Manufacturing and High Heat Flux Testing of Brazed Flat-Type W/CuCrZr Plasma Facing Components

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Abstract Water-cooled flat-type W/CuCrZr plasma facing components with an interlayer of oxygen-free copper (OFC) have been developed by using vacuum brazing route. The OFC layer for the accommodation of thermal stresses was cast onto the surface of W at a temperature range of 1150°C-1200°C in a vacuum furnace. The W/OFC cast tiles were vacuum brazed to a CuCrZr heat sink at 940°C using the silver-free filler material CuMnSiCr. The microstructure, bonding strength, and high heat flux properties of the brazed W/CuCrZr joint samples were investigated. The W/Cu joint exhibits an average tensile strength of 134 MPa, which is about the same strength as pure annealed copper. High heat flux tests were performed in the electron beam facility EMS-60. Experimental results indicated that the brazed W/CuCrZr mock-up experienced screening tests of up to 15 MW/m² and cyclic tests of 9 MW/m² for 1000 cycles without visible damage.

Keywords: W/CuCrZr mock-up, vacuum casting, vacuum brazing, high heat flux tests

PACS: 28.52.Fa, 52.40.Hf, 61.80.Fe

DOI: 10.1088/1009-0630/18/2/15
(Some figures may appear in colour only in the online journal)

1 Introduction

The joining of tungsten (W) armor materials to copper-based heat sink materials is a very important issue in the manufacturing of water-cooled plasma facing components (PFCs). According to the fusion development strategy of China, a Chinese fusion experiment testing reactor (CFETR) is being designed and an ITER-like divertor wall might be tested at the first operation phase [1]. Mono-block [2] and flat-type [3] structures are two of the most popular concepts for the ITER-like W/CuCrZr divertor. Both the mono-block and the flat-type W/CuCrZr PFCs were developed in China. The monoblock PFCs have been prepared by hot isostatic pressing (HIP) and hot radial pressing (HRP) [4,5]. The flat-type PFCs have been studied using coating technology [6–8], brazing technology [1,9,10], explosive welding [11] and diffusion bonding [12,13]. One of the main problems in the development of W/CuCrZr PFCs is the mismatch in the coefficient of thermal expansion (CTE) and elastic modulus between the W armor and the Cu heat sink, which may cause high thermal stress during fabrication and service process. Interlayer materials such as pure Cu [14–16] and W/Cu functionally graded materials (FGM) [17,18] have been used for the accommodation of this thermal stress.

In this paper, water-cooled flat-type W/CuCrZr mock-ups have been manufactured by using oxygen-free copper (OFC) as the interlayer. Casting of OFC on W tiles was performed, followed by machining, polishing and ultrasonic cleaning of the samples. The W/CuCrZr mock-ups were vacuum brazed at 940°C using a CuMnSiCr brazing filler material. The microstructure, bonding strength and high heat flux properties of the W/CuCrZr mock-ups were then investigated.

2 Manufacturing of W/CuCrZr mock-ups

2.1 Casting of a W/OFC joint

Commercially hot-rolled pure W with purity of 99.94% was supplied by Beijing Tian-Long Tungsten & Molybdenum Co., Ltd., China. The purity of OFC for the casting experiment was 99.9999%. W and OFC tiles were machined and polished to remove the oxide layer. The polished materials were ultrasonically cleaned in an ethanol bath. Casting of OFC on the W surface was performed in a vacuum furnace with a residual pressure < 5 × 10⁻³ Pa and at a temperature range of 1150°C-1200°C for 15 min. Finally, the W/OFC cast tiles were mechanically machined and polished to get a uniform flat surface. A perfect wetting of the W/OFC tile was obtained, as shown in Fig. 1.
In order to characterize the W/OFC cast tiles, the interface microstructure and bonding strength were analyzed and a good joining structure was observed. Fig. 2 shows the cross-section of the W/OFC tile. No pores, cracks or detachments were found at the bonding interface. The OFC layer had a coarse grain structure and was close to full density. The Vickers microhardness of the OFC layer is about 63 ± 3, which is much lower than that of the W armor and the CuCrZr heat sink. To determine the mechanical properties of the W/OFC tiles, tensile tests of the W/OFC joints were performed at room temperature. The results of three samples with length of 50 mm and thickness of 3 mm are shown in Fig. 3. The fracture occurred entirely at the OFC part. The bonding strength of the joints was found to be 134 ± 4 MPa, which is approximately the same as the strength of pure annealed copper.

