Embedding Fiber Optic Sensors in Metal Components via Direct Energy Deposition

Elias B. Snider*, Rony Kumer Saha+, Cesar Dominguez †, and Jie Huang+, Douglas A. Bristow*

*Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65401
+Department of Electrical Engineering, Missouri University of Science and Technology, Rolla, MO 65401
†Los Alamos National Laboratory, NM 87545

Abstract

Fiber optics are useful as strain and temperature sensors in a variety of applications involving high-value parts. Embedding fiber optic sensors into end-use parts can allow for real-time strain and temperature monitoring of these parts in extreme conditions. Direct energy deposition processes have distinct advantages for producing parts in high-value embedded sensing applications, however, ensuring survival of the optical fiber during embedment is challenging. A method of fiber embedment using high-temperature ceramic adhesives is presented as a flexible method of embedding fiber optic sensors into end-use parts such as to preserve fiber transmission and sensor integrity. Example specimens are presented, and functionality of sensing capabilities is demonstrated.

I. Introduction

Optical fibers are useful as strain and temperature sensors and have gained significant attention in structural heath monitoring especially in large civil and infrastructural applications [1, 2, 3]. Recent interest has developed in using optical fibers in embedded sensing applications for smaller-scale metal parts to monitor strain and/or temperature distributions during use in engineering applications. Additive manufacturing processes are well-suited to embedding optical fibers in that they can deposit material around or over optical fibers. As a result, optical fiber sensors can be placed inside a part, allowing for more detailed strain and temperature information. In addition, by using optical frequency domain reflectometry (OFDR), a sensing technique capable of determining distributed strain measurements along the length of an optical fiber, strain distributions and concentrations can be determined continuously over a fiber sensor embedded in a part.

Three main additive manufacturing methods, each with distinct advantages and disadvantages in part applications, have shown promise for integrating fiber optic sensors into metal parts: ultrasonic additive manufacturing (UAM), selective laser melting (SLM), and directed energy deposition (DED). Significant demonstrations of embedded optical fibers have been performed on ultrasonic additive manufacturing (UAM) machines specifically with aluminum [4, 5, 6] and stainless steel [7]. Embedded fiber sensors with electroplated metal coatings have been incorporated into SLM parts made with stainless steel and other metal alloys [8, 9, 10]. DED embedment attempts have also produced embedded fiber sensors in titanium and Inconel alloys [11, 12] by employing substantial metal coatings on the optical fibers.

This work explores the use of a high-temperature adhesive to embed optical fibers within DED additively manufactured stainless steel parts and demonstrates the practical advantages of using this method as opposed to the use of significant metal coatings in embedded fiber sensors.

II. Metal-Coated Embedded Fiber Sensors

Many of the efforts toward embedded fiber sensors in DED and SLM additive manufacturing have used electroplating methods to deposit very large nickel or copper coatings onto the fiber sensors [8, 11, 12]. These coatings serve to protect the fiber from laser exposure during the embedment process and allow for direct metal-to-metal fusion of the fiber coating to the deposition metal. The process for embedding nickel-coated fiber (Figure 1) begins by electroplating either copper-clad or bare silica fiber [13] to relatively large diameters (350μm – 2mm compared to the fiber core diameter of 125μm) as shown schematically in Figure 1.a. A base material is printed using the additive manufacturing process (Figure 1.b) and a slot is either incorporated into the geometry of the print or machined into the material (Figure 1.c). The metal-coated fiber sensor is then placed into the slot (Figure 1.d). Lastly, printing resumes, thereby consolidating the fiber into the material of the part (Figure 1.e).

