Advanced Sensors and Instrumentation

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ASI program update

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Welcome to the 21st edition of the ASI program newsletter. ASI newsletters report on people and research activities dedicated to the development of advanced nuclear instrumentation and controls. In this issue we report on the outcomes of a technical workshop sponsored by ASI discussing the use of advanced manufacturing processes to fabricate embedded sensors. The focus of ASI research in this area is to develop Structural Health Monitoring (SHM) systems that can operate reliably in the harsh operating conditions of advanced nuclear reactors.

These include temperatures compatible with non-water coolants, in the range between 400 and 1000°C, and exposure to gamma and neutron fluxes of varying intensity, depending on the intended function and location. SHM technologies rely primarily on acoustic or optical sensing, or a combination of both. The primary technical gap addressed by ASI is how to ensure proper contact between the sensing element and the component to be monitored throughout its lifetime. For most industrial applications this function is performed by a variety of coupling materials, such as glues and adhesives for low-temperature applications and ceramic-based cements at higher temperatures.

However, even if commercial solutions exist in the target temperature range, radiation effects degrade the coupling performance, causing drift in the measurement and challenging reliability and lifetime. In this context ASI is investigating the use of advanced manufacturing processes to provide reliable contact between the sensing

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element and the structural component without the use of coupling materials.

However, the sensor may be encapsulated in an intermediate element, such as a feedthrough, which is then attached to the structural component by conventional processes, such as brazing or welding, but does not have the same functional requirements. This intermediate element is fabricated separately from the structural component and does not have to follow the qualification processes required of structural materials. In this context the term "embedded sensor" may be misleading, as for other research and industrial applications it refers more broadly to the fabrication of advanced materials that simultaneously perform structural and self-diagnostic functions. While ASI is interested in leveraging from R&D outcomes in other fields, the applied nature of the program prioritizes research that can provide near-term solutions to the primary technology gaps identified by stakeholders.

The workshop was hosted by Pacific Northwest National Laboratory (PNNL) on Aug 27-29, 2024. To open the workshop Dr. Mark Nutt, manager of the Nuclear Energy Market Sector, presented a highlight of the nuclear energy research being conducted at PNNL, all aimed at sustaining nuclear power as a carbon-free source of energy in the 21st century. Key projects summarized included developing durable waste forms for iodine immobilization, exploring recycling methods for high-assay low-enriched uranium (HALEU) and TRISO fuels, recovering uranium from seawater, innovating metal-organic frameworks for capturing radioactive gases, and materials research to extend reactor permits. Uncrewed Aerial Vehicles (UAVs) for radiation detection associated with reactor decommissioning, structural analysis of transportation casks, transport safety, cybersecurity, and environmental justice were also summarized. PNNL's cutting-edge facilities and collaborations foster advancements in materials characterization, non-destructive evaluation, and nuclear fuel fabrication—all contributing to innovations in clean energy and national security.

Embedded Sensors for Advanced Reactor Systems Workshop Overview

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This summer, Pacific Northwest National Laboratory hosted the US Department of Energy Office of Nuclear Energy (DOE-NE) Advanced Sensors and Instrumentation (ASI) Embedded Sensors for Advanced Reactor Systems Workshop. This workshop was sponsored by DOE-NE to capture the current advancement in technologies for embedding sensors within structural materials for monitoring of system health. Due to the focus on fabrication technologies, the workshop was attended by Meimei Li, the National Technical Director (NTD) for Advanced Materials and Manufacturing Technologies (AMMT). Federal Office Director Suibel Schuppner was in attendance and provided introductory comments for the workshop. The final technical session of the workshop was a discussion led jointly by Meimei and ASI NTD Pattrick Calderoni. The workshop had over 30 attendees, and technical presentations were contributed by Argonne National Laboratory (ANL), Boise State University (BSU), DOE-NE, the Electric Power Research Institute (EPRI), Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), the University of Notre Dame (ND), and the University of Pittsburgh (Pitt). Technical sessions were held

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August 27th and 28th, followed by a tour of PNNL spaces relevant to the workshop in the afternoon.

At the first stop of the tour, Robert Montgomery and Chris Hutchinson presented PNNL's capabilities for non-destructive evaluation (NDE), as well as laboratories for development of ultrasonic sensors located within the 2400 Stevens building. Adjacent to 2400 Stevens is the Accelerated Real-Time Environmental Nodal Assessment (ARENA) Test Bed, shown in Figure 1, that was presented to the workshop tour participants by Leo Fifield. The ARENA focuses on studying how electrical cables degrade in extreme conditions, such as advanced reactor systems, and how their performance can best be monitored.

Subsequently, the tour visited the Solid Phase Processing (SPP) capabilities (Figure 2) housed within the Applied Engineering Laboratory (AEL) where David Gotthold, Kenneth Ross, Mageshwari Komarasamy, and Isabella Van Rooyen discussed capabilities and recent applications for the nuclear industry for friction stir welding and processing, cold spray, and shear assisted processing and extrusion. These capabilities can be used for fabricating novel structural materials for advanced reactor systems, and sensor embedding processes could potentially

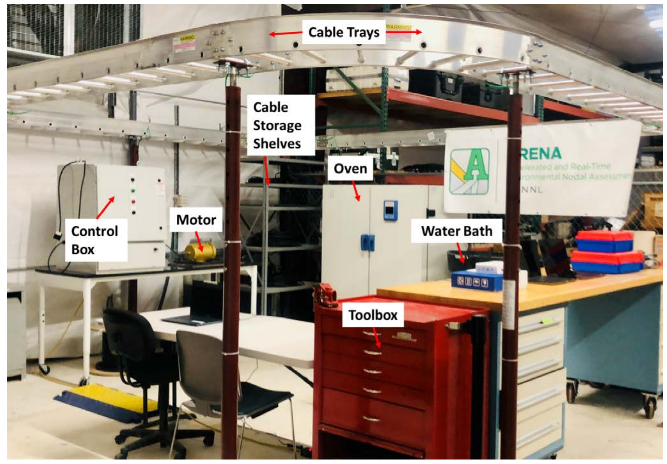

Figure 1: Accelerated Real-Time Environmental Nodal Assessment (ARENA) Test Bed. For more information, visit https://www.pnnl.gov/accelerated-real-time-environmental-nodal-assessment-arena-test-bed.

be developed and deployed during these fabrication processes.

