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SS-OCT technology for the in-process inspection of the Automated Fiber Placement manufacturing process

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ABSTRACT

Automated Fiber Placement (AFP) is an additive manufacturing process that enables the fabrication of complex parts for the aerospace industry. In-process inspection (IPI) for AFP is a technology that has been in high demand by most manufacturers for a long time since the current quality control, based on visual inspection, is a time-consuming process. The development of an IPI system for AFP presents many challenges. We show that the Swept-Source Optical Coherence Tomography (SS-OCT) technology addresses these challenges to provide a welcomed solution to the AFP manufacturing industry.

Keywords: optical coherence tomography, optical inspection, interferometry, composite manufacturing.

1. INTRODUCTION

Automated Fiber Placement (AFP) is an important additive manufacturing process used in the aerospace industry to manufacture large and complex structures. It enables the accurate and repeatable fabrication of lightweight and complex parts with strong mechanical properties [1]. Typical parts fabricated with the AFP process include both exterior aerodynamic surfaces and interior structural elements of an aircraft. The AFP process is akin to a large industrial multi-lane tape dispenser. Multiple aligned fiber strips (called tows) are fed towards the surface, heated, and compressed under the compaction roller of the AFP head mounted on a gantry/robotic system. AFP machines are quite complex since they deposit large amounts of material simultaneously (bands of up to 32 tows) on curved surfaces with high precision. Tows are typically a few millimeters in width and a fraction of a millimeter in thickness. Successive layers, called plies, of bands of tows are laid on the surface of a tool to form a part. Two examples of AFP systems are presented in Figure 1 along with an enlarged view of an AFP head.

Although the AFP manufacturing process creates very few defects, they all must be detected and corrected due to the critical role of the parts fabricated. Typical defects involve positioning defects (e.g.: gaps, overlaps, missing tows, twisted tows), bonding defects (e.g.: bridging, air pockets) and foreign objects that can fall onto the surface [2]. Manual ply-by-ply visual inspection is the standard procedure for detecting defects. This process is time consuming and can take on the order of 20%-30% of the total fabrication time of a part.

Automated In-Process Inspection (IPI) has been identified as a key element to increase AFP manufacturing efficiency by minimizing the cost and time to produce a part. IPI also brings additional benefits: inspection stability, automated defect logging, and manufacturing process optimization. Optical imaging techniques are prime candidates to replace human visual inspection. By monitoring the surface quality during the deposition of each layer, instead of after the deposition of each layer, the manufacturing process is more efficient.

There are various challenges that must be addressed for the development of an IPI system based on an optical technique. These are related to the imaging conditions, the AFP system integration, and AFP process requirements. The challenging imaging conditions stem from the varying orientation of the AFP head and from the poor diffuse reflectivity of the

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composite material. The AFP system integration involves mounting the additional inspection hardware and information exchange aspects between the IPI and AFP control systems. The AFP process also requires a fast measurement system providing high quality data to enable responsive automatic defect detection and part compliance.

In this paper, we demonstrate that swept-source optical coherence tomography (SS-OCT) technology is an enabling optical technology to address all these challenges related to the development of an IPI system for the monitoring of the AFP manufacturing process.

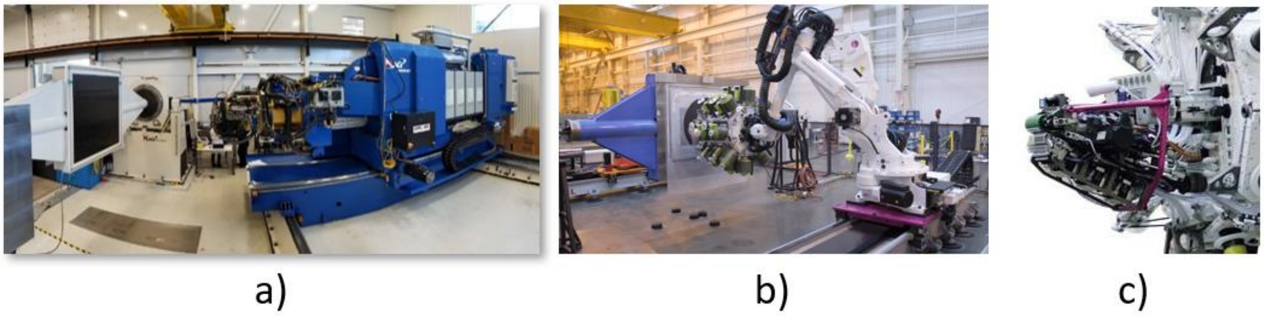

Figure 1. a) Picture of a special purpose 7-axis AFP system. b) Picture of an articulated AFP system. c) The AFP head of a system cuts, feeds and applies tows on the surface of a tool. Its compaction roller is visible in green at the tip of the head.

