Design and Fabrication of the Active Cooling Divertor Components for HL-2M Tokamak

Xiang Liu[1], Lijun Cai[1], Youyun Lian[1], Guorao Zheng[1], Jian Liu[1], Fan Feng[1], Jianbao Wang[1], Yingmin Wang[2], Qiang Li[1], Xuru Duan[1], Yong Liu[1]

[1] Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, Sichuan, China
[2] Dalian University of Technology, Dalian 116024, Liaoning, China
E-mail contact of main author: xliu@swip.ac.cn

Abstract. HL-2M is a new tokamak machine under construction and has the capability of advanced divertor configuration operation, such as snowflake and tripod. It is expected that the peak heat flux at the divertor target plates could be reduced from 7 MW/m^2 at a standard divertor configuration with 3 MA plasma current and 25 MW heating power to approximately 3 MW/m^2 when the advanced divertor configuration is operated. Therefore the divertor components must be compatible with the heat removal capability of 3-7 MW/m^2 heat flux. An open cassette divertor structure with active water cooling similar to ITER divertor has been disigned, in which CFC material CX-2002U is suggested as the armor tiles of CuCrZr heat sink by brazing joining and Inconel 618 is selected as the support material. In this paper, the progress of HL-2M divertor components design and fabriction will be introduced, including fluid, thermal and mechanical analysis of divertor cassettes, small scale CFC/CuCrZr mockup manufacture and its HHF (high heat flux) tests. The results indicated that surface matallization of CFC armor using Cr slurry and following by vacuum brazing with CuCrZr heat sink could be a feasible solution for HL-2M divertor fabrications.

1. Introduction

HL-2M is a new tokamak machine under construction and three missions are expected, they are high performance plasma, advanced divertor configurations and PWI (plasma wall interaction) issue based on the high density edge plasma and the flexible divertor unit design [1, 2]. HL-2M has major radius of 1.78 m and minor radius of 0.65 m. The designed maximum plasma current is 3 MA and the heating power can be up to 25 MW. A demountable toroidal field (TF) coils is designed for HL-2M. When the poloidal field (PF) coils are placed inside the TF coils, it will reduce the PF coils current requirements to achieve the advanced divertor configurations, such as snowflake and tripod divertor configurations [3, 4]. Considering that the heat loads on divertor target plates could be varied in the range of 3-7 MW/m^2 based on the advanced divertor or standard divertor operations [5], as well as the replaceability of divertor components to meet the requirements of PWI study, a casstte divertor structure is proposed. The low divertor will be composed of total 80 individual casttes, each casstte consisits of active water cooled inner divertor, outer divertor targets and dome combined together by a support box, the conneted cooling tubes are embeded in the box. At the first operation compaign of HL-2M, CFC will be selected as the armor materials of divertor components owing to its good compatiability with core plasma and plenty of operation experience, but tungsten armor could be tested by a movable material irradiation manipulator or replacing an individual divertor casstte. CFC will be brazed with CuCrZr heat sink and cooling channels will be drilled in CuCrZr plates. Up to now the fluid, thermal and stress analysis of divertor casstte structure have finished and the design review is ongoing. The technology optimization of CFC brazing with CuCrZr heat sink was carried out by means of Cr slurry or Ti coating following with pure copper casting and vaccum brazing, and a small scale CFC/CuCrZr mockup has been prepared and evaluated by an electron beam heat load facility. Moreover, a dummy casstte structure was in the process of machining. In this paper, the progress of the design and fabrication of HL-2M divertor components will be introduced.

2. Results and discussions

2.1 Design of HL-2M divertor components

One of the missions for HL-2M tokamak is advanced divertor, snowflake and tripod divertor configurations can be achieved. As divertor components of HL-2M tokamak, which will be compatible to the operation of both standard and advanced divertors. According to the designed maximum plasma current of 3MA and the maximum heating power of 25 MW, the peak heat flux at the divertor targets will be in the range of 3-7 MW/m^2 depending on the advanced divertor or standard divertor configurations. Therefore active cooling divertor components have to be adopted. Considering the easy installation and replacement, a cassette divertor struction with active water cooling was designed as shown in Fig. 1, and total 80 cassette units for

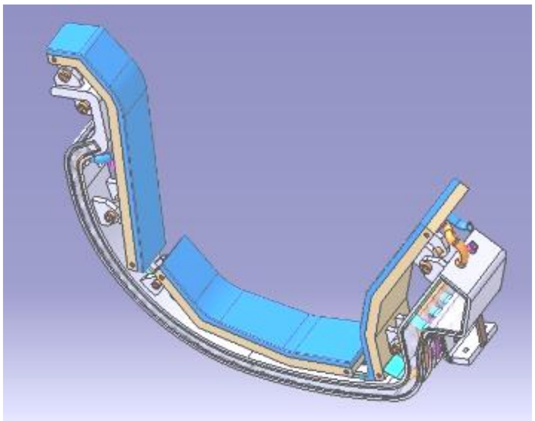

Fig. 1. A concept design of HL-2M divertor.

