



Section 8. Materials: miscellaneous

Thermal conductivity and retention characteristics of composites made of boron carbide and carbon fibers with extremely high thermal conductivity for first wall armour

R. Jimbou^{a,*}, K. Kodama^a, M. Saidoh^a, Y. Suzuki^b, M. Nakagawa^b, K. Morita^c,
B. Tsuchiya^c

^a Naka Fusion Research Establishment, Japan Atomic Energy Research Institute (JAERI), 801 Mukoyama Naka-machi, Ibaraki-ken, 311-01, Japan

^b Hitachi Research Laboratory, Hitachi Ltd., 3-1-1 Saiwai-cho, Hitachi-shi, 317, Japan

^c Department Crystalline Materials Science, Nagoya University, Furo-cho Chikusa-ku, Nagoya, 464, Japan

Abstract

The thermal conductivity of the composite hot-pressed at 2100°C including B₄C and carbon fibers with a thermal conductivity of 1100 W/m·K was nearly the same as that of the composite including carbon fibers with a thermal conductivity of 600 W/m·K. This resulted from the higher amount of B diffused into the carbon fibers through the larger interface. The B₄C content in the composite can be reduced from 35 to 20 vol% which resulted from the more uniform distribution of B₄C by stacking the flat cloth woven of carbon fibers (carbon fiber plain fabrics) than in the composite with 35 vol% B₄C including curled carbon fiber plain fabrics. The decrease in the B₄C content does not result in the degradation of D (deuterium)-retention characteristics or D-recycling property, but will bring about the decreased amount of the surface layer to be melted under the bombardment of high energy hydrogen ions such as disruptions because of higher thermal conduction of the composite.

Keywords: JT-60; Poloidal divertor; Low Z wall material; Wall particle retention

1. Introduction

The composite made of 35 vol% B₄C and carbon fibers with a high thermal conductivity of 600 W/m·K by hot-pressing had advantages concerning the hydrogen retention and erosion behavior compared to B₄C, and the heat resistance compared to a felt type C/C (carbon fiber reinforced carbon) [1–4]. However, the trace of melted B₄C was observed on the surface of the composite at the peak temperature of 2500°C with an irradiating electron beam power of 22–23 MW/m² for 5 s without cooling [3].

In this paper, two types of composites are compared with the thermal conductivity at room and higher tempera-

tures, and the D (deuterium)-retention characteristics. One is the composite mentioned above and the other is a new composite made of carbon fibers with an extremely high thermal conductivity of 1100 W/m·K.

D-retention characteristics of the composite were investigated because the structure of carbon fibers may influence the retention.

2. Experimental

Table 1 shows the raw materials for the composites made by mixing 35 vol% B₄C into carbon fiber plain fabrics and then curling or stacking the plain fabrics before sintering in a hot-pressing apparatus. The hot-pressing temperature was set to 1700 and 2100°C as established in a previous paper [3].

* Corresponding author. Tel.: +81-29 270 7551; fax: +81-29 270 7558; e-mail: jimbou@nbsun10.naka.jaeri.go.jp.

Table 1
Raw materials for B₄C-carbon fiber composites

	Boron carbide B ₄ C powder	Carbon fiber		
		K13C2U	P120S	K1100X
Averaged size (μm)	1.5	10 (diameter)	10 (diameter)	10 (diameter)
Composition (wt%)	C:20.4, B:77.9	—	—	—
Density (g/cm ³)	(hot-pressed: 2.48)	2.19	2.18	2.23
Crystallite thickness of (002) plane (Å)	—	350	390	790
Thermal conductivity (W/m · K)	(hot-pressed: 22)	650	640	1100

The high thermal conductivity carbon fibers shown in Table 1 are very fragile. Therefore, another type of high strength and unbreakable carbon fibers was used as the

threads that run crosswise to the high thermal conductivity carbon fibers. The volume of the high strength carbon fibers is 17% in all carbon fibers. The high strength carbon fibers are omitted in the following explanation because they are smaller in the content. They are almost embedded below the surface of the composite because they are arranged parallel to the surface, as seen from Fig. 1.

Fig. 1 illustrates the structure of carbon fiber plain fabrics arranged in the curled and stacked ways. The curled plain fabrics prevented thermal crack initiation under the electron beam irradiation for the heat resistance test, while the crack initiation could not be prevented in the composites including one dimensional carbon fibers [3]. There was no difference in the thermal conductivities perpendicular to the surface of the composites including curled or stacked carbon fiber plain fabrics and one dimensional carbon fibers when there is the same content of the high thermal conductivity carbon fibers in them.

