Research Paper

In-process and in-situ monitoring of process parameter in fusion bonding of thermoplastic composites.

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Preface

Polymer innovation: inspiring new possibilities in weld validation

Induction welding is used in a whole host of industries and applications where safety is of paramount importance and as a result, weld integrity is crucial. However, vital as it is, the process of validating a compositive weld zone is time-consuming and expensive.

Zeus was recently involved in extensive research seeking to replace traditional electrical thermocouple test methods with fiber optic sensors in a bid to simplify this lengthy, costly process. Unlike thermocouples, which affect the mechanical properties of the bond, fiber optic sensors have the potential to accurately monitor temperature and pressure during the weld process without threatening a component's structural integrity.

Enlisting industry expertise

A proposal was initially put forward by the SmartState Center for Multifunctional Materials and Structures at the University of South Carolina (USC), which sought to modify the standard coating and cladding applied to the core of a fused silica optical fiber.

With funding from the South Carolina Research Authority (SCRA), and support from GKN Aerospace, the research looked to implement a polymer coated optical fiber sensor that would effectively melt into the weld line. By selecting a polymer that could blend with the composite part, the investigation hoped to facilitate in-situ monitoring. To be successful, the polymer coating needed to fully incorporate, leaving a functional sensor safely embedded in the joint.

USC McNair Aerospace Center enlisted Zeus to develop a custom polymer coated optical fiber that would be entirely compatible with the composite weld of the part. Zeus coated the sensors with a specific grade of PPS resin designed to match the melt and flow rate of the chosen composite material; a carbon fabric reinforced polyphenylene sulfide (CF/PPS) from TenCate Advanced Composites. The sensors were subsequently provided to Luna Innovations, for keying and integration with the company's ODiSI-B 5.0 interrogator system, which would perform in-process and in-situ monitoring during testing.

Findings transform in-process monitoring

Results have been incredibly positive. Not only did the PPS polymer coating melt away from the fiber optic sensor, reducing its final diameter and creating a tight, secure bond to the part, it also left the sensor in place for real-time monitoring of in-process temperatures throughout the length of the bond line.

With data such as this at their disposal, composite manufacturers can determine optimal process control for bonding stronger cohesive joints. A more precise picture of weld quality reduces uncertainty in joint strength. And by proving the feasibility of a non-destructive validation method, scrappage costs can be significantly and immediately reduced. GKN Aerospace, which has supported this research, could ultimately see savings of up to $500,000 per part validation run.

For the wider engineering and scientific community, the findings also open up exciting opportunities for innovative real-time monitoring applications – even after components are fitted and deployed in the field. “Smart structure” monitoring could revolutionize the aerospace industry by providing real-time data highlighting structural issues before flight, providing a cue for preventative maintenance on composite parts without the need for external secondary monitoring equipment – just one of the many potential applications we’re excited about.

Jason Fant
Global Market Manager, Fiber Optics, Zeus

> Fiber optic sensors have the potential to accurately monitor temperature and pressure during the weld, avoiding the need to rely on process parameters to qualify induction welds, and without threatening a component’s structural integrity.

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Abstract

Fusion bonding of thermoplastic composites offers the possibility of fastener free assembly. It involves the melting of two parts along their respective contact surfaces, at or above a specific temperature for a minimum time, and application of pressure during melting and cooling to allow a cohesive bond to form. The quality of the cohesive bond is highly dependent on the temperature and pressure at the bonding zone, and the time the temperature and pressure are sustained. Since the area of interest during bonding is almost always covered by the parts, measuring the critical process parameters during bonding becomes non-trivial. The following work describes a method to address this problem by modified minimally invasive fiber optic sensors that can be positioned along the fusion bonding zone and allow for process parameter monitoring during series production for parts and components. The new sensors have been successfully tested and used to measure in-situ temperatures during welding.

Keywords:

Induction welding, Thermoplastic composites, In-process monitoring, Fiber optics

Part 1

Introduction

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 over 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.

