High Heat Flux Tests of Small-scale Be/Cu Mock-ups for ITER

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Abstract. Several kinds of Be/Cu joints have been made by hot isostatic press (HIP) in China in order to develop the ITER-FW blanket fabrication technology. At the first stage, high temperature HIP technology was investigated, and both Ti film and PVD (physical vapor deposition)-coating were adopted as intermediate layers between high purity beryllium made by HIP and CuCrZr alloy. The average bonding strength of Be/CuCrZr joints is larger than 60 Mpa and a good metallurgical bonding was formed. The Be/CuCrZr joints at optimized technology can sustain 1000 cycles under an absorbed power density of about 2.5 $MW.m^{-2}$, which shows relatively good thermal fatigue properties. Temperature and stress distributions were also calculated by 2D ANSYS, showing a good accord with experimental results. Low temperature HIP joining is being developed and the heat load evaluation is also under way.

1. Introduction

China, as one of the members of ITER (International Thermonuclear Experimental Reactor) project, will share tenth of ITER construction tasks. One of the challenging tasks is the fabrication of shield blankets, which consist of first wall panels and shield blocks. Since beryllium has been selected as the plasma facing material in the main vacuum chamber of ITER, the first wall mock-ups made by the bonding of Be, Cu and stainless steel plates will be the key engineering technology of ITER and might be one of the crucial issues of the future reactors too. Before the fabrication of the first wall mock-ups every PT' technology (Participate Team) must be qualified by IT (ITER Team) according to a common criterion based on the ITER operation conditions [1].

Since the autumn of 2004, an associated research team for this qualification task has been established in China, which consists of Southwestern Institute of Physics (SWIP), Chinese Institute of Engineering Physics, Ningxia Non-ferrous Metal co. ltd and Nuclear Power Institute of China. Up to now, several series of interlayer for hot isostatic press (HIP) bonding of beryllium and CuCrZr alloy have been tested, they are titanium film or coating, Cu coating and Al or AlSiMg alloy etc. The bonding strength (tensile or shear strength) of HIPed Be/Cu joints is up to 100 Mpa.

Metallurgical observation indicates that most of the joints have good metallurgical bonding.

High temperature HIP joining technology of Be/CuCrZr alloy or DS-Cu has been established by Europe and Japan [2-3]. At the first stage of our research, high temperature HIP joining of Be/CuCrZr alloy was investigated by referencing their successful experience and Ti was selected as interlayer. Since the first wall will receive high heat flux during ITER operation, a crucial criterion of FW mock-ups is the heat load resistance capabilities, in particular thermal fatigue property. In order to test the heat load resistance capabilities of Be/CuCrZr joints, an electron beam heat load facility with beryllium handling capability has been constructed and heat removal performances and thermal cycling tests of Be/CuCrZr joints were carried out. In this paper, the high heat flux tests of Be/CuCrZr mock-ups fabricated by high temperature HIP will be reported.

Recently, lower HIP temperature is proposed. Low temperature HIP joining technology has been developing in China and some promising results have been achieved. Detailed contents can be found elsewhere [4].

2. Experiment Procedure

2.1. Fabrication of Be/CuCrZr Alloy Joints

Hot isostatic press beryllium (made by Ningxia Orient Non-ferrous Metals Group Co. Ltd, China) and CuCrZr alloy were used as the armor material and the heat sink material, respectively. The content of Cr is 0.61wt% and Zr is 0.10 wt% in this CuCrZr alloy. The physical properties of HIP-Be are listed in table 1.

Table 1 Mechanical properties of HIP-Be at ambient temperature

Materials	Purity	Density	Yield strength	Ultimate tensile strength	Total elongation rate
HIP-Be	98.5 %	1.84 $g.cm^{-3}$	≥ 340 MPa	≥ 450 MPa	≥ 3 %

Ti film or coating was used as interlayer, main HIP parameters are as follows: temperature of 850 °C, pressure of 140 Mpa and holding time of 2 h. After HIP process, non-destructive tests (NDT) of Be/CuCrZr joints were carried out by means of supersonic waves with detection limitation of 1 mm defect, which has been calibrated by a standard sample with artificially made defects. Part of the joints was

Table 2 Main physical properties of Be/CuCrZr alloy joints

Mock-ups	Interlayer (film / coating)	HIP parameters	Bonding strength	NDT
Be/CuCrZr	80 μm / 50 μm	850°C/140Mpa/2h	60 Mpa	≤10% defects

cut for mechanical property tests and metallurgical observation, and other part was used for high heat load tests. The main physical properties of the Be/CuCrZr joints are shown in table 2.