The detailed explanations on the measurements for thermal conductivity at room and high temperatures, D-concentration after implantation, and D-retention by ERDA (elastic recoil detection analysis) were explained in previous papers [1,3].

Table 2 shows the composites used for the measurements for thermal conductivity and D-retention. All the composites in Table 2 were made of 35 vol% B₄C–65 vol% carbon fibers by hot-pressing at 2100°C. Rutherford back scattering spectroscopy (RBS) and D-retention were measured in a small area, about 1 mm in diameter. The composites for the first wall armour made in these conditions were reported [3]. It is referred in Table 2 as 'composite for test tile' which was installed in a part of JT-60 divertor in December, 1995 and was experienced with 572

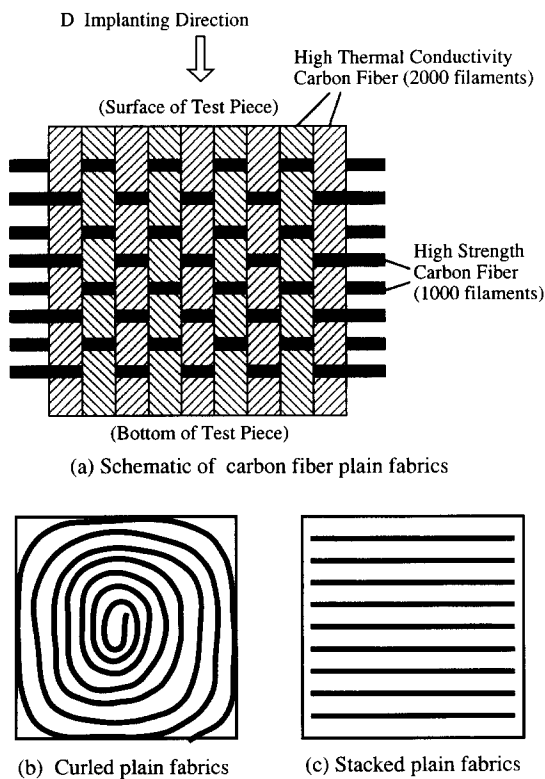


Fig. 1. Schematic layout of carbon fibers in the composite; viewing from D implanting direction (b, c).

Table 2
Composites for thermal conductivity and retention measurements

Composite item	K13C2U composite	P120S composite	K1100X composite	Composite for test tile ^a
Carbon fiber	K13C2U	P120S	K1100X	P120S
Structure of carbon fiber	stacked plain fabrics	stacked plain fabrics	stacked plain fabrics	curled plain fabrics
B/C ratio	0.225	0.222	0.225	0.372
Density (g/cm ³)	2.23	2.14	2.17	2.17

^a Reference material reported in Ref. [3].

shots of plasma discharge with the maximum power of 30 MW NBI (neutral beam injection) heating for 2 s from February 2 to April 18, 1996.

3. Experimental results

The crystallinity of graphite in the carbon fibers or the graphitization of the carbon fibers can be seen from the crystallite thickness of (002) crystal plane shown in Table 1. A larger thickness of the crystal plane corresponds to a better crystallinity which means to be closer to the single crystal. The K1100X carbon fibers have the highest thermal conductivity and the largest crystallite thickness or the best crystallinity. There is no significant difference in the thermal conductivities of P120S and K13C2U carbon fibers, but the crystallinity of P120S is a little better than that of K13C2U.

Fig. 2 shows the thermal conductivities of B_4C , P120S and K1100X carbon fibers and the four kinds of composites which were made of the former two components by hot-pressing at 1700 and 2100°C. The composite including K1100X carbon fibers (K1100X composite) shows a higher thermal conductivity when it is hot-pressed at 1700°C, but its value becomes nearly the same as that of P120S composite when it is hot-pressed at 2100°C.

Fig. 3 shows schematic sectional views of three kinds of carbon fibers in the composites. The cross sections of P120S and K13C2U carbon fibers are circular, but some of K1100X carbon fibers are not circular.

Fig. 4 shows the temperature dependence of the thermal conductivities parallel to carbon fibers in K1100X and P120S composites, and of a felt type C/C. Above 400°C, the thermal conductivity of the composites becomes higher than that of the felt type C/C.

Fig. 5 shows the D-profile in a small area (about 1 mm in diameter) with a B/C ratio of 0.222 measured by

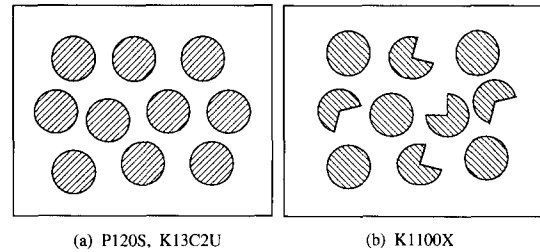


Fig. 3. Schematic sectional views of carbon fibers in sintered composites.

