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Stability of Tungsten Coated NITE-SiC/SiC Composites under High Heat Loading by ACT2

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Abstract: SiC/SiC composites are expected as one of the promising candidate materials for the blanket/divertor of post DEMO fusion reactor due to their many advantages, such as superior high-temperature thermo-mechanical properties, radiation-resistance, low activation properties, and so on. In recent, W coated SiC/SiC composites are under development in order to increase sputtering resistance under the fusion environment. W coated SiC/SiC composites were prepared by using the hot-pressing method and investigated their interfacial microstructure. Because thermomechanical properties of SiC/SiC composites are strongly dominated by the fiber reinforcing architecture, it was investigated the in-plane/through-thickness thermal conductivity of SiC/SiC composites. The stability of W-coated SiC/SiC composite under high heat loading was evaluated by ACT2 in NIFS. After the high heat loading, any damage in W-coated SiC/SiC composites were not found from the μ-focus X-ray CT observation.

Keywords: W-coating, SiC/SiC composites, Heat transfer, Stability

1. Introduction

According to ITER divertor strategy, the baseline option involved a mixed carbon/tungsten (CFC/W) divertor for the non-nuclear phase and full tungsten (W) divertor for the nuclear phase. Because of the erosion of carbon-based materials in steady-state deuterium plasma for the materials damaged to 1-10 dpa, Tungsten is considered as the most promising plasma facing material for ITER and DEMO.[1-3]

Basically, carbon is a low activation material, and it provides excellent thermal shock resistance, thermal conductivity, heat resistance and so on. Thus, in a satellite tokamak program (JT-60SA), W coated carbon fiber composites (CFC) is under developing to apply on the surface of the first wall and divertor.[4] However, it has several drawbacks like low CTE and dimensional instability under neutron bombardment.

Silicon carbide (SiC) is also an excellent low activation material with high-temperature resistance. There are several design concepts of fusion reactor using SiC fiber reinforced SiC matrix (SiC/SiC) composites.[5-7] Tungsten is also applicable to an armor material for SiC/SiC composites to protect the high heat flux, erosion from the energetic ions and neutral atoms escaping from the plasma. And the coefficient of thermal expansion (CTE) of SiC is very close to that of tungsten. Potential joining/bonding techniques utilizing simple diffusion bonding and sinter bonding method were already studied for the preparation of W coated SiC/SiC composites.[8-10]

In general, thermo-mechanical properties of continuous fiber-reinforced composites were strongly dominated by their unique fiber-reinforcing architecture. SiC/SiC composites are one of continuous fiber-reinforced composites and it has anisotropic mechanical properties. For their application of fusion reactor, their mechanical properties were precisely evaluated.[11] Unfortunately, there are insufficient reports on their anisotropy in thermal properties. For the practical material design, it is strongly required to establish the integrated database including mechanical properties as well as thermal properties.

In this study, the effects of fiber reinforcing architecture on the thermal conductivity of NITE-SiC/SiC composites. Moreover, the stability of W coated NITE-SiC/SiC under high heat loading were investigated as a preliminary study to extract the technical issues for the practical material design, fabrication and use.

2. Experimental Procedures

High crystalline near-stoichiometric SiC fiber (Hi-Nicalon Type-S) were adopted as a reinforcing fiber. Pyro-carbon (PyC) has been formed on the fiber surface by using conventional chemical vapor deposition (CVD) method. The thickness of PyC interface is less than 500nm. A mixed slurry including SiC powder, small amount of oxide additives and polymeric binders, was prepared and infiltrated into fiber bundles, in order to produce a unidirectional (UD) prepreg sheet. 0/90 cross-ply (XP) preform were fabricated by the lay-up of UD prepreg sheets. The preforms have been densified by a hot press (Hi-multi 5000, Fujidempa Co., Ltd., Japan). The maximum temperature, time and pressure for hot pressing are 1820°C, 1.5hr and 20 MPa, respectively. The density of 0/90 XP NITE-SiC/SiC composites is

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about 2.7 g/cm^3. Estimated volume fraction of fiber, PyC interface and matrix in SiC/SiC composites is 50 vol%, 5 vol% and 45 vol%, respectively.

