

Damage Progression and Failure of SiC/SiC Composite Tubes under Hard-Contact Radial Expansion

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Abstract

The response of silicon carbide (SiC) fiber-reinforced SiC matrix (SiC/SiC) composite cladding to mechanical interaction with fissile fuel is a knowledge gap that must be overcome to design and assess SiC-based cladding systems for advanced nuclear applications. This study developed the relevant mechanical testing capability and identified the failure behavior and the critical microstructural features and processing defects. Sections of SiC composite tube were subjected to a modified expansion-due-to-compression (EDC) test in an X-ray computed tomography microscope: a polyurethane plug pressed surrogate Al_2O_3 into the inner walls of the SiC/SiC composite tubes to achieve hard contact. A pure EDC test with just a polyurethane plug was also performed as a reference. Through the use of displacement fields, digital volume correlation revealed inhomogeneous deformation fields in the tubes, even for pure EDC, which was related to the inherent defects in the structure. Deep learning-aided segmentation and systematic data analysis revealed that the presence of inhomogeneous deformation applied by the hard contact was exaggerated by the presence of inner surface imperfections left behind from the matrix densification process. The findings provide insights into the applications, highlighting the necessity for improvements in inner surface roughness and the incorporation of localized contacts in pellet-cladding mechanical interaction computational models.

1. Introduction

After the Fukushima Daiichi nuclear accident, motivation to develop accident-tolerant fuel (ATF) tubes led to the investigation of interim and long-term solutions. The near-term solution involved using current fuel tubes with protective coatings that minimize steam oxidation of the zirconium-base tube during transients, thereby reducing highly reactive hydrogen release [1, 2]. While near-term solutions are in place, the long-term solution moves toward drastically reducing or eliminating the steam oxidation by using steam-oxidation-resistant iron–chromium–aluminum (FeCrAl) alloys or silicon carbide (SiC) fiber-reinforced SiC matrix (SiC/SiC) composites with extended load-carrying capability [2, 3]. The FeCrAl alloys benefit from alumina formation, which drastically reduces steam oxidation during transient conditions [4]. However, these alloys suffer from the formation of brittle second-phase particles under neutron irradiation and a neutronic penalty compared to zirconium-based alloys. More research is needed to find ways to extend their deformability under irradiation and guarantee operational safety [5].

High purity SiC poses as an attractive cladding candidate for these applications. It has a low coefficient of thermal expansion, high strength retention at high temperatures ($>1500\text{ }^{\circ}\text{C}$) [6], low chemical reactivity [6, 7], high steam oxidation resistance [2, 8], and high stability under neutron irradiation [9] with swelling saturation up to 100 dpa [7, 10]. However, monolithic SiC is extremely brittle and can fail catastrophically and unpredictably under mechanical deformation (e.g., fuel swelling).

Further load-carrying capability above the proportional limit strain is attainable while preserving the initial geometry once SiC is engineered as a SiC/SiC composite [3, 11], which is commonly a

SiC continuous-fiber reinforced SiC matrix structure. However, the residual porosity from the matrix infiltration process makes the SiC/SiC composite permeable to both gases and liquids. Therefore, to enable applicability as a cladding candidate, a monolithic layer of SiC is deposited to hermetically seal the inside, outside, or both sides of the composite tubing [11, 12].

Fiber-reinforced composite structures are designed to have a pseudo-ductile failure mode with more predictable fracture kinetics (due to highly oriented fibers) and significantly improved damage tolerance compared with monolithic SiC [13, 14]. Still, significant efforts are required for this lower technological readiness level (TRL) research although this composite family has advanced manufacturing readiness level for nuclear [15-17].

The low TRL challenges are mostly related to operational feasibility, such as corrosion under certain light-water reactor (LWR) water chemistries [18, 19], dimensional stability [20, 21], and microcracking under power cycles and fuel-driven straining [22, 23]. In particular, the microcracking may result in a loss of hermeticity of the tube and affect mechanical integrity during reactivity insertion transients, reactor start-ups/shut-downs, and power ramps [22]. In one study, failure of the inner monolith was reported to occur at 140 MPa (hoop stress), but permeability loss has been documented as early as 60 MPa where nominal operating pressures were reported to be in the 15–20 MPa range [11].

Under all these conditions, the SiC/SiC tube is expected to be deformed by the nuclear fuel where the fuel tube gap can close, depending on the initial fuel-cladding gap thickness above burnup levels of 10 GW-Day-per-ton (GWD/t), with an assumed gap similar to those used with zircalloy claddings. The mechanical behavior of SiC/SiC that mimics the strain-driven conditions

have been investigated using plug expansion tests, such as expansion-due-to-compression (EDC) tests [11, 24-27] or dissimilar internally pressurized tubes (modified burst tests) [22]. In most cases, a SiC/SiC composite is expected to have a unique failure behavior, depending on the SiC fiber architecture and the loading path. It exhibits nonlinear mechanical behavior [28] related mainly to the formation of microcracks under deformation [29] wherein a fracture event can occur at the most critical flaw (e.g., pores between tows [30]). Considering that these studies are performed under uniaxial tensile deformation (a relatively uniform deformation mode), this condition is further complicated by the hard contact between the fuel and the cladding under operational scenarios.

Advanced microstructural characterization with high-resolution X-ray computed tomography (XCT) plays an important role in deconvoluting the complex deformation and failure mechanisms in these composites. Previously, XCT was employed to help identify crack formation and propagation, toughening mechanisms, and the effect of pores on crack propagation and blunting in SiC/SiC composites by employing in-situ loading [28-32].

However, for potential nuclear applications another equally important aspect of deformation is the fuel-clad interactions. In a swelling scenario, the fuel becomes a deforming medium, which, by expansion, applies deformation to the cladding. In this study, we used in-situ XCT to investigate the microscopic failure characteristics of the SiC/SiC tubes that were subjected to strain-driven deformation via hard-contact expansion imitating nuclear fuel expansion at low speeds. The objectives of this work were to develop a mechanical test method relevant to pellet-clad mechanical interaction (PCMI) of SiC/SiC composite tubes, to identify the failure process of

the composite and key processing defects for improvement of manufacturing, and to provide feedback to fuel performance models. Identical samples tested with soft-contact expansion using a polyurethane plug helped differentiate the sample-related inhomogeneities in deformation and emphasize the effect of hard contact on the observed failure behavior.

2. Experimental Details

2.1. SiC/SiC composite samples

Composite tubes of chemical vapor infiltrated (CVI) SiC matrix reinforced with continuous Hi-Nicalon Type-S SiC fibers coated with pyrolytic carbon were used for this study and provided by General Atomics (Sample ID: 1909OR028-19). The material grade was the same as the one used in the previous study involving mechanical testing under steam [33]. The SiC/SiC composite tube possessed a duplex structure with an outer monolithic SiC coating (~40% of the total thickness). The nominal fiber volume fraction of the overall engineered structure (composite layer and monolithic layer) was approximately 20%. The inner surfaces were coated with a thin SiC layer, and no fibers were exposed on the inner and outer surfaces. A total porosity of approximately 6.3 vol % was calculated from the segmented XCT data; however, this value is limited to the observed volume and represents a lower limit because pores smaller than about 16 μm cannot be reliably detected at the resolution at which porosity was calculated. It must also be noted that when presenting 3D images on a 2D plane, the perspective can be misleading (i.e., visually pores can appear significantly higher in volume than they are quantitatively). The SiC/SiC composite tubes had an outer diameter of 10 mm and an inner diameter of 8 mm. Typical length of the test specimen was 10 mm.

2.2. In-situ loading studies with XCT

The in-situ test fixture was designed to simulate hard contact between a fuel surrogate and the SiC/SiC composite specimen. Because of its lower X-ray absorption and similar elastic modulus to fresh UO_2 (~ 213 GPa [34]), Al_2O_3 (Machined Ceramics Inc., 99.8% pure) was chosen as the surrogate material. For this testing, the EDC test method was modified to include a high-hardness polyurethane plug (118 durometer) and a two-piece collet (Al_2O_3) design. A steel plunger was used to compress the plug and achieve the EDC effect by pushing the two pieces of the collet toward the inner surface of the section of SiC/SiC composite tube, thereby achieving hard contact. This setup is shown in Figure 1. Three hard-contact and two soft-contact tests were performed within this study.

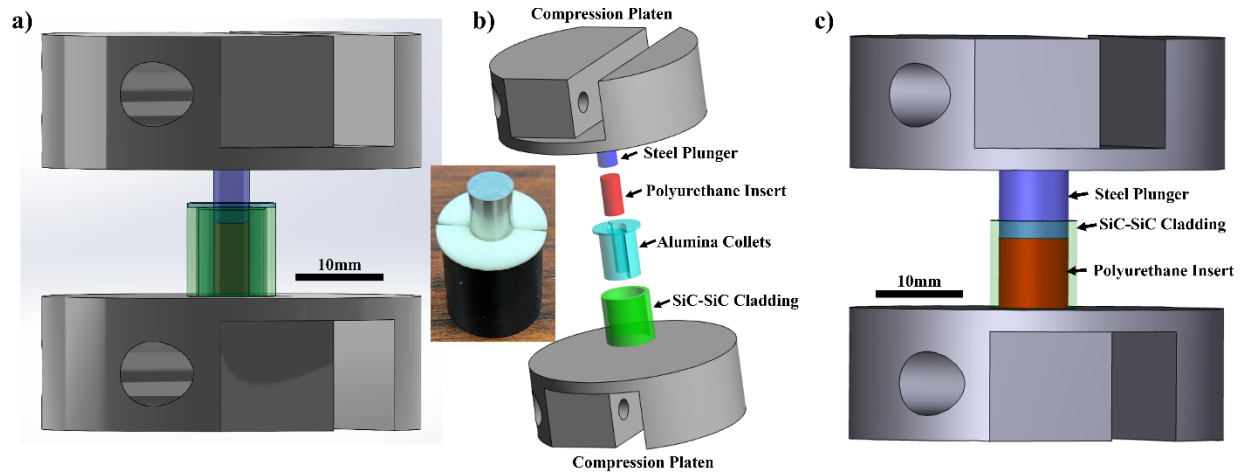


Figure 1. (a) The schematic of the in-situ loading setup and (b) its exploded view for hard contact. The assembled setup is shown in the inset with the actual sample. (c) The soft contact deformation setup.

For comparison, a pure EDC test was also performed using the same type of polyurethane insert that was larger to accommodate the lack of alumina collets (i.e., close in size to the internal

diameter of the SiC/SiC tube). The insert was again pushed using a steel plunger with a slightly smaller diameter than the plug (Figure 1c). The test setup is derived from ASTM C1819-21 [24], with modifications to the sample and insert size to fit the confines of the miniature loadframe while enabling XCT data collection.

The in-situ XCT measurements were performed using a Zeiss Xradia Versa 520 system with a Deben 5 kN miniature loadframe that is specialized for XCT measurements. First, ex-situ tests were performed with identical setups for each test (collet and polyurethane only) to determine the loading behavior. Example load curves are presented in Figure 2, where the force corresponds to the total system load in newtons, and the travel corresponds to the load-head displacement in millimeters. The total load levels (in applied compressive force) are different between the two tests even though the tests were performed on the same batch of samples. These differences are attributed to changes in the loading setup, and they do not necessarily translate into vastly different stresses on the SiC/SiC tubes. Thus, these load levels are only used for reference. It must also be noted that due to the limitations imposed by the miniature load frame with a glassy carbon enclosure that also acts as the main support structure (instead of beams) neither an extensometer could be attached to the specimen nor digital image correlation (DIC) could be used to determine strains.

