CHARACTERIZATION OF CHEMICALLY VAPOR INFILTRATED SILICON CARBIDE COMPOSITES REINFORCED BY VARIOUS HIGH MODULUS FIBERS: I. THERMAL CONDUCTIVITY—T. Nozawa, Y. Katoh, L. L. Snead (Oak Ridge National Laboratory), T. Hinoki and A. Kohyama (Kyoto University, Japan)

OBJECTIVE

The objective in this study is to evaluate in-plane and through-thickness thermal conductivities of various architecture types of the SiC/SiC composites and the hybrid SiC-C/SiC composites incorporated with high-modulus SiC and carbon fibers.

SUMMARY

The Tyranno™-SA fiber composites remarkably improved their thermal conductivity, in particular the through-thickness thermal conductivity in the orthogonal three-dimensional (3D) composite system due to excellent thermal conductivity of Tyranno™-SA fiber itself. The carbon fiber was in general beneficial to obtain high thermal conductivity of the composites. However, many matrix cracks, induced by the mismatch of coefficients of thermal expansion during processing, restricted heat transfer via matrix of carbon fiber containing composites, limiting the improvement of the thermal conductivity.

PROGRESS AND STATUS

Introduction

Silicon carbide fiber reinforced silicon carbide (SiC/SiC) composites are candidate materials for nuclear fusion and advanced fission reactors because of elevated-temperature chemical and mechanical capability, low induced-radioactivity and after-heat [1]. The latest composites fabricated from the high modulus SiC fibers, i.e., highly-crystalline and near-stoichiometric SiC fibers such as Tyranno™-SA and Hi-Nicalon™ Type-S, and the β-SiC matrix provide good geometrical stability and strength retention after neutron irradiation [2–4]. Also, enhanced thermal and thermo-mechanical properties of the highly crystalline SiC composites have the added advantage to providing higher system efficiency. In addition, higher thermal conductivity and strength also allow higher resistance to thermal shock.

Constituent materials are one important factor to maximize the thermal properties of composites. Among various processing techniques, chemical vapor infiltration (CVI) is regarded as the technique that produces the highest crystallinity SiC with inherently high thermal conductivity [5]. Tyranno™-SA and Hi-Nicalon™

Type-S fibers are also beneficial to use due to their crystalline structure. Tyranno™-SA fiber possesses the thermal conductivity of 65 W/m-K, while 18 W/m-K for Hi-Nicalon™ Type-S. Further thermal conductivity improvements have been proposed whereby hybrid composite concepts using carbon fibers as reinforcements mixed with SiC fibers (SiC-C/SiC composites) are utilized [6]. Specifically, pitch-based carbon fibers possess much higher thermal conductivity (22~1000 W/m-K), as compared to SiC or other graphite fibers. For many nuclear applications, heat transport in the direction orthogonal to the plane of the primary stress is required. For this reason, a Z-stitch of high conductivity graphite fiber into an X-Y weave of SiC fibers has been considered. Matrix densification is also important to keep good heat transfer via matrix. The through-thickness thermal conductivity of ~70 W/m-K, which is higher than that of the conventional composites (~20 W/m-K), has been reported for two dimensional (2D) SiC/SiC composite with the density of ~3.1 g/cm^3, fabricated by nano-infiltration transient eutectic phase sintering (NITE) process [7].

Experimental Procedure

Materials

The materials were SiC matrix composites with the highly crystalline and near-stoichiometric SiC fibers: Tyranno™-SA Grade-3 and Hi-Nicalon™ Type-S. Also hybrid SiC matrix composites with Tyranno™-SA Grade-3 and pitch-based carbon (P120S: ~640 W/m-K) fibers was prepared (Table 1). All materials were produced by isothermal/isobaric CVI process. Two types of 2D SiC/SiC composites with plain-weave (P/W) Tyranno™-SA and 5-harness satin-weave (S/W) Hi-Nicalon™ Type-S, two types of orthogonal 3D SiC/SiC composites with differed through-thickness (Z-direction) fiber content: X: Y: Z = 1: 1: 1 and 1: 1: 4, and two types of hybrid composites with a P/W and an orthogonal 3D architecture composed of Tyranno™-SA and P120S fibers (Figure 1) were fabricated, respectively. It is noted that the Z-direction fibers of both 3D SiC/SiC composites were made into SA grade (Si-Al-C) from AM grade (Si-Al-C-O) Tyranno™ fiber at the temperature of ~2073 K in inert environment after weaving. All composites had 150 nm thick pyrolytic carbon (PyC) as fiber/matrix (F/M) interphase.

