Dimensional stability and anisotropy of SiC and SiC-based composites in transition swelling regime

Yutai Katoh a,b, *, Takaaki Koyanagi a, Joel L. McDuffee a, Lance L. Snead c, Ken Yueh d

a Oak Ridge National Laboratory, Oak Ridge, TN, USA
b University of Tennessee, Knoxville, TN, USA
c Massachusetts Institute of Technology, Cambridge, MA, USA
d Electric Power Research Institute, Charlotte, NC, USA

A R T I C L E   I N F O
Article history:
Received 28 September 2017
Received in revised form 23 November 2017
Accepted 6 December 2017
Available online 8 December 2017

A B S T R A C T
Swelling, or volumetric expansion, is an inevitable consequence of the atomic displacement damage in crystalline silicon carbide (SiC) caused by energetic neutron irradiation. Because of its steep temperature and dose dependence, understanding swelling is essential for designing SiC-based components for nuclear applications. In this study, swelling behaviors of monolithic CVD SiC and nuclear grade SiC fiber–SiC matrix (SiC/SiC) composites were accurately determined, supported by the irradiation temperature determination for individual samples, following neutron irradiation within the lower transition swelling temperature regime. Slightly anisotropic swelling behaviors were found for the SiC/SiC samples and attributed primarily to the combined effects of the pre-existing microcracking, fiber architecture, and specimen dimension. A semi-empirical model of SiC swelling was calibrated and presented. Finally, implications of the refined model to selected swelling-related issues for SiC-based nuclear reactor components are discussed.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction
Silicon carbide (SiC) and its continuous fiber-reinforced ceramic matrix composite form (i.e. SiC/SiC composites) are considered for use in the current and next generation nuclear power systems. Specific applications under considerations include fuel assembly components, core internal and other in-vessel components of light water reactors [1,2], control rod drive components and hanger straps for high temperature [3] and very high temperature reactors [4], cladding and other components of the gas fast reactors [5–7], core barrel, internals and control rods of molten salt reactors [8], fuel cladding of sodium fast reactors [9], non-sodium liquid metal reactors [10], and fusion reactors [11]. The attractiveness of SiC/SiC composites for nuclear applications relies on the inherent properties of SiC [12] and the engineered features of the continuous fiber composites [13].

SiC in a stoichiometric and crystalline form offers a combination of outstanding high temperature strength, chemical inertness, radiation tolerance, neutron transparency, low activation/low decay heat, and reasonable thermal conductivity [14]. The inclusion of continuous fibers provides reasonable fracture toughness to the material while ensuring a statistically reliable failure mode thus insuring against catastrophic failure [13]. Moreover, the continuous fibers (or other secondary reinforcing SiC materials) can be considered an engineered isotropic or anisotropic inclusion determined based on the application need. The SiC/SiC composites presently considered and most widely studied are the specialty industrial materials that have been optimized and are commercially available from independent suppliers.

Swelling, or dimensional expansion in a stress-free environment (i.e. not irradiated in a constrained or stressed state), is an important radiation-induced phenomenon for SiC. Swelling at

* This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

* Corresponding author. Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6134, USA.
E-mail address: katohy@ornl.gov (Y. Katoh).
temperatures between the amorphization threshold (~150 °C) and the onset of radiation-induced void contribution (~1000 °C) is referred to as either the transient swelling, point defect swelling, or intermediate temperature regime swelling in the literature. Importantly, this regime corresponds to the design space for most nuclear applications [15]. Mechanistically, the lower temperature bound for the transient swelling has been linked to long range migration of Si self-interstitial atoms (SIA), whereas the upper temperature bound is likely determined by the long range migration of Si vacancies. In magnitude the transient swelling of SiC accumulates at a rate (dpa⁻¹) depending on the irradiation temperature and dose until it reaches a saturation value that is a function of irradiation temperature [15]. Approximate magnitudes of saturation volumetric swelling are ~2% at 300 °C and ~0.7% at 800 °C [12,15]. Recent experiments showed that this swelling remains saturated at least up to a dose of ~70 dpa [16].

