Joining Technologies of Be/RAFM Steels for a Fabrication of the TBM First Wall

Jung-Suk Lee [a]*, Jeong-Yong Park [a], Byung-Kwon Choi [a], Bong-Guen Hong [b], Ki-Jung Jung [c] and Yong-Hwan Jeong [a]
[a]*Advanced Core Materials Lab., Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea*
[b]*Fusion Engineering Center, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea*
[c]*National Fusion Research Institute, ITER Korea Project Office, Daejeon 305-353, Republic of Korea*
** jslee71@kaeri.re.kr*

1. Introduction

The test blanket module (TBM), which will be installed in a specific port of the International Thermonuclear Experimental Reactor (ITER), is a kind of experimental equipment to demonstrate the availability and integration of technologies essential for a fusion reactor by testing the components for a fusion reactor.

One of the main issues about the R&D on the TBM is to develop the fabrication technology for the TBM first wall. The TBM first wall is a multilayer of components consisting of plasma facing armor materials and structural materials including the cooling channels to resist and remove the high heat flux from the fusion plasma. Beryllium (Be) and reduced activation ferritic/ martensitic (RAFM) steels are the primary candidate materials for the armor and structural materials of the TBM, respectively [1]. The joining of two different materials has been a critical issue in the fabrication of the TBM first wall. For a successful fabrication of such complex components, the diffusion welding method is favored. Hot isostatic pressure (HIP) is one of the promising diffusion welding methods that allows a uniform distribution of the pressure and a good dimensional tolerance [2].

However, the joining of Be to RAFM steels still needs to be developed further before starting a mass production of an TBM first wall. Direct Be/RAFM steels bonding has not been successful due to the formation of brittle diffusion barrier layers that cause a cracking at the bonded interface, and these formed intermetallic compounds have a strongly negative influence on the performance of TBM mock-ups. In order to avoid this and optimize the joining conditions, the application of interlayer materials had been proposed. In this study, several interlayer conditions were investigated by preliminary tests.

2. Experimental procedure

The structural material was chosen as RAFM steels which was produced by KOUFU Co., LTD., Japan, and Be, S-65C vacuum hot pressed (VHP) was selected as the reference Be grade for the armor material due to its lowest BeO and other impurity contents and high ductility at an elevated temperature.

In this study, two types of interlayer, Cr/Cu and Ti/Cu were coated to investigate the effect of an interlayer type on the Be/RAFM steels joining properties. The interlayer was coated onto a Be surface by a physical vapor deposition (PVD) method after an ion etching was performed to remove the oxide layer on the Be surface. The coated Be tiles and RAFM steels were assembled and encapsulated with 1.5 mm SS304 plates by a TIG welding method. The canisters were out-gassed at 400℃ for 3hrs in a vacuum of less than 10^{-5} torr and then HIPed at 850℃, 100 MPa and 2 hrs. The details of the interlayer conditions are shown in Table 1.

To evaluate the strength of the HIP bonded Be/RAFM steels joints, four-point bending tests and shear tests were performed in accordance with ITER recommendation for standard test methods [3]. And the fracture surface of the tested specimens was observed by a scanning electron microscopy (SEM) and an electron probe micro analyzer (EPMA).

Table 1. Interlayer types and HIP conditions for the Be/RAFM steels joining.

No.	Interlayer	HIP condition
#1	1.5Cr/5Cu	
#2	3Cr/10Cu	850℃, 100 MPa, 2hrs
#3	5Ti/15Cu	

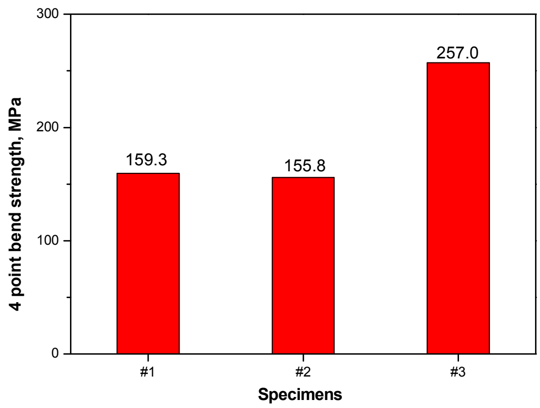

Figure 1. Four-point bending test results of the Be/RAFM steels joint specimens.

3. Results and discussion

3-1. Mechanical properties of the Be/RAFM steels joint specimens

Mechanical test of the Be/RAFM steels joint specimens was performed to examine the effect of the interlayer types and the thickness of the coated interlayer on the bonding strength. Fig. 1 shows the results of the four-point bending test of the Be/RAFM steels joint specimens. The joined specimen with Ti/Cu interlayers showed a higher bending strength, 257 MPa, when compared with the Cr/Cu interlayers. The effect of interlayer thickness could not be confirmed from the results of experimental #1 and #2.