### 2.2 Brazing of W/OFC tile to CuCrZr heat sink

The W/OFC tiles were brazed with a CuCrZr heat sink using the silver-free filler material CuMnSiCr. The brazing filler material has a composition of 63 at.% Cu, 36 at.% Mn, 0.5 at.% Si, 0.5 at.% Cr, and its solidification and liquefaction temperatures are 865 °C and 905 °C, respectively. The brazing filler material was applied in the form of a metal foil with thickness 100-200 µm. The CuCrZr heat sink with content of 0.6 wt.% Cr and 0.079 wt.% Zr was treated with a solid solution and an aging treatment. Prior to brazing, the W/OFC tiles, CuCrZr block and the brazing filler material were polished and ultrasonically cleaned. The samples of W/CuCrZr were brazed in a vacuum furnace with a residual pressure < 5 × 10⁻³ Pa at a temperature of 940 °C for 15 min. Then, fast cooling followed by aging treatment (2 h at 480 °C) was performed. Ar gas was introduced into the vacuum chamber to cool down the brazed joints at a cooling rate above 60 °C/min. The OFC/CuCrZr joints for tensile tests were also brazed at 940 °C for 15 min, followed by a fast cooling and aging treatment.

The brazing process was similar to the solid solution and aging treatment of CuCrZr alloy and was used to control the strength loss of CuCrZr alloy. The Vickers microhardness of the brazed CuCrZr is about 120 ± 8, which is similar to that of the heat treated CuCrZr alloy (Vickers microhardness: 127 ± 6). Fig. 4 shows the microstructure in the brazing region. The thickness of the brazed layer is approximately 60 µm. Significant Mn diffusion towards the OFC and CuCrZr was found at the brazing region. This diffusion supports the good bonding between OFC and CuCrZr. The bonding strength of the OFC/CuCrZr joints was also tested at room temperature. The tensile strength of the joints was found to be approximately 131 ± 6 MPa. The fracture of these joints also occurred entirely at the OFC part, which is similar to the result occurring in the W/OFC joints. The OFC layer has low yield strength and tensile strength, which means that this interlayer can play the role of releasing internal stresses caused at the bonding interface during the fabrication and service process.
2.3 Characterization of the mock-up

Actively cooled flat-type W/CuCrZr mock-ups were manufactured by using the optimized casting and brazing parameters. Fig. 5 shows the geometry and photograph of the mock-up. The overall dimensions of the mock-up are 74 mm × 24 mm × 31.5 mm (single W tile: 24 mm × 24 mm × 6 mm, OFC layer: 24 mm × 24 mm × 1 mm). The cooling channel of the CuCrZr heat sink is 12 mm in diameter. The clearance between the W tiles is approximately 1 mm. In the flat-type mock-up, the W tile is subdivided in small rectangular lamellae by the clearance. The advantages of this structure are that the stress at the W/Cu interface is reduced and the single elements are free to expand under the heat flux [19].

Fig. 5  Photograph of the W/CuCrZr mockup for HHF tests

3 High heat flux tests

3.1 High heat flux tests

The high heat flux (HHF) tests of the brazed W/CuCrZr mock-up were performed in the electron beam facility EMS-60 [8] at the Southwestern Institute of Physics (China) to assess the joining technique. Table 1 shows the operating parameters of EMS-60. This device provided an electron beam with a maximum power of 60 kW. The electron beam can be focused to a diameter of approximately 1 mm with pulse duration from 1 ms to continuous. Fairly homogenous heat distribution was loaded on a well-defined area of mock-up by fast scanning of the electron beam.

The high heat flux tests were carried out under the cooling condition with water flow velocity, pressure and temperature of 6.0 m/s, 1 MPa and 25 (±5) °C, respectively. The loaded area of the mock-up was approximately 70 mm × 22 mm covering almost 87% of the whole surface. The acceleration voltage of the electron beam was 120 kV. The beam scanned across the surface with a fast frequency of 8.5 kHz in the X and Y directions. The mock-up was monitored using a CCD color camera in the HHF tests. The surface temperature distribution of the mock-up was monitored by using a short wavelength infrared camera FLIR SC2500 (short wave: 0.9-1.7 μm, 350°C-3000°C). Local surface temperature was measured by using a one-color pyrometer IGA740 (Response time 6 μs, 350°C-3500°C) and focusing on one of the W tiles. Temperatures of the interfaces were measured using K-type thermocouples with range from 0°C to 1300°C. Before the HHF tests, the infrared camera and pyrometer were calibrated using K-type thermocouples. The calibration W tile with dimension of 25 mm × 25 mm × 3 mm was installed in the main chamber and supported by two shielded thermocouples with a diameter of 1.5 mm which were inserted into the W tile [1,10]. The performed tests comprised screening tests aiming at the finding of thermal load limitation of the mock-ups and cyclic loading tests aiming at the finding of fatigue endurance. The testing parameters for the mock-up are summarized in Table 2. The incident power density is calculated based on the acceleration voltage and electron beam current and surface area of the mock-up. Absorbed power density is determined by flow-rate and temperature difference of the cooling water across inlet and outlet of the mock-up. If the power density is calculated, then the result depends strongly on the reference area. These discrepancies lie between 5% and 25%, depending on the size of the mock-ups [20]. In the present experiment, the discrepancy is less than 13%. For the assessment of the joints, a power density which refers to the whole surface area is thought to be more suitable [20].