The transient swelling phenomenon often raises serious design challenges for use of SiC for nuclear application, because of its magnitude and dependence on irradiation temperature and neutron dose. A well-discussed, notable example is the “inverse thermal stress” in SiC-based fast fuel claddings and other applications in which a steep temperature gradient is inevitable [17]. Because of the negative temperature dependence of swelling, an internal stress is developed in the opposite signs from the usual secondary stress arising from the normal thermal expansion. The magnitude of the temperature dependent coefficient of linear saturated swelling of SiC exceeds its coefficient of linear thermal expansion within the transient swelling temperature regime. Because of this, for the SiC fuel cladding, the secondary stress is tensile toward the inner surface where temperature is higher and compressive toward the outer surface that is in contact with the coolant (once the swelling gradient over-compensates the thermal expansion gradient) [18,19]. The highest secondary stress occurs during the reactor outage, when the temperature gradient disappears but the swelling gradient does not.

Another example of the important design issues due to SiC swelling is the proposed accident-tolerant channel boxes made of SiC/SiC composite for the boiling water reactors (BWRs) [20]. For the fuel assemblies located at the periphery of the core, there will be significant horizontal (and axial) gradients in neutron fluxes. Lateral swelling gradients expected to occur before swelling reaches the saturation due to the presence of neutron flux gradients may result in significant bending for the SiC/SiC channel boxes, potentially causing interference with the reaction control and the coolant flow.

Based on the needs to better understand the quantitative aspects of SiC swelling, the present work is intended to establish the absolute swelling as a function of the irradiation temperature and the displacement damage level in a convenient form for the thermo-mechanical modeling and analysis of SiC-based nuclear components and structures. A precise mapping is attempted for swelling of the ideal quality SiC in the polycrystalline beta-phase monolithic form and the reference nuclear grade SiC/SiC composites. In addition, the anisotropy in swelling is studied in details for the SiC/SiC composites.

2. Experimental procedure

2.1. Materials

The monolithic material used was chemical vapor deposition (CVD) SiC from Rohm & Haas, Advanced Materials (presently PremTech Advanced Ceramics, Worcester, Massachusetts). High resistivity Grade SC-001 was chosen for its high purity (<5 mass ppm total metallic impurities) and the nitrogen-free chemistry. The measured room temperature thermal conductivity ~380 W/m-K confirms the high chemical purity and total crystallinity of this material.

In addition to the CVD SiC, three different SiC/SiC composites of nuclear grade were used in this study. A Hi-Nicalon™ Type S (HNS) SiC fiber (NGS Advanced Fibers, Toyama, Japan), pyrocarbon (PyC) interphase of nominally 100 nm thickness, chemical vapor infiltrated (CVI) SiC-matrix composite coupons were machined out of a prototypical SiC/SiC channel box manufactured by Hyper-therm High Temperature Composites, Inc. (presently Rolls-Royce High Temperature Composites, Huntington Beach, California). The prototypical channel box was a rectangular cross-section tube with dimensions of roughly 100 mm x 100 mm x 300 mm and a wall thickness of 1.5 mm. It consists of four fabric layers: two layers of 0°/90° orthogonal 8-harness satin-woven fabrics sandwiched between a pair of 0°/±60° tri-axially braided layers. Details of this material is given elsewhere [20]. This material is denoted as HNS-CB hereafter.

The other two composite materials were nominally PyC interphase, CVI SiC-matrix composites with HNS or Tyranno-SA3 (Ube Industries, Ube, Japan, SA3 hereafter) 5-harness satin-weave, 0°/90° løy-up reinforcement in a form of flat plate measuring 150 mm x 150 mm x 2 mm. These materials were also fabricated by Rolls-Royce High Temperature Composites, Inc. The PyC interphase thickness was chosen to be 100 nm for HNLS and 300 nm for SA3 to achieve the optimum mechanical properties for the fiber surface roughness. Descriptions for these SiC/SiC plates are found elsewhere [21]. The materials are denoted as HNS-SW and SA3-SW in this article. The materials used in the present study are summarized in Table 1.