Part 1.1

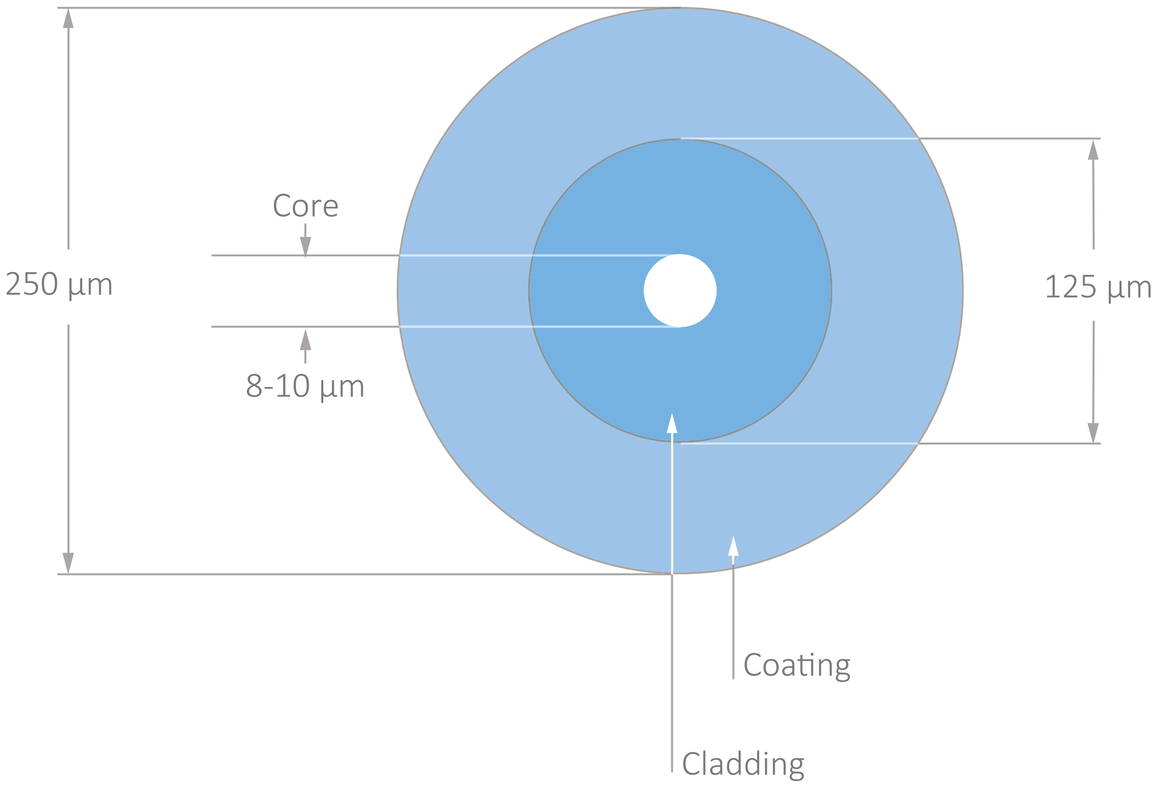
Process Monitoring Methods

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

Using Inferred (IR) cameras requires a translation of the surface temperatures to temperatures in the bond zone. The obvious choice to overcome this problem is to use thermocouples. Although this will deliver the temperatures at the bond line, 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 the 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). The core and part of the cladding are required for the sensing function and the coating for handling protection; however, the material, cladding and coating diameters can be changed which is the topic of this paper.

Figure 1. Optical Fiber Cross Sectional Layers



Part 1.2

Optical Sensor Modifications

The core is a doped silica fiber which acts as the physical medium to transport optical data signals gathered from fiber using a light source and receiving device (integrator). 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 125µm. 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. The coating adds to the diameter of the fiber optic sensor and creates an overall diameter of around 165 - 250µm [1,2]. Comparison with the silica fiber core or glass and carbon fibers, which have diameters no larger than 10µm, a 250µm 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. Therefore, normally 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 decreasing the size of the cladding and replacing the coating of the sensor 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 systemand equipment [1,2].

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 replacing the cladding and coating of a normal fiber optic sensor, with a diameter of 250µm, a non-conventional size fiber optic sensor is selected with reduced layer sizes of cladding and coating summating to an overall diameter of 95µm. Using this non-conventional fiber optic sensor, an additional dissolvable coating is added on top of the two layers to increase the overall sensor diameter to 220µm. This non-conventional optical fiber 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. For this research, induction welding was the fusion bonding technique used for testing of the modified sensors. Induction welding is a fusion bonding technique using induction heating for cohesively bonding thermoplastic composite parts. Tests were carried out using sacrificial sensors placed in the bond line during induction welding. The resulting welds were examined using microscopy. Additional thermal microscopy analysis of only the coated sensor was performed to visually verify the melting of coating from the fiber. Last, tests were performed in which the coated sensors were used to in-situ monitor temperatures during induction welding to check if the melt-off of the coating would influence functionality of the sensors.