The tour concluded with a visit to the radiological wing of the Materials Science and Technology Building to see the rolling capabilities currently being used by Vineet Joshi and Rajib Kalsar to embed fiber-optic cables within stainless steel, shown in Figure 3.

Figure 2: Solid Phase Processing Capabilities in the Applied Engineering Laboratory (AEL) For more information, visit https://www.pnnl.gov/solid-phase-processing

Figure 3: Rolling mill currently being used to embed fibers within stainless steel for ASI. This capability is located within the Materials Science and Technology building https://www.pnnl.gov/materials-science-and-technology-building

State of the Art in Embedded Sensors for Nuclear Applications

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Introduction

The US Nuclear Regulatory Commission and other international standards organizations provide detailed guidance regarding aging-related degradation mechanisms, required inspections, and mitigation techniques that are applicable to the current light-water reactor (LWR) fleet [1-3]. Structural health monitoring (SHM) is perhaps more important for microreactors [4] that require reduced operation and maintenance costs to remain economical when producing less power relative to LWRs. Improved SHM could help provide more information to a limited number of reactor operators (reduced staffing) and minimize the costs associated with time-consuming manual inspections, some of which may not be possible due to limited access in a smaller reactor.

Temperature limitations of current SHM solutions (primarily vibration monitoring) have motivated research on high-temperature sensor transducers, as well as bonding/attachment techniques for coupling sensors to components relevant to microreactors and/or advanced high-temperature reactor applications. Depending on the specific application, surface mounting could suffice, or the sensor may need to be embedded within components via advanced manufacturing processes. The Advanced Sensors and Instrumentation (ASI) program of the US Department of Energy's Office of Nuclear Energy recently organized a workshop to discuss the state of the art in SHM transducers and sensor embedding techniques that are compatible with advanced reactor operating temperatures.

Overview Presentation

An overview presentation described some of the historical applications of strain and vibration monitoring technologies within LWRs, early gas-cooled reactors, and even some in-pile irradiation experiments. Fiber optic sensors were identified as the most promising technology for vibration monitoring due to their accuracy, small size, tolerance to both high temperatures and radiation, and ability to perform spatially distributed strain or vibration measurements. The remainder of the overview presentation focused on the challenges with bonding, embedding, or otherwise integrating fiber optic sensors within metal reactor components. Figure 4 shows examples of optical fibers embedded via (top) ultrasonic additive manufacturing (UAM) [5, 6] and (bottom) laser powder bed fusion (LPBF) [7].powder bed fusion (LPBF) [7].

Figure 4. Pictures of (top) an optical fiber embedded in aluminum via UAM and (bottom) a cross section of a fiber with copper and nickel coatings embedded in stainless steel via LPBF.

The primary challenge in embedding optical fibers for SHM is associated with the significant mismatch in the thermal expansion coefficients of glass fibers vs. those of most metal alloys. Figure 5 shows (qualitatively) that if the bond between the fiber and the component is established when the component temperature is relatively low, then the differential thermal expansion at higher temperatures puts the fiber under significant tension and eventually causes

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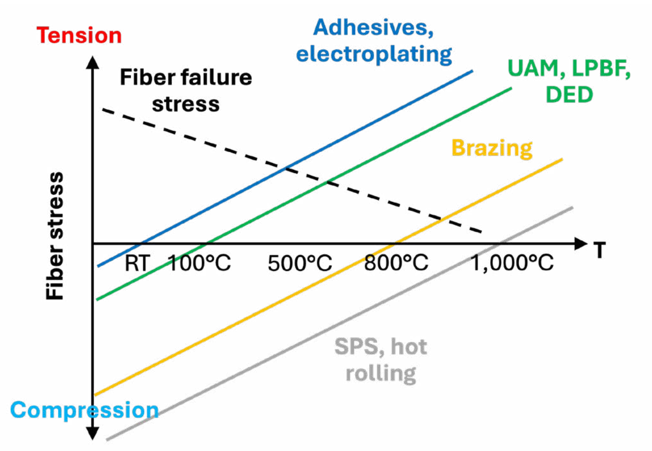

Figure 5. Qualitative summary of the fiber stress vs. temperature (T) when the fiber is bonded via techniques such as adhesives, electroplating, UAM, LPBF, directed energy deposition (DED), brazing, SPS, and hot rolling

the fiber to break. Low-temperature bonding techniques or those that rely on localized heating include electroplating, solid-state joining (e.g., UAM), and welding.

Bonding the fiber at higher temperatures has the potential to place the fiber in compression at temperatures below the bonding temperature and allow the fiber to survive to higher operating temperatures. Techniques such as furnace brazing, hot rolling, chemical vapor infiltration, and spark plasma sintering (SPS) have been proposed to enable higher-temperature operation. Research into embedding fiber optic sensors via high-temperature processes will continue under ASI during fiscal year 2025.

Benefits to the Nuclear Industry

The clearest benefit to the nuclear industry is the ability to monitor reactor components or systems remotely and identify early signs of degradation, thereby informing a condition-based maintenance approach and ultimately reducing operation and maintenance costs. Techniques such as fiber optics offer the additional benefit of distributed sensing, which could further enable the localization of damage/degradation so that the issue can be more efficiently addressed during costly reactor outages. Finally, there is research into using embedded sensors for quantifying component stresses and how they evolve during additive manufacturing. This research could aid in the understanding and optimization of additive manufacturing process conditions and, ultimately, the qualification of these components for nuclear reactor applications.

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Embedded Fiber Optic Sensors Enabled by Electric Field-Assisted Sintering

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Introduction

Advanced energy systems, including nuclear reactors, have attracted considerable interest for the transition toward deep decarbonization and a net-zero future. Significant efforts have been made towards the development and deployment of advanced reactors with enhanced efficiency, safety, and autonomous operation capabilities. Critical components in these systems are typically subjected to an extremely harsh environment. Therefore, online structural health monitoring is essential to ensure the safe operation of these systems and decrease operation and maintenance costs. Fiber optic sensors have attracted particular interest in nuclear fields for their remarkable properties, including distributed sensing capability, robust functionality in extreme environments, light weight, and small size [1].