2.2. Neutron irradiation

Specimens of the materials above were irradiated in the High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (Oak Ridge, Tennessee), using the Flux Trap irradiation facility. The fast neutron flux at the specimen locations were ~1 x 10^{16} n/m²/s. The equivalence of 1 dpa in SiC with a fast fluence 1 x 10^{16} n/m² (E > 0.1 MeV) is assumed hereafter. The irradiation vehicles were designed for temperatures of 260 °C or 280 °C. The conditions of irradiation are summarized in Table 2.

2.3. Dimensional measurement

Dimensional measurements were performed to an equipment accuracy of less than ~1 μm before and after irradiation. On-site intermittent calibration measurements using certified gauge blocks were incorporated in the standard measurement procedure to assure the absolute accuracy. A digital micrometer was used for the width and thickness measurements, whereas a high precision digital jaw gauge was used for the length measurements. The overall accuracy of these envelope dimensions measurements is determined mainly by the equipment accuracy, a specimen misalignment during measurement, and the specimen distortion factors such as the parallelism and the very slight bending. In addition to measurements of the specimen dimensions, physical markings were engraved using a micron laser near the corners of rectangular coupon specimens so that the distance between the markings may be measured with Keyence VHX-1000 digital microscope with a precision stage that offers a 0.1 μm positioning accuracy. In practice, accuracy of this distance measurement, limited by the operator’s ability to visually locate the reference measurement points on the microscope screen, is considered to be within a few μm.

The absolute dimensional measurement accuracy of ±0.5 μm
translates into the swelling measurement accuracy due to the instrument reading error of ±0.002% for 25 mm-length, ±0.011% and ±0.018% for 4.5 mm and 2.8 mm-length, respectively, and ±0.037% and ±0.050% for 1.35 mm and 1.0 mm-thickness, respectively.

2.4. Thermometry

Temperatures of irradiation were determined for individual specimens. In doing so, the SiC and SiC/SiC specimens were subjected to the dilatometry-based post-irradiation thermometry following completion of the swelling measurement. We estimate the absolute accuracy of irradiation temperature determination about ±10°C with the specimen length 25 mm in the temperature range of ~300°C. Details of the thermometry method used are found in Ref. [22]. Approximately 1/3 of the irradiated specimens were measured when the irradiation temperatures were confidently determined for most of the specimens based on the dilatometry results and the calculated temperature distribution within the capsules using a three-dimensional finite element modeling. The maximum range of specimen temperature distributions within a capsule was 40–60°C.

3. Results

Results from the measurements of specimen envelope dimensions are plotted in Fig. 1. The linear swelling values from the digital microscopy measurements appeared to generally be in excellent agreement but randomly deviated from those determined by the specimen envelope dimensions with the average absolute deviation ~3 μm. Therefore, results from the envelope dimensions measurements are reported and analyzed hereafter. In Fig. 1, the fractional dimensional changes are shown separately for length, width, and thickness of the SiC/SiC composite coupon specimens. Isotropy was confirmed for the CVD SiC swelling; therefore the length swelling data are plotted in the width and the thickness plots for CVD SiC so that the most accurate data are presented.

The labels HNS-CB Transverse and Axial denote that the specimen length is in parallel with the transverse and axial orientations of the original prototypical channel box, respectively. There found no detectable difference in swelling behavior between the transverse and the axial specimens. Both orientation specimens have nominally identical outer fabric layers that are orthogonally symmetric in terms of the fiber architecture, whereas the inner triaxially braided fibers are oriented 0°/±60° in the axial specimens and ±30°/90° in the transverse specimens.

In general, the length swelling trend follows the previous understanding, monotonically increasing with dose likely following the 2/3 power law until saturated. The apparent dip at 1 dpa is an artifact caused by the higher temperature of irradiation that happened to this particular capsule. No significant difference is
found between the CVD SiC swelling and the SiC/SiC composite length swelling (not shown in Fig. 1) with an exception of the data at 11.8 dpa where the HNS-SW length swelling is smaller than the CVD SiC swelling to a slight yet statistically significant extent.