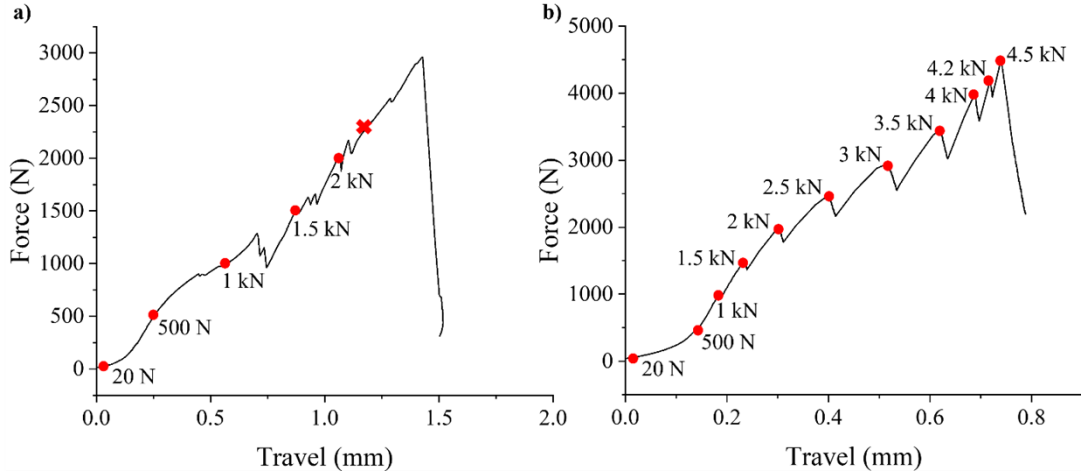


Figure 2. The force (N)–travel (mm) curves obtained from ex-situ deformation of SiC/SiC tubes with (a) alumina collets and in-situ deformation from (b) polyurethane plug only. Marked on the curves are the load levels used for in-situ deformation in each test. The red “X” marks the approximate level where the in-situ sample failed (with alumina collet) as opposed to the higher loads carried by the pure EDC sample.

Finally, it must be stressed again that these are only example load curves to illustrate the loading points used for each presented dataset. For example, the ex-situ hard contact tested sample in Figure 2a has lasted longer than the in-situ one and accordingly an X mark is used on the load curve to indicate where the in-situ sample has failed. For the soft contact sample (Figure 2b) ex-situ data was not available and therefore the in-situ load data is used with measurement points highlighted. It can be noticed that during holding loads, force relaxation has occurred. However, this is not expected to greatly affect the deformation behavior as any cracking, etc. would take place at the peak load of each step.

Using the load curves in Figure 2, several steps were selected for in-situ testing along the force–displacement curves, indicated with red dots. The tests were then performed in a stepwise

fashion wherein the sample was loaded to a predetermined level and held for XCT data collection. The XCT data were collected using an X-ray energy of 120 kV at 10 W total power. A 0.4× scintillator objective was used to maximize the field of view, allowing the entire sample to be imaged. When the specimen is placed at the center of rotation, it is accepted to be the zero point. Within this geometry a source distance of 63.29 mm and a detector distance of 309.93 mm were used for geometric magnification. 1601 projections were used for each scan at 9 second projection time each. A 1×1 binning was used on the detector side to maximize the resolution achievable with this setup, and a voxel size of 5.77 μm was obtained.

Higher resolution post-deformation scans were also performed on select locations to investigate the cracks/failure surface in more detail. These scans used a 4× scintillator objective with the source distance of 18.37 mm and detector distance of 23 mm. Coupled with 1×1 binning on the detector, this setup yielded a voxel size of 1.26 μm (for high resolution fracture surface 20.95 mm source distance, 50.39mm detector distance with a 0.996 μm voxel size). Similar to the in-situ scans, 1601 projections were utilized for these scans with each projection acquired for 6 seconds.

The data analyses with segmentation were performed using the DragonFly PRO version 2022.2 coupled with a deep learning segmentation tool. Deep learning–aided segmentation was instrumental in separating features with similar X-ray absorption levels such as cracks and pores as well as fibers and matrix. Such distinction would not have been possible with classic histogram-based segmentation.

Further analyses were performed using the Avizo software equipped with the digital volume correlation (DVC) add-on to resolve the displacement and strain distributions within the bulk of the specimens. The 20 N resting load was taken as the reference for both test setups (Figure 2). The remaining loads were corrected for sample displacement using the Avizo image registration and transformation routines before commencing the DVC procedure.

The DVC was performed using a global approach that uses finite element modeling to calculate the displacements and strains. A relatively coarse mesh (300 μm) was constructed for this process. Coarser meshes of 500 μm and 700 μm were also tested and revealed similar results. The mesh volume was smaller than the actual sample volume and was aligned so that the edges of the mesh remained within the sample because any sharp changes in contrast (e.g., from outside air into the sample) would lead to erroneous strains. A small strain approach was selected between the load steps. Iterative initialization was applied to each consecutive step and convergence was achieved in the first 100 iterations.

3. Results

3.1. In-situ deformation of SiC/SiC tube with XCT

To begin the 3D microstructural investigation of cracking behavior, the results from the large field of view scans were used and are presented in this section. Only the results from the hard contact testing are presented because pure EDC tests did not reveal additional information at this scale.

Per the in-situ deformation setup described in Section 2.2, mechanical loading was applied in a stepwise fashion until ultimate failure with macroscopic crack opening. The total system load was used to determine the steps of the deformation because, in this test setup, load levels are chosen to cover the entire deformation process. Therefore, 20 N was applied as the resting load (to remove the slack in the load train) followed by steps to 500, 1000, 1500, and 2000 N. Unlike the ex-situ sample, which failed at about 2.5 kN, the in-situ sample reached ultimate failure with a through-thickness crack opening at a load of slightly over 2 kN: multiple hoop-type cracks spanning the entire height of the tube were present at 2 kN.

Figure 3 shows 3D reconstructed images¹ obtained at 2 kN total load. The cracks and pores (separated via deep learning-aided segmentation) shown in green and purple, respectively. The crack opening had to be larger than the voxel size for cracks to be reliably detected. Regardless, the through-thickness crack (that led to ultimate failure) can be clearly identified (Figure 3a), and it is investigated in more detail later in Section 3.4 with a higher resolution scan of the failure surface.

¹ In 3D images, because of the isometric projection used, accurate scale bars cannot be presented. Accordingly, key dimensions are instead presented either on the 3D images or their captions for reference.

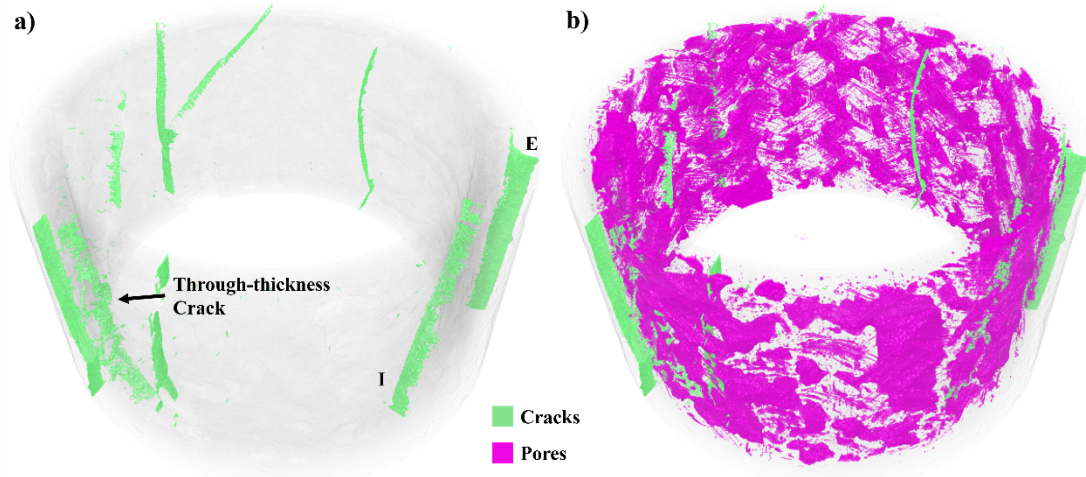


Figure 3. Following hard-contact testing, (a) cracks segmented in a close-to-ultimate failure state (i.e., macrocrack opening) with the through-thickness crack indicated. Also shown are two cracks marked with E (exterior) and I (interior) that are investigated in more detail later in Section 3.3. (b) The same image with the pores segmented in purple. For size reference, the tube outer diameter is ~ 10 mm.

As shown in Figure 3a, the through-thickness crack takes the appearance of two separate pieces, indicating that the deflection processes must have occurred in the interior layers. The rest of the major cracks were single pieces and are classified here as either an exterior (E) or an interior (I) crack. These cracks were also observed to span the entire height of the tube in a relatively straight path, as expected from the application of hoop stresses.

Figure 3b presents the pores in addition to the cracks. Most of the pores observed with the low-magnification setup were very large (potentially as large as or larger than ~ 3 mm high, ~ 2 mm wide, ~ 150 μm thick), and are due to incomplete matrix infiltration between adjacent composite layers during the CVI process. Also present are the string-like pores that mimic a weave

structure, suggesting that these pores are situated along the fiber tows between the SiC fibers that the CVI process failed to infiltrate. At these relatively low magnifications, very fine pores cannot be accurately observed because of voxel size limitations. In this case, observable pores are about 16 μm and larger ($\sim 3 \times$ voxel size).

To offer a better perspective, the volume around the through-thickness crack has been isolated and presented in Figure 4 both from exterior (a, b) and interior (c, d) perspectives, both in solid (a, c) and segmented (b, d) views. Starting with the two sections of the crack (exterior and interior), the main difference between them is in their morphology. Whereas the exterior crack is uniform and rather straight through, the interior crack is well-segmented. This result is mainly because the single-phase, dense outer monolithic layer shows little to no resistance to crack growth. By contrast, the inner cracks have to interact with the inherent porosity of the inner layers before even reaching the fiber layer, as evident from Figure 4b and d.

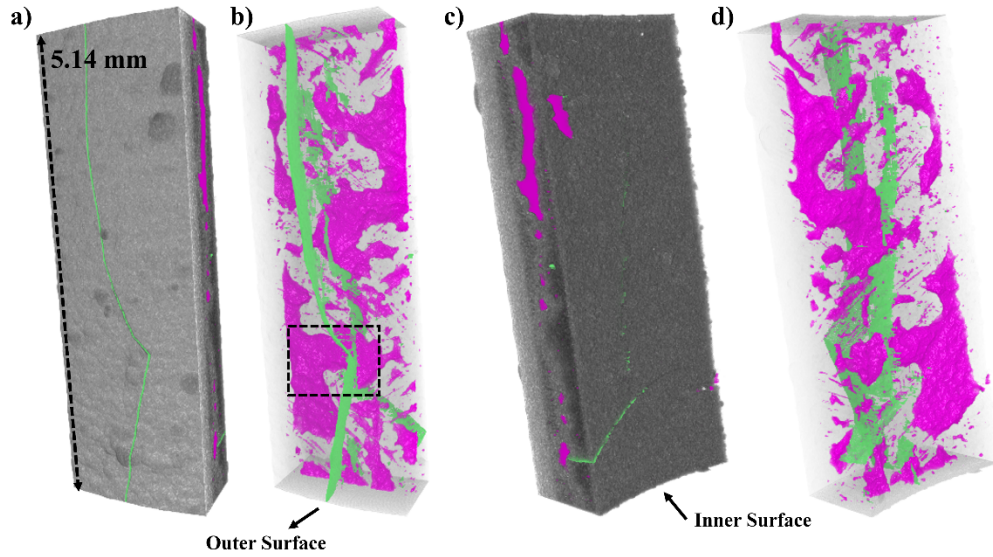


Figure 4. The through-thickness crack shown from (a, b) the outer and (c, d) inner surfaces both in (a, c) solid and (b, d) segmented views for the hard contact deformed sample. A black dashed rectangle indicates the area that is shown in more detail in Figure 5.

The area marked with a dashed rectangle in Figure 4 is shown in more detail in Figure 5, wherein a crack deflection can be clearly observed. The deflection points are indicated with yellow arrows in Figure 5a. The zone between the arrows corresponds to the fiber layer, as illustrated by the presence of the string-like pores in this section in Figure 5b. Higher resolution images presented in the next section offer better detail for the observed crack deflections through the SiC fiber layer.

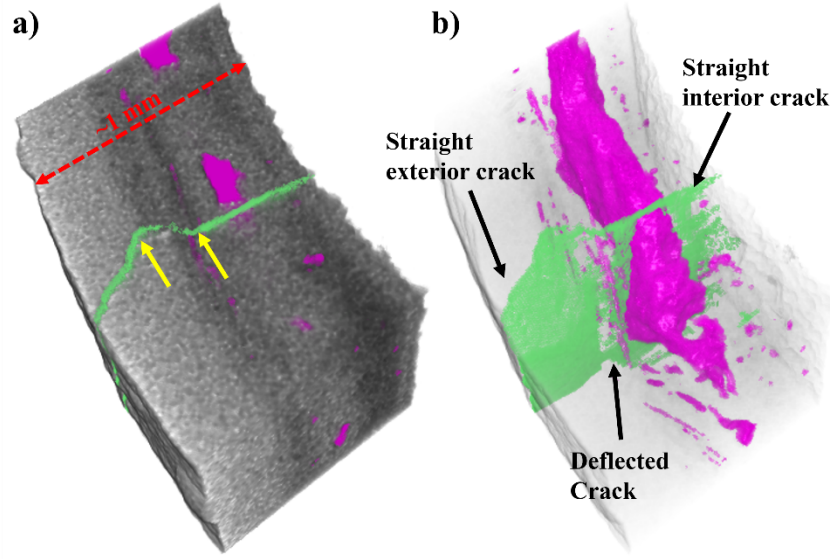


Figure 5. A 3D section (see black dashed rectangle in Figure 4b) of the through-thickness crack shown in (a) solid view and (b) segmented view for the hard-contact deformed sample. The crack is shown in green, and the pores shown in purple. The crack deflection is denoted with yellow arrows in (a).

