IN-PROCESS MONITORING OF INDUCTION WELDING OF THERMOPLASTIC COMPOSITES BASED ON FIBER OPTICS

Jaspreet Pandher[1], Dr. Michel van Tooren[1]
[1]SmartState Center for Multifunctional Materials and Structures, University of South Carolina
Mathew Davis[2], Jason Fant[3]
[2]Luna Innovations Incorporated
[3]Zeus Industrial Products

Abstract

Successful induction welding of thermoplastic composites relies on assuring temperature and applied pressure to be in a certain window for a specific time period. Qualifying an induction welding process therefore requires measurement and control of these parameters, with the most important being temperature at the weld surface during process qualification. Temperature measurements are normally done with thermocouples. However, thermocouples are not accepted in the final part, so all components used for qualification need to be scrapped and no thermocouples can be placed in the series components. For the series products, we therefore have to rely completely on the repeatability of the process. If any design changes are required in the part which affect the joint geometry, requalification using thermocouples is required for the development of process parameters for induction welding the joint.

A novel fiber optic based temperature sensor that can be left in the part after manufacturing has been developed and tested. The new sensor allows for quality inspection at the weldline during welding of each part, including the series components and therefore reduces uncertainty in joint strength. This will ease process control and design changes, and will allow for feedback control in the welding process. Standard fiber optic based sensors do not allow for this. Their diameter is too large and will act as a stress raiser in the weld, causing potential failure under cyclic loading. The proposed concept features a sensor with a coating that dissolves (diffuses) during the welding process, having the coating on the sensor blend into the base polymer. The remaining optical fiber is much smaller in diameter and leaves the strength of the part unchanged. The sensor has been successfully used to visualize the temperature distribution in different work pieces during welding in real time. The research has been performed by a team of researchers from USC, Luna Inc. and Zeus Inc. The research was sponsored by the South Carolina Research Authority (SCRA).

1. Introduction and Background

Fiber composites based on thermoplastic polymer matrix materials offer the possibility of fastener free assembly of composite parts and components. The nature of the thermoplastic matrix material allows repeated melting and solidifying of the polymer. If two parts are melted at their surface, application of pressure for a limited time will allow a cohesive bond to form; this process is referred to as fusion bonding. Cohesive bonding of thermoplastic composites is very different from bonding cured thermoset parts, where the resulting bond relies on adhesion between carefully prepared surfaces prior to bonding. This joining method is commonly referred to as adhesive bonding. Using cohesive bonding instead of adhesive bonding for composite parts allows fastener free assembly during manufacturing. There is no longer a need for a structural safeguard in the form of rivets or bolts to enable certification. Advantages of cohesive bonding and elimination of fasteners are weight and cost savings for structures. A special type of fusion bonding of thermoplastic composites is induction welding, which is the fusion bonding method used for this research. This type of welding is especially interesting for the bonding of thermoplastic polymers reinforced with carbon fibers. The conductivity of these fibers allows the development of eddy currents in the composite that are strong enough to heat the polymer above its melting point. The process parameter settings for successful welding depend on the specifics of the laminates being welded. Fiber directions, stacking sequence, ply thickness, homogeneity of plies, and fiber volume fraction all have a considerable influence on the heat generation. Being able to cost effectively sense temperatures in-situ during process window determination and series production would be highly beneficial. Recent development in fiber optics combined with the modifications explored in the current research have great promise to enable this in-situ, in-process monitoring of temperatures for induction welding.

1.1 Process Monitoring Methods

The quality of a cohesive bond will depend on the pressure and temperature time cycle in the welding zone. Since the welding zone is covered by the parts being bonded it is not trivial to measure those critical parameters in process.

Using Infrared (IR) cameras requires a translation of the surface temperatures to temperatures in the weld zone. The obvious choice to overcome this problem is to use thermocouples. Although this will deliver the temperatures at the weldline, the thermocouples themselves, by their size and constituents, influence the mechanical properties of the bond line. Therefore, they can only be used in process development, not series production.

This paper investigates a third option using fiber optic sensors applied to the surface of one of the parts being bonded. The size (diameter) of fiber optic sensors is normally such that they will act as an anomaly in the joint and adversely influence its strength. A closer look at the cross-section of a traditional fiber optic sensor shows two “layers” of material surrounding the silica fiber core (see Fig.1).

