Thermal-Fatigue Analysis of W-coated Ferritic-Martensitic Steel Mockup for Fusion Reactor Components

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1. Introduction

Tungsten (W) and ferritic-martensitic steel (FMS) as armor and structural materials, respectively, are the major candidates for plasma-facing components (PFCs), such as the blanket first wall (BFW) and the divertor, in a fusion reactor. The joining of the armor and the structural materials are key issues for the fabrication of these components to endure high-energy neutrons and extreme heat fluxes. Through the ITER blanket first wall (BFW) development project in Korea, the joining methods were developed with a beryllium (Be) layer as a plasma-facing material, a copper alloy (CuCrZr) layer as a heat sink, and type 316L austenitic stainless steel (SS316L) as a structural material [1-4]. And joining methods were developed such as Be as an armor and FMS as a structural material, or W as an armor and FMS as a structural material were developed through the test blanket module (TBM) program [5, 6].

As a candidate of PFC for DEMO, a new W/FMS joining methods, W coating with plasma torch, have been developed. In the present study, the W/FMS PFC development was introduced with the following procedure to apply to the PFCs for a fusion reactor: (1) Three W/FMS mockups were fabricated using the developed coating method in Chonbuk University. (2) Because the High Heat Flux (HHF) test should be performed over the thermal lifetime of the mockup under the proper test conditions to confirm the joint's integrity, the test conditions were determined through a preliminary analysis.

In this study, commercial ANSYS-CFX for thermal-hydraulic analysis and ANSYS-mechanical for the thermo-mechanical analysis are used to evaluate the thermal-lifetime of the mockup to determine the test conditions. Also, the Korea Heat Load Test facility with an Electron Beam (KoHLT-EB) will be used and its water cooling system is considered to perform the thermal-hydraulic analysis especially for considering the two-phase analysis with a higher heat flux conditions.

2. Preliminary analysis to determine the test conditions

Preliminary analyses are carried out to specify the appropriate testing conditions for the mockups. Because the node, element, and temperature information from the thermal-hydraulic analysis should be transferred to the thermo-mechanical analysis, hexa meshes which have a consistency between interfaces were used, as shown in Fig. 1. Total number of elements is 215,590 and its minimum and average qualities are 0.51 and 0.91, respectively.

In the analysis, only the surface heat flux was considered, and the water condition was reflected by considering the KoHLT-EB water supply system (0.3 MPa, 25°C). To determine the proper test time and to avoid the W evaporation temperature, the heat fluxes were assumed to be a 0.5 and 1.0 MW/m^2.

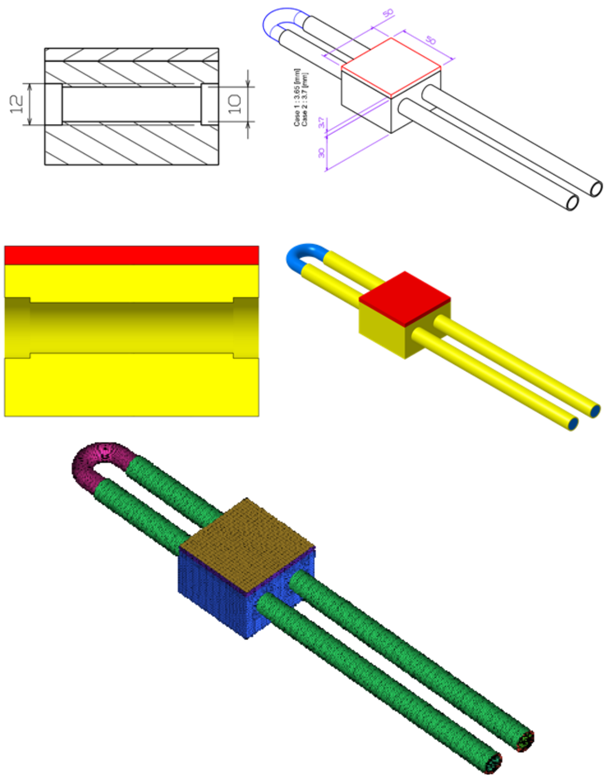

Fig. 1 Schematic of the mockup and its meshes for thermal-hydraulic and thermo-mechanical analyses.

2.1 Thermal-hydraulic analysis

From the previous single-phase analysis as shown in Table 1, heating and cooling time is determined to be 60 sec (30 sec heating and 30 sec cooling). As shown in Fig. 2, the maximum temperature at W armor was about 508.0 °C and overall heat transfer coefficient (HTC) is about 9.5 kW/m^{2}K. However, the subcooled boiling should be considered considering the cooling tube temperature of over 150 ^{o}C and coolant pressure of 3.0 MPa. From the two-phase analysis in the present study, after 30 sec heating with 1.0-MW/m^2, W armor temperature reaches 468.2 ^{o}C and the temperature return to 71.1 ^{o}C after 30 sec cooling. It does not increase for 5 repeated cycles, as shown in Fig. 3. The temperature distribution of the 5th cycle of the mockup is shown in Fig. 4. Compared to the single-phase analysis, the maximum temperature is lowered about 39.7 ^{o}C. The same simulation is performed with the 0.5-MW/m^2 heat flux.