2. SS-OCT TECHNOLOGY

SS-OCT is an interferometric imaging technique which has been mainly developed for biomedical applications, with large impact in the fields of ophthalmology and cardiology [3]. A schematic representation of a typical optical fiber SS-OCT system is shown in Figure 2. The light from a swept-laser source is split by an optical fiber coupler between one arm containing a sample and a second arm containing a fixed reference mirror. The reflection from both arms is sent back to an acquisition and processing system through the coupler. As the wavelength of the laser is swept, the interference pattern is recorded by the acquisition system. The location of reflecting structures in the sample arm are recovered from the Fast Fourier Transform (FFT) of the recorded interferogram.

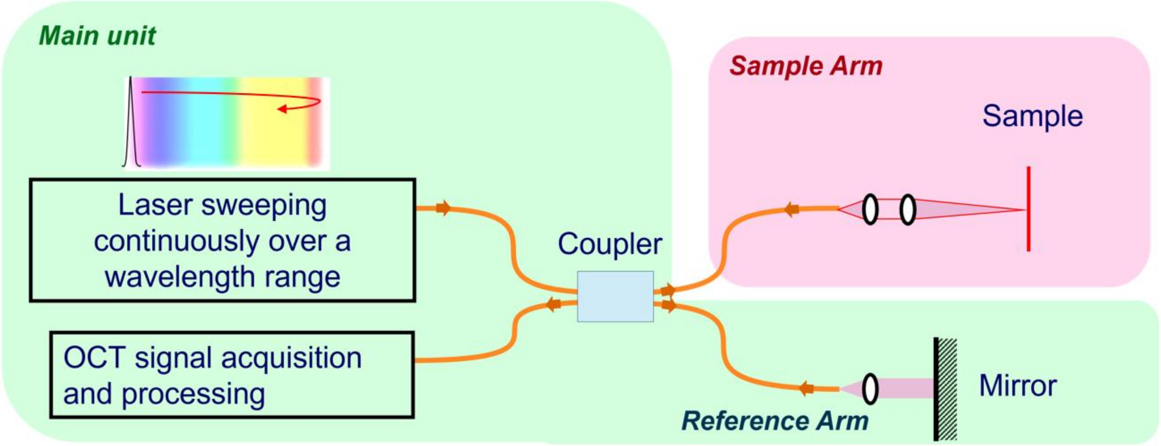

Figure 2. Schematic representation of an SS-OCT system.

Although SS-OCT technology has been mostly used to image the inner structure of biological tissues or other transparent materials, it can also be used for surface profilometry. For AFP parts made of opaque carbon fibers mixed with polymer resin, there is one main reflection coming from the surface of the sample. By directing the light to scan the surface, single OCT peak positions in interferograms can be recorded at various locations to reconstruct the surface topology. A single axis galvanometer provides a 2D surface profile and the forward motion of the AFP head during the fabrication process is used to add space between subsequent profiles, producing the 3D topology map.

All the results presented in this paper were obtained with a custom SS-OCT system based on an Akinetic swept-laser (Insight Photonics) sweeping around 1550 nm. The programmability (sweep range, number of wavelengths) of the Akinetic laser was an important feature for the optimization of the AFP IPI system. The acquisition was performed with an ATS-9360 (Alazar Tech) externally triggered at 400 MHz by the Akinetic swept-laser. The single axis galvanometer swept the layup surface across approximately 115 mm, covering the width of material deposited by the AFP machine in a single band (approximately 100 mm wide).

Figure 3 shows the raw FFT SS-OCT data recorded for sections of 16 tows along with a 2D profile. These 16 tows were laid on a base layer of orthogonal tows covering a flat surface. A curvature caused by the scanning mechanism is observed in the FFT data shown in Figure 3 a), but is later corrected when reconstructing the 2D profiles, as can be seen in Figure 3 b).

