Experimental Investigation on Pellet-Cladding Interaction Behavior of SiCf/SiC Composite Cladding with Mandrel Test under Ambient and Elevated Temperature Conditions

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Date: 2025-05-17T12:00:47+00:00

Abstract

This study focuses on the Pellet-Cladding Mechanical Interaction (PCI) behavior of silicon carbide fiber-reinforced silicon carbide composite (SiCf/SiC) cladding as an Accident-Tolerant Fuel (ATF) material. A specialized mandrel expansion test apparatus was developed to systematically investigate its failure characteristics under ambient and elevated temperatures (up to 920°C) and varied loading rates (0.5–1 mm/min). The experimental setup integrated Digital Image Correlation (DIC) and strain gauge systems to quantify stress-strain responses and critical failure parameters. Results demonstrated that elevated temperatures significantly degraded the load-bearing capacity of SiCf/SiC cladding, with average failure loads decreasing by 36.7% and failure strains reducing by 9.8%. Increased loading rates exacerbated non-uniform plastic deformation, leading to approximately 30% lower failure loads under room-temperature conditions. Furthermore, the failure process of SiCf/SiC cladding exhibited five distinct stages, with Stage IV (plunger-induced radial compression triggering cladding rupture) identified as the critical failure phase. This research provides essential experimental data for evaluating PCI performance of SiCf/SiC composite cladding, elucidates its high-temperature mechanical degradation mechanisms, and offers theoretical insights for optimizing nuclear fuel element design.

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Abstract

This study investigates the Pellet-Cladding Mechanical Interaction (PCI) behavior of silicon carbide fiber-reinforced silicon carbide composite (SiCf/SiC) cladding as an Accident-Tolerant Fuel (ATF) material. A specialized mandrel expansion test apparatus was developed to systematically characterize failure mechanisms under ambient and elevated temperatures (up to 920°C) at varied loading rates (0.5–1 mm/min). The experimental setup integrated Digital Image Correlation (DIC) and strain gauge systems to quantify stress-strain responses and critical failure parameters. Results demonstrate that elevated temperatures significantly degrade the load-bearing capacity of SiCf/SiC cladding, with average failure loads decreasing by 36.7% and failure strains reducing by 9.8%. Increased loading rates exacerbated non-uniform plastic deformation, leading to approximately 30% lower failure loads under room-temperature conditions. Furthermore, the failure process of SiCf/SiC cladding exhibited five distinct stages, with Stage IV (plunger-induced radial compression triggering cladding rupture) identified as the critical failure phase. This research provides essential experimental data for evaluating PCI performance of SiCf/SiC composite cladding, elucidates its high-temperature mechanical degradation mechanisms, and offers theoretical insights for optimizing nuclear fuel element design.

Key Words: SiCf/SiC composite cladding; Pellet-Cladding Mechanical Interaction; Mandrel expansion test; Experimental data

Introduction

As the primary safety barrier in nuclear reactors, fuel cladding plays a pivotal role in fission product retention and operational safety assurance. Systematic evaluation of cladding performance represents a fundamental requirement in nuclear fuel element design, particularly concerning geometric stability maintenance to prevent coolant channel blockage from excessive swelling or catastrophic structural failure [1-3]. Zirconium-based alloys, the prevailing cladding materials in light water reactors, have demonstrated satisfactory performance under normal operating conditions through advantageous neutron transparency and Pellet-Cladding Mechanical Interaction (PCMI) adaptive ductility. Nevertheless, post-Fukushima analyses have exposed three critical vulnerabilities [4-5]: (1) temperature-dependent strength degradation with compromised high-temperature load-bearing capacity; (2) time-dependent mechanical deterioration exacerbated by oxidation and corrosion susceptibility; and (3) exothermic zirconium-water reactions with hazardous hydrogen generation during beyond-design-basis accidents. Consequently, researchers worldwide have focused on developing alternative Accident-Tolerant Fuel (ATF) claddings through experimental and simulation studies [6-8].