In the case of the shear tests, the test specimens of experimental #1 and #2 could not be manufactured in the form of shear test specimens due to their weak bonding strength. But, the joined specimen with Ti/Cu interlayers (#3) showed a shear strength of 130.4 MPa. This value was slightly higher when compared with the previous result [4]. In a previous result, a Be/Cu alloys joint specimen for the fabrication of the ITER first wall which was HIP joined at 850℃ showed a shear strength of 108 MPa. In this study, HIP joined Be/RAFM steels which were coated by Ti/Cu interlayers showed optimized properties.

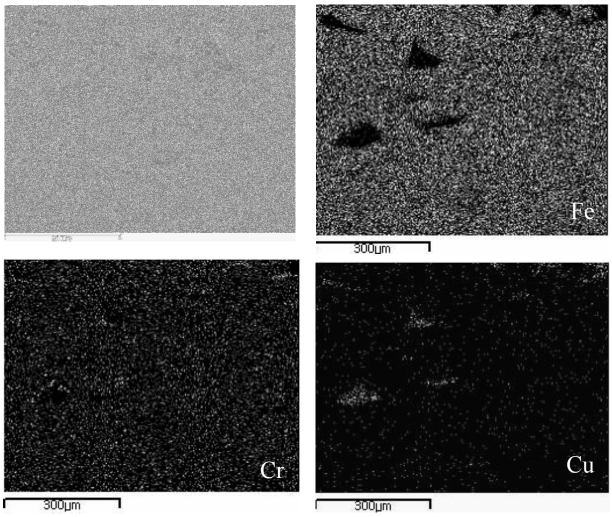

Figure 2. Fracture surface and EPMA element mapping image of the Be side after four-point bending test of the Be/RAFM steels joint specimen with 1.5 ㎛ Cr/5 ㎛ Cu interlayers.

3-2. Fracture surface of the Be/RAFM steels joint specimens after four-point bending tests

The fracture surface of the HIP joined specimens were observed to confirm their fracture behavior. Fig. 2 and Fig. 3 show the fracture surface and EPMA element mapping image of the Be side after the test of the Be/RAFM steels joint specimen with the Cr/Cu interlayers and Ti/Cu interlayers, respectively. It was found from those results that the joint specimen with Cr/Cu interlayers was mainly fractured at the diffusion barrier layer of a 8-10 ㎛ thickness which was formed on the RAFM steels, and partially fractured at the Cu interlayer. On the other hand, in the case of the Ti/Cu interlayers, the fracture was propagated at the interface between the diffusion barrier layer onto the RAFM steels and another diffusion barrier layer which was diffused by the Ti and Cu interlayer. It is suggested that the beneficial effect obtained by the application of the Ti/Cu interlayers could be compensated for by formation of brittle intermetallic compounds at the diffusion barrier layer onto the RAFM steels. In the future, we need to analyze further the microstructure of joining interface.

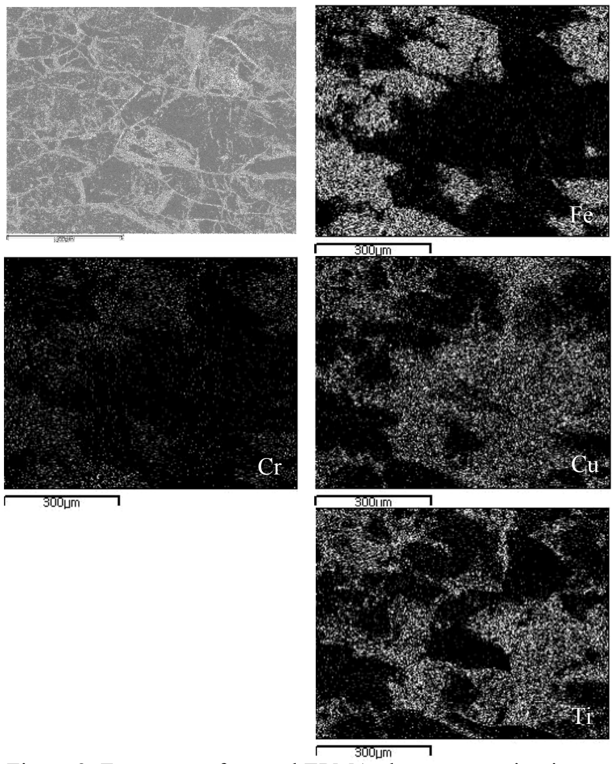

Figure 3. Fracture surface and EPMA element mapping image of the Be side after four-point bending test of the Be/RAFM steels joint specimen with 5 ㎛ Ti/15 ㎛ Cu interlayers.

4. Conclusion

In this study, the effect of the interlayer types and the thickness of the coated interlayer was investigated to optimize the HIP joining conditions for the joining of Be to RAFM steels without a delamination of the Be/RAFM steels joint specimens. Be and RAFM steels were bonded successfully by the application of Ti/Cu interlayers and a HIPing at 850℃, 100 MPa and 2hrs.

5. Acknowledgements

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