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.

Part 2

Design

The following section details the experiments: 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.

Part 2.1

Material

The composite material selected is a plain weave carbon fabric reinforced polyphenylene sulfide (CF/PPS) of TenCate Advance Composites. Four-ply CF/PPS laminates, dimensions of 24" x 4", were consolidated in a hot platen press between two Upilex-S release films. Laminates were consolidated at a temperature of 610°F and a pressure of 150 psi, conforming to specifications in the material data sheet [3]. The thickness of the consolidated laminates was 0.5 mm. The consolidated laminates were cut to lengths of 6" x 4", dried in an oven at 250°F for 4 hours, and degreased with acetone prior to welding.

Part 2.2

Fiber Optic Sensors

High Definition Fiber Optic (HD-FOS) sensors were selected as the fiber optic sensors for this work. HDFO sensors have an overall diameter much smaller than typical fiber optic sensors of 95µm[4]. These sensors were coated with PPS resin by Zeus Incorporated (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 [5]. Fig. 2 shows microscopy pictures of the sensors with (left) and without (right) PPS coating. The PPS coated fiber (note: white layer PPS) is shown in its crosssectional view due to no longer having transparency from the PPS coating and increasing the overall fiber diameter to 220µm. The HDFO sensor without PPS coating is shown with backlight microscopy due to the transparency of the polyimide and cladding coatings.

PART 2.3

Experimental Setup

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 (see Fig. 3), and a Luna ODiSI-B 5.0 interrogator system. More information regarding the Luna interrogator system can be found in reference [5]. The consolidated laminates were placed in a lap shear configuration with a 1" overlap for all tests (see Fig. 4). 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 (see Fig. 5). The sections highlighted with a colour

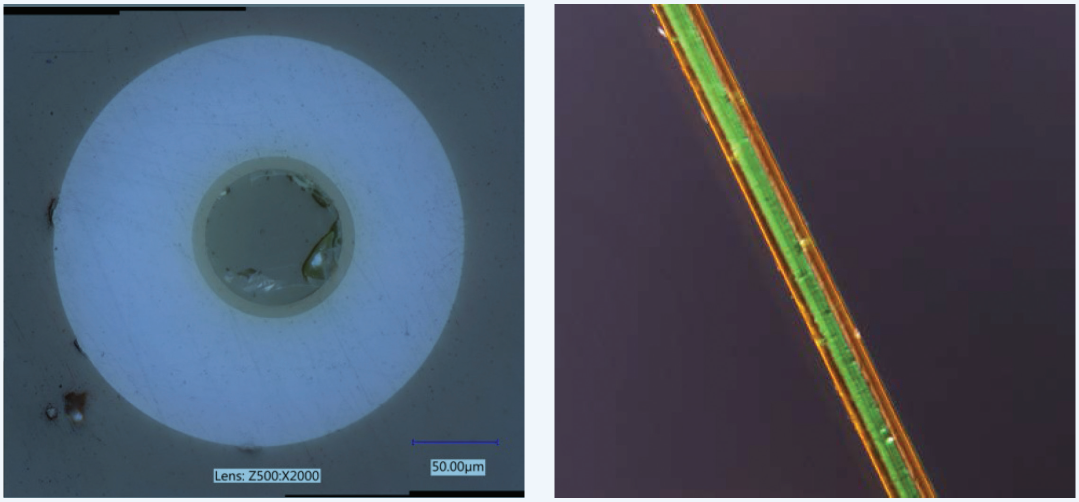


Figure 2. (Left) PPS Coated HD-FOS Sensor
(Right) HD-FOS sensor with Polyimide Coating