Table 1. Parameters of the electron beam test facility EMS-60

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB gun power (kW)</td>
<td>0-60</td>
</tr>
<tr>
<td>Acceleration voltage (kV)</td>
<td>90-150</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0-400</td>
</tr>
<tr>
<td>Ramp time (ms)</td>
<td>&lt;0.3 ms</td>
</tr>
<tr>
<td>Plus duration (ms)</td>
<td>1 ms-continuance</td>
</tr>
<tr>
<td>Irradiated area (mm²)</td>
<td>4×4-150×150</td>
</tr>
<tr>
<td>Scanning frequency</td>
<td></td>
</tr>
<tr>
<td>along X, Y direction (kHz)</td>
<td>≤ 50</td>
</tr>
<tr>
<td>Maximum coolant (water) flow rate (L/s)</td>
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</tr>
</tbody>
</table>

Table 2. Parameters of HHF tests for W/CuCrZr mock-ups in the EMS-60 facility

<table>
<thead>
<tr>
<th>Testing steps</th>
<th>Screening tests</th>
<th>Cyclic tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident power density (MW/m²)</td>
<td>10.2-25.5</td>
<td>15.3</td>
</tr>
<tr>
<td>( P_{inc} = U \times I/A )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(( U ): acceleration voltage, ( I ): e beam current, ( A ): area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorbed power density (MW/m²)</td>
<td>6.02-15.1</td>
<td>9</td>
</tr>
<tr>
<td>( P_{abs} = C_p \times Q \times \Delta T/A )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(( C_p ): specific heat, ( Q ): flow rate, ( \Delta T = T_{outlet} - T_{inlet}, A ): area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading cycle (s)</td>
<td>30 on/15 off</td>
<td>15 on/15 off</td>
</tr>
<tr>
<td>Cycle numbers</td>
<td>2</td>
<td>1000</td>
</tr>
</tbody>
</table>
3.2 Results of the tests

Screening tests were conducted starting from 6.02 MW/m² and increasing the absorbed power density at steps of approximately 1 MW/m² up to 15.1 MW/m². The cycle duration is 45 s with a heating phase of 30 s and a dwell phase of 15 s. Two cycles were used for every power density. During the heating phase, the surface temperature and the temperature difference between outlet and inlet water coolant reached heat balance (see Fig. 6). Actually, a few seconds are sufficient to reach the steady state condition. During the dwell phase, 15 s is also sufficient to bring the mockup back to its original thermal state. Fig. 7 shows the absorbed power density calculated and measured by cooling water calorimeters during screening tests. The absorbed power density increased linearly with the increase of incident power density. It was calculated that the power absorption coefficient for this flat-type W/CuCrZr mock-up kept stable at the value of 59% during the present set of experiments. The power absorption coefficient can be calculated by the formula below:

$$\alpha = \frac{P_{\text{abs}}}{P_{\text{inc}}}$$

where $P_{\text{abs}}$ is the absorbed power density and $P_{\text{inc}}$ is the incident power density. The electron absorption coefficient for pure W is 55% obtained by means of Monte-Carlo simulations [21]. For the W mock-ups, large differences between experimental results and calculations have previously been observed by Duwe et al [22]. In our previous experiments, the power absorption coefficient calculated for small W/CuCrZr mock-ups with single W tile by means of cooling water calorimeter is approximately 55% [10], which is in a good agreement with the result of Monte-Carlo simulations. For the 30 mm×60 mm W/CuCrZr brazed mock-up with 3 slits in X-direction and 1 slit in Y-direction, the power absorption coefficient is about 63% [1]. These results indicate that the absorption coefficient of the W/CuCrZr mock-up increased with the increase of the number of slits. This happens because the power absorption in the slits could approach to nearly 100%. The calculated absorption coefficient of the present mock-up is actually lower than 59% if only the absorption in the slits is considered. Another reason for this disagreement is the increased ambient temperature of the vacuum chamber. A strong heating of both the vacuum chamber and the clamping system was observed due to the reflected electrons and secondary electrons in the experiments. This phenomenon can also be found in Ref. [23]. This reflected the fact that heating might heat up the sides of the mock-up which contributes to the temperature increase of the cooling water without affecting the surface of the mock-up and the W/Cu joint. Hence cooling water calorimetry overestimates the absorbed power density [23].