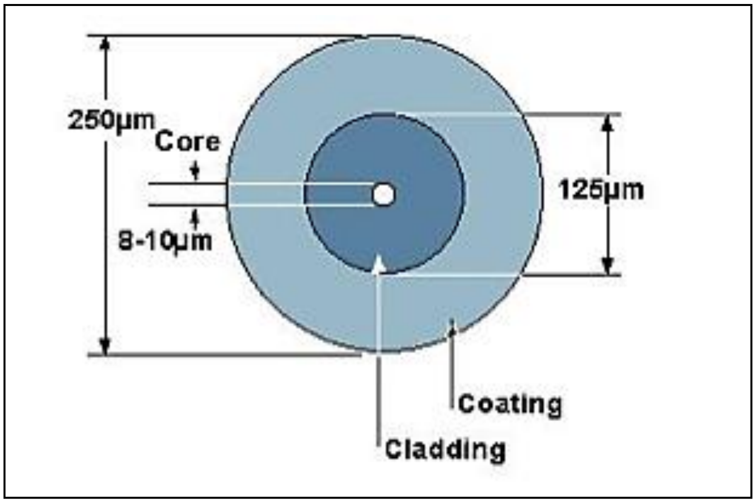

Figure 1 Optical Fiber Cross-Sectional Layers

The core and part of the cladding are required for the sensing function while the coating is applied for handling protection; however, the cladding and coating materials and diameters can be changed, which is the topic of this paper.

1.2 Optical Sensor Principles and Modifications

The core of a typical fiber optic sensor is a doped silica fiber which acts as the physical medium to transport optical data signals gathered from the fiber using a light source and receiving device (interrogator). The cladding is a barrier layer that surrounds the silica fiber core, creating a sufficient index of refraction difference to contain the light traveling through the fiber. This layer is typically also pure silica and is manufactured with the core as part of the fiber drawing process. The silica fiber core and cladding combined have a typical diameter of $125\mu m$. A coating is applied around the core and cladding to protect them during handling. Materials used as coating are durable and high temperature resistant polymers (although metals are sometime used as well). The coating adds to the diameter of the fiber optic sensor and creates an overall diameter of around 165 –250 μm [1,2]. In comparison with the silica fiber core or a carbon fiber, which have diameters no larger than $10\mu m$, a $250\mu m$ diameter sensor is very large, and if left inside a bond line after process monitoring could negatively influence static and fatigue strength of the part. For the same reason, parts equipped with thermocouples for process development and cohesive bond strength evaluation, are normally scrapped.

A modification of the fiber optic sensor is proposed by reducing the core/cladding size and replacing the primary coating with a polymer that is identical to or can be blended with the polymer of the composite part the sensor is to be placed within for process monitoring. During processing the polymer coating would melt and “dissolve” into the composite reducing the sensor diameter to a comparable size of almost that of the fibers in the composite. Using this approach for Rayleigh Scatter based sensor technology instead of Fiber Brag Grating (FBG) type sensors would decrease sensor cost to a level that allows for “disposable” sensors in series production parts. The Rayleigh Scatter technique is a fiber sensing technique commonly used by Luna Innovations Incorporated (Luna) interrogator system and equipment [1,2].

The Luna fiber optic sensors are manufactured from standard off-the-shelf telecommunications fiber with a Ge-doped fused silica core and fused silica cladding with a polymer protective coating. An individual sensor can be tens of meters in length and provide thousands of measurements at configurable points distributed along its length. Measurements are made using the Rayleigh scatter in the fiber, a random but stable pattern of reflections inherent to each fiber as a result of small-scale non-homogeneities (imperfections within the silica core). This random pattern of reflections is unique to each fiber and constant for the life of the fiber, forming a reflection signature unique to each sensor. Strain or temperature results in an apparent stretching of this signature, which translates to a shift in the spectral content of the pattern. As both stimuli affect the fiber in a similar manner, sensors designed to measure temperature are mechanically isolated from strain by sheathing them in a PTFE, stainless steel, or other suitable tubing. An alternative method, without sheathing, can be used for temperature measurements through post-processing strain measurements. Use of a reference temperature sensor (e.g. PTFE sensor, thermal couple, etc.) may be used to separate the influences of mechanical and thermal strains picked up by the fiber optic sensor and create a proper reference state for monitoring.

Sensors are interrogated using optical frequency domain reflectometry (OFDR), an interferometric technique that can distinguish scattering points at different locations along the fiber [[3]-[5]]. Fig. 2 describes the basic OFDR network while Fig. 3 walks through the steps taken to obtain, in this case, a strain measurement. Light from a swept-tunable laser is split between the measurement path and a reference path by a fiber optic coupler. Light in the measurement path is sent to the sensor through the input path of an optical coupler. Light reflected from the sensor returns through the coupler and is recombined with light from the reference path. This combined signal then passes through a polarization beam splitter, which splits the light into orthogonal states recorded at the S and P detectors. A Fourier transform of these signals yields the phase and amplitude of the signal as a function of length along the sensor, i.e., the sensor signature.

