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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.

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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).

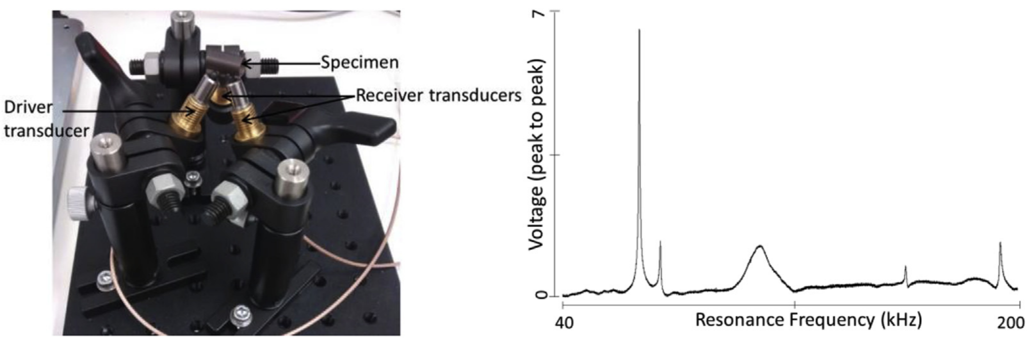

Fig. 2. Specimen placed on the RUS transducers to obtain experimental spectra (left). Frequency spectrum of a CVD SiC specimen (right).

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

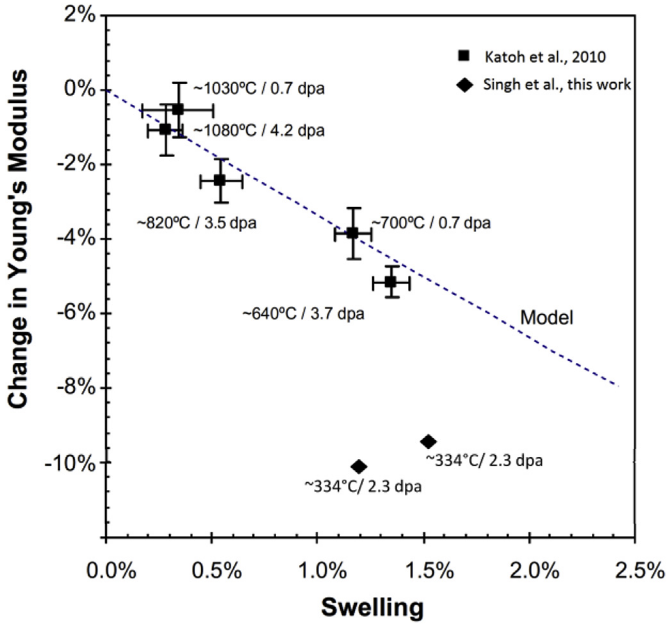

Fig. 3. Variation of elastic modulus with volumetric swelling [15]. Dashed line indicates prediction of modulus decrease by uniform lattice swelling based on Tersoff model. Temperatures shown for the specimens used in this work are outer surface temperatures estimated using finite element analysis [11].

no significant changes due to irradiation.

The volumetric swelling for specimens 1 and 7 are 1.17% and 1.53%, respectively, based on linear swelling measurements [11]. As shown in Fig. 3, the decrease in elastic moduli of specimens 1 and 7 due to irradiation is greater than the expected value based on a previous study using CVD SiC plates [15]. In this earlier study, the decrease in the elastic modulus was reported to be caused by lattice swelling. The greater-than-expected decrease in elastic modulus indicated the possibility of cracks in the irradiated specimens.

Both non-irradiated and irradiated specimens were mounted in epoxy and cut into ring-shaped slices at different axial distances using a low-speed saw. The optical microscopy images of the slices reveal the presence of cracks in the irradiated specimens, with some cracks originating from the inner surface and terminating halfway through the thickness, as shown in Fig. 4. No cracks were observed for non-irradiated specimens. The microscopy images did not reveal any signs of molybdenum and SiC reaction on the inner surface of the specimen.