In addition to the deflected crack, the exterior and interior components of the through-thickness crack are relatively straight and nearly perpendicular to the outer/inner surfaces of the tube in Figure 5b, signifying little to no contribution to toughness. These regions of the multi-layered tube are monolithic, so this low-toughness behavior in these areas is expected.

Finally, Figure 6 shows (a) exterior and (b) interior cracks (indicated by “E” and “I” in Figure 3, respectively) in their isolated volumes as examples.

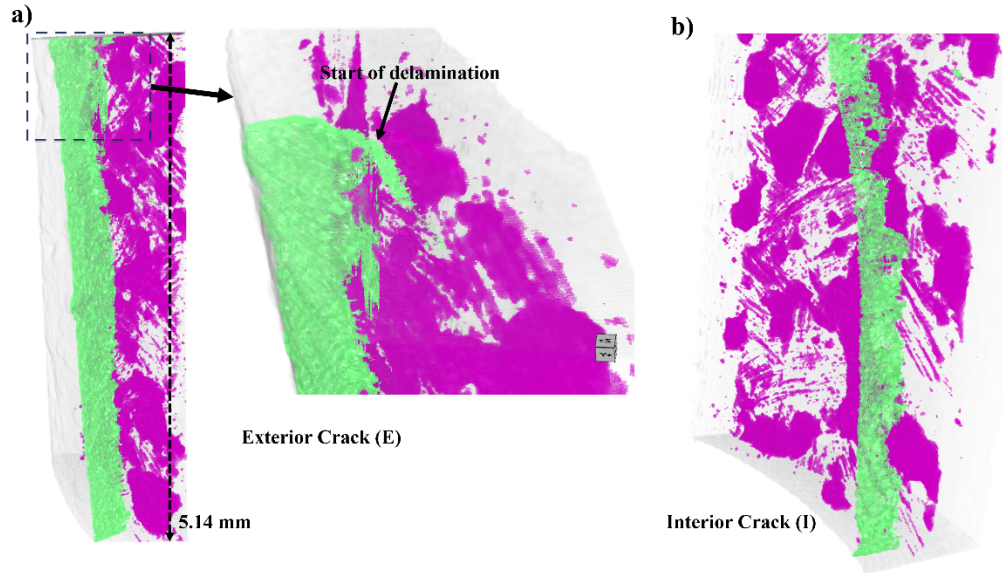


Figure 6. Example exterior and interior cracks (marked with “E” and “I” in Figure 3) shown in segmented views together with the pore structure for the hard-contact deformed sample.

In either case shown in Figure 6, the cracks are arrested in their local regions (i.e., could not penetrate through the fiber layer). However, the cracks follow the path of least resistance when possible, and this trend is illustrated in Figure 6a for the exterior crack. Here, upon reaching the fiber layer, the crack starts to run parallel to it, through likely a weak point in the interface between the outer monolith and the inner SiC woven layer, leading to the start of a delamination. This delamination is expected to cause localized spalling of the outer layers with continued deformation.

3.2. Inhomogeneous displacement fields revealed by DVC

A critical understanding of the deformation/failure behavior in a relatively complex loading scenario, such as this one, benefits from a 3D qualification and quantification of applied

displacement within the structure of the specimen. This investigation is made possible by DVC, and results are presented in this section starting with pure EDC testing in Figure 7.

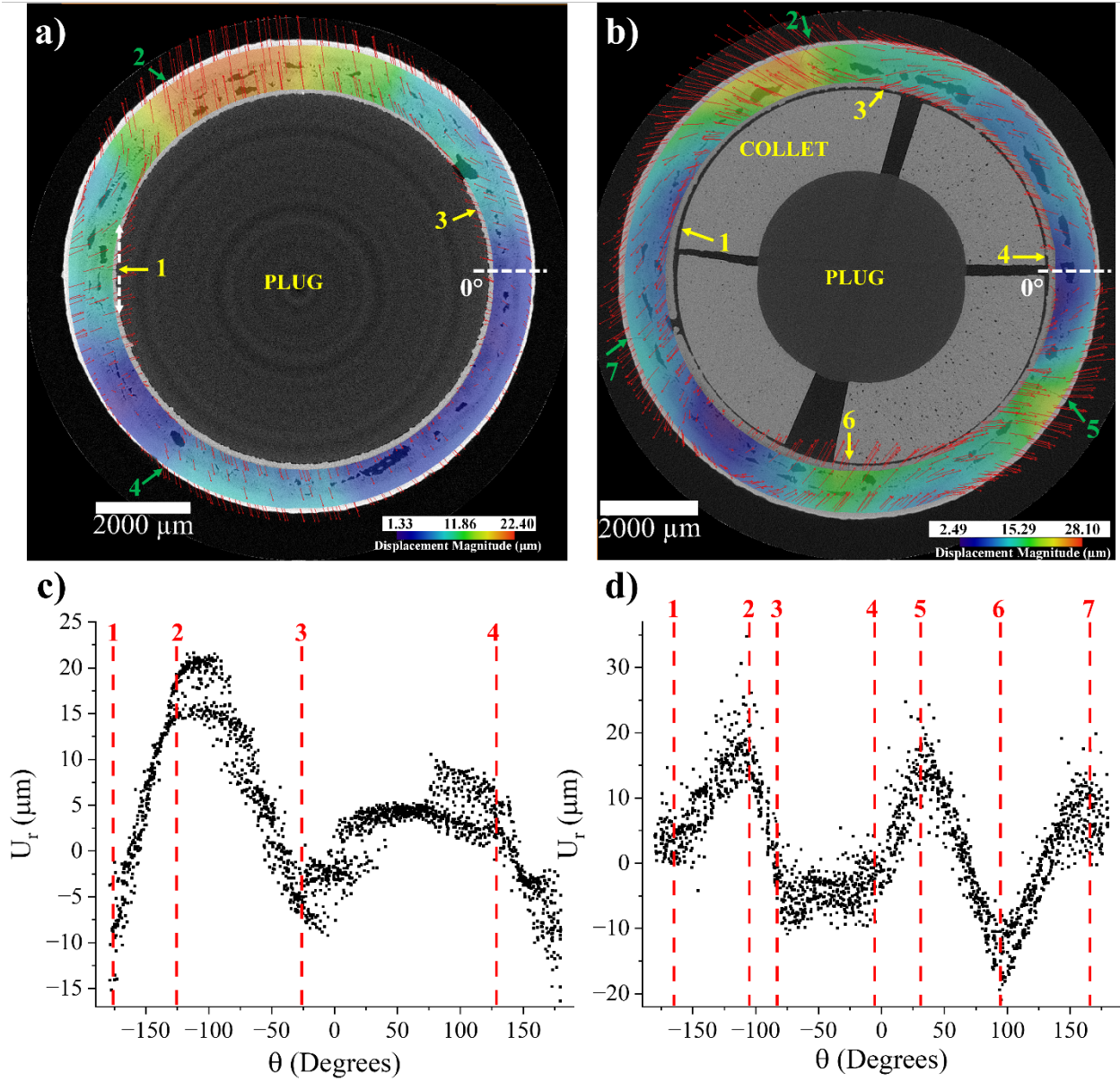


Figure 7. (a) 2D horizontal slice image taken at 4.2 kN system load during the EDC test. Yellow arrows point to inner cracks, and green arrows to outer cracks, shown with the displacement magnitude map obtained from DVC overlaid in color. Displacement vectors are shown with red arrows, wherein the direction and magnitude are indicated by the point and length of the arrows. White dashed arrows indicate the direction of tensile hoop strains. (b) 2D horizontal slice image

taken at 2 kN system load during the hard-contact test similar to that shown in (a). (c, d) Radial displacement (U_r) distributions as a function of angle (θ) for pure EDC and hard-contact tests, respectively. Red dashed lines mark the positions of the cracks that are numbered on the maps and the graphs. The 0° angle (θ) is marked on the images with white dashed lines for reference.

Figure 7a presents a 2D horizontal slice image obtained at 4.2 kN system load under pure EDC (load curve, Figure 2b). Here, arrows indicate interior (yellow) and exterior (green) cracks for reference. Overlaid on the same image in color is the displacement magnitude map (obtained from DVC) as well as the displacement vectors in red. The direction of these vectors coincides with the direction of movement, and their lengths signify relative magnitude.

In classical hoop deformation of a tube, the highest strains are expected to be on the outer surface, so the presence of such interior cracks was at first rather puzzling. The inhomogeneous nature of deformation becomes evident from Figure 7a, which shows concentrations of displacement magnitudes that would not be expected in a uniformly expanding tube. The EDC test with a hard polyurethane plug is the closest form to apply a uniform expansion to a SiC/SiC tube. However, the vector fields in Figure 7a reveal two clear zones of expansion and two clear zones of contraction within the tube. In turn, where expansion occurs, tensile hoop strains are experienced by the outer surface of the tube, leading to the formation of exterior cracks (indicated by green arrows). Conversely, where contraction occurs, tensile hoop strains are naturally expected to be experienced by the inner surface of the tube, leading to the formation of interior cracks. As an example, the tensile hoop strains acting on an interior crack are schematically indicated by white dashed arrows in Figure 7a.

This highly nonuniform deformation, even with pure EDC with a polyurethane plug that can conform to the interior surface of the tube, can be related to (1) the nonuniform inner diameter of the tube as opposed to the perfectly cylindrical plug and (2) the nonuniform microstructure of the SiC/SiC tube. The microstructural nonuniformity mainly stems from the presence of inherent defects (e.g., pores both large and small) that is exaggerated by the presence of the woven SiC fiber structure that is, by design, not strongly bonded to the surrounding matrix.

The DVC displacement results for the hard-contact test are presented in Figure 7b in a similar fashion to the pure EDC results: a horizontal slice image is shown with DVC results overlaid. Similarly, the yellow arrows point to interior cracks, and green arrows point to exterior cracks.

Similar to pure EDC results, the external and internal cracks line up well with the displacement vectors; with tensile Hoop strains imposing on the outer and inner surfaces with macroscopic expansion and contraction, respectively. However, despite similar crack formation mechanisms, differences are evident between the two samples, as revealed by the overall displacement vector distributions (Figure 7a vs. 7b).

In pure EDC, relatively symmetric zones of expansion and contraction are present with relatively well-defined boundaries between them (Figure 7a). By contrast, the hard-contact experiment revealed a more fluid motion between zones of expansion and contraction that were not necessarily symmetric (Figure 7b). As a result, three external and four internal hoop cracks are present in the sample that was subjected to hard-contact deformation as opposed to two of each type of cracks in the sample deformed under pure EDC. Other samples for each condition were

tested with similar results (not presented here); however, we realize that this is not necessarily a large systematic study mainly due to the lack of specimens and the time it takes to run in-situ measurements. The presence of multiple hard bodies (exaggerated by the broken collets) acting along different directions is more analogous to a broken/fragmented fuel pellet and introduces another layer of complexity to the inhomogeneous deformation of SiC/SiC composite tubes.

The displacement data from DVC (in Cartesian coordinates) was converted to radial coordinates, where U_r is the radial displacement, and θ is the angular position covering the entirety of the investigated DVC volumes (i.e., for all the slices combined). The U_r - θ plots are presented in Figure 7c and d for soft- and hard-contact tested samples, respectively. Here, θ extends from -180° to $+180^\circ$, forming a whole circular coordinate system wherein the points join at the opposite ends (i.e., -180° and $+180^\circ$ converge to the same location). The locations of each crack are also indicated on these plots with dashed lines that are numbered corresponding to the cracks shown in the images in Figure 7a and b. These data help quantify the character of radial displacement (expansion vs. contraction) and correlate the location of the cracks (outer and inner). As shown in Figure 7c and d, the crack locations tend to line up with local maxima and minima points of radial displacement, U_r .

