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Evaluation of the integrity of divertor models of tungsten or SiC/SiC composites joined with copper

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Abstract

From viewpoints of thermal shock resistance, control of plasma particles, low activation, thermal efficiency and so on, it is planned to use heat-resisting metals and ceramic composites as plasma facing materials for the next experimental, demonstrative and commercial fusion reactors. In this study, a tungsten material and SiC/SiC composites were joined with oxygen free copper as a heat sink material using foils of titanium and copper, and a molybdenum plate was also inserted for the relaxation of residual thermal stresses in the case of a SiC/SiC-copper joint. The divertor model specimens using the joining materials were manufactured and heat load tests were carried out. Thermal cracks in the tungsten material and delaminating cracks at the joining boundary of SiC/SiC composites were observed during several heat load tests. Therefore, tungsten and SiC/SiC composites need to be improved further with respect to the thermal shock resistance, thermal conductivity and fracture toughness.

Keywords: Integrity; Plasma facing components; Tungsten; SiC/SiC composites; Joint; Electron beam heating

1. Introduction

The next experimental, for example ITER, demonstrative and commercial fusion reactors have been studied and developed as an energy source for humankind. In the field of fusion reactor technology, one of the most important tasks is the development of high performance plasma facing components. In particular, the divertor as a plasma facing component for fusion reactors, which receives severe localized and cyclic heat loads during operation, requires high thermal conductivity, excellent thermal shock resistance, good control of plasma particles and good connection with heat sink materials for active cooling. Resistance against radiation damage, low activation and high thermal efficiency are further important issues. Hence it has been proposed to use tungsten and SiC/SiC composites as plasma facing materials for fusion reactors.

The purposes of this study are to establish the joining technique between heat sink materials and armor materials such as tungsten and SiC/SiC composites, and to evaluate the integrity of plasma facing components at the joining boundary by electron beam heating tests. In this study, tungsten or SiC/SiC composites used as armor tiles in the divertor were joined with oxygen-free copper as a heat sink material. These divertor model specimens were tested by an electron beam heating apparatus. Before and after the heat load tests, the microstructures and the mechanical properties were evaluated by SEM analysis and shear test.

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2. Experimental

2.1. Materials tested

Tungsten has excellent heat resistance, high mechanical properties and chemical stability. Since it has comparatively high thermal conductivity, low thermal expansion coefficient and low specific heat, its thermal fatigue properties are excellent. Tungsten tested in this study is a pure W plate made by a rolling method. Its thermal conductivity is 167 W/mK [1].

SiC/SiC composites tested in this study are NICALOCERAM and HINICALOCERAM made by Nippon Carbon Co. Ltd. and a SiC/SiC composite (A-2-100) by Kyoto University [2,3]. The thermal conductivity is not measured yet and is estimated below 15 W/mK [4]. They have comparatively high thermal shock resistance, high mechanical properties at high temperature, light weight, good corrosion and acid resistances, and low activation.

2.2. Divertor model specimens

Jointing of tungsten or SiC/SiC composites was carried out under conditions of 15 or 30 min holding, respectively, adding a weight pressure (7 kPa) at 1000 °C in vacuum of 1×10^5 Torr after acetone washing and polishing of the joining surfaces.

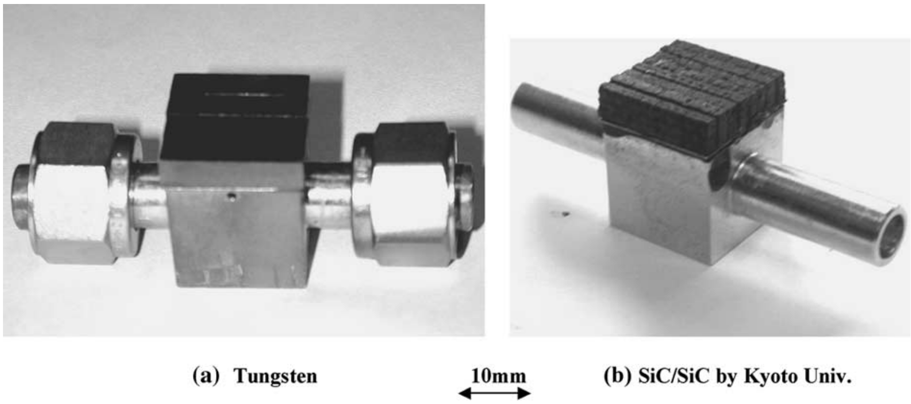
Fig. 1 shows the divertor model specimen of tungsten or a SiC/SiC composite manufactured in this study. The height of the tungsten or SiC/SiC composites is 5 mm, the 4–10 pieces were joined with an oxygen free copper block ($20 \times 20 \times 20$ mm) having a cooling pipe (7 mm in inner diameter and 10 mm in outer diameter) inserting foils of titanium (0.05 mm in thickness) and copper (0.01 mm in thickness). In the case of a SiC/SiC-copper joint, a molybdenum plate of 0.5 mm in thickness was also inserted for the relaxation of residual thermal stresses. Then a hole of 1 mm in diameter and 10 mm in depth was made at the point 1.5 mm below the joining boundary for temperature measurement by thermocouples.

