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Fabrication and High Heat Flux Testing of Super Mechanically Joined Divertor Plate for LHD

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Abstract

For the helical divertor plate of large helical device (LHD) in the phase II, a super mechanically joined module(MJM) without a copper heat sink has been developed using a test facility ACT with a 100 kW EBS. The thermal performance of the MJM has been drastically improved by the optimizations for structure, material, and condition comparing with those of the previous MJM with a heat sink. The structure of the super MJM, thermal fatigue test, and high heat flux test up to 3.75 MW/m^2 for steady state operation are mainly described.

Keywords:

LHD, high heat flux, graphite, armor tile, electron beam, divertor, mechanically joined module, and thermal fatigue test.

1. Introduction

Mechanically joined modules (MJM) more than 1700 are now installed as the divertor plate in large helical device (LHD) [1,2] ,which began operation in 1998.

The MJM mainly consists of a graphite armor tile, copper heat sink, stainless steel (SS) backing plate, SS cooling pipe, and graphite sheet. The module works well as a divertor plate under heat flux lower than about 0.5 MW/m^2 for a steady operation. However, if the heat flux on the armor tile exceeds the flux level, the thermal performance of the MJM becomes worse abruptly because the copper heat sink is deformed by the high heat flux flowing through the armor tile from divertor plasma. The deformation of copper comes from the high coefficient of expansion and the poor strength at temperature above about 200°C. To prevent the deformation of the heat sink, several materials and configuration were tested and evaluated. Through the tests and evaluation, super MJM without a separate heat sink has been developed as a divertor plate to be used in the next experimental stage (phase II) of LHD.

2. Experimental Test Device ACT

In order to evaluate the thermal property of MJM, a test facility called ACT [3,4] has been used, as shown in Fig. 1. The facility consists of a 100 kw electron beam source, vacuum pumping system, 400 L vacuum vessel, water cooling system, and data acquisition system. The test sample is located on a copper plate isolating from ground under a beam limiter and cooled actively by cooling water flowing from the water pump (7.5 kW) system. The thermal properties of MJM are evaluated using a fiber optical thermometer and two thermo-couples. The main parameters of ACT are shown in Table 1.

3. Structure of Super MJM

Fig. 2 shows a schematic view of super MJM that consists of a unified armor tile/heat sink, backing plate, cooling pipe, and compliant sheet. The former two parts

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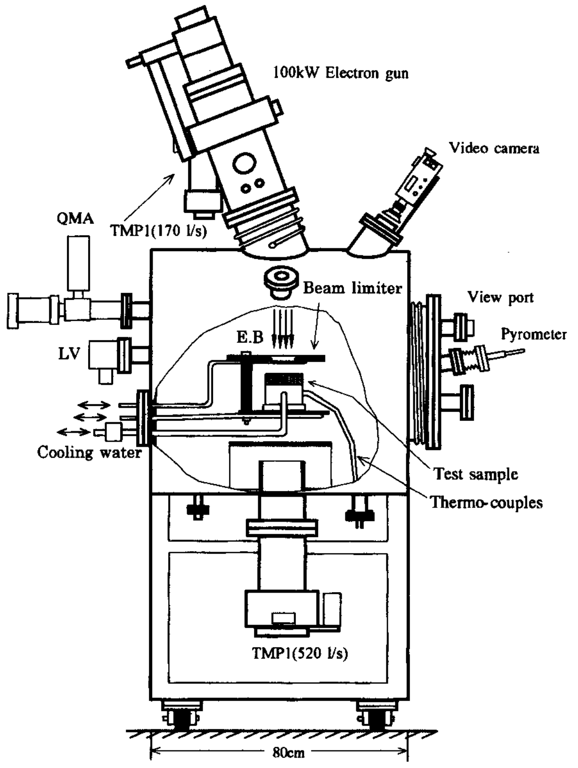

Fig.1 Cross-sectional view of a test facility ACT.