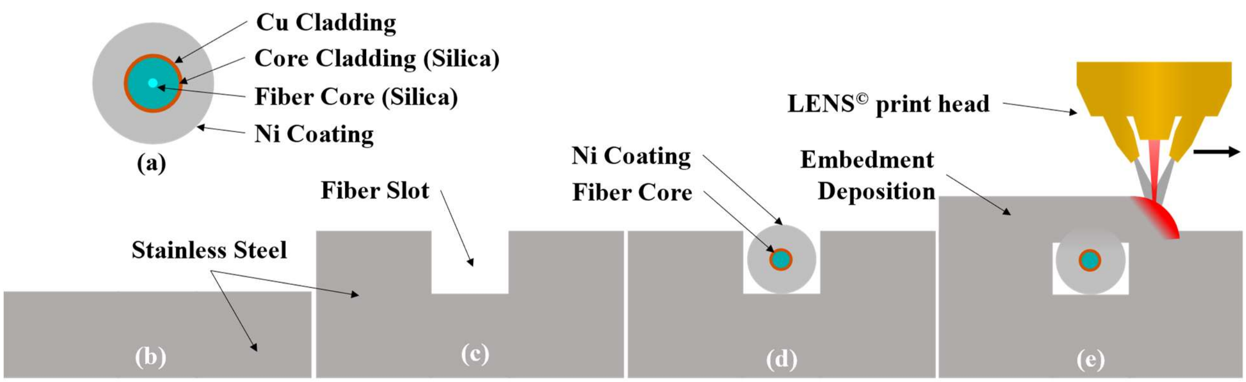

Figure 1: Fiber Sensor Embedment Procedure with Nickel Coatings

The electroplating process can be time-consuming and difficult, often resulting in significant variations in the diameter and straightness of the metal coatings. Because of these variations, the slot often requires oversizing to accommodate the fiber (Figure 2). Further, the final coated metal fiber is easily susceptible to damage if significantly bent or deformed. As a result, the optical fiber must be electroplated into the geometry of the final application, which presents significant challenges if the application geometry is not relatively straight.

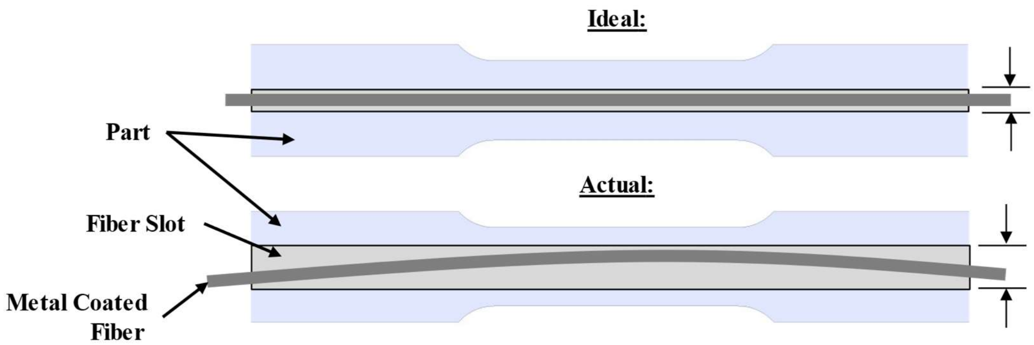

Figure 2: Example of Oversizing Fiber Slot

It has also been observed that embedding nickel coated fibers with DED or SLM additive methods results in limited bonding to the fiber; because of the constraints of these processes, the deposition material only bonds to the top surface of the fiber, leaving a cavity beneath the fiber that is not bonded to any of the surrounding material. This phenomenon is worsened with processes that have coarser resolution as it forces a deeper slot with less precise geometry unless the slot is machined.

III. Adhesive-Embedded Fiber Sensors

Noting the difficulties involved with securing and embedding nickel-plated fiber sensors, an alternative method was developed using high-temperature adhesives to allow more flexibility in embedment design and reduce some of the constraints imposed by the larger nickel coatings. The cross-sections of the embedment process are shown in Figure 3. This process begins with securing the same copper-clad optical fibers (Figure 3.a) with the exception that the fiber is not electroplated with nickel. The base material is printed (Figure 3.b) in the same way as in Figure 1.b. A slot is again either incorporated into the path planning of the build or machined into the existing material (Figure 3.c); however, the dimensions of the slot may now be considerably smaller. A high-temperature adhesive is then injected into the slot (Figure 3.d) and the fiber sensor is immediately placed into the slot while the adhesive sets (Figure 3.e). Before the adhesive has set, a sacrificial plug is placed over the open interface of the slot (Figure 3.f). This sacrificial plug should be of a similar or compatible material to the deposition material such that it will fuse well to the deposition material and serves to both protect the fiber and adhesive as well as to act as a bonding medium between the deposition and the adhesive. Additionally, incorporating a bevel into the slot aids in placement and seating of the plug onto the surface of the slot. Material deposition then resumes, consolidating these components into the part (Figure 3.g) and yielding a finished part capable of embedded sensing.

