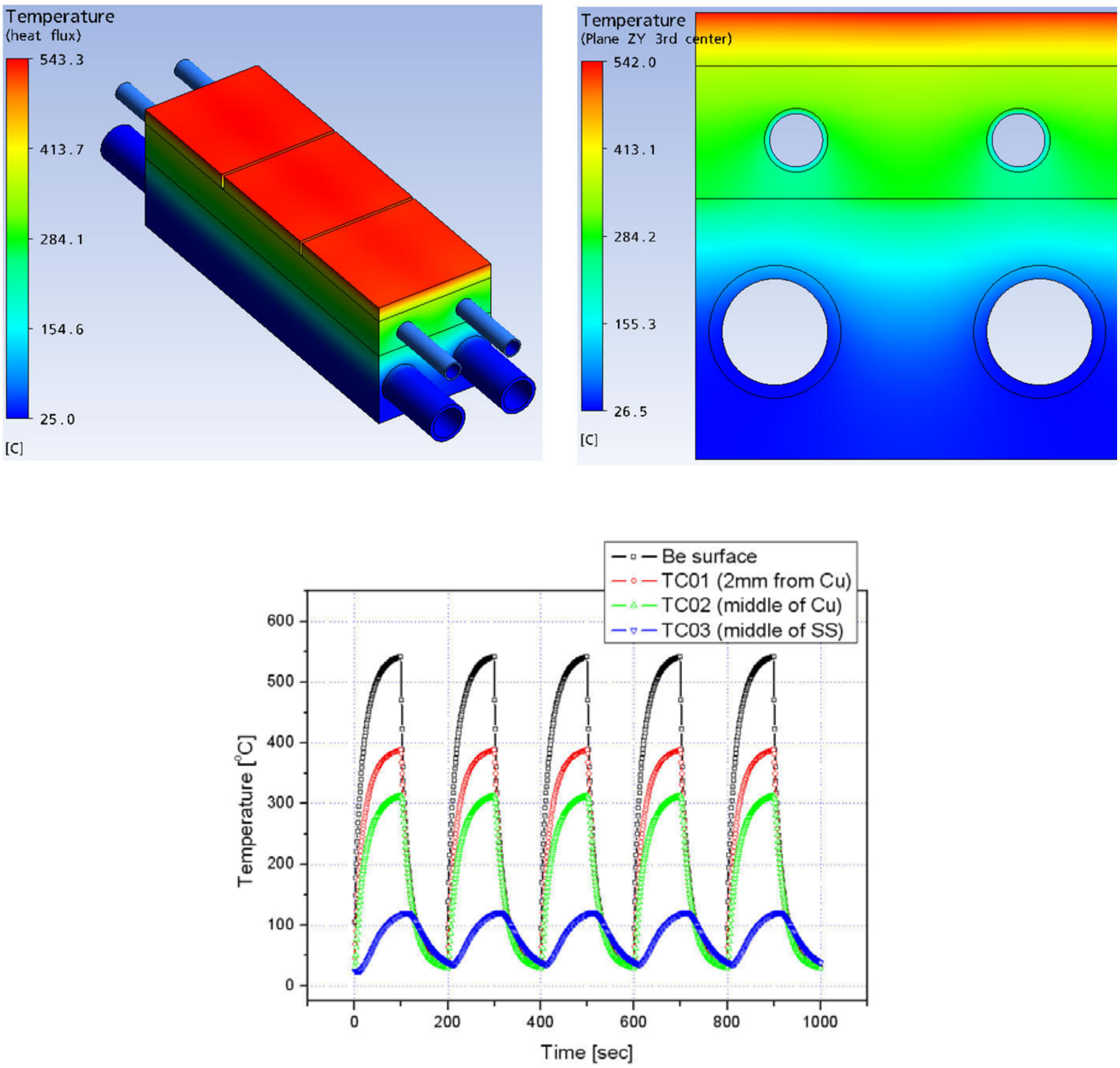


FIG. 4. Temperature distribution and evolution for the case of the 80x80x3 Be/CuCrZr/SS mock-up.