Currently, SiC fiber-reinforced SiC matrix (SiCf/SiC) composite cladding has emerged as a leading candidate for next-generation fuel element cladding technologies, owing to its low neutron absorption cross-section, exceptional oxidation resistance, and superior creep resistance [9-12]. The SiCf/SiC composite cladding fundamentally differs from metallic claddings by eliminating hydrogen generation during high-temperature oxidation under Loss-of-Coolant Accident (LOCA) scenarios [13-14], thereby preventing hydrogen explosions at their source. Nevertheless, despite possessing ceramic-like wear resistance and metal-like pseudo-ductility enabled by the outer monolithic CVD SiC layer and internal fiber-woven CMC SiC structure [15], the inherent brittleness of ceramic materials inevitably increases stress-induced failure probability. When pellet-cladding gap closure occurs, neither SiC nor fuel pellets possess sufficient creep deformation capacity to relieve PCMI-induced stresses, potentially leading to cladding failure under elevated hard-contact pressures [1-2].

More importantly, irradiation effects and fiber architecture cause the thermal conductivity of SiCf/SiC composite cladding to decrease sharply, leading to high temperature gradients in fuel pellets and additional radial expansion. Both simulation and experimental results [16] reveal that the irradiation swelling of SiCf/SiC composite cladding is directly affected by its temperature, and temperature gradients cause significant radial swelling strain gradients, which manifest as increased cladding stress and adversely affect cladding integrity during power reduction [9,17]. Consequently, it can be predicted that fuel elements using SiC composite cladding will have reduced probability of in-reactor failure caused by foreign objects or grid fretting wear, but their main failure mode will shift to stress-induced failure [18].

To investigate the PCI characteristics of advanced claddings, researchers typically conduct RAMP tests in test reactors to simulate commercial reactor environments for leading fuel rods. However, considering the current global scarcity of test reactors capable of performing RAMP tests, particularly after the permanent shutdown of the Halden Reactor that previously supported such experiments, the international community has increasingly adopted mandrel tests in recent years to replicate key mechanical features of PCI behavior in novel claddings. This approach partially compensates for RAMP test limitations under cost, schedule, and infrastructure constraints. For instance, Sweden's Studsvik AB, as an OECD-NEA SCIP (Studsvik Cladding Integrity Project) participant, has developed in-pile mandrel test facilities to study post-irradiation zirconium alloy cladding PCI behavior.

Figure 1 [Figure 1: see original paper] illustrates the schematic of a typical mandrel expansion test [19]. The fundamental principle involves using a plunger's axial displacement to simulate pellet-cladding interaction, where the cladding specimen deforms under radial compression from simulated pellets, leading to crack propagation. This process is conducted under controlled atmosphere and temperature to replicate chemical and thermal effects on PCI behavior during reactor operation. Studsvik's comparative studies demonstrate that mandrel-expanded specimens exhibit similar strain ranges at failure and comparable crack surface micro-structures to RAMP-tested counterparts. Both macroscopic inspection and microscopic analysis confirm that mandrel expansion testing serves as an effective out-pile surrogate method analogous to RAMP testing.

Figure 1 Schematic diagram of the mandrel expansion experimental setup [19]: (1) Pellets; (2) Cladding; (3) Plunger; (4) Sealing Fixture

However, current international research on mandrel testing for SiCf/SiC composite claddings, particularly under high-temperature conditions ($ 900°C), remainsinsufficienttoprovideenoughrelevantexperimentaldata, suchasfailurestressandultimate$
21]$.Againstthisbackground, thisstudyconductedmandreltestsonSiCf/SiCcompositecladdingsatbothambient$
investigating the correlation between loading stress and cladding surface displacement, as well as the stress-strain relationships under different loading rates. By varying loading speeds, comparative analyses of failure processes and stress/strain data were performed, ultimately establishing strain and loading limits.

It should be noted that while cladding strain during mandrel testing can be experimentally measured, cladding stress cannot be directly obtained through testing. Therefore, numerical simulation methods should be used to establish a finite element model analyzing the progress, and this has been completed in another paper to guide PCI performance evaluation of SiC cladding materials.

Experimental Setup for Mandrel Testing of SiCf/SiC Composite Cladding

According to the experimental requirements, the fuel element typical grid cell mandrel expansion test bench should be able to simulate the failure processes of SiCf/SiC composite fuel cladding under different loading speeds and temperatures, obtain stress/strain data, with the inner diameter of the SiC-based composite cladding being approximately 9.5 mm. The cladding strain measurement in room-temperature mandrel tests includes two schemes: strain gauges and DIC (Digital Image Correlation), to ensure mutual verification between the methods.