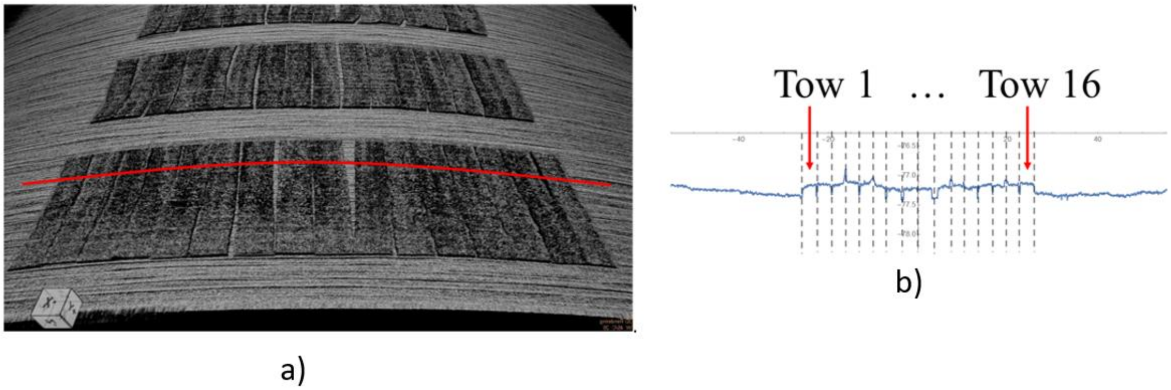

Figure 3. a) SS-OCT FFT data measured for sections of 16 tows. b) 2D profile corresponding to the location of the red line in (a). Tows have a width of 3 mm and a nominal thickness of 0.15 mm.

3. CHALLENGE: IMAGING CONDITIONS

AFP is often used to manufacture complex parts with curved surfaces. To accommodate this curvature, the AFP head will constantly change orientation during fabrication. Figure 4 illustrates an optical scanner mounted on an AFP whose orientation varies during the manufacturing process. This motion brings in two challenges: a variation of the distance between the scanner and the surface of the part along with a variation of the angle of incidence of the light beam.

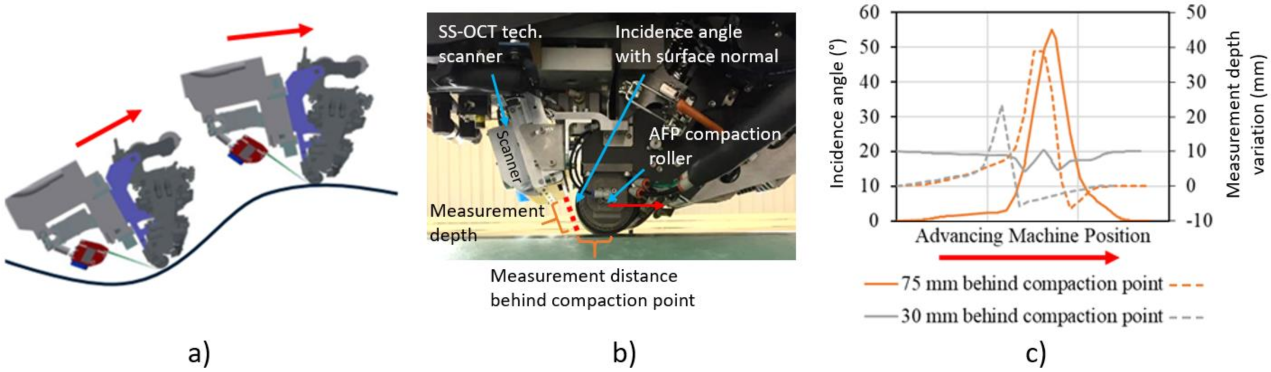

Figure 4. a) Schematic AFP layup on a curved surface. b) As-installed sensor position on the AFP machine with respect to the AFP compaction roller. c) Variation in incidence angle (solid lines) and measurement depth variation (dashed lines) for two hypothetical measurement distances behind the AFP compaction roller (75 mm behind oriented at 0° and 30 mm behind oriented at 20°). Red arrows indicate the direction of the machine motion in all the images.

