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Evaluating the irradiation effects on the elastic properties of miniature monolithic SiC tubular specimens☆

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ABSTRACT

The initial results of a post-irradiation examination study conducted on CVD SiC tubular specimens irradiated under a high radial heat flux are presented herein. The elastic moduli were found to decrease more than that estimated based on previous studies. The significant decreases in modulus are attributed to the cracks present in the specimens. The stresses in the specimens, calculated through finite element analyses, were found to be greater than the expected strength of irradiated specimens, indicating that the irradiation-induced stresses caused these cracks. The optical microscopy images and predicted stress distributions indicate that the cracks initiated at the inner surface and propagated outward.

The high temperature strength, chemical inertness, and stability under neutron irradiation make stoichiometric, crystalline silicon carbide (SiC) an attractive choice for nuclear applications. Although SiC has been used for nuclear application since the 1960s, it is now being considered for several new applications such as fuel cladding systems and channel boxes in light water reactors (LWRs) [1,2], as well as for components in advanced fission reactors [3–8] and future fusion energy systems [9,10]. Deployment of SiC for these applications will require extensive evaluation and assessment of the mechanical properties of the SiC components in different shapes such as tubes, rectangular pipe, flat disks, etc.

Recently experiments were conducted with the purpose of understanding radiation effects on SiC tubular specimens irradiated with representative LWR temperatures and heat flux. The experiment involved irradiating miniature SiC tubular specimens for one cycle in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. The details of the study are provided in Petrie et al. [11] and briefly summarized below. The work presented herein describes the effects of neutron irradiation under a high radial heat flux on the elastic properties of CVD SiC tubular specimens.

The study presented herein evaluates 7 monolithic CVD β-SiC tubular specimens with and without exposure to reactor radiation. The material was obtained from The Dow Chemical Company. The nominal specimen dimensions are 8.5 mm outer diameter, 7.1 mm inner diameter, and 16 mm length. The specimens were irradiated in the HFIR to a total fast neutron fluence of 2.4×10^{25} n/m^2 ($E > 0.1$ MeV) during one reactor cycle that lasted a total of 25 days. The specimens were placed inside an irradiation capsule specifically designed to achieve a constant cladding surface temperature despite swelling of the cladding tubular specimens [11].

As shown in Fig. 1, the irradiation capsule consisted of a molybdenum heater (dense gamma absorbing cylinder) at the center which generated a heat flux of approximately 0.6 MW/m^2 at the outer surface of the cladding. The outside of the specimen was

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Fig. 1. Cross-section of assembled rabbit capsule (left) [11] and a CVD SiC tubular specimen (right).

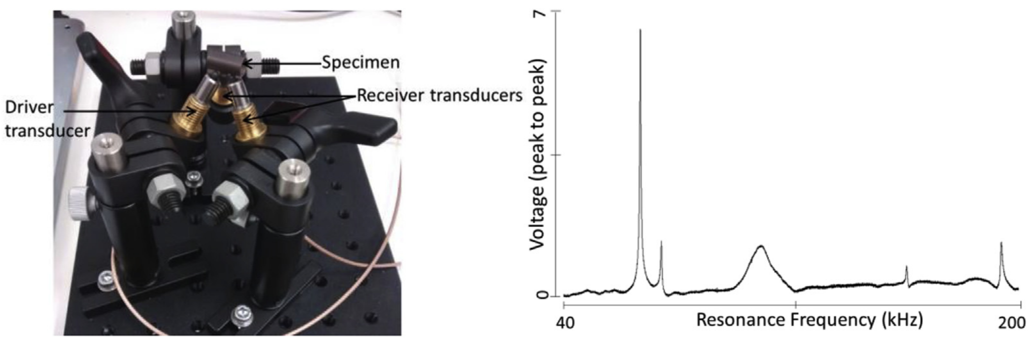

Fig. 2. Specimen placed on the RUS transducers to obtain experimental spectra (left). Frequency spectrum of a CVD SiC specimen (right).

Table 1
Elastic modulus values for CVD SiC tubular specimens evaluated using RUS.

Specimen	Elastic modulus (non-irradiated) (GPa)	Poisson's ratio (non-irradiated)	Elastic modulus (irradiated) (GPa)	Poisson's ratio (irradiated)
1	444.69	0.125	399.66	0.105
2	435.62	0.105	[a]	[a]
3	432.14	0.093	[a]	[a]
4	439.40	0.113	[a]	[a]
5	444.12	0.121	[a]	[a]
6	440.62	0.118	[a]	[a]
7	442.19	0.124	400.84	0.126

[a] Specimen not available after irradiation.

surrounded by an aluminum sleeve, an embossed aluminum foil, and an aluminum housing, which is directly cooled by the reactor primary coolant. The embossed foil allowed the specimen to swell under irradiation while maintaining good thermal contact between the sleeve and the housing. The sleeve prevents large circumferential temperature variations on the outer surface of the cladding due to the periodic contact that would otherwise exist between the cladding and the foil. The gap between the heater and specimen was kept large enough to prevent any hard contact between them during irradiation. The irradiation temperature was estimated to be 300–350 °C based on finite element analyses (FEA) [11]. The FEA results were validated using passive SiC temperature monitors located inside the molybdenum heaters [12].

The specimens were assumed to be isotropic. The elastic moduli and Poisson's ratios of the irradiated and non-irradiated specimens were evaluated by fitting the resonant frequencies computed using FEA to the resonant frequency data measured using Resonant Ultrasound Spectroscopy (RUS). The elastic modulus and Poisson's ratio were systematically varied until the predicted resonant frequencies matched the experimental measurements. The resonance frequencies for the specimens were measured using a Magnaflux RUS System™ (Magnaflux Quasar, ITW Magnaflux, Glenview, IL), as shown in Fig. 2. Five spectra were taken for each specimen in the frequency range of 1–400 kHz. The Block Lanczos iterative algorithm was used to compute the resonance frequencies numerically. The first 19 vibrational modes were used for the fit.

Table 1 shows the elastic properties obtained for each of the specimens. The mean Young's modulus and Poisson's ratio for all the specimens are 439.8 GPa and 0.114 respectively, and the corresponding standard deviations are 4.6 GPa and 0.012, respectively. These elastic properties agree with the generally reported values in the literature [13,14]. The elastic modulus of the irradiated specimens 1 and 7 were found to be 399.7 GPa and 400.8 GPa, indicating a 10.1% and 9.3% reduction in the elastic modulus, respectively, due to irradiation. The computed Poisson's ratio for specimen 1 is shown to decrease, while the Poisson's ratio for specimen 7 shows