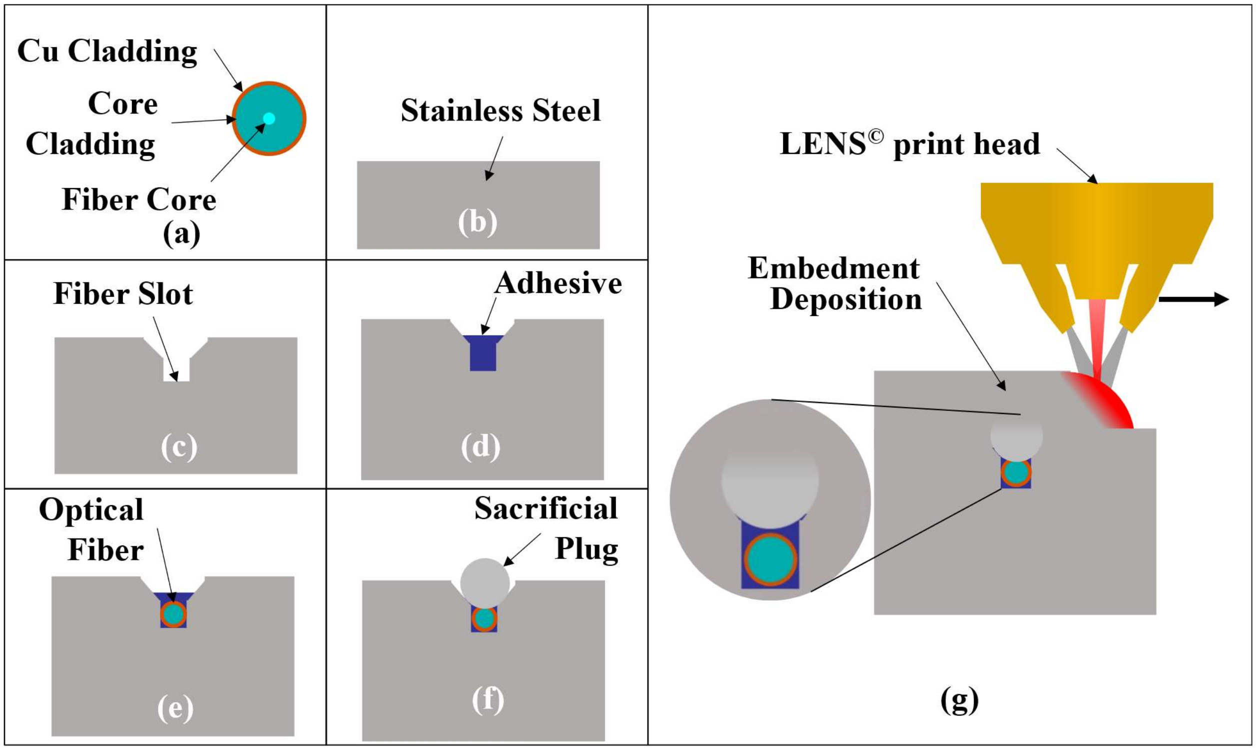

Figure 3: Fiber Sensor Embedment Procedure with Adhesive

This method of using an adhesive to embed the fiber sensors overcomes several of the challenges inherent to using large nickel coatings for embedded fiber sensors. Firstly, it eliminates the need to electroplate large amounts of nickel onto the fibers. Small-diameter copper coated fibers are commercially available and have less variance in diameters as compared to the large-diameter nickel coated fibers. In addition, small-diameter copper coated fiber is very flexible and much more robust to bending than nickel coated fibers, allowing for the design of more complex embedment geometry.

In addition, the slot may be significantly smaller than with the previous method resulting from the reduction in diameter and removal of the oversizing constraints. This allows for a much smaller footprint in the part and more precise placement of the fiber, especially if the slot is machined rather than incorporated into the build path. Lastly, the fiber is adhered on all sides by the adhesive, eliminating the void below the fiber sensor and enabling the fiber to be fully bonded. The adhesive is bonded to all three surfaces of the slot and is also bonded to the sacrificial plug which is in turn fused to the deposition material.

IV. Experimental Setup

Using the proposed method, an ASTM E8/E8M subsize tensile specimen was produced using Laser Engineered Net Shaping (LENS©) Print Engine and 53-150μm stainless steel 316L powder. The initial deposition was oversized such that machining would bring the specimen to exact ASTM geometry. The adhesive embedment procedure was followed with the slot (Figure 3.c) being incorporated into the build path planning (as opposed to being machined after initial deposition). After embedment (Figure 3.g), the specimen was separated from the build plate with a wire EDM and machined to precise geometry according to the ASTM specifications with rectangular cross-section and a thickness of 5.74mm (Figure 4). A single mode, copper-coated optical fiber was used with a core diameter of 9µm, a cladding diameter of 125µm, and a copper coating thickness of 15µm. The adhesive used was a zirconia-based ceramic adhesive and is rated up to 2200 °C, Resbond™ 904. Lastly, a 316L stainless steel drawn wire was used as the sacrificial plug material.