These divertor model specimens were tested at heat fluxes from 1 to 15 MW/m^2 by a bias type electron beam heating apparatus. A shunt resistance (0.2 Ω) was inserted between the sample holder and the earth potential and the heat flux was calculated by the potential difference proportional to the beam current. The electron beam was applied for 15 s at an interval of 10 s. The water coolant flow rate was 15 l/min at 15 °C. Before and after the tests, the microstructure was analyzed by SEM and mechanical properties at the joining boundary were examined by shear test. Fig. 2 shows the bias type electron beam heating apparatus. The system consists of a power source for the electron beam, a vacuum chamber, a beam controller and cooling and data processing systems [5]. The electron beam was switched between the test sample and a dummy surface. The integrity and the thermal response properties of the divertor model specimens were evaluated by this apparatus like in other studies [6–9].

3. Results and discussions

3.1. Joint of tungsten or SiC/SiC composites

Fig. 3 shows the microstructure of the joining boundary of tungsten or a SiC/SiC composite. The joint between tungsten and copper was established mainly by diffusion of titanium and copper into the tungsten material. In the joining boundary, grown-up copper particles were observed by etching of the surface. Since the residual thermal stresses were relaxed due to insertion of a molybdenum plate, no defects were observed at the joining boundary between the SiC/SiC composite and the copper heat sink material.



(a) Tungsten **(b) SiC/SiC by Kyoto Univ.**

Fig. 1. Divertor model specimen of tungsten or a SiC/SiC composite.

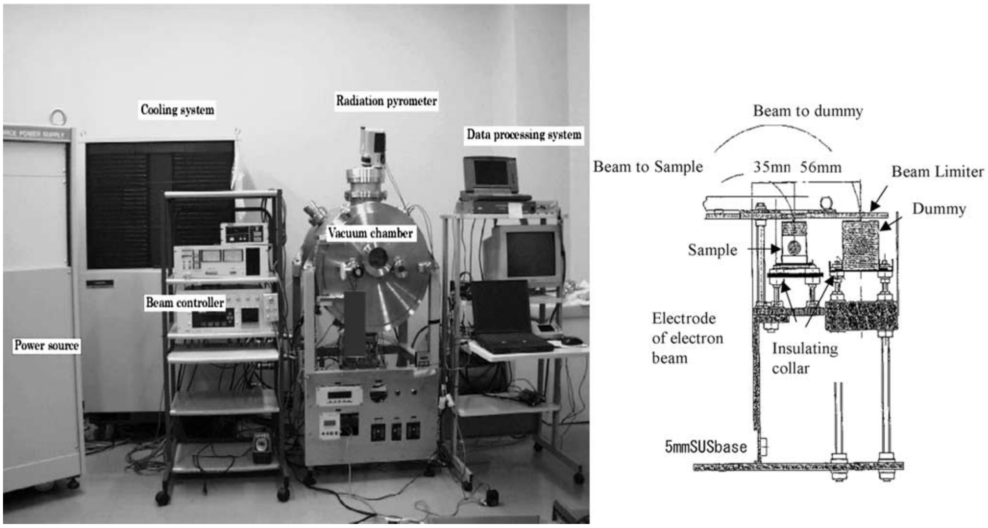
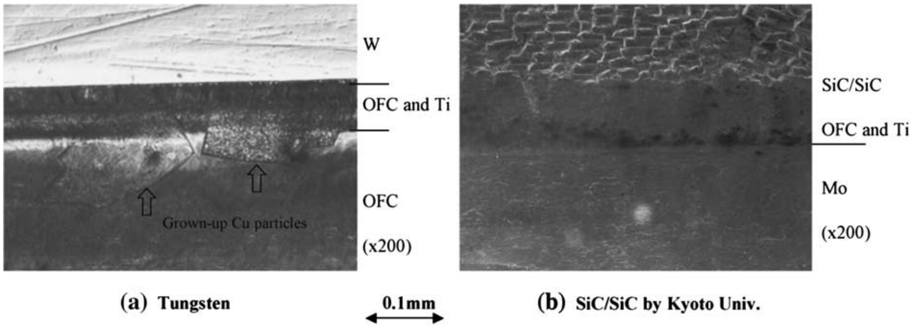


