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Effect of Fiber Volume Fraction on Hoop Strength of SiC Triplex Tube

Daejong Kim*, Hyun-Guen Lee, Ji Yeon Park, and Weon-Ju Kim
Nuclear Materials Division, KAERI, 989-111Daedeok-daero, Yuseong-gu, Daejeon 305-353
**Corresponding author: dkim@kaeri.re.kr*

1. Introduction

Recently, there have been extensive efforts to develop better materials to replace Zr alloys for LWR fuel cladding. A fully replacement concept such as SiC triplex is most noteworthy because the hydrogen liberation rate of SiC is hundreds times less than Zr alloys. It also has excellent neutron irradiation and corrosion resistance [1].

In this study, SiC triplex tubes which consisted of a monolith SiC inner layer, a SiC_f/PyC/SiC composite intermediate layer and a monolith SiC outer layer were fabricated by the chemical vapor processes such as CVD and CVI. Influences of a fiber volume fraction and a type of reinforcement SiC fiber on hoop strength of the composite tubes were examined.

2. Experimental Procedure

SiC was chemically vapor-deposited using methyltricholorosilane (MTS, CH_3SiCl_3) onto the high purity graphite rods. The SiC_f/SiC composite as an intermediate layer was reinforced by commercial generation III SiC fibers such as Tyranno SA3 and Hi-Nicalon Type S which were filament-wound onto a monolith SiC inner layer with $\pm 55^o$ of the winding angle. The properties of crystallized and near-stoichiometric SiC fibers are listed in Table I.

Table I. Properties of SiC fibers used in this study

SiC fiber	Compositions (wt%)	Filament dia.(μm)	Filament /yarn
Tyranno SA3 -0.8k	68Si+32C+0.6Al	7.5	800
Tyranno SA3 -1.6k	68Si+32C+0.6Al	7.5	1600
Hi-Nicalon Type S	69Si+31C+0.2O	12	500

Hoop stress of the tubular specimens with dimension of a length of 30 mm, an inner diameter of 8.5 mm, and an outer diameter of 9.6 – 10.1 mm was measured via internal pressurization through polyurethane plug at room temperature using screw driven universal testing machine.

3. Results and Discusion

3.1 Microstructure of SiC triplex tube

Fig. 3 shows microstructures of the SiC triplex tube, and its constituent layers of a SiC inner layer and a Tyranno SA3-reinforced SiC_f/SiC composite layer. The dense SiC inner layer with columnar structure was deposited with 320 μm of the average layer thickness. For the SiC_f/SiC composite layer, a dense SiC matrix phase was obtained by a CVI process and a density gradient of matrix was also little to the growth direction.

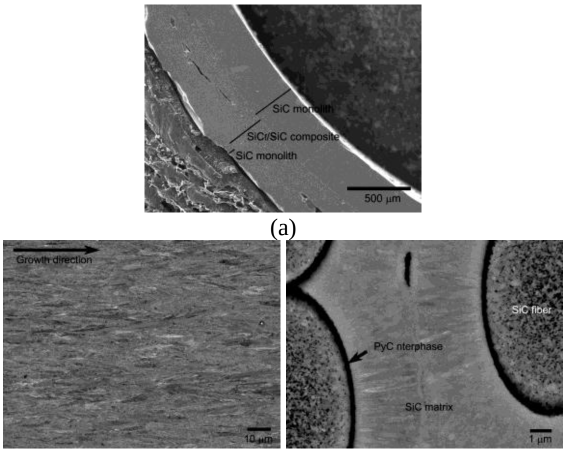


Fig. 1. Typical microstructure showing (a) the SiC triplex tube fabricated by the chemical vapor processes, (b) SiC monolith, and (c) Tyranno SA3-reinforced SiC_f/SiC composite.

3.2 Effect of fiber volume fraction

The mechanical properties of a composite are usually determined by the properties of matrix and fiber, volumetric ratio, matrix density and fiber orientation [2, 3]. When the fiber strength is much higher than that of matrix, the fiber properties and fraction have a significant effect on the composite strength. As shown in Fig 2, the properties of composite will be close to the properties of fiber when the volumetric ratio of fiber increases.

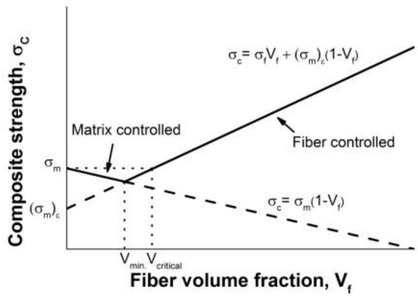
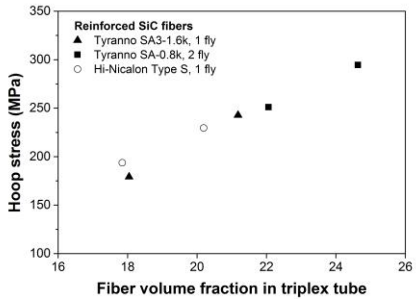


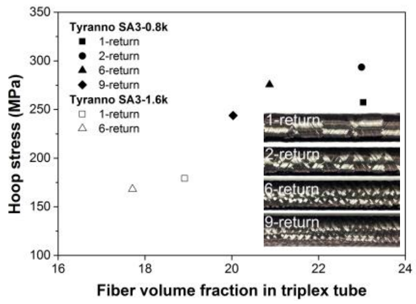
Fig. 2. Relationship between composite strength and fiber volume fraction.

