Material Issues for the Application of SiC Composites to LWR Fuel Cladding

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1. Introduction

Silicon carbide (SiC)-based ceramics and their composites (SiC_f/SiC) have extensively been studied for fusion and advanced fission energy systems due to the excellent high temperature properties, irradiation tolerance, inherent low activation and other superior physical/chemical properties [1]. In the high-temperature gas-cooled reactors (HTGRs), SiC is being utilized as a coating layer of TRISO particle fuel and SiC_f/SiC composites can also be applied to in-/out of core structural materials including control rod sheath and intermediate/process heat exchanger components. In addition, SiC_f/SiC composites have been considered as blanket structural materials and flow channel insert in fusion reactors. Recently, there have also been efforts for applying the SiC_f/SiC composites to light water reactor (LWR) fuel cladding [2]. However, there are a lot of technical issues need to be clarified for the LWR application because the previous research on the SiC_f/SiC composite has mostly been focused on the high-temperature application. In this study, we reviewed material issues regarding to the application of SiC composite to LWR fuel cladding. We tried to draw a research direction and important issues to assess the technical feasibility of SiC composite cladding.

2. Material Issues of SiC Composite for LWR Fuel Cladding

The SiC composite tube for the application of LWR fuel cladding consists of multiple layers as shown in Fig. 1. The innermost layer is high-density monolithic CVD SiC to render a primary retention of fission products. The second layer consists of SiC fiber-reinforced SiC matrix (SiC_f/SiC) composite to increase a mechanical property and prevent a brittle fracture of the composite tube. Another CVD SiC is finally coated to improve the corrosion resistance of the composite layer. The primary focus of SiC research for nuclear applications has been on the high-temperature reactors such as VHTR and fusion reactors. Therefore, the property and performance data of SiC ceramics are rather scarce in LWR environments. Important issues need to be clarified before the deployment of SiC composite cladding are described in the following sections.

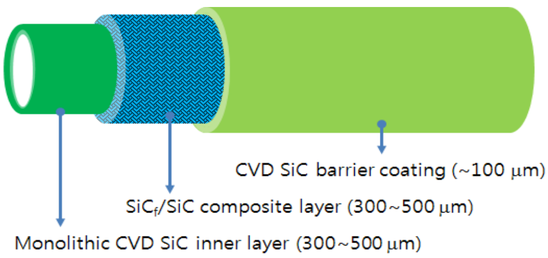

Fig. 1. Structure of triplex SiC composite tube for LWR fuel cladding.

2.1 Corrosion Resistance

Generally, SiC ceramics are highly corrosion resistant by forming a protective SiO_2 layer in an air atmosphere. In a high-temperature and high-pressure water or a steam environment, however, the corrosion resistance of SiC is decreased because the protectiveness of SiO_2 layer is deteriorated. Fig. 2 shows some results of corrosion tests at different conditions [3,4]. The CVD SiC ceramics exhibited a preferential corrosion at grain boundaries.

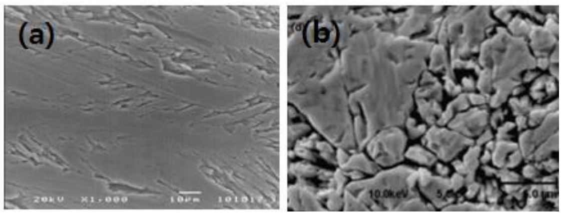

Fig. 2. Microstructures after corrosion tests of CVD SiC ceramics at different conditions. (a) 5 days test at 360℃, 15 MPa water [3] and (b) 21 days test at 500℃, 25 MPa supercritical water [4].

Henager Jr. et al. [5] reported a pitting corrosion of CVD SiC after long-term corrosion tests up to 5400 h at 300℃ and 10 MPa water. Stempien et al. [6] also reported a corrosive pitting of SiC composite tube in the test using MITR-II LWR simulating test loop. Until now, the exact corrosion behavior of SiC in LWR condition is not clear due to the difference in the test sample and condition. The exact corrosion rate of SiC is needed to be defined to confirm the possibility of burn-up extension and the cost-benefit effect. In addition, the oxidation behavior in a high-temperature steam environment should be clarified to define the performance of SiC composite cladding under LOCA condition.

2.2 Hermetic Joining

A technology for end-plug joining with gas tightness should be developed because the SiC ceramics cannot be welded. Several SiC joining technologies has been developed aiming at the application for fusion reactors. However, a robust joining technology which can be applied to the SiC composite cladding is not proved yet. A reaction bonding method using Ti-SiC has recently been shown a possibility in the MITR-II irradiation test [6]. The end-plug joint should be both corrosion resistant and irradiation stable as well as economically feasible, being a great challenge.

2.3 Thermal Conductivity

The high-purity CVD SiC has a very high thermal conductivity above 300 W/m·K. Thermal conductivity in a composite form, however, is significantly lower than the CVD SiC as shown in Fig. 3. The thermal conductivity of SiC composite is further decreased by neutron irradiation especially at relatively low temperatures such as LWR condition. The thermal conductivity of triplex composite tube is expected to be around 4-5 W/m·K.

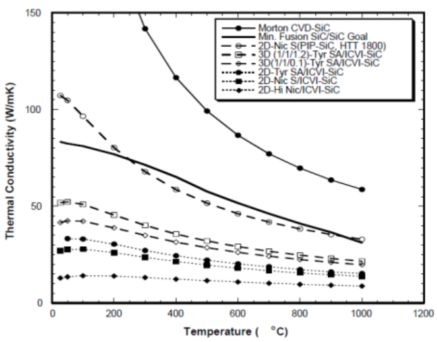

Fig. 3. Temperature-dependent thermal conductivity of various SiC ceramics [7].

The low thermal conductivity of composite cladding can increase the fuel temperature and decrease a fuel safety margin. Another consequence of the low thermal conductivity is a generation of secondary stress due to the thermal expansion mismatch between inner and outer walls of the composite tube. In addition, a stress can be developed due to the swelling gradient through the wall thickness.

2.4 Reliability

The SiC_f/SiC composite has an even higher reliability than the monolithic form and shows a pseudo-plastic fracture behavior. The Weibull modulus of ultimate tensile strength of SiC_f/SiC composite has been reported to be high value around 25. The microcracking stress of SiC matrix, however, is significantly lower than the ultimate tensile strength of composite and shows a large scatter. Therefore, the stress applied to the composite tube should be kept a very low value in order to prevent a release of fission products through the microcracks.

2.5 Fabrication

There are several manufacturers producing SiC_f/SiC composites in worldwide and more limited companies capable of producing nuclear-grade composites. The current facilities in worldwide can produce ~1.5 m long tubes to the best knowledge of the authors and an infrastructure should be established for the fabrication of a full length tube. The requirements of strict dimensional control and straightness of tube are of a great challenge for composite community. In addition, the high-performance SiC fibers are still very expensive and the fiber cost should be lower through a mass production.

3. Summary

The technology of SiC composite cladding for LWR fuel is in the very early stage of development. Among the various issues described in this paper, the corrosion behavior of SiC in LWR condition is needed to be clarified above all. For the exact determination of corrosion behavior, the fabrication of composite tube with well-controlled properties should be preceded. In spite of the various technological hurdles, the SiC composite cladding would significantly increase the safety of LWR fuel both in normal and accident conditions if successfully applied. Therefore, a long-range development program including materials development and system design is encouraged.

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