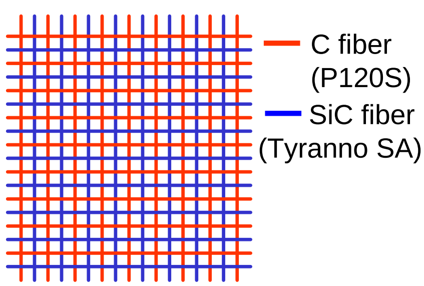
Thermal Conductivity

Room temperature thermal diffusivity was measured using a xenon flash technique and thermal conductivity was calculated using the measured composite density and specific heat. Specific heat of composites was calculated assuming the rule of mixtures. Microstructures were examined with an optical microscopy and a field emission scanning electron microscopy (FE-SEM).

Table 1. SiC/SiC and hybrid SiC-C/SiC composites under investigation

ID	Fiber	Architecture	X- (and Y-) fiber volume fraction [%]	Z-fiber volume fraction [%]	Density [Mg/m^3]	Porosity [%]
P/W SA	SA*1	P/W	20	-	2.51	20
S/W HNLS	HNLS*2	5-harness S/W	22	-	2.52	19
3D(1:1:4) SA	SA*1	3D(X:Y:Z=1:1:4)	10	40	2.76	10
3D(1:1:1) SA	SA*1	3D(X:Y:Z=1:1:1)	15	15	2.78	11
Hybrid 2D	SA*1+C*3	P/W	SA*1:8, C*3:18	-	2.25	19
Hybrid 3D	SA*1, C*3	3D(X,Y:SA*1, Z:C*3)	SA*1:12	C*3:21	2.19	25

*1SA: Tyranno™-SA Grade 3 fiber, *2HNLS: Hi-Nicalon™ Type-S fiber, *3C: P120S fiber



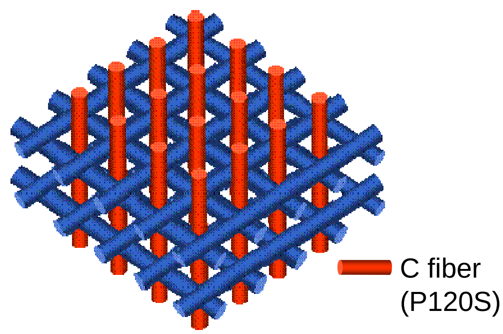


Fig. 1. Schematic illustrations of hybrid 2D and 3D SiC-C/SiC composites.

Results and Discussion

Figure 2 shows the typical cross-sectional images of as-received composites. Two dimensional SiC/SiC composites had large pores in most cases in weaving cross-sectional pockets, resulting in a density of ~2.5 g/cm^3. By contrast, both 3D SiC/SiC composites were well-densified even in the pocket regions, yielding a density of ~2.7 g/cm^3. Both 2D and 3D hybrid composites had large pores in pocket regions. Therefore less densification of the matrix yielded a lower density (~2.2 g/cm^3) than that of ideally densified composites (~2.8 g/cm^3). In addition, the hybrid composites contained transverse matrix cracks around every carbon fiber bundle. Specifically major cracks propagated within laminated plies for some 2D hybrid composites. This is attributed to the large CTE mismatch between the SiC matrix and the carbon fiber.

