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High heat load properties of actively cooled tungsten/copper mock-ups by explosive joining

H. Li [a,*], J.L. Chen [a], J.G. Li [a], Z.X. Li [b]

[a] *Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126, Hefei, Anhui 230031, PR China*
[b] *Northwest Institute for Nonferrous Metal Research, Xi'an 710016, PR China*

Abstract

Two actively cooled mock-ups with 2 mm thick tungsten armor joined to chromium copper alloy by explosive welding were developed, tested and analyzed in ASIPP of China. The heat load limit of the mock-up is 7 MW/m^2, and delamination was observed along the W/Cu interface. The mock-ups can withstand the maximum heat flux of 6 MW/m^2. SEM investigations showed that some cracks and failures appeared in filler materials and at copper/filler interface, but intactness was found at tungsten/filler interface. Numerical simulations indicated that if the distance decreases between the vertex of channel and the interface, the mock-up had the better structure reliability due to the reduction of temperature and stress. Under 4 MW/m^2 heat flux, the mock-up showed good heat transfer capabilities and high joint reliabilities. All these results demonstrate the explosive joining is also an alternative way to realize the W/Cu joint for the plasma facing components.

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Keywords: Plasma facing component; Tungsten; Heat load; Simulation

1. Introduction

Due to its high sputtering resistance and low deuterium/tritium retention, tungsten has been recognized as a promising candidate plasma facing materials (PFM) for fusion devices. For the application to the divertor vertical target plate, the reliable joint of W/Cu should be realized. The technologies joining W to copper alloy [1–4] and the evaluation of its reliability under high heat flux are the key issues for the research and development of W/Cu plasma facing components (PFCs) [5–7].

For W/Cu joints, main difficulty lies in the large residual stress at the interface due to the large difference in thermal expansion coefficients (CTEs). Under high heat loads, the large stresses originated from heat loading will be superposed on residual stress field and the stress concentration happens at the interface near the free edge [8,9]. The cracks or failures often originate from the concentration site and result in detachment. Failures or cracks occurred in the joints will decrease the heat transfer capability and increase the surface temperature. By measuring the change of the temperature

* Corresponding author.
E-mail address: lhua@ipp.ac.cn (H. Li).

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distribution in the mock-up, the heat load properties and the structure reliability under high heat loading can be evaluated.

In ASIPP of China, two actively cooled mock-ups with 2 mm thick tungsten armor joined to chromium copper alloy by explosive welding were developed, tested and analyzed. Integrating the heat load properties, numerical simulations and microstructure analyzes, the reliability of the joints were evaluated.

2. Experimental set-up

Two mock-ups with tungsten as PFM and chromium copper alloy as heat sink joining by explosive joining were fabricated. One mock-up (mock-up A) has the surface area of $30 \times 60\ mm^2$ and another one has $30 \times 30\ mm^2$(mock-up B). The cross-sectional view of mock-ups is showed in Fig. 1. The tungsten armor is 2 mm thick, and the copper chromium alloy heat sink is 23 mm. The cooling channel with the diameter of 10 mm was directly drilled in the heat sink to provide the pressurized cooling water. The distance between the vertex of the channel and the interface is 6 mm.

High heat load tests were performed by an electron beam facility in ASIPP, which can provide the maximum electron beam power of 20 kW and the minimum beam diameter of 1 mm. The high heat load tests on two mock-ups were carried out to investigate the heat load limit and the heat transfer properties, respectively. During experiments, the cooling conditions did not change and were selected as: water flow rate of $3\ m^3/h$, inlet water temperature of 30 °C and the inlet pressure of 0.3 MPa. Surface temperature was measured by IR and optical pyrometer. Two thermocouples were inserted in the center of the mock-ups to measure the interface and the copper temperature, respectively. One of them was at the interface (near the tungsten armor), and another one is 3 mm beneath the interface.

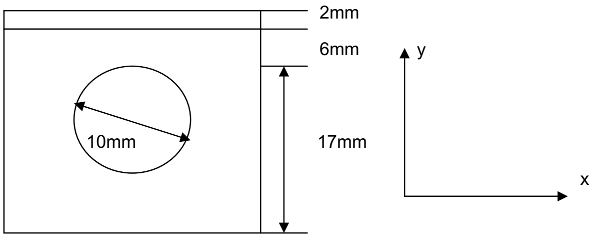

Fig. 1. The cross-sectional view of the W/CrCu mock-ups.