From Fig. 1, disagreement in linear swelling magnitude among length, width, and thickness of the composite specimens is apparent. In fact, the width swelling is clearly smaller than the length swelling for the composite specimens, and the thickness swelling appeared even smaller and sometimes negative meaning contraction. There is no difference between the transverse and the axial composite specimens in either length or width swelling, indicating the in-plane swelling anisotropy (i.e., length vs. width) is not because of the material anisotropy but an effect of specimen dimension. It is also noted that the reduced swelling in the composite width and thickness accompanies an increased data scatter, with the scatter of length swelling being smallest and that of thickness swelling being the most significant.

The post-irradiation thermometry results are plotted in Fig. 2 against the length swelling of the same specimen. Swelling and irradiation temperature are negatively correlated with each other as expected, and the correlation is more obvious at higher dpa levels but is not at 0.03 dpa. Note that the determination of irradiation temperature with the 0.01 dpa specimens was compromised by the small swelling at this low dose thus is not included in this plot.

The data in Fig. 2 indicate significant variations in the irradiation temperature and its significant deviation from the design target temperature for some specimens. A closer look at the plot reveals that a majority of irradiation temperatures fall within or vicinity of the target temperature range (250–310 °C), whereas the other population had experienced irradiation at significantly higher temperatures. It is suspected that such off-target high temperatures had occurred due to an inadequate thermal contact between the specimen and the specimen holder during irradiation.

The dashed lines in Fig. 2 present the temperature dependent linear swelling calculated based on a simple rate theory model [23]. The steeper temperature dependence at a higher temperature in the present data is qualitatively consistent with the model prediction. However, the model needed to be calibrated to fit data from the present work. The model calibration and the application of the calibrated model to analyze the swelling data are discussed in the following section.

4. Discussion

4.1. Swelling model calibration

The model of SiC swelling during irradiation was proposed by Katoh et al. based on a rate theory of point defect diffusion, reactions, agglomeration, and cascade resolution of point defect clusters [23] and calibrated using the limited experimental data of unassured quality [12]. The original model describes the swelling rate by the following equation:

$$\frac{dS}{dt} = k_s y^{-1/3} \exp \left(\frac{-\gamma}{\gamma_C}\right)$$  (1)

Where S denotes swelling, gamma the displacement damage dose in dpa, $k_s$ the rate constant, and $\gamma_C$ the characteristic dose for swelling saturation. The model assumes mobile SIAs freely migrate until reacting with other defects, whereas vacancies and any point defect clusters are immobile. The dose dependence exponent $-1/3$ is for SIAs forming two-dimensional clusters, i.e., extrinsic dislocation loops. The exponent becomes $-2/5$ in case SIAs form three-dimensional clusters. The effective exponent will be between these two because very small SIA clusters likely react with incoming SIAs as the three-dimensional cluster would, then transition to edge dislocation – SIA reactions as the clusters grow into larger loops. However, in the present analysis the assumption of $-1/3$ power law is maintained because the impact of using the alternative exponent is minor.

Equation (1) can be re-written using incomplete gamma function as below, using $k_s'$ as a rate constant related with $k_s$, to give swelling as a function of dose during isothermal irradiation:

$$S = k_s' y^{-2/3} \Gamma\left(\frac{2}{3}, \frac{\gamma}{\gamma_C}\right)$$  (2)

For convenience, this can be approximated by:

$$S = S_3 \left[1 - \exp \left(\frac{-\gamma}{\gamma_C}\right)\right]^{-2/3}$$  (3)

The saturation swelling, $S_3$, and $\gamma_C$ are determined solely by absolute temperature of irradiation and are given by ad-hoc polynomial functions:

$$\gamma_C = \sum_{i=0}^{3} a_i T^i$$  (4)

$$S_3 = \sum_{i=0}^{3} b_i T^i$$  (5)

From the fitting to the present data on length swelling for CVD SiC and CVI SiC/SiC combined, we obtain $a_0 = -0.57533$, $a_1 = 3.3242 \times 10^{-3} \text{ K}^{-1}$, $a_2 = -5.3970 \times 10^{-6} \text{ K}^{-2}$, $a_3 = -2.9754 \times 10^{-9} \text{ K}^{-3}$, $b_0 = 5.8366 \times 10^{-2}$, $b_1 = -1.0089 \times 10^{-4} \text{ K}^{-1}$, $b_2 = 6.9368 \times 10^{-8} \text{ K}^{-2}$, and $b_3 = -1.8152 \times 10^{-11} \text{ K}^{-3}$ for the temperature range 493 K < $T$ < 713 K.