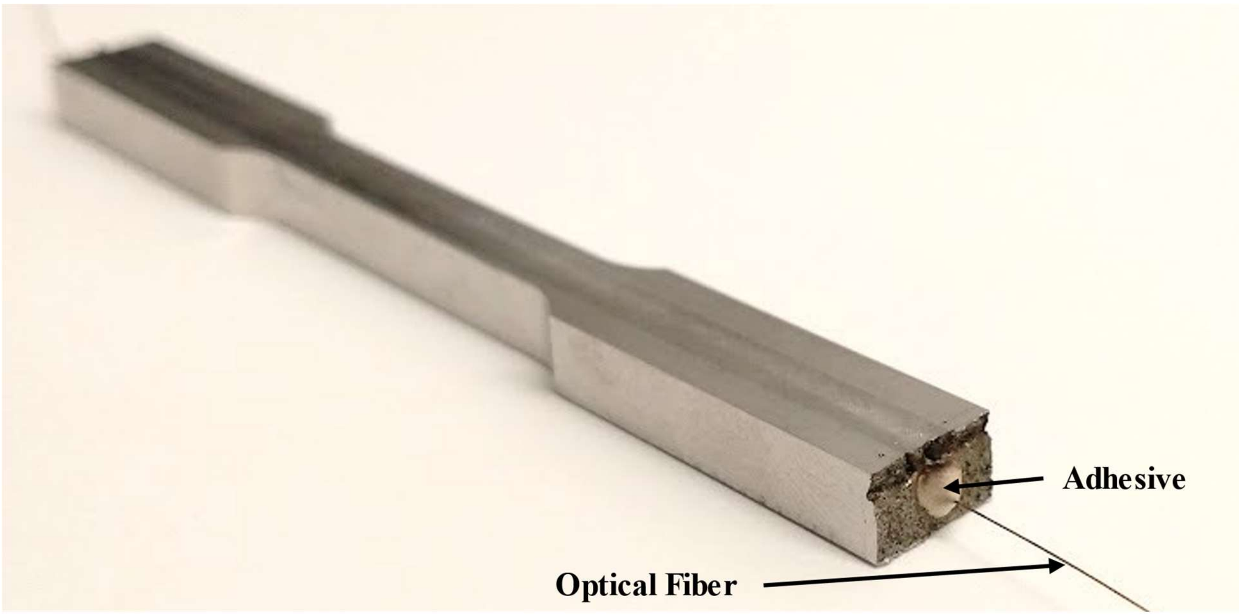

Figure 4: Embedded Fiber Tensile Specimen

The strain sensing capabilities of this method were verified by performing an axial strain test in which the tensile specimen was loaded into a Tinius Olson T25 running Horizon control software with a 5kN load cell and subjected to a set of small deformations over approximately 15-30% of the elastic region of the tensile specimen (though this is difficult to determine as the specimen did not undergo any thermal treatment and as-deposited material characteristics can be unpredictable). The termination end of the sensor was adhered to the machine to prevent motion and subsequent noise in fiber strain measurements. The strain was monitored during the tensile test using an Epsilon® Model 3542 Axial Extensometer and recorded in time. The distributed strain data from the fiber sensor over the 20mm extensometer section was similarly recorded using a Luna ODiSI 6000 OFDR system sampled at 1 Hz with a spatial resolution of 0.65mm and the resulting elongation over the extensometer section was calculated. This loading was applied in two separate tests for the specimen. Figure 5 contains the tensile test experimental setup.