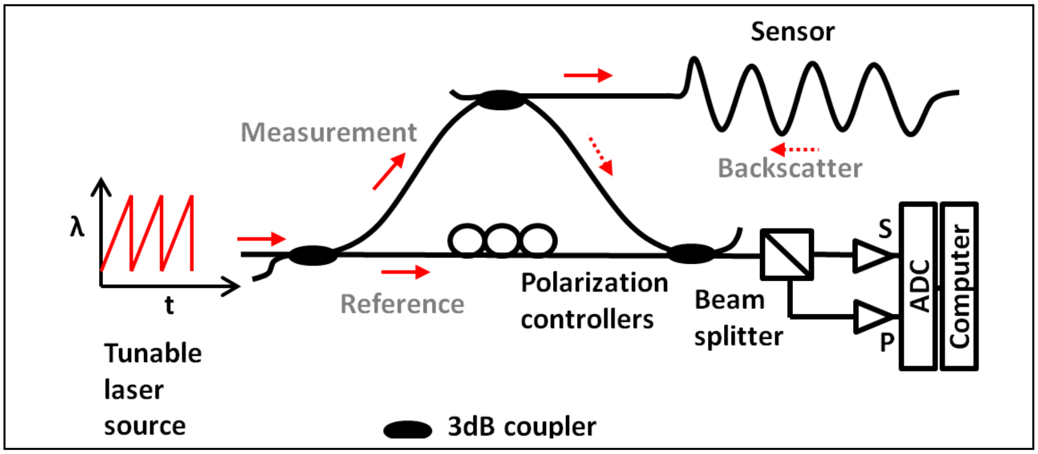

Figure 2 Basic OFDR optical Network [6 and 7].

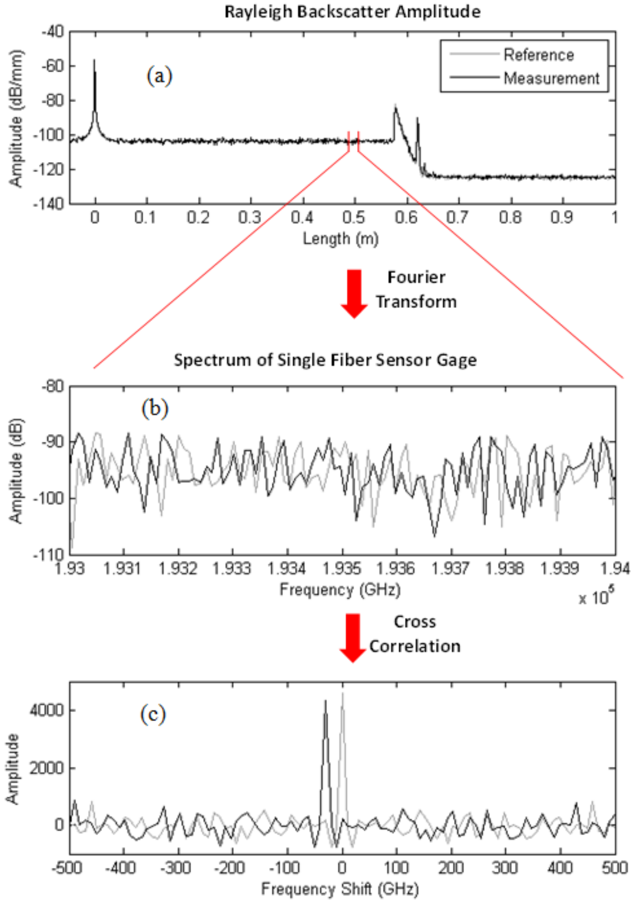

Figure 3 Frequency shift calculation from Rayleigh Scatter Measurement. (a) Rayleigh Backscatter along optical path. (b) spectrum of single sensor gage. (c) Cross-correlation of reference and measurement spectra. [7]

To calculate either a strain or temperature measurement, the spectral content of the sensor is compared between the measurement and reference state. Complex Fourier transform data is windowed around a desired measurement location, Fig.3(a). This window determines the gage length of the measurement. An inverse Fourier transform of the windowed data gives the spectral content from a particular gage in the sensor, Fig.3(b), which is cross-correlated, Fig.3(c), with the spectrum from the same location of the sensor in a baseline state. Finally, the cross-correlated shift is converted to strain using an empirically determined calibration coefficient, or gage factor, analogous to that of the electrical strain gage. This process is repeated along the length of the sensor, forming a distributed measurement [6,7].

2. Description of Equipment and Processes

The following section details: the thermoplastic composites selected for this work, fiber optic coating using the proposed technology, induction welding equipment, fiber optic equipment, and welding configuration used for dissolve testing and in-process monitoring.