The overall test loop is shown in Figure 2 [Figure 2: see original paper]. The test loop mainly includes the mandrel test section and fixture loading system, gas loop and monitoring system, temperature control system, force loading system, test section resistance monitoring system, strain measurement system, and data acquisition system.

Figure 2 Schematic diagram of the fuel element typical grid cell mandrel expansion test bench

Main Functions and Descriptions of Each System:

1. **Mandrel Test Section System:** The main function of the mandrel test section is to fix simulated pellets and different types of SiC cladding tubes to conduct mandrel expansion experiments. The mandrel test section is shown in Figure 3 [Figure 3: see original paper] and is mainly composed of simulated pellets, cladding tube test specimens, grooved base, high-temperature ceramic fiber tapered sealing gaskets, etc.: (1) Simulated pellets: Ring-shaped alumina ceramic is used, with height and outer diameter consistent with actual fuel pellet dimensions. Four mutually symmetrical initial cracks (depth and width both 1 mm) are preset on the outer surface to allow gas flow in the test section and simulate stress concentration during PCMI; (2) Test specimens: SiCf/SiC composite cladding with an inner diameter of 9.5 mm is adopted, and the length is selected as 500 mm; (3) Grooved base: A chamfer is set on the side contacting the simulated pellets to ensure gas flowability when initial cracks and grooves are misaligned; (4) High-temperature tapered sealing gaskets: Used for sealing both ends of the test specimen to facilitate control of oxygen content inside/outside the cladding, enabling detection of failure in specially-shaped SiC monolithic cladding.

Figure 3 Mandrel Test Section

2. **Fixture Loading System:** The fixture loading system is shown in Figure 4 [Figure 4: see original paper]. Its primary function is to isolate the internal and external gas environments of the test specimen throughout the experiment. The system material is 316 austenitic stainless steel (0Cr17Ni12Mo2). The material in localized regions sealingly contacting both ends of the test specimen adopts oxygen-free copper with higher ductility.

Figure 4 Schematic diagram of the mandrel test section and fixture loading system

3. **Gas Loop and Monitoring System:** Used to generate required environmental gases, control and monitor oxygen content, and treat exhaust gases. Mainly includes two test loops: (1) Helium loop outside the cladding tube: Connected from high-pressure helium cylinders to the

furnace interior (external to the mandrel test section), primarily ensuring constant external pressure, providing an inert gas atmosphere to prevent high-temperature oxidation of the cladding and heating elements. Cladding failure is determined by monitoring the helium leakage rate into the cladding tube. Note: Due to the high porosity of SiCf/SiC composites, cladding failure cannot be assessed via oxygen content measurements; thus, resistance monitoring is used to evaluate the failure behavior of SiC-based composite cladding. (2) Argon loop inside the cladding tube: Comprising pressure relief valves, the interior of the mandrel test section, helium-in-argon detectors, and exhaust treatment tanks. It controls oxygen content to prevent oxidation films on the cladding inner surface from hindering stress corrosion cracking. Adjusting argon flow maintains constant internal pressure. Helium leakage into the cladding tube during cracking is detected by gas analyzers.

4. **Temperature Control System:** The primary function is to achieve and maintain the required temperature for high-temperature mandrel expansion experiments over extended periods. The system consists of a temperature-controlled furnace. The furnace has front/rear visualization windows for non-contact strain measurements. Temperature-measuring thermocouples are installed both inside the furnace and on the outer side of the mandrel test section to monitor furnace and cladding temperatures, enabling feedback control of the furnace heating power.

5. **Loading System:** The main function is to drive axial displacement of a plunger via a servo motor, forcing simulated pellets to interact with zirconium alloy cladding tubes until radial expansion and rupture occur. The mandrel expansion test employs a servo motor with a reducer.

6. **Strain Measurement System:** Designed to measure real-time maximum cladding outer diameter deformation during testing while ensuring ambient factors (e.g., furnace temperature) do not affect measurement devices or accuracy. Per client requirements: (1) Room-temperature tests: Combine strain gauges and DIC (Digital Image Correlation) for mutual validation; (2) High-temperature tests: Use non-contact DIC with corrections: optical filters on viewing windows, external air circulation fans, and grayscale averaging method for image post-processing to minimize thermal errors. Two VIC-3D DIC measurement systems ($±$1 m) are employed for high-temperature cladding strain measurement. After standard calibration, radial cladding deformation is measured using dual 8 mm CCD cameras (resolution: 1-29 million pixels; frame rate: 1–10 million FPS) positioned at 25°–60°, as shown in Figure 5 [Figure 5: see original paper]. Calibration plates determine camera parameters (relative distance, object-to-camera distance). Disparity data from matched camera algorithms reconstruct 3D surface morphology from images, yielding digital measurement results.