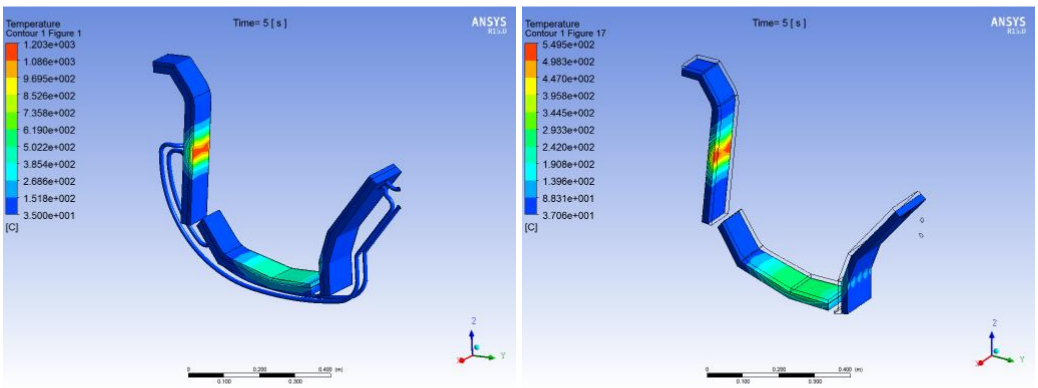

Fig. 2. The surface temperature distribution of the CFC armors (left) and the temperature profile at the bonding surface of CuCrZr heat sink (right) at 10 MW/m^2 peak heat flux and 5 s discharge time.

low divertor. The target plate is a sandwich structure with CFC as the plasma facing material brazed on CuCrZr heat sink, which are integrated onto the flexible support frame via hinge joints to allow thermal expansion and certain deviance caused by fabrication. Cooling and baking channels are drilled inside the target copper plates to feed cooling water during plasma discharge and hot nitrogen during baking, and these channels are connected to pipes embedded inside the support frame to minimize the water leak risk caused by plasma bombardment on coolant pipes. High precision flexible support ring is designed and located on the inner vessel shell to provide sufficient fatigue life of divertor.

According to the simulation analysis of the heat flux on the divertor targets, the maximal wall load on divertor target plates will reach to 7 MW/m^2. Carbon fiber enhanced carbon (CFC) is selected as the armor materials, CuCrZr alloy and Inconel 625 are considered as heat sink and structural materials, respectively. Brazed CFC/CuCrZr flat plates with active cooling are designed as the divertor components. Based on the database of CX-2002U and CuCrZr-IG [6], thermal analysis of the target plates by Ansys code indicated that the highest surface temperature of CFC tiles under a peak wall load of maximal 10 MW/m^2 for 5s loading time is about 1200°C, and the highest temperature at the bonding surafce of CuCrZr heat sink is about 550°C as shown in Fig. 2, in this calcalation the thickness of CFC tiles is taken as 12 mm and the thickness of CuCrZr heat sink is chosen to be 20 mm, and cooling conditions of water are 4 MPa for inlet pressure and 4 m/s for flux rate. When the wall load is reduced to 7 MW/m^2, the highest temperature on CFC surface will drop to 850 °C. The peak temperature appeared at a narrow regime at the inboard target plates. The results also indicate that the peak temperature at CFC tiles is much lower than 1200°C, avioding the eruption of carbon impurity owing to the heat sublimation, meanwhile the temperature at the brazing interface is far below the melting point of the brazing filler metal, guaranteeing the safty of divertor components at plasma operations. Moreover, a fluid analysis was carried out to optimze the coolant parameters, the result shows that the local boiling of the cooling water can not happen at 4 MPa inlet pressure and 4 m/s flux rate, thus the working safety of the divertor components was demonstrated.