The SiC/SiC disks with in-plane (IP) fiber reinforcing direction and through-thickness (TT) fiber reinforcing direction were prepared, as shown in Fig. 1. And the dimension of SiC/SiC disks for the thermal conductivity measurement was ϕ10 mm × 2 mm. The thermal conductivities of SiC/SiC disks were measured at room temperature by a laser flash thermal constant measuring device (ULVAC TC7000).

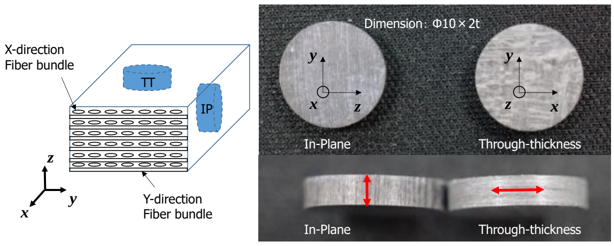

Fig.1. Conceptual diagram and appearances of SiC/SiC disks with In-plane direction and Through-thickness direction.

The dimension of specimen for the W-coating process and the high heat loading test using ACT2 (Active Cooling Teststand 2) was 20mm^W × 20mm^L × 3 mm^t. The dimension of W plate for bonding process was 20mm^W × 20mm^L × 2 mm^t. W plate having 20mm^W × 20mm^L × 5 mm^t also prepared as reference material. Top and bottom surfaces of the reference W plate were mirror-polished. The W coating on SiC/SiC composites were performed by a simple diffusion bonding. The details of bonding were described elsewhere.[9,10]

For the high heat loading test at ACT2, specially designed test module were prepared. W-coated SiC/SiC plate, SiC/SiC plate and W plate were attached on a Cu block by using active Ag-Cu-Ti brazing paste (TB-608T, Tokyo Braze Co., Ltd., Japan), as shown in Fig. 2. The melting temperature of the brazing material used in this study is about 800℃. Small holes (ϕ1.2mm) for the installation of the thermocouples were machined in the attached specimens and Cu block.

For the high heat loading test, ACT2 in NIFS were utilized. ACT2 is a high heat flux test facility using electron beam has been upgraded from ACT facility. The detail specification of ACT2 were described elsewhere.[12] The accelerated voltage of electron beam was 40 kV. The current of electron beam was ranged from 40~100 mA. Accumulated time for high heat loading test was 5 hours approximately. After the high heat loading test, the non-destruction test were performed by μ-focus X-ray CT(XT H225 ST, Nikon Corp., Japan).

Based on the temperature data obtained from thermocouples and radiation thermometer, the status of temperature distribution during the high heat loading test were estimated by using a conventional FEM program (ANSYS 19.0, ANSYS Inc., USA). Because of the limitation in calculation resources, a steady-state heat transfer analysis using a simplified partial model and boundary condition were performed.

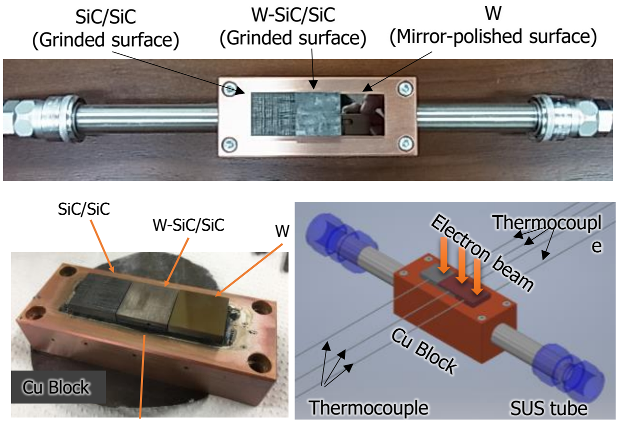

Fig.2. The test module for the high heat loading by ACT2.