2.1 Material

The composite material selected is a plain weave carbon fabric reinforced polyphenylene sulfide (CF/PPS) from TenCate Advanced Composites. Four-ply CF/PPS laminates, dimensions of 610mm x 100mm, were consolidated in a hot platen press between two Upilex-S release films. Laminates were consolidated at a temperature of 340 ℃ and a pressure of 10.3 Bar, conforming to specifications in the material data sheet [8]. The thickness of the consolidated laminates was 0.5 mm. The consolidated laminates were cut to lengths of 152mm x 100mm, dried in an oven at 120 ℃ for 4 hours, and degreased with acetone prior to welding.

2.2 Fiber Optic Sensors

High Definition Fiber Optic (HD-FOS) sensors were selected as the fiber optic sensors for this work. HD-FOS sensors have an overall diameter much smaller than typical fiber optic sensors of 95μm [9]. These sensors were coated with PPS resin by Zeus Industrial Products, Inc. (Zeus). After coating, the sensors were provided to Luna for keying and integration with ODiSI-B 5.0 interrogator system for in-process and *in-situ* monitoring during experimental testing [10]. Fig. 4 shows microscopy pictures of the sensors with (left) and without (right) PPS coating. The PPS coated fiber (note: white layer PPS polymer) is shown in its cross-sectional view due to no longer having transparency from the PPS coating and increasing the overall fiber diameter to 220μm. The HD-FOS sensor without PPS coating is shown with backlight microscopy due to the transparency of the cladding and polyimide coatings. Fig. 5 shows an example of a coated and keyed sensor from Luna used for in-process monitoring.

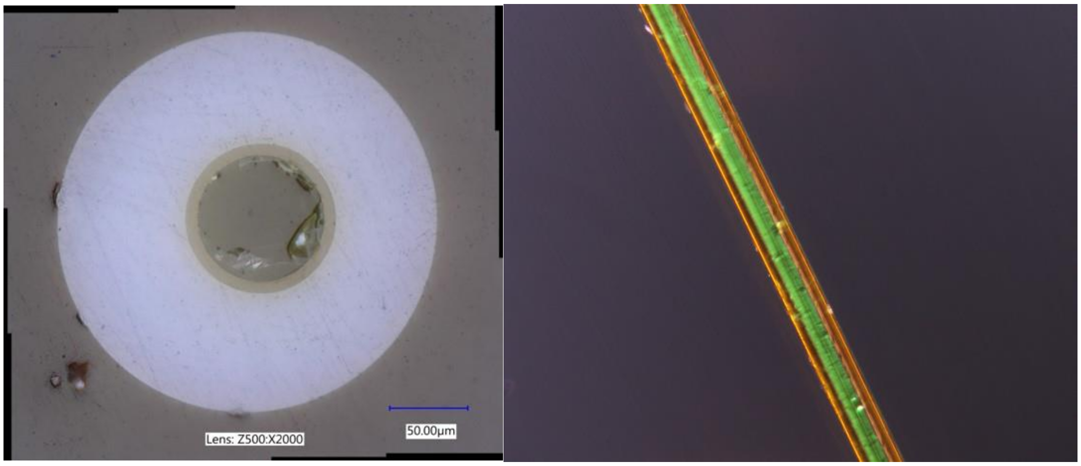

Figure 4 (Left) PPS Coated HD-FOS Sensor (Right) HD-FOS sensor with Polyimide Coating

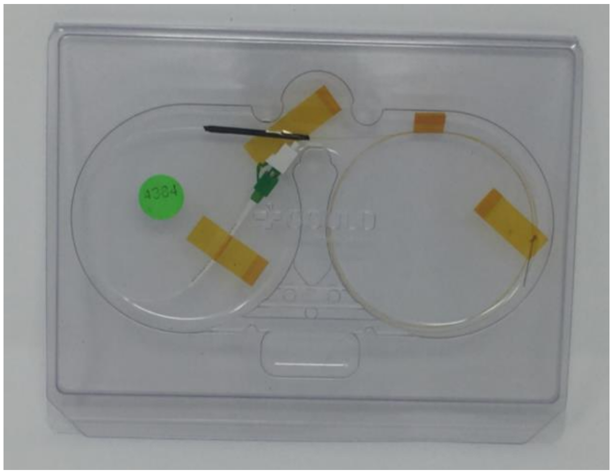

Figure 5 Example HD-FOS Sensor coated by Zeus and Keyed by Luna

2.3 Experiments

Two types of experiments were carried out for testing the proposed sensor technology: Sensor Coating Experiments and in-process monitoring experiments.