Thermo-mechanical analyses by finite element model were done under the same heat load and cooling conditions as that in the experiments. In thermal analyses, no radiation or energy exchange was considered at the outside surfaces except the heating and the cooling surface. In mechanical analyses, only the stress resulted from heat loading was calculated, and the residual stress produced in manufacturing process was not considered. Through the comparison between numerical simulation and tests, the heat transfer properties and the structure reliability of the mock-up were evaluated.

3. Results and discussion

3.1. Heat load limit tests

To investigate its heat load limits, mock-up A was exposed to electron beam irradiation from the heat flux of $2–7\ MW/m^2$ with the rising step of $2\ MW/m^2$. At each heat flux, the exposure time was about 200 s. The interface and copper temperature dependence of the heat flux are shown in Fig. 2.

Under the heat flux of 2, 4 and $6\ MW/m^2$, the saturated temperatures were kept stable until changing the heat flux. Under $6\ MW/m^2$, the saturated temperature at the interface and the copper reached about 380 °C and 290 °C, respectively, and the maximum surface temperature was about 580 °C, which was measured by IR and optical pyrometers. When the heat flux increased to about $7\ MW/m^2$, the saturated interface temperature of about 470 °C was reached and was kept for a short time, and then increased suddenly and rapidly. Continuous hot spots appeared on the side part of the

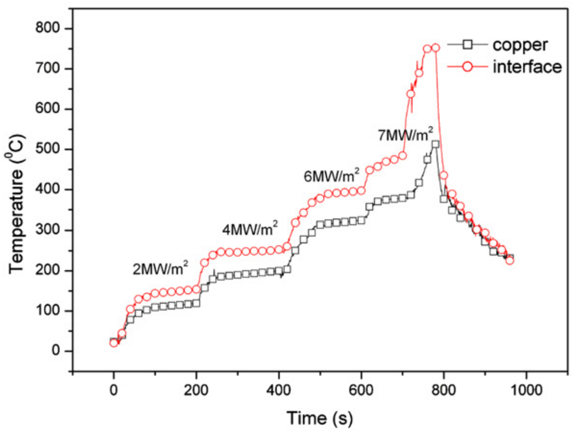

Fig. 2. Temperature dependence of heat flux.

mock-up and expanded from the edge to the center. After experiments, obvious delamination was observed along the W/Cu interface.

The heat load limit tests indicated that (1) the heat load limit was 7 MW/m^2 for the W/CrCu mock-up joining by explosive compound. (2) The cracks and failures originated at the interface near the edge and then rapidly expanded to the center. The rapidly spreading velocity of the cracks also meant that cracks or failures had been in existence before delamination happened. (3) The delamination was mainly induced by large stresses near the interface and the deterioration of strength in the copper alloy, which were resulted from the excessively high interface temperature (exceeded 470 °C) under 7 MW/m^2 heat loading. The interface temperature should be limited.

3.2. High heat load tests

The heat transfer properties were investigated under the heat flux of 2, 4 and 6 MW/m^2 for the mock-up B. At each heat flux, the saturated temperature was maintained for about 80 s, and then the heat load was shut down to cool the mock-up down to room temperature. After the experiments, no obvious failures were observed both at the surface and the interface.

The interface and copper temperature dependences of exposure time under the heat flux of 4 and 6 MW/m^2 are shown in Fig. 3. When the heat flux was 4 MW/m^2, the saturated temperature at the interface and the copper reached about 240 °C and 200 °C, respectively, and no undulation can be seen in the temperature curves. It meant that the mock-up had good thermal contact at the W/Cu interface and had high heat exhaust capabilities. Under 6 MW/m^2, the maximum temperature at the interface and in the copper alloy reached about 400 °C and 290 °C, respectively. The temperature difference of 110 °C between the interface and the copper was higher than that of 40 °C under 4 MW/m^2. The possible reason was the reduction of heat transfer capability due to cracks or failures occurring at the joint. And at the end of the heat loading, the temperature had a slight rise, which also indicated that the cracks or failures maybe grow and enlarge.