Embedding fiber optic sensors within parts of interest is a key step for structural health monitoring, as it enables real-time monitoring of internal and distributed information, enhances sensing accuracy and sensitivity (e.g., fiber-matrix strain coupling), benefits structure compactness, and enables shielding from external environmental influences (e.g., corrosive media) that may affect sensor durability [2]. Integration of sensors into materials has been investigated [3, 4]. The challenge is to achieve good bonding between fiber and matrix while ensuring good functionality of the embedded sensor.

Methodology

This study demonstrates a technique to embed fiber optic sensors in high-temperature structural materials using electric field-assisted sintering (EFAS) [5]. EFAS utilizes electric current to synthesize materials and can process a diverse array of metallic, ceramic, and composite materials in a short time. This study demonstrates successful embedding by investigating the following key aspects: 1) inspection of fiber integrity and functionality through advanced microscopy and optical frequency domain reflectometry (OFDR); 2) characterization of fiber-matrix bonding using advanced microscopy and helium leak testing; 3) machinability of parts with embedded sensors; and 4) assessment of fiber integrity and bonding condition after cyclic thermal treatment.

Copper-coated and gold-coated fused silica optical fiber were selected for embedding. The matrix materials include stainless steel 316L and pure nickel due to their extensive use in high- temperature applications. Figure 6 illustrates

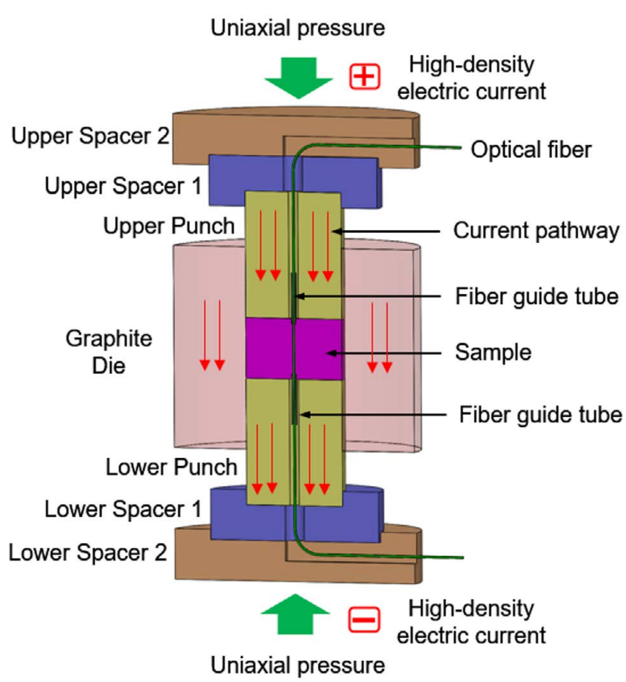

Figure 6. Schematic representation of the fiber embedding process using EFAS.

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the schematic representation of the embedding process. Matrix bonding without voids or gaps near the interface was achieved. Examination of elemental distribution across with EFAS. The optical fibers were placed in graphite die with metal powder, which were sintered at various conditions (temperature, pressure, and hold time) by launching electric current into the die assembly. These parameters were varied over a wide range in this study to explore the relationships between fabrication conditions and embedding properties.

Figure 7a shows a typical as-fabricated sample with an embedded fiber. Fibers embedded at all the EFAS conditions were tested by launching light through the fiber to assess fiber integrity before quantitative analysis using OFDR. The testing indicated that all fibers remained intact and capable of transmitting light, which was also confirmed by examining the cross-sections under an advanced microscope. Figure 7c shows an X-ray computed tomography (X-CT) scan of a SS316L sample with embedded copper-coated optical fiber, showing the fiber within the part.

Effective bonding between embedded fiber and matrix is a critical factor to indicate successful embedding. The bonding between the fiber/SS and fiber/nickel is shown in Figures 7d and 7e, respectively. A good continuous fiber-matrix bonding interface indicates diffusion of elements across the matrix materials and the coatings, which suggests effective strain coupling between the sensor and matrix (Figure 7f). The good fiber-matrix bonding was also confirmed by helium leak testing. For leak testing, the samples were machined by lathe to achieve smooth surfaces with high geometric tolerance (Figure 7b). The machined samples were mounted onto a helium leak tester and subjected to high vacuum pressure on one side, while the other side was exposed to helium. Leak testing indicates that the samples made at optimal conditions passed the test, suggesting good fiber-matrix bonding for high-pressure sensing applications.

Functionality of the embedded fibers was evaluated by OFDR, which is a distributed measuring technique that relies on natural imperfections in optical fibers to provide backscattered signal. The measurements indicate insertion loss of 0.43 dB and 0.52 dB for the fiber embedded in Ni at 800°C and 900°C, respectively, as shown in Figure 8, and 0.75 dB for the fiber embedded in SS316L. This level of insertion loss is minimal and comparable to the loss at a