As you well known, when plasma disruptions, in particular VDEs (vertical displacement events) take place, a induced holo current will be created in the casstte structure, thus a electromagnetic force will load on the cassette structure owing to the interaction of the holo current with toriodal fields. DINA and ANSYS codes are used to calculate the electromagnetic loading of the casstte and the calculation result is demonstrated in Fig. 3. The maximum electromagnetic force is 397 MPa, which quite lower than the ultimate tensile strength of Inconel 625 material

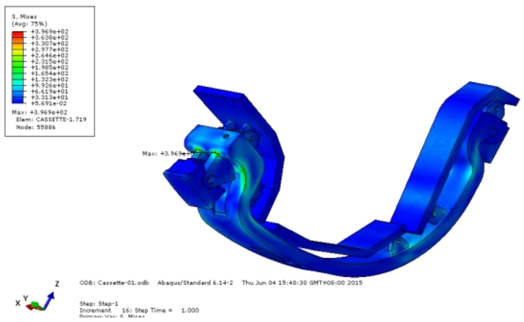

Fig. 3. A electromagnetic loading analysis of the divertor casstte by DINA and ANSYS codes.

[6], demonstrating the structure safety of the casstte.

2.2 R&D of HL-2M divertor components fabrication

A flat type CFC/CuCrZr divertor components are designed and two options of CFC joining with CuCrZr heat sink are being investigated, one is a metal slurry method, in which a Cr slurry layer will coat on CFC surface firstly, and then sintered at high temperature to form dense CrC interface, after that a pure copper adaptive layer is casted on the CFC surface already treated by slurry, finally brazed with CuCrZr heat sink by a new developed CuPNiSn brazing filler metal. This filler is an amorphous alloy and its melting point is around 750°C, thus the brazing temperature of CFC with CuCrZr using this amorphous filler can be controlled below 800°C. In this way the strength loss of CuCrZr alloy is not significant and a fast cooling process after vacuum brazing becomes not necessary to aviod the large residual stresses induced by fast cooling, which could make the fracture of CFC tiles during the cooling process since the tensile strength of CX-2002U is only 31-35 MPa in X and Y directions [6]. The other method is Ti coating on CFC surface by PVD (physical vapor deposition) technology at high temperature. PVD coating was performed by means of multi-arc ion plating and the temperature of CFC tiles during plating can be contolled by adjusting the arc current and bias voltage to make TIC formation with a suitable thickness in-situ. After that, CFC tiles were joined with CuCrZr heat sink by the same pure copper casting and vacuum brazing processes above.

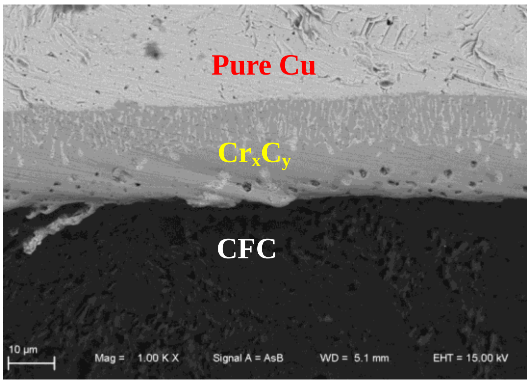

Fig. 4. Microstructure interface of a CFC/CuCrZr joint by Cr slurry method.

A small scale mockup by Cr slurry method has been prepared and the microstructure of the interface was observed (Fig. 4). A obvious Cr layer was found and EDS analysis indicated that this layer consisted of CrC layer and pure Cr layer. Such interface structure is expected because it can make a good bond both between CFC with Cr layer and Cr with pure copper layer. Similar microstucture was also found in CFC-Ti-Cu interface by means of PVD-Ti coating.

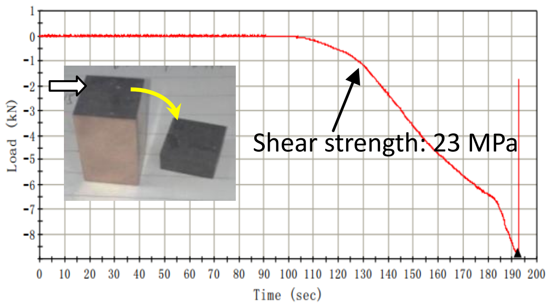

Fig. 5. A shear strength test of CFC/CuCrZr joints.

In order to evaluate the joining properties of CFC/CuCrZr mockups, a shear test was carried out and the testing result was demonstrated in Fig. 5. The shear strength of the CFC/CuCrZr joints is 23 MPa and the fracturing occurred inside CFC tile as shown in the SEM photo inserted in Fig. 5. In fact, the measured shear strength is close to the shear strength of CFC material. The shear test identified a good bonding of CFC tiles with CuCrZr heat sink.