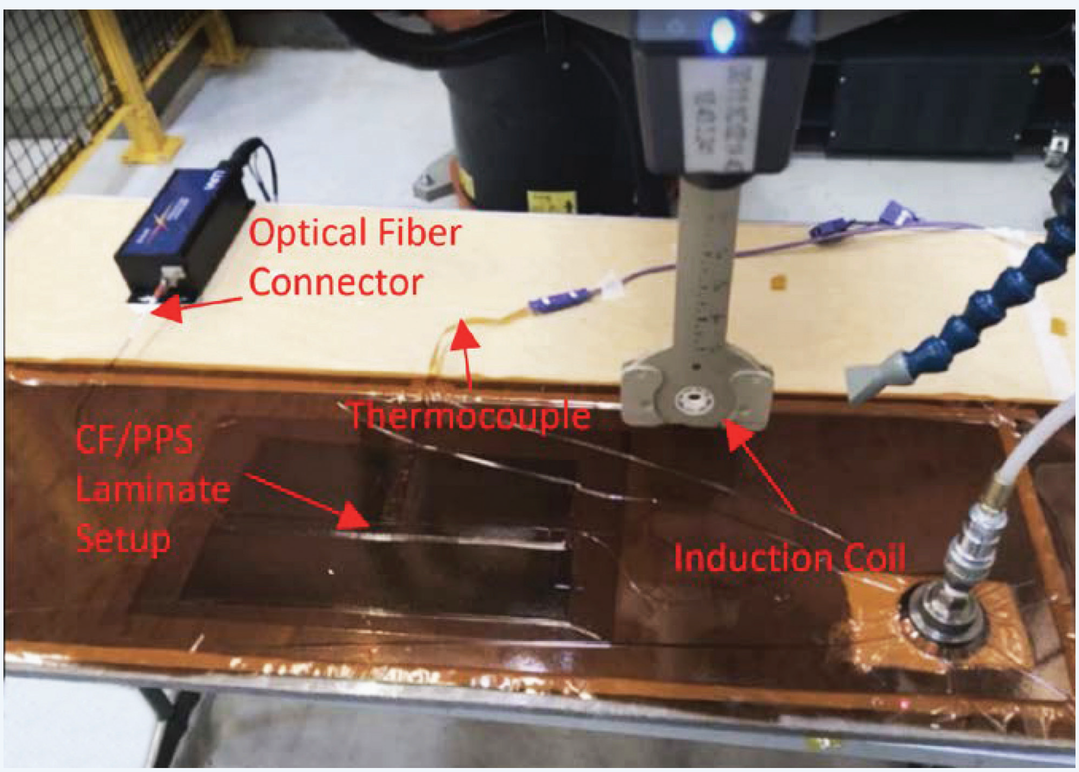


Figure 3. Induction Welding Setup

gradient in Fig. 5 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 first test, PPS coated fiber optic sensors were placed within the bond line during induction welding, with no connection to the Luna interrogator system. This was done since the bonded laminate was to be cut into small sections for microscopy analysis to qualitatively verify the dissolving of PPS coating to the surrounding composite during induction welding. For the second test, the setup shown in Fig.5 was used for in-process monitoring of temperature of the laminates during induction welding to determine if processing temperature was being reached. Static tests (fixed coil) were performed at the center of the laminates for ease of in-situ monitoring of temperature at a fixed location.