3. Results and Discussions

3.1. Effects of fiber direction on thermal conductivity of SiC/SiC composites

Thermal properties of NITE-SiC/SiC composites in the direction of in-plane and through-thickness were shown in Table 1. The thermal conductivity of IP specimen is 43 % higher than that of TT specimen. In this study, Hi-Nicalon Type-S fiber was adopted as a reinforcing fiber for 0/90 XP NITE-SiC/SiC composites. The thermal conductivity of Hi-Nicalon Type-S is 16~18 W/m·K. That is the similar value of SiC matrix including a small amount of pores.[13] However, the thermal conductivity of PyC F/M interphase formed by conventional isothermal CVD method is greatly changed by its forming direction. The in-plane and radial direction thermal conductivity of PyC is 170~420 W/m·K and 2~4 W/m·K, respectively. Although, the roughly estimated volume fraction of PyC interface is 5 vol%, it can be the reason of high conductivity of IP specimen. Moreover, the volume fraction of PyC interface could be increased by increasing of fiber volume fraction. The effects of fiber direction and volume fraction were estimated by using a simple rule of mixture, as shown in Fig. 3. The thermal conductivity of IP specimen was calculated by under the consumption of parallel deploy and the thermal conductivity of TT specimen was calculated by under the consumption of series deploy. It seems that the thermal conductivity of IP specimen increases with the increase of fiber volume fraction, while, that of TT specimen decreases with the increasing of fiber volume fraction.

Table 1
Thermal properties of NITE-SiC/SiC composites in the direction of In-plane and Through-thickness

Direction	Thermal diffusivity [$\times10^{-5}m^2/s$]	Specific heat [J/(g·K)]	Thermal conductivity [W/(m·K)]
Through-Thickness, TT	0.82	0.64	14.4
In-plane, IP	1.23	0.63	20.7

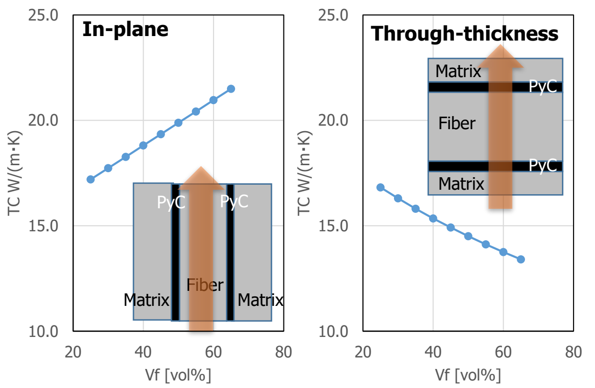

Fig.3. The effects of fiber direction and volume fraction on thermal conductivity of 0/90 XP NITE-SiC/SiC composites

3.2. High heat loading on W-SiC/SiC composites

Fig. 4 shows the appearance of the test specimen from the observation window during the test and the estimated status of temperature distribution obtained by 3D FEM analysis. Moreover, Fig. 5 shows the status of temperature distribution obtained from the steady-state heat transfer FEM analysis. The surface temperature of SiC/SiC and W coated SiC/SiC composites obtained from the radiation thermometer was up to 860℃ and 590℃, respectively. It was failed to measure the surface temperature of W by using the same thermometer, because of the lower surface temperature. It seems that the surface temperature of W plate was about 170℃. It was calculated by numerical analysis based on the inside thermocouple temperature of W plate. The surface temperature of SiC/SiC plate is significantly higher than that of W coated SiC/SiC composites and W plate. It is well known that, a part of electron do not contribute on current because of its reflection. Estimated EB absorption rate of SiC and W is 0.9 and 0.51, respectively.[14] Moreover, the thermal conductivity of W is 150~200 W/m·K. It is 10 times higher than that of SiC/SiC composites. These high EB absorption rate and low thermal conductivity of SiC/SiC composites can be a reason of their high surface temperature. Anyway, the temperature of SiC/SiC specimen was reached to the melting point of the active brazing material (Ag-Cu-Ti). As a result, the SiC/SiC plate were separated from Cu block after the test.