2.3.1. Sensor coating experiments

Due to the difficulty of stripping and replacing both the coating of an optical sensor and evenly coating silica fiber directly, a set of explorative experiments have been done as first steps to test the proposed idea. Instead of using the cladding and coating of a normal fiber optic sensor, with a total diameter of $250\mu m$, a non-conventional size fiber optic sensor is selected with reduced layer sizes of cladding and coating summating to an overall diameter of $95\mu m$. Using this non-conventional sized fiber optic sensor, an additional dissolvable coating is added on top of the two layers to increase the overall sensor diameter to $220\mu m$. This non-conventional fiber optic sensor with the large coating size tests if the “dissolvable” coating melts off, reducing the sensor size by almost half, and blends with the composite while still preserving the sensor’s functions for *in-situ* monitoring. PPS has a high degree of crystallinity which carries with it certain characteristic material attributes such as melt flow rates and temperature stability. Zeus’ proprietary extrusion of PPS for the fiber optic coating was able to match the polymer matrix of the typical composite PPS. This similarity was vital to achieving homogenous melt-flow of the coating and of the TenCate CF/PPS during welding. With matched fiber optic coating and composite material, a near-perfect weld and embedding of the optical fiber can be achieved as the fiber optic coating melts and flows from the fiber to the surround composite matrix. The result is a tight, secure bond and minimal surface imperfections within the weld zone due to the dissolvable coating.

PPS coating was applied to the fiber via extrusion. PPS was extruded over the optical fiber using a thermoplastic crosshead design extruder. During extrusion, the optical fiber was fed into the crosshead while PPS was extruded in tubular form utilizing a die / mandrel (or pin / bushing). The crosshead-type extruder mated the optical fiber with the PPS creating a tight buffer. A proprietary extrusion process by Zeus was used to control crystallinity and thermal stability of the coating to produce a more homogenous coating which would better conform to the composite during the composite weld process.

After Zeus completed their coating process, the first set of experiments were carried out using sacrificial PPS coated sensors placed in the weld line during induction welding with no connection to the Luna interrogator system. This was done because the welded laminate was to be cut into small sections for microscopy analysis to qualitatively verify the dissolving of PPS coating to the surrounding CF/PPS composite during induction welding. Additionally, thermal microscopy analysis of only the PPS coated sensor was performed to qualitatively verify the melting of coating from the fiber.

2.3.2 Welding experiments

The induction welder used for the tests consisted of an Ambrell EasyHeat Induction Heating System, Dimplex Thermal Solutions Chiller for induction coil liquid cooling, KvE proprietary induction welding end effector and vacuum bag setup, optical fiber connector, and thermocouple for calibration of fiber optic temperature measurements, Fig.6, and a Luna ODiSI-B 5.0 interrogator system. More information regarding the Luna interrogator system can be found in reference [10]. The consolidated laminates were placed in a lap shear configuration with a 1” overlap for all tests (see Fig.7). The single fiber optic sensor for in-process monitoring started at the bottom surface of the laminate, then continued across the bond line, and finally across the top surface of the laminate, Fig. 6. The sections highlighted with a colour gradient in Fig. 8 show the locations of interest along the fiber that were selected using Luna’s proprietary software for monitoring during the induction welding process. For the second set of experiments, the setup shown in Fig. 8 was used for in-process monitoring of temperature of the laminates during induction welding to determine if processing temperature was being reached and to check if the melt-off of the coating would influence functionality of the sensors. Static tests (fixed coil) were performed at the center of the laminates for ease of *in-situ* monitoring of temperature at a fixed location.