Table 1 Simulation conditions by thermal-hydraulic analysis

Items	Conditions	Remark
Surface heat flux [MW/m^2]	0.5 / 1.0	5 cycles per each heat flux
Total water flow	0.15 kg/sec	
Inlet water conditions	3.0 MPa, 25 ^{o}C	Test conditions
Duration time	30 sec heating 30 sec cooling	60 sec duration time

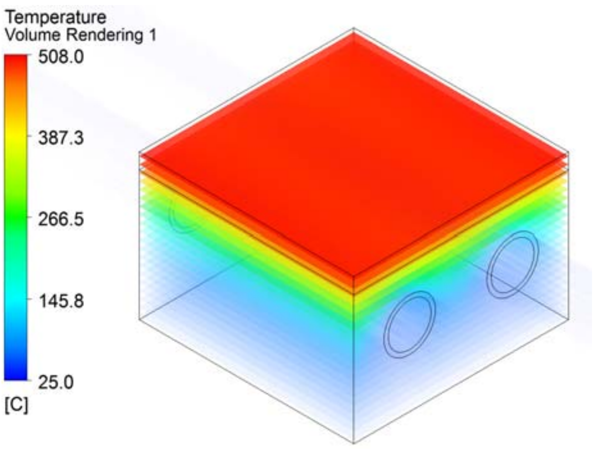

Fig. 2 Temperature distribution at heating time (270 sec, 5th heating) with 1.0 MW/m^2 heat flux with single-phase analysis

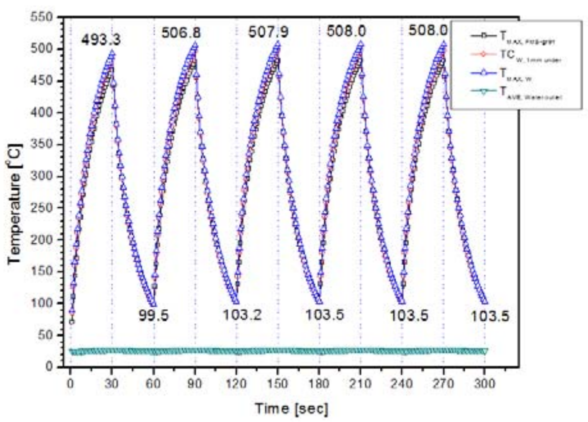

Fig. 3 Temperature evolution during 5 cycles with 1.0 MW/m^2 heat flux.

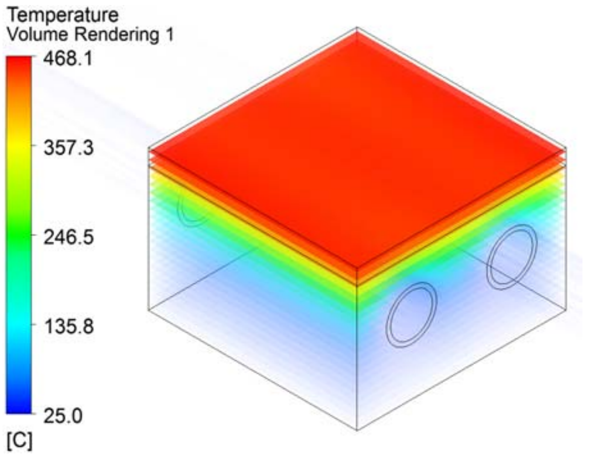

Fig. 4 Temperature distribution at heating time (270 sec, 5th heating) with 1.0 MW/m^2 heat flux with two-phase analysis

2.2 Thermal-mechanical analysis

The temperature distribution, as well as the node and element information from the thermal-hydraulic analysis, is transferred to the thermo-mechanical analysis, and the stress and strain results are obtained. In the elastic analysis, the stress results based on Fig. 5 showed that the maximum von Mises stress is 677.9 MPa in the FMS, which is higher than twice the yield strength (360 MPa at 500 ^{o}C) of FMS. According to the following ASME rule, the elastic-plastic analysis is performed: the ASME code [7] recommends that if the general thermal stress associated with a distortion in the structure exceeds twice the yield strength of the material, the elastic analysis might be invalid.