Fig. 2. Bias type electron beam heating apparatus.



(a) Tungsten **(b) SiC/SiC by Kyoto Univ.**

Fig. 3. Microstructure of the joining boundary of tungsten or a SiC/SiC composite.

3.2. Shear test

The shear strength of the joining boundary of tungsten was 310 MPa and was higher than that of the base material (214 MPa). The shear strength of the joining boundary of the SiC/SiC composites increased remarkably due to the molybdenum interlayer (50–76 MPa). These strengths were higher than that of a C/C composite (CX-2002U; 25 MPa). Therefore, these joining boundaries were considered to have sufficient strength.

3.3. Heat load test

Fig. 4 shows the relationship between temperatures of divertor model specimens and the heat flux of electron beam heating. Black circles, square marks and white circles indicate the data of divertor model specimens made of tungsten, SiC/SiC by Kyoto University and a C/C composite (CX-2002U) as a comparative material, respectively. The temperatures were measured actually by a radiation thermometer and thermocouples. These temperatures increased linearly with increasing heat flux

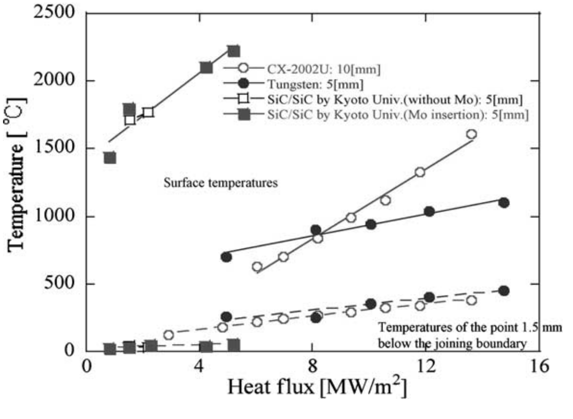


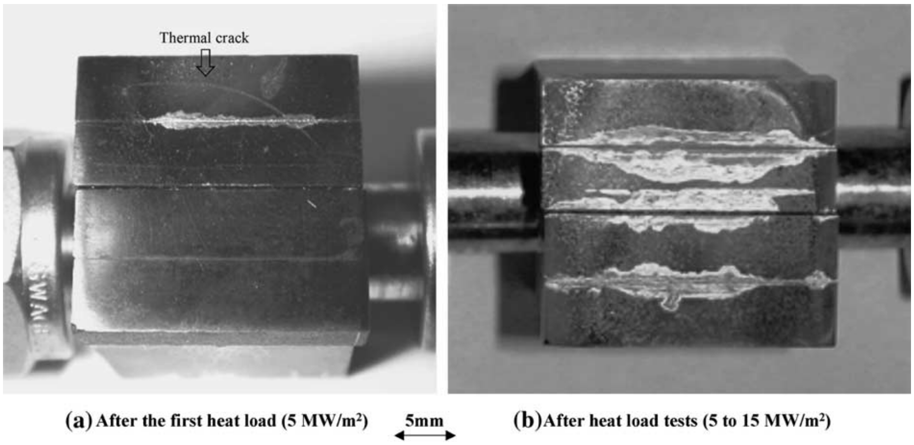
Fig. 4. Relationship between temperatures of divertor model specimens and the heat flux of electron beam heating.

since the divertor model specimen was cooled effectively. The temperature of the tungsten surface was comparatively low at the high heat flux of over 8 MW/m^2 (1150 °C at 15 MW/m^2), and that of the point 1.5 mm below the joining boundary was comparatively high (450 °C at 15 MW/m^2). On the other hand, the surface temperature of SiC/SiC composites increased very abruptly at rather low heat fluxes (2100 °C at 4 MW/m^2), and that of the point 1.5 mm below the joining boundary increased little in the range of heat flux (40 °C at 4 MW/m^2). The thermal energy from the electron beam was almost radiated by the sublimation and the erosion of the SiC/SiC composites.