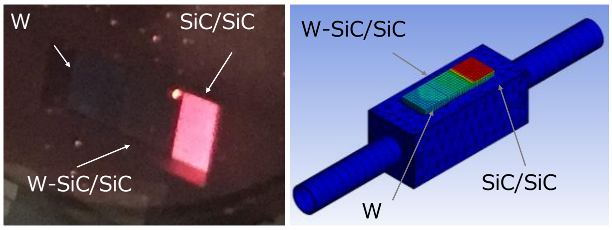

Fig.4. Appearance of specimens heated by electron beam and the temperature distribution status estimated by 3D FEM analysis

In the case of W coated SiC/SiC composites, the increase of surface temperature was significantly suppressed by the high thermal conductivity and low EB absorption rate of W coating. Fig. 6 shows the μ focus X-ray CT image of specimens after the high heat loading test. There is no evidence of degradation caused by cyclic heat loading by ACT2

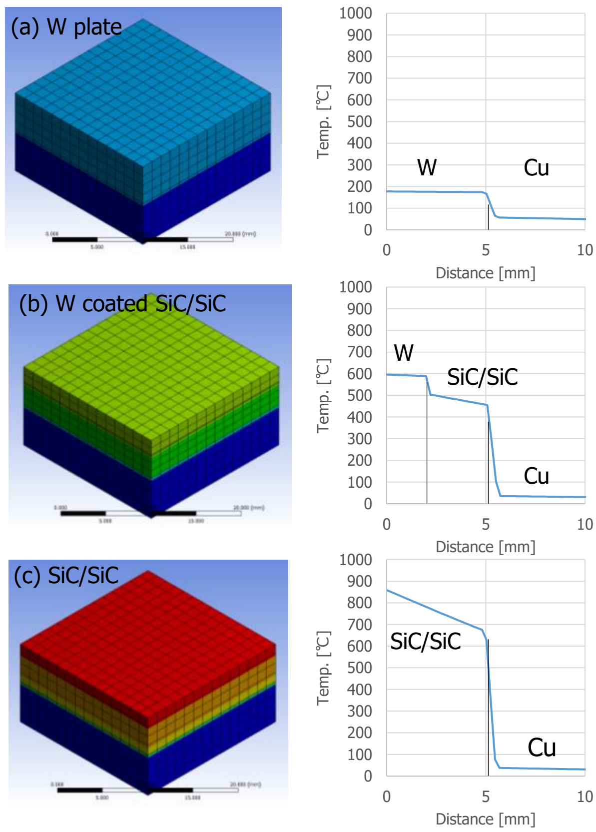

Fig.5. The status of temperature distribution obtained from the steady-state heat transfer FEM analysis

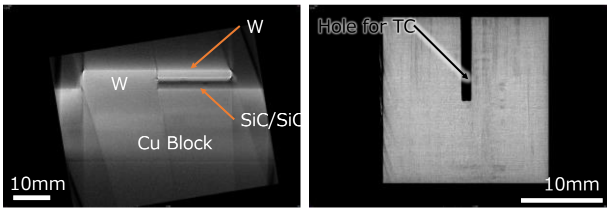

Fig.6. μ focus X-ray CT image of the specimen after the high heat loading test.

3. Summary

In order to utilize W coated SiC/SiC composites at blanket/ divertor of the fusion reactor, it was performed the investigation of the effects of the fiber architecture on their thermal properties. High heat loading test using ACT2 was also performed to investigate the stability of W-coated SiC/SiC composites. It was revealed that the thermal conductivity of 0/90 XP NITE-SiC/SiC composites is affected by their fiber reinforcing architecture, such as fiber direction, fiber volume fraction and PyC F/M interface.

During the high heat loading by ACT2, the surface temperature of SiC/SiC was higher than that of other specimens due to their high EB absorption rate and low thermal conductivity.

It was shown that W-coating could suppress the increase of temperature. Despite accumulated cyclic heat loading, it was confirmed the absence of any damage and degradation in all specimen.

Acknowledgments

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