Finally, in the cracked regions, the maximum principal strains (ϵ_1) were found to be approximately 1% at the highest points, regardless of the test method. An example image is presented in Supplementary Materials.

3.3. Investigation of crack propagation at higher resolution

The 3D reconstructed and segmented images of an exterior and an interior crack (from the hard-contact specimen) obtained ex-situ at higher resolution are shown in Figure 8. Here, the deep learning-aided segmentation was able to differentiate cracks (green color) and small (yellow) and large (blue) pores (essentially all air). This capability was instrumental in understanding the crack propagation behavior.

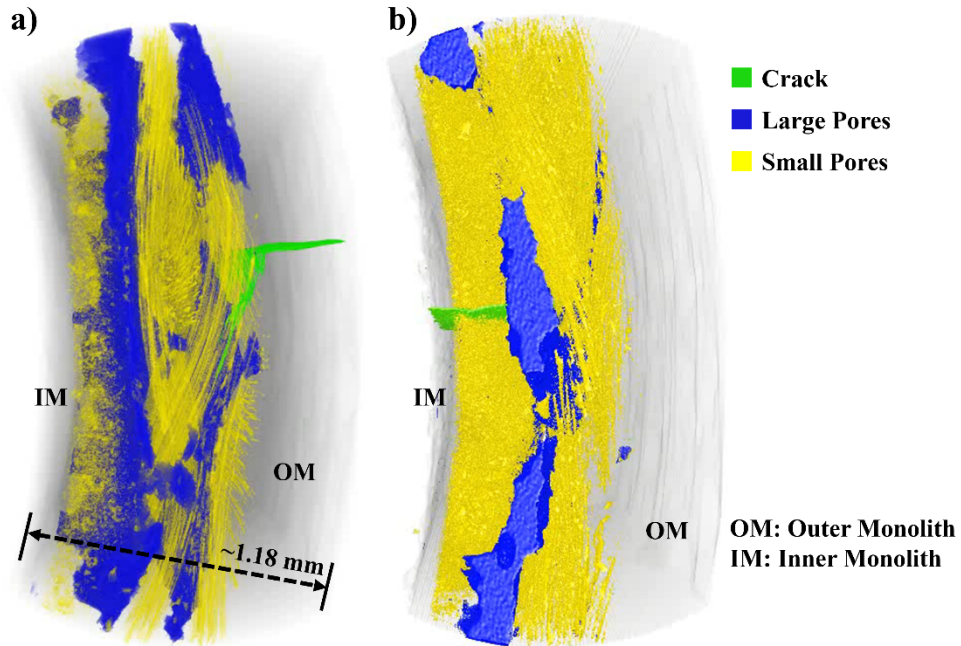


Figure 8. High-resolution 3D reconstructed images from (a) an outer crack and (b) an inner crack of the hard-contact deformed sample. Here, the cracks are again segmented in green. The pores are classified as large and small pores and are shown in blue and yellow, respectively.

The pores are also used to indirectly identify the monolithic layers, which are dense layers of monolithic SiC and thus are free of defects, except for cracks. These features are shown in Figure 8 with the “OM” (outer monolith) and “IM” (inner monolith) designations. As shown in the

figure, the OM is significantly thicker than the IM. This is by design as the outer monolith needs to withstand hydrothermal corrosion attack and is expected to see higher compressive loading in application inside a nuclear reactor [35]. The cracks can move with relative ease within these monolithic layers, as has already been established (and shown in these images). However, cracks exhibit very different behaviors once they propagate through their respective monoliths.

The smaller pores here are divided into spherical-like pores (closer to IM) and weave-like pores (closer to OM), which were previously indicated to be the empty space between the fibers that follow the weave pattern. Next, the exterior crack (Figure 8a) can be seen to follow the direction of the fiber weave; it is deflected as it reaches the fiber-reinforced zone. By contrast, the inner crack (Figure 8b) appears to cut through its neighboring layer with the small pores and terminates at a large pore.

The exterior crack is shown in more detail in Figure 9, starting with the crack-only segmentation (a) where two regions of interest are marked with “R1” and “R2.” These areas are shown in more detail in Figure 9b and c, respectively, with the accompanying pore structure classified into small and large pores.

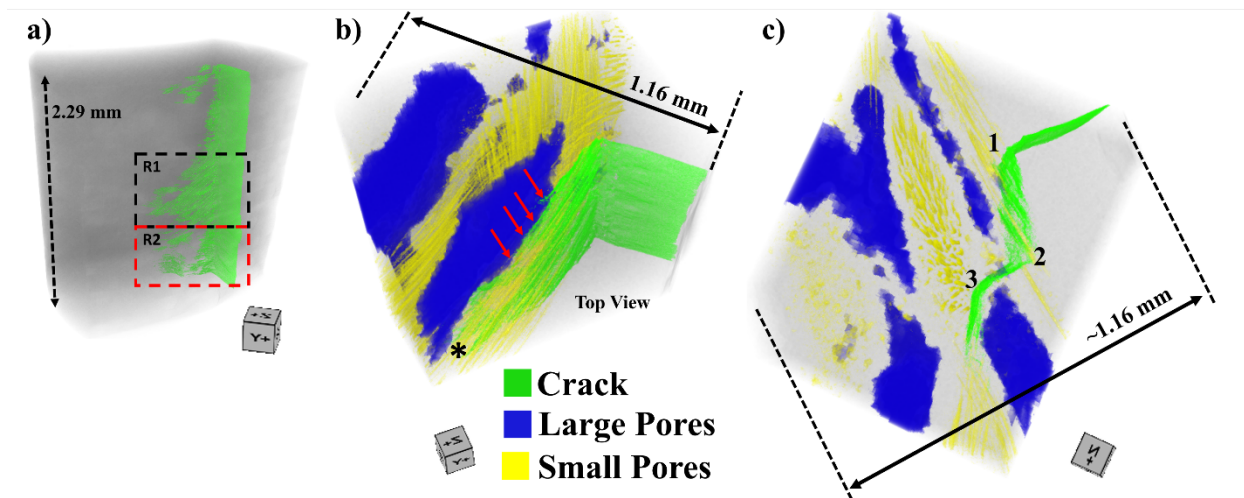


Figure 9. (a) The exterior crack with regions of interest R1 and R2. Detail views with all components (i.e., cracks and pores) for the hard-contact deformed sample of (b) R1 and (c) R2 with the crack deflection points shown with numbers 1, 2, and 3. A 3D orientation cube is presented in each figure to indicate their relative positions.

Starting with R1 in Figure 9b, the crack can be seen to deflect at the fiber layer after traversing the OM. The crack then follows the weave pattern (i.e., takes the path of least resistance through the string-like voids between the fibers). Here, the large pores also play a role in the crack progression: the crack terminates at a large pore as it propagates through the weave structure, indicated by red arrows. However, the crack deflects again toward the interior surface immediately below the large pore, moving past the termination point of its upper part. This section is marked with an asterisk (*). This particular pore is situated between two diagonal tows with a vertical tow behind it. This second row of fibers would likely be the arrest point of the deflected crack (*).

Next, the R2 region is shown in Figure 9c in more detail. This particular crack deflects three times, as indicated by the numbers 1, 2, and 3. Here, two types of cracks can be observed: straight and diagonal. As has been established previously, straight cracks form when there is little to no resistance to crack propagation and diagonal cracks form when the crack front reaches a fiber tow. Deflection point 2 is more of interest as it showcases the fact that any defect between the reinforcing fiber tows is a shortcut for cracks to take. To elaborate, between points 2 and 3, a fiber-diminished region allows the crack to freely move in accordance with the hoop stress state, later to be deflected by the fiber bundle at point 3.

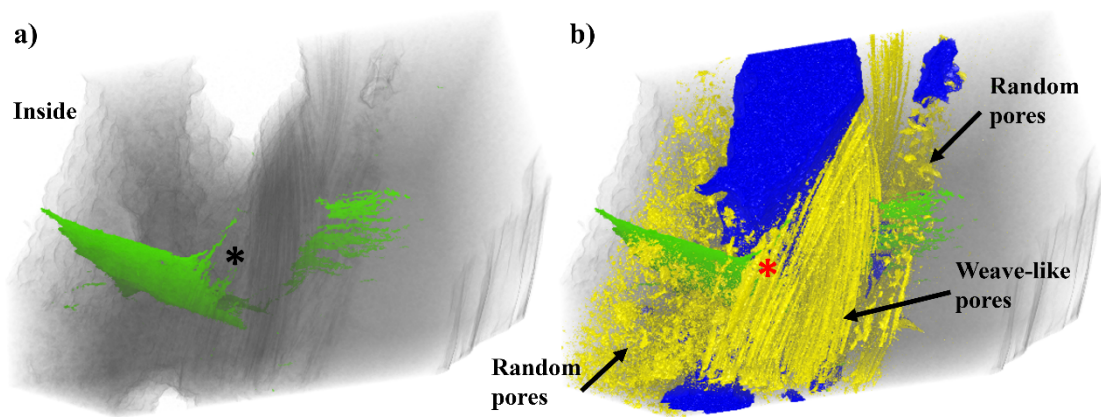


Figure 10. Detail view of the interior crack in Figure 8b with segmented components showing (a) only the crack and (b) cracks and pores for the hard contact deformed specimen. The wall thickness is about 1.16 mm.

A smaller section of the inner crack (Figure 8b) is shown in higher detail in Figure 10 with the crack-only view in (a) and with pores added in (b). Here, the asterisk shows the crack deflection point from the inner crack growing outward. In Figure 10b, this deflection can be seen to occur where the fiber tows are situated. In these images, an obvious connection between the cracks on

either side of the asterisk is missing, possibly related to the lack of voxel resolution to clearly visualize the crack in this region. The other possible reason for this result would be the lack of deformation (i.e., load was removed), which may have caused the closing of the already fine cracks during imaging *ex-situ*. Regardless, the crack continues past these tows but does not quite reach the exterior part of the tube. In other words, no exterior-originated crack reaches inward to connect with this interior crack. Therefore, the interior crack deflected through the space between the tows and continued outward.

Similar to the observations for Figure 9c, an area of random pore structure (i.e., no fibers) is shown between the tows in Figure 10b. This area offered the path of least resistance wherein the crack could propagate through, as evidenced by the straight, clean crack pathway absent any evidence of crack deflection or branching. The structure with these random pores (Figures 8b and 10b) appears to correspond to regions in between fiber tows which have been only partially filled by CVI-derived matrix, which are not resistant to crack formation or penetration. There is likely a heavily CVI filled zone in the inner regions above IM. This can be deduced because of the structural difference observed so far, wherein the monolithic zones are fully dense while this “porous zone” is not. The 2D horizontal slice images are shown in Figure 11 to present these layers from two different sections of the interior crack. The segmented crack is highlighted in green for better discrimination.

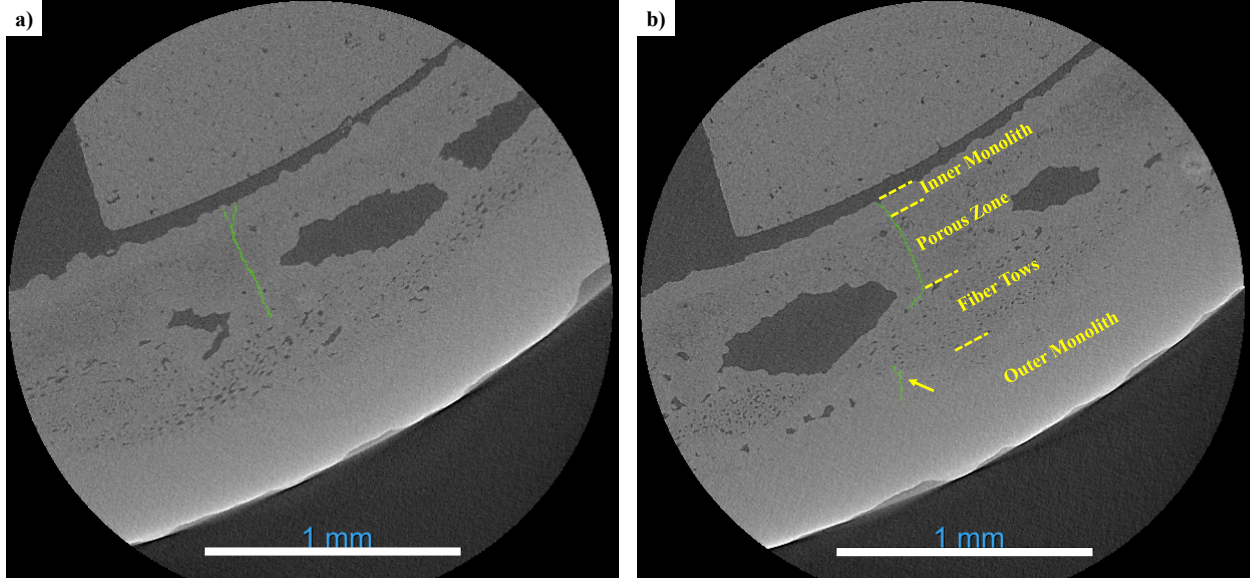


Figure 11. Horizontal slice images of the internal crack (3D shown in Figure 8b) showing different stages of the crack, highlighted in green (hard-contact, 2 kN).