Using these parameters, swelling of SiC during isothermal irradiation is plotted as a function of dose and temperature in Fig. 3. In these plots the range of temperature is expanded to 200–800 °C, significantly beyond the range calibrated with the present data.
However, the trend lines indicate excellent agreement with previously published swelling data for CVD SiC and CVI SiC/SiC at temperatures up to 800 °C [12,15].

4.2. Analyzing normalized swelling and anisotropy

Eqs. (3)—(5) allow the normalization of swelling values to those at a reference temperature when exact temperatures of irradiation are known for individual specimens. This normalization is useful to reduce noise arising from scattered irradiation temperatures so that extended discussion based on improved quality data is enabled. Fig. 4 demonstrates the result of normalizing operation, where each data point presents the linear swelling of an individual specimen corrected to the reference temperature of 300 °C by using the temperature derivative of swelling at the pertinent dose in Fig. 3.

Fig. 4 indeed reveals a few important features that are not obvious in the plot prior to data normalization in Fig. 1. First, the linear swelling behavior is consistent between the CVD SiC and the HNS SiC/SiC length at doses up to at least 2 dpa. However, the SiC/SiC length swelling exhibits a slight negative deviation from the CVD SiC saturation value at 12 dpa. Second, the normalized data indicate slight yet distinctive discrepancy from the model trend line based on Eq. 3. This discrepancy does not disappear after slightly adjusting the exponent but is dominated by the data points at 0.3 dpa. This implies an inadequate treatment of swelling saturation in the simple model that assumes a linear correlation between the cascade resolution rate and the absolute swelling and/or the lack of non-cascade swelling saturation mechanism. Identification of the exact physical mechanisms contributing to the swelling saturation and a more sophisticated modeling of such mechanisms are required in future research.

The same temperature correction scheme is applied to the SiC/SiC coupon width and thickness changes and the results are plotted in Fig. 5. Data for HNS and SA3 fiber SiC/SiC are plotted together. The dose dependence plot highlights the striking anisotropy in the composite coupon swelling as previously described: in-plane anisotropy due to the dimension effect and the major swelling difference in the thickness orientation from the in-plane swelling ("transverse anisotropy" hereafter). The plot clearly depicts that the composite thickness swelling is significantly smaller than the width swelling that is slightly smaller than the length or CVD SiC swelling in a consistent manner. Moreover, the composite swelling at 12 dpa appears slightly yet consistently smaller than at 2 dpa in all dimensions. However, this reverse trend is not believed to continue progressively, since swelling for a similar HNS SiC/SiC is reported to stay within the range found in this study after irradiation to a dose exceeding 70 dpa [16]. The differences between the HNS and SA3 composites are not statistically significant.

A closer look into Fig. 5 reveals likely slight difference between the CVD SiC and SiC/SiC swellings. Presence of the discrepancy is
not convincing because it is as small as than the standard deviation of data scatter; however, the CVD SiC swelling is nearly always greater than the SiC/SiC length swelling by an average difference of ~0.02%. The gap between the SiC/SiC length and width swellings is roughly 0.1% until it gets wider at doses beyond ~0.3 dpa. The SiC/SiC thickness swelling appears nearly constantly smaller than the width swelling by ~0.2% with larger scatters.

4.3. Origin for composite swelling anisotropy

The swelling difference between the monolithic CVD SiC and HNS CVI SiC/SiC was previously reported. Newsome et al. reported that at 300 °C CVD SiC swelling saturated at ~1.9% whereas the HNS SiC/SiC swelling reaches ~1.7% at 1.2 dpa then reduces to ~1.4% at 3.4 dpa [24]. These SiC/SiC swelling data are considered less reliable because of the reported large measurement error and the lack of information of the method of measurement. However, the reported trends are qualitatively consistent with the present observations.