Table 1 Main parameters of test facility ACT

Item	parameter
Maximum beam output	100 kW
Electron beam energy	30 keV(fix)
Minimum beam size	8 mm ϕ
Beam irradiation area	1~400 cm^2
Flow rate of cooling water	~10 m/s

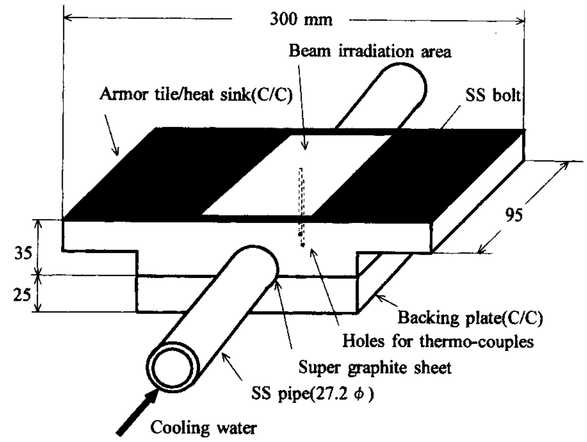

Fig. 2 Schematic view of super MJM with an unified armor tile/heat sink made of C/C.

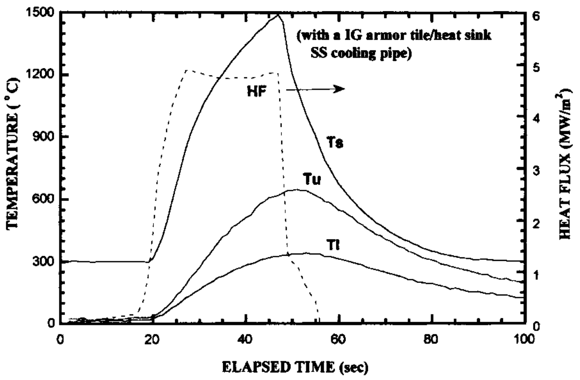

Fig. 3 Thermal responses (Ts,Tu,Tl) of super MJM under a high heat flux of 5 MW/m^2 for 20 sec.

are made of graphite or carbon carbon composites different from that of the previous MJM, which is useful for weight reduction. Moreover, as a compliant sheet, a super graphite sheet (made by Matsushita Co. ltd.) with an excellent thermal and mechanical properties is used instead of carbon sheet used in the previous MJM.

4. High Heat Flux Test of Super MJM

4.1 Short operation mode

To evaluate the thermal performance of super MJM with a unified armor tile/heat sink made of graphite and a SS cooling pipe, high heat flux tests up to 5 MW/m^2 have been carried out for 20 sec pulse duration with a rise time of 20 sec. After the test, no damage on the tile surface was observed. Fig. 3 shows the thermal responses (Ts,Tu,Tl) measured using a fiber type of optical pyrometer and two thermo-couples. Each edge of the thermo-couples is inserted in a small hole bored side of the unified armor/heat sink. The maximum surface temperature (Ts) reaches 1500°C at the end of heat load under 5 MW/m^2. However, if carbon carbon composites is used as the armor tile material instead of graphite, the maximum surface temperature may reduce lower than 1000°C.

4.2 Steady state operation mode

To evaluate the thermal performance of the super MJM under near steady high heat flux for 1000 sec, thermal responses (Ts,Tu,Tl) were measured. As the result, high heat flux tests up to 3.75 MW/m^2 have been carried out without any apparent damage or loss in the performance of the MJM. Fig. 4 shows the thermal responses of the super MJM with a copper cooling pipe and super graphite sheet under a heat flux of 3.75 MW/ m^2. As the material of the unified tile/heat sink, carbon carbon composites (CX-2002U) with a high transverse thermal conductivity of 390 W/(mK). The temperatures (Ts,Tu,Tl) saturates nearly after 400 sec passed. The maximum surface temperature (Ts) reaches 1100°C, which is allowable value for armor tile of divertor plate.

4.3 Thermal fatigue test

To ensure the durability of the super MJM with a unified tile/heat sink made of graphite and SS cooling pipe, thermal fatigue test has been carried out under a high heat flux of 2 MW/m^2 with a cycle of 1000 s load and 600 s rest. The temperature (Ts,Tu,Tl) of the MJM increase gradually with cycle number. The rise rates per cycle are 2.1°C, 1.4°C, and 1.4°C for Ts, Tu, and Tl, r respectively. The test result indicates that the durability of this type of super MJM is not sufficient under such a high heat flux as 2 MW/m^2 for the steady operation.

4.4 Effect of thickness of graphite sheet

The thermal performance of the MJM depends largely on the thickness and kind of graphite sheet or the pressure applied on the sheet, which is used as a compliant sheet. To find out the optimum thickness of graphite sheet to be used between heat sink and cooling pipe of MJM, temperature at heat sink of the super MJM was measured as a parameter of thickness of graphite sheet. Fig. 5 indicates the test result performed under high heat fluxes of 0.5 to 2.5 MW/m^2 using a super MJM with a tile/heat sink made of graphite and SS cooling pipe. As shown in the figure, the thicker graphite sheet shows lower temperature comparing to the thinner one under same heat flux. This result indicates that the thicker one is better as a compliant sheet between these graphite sheets.