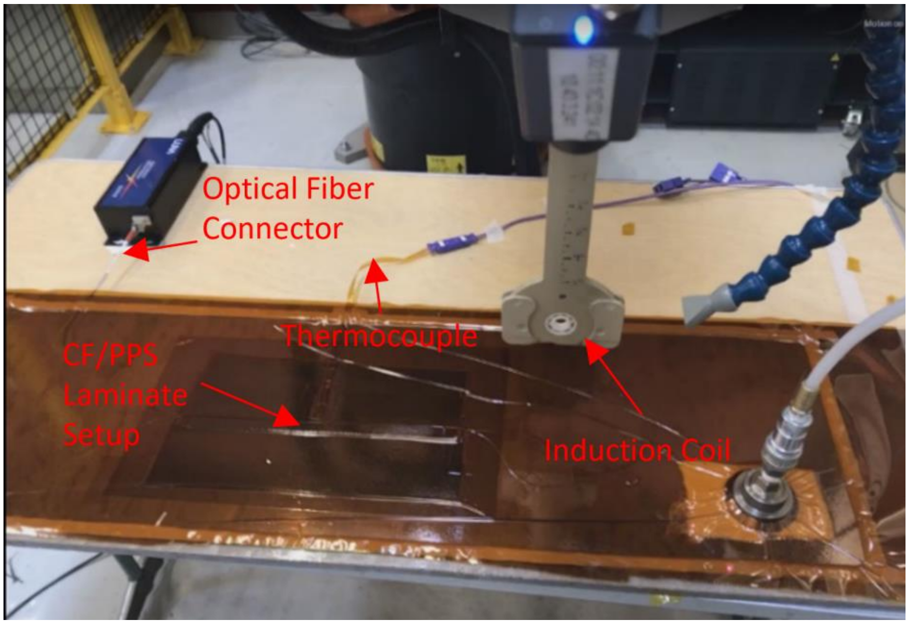

Figure 6 Induction Welding Setup

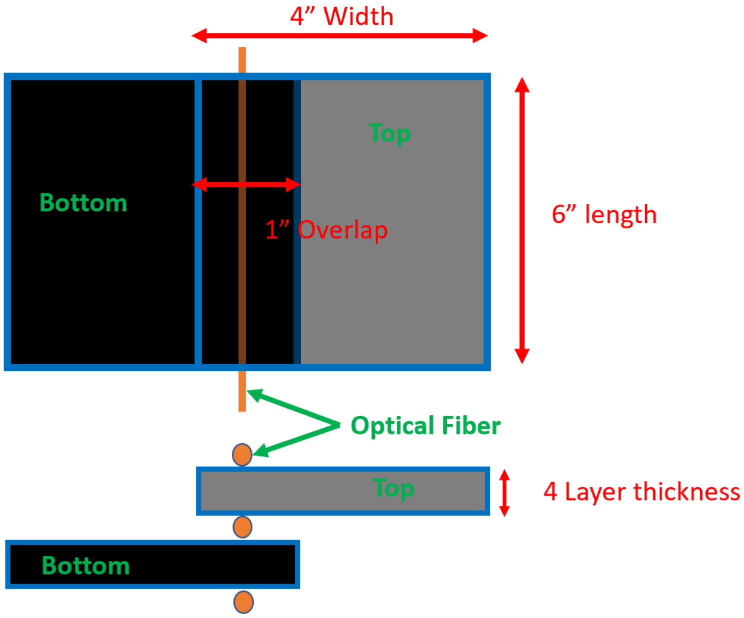

Figure 7 Laminate Welding Configuration

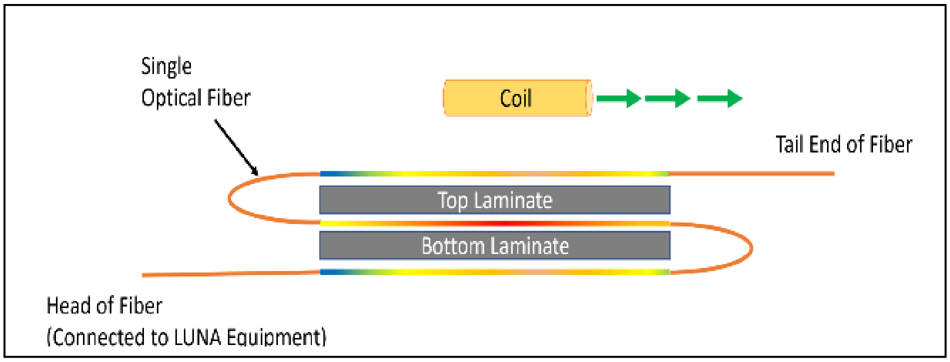

Figure 8 Optical Fiber placement and sensor selection along length of fiber for data collection

3. Results

The first phase research confirms the possibility to dissolve the polymer coating to reduce the sensor size during processing while still preserving the sensor's function for *in-situ* monitoring of process parameters. In this section, the results from the sensor coating experiments and welding experiments are discussed

3.1 Sensor Coating

After welding of the laminates with sacrificial sensors, the laminates were cut into small sections for microscopy analysis. Fig. 9 shows an example of one of the microscopy pictures taken at the bond line of the welded laminates. From qualitative analysis, it is observed that the PPS coating (white resin material seen in Fig. 9) melted away from the fiber optic sensor during welding and dissolved into the laminates. Although the PPS resin remained close to the optical fiber, it no longer performed as a part of the overall diameter of the optical fiber and has solidified within the CF/PPS laminates. This caused a decrease in the overall diameter of the optical fiber from 220μm to the original HD-FOS sensor diameter of around 95μm. Results from this preliminary test show the proposed technology of dissolvable coating was successful in decreasing the sensor diameter during processing. An additional melting test was performed using a heating bed and measured with an OLYMPUS microscope. The test qualitatively shows and verifies the dissolving/melting phenomena of the PPS resin coating when processing temperature is reached (340℃). Fig. 10 shows a before (left) and after (right) snapshots of the PPS coating melting off the sensor and decreasing diameter size.