2.2. Facility for HHF Tests

Owing to the toxicity of beryllium powder and vapor to human body, high heat load tests of Be/Cu joints require special protection. Before HHF tests, a modification of the previous electron beam heat load facility had been made according to the criterion of national environment protection. The main protection system includes an isolation of the facility with operators and filtering processes of exhaust gas from the vacuum chamber by using a special air filter with filtering efficiency of 99.95 % and liquid filtering system as shown in Fig. 1. An electron beam with Gaussian distribution and energy of 6 keV was used. Test sample of Be/CuCrZr joints has size of 20 × 20 × 32 mm (including 10 mm Be tile and 22 mm copper plate in thickness), a copper tube with inner diameter of 10 mm was inserted in the copper plate for active cooling and a hole of 1.5 mm in diameter located at a distance of 3 mm from the joining interface in the copper plate for the installation of thermocouples. The surface temperature of Be tiles was measured by a two-color optical pyrometer.

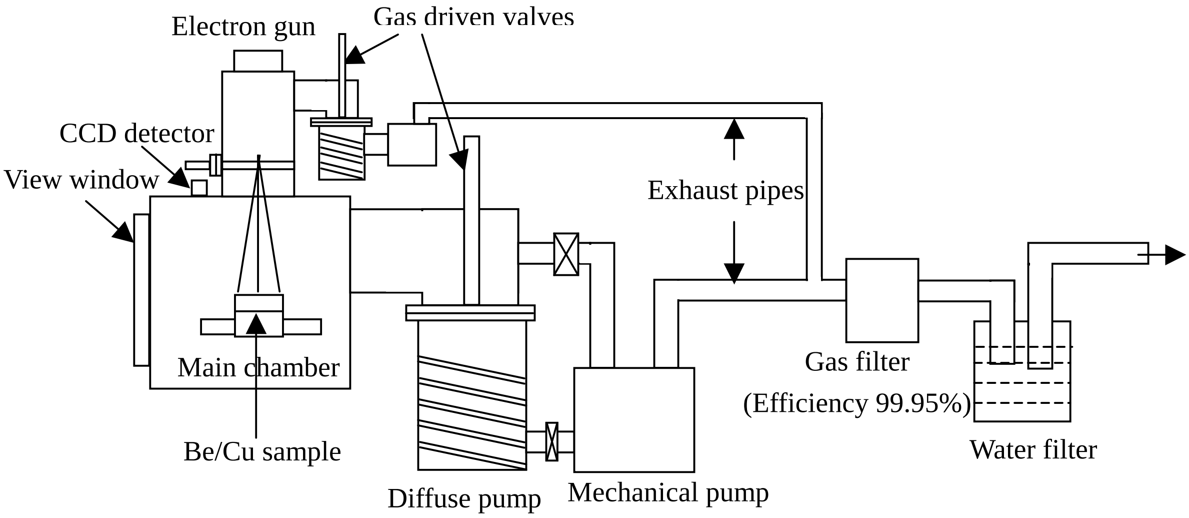

Fig. 1 Sketch drawing of the electron beam facility and protection system

2.3. Absorbed Energy Measurement of Be Armor

Usually, energy absorption coefficient depends on materials, surface conditions, such as surface roughness and surface compositions. S65-C beryllium made by vacuum hot press (VHP) is recommended as the ITER-FW armor material and its absorption coefficient is around 0.80 depending on experiment conditions, however there is no such data for HIPed beryllium although the difference might be very small. Therefore the energy absorption coefficient of HIP-Be was measured firstly before HHF tests.

A disk with size of ϕ15 × 5 mm and same surface roughness with the armor surface of the tested mock-ups was used for absorbed energy measurement, and a stainless steel armored thermocouple of 1.5 mm in diameter was embedded in the center of the disk, which can be used for both bulk temperature measurement and adiabatic support. An absorption coefficient of 0.77 was evaluated. This data is same as the measurement result of Rodig's [5]. Meanwhile, the optical pyrometer was also calibrated.

2.4.Heat Load Tests of the Mock-ups

In the present study, heat removal performance and durability for thermal cycles were evaluated. The former was investigated by the temperature change of Be armor and CuCrZr alloy with the increase of heat loads and the latter was evaluated by the change of temperature at different locations of the mock-ups as a function of cycles. Condition of heat load tests was listed in table 3.

Table 3 Conditions of heat load tests

Tests	Absorbed power ($MW.m^{-2}$)	Cycle	Load period (s)	Interval period (s)	Cooling water (press / flux)
Heat removal tests	1.5-3	1	16		0.4Mpa / 3L/min.
Thermal cycle tests	2.5	1000	16	36	0.4Mpa / 3L/min.