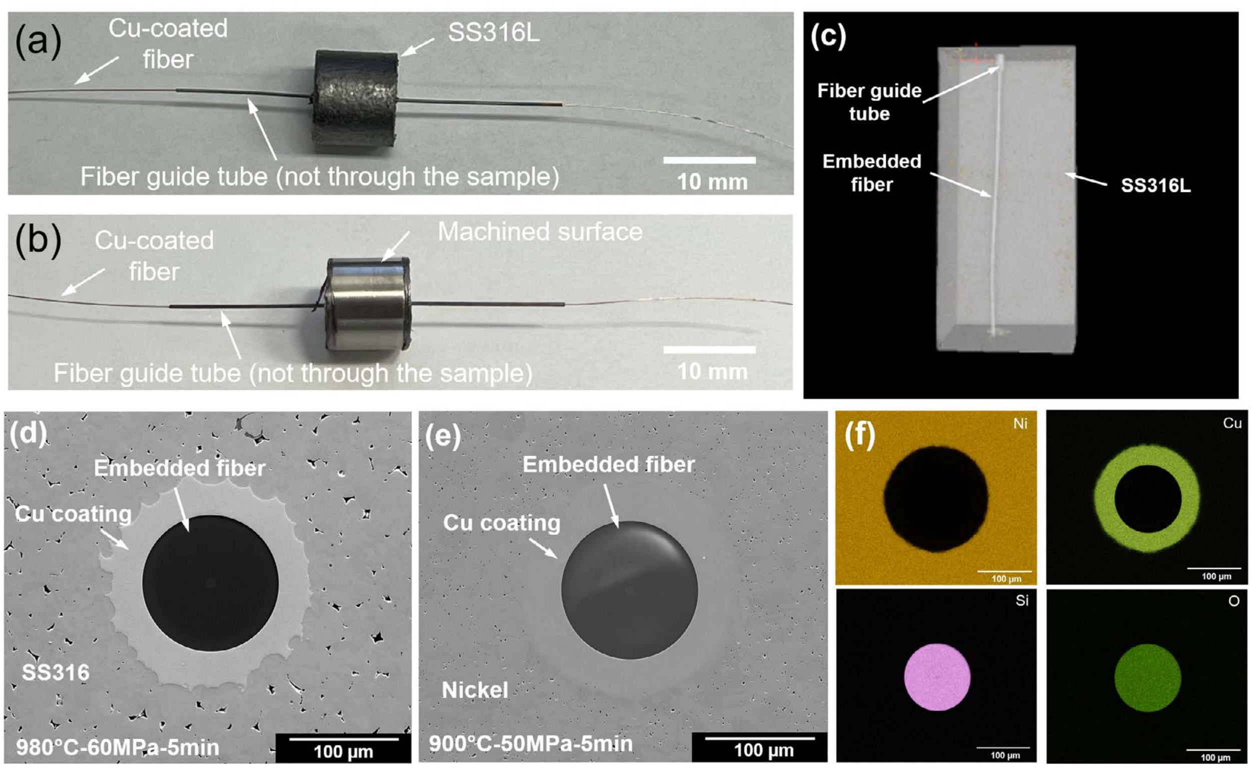

Figure 7. (a) As-fabricated and (b) machined samples with embedded fiber. (c) X-CT scan of a sample with fiber. Micrographs showing the interfacial characteristics in (d) SS and (e) nickel. (f) Elemental distribution maps.

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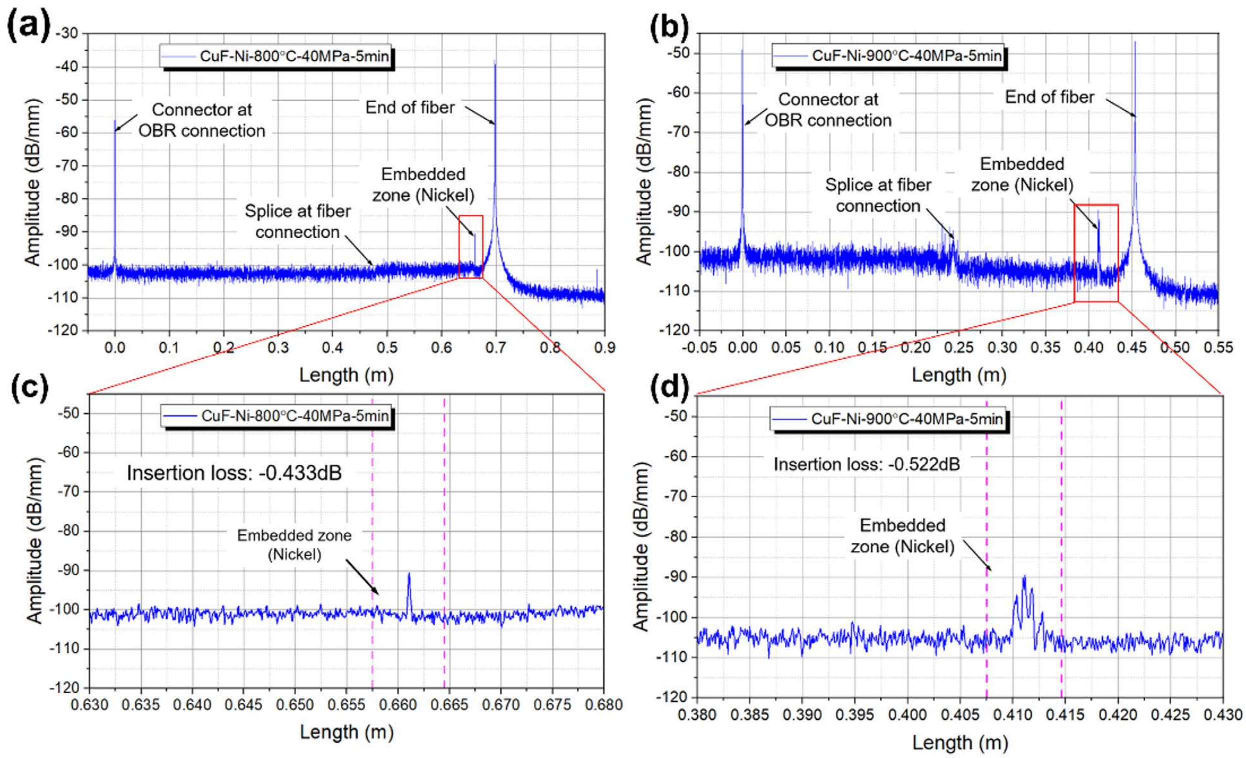

Figure 8. Backscattering patterns of the Ni samples with embedded fibers fabricated at (a) 800°C and 900°C. (c, d) Magnified view of the patterns near the embedding site.

clean fiber connection. The low insertion loss associated with embedding via EFAS indicates good optical properties of the fiber once encapsulated in the metals. Additionally, examination of the samples after 50 cycles of thermal treatment between 500°C and 700°C shows good fiber integrity and fiber-matrix bonding, suggesting the thermal stability of the samples with embedded fiber optic sensors.

Impact

Embedding fiber optic sensors in high-strength materials is challenging but critical to achieve structural health monitoring. This study demonstrated successful embedding of fiber optic sensors via EFAS, which provides a solution to support online monitoring of advanced nuclear reactors and their deployment. The embedding technique also enables the construction of smart structures and structural nervous systems for autonomous operations of systems and Internet of Things (IoT).