The surface temperatures measured via the pyrometer were compared with those calculated by using ANSYS code (see Fig. 8). The pyrometer observed the temperature in an area of 6-7 mm diameter at the center of the heated surface through a quartz window and with a viewing angle of approximately 45°C. The surface temperatures increased linearly with increasing power density. Simulated temperatures match the experimentally observed surface temperatures within a 10% deviation when the absorbed power density is less than 12 MW/m². Thermal radiation should be responsible for the deviation because the ANSYS analysis does not take into account the radiation from the sides of the mock-up. The experimental results became much lower than those of the simulated temperature when screening.
tests were performed at higher absorbed power density. The problem of W surface emissivity calibration should be considered as another reason. The W surface emissivity is strongly dependent on the surface condition and temperature. The infrared camera and pyrometer were calibrated by the K-type thermocouples, which have a maximum applicable temperature of 1300 °C. When the temperature exceeded 1300 °C, the W surface emissivity was not calibrated and was set as 0.25 for the pyrometer. The mock-up successfully survived screening tests from 6 MW/m² to 15 MW/m². No hot spot was observed from the infrared camera or from the CCD camera. No crack or delamination occurred on the W surface or at the W/OFC/CuCrZr interface. Furthermore, the absorption coefficient of the mock-up was stable and maintained at 59%, indicating that the heat transfer was not affected by the incident high heat flux.

Thermal fatigue tests were performed at 9 MW/m² for 1000 cycles with a heating phase of 15 s and a dwell phase of 15 s. The main purpose of this testing is to check if the components maintain its thermal characteristics during its service life. At absorbed power density of 9 MW/m² the surface temperature of the brazed mock-up reached nearly 1000 °C, which is lower than the recrystallization temperature of pure W. The surface temperature distributions in various cycles were measured by the pyrometer and infrared camera. Fig. 9 shows the temperature profiles of the mock-up at the end of the thermal loading in the corresponding cycle. It can be seen that no obvious change of the surface temperature was observed during 1000 cycles of thermal loading. This was also indicated by the surface temperature within 5% deviation from the first phase to the last phase as measured via the pyrometer.

The W/CuCrZr mockup survived 1000 cycles at power density 9 MW/m² without visible damage. This finding is also supported by the non-destructive test (NDT) inspection and post-mortem metallographic analysis. An ultrasonic inspection technology was developed for the flat-type W/CuCrZr mock-ups at Southwestern Institute of Physics (China) and a 2 mm defect can be clearly found [1]. No detectable defects were found for the brazed W/CuCrZr mock-up pre- and post-HHF tests. Microstructure investigation was performed on the mock-up after the HHF tests and NDT inspection. After the experiment the scanning area can be recognized as a shadow on the mock-up surface. No obvious change in the surface morphology or grain growth was observed for the investigated W tiles. In addition, there was no melting of W and Cu between the W tile clearances. However, the brazing filler material, which climbed the W sides during the brazing, melted due to the high temperature during HHF tests. Fig. 10 presents the cross-section of the mock-up. This mock-up is completely free of pores and cracks. The bonding of W/OFC and OFC/CuCrZr does not have any damage.

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![Fig.10 SEM analysis of the cross-section of the W/CuCrZr mock-up after HHF tests and NDT inspection](image)

### 4 Conclusion

- Actively cooled flat-type W/CuCrZr mock-ups with an OFC interlayer were fabricated through a vacuum brazing process using a silver free brazing filler material.
- Microstructure analyses and tensile test results of the joints show excellent bonding of the W/Cu and Cu/CuCrZr interfaces. The bonding strength of the joints was larger than the strength of the OFC layer.
- The brazed W/CuCrZr mock-up can withstand screening tests of up to 15 MW/m² and cyclic tests of 9 MW/m² for 1000 cycles without visible damages.
- The tested results indicate that this brazed W/CuCrZr mockup has good thermo-mechanical performance as a plasma facing component.

### Acknowledgments

The authors would like to thank Mr. Jianbao Wang.
LIAN Youyun et al.: Manufacturing and High Heat Flux Testing of Brazed Flat-Type W/CuCrZr PFCs for the tests of tensile strength.

References

(Manuscript received 13 February 2015)
(Manuscript accepted 27 May 2015)
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