Evaluation of Irradiation-Induced Strain in SiC Tubes by a Combination of Experiment and Simulation

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INTRODUCTION

In recent years, silicon carbide (SiC) fiber-reinforced SiC matrix composites have been actively studied for use in developing an accident tolerant fuel cladding for light water reactors because of their superior steam oxidation and irradiation resistance and relatively low neutron absorption cross section. One of the potential issues for this technology is loss of hermeticity of the cladding due to micro-cracking under normal operation conditions. Recent numerical simulation on the in-pile stress state of the SiC/SiC cladding predicts near equi-biaxial tensile stress along the axial and hoop directions at the inner surface, which will potentially be beyond the matrix cracking stress of the SiC/SiC cladding. According to the simulation, the stress is caused by a through-thickness gradient of swelling due to a temperature gradient produced by the presence of hot fuel and cold coolant. Although modeling of the in-pile stress states of SiC cladding has been conducted, the analysis is challenging because of the complex stress states that depend upon swelling and thermal conductivity, each of which are both temperature and dose-dependent. Moreover, the anisotropic structure of SiC/SiC composite makes modelling challenging. A current issue is that these integral models have not yet been verified by experiments.

To address this issue, we have conducted irradiation of SiC tubes with a high radial heat flux. This paper presents results of post irradiation examination of these irradiated tubes. The overall goal of this study is validation of modeling of the in-pile stress of the SiC tubes by experiment. This paper mainly studies irradiated monolithic SiC tube.

EXPERIMENTS

Material used was high-purity chemical vapor deposited (CVD) SiC monolithic tubes fabricated by Dow Chemical Company. Purity of the material was 99.9995% as claimed by the vendor. The specimens have an outer diameter of 8.5mm, an inner diameter of 7.1mm, and a length of 16mm.

Neutron irradiation was conducted in the High Flux Isotope Reactor. The neutron dose was 2.3 dpa based on the assumed conversion of 1 dpa = 1.0×10^15 n/m^2 (E > 0.1MeV) ^4. The nominal radial heat flux was 0.7 MW/m^2.3.

RESULTS

Irradiation temperature and strain of the CVD SiC tube following irradiation were simulated using a finite element method, as shown in Fig. 1. The details of simulation method can be found elsewhere. The simulation considered effects of irradiation on dimensional stability, thermal conductivity, elastic constant, and coefficient of thermal expansion. The irradiation temperature at the outer surface of the tube and through-thickness temperature gradient were approximately 350 and 50°C, respectively. The simulated stress state exhibited a near-equibiaxial tensile axial and hoop stress of -200 MPa at the inner surface of the tube. The stress state of the outer surface was a near-equibiaxial compression axial and hoop stress of -200 MPa. This stress level can potentially cause cracking at the inner surface of the tube based on the mechanical properties of monolithic SiC.

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The irradiation temperature of the specimen was experimentally evaluated using Raman spectroscopy in a previous work. The analysis showed average irradiation temperatures of 330 and 410°C for two different specimens. The result was reasonability consistent with the simulation shown in Fig. 1a, although the Raman spectroscopic analysis did not capture the temperature gradient because the spectra was not sensitive enough to detect such temperature difference.

Due to potential cracking due to irradiation-induced stress (Fig. 1b,c), the presence of micro-cracking was investigated based on elastic modulus change due to irradiation. Resonant ultrasound spectroscopy analysis using a Magnaflux RUS System™ found reduction of the Young's modulus of the irradiated CVD SiC tubes was around 10%. This reduction was greater than the previous measurement of CVD SiC plate, which shows a reduction of the Young’s modulus of up to 6%. This result indicates the presence of cracks due to irradiation. The cracking was investigated by cross-sectional observation using optical microscopy. The specimen was mounted in epoxy followed by cutting using a low-speed diamond saw. Upon observation, cracks appeared to initiate from the inner surface of the tube in the irradiated specimen, while no cracks were found on the cross-section of the non-irradiated tube. Since irradiation-induced cracking was likely, it is important to address hermeticity of the irradiated tube to investigate presence or absence of through-thickness cracks.

Hermeticity of the irradiated CVD SiC tube was evaluated using a permeation test station developed at Oak Ridge National Laboratory (Fig. 2); the helium and deuterium permeation flux through a neutron-irradiated CVD SiC tube was measured. The results showed that the CVD SiC tube was hermetic both before and after irradiation, as indicated by the extremely low helium and deuterium permeation flux at various gas pressures.

Fig. 2 The permeation testing system and (inset) test specimen.

In summary, the measured elastic modulus reduction and optical microscopy on the cross-sectional specimen confirmed presence of cracks in the CVD SiC tubes, likely introduced by the simultaneous loading of neutron irradiation and radial high heat flux. Still, the irradiated CVD SiC maintained hermeticity. It is suspected that axial and hoop compressive stresses at the outer surface of the tube (Fig. 1b, c) prevented formation of through-thickness cracks. Further investigation is in progress to experimentally evaluate irradiation-induced strain and the radial distribution of irradiation temperature.

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REFERENCES