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Embedding Fiber Optic Sensors in SS316 Wrought Products Using Confined Rolling for Nuclear Applications

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Introduction

Embedded sensors are increasingly utilized for real-time data acquisition, particularly in monitoring temperature and strain in structural materials across industries like nuclear and power generation. Fiber-optic sensors are especially valuable due to their durability in high-temperature corrosive environments, and their resistance to high radiation doses. Thus, it is essential to develop scalable processes, such as rolling, to integrate these sensors into structural components while maintaining the material's properties. A novel confined rolling technique has been designed to fabricate high-temperature materials, such as stainless steel SS316, with embedded fiber-optic sensors tailored for extreme environments with high radiation exposure. This method enables the production of wrought components that incorporate optical fibers, capable of measuring temperature and strain in harsh conditions. Figure 9a shows the rolling assembly of SS316 steel with embedded optical fibers, while Figure 9b illustrates the rolled steel sheet containing the embedded fibers.

In fiscal year 2024, we were funded to develop a wrought SS316 steel product with embedded optical fibers. This project focuses on developing analytical and finite element modeling (FEM) to analyze through-thickness strain distribution, stress accumulation on the fibers, and their fracture behavior during the rolling process. The modeling guided the experimental design, focusing on reduction per pass, optimal fiber placement, and the use of miniature tubes to minimize fiber damage during rolling.

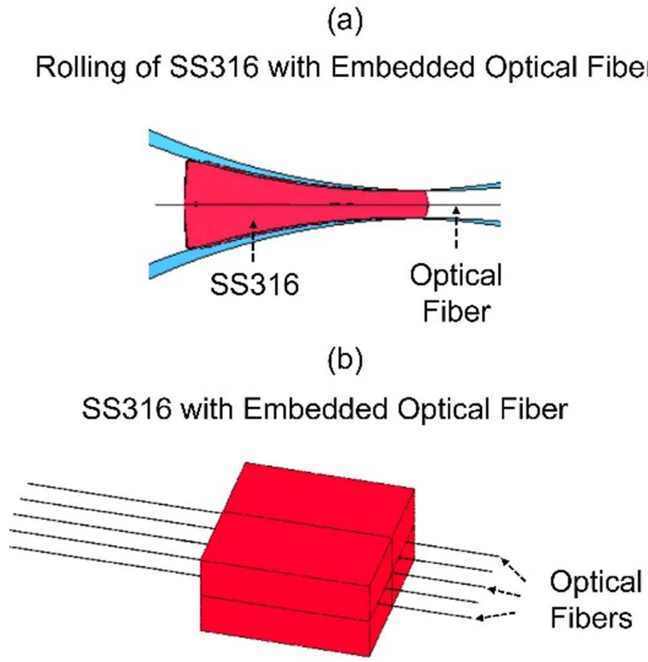

Figure 9. (a) Schematic diagram illustrating the rolling assembly of an SS316 stainless steel plate with sapphire fiber embedded. (b) Rolled SS316 steel featuring embedded fibers.

Based on the modeling results, we devised two distinct experimental approaches for fabricating wrought products with embedded fibers: the drill hole method and roll bonding. In the drill hole method, a 0.5 mm hole was drilled at the center of the plate, where a miniature tube and fiber were inserted. The assembly was then hot rolled at 900°C with a 50% thickness reduction and 5% reduction per pass. During rolling, the hole and tube collapsed, resulting in effective bonding between the steel plate and tube, as well as between the tube and fiber. No significant defects were observed at the interfaces, which is crucial for enhancing sensor performance. Figure 10 shows the rolled steel sheet with embedded optical fiber, and the cross-sectional microstructure indicates good adhesion between the fiber, tube, and steel sheet without major interface defects.

In the roll bonding process, two steel sheets were used with a miniature tube and fiber placed between them. The assembly was hot rolled at 850°C, achieving up to a 60% reduction in a single pass. An analytical model determined the necessary temperature and reduction for effective metallurgical bonding. Following this model, the top and bottom steel sheets were successfully joined with the

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optical fiber positioned at the center. The resulting bonded sheets exhibited strong properties with no significant interface defects.

In fiscal year 2024, PNNL successfully demonstrated the concept of embedding optical fibers in high-temperature materials through rolling, alongside strategies for future scaling. Various destructive and non-destructive tests are currently being conducted to assess fiber connectivity and interface integrity. The performance of these optical fibers will be evaluated in fiscal year 2025.

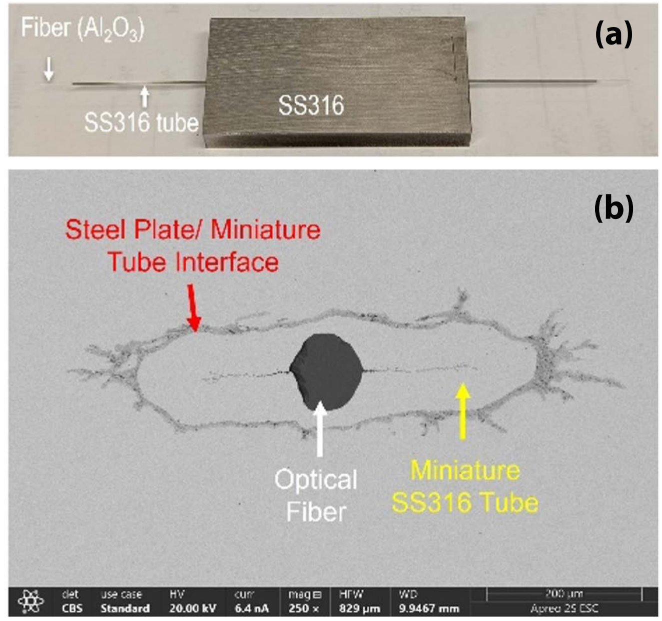

Figure 10. (a) Rolled SS316 steel sheet featuring an embedded optical fiber sensor, and (b) cross-sectional microstructure highlighting the fiber, the fiber/miniature tube interface, and the miniature tube/steel sheet interface.

An Integrated Laser Approach for Fiber Sensor Embedding in Metal Parts for Fission and Fusion Energy Systems

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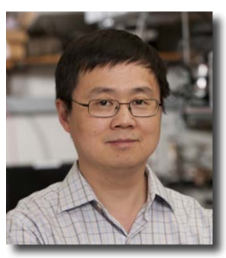

Motivation and Objectives

Fiber optical sensors have gained prominence as crucial sensing tools for real-time monitoring of temperature, strain, acoustic emission, and pressures for energy, infrastructure, and aerospace applications. Their lightweight nature, immunity to electromagnetic interference, and high-temperature resilience make them particularly suitable to support both fusion and fission nuclear energy systems. The current practice of sensor installation for monitoring nuclear power systems is usually done after a nuclear power system has been constructed, almost as an afterthought. This engineering practice, however, significantly increases the cost of sensor installation, reduces measurement efficacy, and incurs additional safety concerns.