In Figure 11a, the crack clearly extends to the fiber tow where propagation stops. In Figure 11b (which corresponds to a slice in the volume shown in Figure 10), the crack deflects upon reaching the fiber tow and continues toward the outer surface indicated by a yellow arrow. The different layers discussed above are also highlighted in Figure 11b.

The high-resolution images from the pure EDC test (after ultimate sample failure) are also presented here to highlight crack formation and propagation mechanisms. Figure 12 shows an internal crack that branches through the vertical fiber tows. Figure 12a shows the raw 2D slice image with the cracks segmented in green in Figure 12b. The branched internal crack (green) is shown in 3D in Figure 12c, and the 3D voids are added in yellow in Figure 12d.

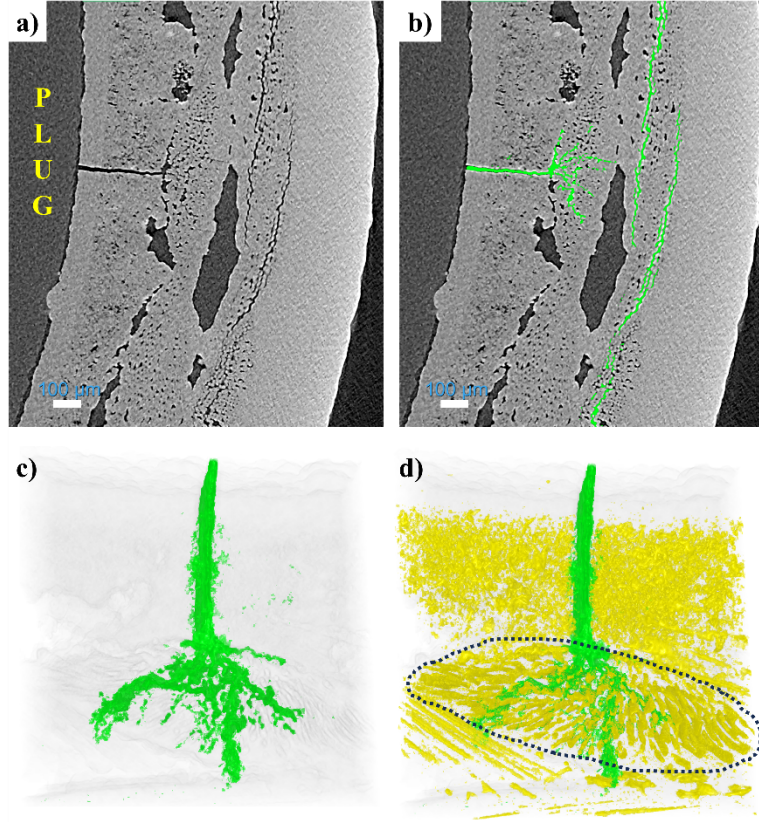


Figure 12. (a) 2D horizontal slice of the failed SiC/SiC tube focusing on a cracked region and (b) the same region with these cracks segmented in green, for the sample deformed under soft contact. (c) Segmented inner crack in 3D and (d) the same area with the pores shown in yellow. A dashed black line outlines the position of a vertical fiber tow (running parallel to the vertical axis of the tube).

The delamination-type cracks are observed closer to the outer edge (Figure 12b) where layer separation becomes more evident with ultimate failure. The inner crack starts as a straight crack through the monolithic layer and easily progresses inward through the porous zone until it reaches the fiber tows, similar to what was observed in the hard-contact sample shown in Figure 11. However, unlike the previous examples, the crack in Figure 12 intersects with a vertical fiber tow instead of a diagonal tow as seen in Figure 9. Therefore, instead of deflecting, the crack

moves through the voids between the fibers by branching out (Figure 12c and d) on its way to connect with the delamination crack. These voids were measured to be as small as 9–10 μm . The vertical fiber tow is highlighted in Figure 12d with a black dashed line. Overall, although vertical fibers offer some resistance to crack propagation, they are not as effective as diagonal fibers in stopping crack propagation during hoop deformation. It must also be mentioned that this observation was independent of the deformation mode (i.e., soft- vs hard-contact) and was highlighted for its potential scientific value to some of the readers.

Another interior crack is shown in Figure 13, which showcases the effect of defects on crack propagation. A 3D volume is shown in Figure 13a where the cracks are segmented in green, large pores in blue, and small pores in yellow. These features are again used to identify the location and orientation of the fibers. Different 2D slice images are shown in Figure 13b and c with fiducial markers (*, a red arrow, and a double dagger ‡) to orient the readers to their location. The horizontal cross section of the 3D image is also approximately sketched on the 2D images with a red dashed rectangle and a reference also shown in the 3D image (Figure 13a). Interior and exterior surfaces are marked with letters “I” and “O,” respectively.

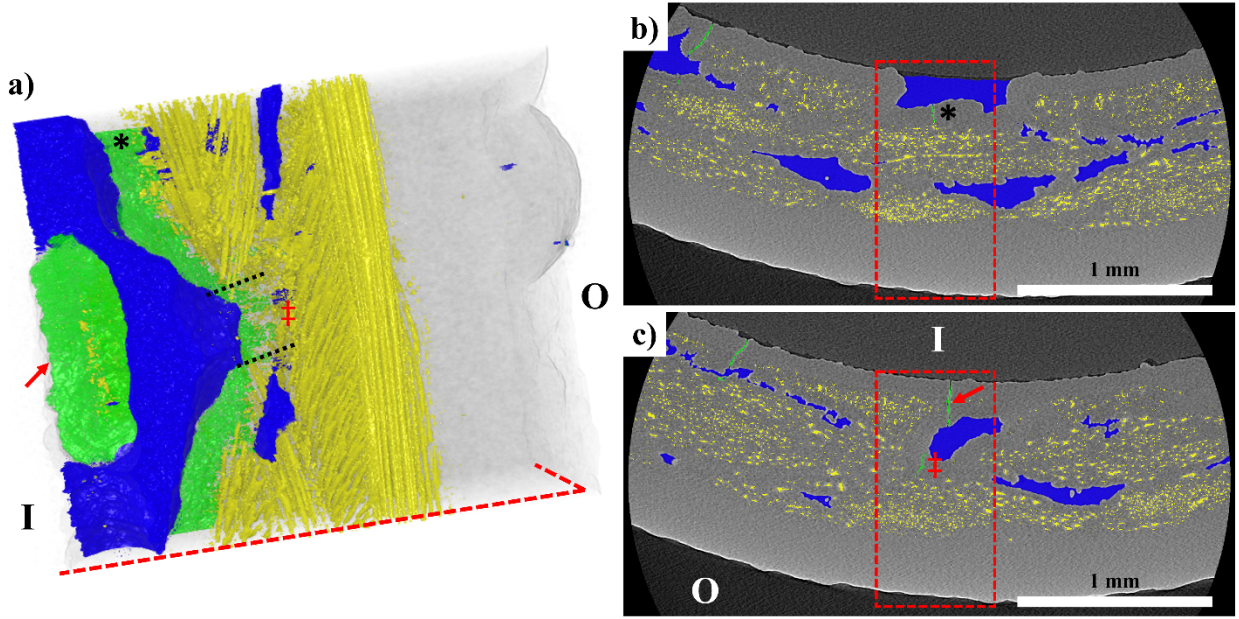


Figure 13. (a) 3D segmented section showing segmented sections of interest. Cracks are shown in green, large pores in blue, and small pores in yellow for the sample deformed under soft contact. (b) and (c) Separate vertical 2D slices with these segments present. Markers (e.g., * or ‡) are used to correlate the 2D and 3D images. A red rectangle outlines the approximate area that corresponds to the 3D section. Two such lines (long and short) are also outlined on the 3D image for reference.

Figure 13 shows that an interior crack forms and moves through the inner monolith without any obstacles, as expected. The crack also interacts with a large pore but fails to arrest. Here, the more external portion of the crack is marked by an asterisk, which is already past the large pore (only a limited part of the sample is observed here). Figure 13b shows this portion of the crack to be arrested by a diagonal fiber bundle, as shown in Figure 13a. While it has been established by this point that the diagonal fiber bundles are effective in arresting/deflecting the cracks, any fault between tows within the bundle can offer a path for crack propagation. One such feature is

captured in Figure 13, indicated with the double dagger (§) that marks an area between the crossing of two diagonal tows wherein the crack freely advances, later to be stopped by another bundle of diagonal fibers. This feature is more clearly shown in the 3D image (Figure 13a) where the crack advancement between the fiber tows is marked with two black dashed lines and the double dagger.

3.4. Investigation of the fracture surfaces

Post-failure analysis was performed on the fracture surfaces via ex-situ high-resolution scans. Figure 14a and b show example horizontal and vertical 2D slice images, respectively, obtained from the hard-contact tests, presenting an overlay of the high-resolution scan of the failed sample (in yellow) with respect to the in-situ sample at 2 kN total load. This overlay also serves as a good example of the inverse relation between resolution and field of view.

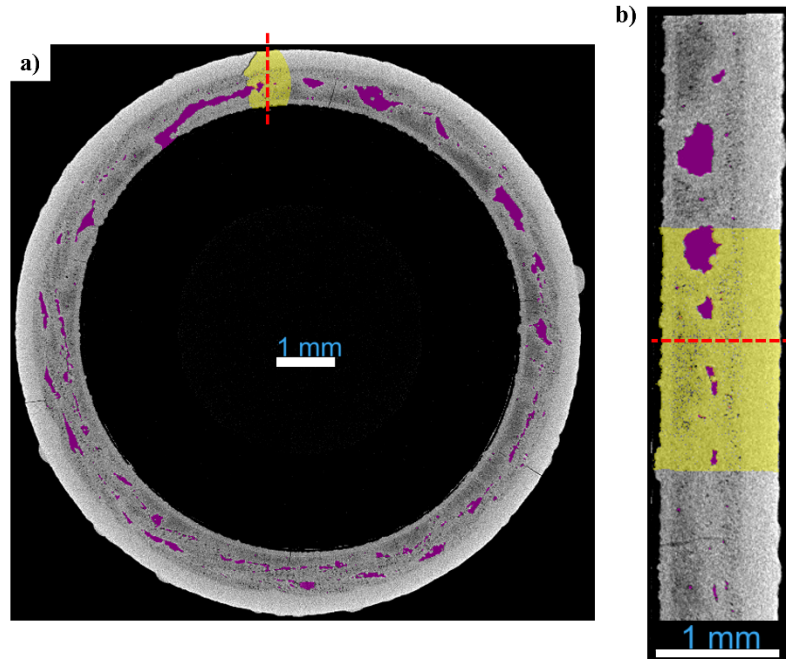


Figure 14. (a) Horizontal and (b) vertical cross sections of the in-situ tested samples with the high-resolution scan of the failed sample overlaid in yellow (hard contact). Red dashed lines on each cross-section (a and b) show approximate slicing planes where the other cross-section (b and a) is taken.

A combination of strategic high-resolution ex-situ scans with the large field of view in-situ scans enabled a composite picture that offers a detailed view of the sample failure. Figure 15 illustrates the through-thickness crack (obtained at lower resolution, larger field of view) overlaid on the failure surface features obtained at higher resolution.