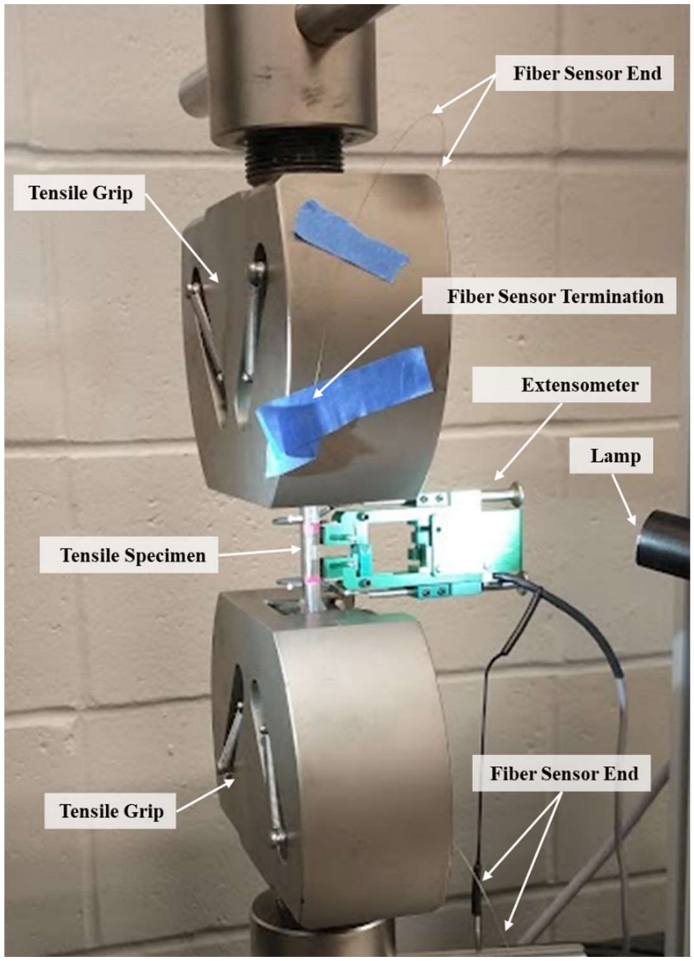

Figure 5: Tensile Test Setup

V. Results

A sample of the distributed strain profile of the optical fiber in the interest region (tensile specimen) at the final loading point of Trial 1 is shown in Figure 6. Note that the ideal strain profile would be uniform in the gauge length and that the extensometer region is smaller than the full gauge length. In calculating elongation (Figure 7, Figure 8, and Figure 9), only the fiber data in the test region was considered as it is the only direct comparison to the extensometer data (expressed as a percent change in distance between extensometer blades). Also note that the strain profile is not to scale; it is included only for a generalization of the shape of the expected strain profile. As discussed in Figure 10, the ideal strain magnitude would be greater than is shown in Figure 6. Some noise is present in the gauge length of the test specimen and is likely due to misalignments of the optical fiber within the slot. Because this slot was not machined to precise tolerances, the slot was not tight against the fiber, allowing for some amount of variation of the fiber placement within the slot. If the fiber was not exactly straight when the adhesive set, any curvature in the fiber results in a misalignment from the axial strain applied to the fiber and would attenuate the strain signal slightly. This is likely the cause of the variations observed in the gauge length and precision-machining a slot with tighter tolerances would allow for more precise control over the placement of the fiber sensor if this were to be of concern in future embedment procedures.

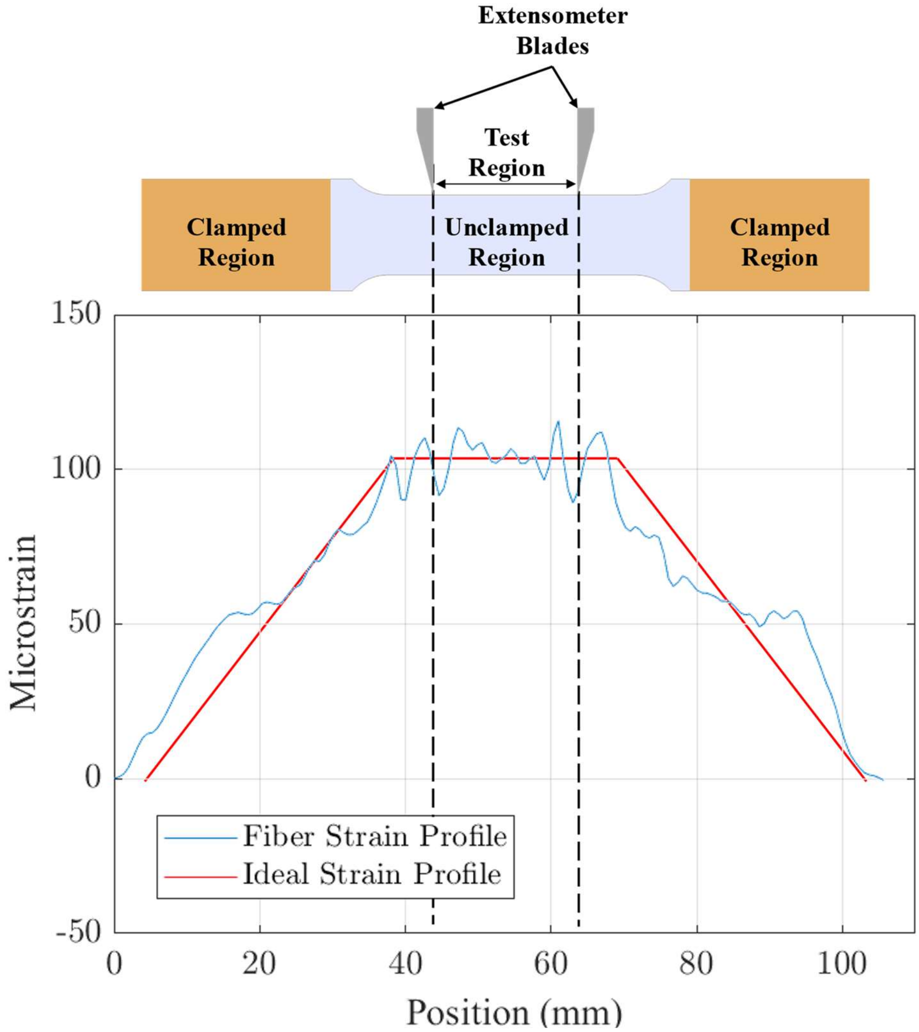

Figure 6: Sample of Strain Profile from End of Loading in Trial 1

Results of each trial are shown in Figure 7 and Figure 8, and are shown together in Figure 9. While the strain transmission to the fiber is dampened, the correlation is relatively linear and is smooth.