3. Results and Discussion

Temperature response of the mock-ups was indicated in Fig. 2. The maximum surface temperature of Be armor and bulk temperature of CuCrZr heat sink was 520 °C and 290 °C, respectively. It can be seen that the thermal equilibrium is not established in the experimental condition. Since a Gaussian distribution electron beam

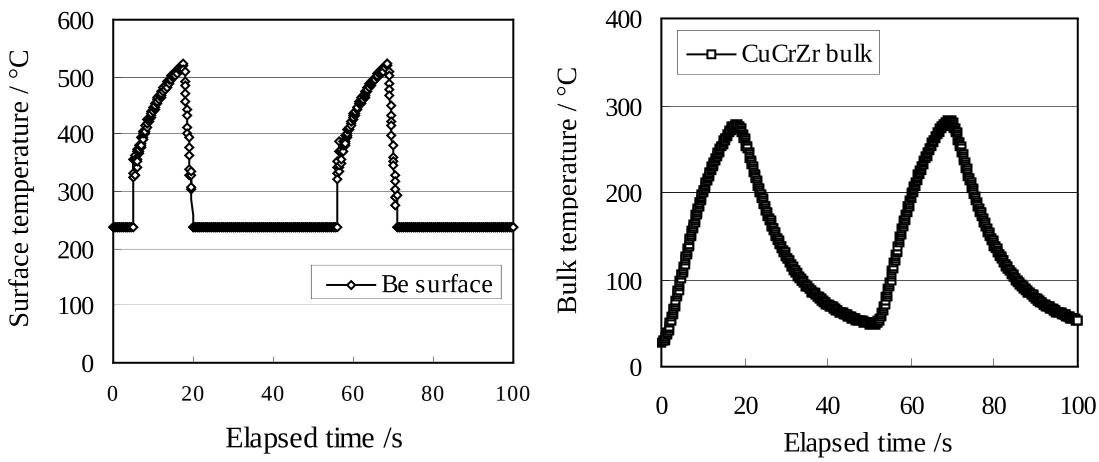

Fig. 2 Temperature response of Be/CuCrZr mock-ups in heat load tests

was adopted and only the surface temperature at central zone was measured, a longer time to thermal equilibrium can be expected than the case of uniform electron beam. In fact, ANSYS analysis indicates that the time to reach thermal equilibrium will be as long as 60 s in the present conditions.

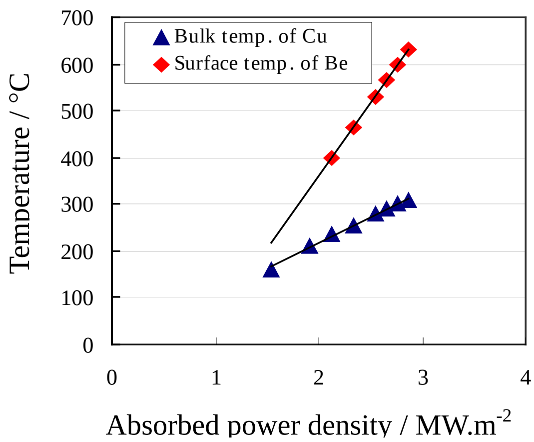

Fig. 3 Heat removal performance of Be/CuCrZr alloy joint

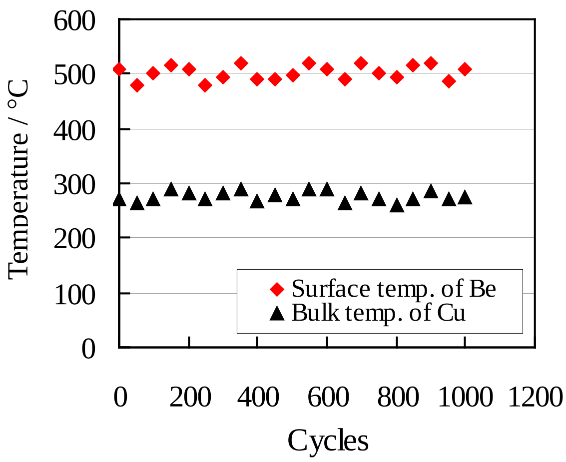

Fig. 4 Temperature as a function of cycles

Fig. 3 shows heat removal performances of this mock-up, and in this test the maximum absorbed power density is about 3 MW.m^{-2}. It is not available to increase further the power density owing to the limitation of the protection system at the present stage. Under the heat flux of 2.5 MW.m^{-2}, thermal cycle tests were performed. No obvious temperature change was observed during 1000 cycles as shown in Fig. 4. It also indicates that this mock-up has good durability to thermal cycles.