To address this challenge, the University of Pittsburgh (Pitt), supported by a Department of Energy NEET grant, explored fiber sensor fused additive manufacturing techniques. Through a combination of modeling, experimentation, and active engagement with nuclear energy system developers and national labs, our research team will develop an integrated additive manufacturing (AM) model and fiber embedding technology that will integrate reactor modular manufacturing and sensor installation in a single manufacturing step.

Over three years, the Pitt team led by Drs. Kevin Chen and Albert To has successfully demonstrated fiber sensor embedding through laser-energetic net shaping (LENS), direct laser metal sintering (DLMS), ultrasonic additive manufacturing (UAM), glass sealant binding and sintering, and wire EDM. Fig. 11 shows some examples of fiber sensor fused smart components.

The functionality of sensor-fused smart parts has been demonstrated to perform high-frequency vibration measurements and enhance low-temperature sensitivity for fiber sensors. Fig. 12a shows fiber sensors embedded in aluminum components for vibration measurement.

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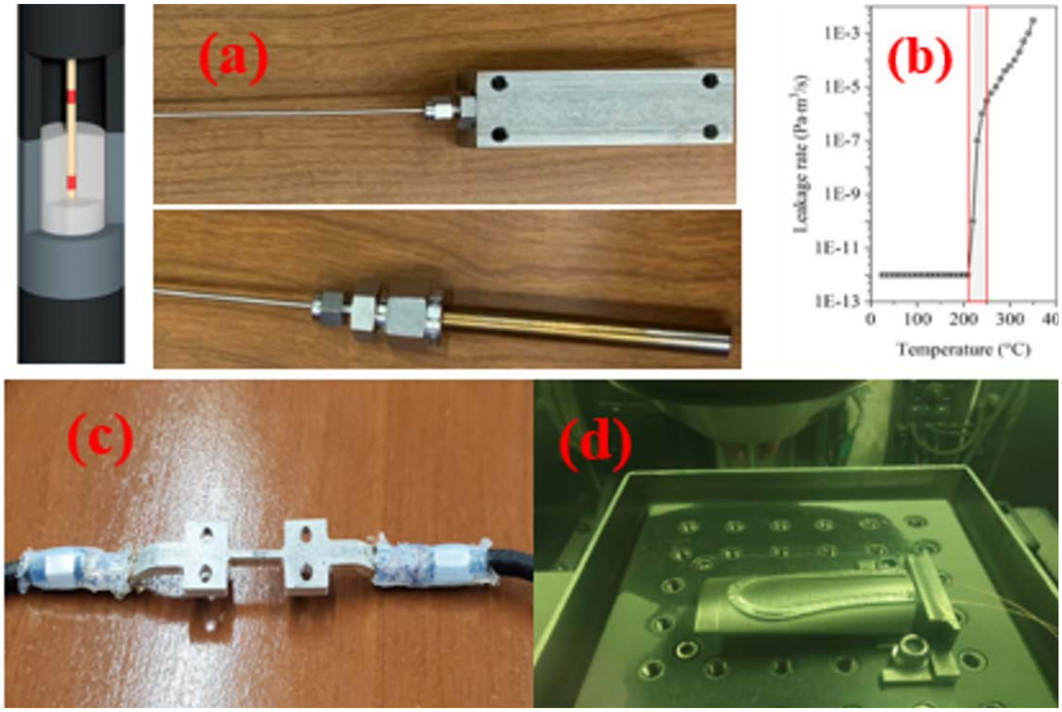

Fig. 11: (a) sensor embedded through glass sealant binding and sintering, (b) helium leak test of sensor embedded in glass sealant through pressure boundary. (c) fiber sensors embedded in the aluminum part using the UAM approach, and (d) sensors embedded in Inconel using the LENS process.

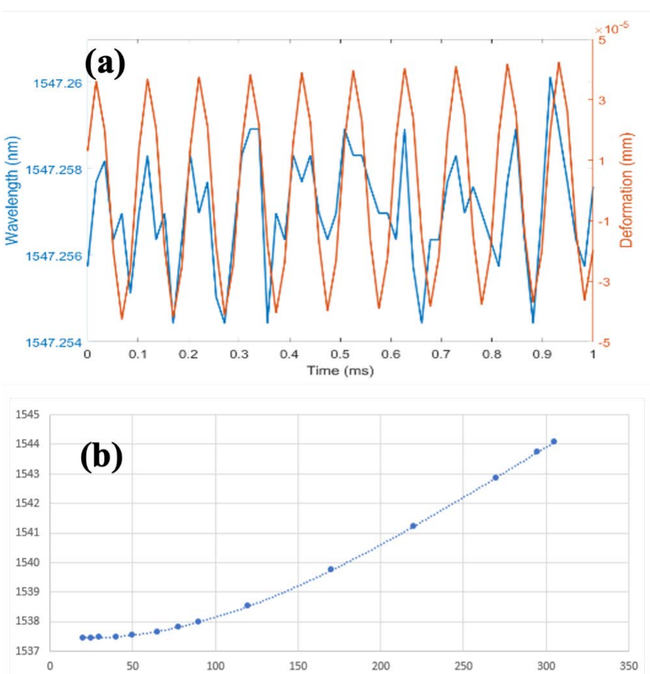

Fig. 12: (a) vibration sensing by embedded fiber sensors (blue trace) vs laser velocimeter measurements (red trace) at 10 kHz and (b) cryogenic temperature performance of embedded fiber sensors from 5 K to 298 K.