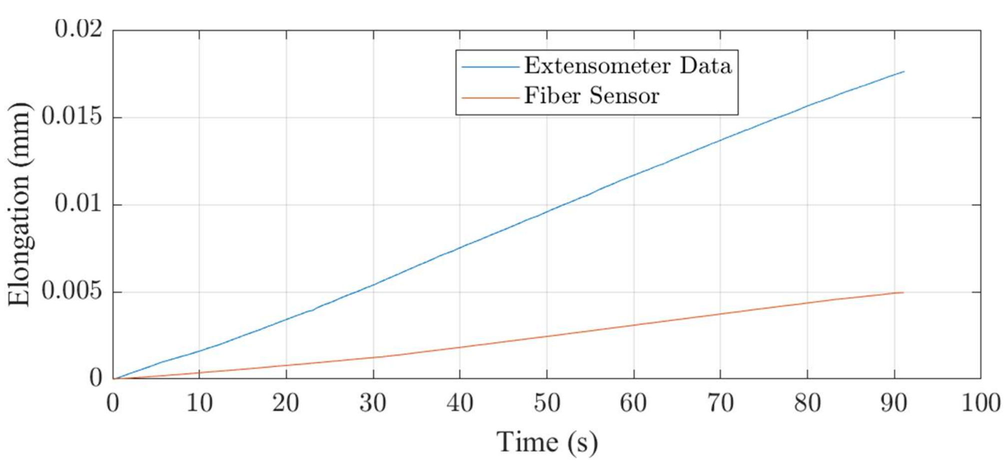

Figure 7: Trial 1 of Axial Strain with Adhesive-Embedded Fiber Specimen

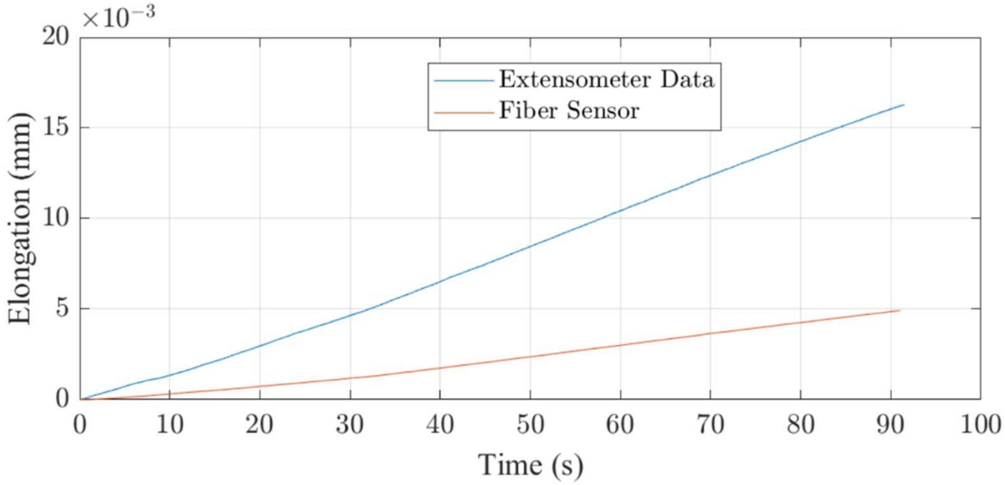

Figure 8: Trial 2 of Axial Strain with Adhesive-Embedded Fiber Specimen

It is interesting to note that the extensometer measurement varies more over the two loading cases in Figure 9 (which should have been identical barring any machine disturbances) and is likely due to misplacement of the extensometer or result of some other experimental disturbance. The fiber strain loading from each trial appears to be very repeatable and is nearly identical for the two trials.