Possible explanations for the smaller overall swelling for SiC/SiC than monolithic CVD SiC include 1) the effect of differential swelling between SiC-based fibers and CVD or CVI SiC, 2) presence of the PyC interphase, and 3) matrix microcracks pre-existing in the as-fabricated SiC/SiC. Kondo et al. reports contraction of the HNS fibers as opposed to swelling of CVD SiC matrix after self-ion irradiation to ~100 dpa at 300 °C [25]. To examine the potential fiber-matrix differential swelling, the side surface profile of HNS SiC/SiC was compared before and after irradiation by a through-focus operation of Keyence VHX-1000 digital microscope with a focus step of 1–2 µm. As shown in Fig. 6, the cross-section indicates significant recession at the locations of fiber tows, confirming the reduced swelling for HNS fibers. In fact, the dip depth at the fiber tow areas increases from 5 to 10 µm at 2 dpa to as much as 40 µm at 11.8 dpa, consistent the reverse swelling phenomena observed between the two doses. Therefore, it is reasonable to consider this as the mechanism contributing to the reverse swelling. However, the fiber-matrix differential swelling does not explain the in-plane swelling anisotropy.

It is plausible that the PyC interphase undergoes contraction during irradiation [26]. A combination of the nominal PyC thickness 100 nm, fiber volume fraction at 40%, and fiber diameter 11 µm gives the PyC volume fraction ~1.5%. When PyC is assumed to contract by maximum of 5% in volume during irradiation, per analogy to nuclear graphite, the maximum contribution to composite volume is estimated to be ~0.07%. Therefore, it is possible for the irradiation-induced PyC contraction to contribute to the reduced swelling for SiC/SiC. However, this mechanism also does not explain the in-plane swelling anisotropy, either.

The CVI SiC/SiC composite contains fairly high density of matrix microcracks in the as-fabricated and as-machined conditions, as shown in Fig. 7. Such a microcracked matrix is capable of absorbing swelling until the cracks become closed, in analogy with the irradiation-induced contraction mechanism for nuclear graphite [27]. This mechanism may explain the in-plain swelling anisotropy, because the pre-existing microcracks may be more open in an orientation of the smaller dimension due to reduced mechanical constraint by the reinforcing fibers. Moreover, such a microcrack closure mechanism better explains the constant swelling gaps at different doses since the other two mechanisms should result in dose-dependent swelling gaps. The transverse anisotropy of swelling may also be explained by the same mechanism because the SiC/SiC composites in fabric lay-up architectures do not contain fibers to constrain the interlaminar-cracked matrix in the thickness orientation.

4.4. Implications on example designs

In this section implications of the present results are briefly discussed using specific examples of the SiC/SiC channel box and the SiC-based duplex fuel cladding.

Channel box: In the reactor core, significant gradients in the fast neutron flux are present both axially and horizontally. The horizontal fast flux gradient is most significant at the periphery of the core, where a bending of the SiC/SiC channel box is anticipated during the swelling builds up at different rates. In fact, a neutronic model analysis for a certain commercial BWR indicates approximately 20% difference between the two sides of a fuel assembly located at the core outer edge. In Fig. 8, the swelling differences between the two parallel faces of a channel box under 3 different fast flux gradient cases are shown as a function of the mid-plane dose. This calculation indicates the peak differential swelling occurring at the dose ~0.1 dpa. Under a 20% flux difference, the peak difference in linear swelling is estimated to be ~0.035%. If the channel box is allowed to freely deform and a 100 mm edge length is assumed for a square cross-section box, this differential swelling corresponds with a axial curvature radius ~285 m. Although there exist significant axial flux gradients in the actual reactor cores, when the full length (~4 m) channel box axially bends at this constant radius with both ends horizontally fixed, the theoretical maximum mid-point displacement of ~7 mm is expected laterally. This extent of deformation is close to or slightly exceeding the maximum allowable bow in the peripheral region of the BWR. More detailed analysis is required to address the issue of potential interference of this deformation with the control blades, since the SiC/SiC channel box deformation is transitional (as compared to the progressive bowing of the zirconium alloy channels), non-uniform along length, and non-monotonic against time.