Fig. 5 shows the surface of the tungsten divertor model specimen after the first heat load (5 MW/m^2) and after heat load tests (5–15 MW/m^2). A thermal crack propagated on the surface of tungsten after the first heat load, and was caused by the residual stress in the joining process and the thermal stress due to the first heat load. The titanium and copper alloy existed not only in the joining boundary but also near the surface through the gaps of the armor tiles. The alloy melted and came out from the gaps of the armor tiles after the heat load tests.

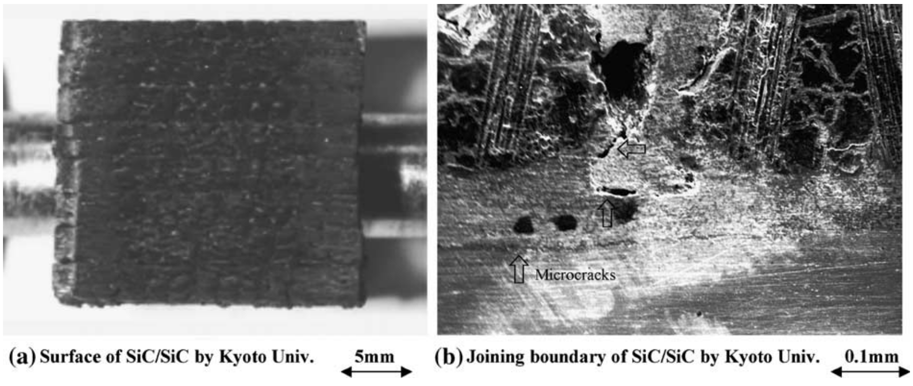
Fig. 6 shows the surface and the joining boundary of the SiC/SiC composite divertor model specimen after heat load tests. The surface of the SiC/SiC composite was eroded remarkably because the thermal conductivity of the SiC/SiC composite was very low and the surface temperature increased very much. In addition thermal microcracks were observed at the joining boundary of the SiC/SiC composite.

Therefore, tungsten and SiC/SiC composites need to be improved further with respect to thermal shock resistance, thermal conductivity and fracture toughness. Recently, a SiC/SiC composite with improved thermal properties has been developed by a liquid phase sintering method using a high thermal conductive SiC fiber [3], and tungsten with improved fracture toughness also has been developed by a mechanical alloying method [10]. These materials can be expected to be used as high performance plasma facing materials for fusion reactors.



(a) After the first heat load (5 MW/m^2) (b) After heat load tests (5 to 15 MW/m^2)

Fig. 5. Surface of the tungsten divertor model specimen.



(a) Surface of SiC/SiC by Kyoto Univ. (b) Joining boundary of SiC/SiC by Kyoto Univ.

Fig. 6. SiC/SiC composite divertor model specimen after heat load tests.

4. Summary

In this study, divertor model specimens using tungsten or SiC/SiC composites as plasma facing materials were manufactured in order to contribute to the development of high performance plasma facing components. The microstructures and mechanical properties at the joining boundaries were examined and the integrity of plasma facing components was evaluated by endurance tests such as electron beam heating tests. Results obtained in this study are summarized as follows.

(1) Metallurgical joints between oxygen free copper and tungsten or SiC/SiC composites were carried out by insertion of foils of titanium and copper, and by additive insertion of a molybdenum plate in the case of a SiC/SiC-copper joint. The joining condition was 15 or 30 min of holding and adding a weight pressure (7 kPa) at 1000 °C in vacuum.
(2) Temperatures of the surface and the point 1.5 mm below the joining boundary increased linearly with increasing heat flux of electron beam heating.
(3) In the case of a tungsten divertor model specimen, a thermal crack propagated on the surface due to residual stresses from the joining process and thermal stresses due to the first heat load (5 MW/m^2).
(4) In the case of SiC/SiC composite divertor model specimens, the surface temperatures of the SiC/SiC composites increased abruptly at rather low heat fluxes and the surfaces were eroded remarkably. Thermal microcracks at the joining boundaries of SiC/SiC composites were observed after heat load tests.

Therefore, tungsten and SiC/SiC composites need to be improved further with respect to thermal shock resistance, thermal conductivity and fracture toughness. The results obtained in this study were useful for the improvement and the development of high performance plasma facing components for fusion reactors.

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