Figure 5 Deformation Acquisition System

7. **Data Acquisition System:** The data measurement and acquisition system consists of plunger axial load, plunger axial displacement, cladding temperature, gas flow rate, oxygen content, furnace pressure, pressure inside the cladding tube, NI acquisition system, and supporting computer.

3.1. Test Procedures

As shown in Figure 6 [Figure 6: see original paper], the test procedures for SiCf/SiC composite cladding mandrel expansion experiments include the following steps: (1) Pre-test status inspection: Examine specimen surface quality (surface roughness, presence of initial defects, flatness of end faces), and record detailed cladding dimensions (length, inner diameter, outer diameter, and wall thickness); (2) Strain gauge installation for room-temperature tests: Attach strain gauges to both sides of the cladding to prevent data loss due to bilateral cracking. These gauges also enable cross-calibration with DIC strain data; (3) Speckle pattern preparation: Apply primer to the cladding and create speckle patterns for DIC strain measurement. Two DIC systems (each with two cameras front/rear) achieve 240° strain measurement through the furnace observation windows; (4) Test section assembly: Install the mandrel and metal base into the cladding, then clamp the cladding with fixtures to secure the test section; (5) DIC system calibration: Adjust camera distance and lighting, perform initial calibration using a calibration plate, align dual lenses in the VIC-3D system to focus on the predicted maximum strain area of the cladding, and record strain variations; (6) Specimen status verification: Check for looseness in the test assembly and ensure the mandrel is within the DIC sampling area; (7) High-temperature test setup: Purge air from the furnace interior and cladding tube by injecting helium/argon to create an inert atmosphere, preventing high-temperature oxidation of the cladding and speckle patterns. Activate the cooling water system to cool furnace windows and test sealing sections. Heat the test section to 920°C according to predefined protocols; (8) Data acquisition system activation: Start the strain measurement and data acquisition systems; (9) Plunger loading control: Drive the plunger downward via predefined programs. Monitor plunger load changes and DIC images to determine cladding failure; (10) Post-test analysis: Inspect specimen structural integrity and document crack characteristics (location, length, depth, etc.).

Figure 6 SiCf/SiC composite cladding mandrel expansion test process

3.2. Specimen Status

This experiment utilizes a three-layer composite cladding material structure: CVD SiC / CMC SiC / CVD SiC. The outer and inner layers are monolithic CVD SiC, primarily serving to protect the woven layer from water-side corrosion and block fission gas release. The middle layer is a 2D woven SiC layer deposited on the matrix using a microscopic process, mainly enhancing the cladding's mechanical properties and providing quasi-plasticity.

The experiment includes two conditions: room temperature (25°C) and high temperature (900°C). Prior to formal testing at room temperature, dimensional measurements and 3D X-ray structural scanning were performed on all specimens. A certain number of interfacial defects exist between the layers of each composite cladding specimen, which may affect test repeatability. The average inner diameter and outer diameters of these specimens are 10.75 mm and 8.38 mm, averaged from multiple measurements taken at different circumferential positions of the top and bottom sections. Results indicate that due to non-uniformity in SiCf/SiC composite manufacturing processes, variations in inner diameter and outer diameter exist across different axial positions. These variations will influence the failure behavior of each fuel cladding during mandrel expansion.

3.3. Relationship Between Plunger Displacement and Load

To determine the relationship between plunger displacement and simulated pellet load, a preliminary test was conducted on Specimen 0. As shown in Figure 7 [Figure 7: see original paper], the metal base positions the simulated pellet at the cladding center for DIC imaging. The force loading system consists of a servo motor, reducer, push rod, and control cabinet. The plunger is adjusted to the cladding top and moved at 10 mm/min, where the plunger remains above the simulated pellet without contact. Subsequently, the plunger is driven at 1 mm/min or 0.5 mm/min. During this process, the plunger compresses the simulated pellet until fracture occurs, followed by further compression until cladding rupture. The resulting load-time curve can be divided into five distinct stages.