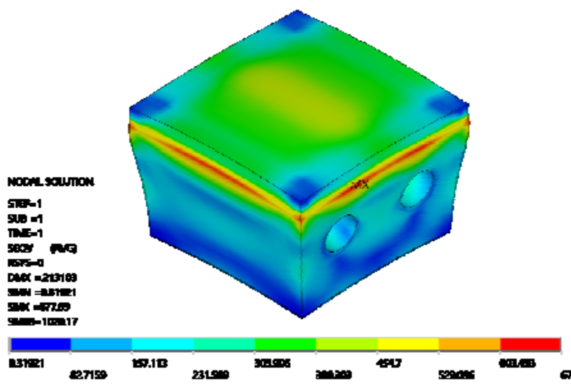

Fig. 5 von Mises stress distribution with 1.0 MW/m^2 heat flux in elastic analysis

Figure 6 shows the von Mises stress distribution and its maximum value is 429.0 MPa. Figures 7 and 8 show the von Mises strain distribution and deformation by the elastic-plastic analysis, in which the maximum values are 0.4970 % and 0.211 mm, respectively. According to the maximum strain in the FMS, as shown in Fig 7, the thermal fatigue lifetime is estimated about 4,306 cycles under the current design and test conditions. In the previous study, in which only single-phase condition was considered, the fatigue lifetime was about 10,355 cycles.

In the same way, the case of 0.5-MW/m^2 heat flux was analyzed and the estimated lifetime was over 100,000, which is improper for thermal cyclic test because it will take too long time.

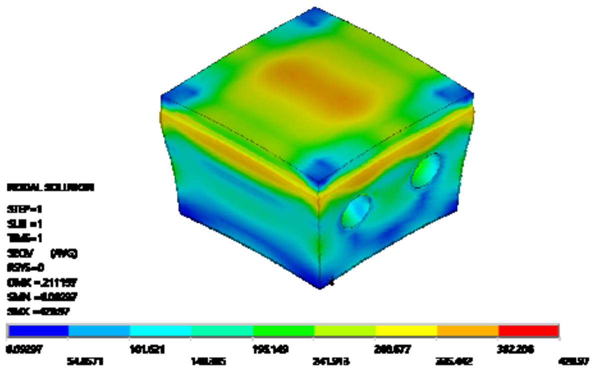

Fig. 6 von Mises stress distribution with 1.0 MW/m^2 heat flux in elastic-plastic analysis

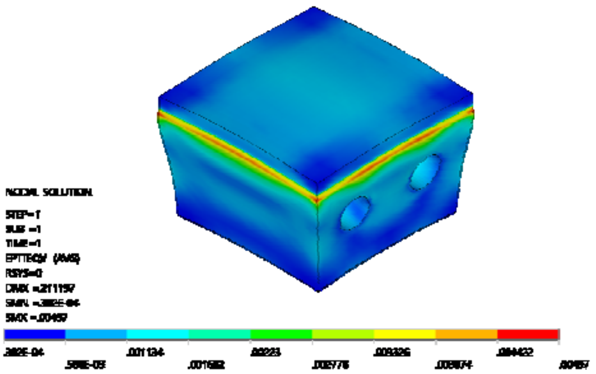

Fig. 7 von Mises strain distribution with 1.0 MW/m^2 heat flux in elastic-plastic analysis**.**

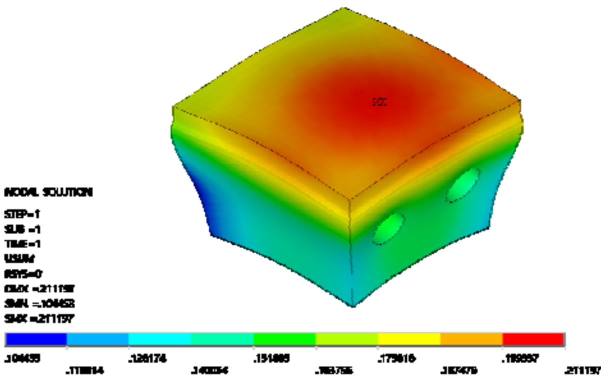

Fig. 8 Deformation distribution with 1.0 MW/m^2 heat flux in elastic-plastic analysis.

3. Conclusions

For application to a fusion reactor, methods to join W to FMS have been developed and various W mockups were fabricated with the developed joining conditions. The HHF test conditions are found by performing a thermal-hydraulic and thermo-mechanical analysis with the conventional codes such as ANSYS-CFX and –mechanical especially for considering the two-phase condition in cooling tube. From the analysis, the heating and the cooling conditions were determined for 0.5- and 1.0-MW/m^2 heat fluxes, respectively. Elastic-plastic analysis is performed to determine the lifetime and finally, the 1.0 MW/m^2 heat flux conditions are determined up to 10,355 cycles.

The test will be done in the near future and the measured temperatures will be compared with the present simulation results.

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