In order to further evaluate the sevice performance of CFC/CuCrZr joining for HL-2M divertor, a thermal fatigue experiment of a small scale CFC/CuCrZr mockup made by Cr slurry method was conducted in a 60 kW electron-beam facility (EMS 60). The small scale mockup consists of three CFC tiles with dimensions of 25 × 25 × 8 mm^3 for each tile, and the gap between two tiles is 0.5 mm. The inner diameter of the cooling tube is 7 mm localized at the center of 20 mm thick CuCrZr heat sink. The EMS 60 equiped with a 60 kW electron beam welding gun, which can supply a fast scanning over 100 × 100 mm^2 area by a maximum scanning frequency of 30 kHz [7]. In this experiment, the inlet temperature and flux rate of the water coolant are 25°C and 1m^3/h, respectively. Before high heat loading tests, the energy absorb coefficient for the electron beam was measured by a calorimeter and the value is 92%, which means most of the incident energy from 120 keV electron beam is absorbed by CFC tiles. First, a thermal fatigue experiment was performed for the small scale mockup at 10 MW/m^2 heat flux for 1000 cycles, the pulse duration of every cycle is 5 s and the time interval between two cycles is 15 s to assure the complete cool down after each cycle. After that, the center tile suffered to an additional 100 cycles at a high heat flux of 15 MW/m^2 to investigate the heat load limitation of the CFC mockup. The peak surface temperature of three CFC tiles under 10 MW/m^2 heat loading is in the range of 1150-1250°C and the temperature deviation during whole 1000 cycles is less than 10 %, indicating a strcture stability of CFC/CuCrZr mockups under 10 MW/m^2 for 1000 cycles. The experimental results of the additional cyclic loading were shown in Fig. 6. In this case the maximal surface temperature of CFC tile is up to 1700°C, but it is quite stable during 100 cycles as shown in Fig. 6. Moreover, one can see that after the whole testing campaign, the CFC/CuCrZr mockup still keeps structural integrity and only a coarser surafce of the central tile is observed due to heat sublimation of carbon at high temperature. Considering that the peak heat flux at divertor targets of HL-2M tokamak is 7 MW/m^2 and the discharge time is only 5 s in general, the experimental results indicate that the present design and fabrication technology of HL-2M divertor can support abslutely the plasma operations and leave plenty of safety space for off-normal operation

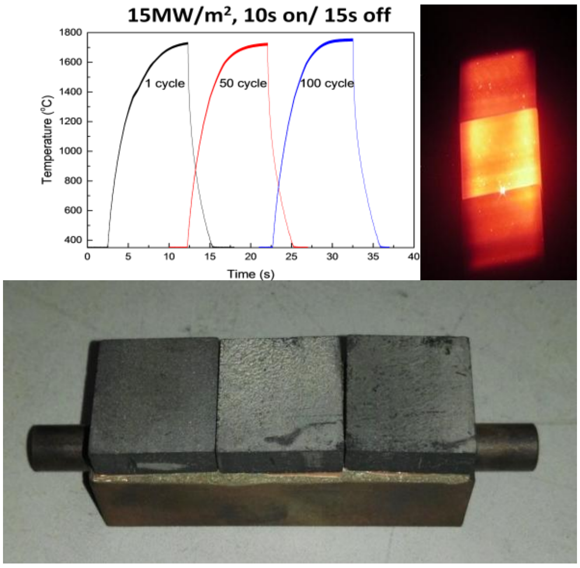

Fig. 6. Thermal fatigue tests of a CFC/CuCrZr mockup. Low picture shows the mockup after tests, left figure is the surface temperature evolution under 15 MW/m^2 heat loads and right figure is the CCD photo.

events.

3. Summary

One of the important missions of HL-2M tokamak is advanced divertor confugration, such as snowflake and tripod divertor configurations. In order to be compatible with both standard and advanced divertor operations, a cassette divertor structure with active water cooling is proposed, in which CFC (for example CX-2002U from Japan) is selected as armor material, CuCrZr alloy as heat sink and Inconel 625 as support materials, CFC tiles will be brazed with CuCrZr heat sink. Up to now, the design optimization of cassette divertor unit has completed by peer analysis of thermal, fluid, mechanical and electromagnetic forces.

Based on the preliminary design of HL-2M divertor, R&D of divertor fabrication were conducted and two technology routes were tried. One is Cr slurry of CFC surface, following by pure copper casting and vacuum brazing with CuCrZr heat sink. The other is PVD-Ti coating on CFC surface at high temperature, and then joining with CuCrZr heat sink by the same processes. Metallurigical observation and shear tests indicated a good bonding property of CFC with CuCrZr. A small scale CFC/CuCrZr mockup was prepared by Cr slurry method and it withstood 10 MW/m^2 heat flux for 1000 cycles and additional 100 cycles at 15 MW/m^2 heat flux without failure. The experimental results confirmed the technology feasibility for HL-2M divertor components fabrication. Further technology optimization for the fabrication of prototype components is under way.

Acknowledgements

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