After 1000 thermal cycles, NDT analysis and metallurgical observations were also conducted. Both the results of NDT and metallurgical observation indicated that the original defect did not extend and no new defects were created. Fig. 5 shows the post-mortem metallurgy observations at two typical zones where one has defects and the other has not distinguished by NDT. The results of metallurgical observations confirm the analysis of NDT. On the other hand, some local cracks were found and the maximum width and length of the cracks were about 3 μm and 2-3 mm, respectively. Based on the metallurgical observation and NDT analysis of the other part of this joint, a reasonable assumption is that these cracks have formed during the fabrication processes of the joint and don't be created by cyclic loads. In light of this viewpoint, it also shows that local cracks with size of 2-3 mm don't extend during cyclic heat loads.

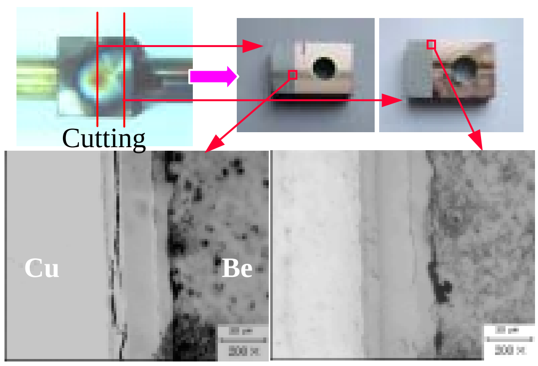

Fig. 5 Post-mortem metallurgy observations of the mock-up

Temperature and stress analyses have been performed by ANSYS code as shown in Fig. 6. In the calculation, a uniform heat flux of 2.5 $MW.m^{-2}$ was adopted and heat transfer coefficient was evaluated as 3300 $W.m^{-2}.K^{-1}$ based on actual cooling configuration and conditions. Calculation results indicate that the maximum surface temperature of Be tile and the bulk temperature of Cu heat sink at the thermo-couples position is 518.5 °C and 320 °C, respectively, which show good agreement with experimental results. Stress analysis indicates that the maximum stress is 535 Mpa, appearing at the edge of the interface.

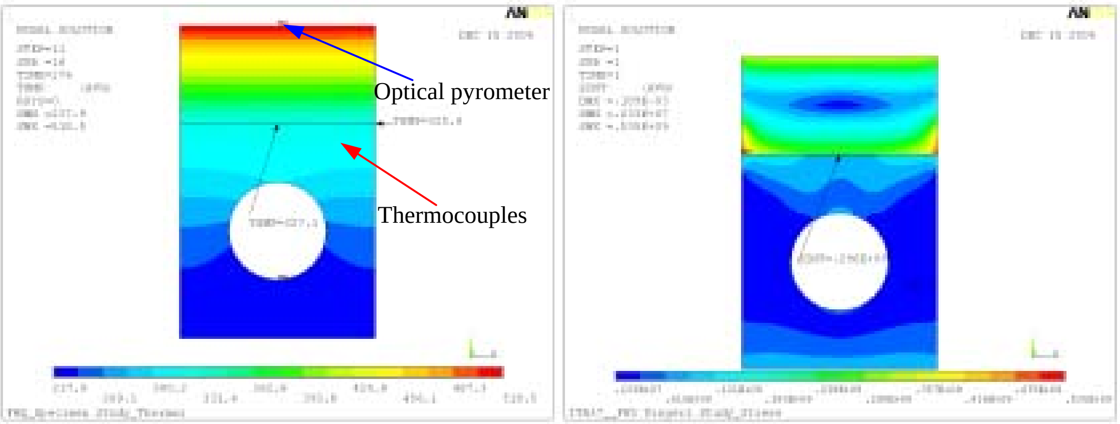

Fig. 6 2D ANSYS temperature (left) and stress (right) analysis of the tested mock-up

4. Conclusion and Outlook

High temperature HIP joining techniques of HIPed Be with CuCrZr alloy were studied by using Ti film and coating as interlayer and their heat load resistance capabilities were evaluated. Experimental results indicate that HIPed Be/CuCrZr joints fabricated at optimized technology can survive 1000 thermal cycles without indication of failure at a heat flux of 2.5 $MW.m^{-2}$ absorbed power density and 16 s pulse duration. Low temperature joining techniques are being investigated and heat load evaluation tests are also being prosecuted.

Temperature and stress analyses have been performed by ANSYS code and a good agreement between simulated calculations and experimental results was obtained. Since it is lack to measure in-situ the spatial distribution of surface temperature of beryllium tiles and its evolution with respect to time in the present experiment, it is not available to detect the local failure of Be/Cu joints due to the formation of interface cracks. Therefore an infrared thermograph with high resolving power is strongly recommended. Furthermore a new heat load facility with higher power and high scanning frequency is required for larger mock-ups. All these are being seriously considered and will be used in the next stage experiments.

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