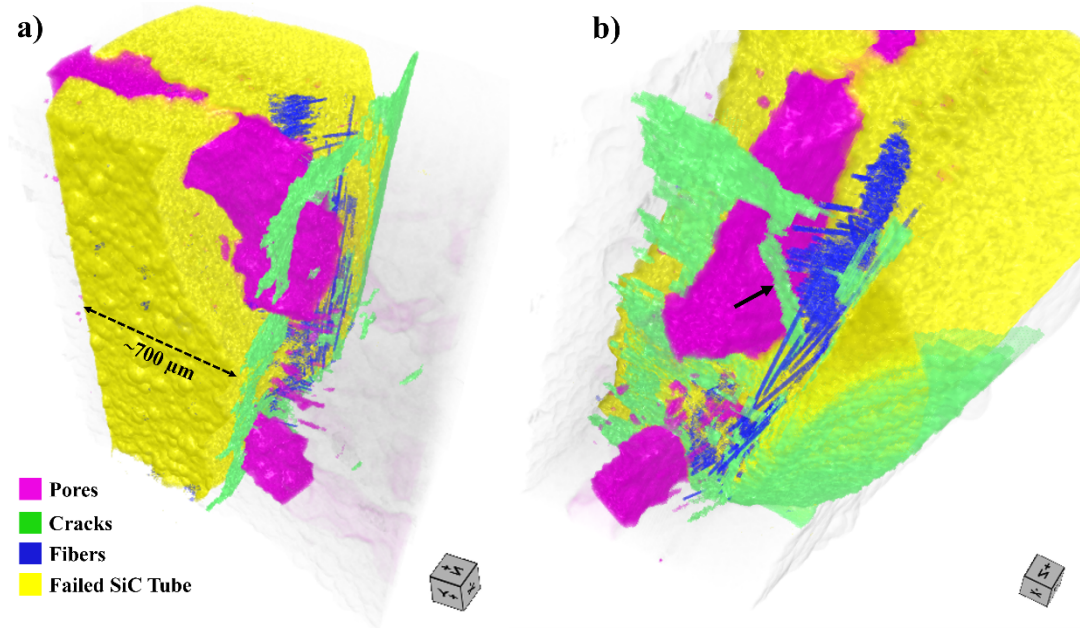


Figure 15. 3D reconstructed images of the failure surface obtained in higher resolution from different perspectives for the sample that failed under hard contact.

Figure 15 shows all the components of the failed surface with the through-thickness crack overlaid in green. The interactions between the crack and the microstructural features appear to occur in two steps. First, the crack starts from the outer monolith and is initially arrested by the fiber bundle, which fails upon further straining and leads to fiber pullout behavior, as evidenced by the clearly distinguishable fibers in the failed surface. Second, the crack propagates inward, cutting through and apparently unaffected by the large pore.

The presence of the fiber pullout mechanism can be better visualized with the help of 2D horizontal slice images presented in Figure 16. Figure 16a shows the failure surface, and yellow arrows highlight a crack that runs through the voids between the fibers. Figures 16b and c show two separate cross sections wherein the fiber pullout mechanism is clearly visible: the fibers are separated from the matrix and voids remain, as highlighted with yellow dashed ellipses.

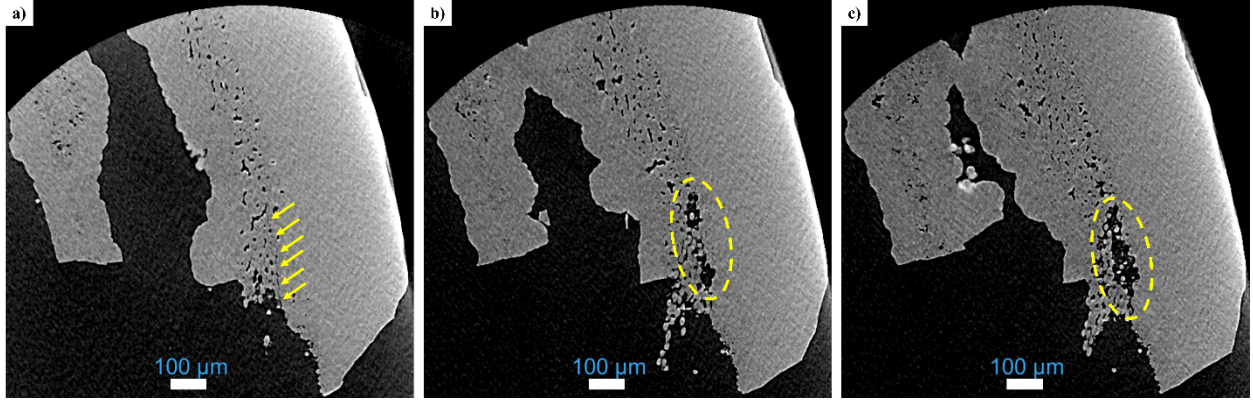


Figure 16. 2D Horizontal slice images of the failure zone of the hard-contact deformed sample. (a) Yellow arrows highlight a crack runs through the fibers and (b) and (c) show areas of fiber pullout. The image in (a) is taken from slice number 136, (b) from 304, and (c) from 355. Slice thickness is approximately 1 μm .

Finally, the fracture surface of the pure EDC tested sample (soft contact) is presented in Figure 17 in higher resolution obtained ex-situ and after failure. Deep learning-aided segmentation was used to separate small and large voids as well as vertical and diagonal fibers in the crack. The small voids between the fibers (in the bulk) are used in tandem with the actual broken fibers to highlight the location and the orientation of the fibers. Two dashed lines outline such a fiber in Figure 17a.

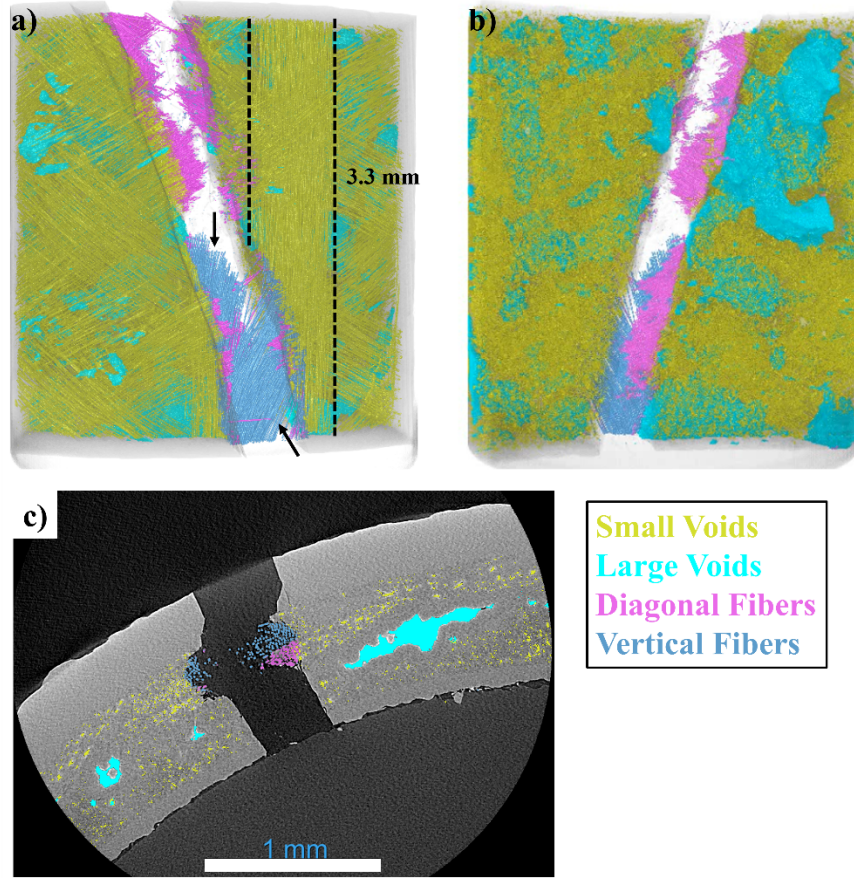


Figure 17. 3D views of the fracture under soft contact deformation from the (a) outside and (b) inside walls of the SiC tube and (c) a horizontal 2D slice. The legend for the segmented features shows the color-coding.

For the diagonal fibers (shown in purple), complete fiber breaking and pullout can be seen in Figure 17. By contrast, the vertical fibers, at least in this example, show the least amount of breaking and the greatest amount of pullout, indicated by black arrows in Figure 17a. This result agrees with the results presented thus far, leading to the conclusion that the hoop stresses are mainly carried by the diagonal fibers. This is expected for this loading configuration, as the diagonal fibers are the only fibers at least partially aligned with the expected failure pathway under hoop loading for the fiber architecture used in these samples.

3.5. Collet-tube interactions

The collet (fuel)-tube interactions are important to investigate because the deformation mechanisms are further complicated by this interaction under hard contact. Under these conditions, the collet is not only the medium through which the deformation is applied but also a deforming body. In a typical EDC test with just a polyurethane plug, the plug would eventually conform to the inner surface of the tube and envelop the imperfections, hence negating any effect they may have on the failure behavior in a PCMI. Accordingly, results from only the hard-contact experiment are presented in this section.

To study the collet-tube interactions, the collet was segmented out as a separate entity. Two different types of cracks were observed in the collet as the deformation progressed. The first were vertical cracks that formed in the collet due to the presence of hoop stresses applied by the polyurethane plug similar to those later observed in the internal and external monolithic SiC coatings of the composite tube. More interestingly, secondary cracks formed in the collet upon hard contact with the surface protrusions of the SiC tube wall. One such point of interaction between a surface imperfection and the collet is shown in Figure 18.

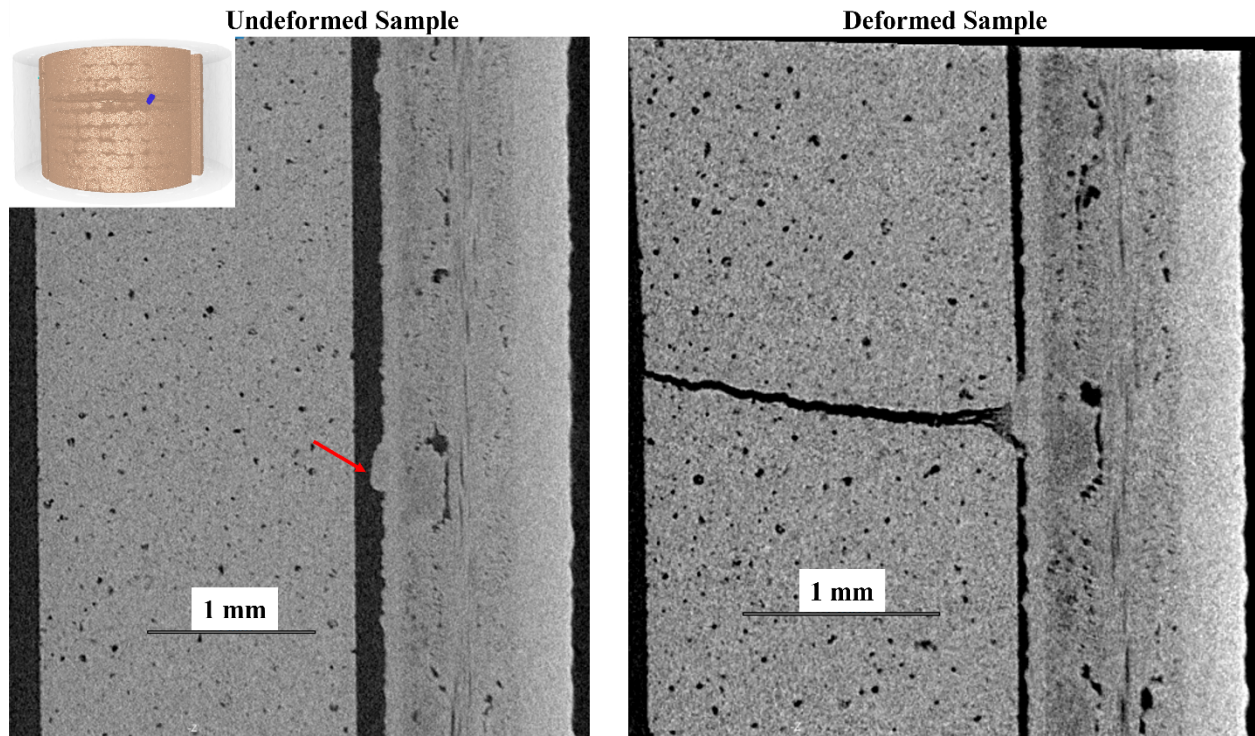


Figure 18. Vertical slice images from (a) undeformed and (b) deformed samples that highlight the collet–SiC interaction leading to the crack in the collet. On the top left corner, the 3D image from Figure 19 is shown to indicate the location of this surface imperfection.