Figure 7 Plunger axial loading process

Based on the plunger loading displacement, the experimental strain curve can be divided into five stages:

Stage I: The plunger is not in contact with the pellet, and the load remains stable at 30–50 N (due to friction between the plunger and sealing ring).

Stage II: The plunger contacts and compresses the simulated pellet until pellet fracture occurs, during which the load continuously increases until pellet rupture.

Stage III: As the plunger continues downward loading, the fractured pellet does not immediately contact the cladding due to existing gaps between the cladding and pellet, resulting in a temporary “unloading” process of the load.

Stage IV: The plunger further compresses the fractured pellet into contact with the cladding. With continued downward loading, the load steadily rises until cladding rupture occurs.

Stage V: Cladding rupture leads to an abrupt load drop, which serves as the failure criterion.

Figure 8 [Figure 8: see original paper] Phases of load variation

4.1. Room-Temperature Mandrel Test Results

Figure 9 [Figure 9: see original paper] shows the appearance and failure locations of the failed SiC composite cladding, while Table 1 details the crack dimensions of each SiCf/SiC composite cladding after failure under different loading rates. It can be observed that the cladding failure positions are primarily located in the central simulated pellet region. Due to the brittle nature of the composite material, cracks in all specimens are positioned in the axial mid-region and are through-thickness cracks, while their circumferential distribution appears relatively random. The crack lengths range from 6 to 14 mm, and the rupture dimensions correlate with the size and location of the simulated pellets.

Figure 9 Failed SiC Composite Cladding

Table 1 Post-Test Condition Inspection of SiCf/SiC Composite Cladding Under Room-Temperature Conditions

Test Conditions	1 mm/min	0.5 mm/min
Specimen No.	Crack Location	Crack Location
	Right Rear Side	Left Front Side
	Rear Right Front	Center Rear Center
Crack Length	Through	Through
Crack Depth	Through	Through

4.1.1. Failure Load under Room-Temperature Conditions

Figure 10 [Figure 10: see original paper] shows the load-time curves of SiC cladding under different loading rates (1 mm/min, 0.5 mm/min). After pellet-cladding contact occurs, the load-time curves exhibit similar trends. Notably, the load-time curve of Test 2 lacks the pellet fracture processes corresponding to Stages II and III. This discrepancy may result from dimensional variations among specimens, where the smaller gap between the cladding and simulated pellet in this test led to tighter contact. However, the slope consistency and trend alignment of curves under identical loading rates confirm stable test condition control and good reproducibility. Additionally, all curves display post-peak load reduction, indicating material fracture/failure after reaching ultimate load. The slower decline of the 0.5 mm/min curve reflects progressive failure behavior under quasi-static loading.

Figure 10 Room-Temperature Composite Cladding Load-Time Curve

From the figure, the curve with a 0.5 mm/min test speed exhibits significantly higher peak loads than the 1 mm/min curve. For example, the 0.5 mm/min test reaches a peak near 5000 N, whereas the 1 mm/min test peaks at approximately 4000 N. This indicates that slower stress loading rates allow the material to withstand higher failure loads, which may be related to material strain hardening or internal damage accumulation under quasi-static loading. These conclusions are further clarified in Table 2 , which details the failure loads and failure times of SiC cladding under different loading rates: the failure load decreases with increasing plunger loading rates. Additionally, at lower plunger loading rates, the cladding experiences slower actual strain rates, leading to more uniform plastic deformation. Higher plunger loading rates elevate stress levels, resulting in non-uniform cladding plastic deformation and consequently lower axial loads. Thus, the significant load response differences under varying loading rates demonstrate the strain rate sensitivity of SiC composite cladding. Its mechanical properties (e.g., strength, toughness) are strongly influenced by loading rates, a critical consideration in fuel design, particularly for pellet-cladding mechanical interaction (PCI) scenarios.

Table 2 Failure load and time under different loading rates at room temperature

Loading speed	Failure load	Average failure load	Failure time	Average failure time
Room temperature 1 mm/min	2594 N	3280 N	1305 s	1262 s
Room temperature 0.5 mm/min	3965 N	4722 N	1204 s	1278 s

4.1.2. Failure Strain under Room-Temperature Conditions

When the radial deformation of the cladding reaches a critical magnitude, defects such as through-thickness cracks or ruptures occur. The corresponding strain at this moment is defined as the failure strain. In SiC cladding mandrel expansion tests, the brittle nature of SiC material ensures that plunger load changes precisely correspond to the cladding failure moment. Cladding rupture and structural integrity loss occur when the plunger load abruptly unloads, thus selecting this moment to determine the failure strain.