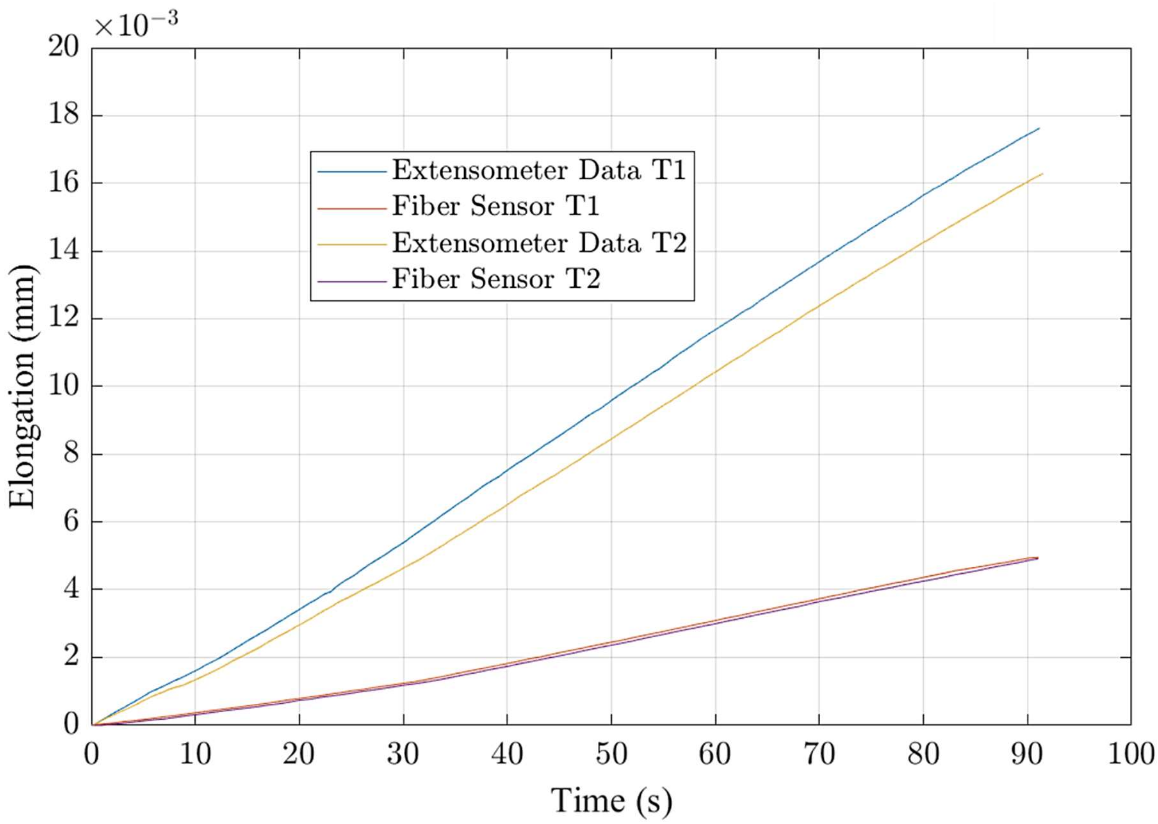

Figure 9: Axial Strain Trials with Adhesive-Embedded Fiber Specimen

Figure 10 shows the sensitivity of the fiber sensor over the two loading trials. The variation in the first few sample points is almost certainly due to numerical error and sensor resolution limitations as the elongation approaches zero. The fiber sensor strain measurements are attenuated to approximately 20-30% of the true strain values and is likely due to the translation of strain through the adhesive, copper cladding, and fiber cladding (a silica coating over the fiber core). While the strain is attenuated, the sensor is still quite capable of measuring even very minute strains (close to 1 µm) with calibration.

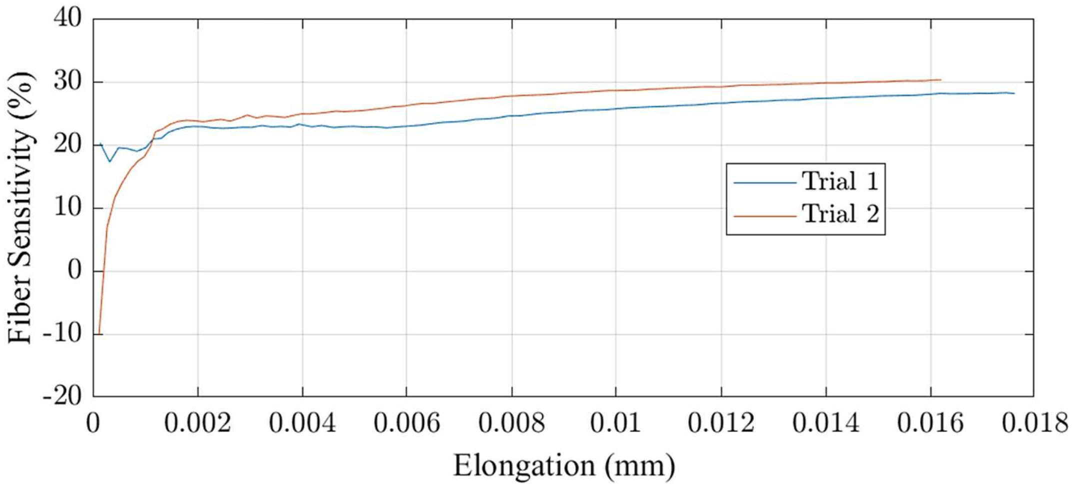

Figure 10: Sensitivity of Fiber Sensor to Actual Strain

VI. Conclusion and Future Work

Optical fibers are useful for a variety of sensing applications and open opportunities for revolutionary embedded strain and thermal sensing capabilities in end-use parts. The flexibility of the process presented in this work retains the flexibility of distributed strain sensing by eliminating the need for substantial metal coatings while also reducing the difficulty in obtaining the materials necessary to produce a part with embedded fiber sensors. In addition, the geometrical impact of the sensor on the part may be lessened, especially with precision-machined slots, and the void and unbonded regions are mitigated. While strain readings are attenuated, these embedded sensors are still capable of measuring very minute strains. Further, by using precision machined slots, the reduction of strain transmission through the adhesive may be lessened to promote a more sensitive strain reading from these embedded sensors.