In the undeformed view (Figure 18a), the imperfection is highlighted by a red arrow. As the deformation continues, the collet contacts the tube at the imperfection and forms a crack that runs orthogonal to the surface of the tube. This crack is due to a compression point loading applied to the collet by the SiC surface imperfection. Such cracks were observed at multiple locations and are better shown in 3D.

Figure 19 shows 3D images of the segmented collet, the key surface imperfections of SiC that led to secondary cracking on the collet upon contact deformation are highlighted in color. Secondary cracks formed horizontally on all occasions. The individual imperfections are

segmented and shown in Figures 19d–f in higher detail. In this instance, an imperfection size of about 60 μm on the inside of the SiC tube wall was enough to cause this type of crack.

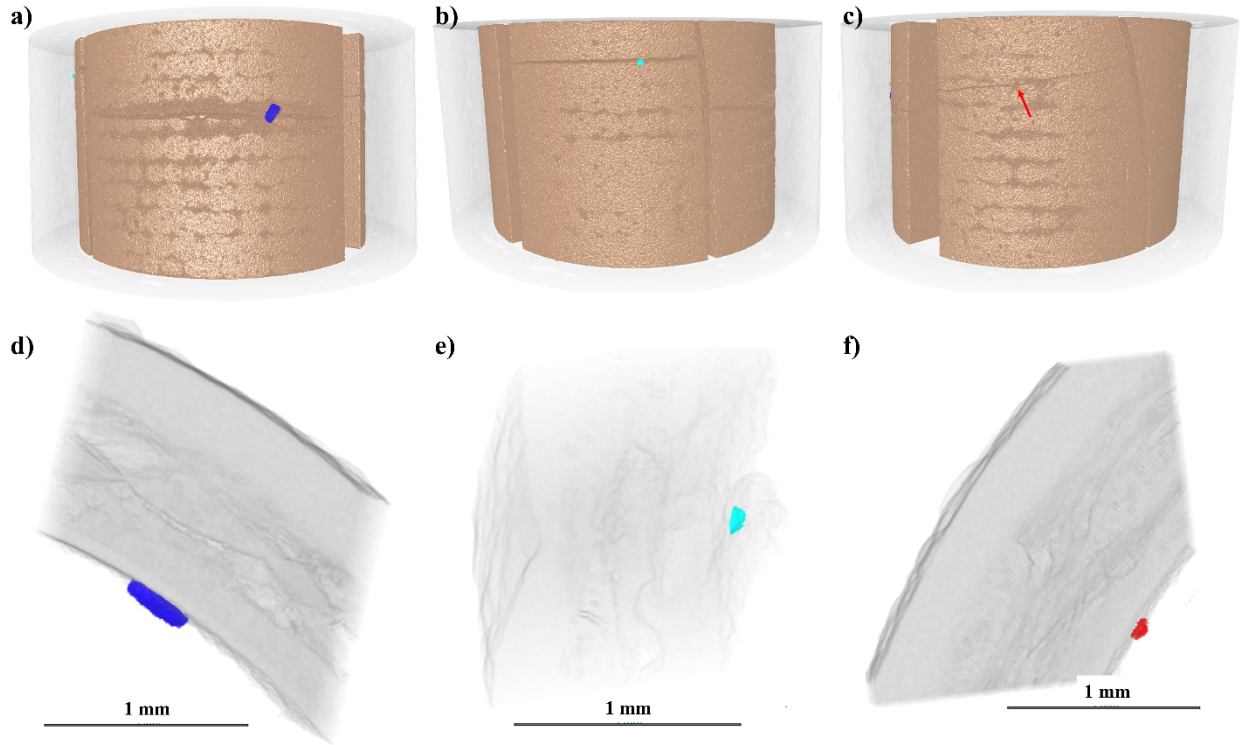


Figure 19. Different sections of the Al₂O₃ collet with surface imperfections from SiC overlaid and highlighted in (a) blue, (b) cyan, and (c) red, corresponding to the points that cause additional failure points in the collet. (d, e, f) These surface imperfections are shown in more detail.

The contact surface between the collet and the tube can be used to better investigate the hard-contact conditions. Because the collet does not conform to the tube surface, the deformation is inhomogeneous and more representative of an actual swelling incident. The contact can be indirectly observed through segmentation of the gap between the collet and the tube.

Figure 20 presents 3D images showcasing the gaps as a function of system load. The gap will never fully close in this instance because of the nature of the inhomogeneous deformation.

Instead, changes in the gap structure become evident with increasing load. The segmented zone is composed of air (hence, the gap) despite appearing solid in the 3D views. Accordingly, empty spaces (or voids) in the segment correspond to the contact points (i.e., solid bond between collet and clad). An example is indicated by a black arrow at 20 N in Figure 20.

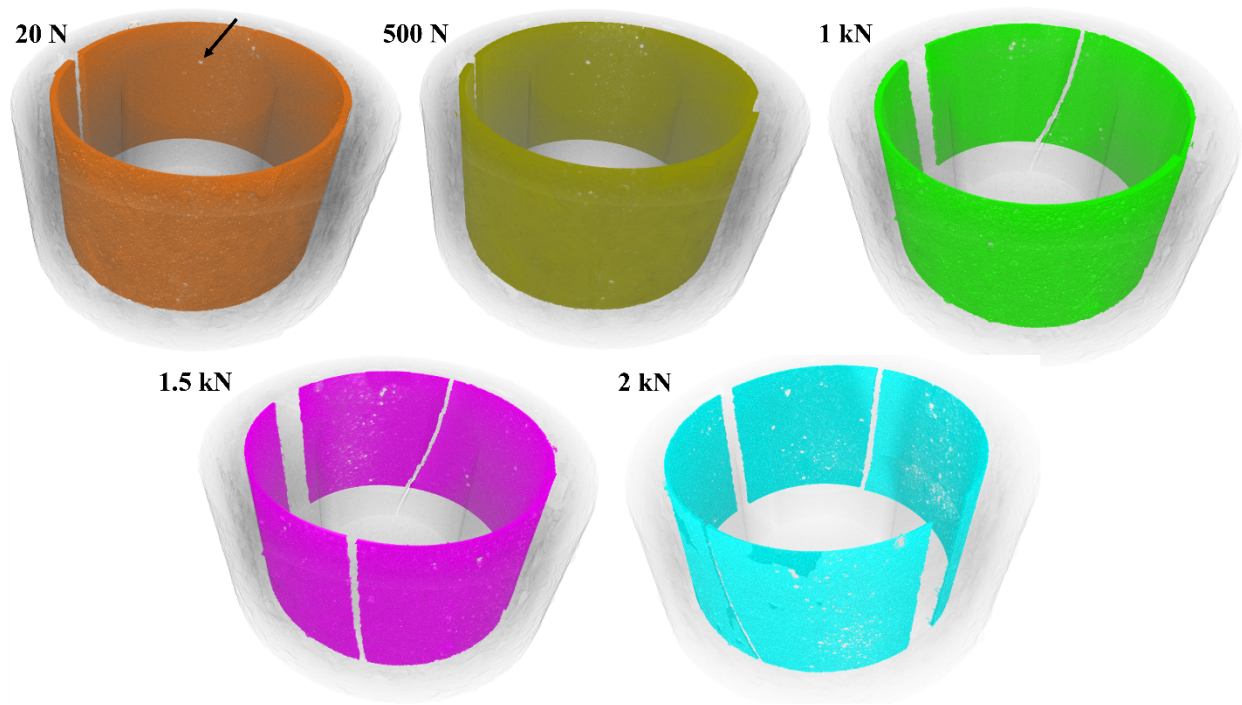


Figure 20. The gap between the collet and the inner surface of the tube segmented and presented as a function of the load. The holes in the segment correspond to where the collet contacts the inner tube surface (see example with black arrow). The tube outer diameter is about 10 mm.

At earlier stages of the loading, the contact points are limited. With increasing total system load, more contact points appear in the segmented gap, as shown in the 2 kN (cyan) image in Figure 20. The major implications of such load transfer would be increased loads on single points of contact. A more uniform load transfer may be achieved if the inner surface is machined to remove imperfections.

4. Discussion

4.1. Tube damage processes

In this study, a modified version of the EDC test was designed and applied to subject SiC/SiC composite tubes to hoop stresses while maintaining hard contact of the SiC tube to the fuel surrogate. To achieve these conditions, a hybrid approach used a split Al_2O_3 collet and a polyurethane plug to form a deformation couple. Initial testing revealed that a pure Al_2O_3 collet design is infeasible because tight tolerances for the collets were nearly impossible to achieve owing to dimensional differences between each composite tube sample. A pure Al_2O_3 collet design was further complicated by the presence of friction forces between the steel plunger (a conical plunger design different from this iteration) and the collets. The addition of the polyurethane plug helped decouple the EDC mechanism from the hard-contact effect, preventing the compressive force applied by the steel plunger from being directly taken by the collets. The plug also acted as a stabilizing medium that held the Al_2O_3 collet together even after the collet cracked, thereby maintaining the hard contact throughout the entire deformation regime.

The damage process is summarized in Table 1 for hard- and soft-contact testing conditions, detailing the crack onset, propagation, and failure behavior.

Table 1. A summary of the deformation processes observed for the hard and soft contact tests.

Highest load corresponds to 2 kN for hard contact and 4.2 kN for soft contact. (These load levels are arbitrary at this point and are only used to highlight where along the deformation curve we started observing cracks.)

Observation	Hard contact	Soft contact
Initial cracking system load	1.5 kN	3.5 kN
Initial crack locations	3 exterior, 1 interior	1 exterior, 2 interior
Number of cracks formed at highest load	4–5 exterior, 5–6 interior	2 exterior, 2 interior
Contact surface area at highest load	Point contact with $\sim 10 \text{ mm}^2$	Surface conformation with $\sim 230 \text{ mm}^2$
Effect of surface defects	Fragments the collet/fuel surrogate	No visible effects
Avg. radial displacement (U_r) at highest load	$2.64 \pm 8.65 \text{ } \mu\text{m}$	$3.97 \pm 7.55 \text{ } \mu\text{m}$
Crack propagation path as observed at ultimate failure	Straight through the monolithic layers. Deflect from diagonal fibers. Pass through vertical fibers through branching. Small pores act as crack propagation paths. Large pores can sometimes help stop crack propagation.	
Fiber pullout behavior	Observed, max distance: $\sim 389 \text{ } \mu\text{m}$	Observed, max distance: $\sim 378 \text{ } \mu\text{m}$

The cracks were first observed at 1.5 kN total system load under hard contact with three exterior and one interior cracks present. For soft contact, the first observable cracks appeared at a total system load of 3.5 kN with one exterior and two interior cracks. At mechanical failure with through-thickness cracking, the hard contact conditions led to the formation of four or five exterior and five or six interior cracks, whereas under soft contact, two exterior and two interior cracks were observed. This cracking was clearly affected by the contact behavior under the two different loading conditions.

The effect of surface imperfections is discussed in Section 3.5 for hard-contact deformation. Aside from the fragmentation of the collets (or fuel surrogate), the surface imperfections led to vastly different contact surfaces during deformation under hard contact and soft contact. This result is better shown in Figure 21a where the contact points between the collets and the SiC tube are highlighted in green with the aid of AI-assisted segmentation. For comparison, the surface conformation of the plug in soft-contact deformation is shown in Figure 21b. Overall, when calculated, the point contact conditions led to a total contact surface of approximately 10 mm^2 within the investigated volume under hard-contact conditions, whereas for soft contact with complete surface conformation, the contact surface area was approximately 230 mm^2 .