As described, speckle patterns were created by spraying primer on the cladding surface. Two VIC-3D DIC (Digital Image Correlation) measurement systems were employed as cladding strain measurement systems, with an accuracy of $±$1 m. To prevent strain data loss due to lateral cracking, 1 mm-diameter strain gauges were installed on both sides of the cladding. The room-temperature strain contour maps are shown in Figure 11 [Figure 11: see original paper].

Figure 11 DIC Strain Contour Maps: (a) Specimen 0 (b) Specimen 1 (c) Specimen 2 (d) Specimen 3 (e) Specimen 4 (f) Specimen 5

Under room-temperature conditions, the strain-time variation curves of SiCf/SiC composite cladding under different loading rates are shown in Figure

12 [Figure 12: see original paper]. After pellet-cladding contact occurs, the radial deformation of the cladding increases linearly and exhibits a time-dependent correlation. Despite dimensional variations among specimens due to manufacturing factors, the actual strain rates (strain slopes) under identical plunger displacement rates remain relatively consistent. When the plunger loading rate increases, the strain variation trend at cladding failure becomes more pronounced compared to lower strain rate conditions.

Figure 12 Strain-time curve of room-temperature composite cladding

Table 3 presents the failure strain and average failure time of SiCf/SiC composite cladding under room-temperature conditions at different loading rates. Specimen failure is primarily determined by the rate of load variation. When the plunger loading rate is 0.5 mm/min, the average failure strain is 0.41%. As the plunger loading rate increases to 1 mm/min, the average failure strain of the SiC composite cladding decreases from 0.416% to 0.295%, with a significant concurrent reduction in failure load.

Table 3 Failure strain of SiC composite cladding at room temperature

Loading speed	Failure strain	Average failure strain	Failure time	Average failure load
1 mm/min	0.28%	0.295%	1305 s	3280 N
0.5 mm/min	0.31%	0.416%	1204 s	4722 N

4.2. High-Temperature Mandrel Test Results

Prior to high-temperature testing, the heating furnace was heated to 920°C within 4.5 h and held for 2 h. After test completion, the furnace was cooled to room temperature at a constant rate over 6 h to prevent glass viewing window damage caused by rapid cooling. K-type sheathed thermocouples were installed at different axial positions of the cladding to ensure axial temperature uniformity, with a maximum axial temperature difference of 12°C across the specimen.

Figure 13 [Figure 13: see original paper] High-Temperature Test Heating and Failed Specimen

Table 4 Post-test condition Inspection of SiC composite cladding

Condition	Room temperature 1 mm/min	Room temperature 0.5 mm/min	High temperature 0.5 mm/min
Specimen	Crack Location Right Front Center	Crack Location Right Front Center	Crack Location Center Front Right

Condition	Room temperature 1 mm/min	Room temperature 0.5 mm/min	High temperature 0.5 mm/min
Crack Length	Through	Through	Through
Crack Depth	Through	Through	Through

4.2.1. Failure Load Under High-Temperature Conditions

Figure 14 [Figure 14: see original paper] shows the load-time curve obtained from the mandrel expansion test of SiC composite cladding at 920°C and 0.5 mm/min. After pellet-cladding contact occurs, the load-time curves exhibit similar trends, demonstrating good reproducibility of the mandrel expansion tests.

Figure 14 Load-Time Curves Under Different Temperatures and Loading Rates

Table 5 lists the failure loads and failure times of SiC cladding under different loading rates. Within the 0.5–1 mm/min loading rate range, the average failure time decreases with increasing plunger loading rates, while the average failure load also shows a declining trend. At high temperature (920°C), the average failure load (2,994 N) decreases by 36.7% compared to room temperature (4,722 N). This reduction may be attributed to: (1) Amorphization of the CVD SiC matrix phase may lead to reduced hardness; and (2) Degraded interfacial shear strength caused by thermal expansion mismatch of interfacial PyC layer between SiC fibers and the matrix.