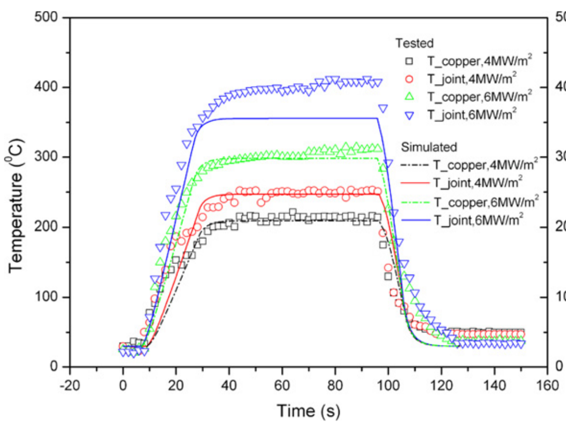

Fig. 3. Temperature dependence of exposure time under 4 and 6 MW/m^2 heat flux. The symbols and the lines denote the tested results the simulation results, respectively.

The cooling time, in which the saturated temperatures were cooled down to the RT, was about 20 s under each heat flux. But the cooling time under 6 MW/m^2 was slightly longer than that under 4 MW/m^2, which also denoted that the heat transfer capability reduced under higher heat flux.

3.3. Numerical simulations

Thermal analyses of the mock-up were finished, and the simulation results compared with the tested are shown in Fig. 3. Under 4 MW/m^2 heat flux, the good agreement between the simulated and tested results indicated that the experimental results were convinced, as well as the thermal contact between the tungsten and the copper alloy was fine. But under 6 MW/m^2, the difference of the interface temperature between simulation and tests was clearly. Because the interface temperature was affected by the thermal resistance of the W/Cu joints, it was deduced that under higher heat flux the cracks or defects happened in W/Cu joints and the heat transfer efficiency was decreased.

Temperature had the most important influence on the stress near the interface. High interface temperature increased the thermal stress and reduced the structure reliability of the mock-up. A thermo-mechanical simulation was implemented for the mock-up with the distance between the vertex of cooling channel and the interface changed from 6 mm to 3 mm. Analysis results showed that under 6 MW/m^2 heat flux the maximum interface temperature decreased from about 360 °C in tests to about 300 °C and the maximum tensile strength decreased from 500 MPa to 350 MPa in copper alloy, as shown in Figs. 4(a) and 4(b). It was expected that the joint of the W/Cu mock-up would have higher reliability.

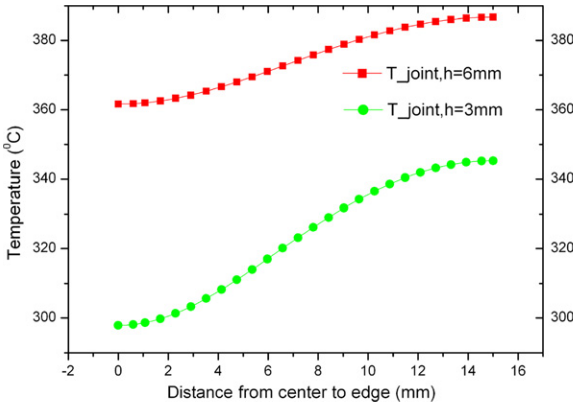

Fig. 4(a). Comparison of the interface temperature distributions under 6 MW/m^2 heat flux. h denotes the distance between the vertex of cooling channel and the interface.

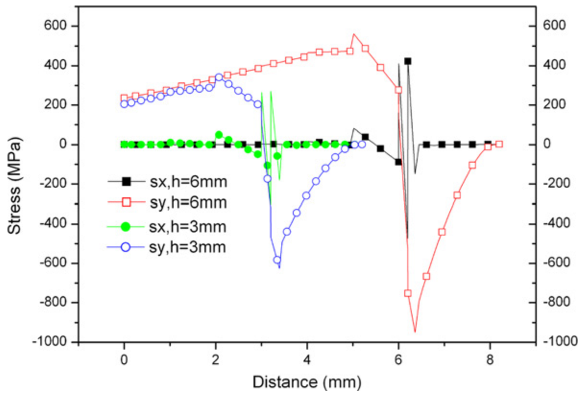

Fig. 4(b). Comparison of the stress distributions along the edge of the mock-up under heat flux of 6 MW/m^2. sx and sy denote x and y components of the stress, respectively, and h denotes the distance between the vertex of cooling channel and the interface. The zero of the axis x is at the vertex of the channel.

3.4. Microstructure investigations

Fig. 5 shows the microstructure at the other side of the mock-up A, where W and copper alloy are still joined together after heat loading. A large number of cracks (several tens micrometer) appeared continuously in the filler material and at the filler/copper interface, but at the W/filler interface no cracks or failures were observed.