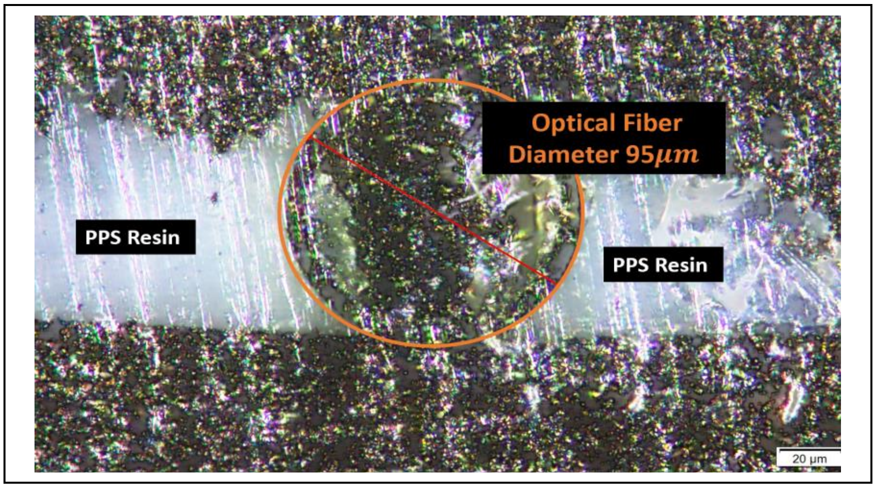

Figure 9 Microscopy of PPS Coating melted off in Bond Line

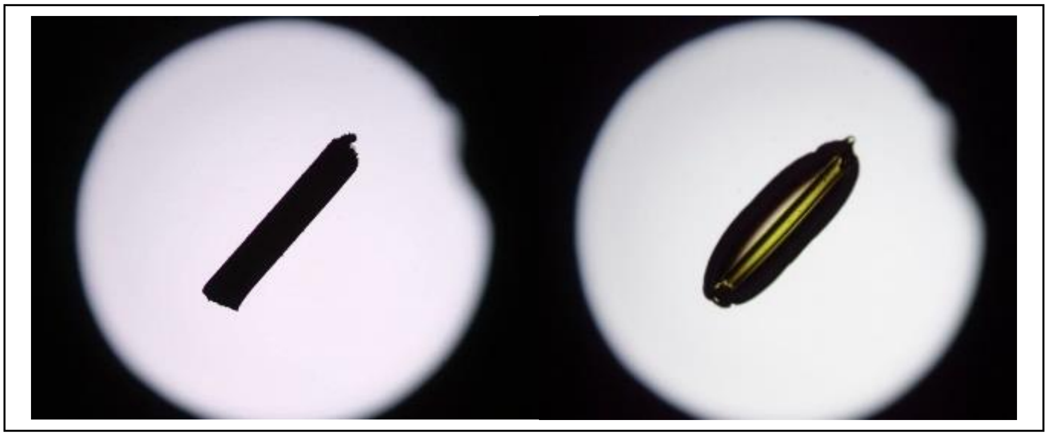

Figure 10 PPS coated fiber optic before (left) and after (right) melting

3.2 *In-Situ* Monitoring of Welding

Results from *in-situ* monitoring during induction welding showed that in fact this is possible and much more. The fiber optic sensor was placed not only in the bond line but also on top and bottom of the weld zone to test if the temperature distribution through the thickness of the joint could be monitored. Fig. 11 shows an example plot constructed using data acquired from Luna's software during in-process monitoring of temperature through the thickness of the bonded joint along a single fiber optic sensor. Post-processing of the collected data was shown to be possible for analysis of the temperature distribution through the thickness of the joint from a single fiber and possibility to later on generate processing models to relate time-above-temperature, processing temperature, and position along the weld line with process parameters of induction welding (e.g. current amperage, coil height, speed, etc). Doing so will assist induction welders to quickly relate process parameters and determine optimal bonding for high static and fatigue strength of cohesive joints. For a manufacturing researcher or engineer that performs process parameter development to fusion bond or weld parts and components together, this offers a real-time verification if processing temperatures are achieved along the full length of the bond line rather than sporadic locations from thermocouples or post-processing correlations to infrared surface readings.