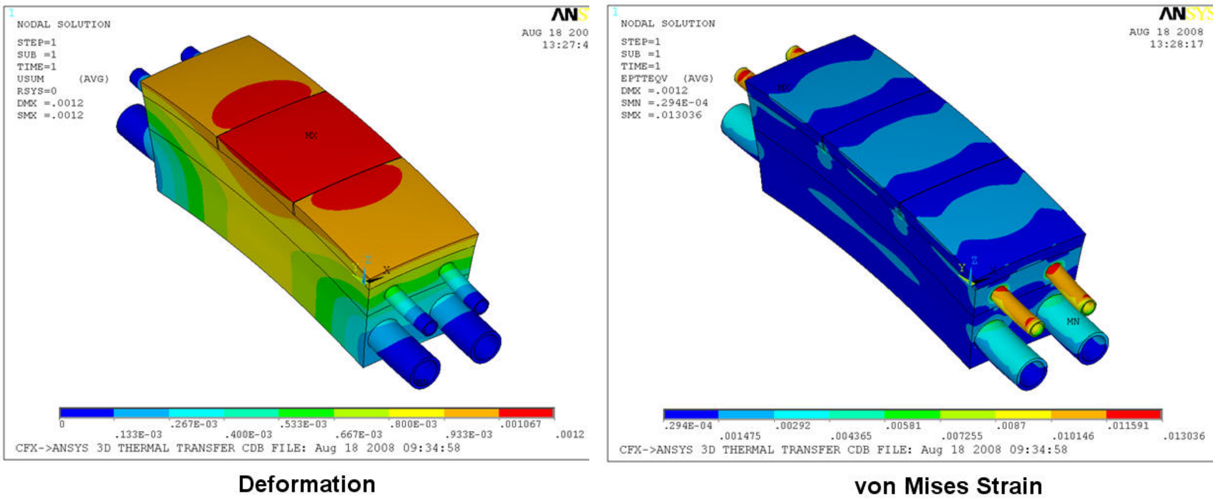
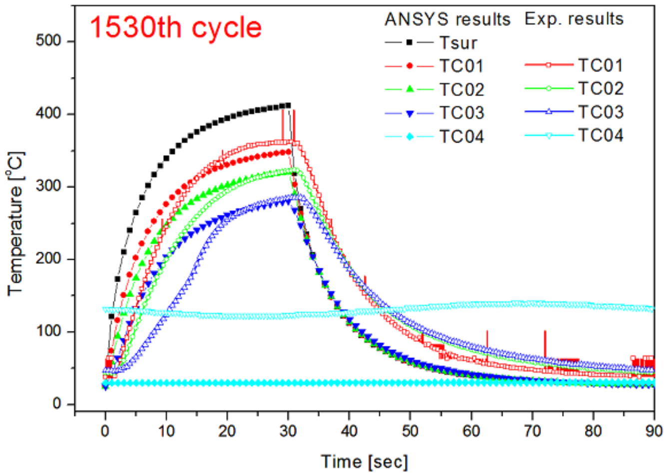
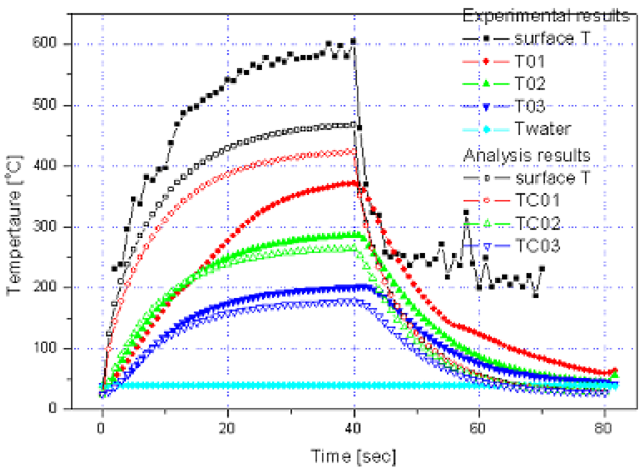


FIG.5. Deformation and von Mises strain distribution at a heating phase for the case of 80x80x3 Be/CuCrZr/SS mock-up.



(a) 50x100 CuCrZr/SS mock-up



(b) 50x50x1 Be/CuCrZr mock-up

FIG.6. Comparison of the temperature between the measured and analytical results

4. Summary

In order to develop the fabrication technology for the ITER FW blanket, several mock-ups were fabricated and tested. (1) 50x100 CuCrZr/SS mock-ups were fabricated with HIP (1050 ^oC, 100 MPa, 2 hrs) and tested at JEBIS (JAEA Electron Beam Irradiation Stand) up to 1530 cycles under a heat flux of 3.2 MW/m^2. (2) 50x50 Be/CuCrZr mock-ups were also fabricated with HIP conditions (1050 ^oC, 100 MPa, 2 hrs for CuCrZr/SS joining and 580/620 ^oC, 100 MPa, 2 hrs for Be/CuCrZr joining with the interlayers such as 1-μm Cr/10-μm Cu and 10-μm Ti/10-μm Cu) and tested at TSEFEY up to 1000 cycles under a heat flux of 2.5 MW/m^2. (3) In addition 80x80x3 Be/CuCrZr/SS mock-ups were fabricated with HIP conditions (1050 ^oC, 100 MPa, 2 hrs for CuCrZr/SS joining and 580 ^oC, 100 MPa, 2 hrs for Be/CuCrZr joining with the interlayer of 1-μm Cr/10-μm Cu) and tested at TSEFEY up to 1000 and 268 cycles under a heat flux of 1.5 and 2.0 MW/m^2, respectively. All the fabricated mock-ups survived up to the expected fatigue lifetime and the measured temperatures showed a good agreement with the analytical results. Based on these results, fabrication of the Be/CuCrZr/SS qualification mock-ups is progressing and a high heat flux test for a mock-up qualification will be performed.

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