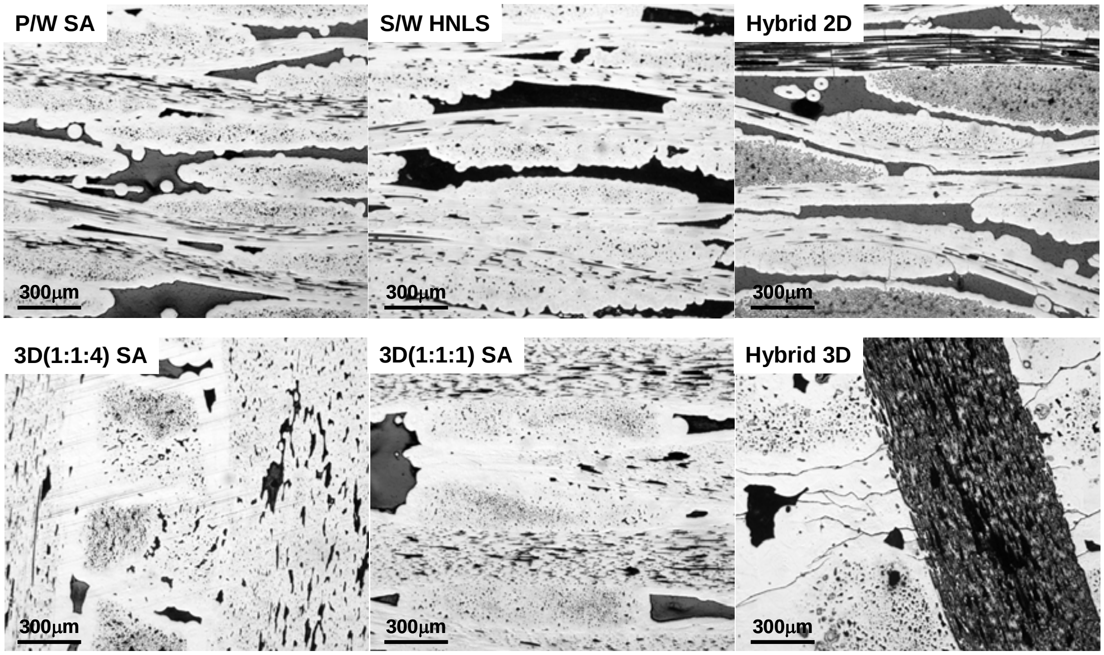


Fig. 2. Typical micrographs of polished cross-sections of various SiC/SiC and SiC-C/SiC composites.

Figure 3 shows a relationship between the axial fiber volume fraction and thermal conductivity. The 3D SiC/SiC composites with the Tyranno™-SA fiber exhibited the highest improvement of the thermal conductivity. Specifically, the presence of continuous Z-direction fibers remarkably improves the through-thickness thermal conductivity. Similarly, the carbon fiber with higher thermal conductivity of 640 W/m-K is, in general, considered effective to provide the high thermal conductivity composite. However many CTE mismatch induced cracks prevented thermal diffusion via matrix of carbon fiber containing composites, resulting in less improvement than the Tyranno™-SA composites. The in-plane thermal conductivity was also high (~50 W/m-K) similar to the through-thickness thermal conductivity due to the presence of continuous X- or Y-direction fibers. In contrast, the SiC/SiC composite of Hi-Nicalon™ Type-S with relatively lower thermal conductivity exhibited less improvement of the in-plane thermal conductivity, though high axial (in-plane) fiber volume fraction.

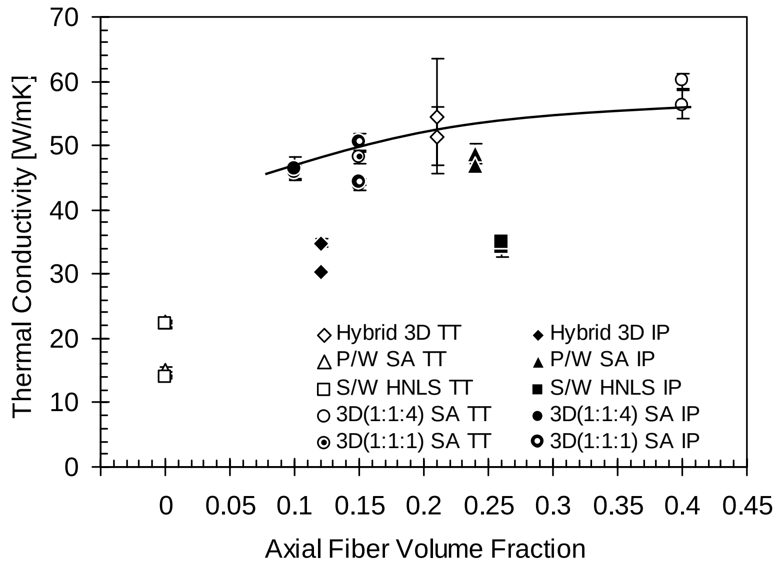


Fig. 3. Through-thickness (TT) and in-plane (IP) thermal conductivity with respective to the axial fiber volume fraction.

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