ERDA after saturation by D-implantation with 4 keV D_2^+ . The concentration peak of D in the composite is 3.4×10^{22} D/cm³ and locates at 60 channels, which corresponds to 35.1 nm, below the surface.

Fig. 6 shows the D-retention in the areas with nearly the same B/C ratios of 0.222 to 0.225 in K13C2U, P120S and K1100X composites, shown in Table 2. The D-retention in the area with B/C ratio of 0.372 in the composite (same material as the test tile installed in JT-60), graphite and $B_{3.73}C$ (boron carbide) were also presented. In general, all the D-retentions in the composites with B/C ratio of 0.222 to 0.372 have nearly the same characteristics, showing a better recycling property than in graphite and boron carbide below 500°C. The D-concentration in boron carbide itself becomes lower at temperatures over 500°C than in the composites.

Fig. 6 also shows the D-retentions at higher temperatures over 600°C for the three composites with nearly the same B/C ratios of 0.222 to 0.225. K1100X composite has the lowest retention and K13C2U composite has the highest retention.

Two pieces of the test tile were taken out of the JT-60 divertor April 18, 1996. A very small volume near one edge was observed to have been cut off by a high power

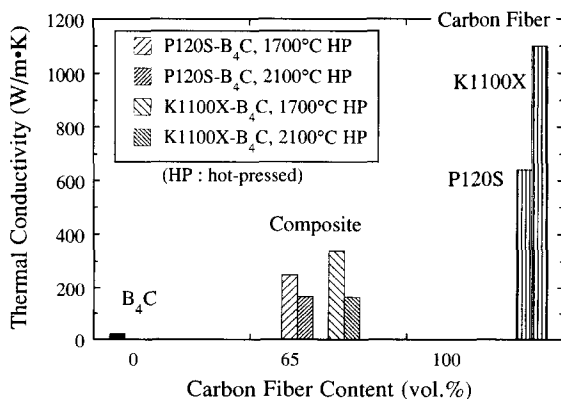


Fig. 2. Thermal conductivity (25°C) of B_4C , carbon fibers and composites hot-pressed at 1700 and 2100°C.

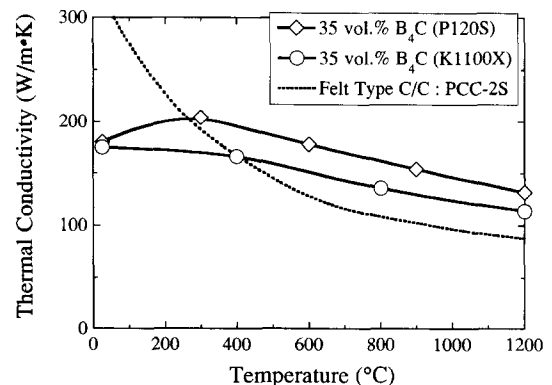


Fig. 4. Temperature dependence of thermal conductivities parallel to carbon fibers in composites including different carbon fibers hot-pressed at 2100°C, and that of felt type C/C.

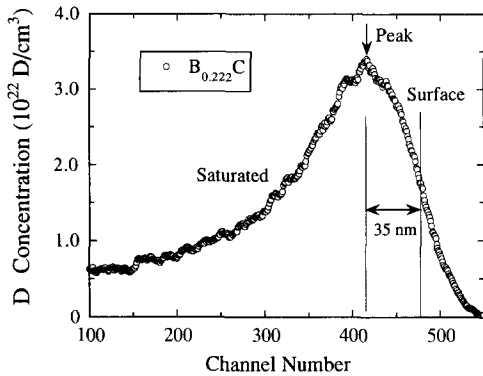


Fig. 5. D-concentration distribution in the area with B/C of 0.222 in the composite saturated with 4 keV D_2^+ (one channel corresponds to 0.585 nm).

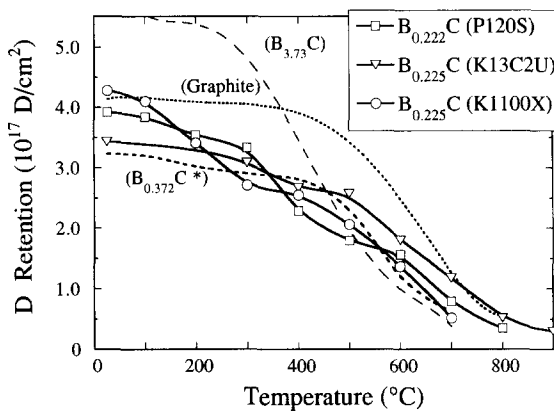


Fig. 6. D retention in composites including different kinds of carbon fibers, showing data for B_4C , graphite and composite for test tile installed in JT-60(*) for comparison.

density plasma. However, no cracks could be detected in the outer surface of the test tile.