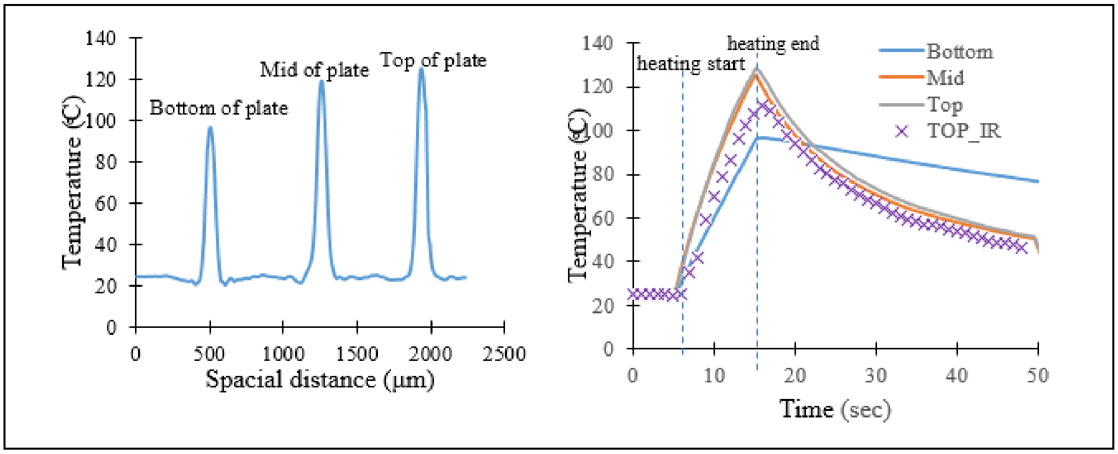

Figure 11 In-process monitoring of temperature (left) temperature values along fiber length (right) temperature values over time

4. Summary and Next Steps

The research in this report aimed for the development of a fiber optic sensor that can be left in a part after manufacturing. It allows for quality inspection on each part, including the series components, and reduces uncertainty in strength due to manufacturing error with minimal invasion. This will ease process control, design changes and allow for faster feedback control during fusion bonding processes for manufactures. Since current research was only to test the feasibility of a dissolvable coating, another study must be performed for testing of removal of the coating and reduced diameter cladding. A method for stripping and handling of the optical fiber without polyimide coating has been developed after completion of this work and is to be implemented for the second phase of the research study along with mechanical and fatigue testing to check impacts on sensor functionality and bond strength.

Acknowledgements

The authors would like to thank the South Carolina Research Association (SCRA) for funding of the presented research.

References

1. M. T. Reaves, D. R. Metrey, M. A. Castellucci, Embedded Fiber Optic Sensing in Composite-Overwrapped Pressure Vessels, (2013)
2. S. M. Klute, D. R. Metrey, N. Garg, N. A. A. Rahim, *In-situ* Structural Health Monitoring of Composite-Overwrapped Pressure Vessels, (2015)
3. Soller, B., Gifford, D., Wolfe, M., and Froggatt, M. “High resolution optical frequency domain reflectometry for characterization of components and assemblies.” Optics Express 13 (2005): 666-674.
4. Soller, B. J., Wolfe, M., and Froggatt, M. E. “Polarization resolved measurement of Rayleigh backscatter in fiber-optic components.” Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference Technical Digest. Anaheim, California, March 6, 2005. Optical Society of America, 2005. Paper NWD3. CD-ROM.
5. Kreger, S., Gifford, D. K., Froggatt, M. E., Soller, B. J., and Wolfe, M. S. "High resolution distributed strain or temperature measurements in single- and multi-mode fiber using swept-wavelength interferometry." Optical Fiber Sensors, OSA Technical Digest. Cancun, Mexico, October 23, 2006. Optical Society of America, 2006. Paper ThE42. CD-ROM.
6. Matt Castellucci, Sandra Klute, Evan M. Lally, Mark E. Froggatt, and David Lowry. "Three-axis distributed fiber optic strain measurement in 3D woven composite structures", Proc. SPIE 8690, Industrial and Commercial Applications of Smart Structures Technologies 2013, 869006 (March 29, 2013)
7. Nur Aida Abdul Rahim, Matthew A. Davis, Luke Routhier, Jason Chevalier, Joseph Bos, Stephen Kreger, and Eric Sanborn. "Accuracy and Survivability of Distributed Fiber Optic Temperature Sensors", 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech
8. TenCate Cetex® TC1100 PPS resin system Product Datasheet, TenCate Advanced Composites, 9 (2016)
9. High-Definition Fiber Optic Strain Sensors, Sensors Datasheet, Luna Inc, 9 (2016)
10. OBiSI-B Optical Fiber Distributed Sensor Interrogator Datasheet, Luna Inc, 2 (2017)