Fig. 3 shows the hoop stresses of the SiC triplex tubes which have the same winding pattern with various fiber volume fraction. The hoop stress of the triplex tube tends to be proportional to the fiber volume fraction. The highest fiber volume fraction was obtained when the Tyranno SA3-0.8k fiber was used so that the Tyranno SA3-0.8k reinforced triplex tube exhibits the highest hoop stress. In the case of the Hi-Nicalon Type S-reinforced triplex tubes, the fiber volume fraction is less than Tyranno SA3 because a diameter of Hi-Nicalon type S is larger than Tyranno SA3 because the Hi-Nicalon Type S fiber is less flexible than Tyranno SA3. Since Hi-Nicalon Type S has higher tensile strength and tensile modulus (Table I). When the fiber volume fraction in the SiC triplex tube is same, the hoop stress of Hi-Nicalon Type S reinforced tubes was slightly higher than the Tyranno SA3-reinforced triplex tube.

Winding pattern have also an effect on the fiber volume fraction and hoop strength. Winding pattern was controlled by adjusting the position of second fiber trajectory. Bamboo-like patterns such as 1-return and 2-return provideed the higher fiber volume fraction and hoop stress, as shown in Fig. 3(b).



(a)

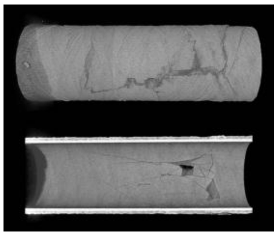


(b)

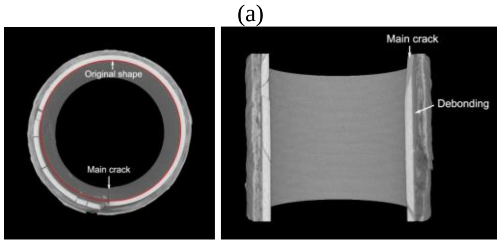
Fig. 3. Hoop stresses of the SiC triplex tubes as a function of the fiber volume fraction: (a) 1-return of the winding pattern and (b) four phase winding patterns

3.2 Fracture behaviors

Fig. 4 shows micro-CT images for the SiC triplex tube after failure. A main crack propagated to the axial direction within polyurethane plug. Near the crack tip, crack propagated along the direction of least resistance which is parallel to the direction of the fiber. The significant debonding between an inner layer and an intermediate layer occurred around the highly deformed region.



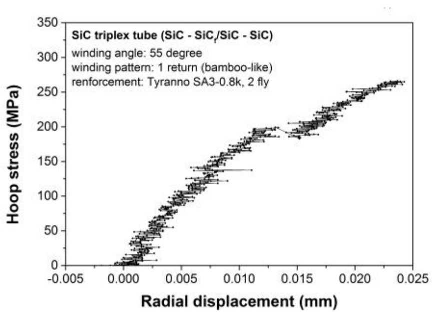
(a)



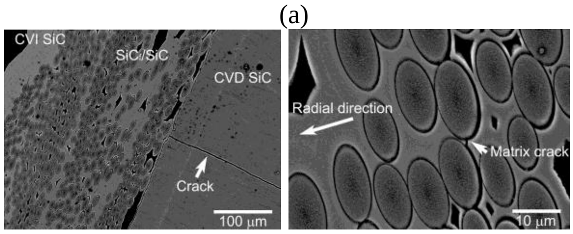
(b) (c)

Fig. 4. Micro-CT images of a SiC triplex tube after failure.

Fig. 5(a) shows the hoop stress vs. radial displacement curve. Hoop stress steeply increased at low strain and the slop decreased above about 150 MPa. This tendency is a typical for the composite materials. The decrease in the slop could be caused by the matrix cracking. Also, a significant load drop was observed at about 200 MPa. In order to clarify the damage process, some triplex tubes were interrupted prior to failure. As shown in Fig. 5(b), the cracking initiated at the inner layer which resulted in the significant load drop. The leading crack propagated through the composite layer along the fiber-matrix interface. This caused a decrease in the slop of the stress-radial displacement curve.



(a)



(b) (c)

Fig. 5. (a) Hoop stress vs. radial displacement curve of a SiC triplex tube and (b) microstructure of the SiC triplex tube showing a crack in a SiC inner layer and (c) matrix cracks in a SiC_f/SiC composite layer.

3. Summary

SiC triplex tubes were fabricated by chemical vapor deposition/infiltration methods for the LWR fuel cladding application. The influence of the fiber volume fraction of SiC fiber on hoop strength and fracture behaviors of the SiC triplex tube were investigated. The hoop stress of SiC triplex tube tends to be proportional to the fiber volume fraction of SiC triplex tube. Tyranno SA3-0.8k with a bamboo-like fiber pattern had the highest fiber volume fraction and hoop stress. Quasi-ductile fracture occurred for the triplex tube. Crack initiated in a SiC inner layer which resulted in the load drop in the stress-displacement curve. Matrix cracking along the fiber-matrix interface caused a decrease in the slop of the stress-radial displacement curve.

Acknowledgement

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REFERENCES

[1] W.-J. Kim, D. Kim, and J.Y. Park, Fabrication and Materials Issues for the Application of SiC Composites to LWR Fuel Cladding, Nuclear Engineering and Design Vol.45, p.565, 2013.
[2] D. Cohen, S. C. Mantell, and Liyang Zhao, The Effect of Fiber Volume Fraction on Filament Wound Composite Pressure Vessel Strength, Composites B, Vol.32, p.413, 2001.
[3] R.M. Jones, Mechanics of Composite Materials, Cripta Book Company, Washington, D.C, USA, pp.128 – 134, 1975.