4. Discussions

As seen from Fig. 3, K1100X carbon fibers in the composite have a larger contacting interface with the B_4C matrix than P120S carbon fibers because of missing parts of some carbon fibers. This might come from fabrication or while the green body was formed and/or the composite was sintered. Therefore, the B-diffusing area in the carbon fibers must be larger in the K1100X composite than in the P120S composite. The thermal conductivity of the K1100X composite will be reduced more during hot-pressing at 2100°C than the P120S composite. It can be said that higher thermal conductivity carbon fibers do not necessarily make a higher thermal conductivity composite in the

case that the carbon fibers are fragile and easily lose parts of them.

As seen in Fig. 4, the temperature dependence of the thermal conductivities of K1100X and P120S composites are less steep than that of a felt type C/C. This is due to the B solution into the carbon fibers from B_4C during sintering. The substitutional B for carbon atoms results in a decrease in the phonon mean free path that is more pronounced at lower temperatures. So, a crossing temperature of about 400°C appears in Fig. 4 above which the thermal conductivity of the composites becomes higher than that of the felt type C/C [3].

As seen in Fig. 5, the concentration profile is not symmetrical as to the longitudinal axis at the concentration peak. It has a tailing toward the inside that can be correlated with the direction of carbon fibers because the D ions may intrude through the small voids between the carbon fibers and the B_4C matrix.

As shown in Fig. 6, all the D-retentions of the four kinds of the composite with B/C ratio of 0.222 to 0.372 show nearly the same D retention characteristics. It can be explained by the stacking of carbon fiber plain fabrics that may result in more uniform distribution of B_4C in the three composites with B/C ratios of 0.222 to 0.225 than in the composites including the curled plain fabrics of carbon fibers with a B/C ratio of 0.372. The D-retentions of all these composites decrease more rapidly with temperature than that of graphite. A detailed comparison with the retentions of the composites with nearly the same B/C ratio of 0.222 to 0.225 shows that K1100X composite including carbon fibers with the best crystallinity has a tendency of the lowest D-retention in the temperature range over 600°C. However, the composite including K13C2U carbon fibers with the worst crystallinity has the highest D-retention. From this tendency, the crystallinity of carbon fibers may have a little effect on the D-retention in such a way that D-atom is a little easier to release from the carbon fibers with the better crystallinity over 600°C, where this D-release from carbon fibers would determine the retention rate of the composites. It can be concluded that B_4C content in the composite can be reduced from 35 vol% to 19–20 vol% which corresponds to 0.222 to 0.225 B/C in the composite by means of mixing B_4C uniformly. However, the erosion yield of this composite is a little higher at 800 K than that for the composite with 35 vol% B_4C [2]. Below 400°C the D concentration in boron carbide is higher than in the composites because of the very high D-saturation concentration at 25°C. However, over 500°C, it becomes the lowest because B_4C has essentially a very good D-recycling property.

No cracks were detected in the outer surface of the test tile which was hot-pressed with 35 vol% B_4C and the curled plain fabrics of P120S carbon fibers. The composite hot-pressed with B_4C and the curled plain fabrics of the carbon fibers with a high thermal conductivity could be used in a thermonuclear fusion reactor instead of C/C.

5. Conclusions

The thermal conductivity of the composite sintered at 2100°C including B₄C and carbon fibers with a thermal conductivity of 1100 W/m · K (K1100X) was not higher than that of the composite including carbon fibers with a thermal conductivity of 600 W/m · K (P120S), because more amount of B diffused into the K1100X carbon fibers through the larger interface with B₄C than into the P120S carbon fibers.

The D (deuterium)-retention of the composite with B/C ratio of 0.222 to 0.372 shows nearly the same D retention characteristics in a whole temperature range. This means a possibility to decrease in the B₄C content from 35 to about 20 vol% that will decrease in the surface layer melting without cooling under the bombardment of high energy hydrogen ions. A detailed comparison with the retentions of the composites with nearly the same B/C ratio of 0.222 to 0.225 shows that the composite including carbon fibers with better crystallinity has a tendency of lower D-retention in the temperatures over 600°C.

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