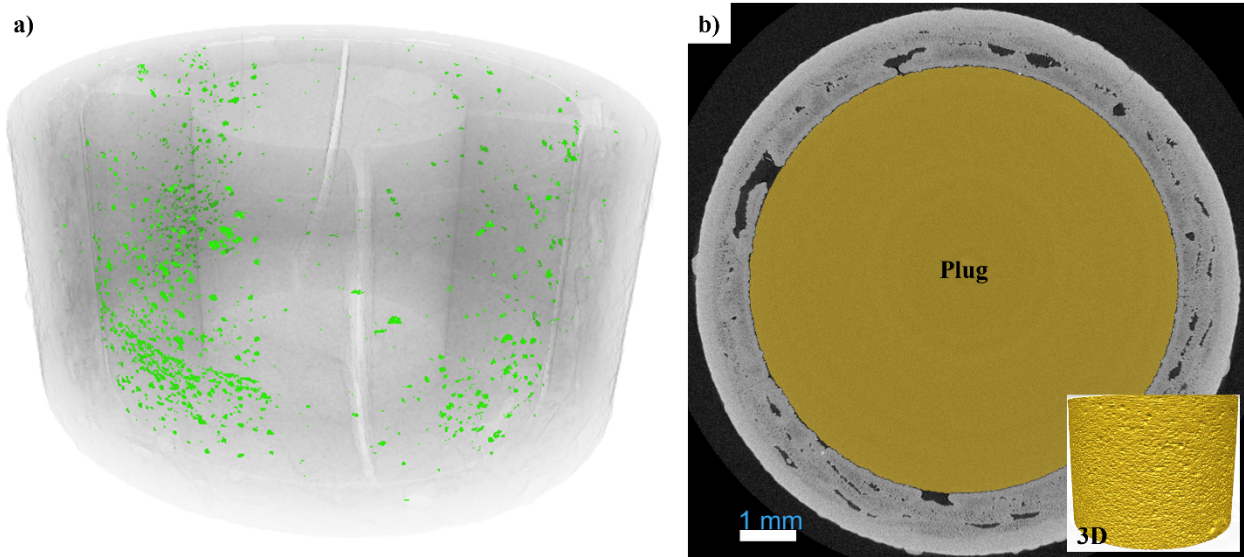


Figure 21. (a) 3D segmented image of the contact points between the collet and the SiC/SiC tube for hard-contact deformation. (b) 2D slice image of the soft-contact condition with the polyurethane plug segmented in yellow. A 3D image of the segmented plug is shown in the inset.

The fragmentation of the collet caused the load to be more unevenly distributed on the SiC/SiC tube, as shown in Figure 7, leading to an increased number of local minima (radial contraction)

and maxima (radial expansion) points under hard contact causing the formation of an increased number of both internal and external cracks compared with soft contact. This result is also manifested as a higher scatter in the average radial displacement under hard contact (Table 1). Thus, irrespective of the SiC/SiC cladding concept employed, the inner surfaces of the tubes need to be machined clean of any imperfections because these not only affect the stresses on the interior surface but also impose stress concentrations on the collet (fuel surrogate), causing cracking and segmentation into smaller pieces.

Independent from the loading mechanism (i.e., hard vs. soft contact), crack formation and propagation mechanisms were similar for all samples, as summarized in Table 1. Crack formation and propagation were found to be in line with the dominant hoop stresses, which caused vertical straight cracks that generally spanned the entire height of the tubes. This result was particularly evident in the monolithic layers that had little to no resistance to either crack formation or propagation. If it were not for the fiber fraction (20% in this case), the failure would have occurred earlier and more catastrophically. The fibers also contributed to material toughness via the fiber pullout mechanism before eventual failure. However, only the diagonal fibers were found to directly contribute to resistance of macroscopic crack opening processes, which is expected in this case of pure hoop loading (the axial fibers are not expected to provide much contribution with this load direction). The vertical fibers contributed little to no resistance to a radial expansion type of deformation, as would be seen in an actual PCMI. Accordingly, more diagonal fibers in the woven structure (in place of vertical fibers) would be beneficial for resisting loading by PCMI. However, the overall reinforcing fiber architecture for a SiC/SiC composite cladding tube must survive more stresses than just those caused by PCMI (including

thermal gradient and swelling-induced stresses, hydrostatic pressure, etc.), and the fiber architecture must be carefully selected to best accommodate a range of anticipated loading conditions.

Although the fiber layers provided the only real resistance to macroscopic crack propagation that led to their deflection and arrest, deviations and flaws in the fiber layers would enable the cracks to penetrate with ease because they act as paths of least resistance. To support this argument, 2D vertical slice images from the through-thickness crack of a hard-contact deformed sample are presented as examples in Figure 22. The crack deflection is indicated by a yellow arrow in Figure 22a, whereas in Figure 22b the crack can be seen to easily move through a relatively fiber-free (defective) area, again indicated by a yellow arrow. Furthermore, although not as significant, the string-like pore network between the fibers that failed to be infiltrated with CVI offers a path of least resistance for cracks to move. This suggests the need for a rigorous QA process to identify and screen for flaws at a scale that would impact the anticipated mechanical performance of the cladding tubes.

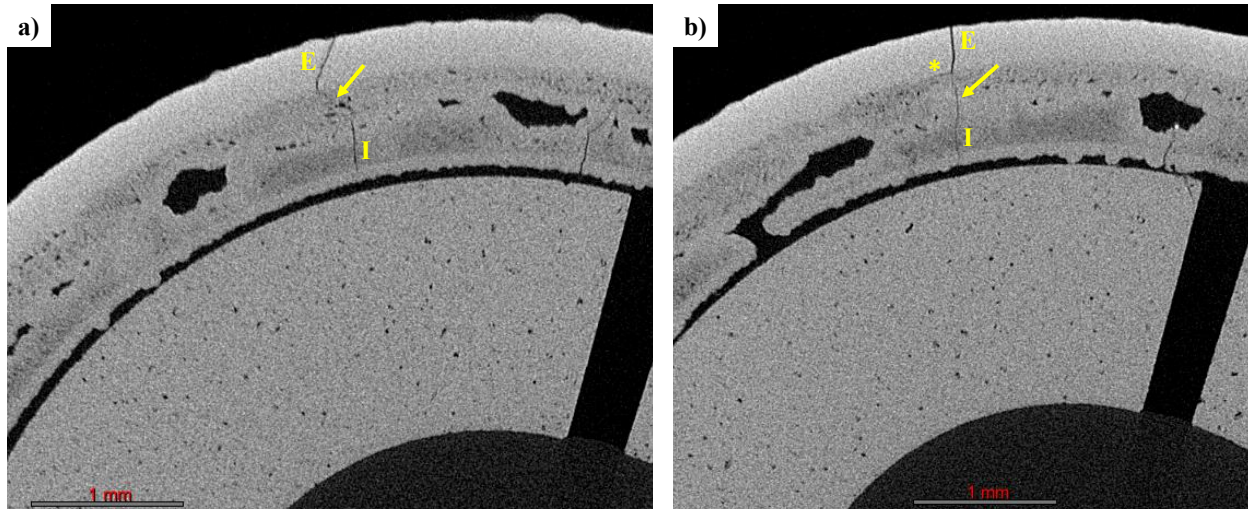


Figure 22. Vertical slices of the critical crack under hard contact. “E” and “I” denote the exterior and interior cracks, respectively, and the yellow arrow shows the mid-section where possible crack deflection (a) takes place. A delamination is indicated in (b) by an asterisk.

Also shown in Figure 22b is the start of a delamination (*). This feature may be related to processing steps (ex. surface smoothing) that occur at different stages of the cladding fabrication, and more investigation is needed to understand microstructural features at the interface between the outer monolith and the fiber layer through which the crack can propagate and cause eventual delamination.

4.2. Implication of the results on the application

The PCMI in LWRs can occur under multiple conditions such as power ramps, start-ups, and reactivity-initiated accidents (RIAs). In all types of scenarios, the fuel tends to thermally expand due to increased fission rate, which imparts a biaxial surface traction between cladding and fuel once the fuel–cladding gap is closed. The time and amount of burn-up required to reach this closure point will depend on the starting gap for a given fuel-cladding design. As an exception,

the same loading occurs very fast (~ 50 ms) during RIAs [36] owing to the prompt reactivity insertion. Because the PCMI is a contact loading, the uniform load transfer to the cladding is critical because the complex surface tractions on a rough surface can concentrate stresses on localized regions, possibly initiating critical cracks and cladding failure.

Current LWR zirconium alloy cladding is manufactured to have low inner surface roughness. However, the stress localization at the contact surface is manifested by the presence of potential critical inner surface defects or unfavorable microstructural features in the zirconium alloy cladding. However, inner surface roughness of SiC/SiC cladding is far more critical because the crack initiation strain is significantly lower than in zirconium-based alloys. For instance, a localized hard contact on a rough SiC/SiC surface can trigger premature failures under PCMI conditions, as discussed in the previous section. Because the SiC/SiC composites and surface fabrication benefits from CVI processes [3, 15, 37, 38], the PCMI type of failure observed in this study is also expected to apply to other vendors' cladding concepts that rely on similar CVI-based manufacturing routes and reinforcing fiber architectures.

This study mainly focused on the ultimate failure of the SiC/SiC tubes that would result in the release of fissile material. However, under normal operating conditions, if microcracks were to form in either of the monolithic SiC layers, then the hermeticity of the tube would be jeopardized because of the pore network between the fibers. Accordingly, in areas where coolant is in direct contact with the cladding, the hermeticity must be a top priority. Therefore, the use of a pure monolithic SiC layer may be a source of risk because it offers little to no resistance to crack formation and propagation. A multilayered approach may be necessary for field deployment: alternating layers of woven SiC fibers and monolithic SiC would provide fail-safes.

Furthermore, although a completely defect-free composite structure is not realistically achievable, an improved CVI process would ensure closest-to-complete filling of the voids between the fibers. This would be beneficial because the cracks can follow these pore networks (as has been shown here) and lead to critical failure or loss of hermeticity.

Because localized loading exhibited significant influence on the observed mechanical response of the SiC/SiC cladding, the fuel performance models need to capture these effects along with the nonuniform, likely randomly distributed, inner surface macroscopic defects/features. To develop a representative fuel performance model, these defects/features can be averaged without bypassing critical defects/features in the model. Importantly, the estimation of load partitioning between the SiC/SiC cladding and nuclear fuel as affected by the defects/features can enable to determine mechanical disintegration of fuel during transients.

Finally, it is well-known that SiC/SiC composites represent a highly complex and diverse class of materials wherein the final mechanical properties can be affected by a multitude of factors such as weave patterns, number of layers, interface materials, etc.. Accordingly, no single study can be generalized to represent the properties at large and it is the aim of studies such as this one to offer a perspective until a gold standard is reached.

5. Conclusions

This study investigated the effects of hard-contact hoop expansion on SiC/SiC composite tubes. Tests were performed with in-situ XCT by employing a modified EDC test with a polyurethane plug and alumina collets to mimic the nuclear fuel's hard contact during potential PCMI-type

loadings in LWRs. Pure EDC testing with just a polyurethane plug (soft contact) was also employed as a reference. Deep learning-based data analysis and DVC revealed the evolution of the mechanical damage at various loading conditions and helped determine the microstructural aspects of the fracture in the SiC/SiC tubes.

Initial XCT results revealed a heterogeneous structure with pores scaling from micrometers to millimeters. These pores were expected to affect the deformation behavior of the tubes coupled with the uneven inner diameters. As revealed by the displacement fields from DVC, even during the pure EDC testing wherein the polyurethane plug conforms to the inner surface of the tube, an inhomogeneous deformation field was observed with distinct zones of expansion and contraction. This result was further amplified under hard-contact testing with a fragmented collet, which led to sharp changes between local minima (contraction) and local maxima (expansion). These caused the formation of multiple internal and external hoop-type cracks. This effect was intensified by the presence of surface imperfections on the inner surface of the SiC/SiC composite tube. These imperfections acted as stress concentration zones on both the SiC tube and the collet (by analogy, the fuel pellet). Imperfections as small as 60 μm diameter were found to impose these effects; therefore, SiC/SiC cladding inner surfaces could be machined smooth to reduce the occurrence of these stress concentration zones.

The tested SiC/SiC composite tubes consisted of four distinct regions: dense outer SiC monolith, a single SiC fiber woven layer, a porous SiC monolith layer, and a dense inner SiC monolith. Specimens failed with through-thickness hoop-axial plane cracks. Cracks were found to initiate either on the outer or the inner monolith and pass through them with little to no resistance, as

evidenced by the lack of crack deflection, and take the path of least resistance whenever possible. The SiC fiber reinforcement provided additional load-carrying capability by deflecting minor cracks along the fiber–matrix interface and by the fiber pullout mechanism. However, only the diagonal fibers were found to effectively deflect the macroscopic cracks in this hoop expansion scenario: cracks could penetrate through the vertical fibers via crack branching through voids between these fibers as small as 9 μm in diameter. Delamination-type failure was also observed in areas where the outer monolithic layer started separating from the woven fiber layer, and the causes of this effect will require further investigation.

Overall, localized loading introduced by hard contact on the inner surface of the SiC/SiC tube significantly contributed to the observed deformation and failure response. In addition to refinement of the manufacturing processes to minimize the defects both interior and exterior to the tube, the fuel performance models would benefit from capturing these effects to develop a more representative model.

Acknowledgments

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