Multiphysics thermomechanical modeling of an irradiated CVD specimen shows that the stress level reached over 220 MPa at the inner surface (see Fig. 4). The Weibull characteristic strength of non-irradiated miniature CVD SiC tubular specimens has been reported to be 312 MPa and 488 MPa with Weibull moduli of 9.7 and 5.0, respectively [18]. A significant deterioration has been reported in the strength of CVD SiC due to irradiation: decreases of 40–60% have been reported [19–21] for the dose levels to which the specimens in this study were subjected (2.3 dpa). Therefore, it is inferred that the strength of the irradiated specimens was low enough for irradiation-induced stresses to initiate cracks in the specimens.

If a hard contact had occurred between the molybdenum heater and SiC specimen, the resulting stress build-up might have contributed to the crack initiation. However, the authors believe that heater-specimen contact did not occur during irradiation. The reason is that the gap between the heater and specimen was kept large enough to not allow heater-specimen contact even after the thermal expansion and swelling of the heater during the irradiation. The coupled thermal-structural design analyses [11] predict a heater-cladding gap of 10 μm during irradiation. All as-inspected component dimensions were within the bounds of the design analyses. The analyses are also corroborated by the fact that molybdenum heater fell right out of the specimens during the disassembling of the irradiation capsule.

The investigation presented herein was enabled using RUS, which is a nondestructive evaluation technique suitable for post-irradiation examination of miniature SiC tubular specimens. It was found that the elastic moduli of CVD SiC tubular specimens were degraded due to the combination of radiation damage and a high radial heat flux. The greater-than-expected decreases in elastic moduli were attributed to irradiation-induced cracks in the specimens. The microscopy images and predicted stress distributions in the specimens, obtained through multiphysics modeling, indicate that the cracks initiated at the inner surface of the CVD tubular specimens and propagated outward. Considering the stress level in the specimen and the significant deterioration of strength of CVD SiC during irradiation, it was inferred that the irradiation-induced stresses were the cause of cracking in the tubular specimens. This is a significant finding, as there is no published work on the experimental validation of the damage of monolithic SiC tubular specimens under irradiation with a through-thickness temperature gradient.

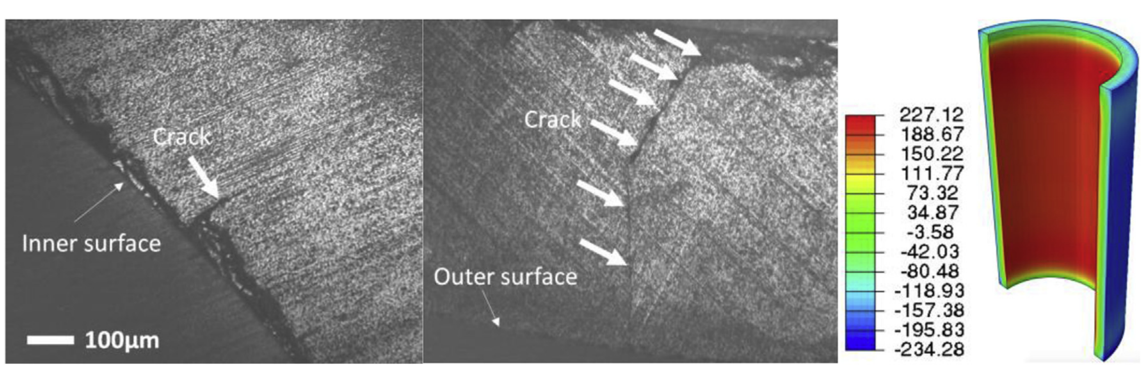

Fig. 4. Cross-section of irradiated specimen slices showing cracks (left). Hoop stress (MPa) distribution in a CVD specimen (right) at room temperature determined through multiphysics modeling; negative stresses are compressive. Details on the computational framework employed for multiphysics modeling are presented elsewhere [16,17].

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