Using a high-speed sensor interrogation system developed by our team using a tunable VCSEL, we can effectively measure vibration-induced strain at vibration frequencies as high as 10 kHz. The compressive strain exerted on fiber sensors by the surrounding metal matrix ensures effective strain transfer for robust strain measurements. The fiber sensor embedded in the metal matrix can significantly improve the low-temperature sensitivity of fiber sensors. It is well known that fiber sensors lose sensitivity as the ambient temperature drops below 20 K. However, through fiber sensor embedding in the aluminum matrix, the temperature sensitivity of embedded fiber sensors can be significantly enhanced. Fig. 12b shows that embedded fiber sensors can retain significant temperature sensitivity down to 10 K. The results presented in Fig. 12 show broad application potential of sensor-fused smart

components for both fission (e.g., novel SMR fission systems for terrain and space applications) and fusion energy systems (e.g., cryogenic sensors for superconducting systems).

A critical concern with AM techniques for embedding fiber sensors is the significant difference in the CTEs between

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optical fiber (5.5 x 10-7°C-1) and metal (>12 x 10-6°C-1). This discrepancy, combined with high-temperature-induced axial and lateral stresses, can lead to slippage of the embedded fiber sensors in the metal matrix. The microstructures of metallic parts produced through AM methods are often less refined compared to those created via traditional manufacturing processes. One method to improve microstructural refinement is through high-temperature post-processing, such as hot isostatic pressing (HIP), which operates at high temperatures (around 1000°C) and pressures (>100 MPa) to enhance densification. However, this method is not viable for embedding fiber sensors, as the extreme conditions would compromise the integrity and survival of the sensors within metal structures.

To address this challenge, our team developed a laser shock peening (LSP) technique to improve the structural properties and high-temperature performance of fiber optical sensors embedded near the surface of metal parts. LSP is a noncontact, maskless process that utilizes high-intensity laser pulses to generate a laser-induced shock wave, enabling precise surface treatment and geometric modification of materials at room temperature. Through the LSP process, compressive strain can be induced around embedded fibers to improve the bonding of embedded fiber in the metal matrix. The LSP can also reduce grain boundary and surface quality of additively manufactured smart parts to improve overall material characteristics. Fig. 13 shows a fiber sensor embedded with the Inconel metal matrix. The LSP process can significantly improve the embedded fiber slippage temperature for at least 50°C, as shown in Fig. 13c.

Overall, combining LSP with the AM process not only enhances the high-temperature resilience of embedded fiber sensors, it also establishes a novel methodology for future research and applications in sensor-fused smart components. Our research program lays a foundation for developing advanced monitoring systems that can operate reliably in demanding environments, ultimately contributing to the evolution of smarter nuclear energy systems. Future investigations will focus on further optimizing these techniques and exploring their potential across various materials for both fission and fusion energy applications.

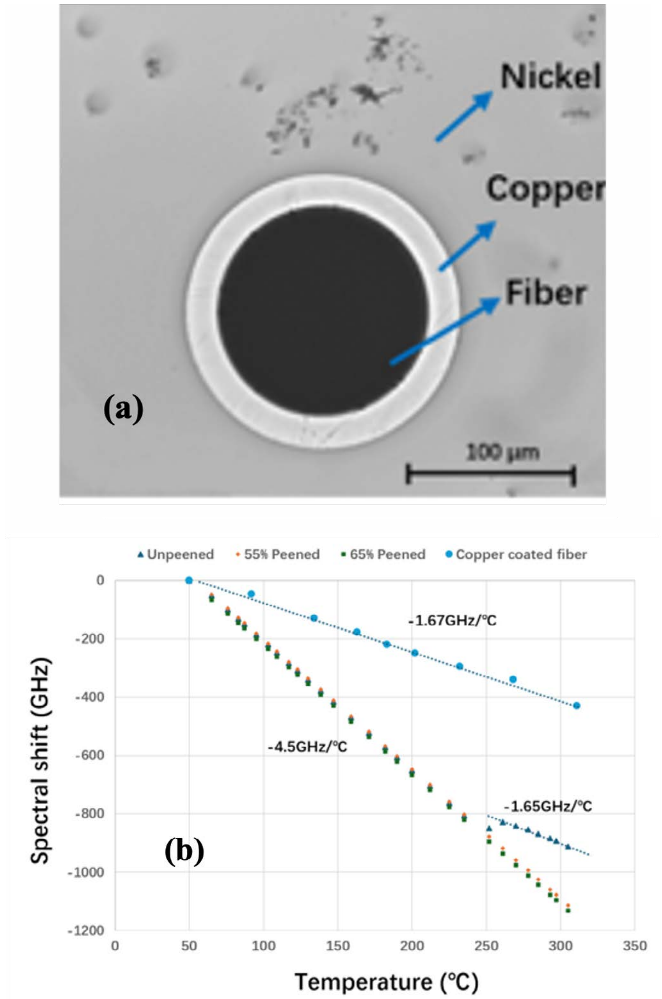

Fig. 13: (a) Scanning electron microscope image of fiber embedded in Inconel metal matrix and (b) spectral shift vs temperatures for embedded fiber sensors and unembedded fiber.

The author and the Pitt team welcome collaboration.

For further technical details, please contact the author (pec9@pitt.edu).

Embedding Fiber Optics Using Ultrasonic Additive Manufacturing and Laser Powder Bed Fusion

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Introduction

Additive manufacturing (AM) processes have the ability to realize complex components not achievable using conventional manufacturing techniques [1]. Most AM processes involve the repetitive layering of material in a controlled manner to build a component. This layer-by-layer method could be leveraged to locate desired materials or even sensors within a component during the manufacturing process. Cavities such as pockets or channels to house the sensor could be machined or built into the structure during the process, before continuing to additively layer more material over the top, thereby embedding the sensor in the matrix [2, 3]. Fiber optic sensors are of particular interest because they can spatially measure distributed temperature and strain along the length of the fiber.

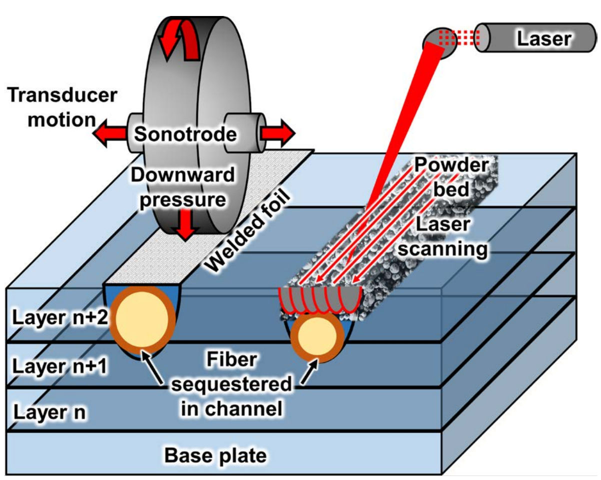

Figure 14. Schematic of the embedding process using either ultrasonic AM (UAM) or laser powder bed fusion (LPBF). UAM utilizes a sonotrode to apply mechanical energy and bond thin metal foils through severe plastic deformation. LPBF involves the selective laser melting of a powder bed to melt and fusion material layer by layer. Both processes can be used to locate sensors in channels during the printing process and then, print over them, thereby embedding them in the matrix.