Duplex cladding: Even though the relative swelling is very similar for composite and monolithic SiC, given the relatively large Young’s modulus for SiC and three-dimensional constraints in small diameter LWR fuel cladding, the differential swelling should be considered in analyzing the stress states. Here a simple exercise is performed to obtain the first-order estimate for effects of the
differential composite-to-monolith swelling on the stress states in hypothetical duplex (composite-monolithic dual layer) fuel cladding with the results shown in Fig. 9.

In this simplified model, the composite layer undergoes slightly reduced linear swelling than the monolithic layer while the fully-bonded bilayer structure swells uniaxially and uniformly. The relative elastic strains in the monolithic and composite layers, $\varepsilon_m$ and $\varepsilon_c$, respectively, are given below regardless of the magnitude of

---

**Fig. 6.** Surface profilometry on the side face of HNS SW SiC/SiC composite before and after neutron irradiation. The height maps (left) indicate significant recess in the fiber bundle regions after irradiation regardless of fiber orientation. The line profiles (right) show significant increase in magnitude of fiber recession as dose increases from 2 dpa to 11.8 dpa.

**Fig. 7.** Examples of pre-existing matrix microcracks (shown by arrows) in as-fabricated H-Nicalon Type S, CVI SiC matrix composite.

**Fig. 8.** Differential swelling between two parallel faces of SiC/SiC channel box under gradients of fast neutron flux.
5. Conclusions

Swelling of monolithic CVD SiC and nuclear grade SiC/SiC composites has been determined with unprecedented accuracy following neutron irradiation at LWR-relevant temperatures. The measurement accuracy is further supported by accurate sample irradiation temperature measurements made on individual samples. Using these data, a model for SiC transient swelling was calibrated to the highest accuracy presently achievable.

Examination and analysis of the swelling data lead to the following findings:

1) SiC/SiC in-plane swelling is close to but may very slightly be smaller than monolithic SiC swelling.
2) SiC/SiC in-plane swelling is susceptible to the specimen dimension effect.
3) SiC/SiC thickness swelling is consistently and significantly smaller than monolithic SiC swelling.

These deviations in swelling behavior for SiC/SiC from that for monolithic SiC may be reasonably attributed to the fiber-matrix differential swelling and the pre-existing matrix microcracks. The fiber-matrix differential swelling was experimentally confirmed. Note that these apply to nuclear grade SiC/SiC composites with 2D fabric lay-up or similar architectures and CVI SiC matrix.

The calibrated model and the monolith-composite differential swelling data from the present work may be useful to estimate the magnitudes of swelling-related issues for SiC-based nuclear reactor components such as the channel box deformation and the stress evolutions in layered fuel cladding.

Acknowledgment

This research was supported by the Electric Power Research Institute under contract NFE-13-04618 and the United States Department of Energy (DOE) Office of Nuclear Energy and Office of Fusion Energy Sciences under contact DE-AC05-00OR22725 with Oak Ridge National Laboratory (ORNL) managed by UT Battelle, LLC. A portion of this research used resources at the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by ORNL. This work also used resources at the Low Activation Materials Development and Analysis (LAMDA) Laboratory at ORNL. The authors would like to thank Nicholas Brown for useful discussion, Mary Snead for coordinating project, and Gyanender Singh and Bill Wiffen for valuable comments to this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jnucmat.2017.12.009.

References


Fig. 9. The effects of differential swelling between composite and monolithic layers on uniaxial stresses in SiC/SiC – SiC duplex fuel cladding structure. The horizontal axis is thickness of the monolithic layer relative to the total wall thickness. A composite–monolith Young’s modulus ratio 2:3 was assumed.

\[
\frac{e_c}{e_m} = \frac{t_m E_m}{t E_c}
\]
Hi-nicalon Type-s CVI SiC Composite Irradiated to 70 Dpa at Elevated Temperatures, ORNL/TM-2012/459, Oak Ridge National Laboratory, 2012.