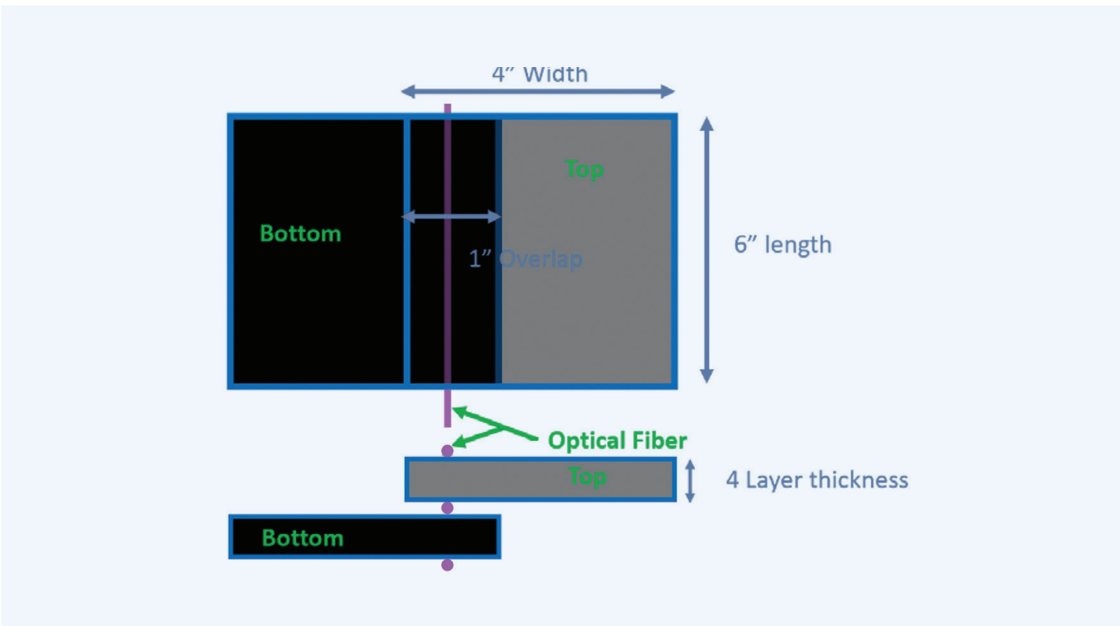


Figure 4. Laminate Welding Configuration

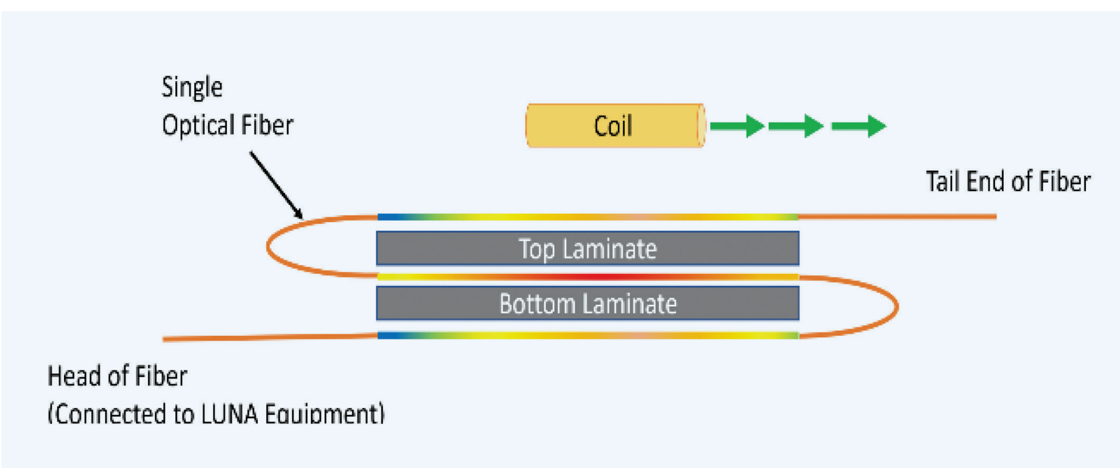


Figure 5. Optical Fiber placement and sensor selection along length of fiber for data collection

Part 3

Results

In this section, the results obtained from the dissolvable coating experiment and the in-process monitoring of temperature are discussed.

Part 3.1

Dissolvable Coating

After welding of the laminates with sacrificial sensors, the laminates were cut into small sections for microscopy analysis. Fig. 6 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. 6) melted away from the fiber optic sensor during welding and dissolved into the laminates. Although the PPS resin remains close to the optical fiber, it no longer acts 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 HDFO sensor diameter of around 95µm. Results from this preliminary test show the proposed technology of dissolvable coating ITHEC 2018, MESSE BREMEN 4/4 was successful in decreasing the sensor diameter during processing. An additional melting test was performed using a heating bed with an OLYMPUS microscope. The test qualitatively shows and verifies the dissolving/melting phenomena of the PPS resin coating when processing temperature is reached (610°F). Fig. 7 shows a before (left) and after (right) snapshots of the PPS coating melting off the sensor and decreasing diameter size.