Table 5 Failure Load and Failure Time of Composite Cladding Under Different Loading Rates at Room Temperature

Test Condition	Failure load	Average failure load	Failure time
Room temperature 1 mm/min	2594 N	3280 N	1305 s
Room temperature 0.5 mm/min	3045 N	4722 N	1204 s
High temperature 0.5 mm/min	2994 N	2994 N	1023 s

4.2.2. Failure Strain of Composite Cladding Under High-Temperature Conditions

Consistent with room-temperature experiments, speckle patterns were created by spraying primer on the cladding surface. Two VIC-3D DIC (Digital Image Correlation) measurement systems were employed as the cladding strain measurement systems. The DIC strain contour maps and strain curves are shown in the figure below.

Figure 15 DIC Strain Contour Maps and Strain Curves: (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) High-Temperature Strain-Time Curve

Figure 15 [Figure 15: see original paper] (d) shows the strain-time variation curve of SiC composite cladding at 920°C. Before pellet-cladding contact, the cladding strain remains low. However, thermal airflow disturbances within the furnace introduce noise points during DIC measurements. After pellet-cladding contact, the radial deformation of the cladding exhibits a linear correlation with time. The consistency of actual strain rates (strain slopes) further demonstrates good reproducibility of the mandrel expansion tests.

Table 6 summarizes the failure strain and average failure time of SiC composite cladding under different temperatures and loading rates. Key observations include: (1) At room temperature with a plunger loading rate of 0.5 mm/min, the average failure strain is 0.41%; (2) At 920°C under the same loading rate, the average failure strain decreases to 0.37%, representing a 9.8% reduction compared to room-temperature conditions. These results indicate significant temperature effects on cladding failure behavior, particularly for pellet-cladding mechanical interaction (PCI) under high-temperature scenarios such as loss-of-coolant accidents (LOCA).

Table 6 Failure Strain of SiC Composite Cladding

Test conditions	Failure strain	Failure time	Average failure strain
Room temperature 1 mm/min	0.28%	1305 s	0.295%
Room temperature 0.5 mm/min	0.31%	1204 s	0.41%
High temperature (920°C) 0.5 mm/min	0.27%	1023 s	0.37%

5. Conclusions

This study conducted out-of-reactor pellet-cladding mechanical interaction (PCI) experiments on SiCf/SiC composite cladding tubes using a mandrel expansion methodology, establishing a numerical simulation framework for SiC cladding tube PCI behavior validated against experimental data.

(1) A specialized out-of-reactor mandrel expansion test apparatus was designed for SiC composite cladding tubes. The developed test bench supports the simulation of mandrel expansion behavior of simulated pellets and SiC cladding tubes at environmental temperatures up to 1100°C, enabling testing under varied loading rates and temperature conditions.

(2) Dual VIC-3D DIC measurement systems and high-precision strain gauges were adopted as the cladding strain measurement system. The CCD imaging technology achieved a measurement accuracy of $±$1 m. For room-temperature tests, axial and longitudinal strain gauges (sampling rate: 10 kHz) provided strain data consistent with DIC results. High-temperature speckle patterns sprayed on cladding surfaces enabled 3D strain field measurement, while digital image processing identified maximum surface strain at failure.

(3) The out-of-reactor PCI behavior of SiC composite cladding exhibited five distinct stages, with critical deformation and failure occurring predominantly in Stage IV. Higher loading rates reduced average failure time and strain while slightly decreasing failure loads, likely due to stress concentration in thin-wall regions caused by non-uniform plastic deformation.

(4) Elevated temperatures reduced the average failure time, load, and strain of SiC composite cladding. Comparative analysis between room-temperature (0.5 mm/min) and high-temperature (920°C, 0.5 mm/min) tests revealed: High-temperature failure strain (0.37%) was 9.8% lower than room-temperature (0.41%); high-temperature failure load (2,294 N) was 51.4% lower than room-temperature (4,722 N); high-temperature failure time (1,104 s) was 12.5% shorter than room-temperature (1,262 s). This degradation correlates with decreased Young's modulus and hardness at high temperatures, highlighting significant temperature effects on PCI-related failure.

(5) Future work will include intermediate loading rates (e.g., 0.75 mm/min) to quantify nonlinear load-rate dependencies and microstructural analysis (e.g., SEM) to validate failure mode variations under differing conditions.

Acknowledgment: This study was supported by National Natural Science Foundation of China (No. 12375172), Shenzhen Science and Technology Program (No. JCYJ20241202124411016) and Guangdong Basic and Applied Basic Research Foundation (No. 2023A1515010961).

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Note: Figure translations are in progress. See original paper for figures.