However, the fiber must be bonded with the matrix for proper strain sensing; moreover, though such bonding is not necessarily required for temperature sensing, it would greatly improve the accuracy of temperature measurements.

Benefits of AM to the Industry

The nuclear industry is constantly striving to improve reactor component designs and overall system efficiencies through an iterative design, analysis, fabrication, and experimental approach. Many of these components or systems naturally evolve toward more complex geometries whose fabrication can be expensive to scale. AM could allow reactor engineers to more rapidly evaluate prototype designs. The ability to embed sensors during AM would further accelerate the evaluation process, enabling more site-specific monitoring that could reduce the number of post-test destructive evaluations. Moreover, deploying embedded sensors during reactor operation could enhance structural health monitoring capabilities that could support more automated reactor operations and/or inform a condition-based maintenance approach.

Presentation Content

This presentation covered the embedding of fiber optic sensors using ultrasonic AM (UAM) and laser powder bed fusion (LPBF); both processes are described in Figure 14. UAM is a solid-state AM process that utilizes a tool called a sonotrode, which operates at some ultrasonic frequency (~20 kHz). The sonotrode is applied to a thin metal foil with a user-defined pressure, using a side-to-side scrubbing motion (Figure 14, left) to bond it to the base through severe plastic deformation. UAM is ideal for larger-scale components and eliminates exposure to the high temperatures found in melting-based AM processes.

LPBF is a melting-based process that involves the selective laser melting of a powder bed (Figure 14, right). Although exposure to high temperatures may be a concern for embedding sensors, the geometric resolution offered by LPBF is among the highest (<200 µm) of any metal AM process, and this method can therefore realize more complex geometries.

Studies have been performed to utilize both UAM [2] and LPBF [3] to embed sensors in stainless steel (SS) 304 and 316L, respectively. The most significant challenges associated with embedding fibers in both AM processes include choosing the fiber coating and proper sizing of the cavity.

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Silica-based fiber optics, such as those used in the studies referenced above, are typically coated with a polymer like acrylic or polyimide. Polymer coatings have been shown to easily shear apart during the mechanical loading involved in UAM [4], and easily decompose at higher temperatures (<350°C) when using melting processes such as LPBF [3]. Therefore, a metallic coating is preferred for both processes. Current commercially available metal coatings are Au, Al, and Cu. Although these coating materials are dissimilar to Fe, the main constituent in SS, they allow for a metallurgical bond to be made between the fiber and the matrix.

As shown in Figure 15(a), an Au-coated optical fiber was properly embedded in an SS304 matrix, and the top layer covering the fiber touched down just enough to the Au coating to bond it with the matrix. Embedding fibers for LPBF required a larger coating because the laser penetration is 100–200 µm; the laser shocks the silica core, causing fiber failure. Commercially available metal coated fibers typically have only 20–30 µm of material surrounding the silica core. Therefore, post- processing a Cu-coated fiber was required before it could be embedded using LPBF. After adding an additional Ni layer via electroplating, a Cu-coated fiber was embedded in an SS316L matrix using LPBF, as shown in Figure 15(b). The laser clearly penetrated the Ni coating, bonding it with the matrix.

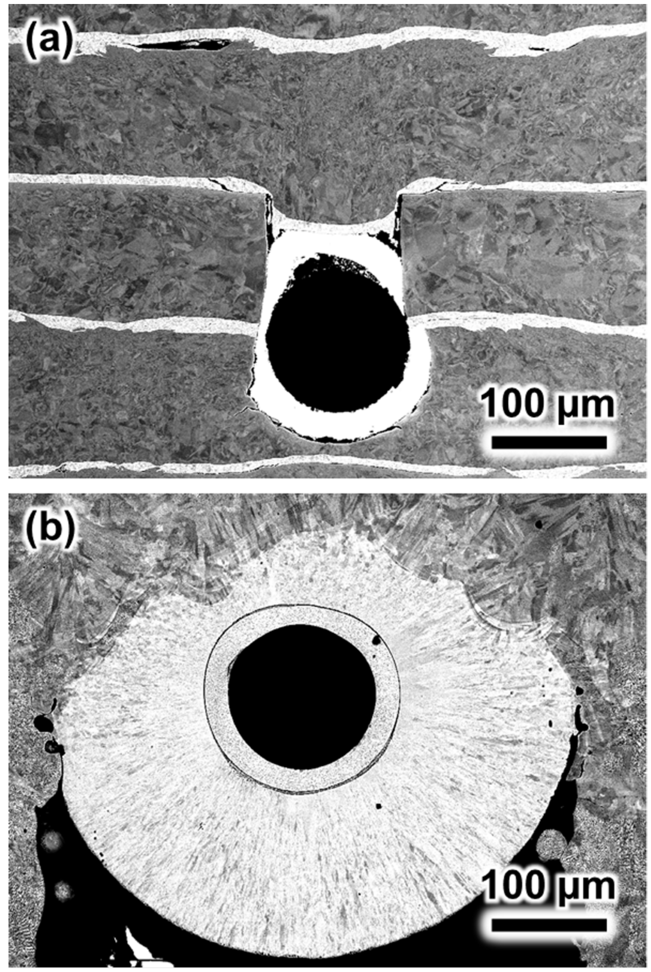

Figure 15. An optical fiber embedded in (a) SS304 using UAM [2] and (b) SS316L using LPBF [3].

Future Work

The embedded fiber optics were used to resolve strains resulting from differential thermal expansion of the SS matrix during heating to temperatures up to 1000°C [3]. Additional studies are warranted to embed sensors in relevant reactor components and confirm their ability to monitor their structural health under more representative conditions (e.g., thermal cycling).

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