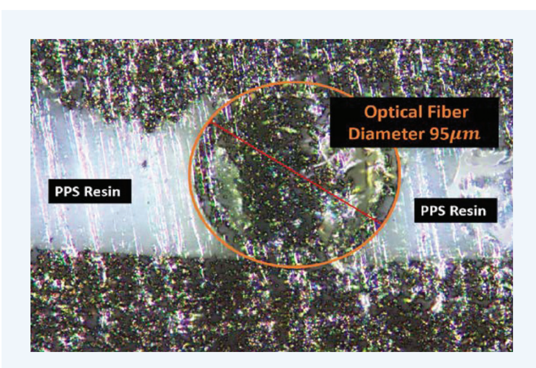


Figure 6. Microscopy of PPS Coating melted off in Bond Line

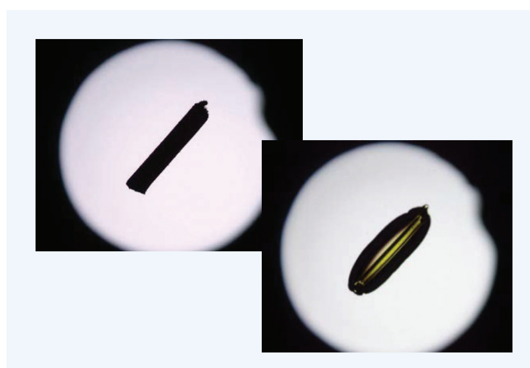


Figure 7. PPS coated fiber optic before (left) and after (right) melting

The test qualitatively shows and verifies the dissolving/ melting phenomena of the PPS resin coating when processing temperature is reached (610°F).

Part 3.2

In-Situ Monitoring

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. 8 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 sensor. Postprocessing 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 bond 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/engineer that performs process parameter development to fusion bond or weld parts and components together, this offers a realtime verification if processing temperatures are achieved along the full length of the bond line rather than sporadic locations from thermocouples or postprocessing correlations to inferred surface readings.

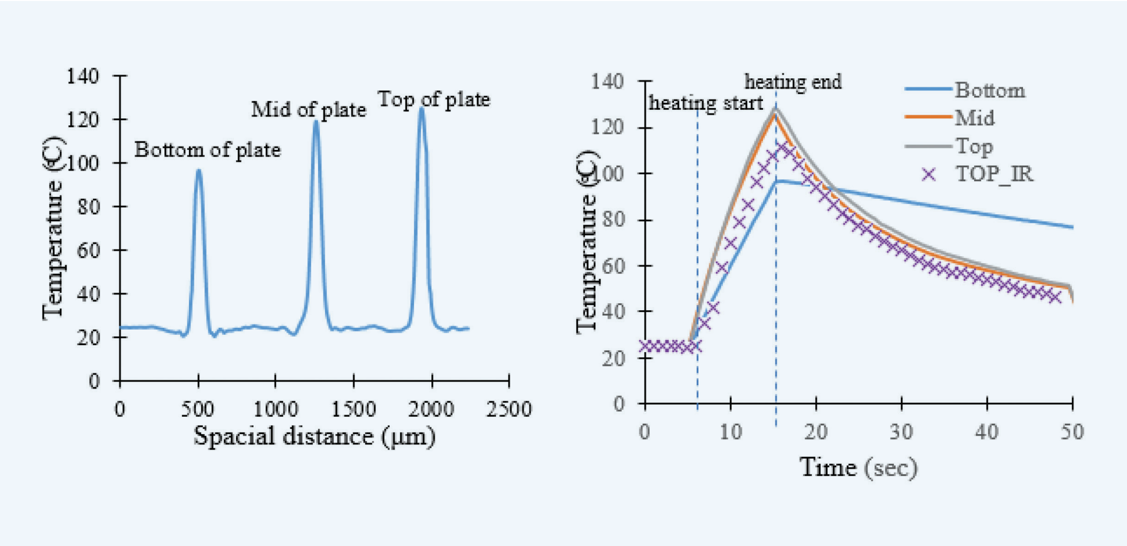


Figure 8. In-process monitoring of temperature (left) temperature values along fiber length (right) temperature values over time

Part 4

Conclusion

The research described 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 reduce 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 the cladding layers. 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.

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. TenCate Cetex® TC1100 PPS resin system Product Datasheet, TenCate Advanced Composites, 9 (2016)
4. High-Definition Fiber Optic Strain Sensors, Sensors Datasheet, Luna Inc, 9 (2016)
5. OBiSI-B Optical Fiber Distributed Sensor Interrogator Datasheet, Luna Inc, 2 (2017)

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