4.5 Comparison of thermal property for MJM

A comparison of the thermal performance (temperature of heat sink vs heat flux) between several types of MJMs under several conditions is made in Fig. 6 for steady operation. As shown in the figure, the temperature at the heat sink of normal MJM labeled 1) IGOFC/SS rises exponentially as heat flux increases. The allowable maximum heat flux of the MJM may be less than 0.5 MW/m^2. The MJM is now used as divertor plate in LHD. The other hand, the temperature of the super MJM labeled 5) OCC/Cu with a heat sink made of carbon carbon composites, copper cooling pipe, and

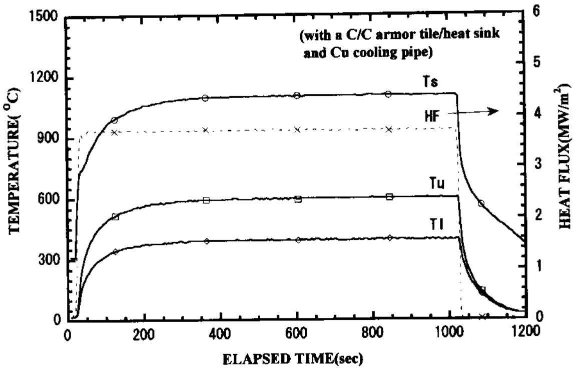

Fig. 4 Thermal responses (Ts,Tu,Tl) of super MJM under a high heat flux of 3.75 MW/m^2 for 1000 sec.

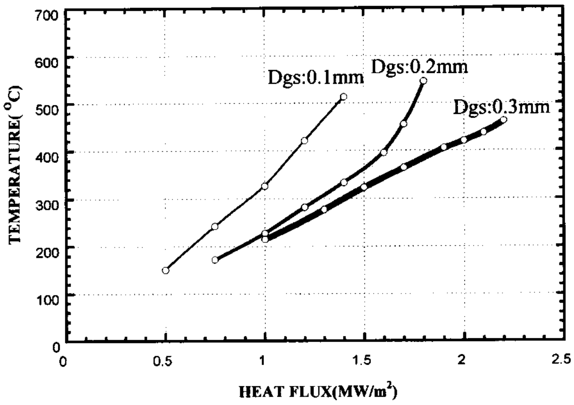

Fig. 5 Effect of thickness of graphite sheet on the thermal performance of super MJM.

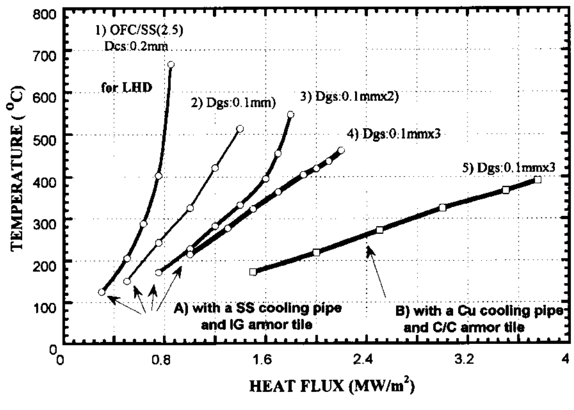

Fig. 6 A comparison for thermal performance of several kinds of MJMs.

super graphite sheet increases linearly with heat flux and shows the lowest value between the MJMs. The comparison indicates that the thermal performance of MJM is highly dependent on the choice of materials and configuration. The super MJM with an unified C/C armor tile/heat sink and Cu cooling pipe can be used for the divertor plate of LHD in the next experimental phase and under steady state high heat flux more than 2 MW/m^2.

5. Conclusion

1) The thermal performance of the super MJM with a unified tile/heat sink made of C/C was drastically improved as compared with the normal MJM with a Cu heat sink. This improvement may allow use of for the divertor plate of LHD in the next phase and under steady operation condition.

2) However, thermal fatigue test result under steady high heat flux of 2 MW/m^2 showed that the durability of the super MJM is not sufficient. To get better result from the thermal fatigue test, more effort to optimize the structure of MJM is required.

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