The development of optical fiber embedment methods is still in its infancy and end-use cases for metal parts with embedded sensors are largely unexplored. Future work should develop the methods necessary to reliably embed and more rigorously characterize the strain readings from these sensors with as little impact on the part as possible. Machining fiber slots should be explored for its advantages in accuracy of fiber placement, especially as the toolpaths for these slot geometries could be more accurately correlated to CAD geometry for viewing strain and temperature data on a virtual representation of the part. Various adhesives may also grant better material properties and strain transmission to the fiber. End-use parts with complex geometries would be well-suited for embedded fiber sensing applications and should also be explored in the interest of furthering this work into applications.

VII. References

[1] H.-N. Li, D.-S. Li and G.-B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering," *Engineering Structures,* vol. 26, no. 11, pp. 1647-1657, 2004.

[2] J. Ko and Y. Ni, "Technology developments in structural health monitoring of large-scale bridges," *Engineering Structures,* vol. 27, no. 12, pp. 1715-1725, 2005.

[3] L. S. M. Alwis, K. Bremer and B. Roth, " Fiber Optic Sensors Embedded in Textile-Reinforced Concrete for Smart Structural Health Monitoring: A Review," *Sensors,* vol. 21, no. 15, p. 4948, 2021.

[4] X. L. He, Z. Q. Wang, D. H. Wang, X. B. Wang, Y. Liu, F. C. Jiang and L. B. Yuan, "Optical Fiber Sensor for Strain Monitoring of Metallic Device Produced by Very High-Power Ultrasonic Additive Manufacturing," *IEEE Sensors Journal,* vol. 19, no. 22, pp. 10680-10685, 2019.

[5] A. Hehr, M. Norfolk, J. Sheridan, M. Davis, W. Leser, P. Leser and J. A. Newman, "Spatial Strain Sensing Using Embedded Fiber Optics," *Additive Manufacturing of Composites and Complex Materials,* vol. 71, no. 4, pp. 1528-1534, 2019.

[6] S. K. Chilelli, J. J. Schomer and M. J. Dapino, "Detection of Crack Initiation and Growth Using Fiber Bragg Grating Sensors Embedded into Metal Structures through Ultrasonic Additive Manufacturing," *Sensors,* vol. 19, no. 22, p. 4917, 2019.

[7] H. C. Hyer, D. C. Sweeney and C. M. Petrie, "Functional fiber-optic sensors embedded in stainless steel components using ultrasonic additive manufacturing for distributed temperature and strain measurements," *Additive Manufacturing,* vol. 52, 2022.

[8] D. Havermann, J. Mathew, W. N. MacPherson, R. R. J. Maier and D. P. Hand, "Temperature and Strain Measurements With Fiber," *Journal of Lightwave Technology,* vol. 33, no. 12, pp. 2474-2479, 2015.

[9] J. Mathew, D. Havermann, D. Polyzos, W. N. MacPherson, D. P. Hand and R. R. J. Maier, "SS316 structure fabricated by selective laser melting and integrated with strain isolated optical fiber high temperature sensor," in *International Conference on Optical Fibre Sensors* , Curitiba, 2015.

[10] M. Davis, J. Middendorf, N. Garg and O. J. O. III, "Additively manufactured components with embedded instrumentation," in *ASME 2016 International Mechanical Engineering Congress and Exposition*, Phoenix, 2016.

[11] R. Zou, X. Liang, R. Cao, S. Li, A. To, P. Ohodnicki, M. Buric and K. Chen, "Optical fiber sensor-fused additive manufacturing and its applications in residual stress measurements," in *Conference on Lasers and Electro-Optics*, San Jose, 2017.

[12] R. Zou, X. Liang, M. Wang, A. Yan, P. Ohodnicki, A. To and K. Chen, "Embedding Distributed Temperature and Strain Optical Fiber Sensors in Metal Components Using Additive Manufacturing," in *Conference on Lasers and Electro-Optics*, San Jose, 2018.

[13] Y. Li, Z. Hua, F. Yan and P. Gang, "Metal coating of fiber Bragg grating and the temperature sensing character," *Optical Fiber Technology,* vol. 15, no. 4, pp. 391-397, 2009.