Figs. 6(a) and 6(b) are the SEM pictures of the W/Cu joint of the mock-up B before and after heat load tests, respectively. Before tests, the interfaces of W/filler and filler/Cu were clearly and closely, but there were some pores in the filler materials, which were produced in manufacturing processes. After heat loading experiments, the tungsten/filler interface was kept good contact, but obvious cracks happened at the filler/copper interface, which would affect the heat transfer and the structure reliability of the mock-up largely. In filler materials, cracks and voids are also in existence.

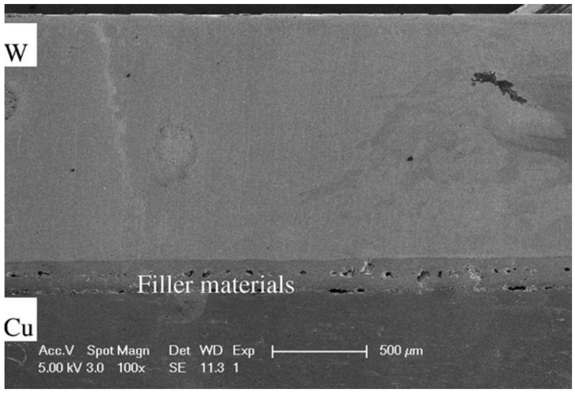

Fig. 5. SEM of the mock-up A after heat loads.

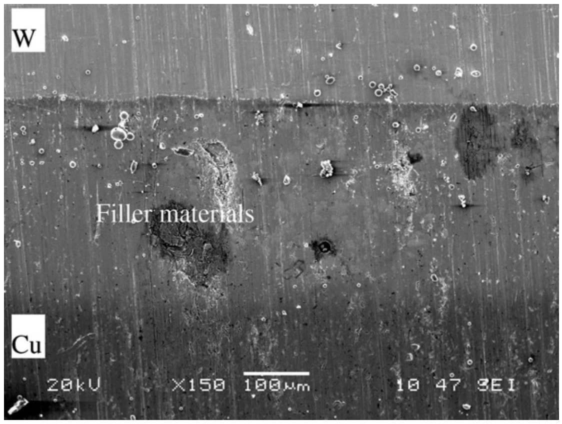

Fig. 6(a). SEM of the mock-up B before heat loads.

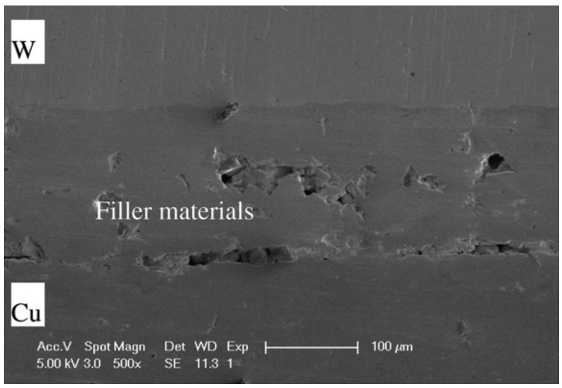

Fig. 6(b). SEM of the mock-up B after heat loads.

Microstructure analyses indicated that cracks or failures were produced due to large stresses and large plastic strains near the interface, which resulted from high interface temperature and the deterioration of the mechanical properties of copper alloy. During heat loading experiments, the cracks grew and expanded, which increased the interface temperature and reduced the heat transfer capability and the structure reliability. For the W/Cu mock-ups by explosive joining, it was important for the selection of filler materials. Proper thermal expansion coefficients, elastic modulus, ductility and adhesion strength can make the stress lower, the structure reliability higher and the lifetime longer.

4. Conclusions

The mock-ups with tungsten armor and chromium copper alloy by explosive joining were researched and developed in ASIPP of China. By high heat load tests, numerical simulations and microstructure investigations, some conclusions can be drawn as following:

(1) The heat load limit of the W/Cu mock-up is 7 MW/m^2, cracks or failures originated and expanded from the edge and resulted in delamination.
(2) The mock-up can sustain heat flux of 6 MW/m^2. The cracks or failures exist at copper/filler interface, but do not appear at the tungsten/filler interface.
(3) Reducing the distance between the vertex of the channel and the interface will improve the joint reliability due to lower temperature and lower stress at the interface.
(4) It is prospective that the mock-up has good heat transfer properties and high structure reliability under 4 MW/m^2 although its thermal fatigue properties should be investigated. Explosive joining is also an alternative way to realize the W/Cu mock-ups for the plasma facing components.

Acknowledgments

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