To minimize the impact of the variation in distance between the OCT scanner and the surface of the part, the light beam should be directed as close as possible to the contact point between the AFP head and the part, *i.e.*, the nip point under the compaction roller. This is illustrated in Figure 4 b). As the distance from the measurement and layup point increases, the variation in incidence angle observed by the sensor increases, reducing the accuracy of the measurement. To minimize this variation SS-OCT technology employs a single point of view or confocal imaging method; light is delivered and collected by the same optics. This facilitates compact sensor design which enables measurement very close to the compaction point, under the shadow of the compaction roller. Considering the complexity of AFP heads, there always remains a finite distance between the measurement location and the layup point. Consequently, the IPI system must accommodate for variations in distance over a range of tens of millimeters to the surface. The parameters of the SS-OCT system can be adapted to meet this requirement. For the system used in this paper, a 35 nm sweep range around 1550 nm was used, allowing a measurement range of 35 mm. Figure 4 c) shows the relationship between required additional range in measurement depth and hypothetical scanner installation distance behind the compaction roller. The further the scan line is behind the compaction roller, the greater the required range in measurement depth for surfaces with contour will be.

As shown in Figure 4, to perform measurement under the compaction roller, the light beam must be directed at the part's surface with a sizeable angle of incidence. Accounting for the varying orientation of the AFP head, this angle of incidence can reach large values up to 60 degrees. Under these conditions, not much light is collected, a condition that is further worsened by the poor diffuse reflectivity of the material.

AFP tows are typically made of carbon fibers embedded in polymer resin. It is a black, light absorbing composite material. For profilometry measurements, this ensures that the reflection comes from the surface of the part, not its internal structure. This is nevertheless a very weak diffuse reflection since the light beam is directed along the axis of the fibers. This is observable in the brightness of FFT data image in Figure 3 a). Fortunately, SS-OCT technology is very sensitive, allowing profilometry measurements despite the weak diffuse reflectivity. The high dynamic range of SS-OCT also provides a significant advantage. Successive layers in AFP are deposited in various orientations and tows that are oriented perpendicular to the propagation axis of light return more light to the system. When there is a gap between tows, the underlying layer is detected. Although the diffuse reflectivity of the top surface is weak, the diffuse reflectivity of the underlying layer is much stronger which facilitates the gap detection, as can be seen in Figure 7 a). SS-OCT technology allows to perform surface profilometry on both surfaces and discriminates sharply the edges of gaps.

The efficiency with which the SS-OCT technology addresses the challenging imaging conditions, inherent to IPI during fabrication, is illustrated in Figure 5. Measurements were performed on three different common AFP thermoset material types for angles of incidence varying from 0 to 60 degrees. The percentage of outlier points in the surface profilometry is used as a metric of the quality of the measurement. This percentage remains well below 1%, even for large angles of incidence.

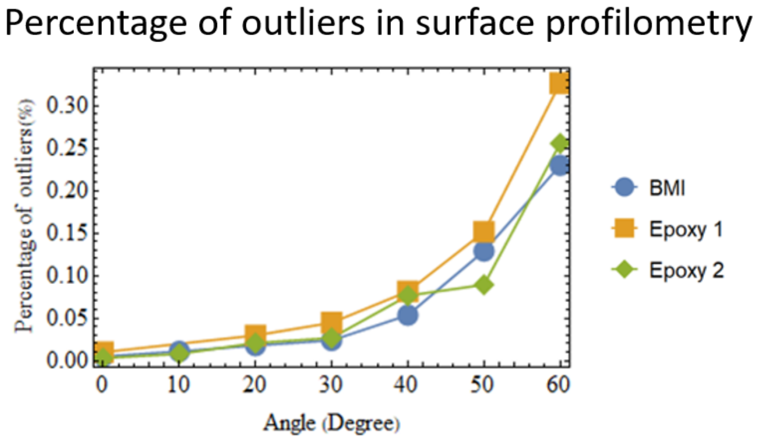

Figure 5. Percentage of outliers in the surface profilometry for three different AFP materials inspected at various angles of incidence with the SS-OCT technology.

4. CHALLENGE: AFP SYSTEM INTEGRATION

Considering that AFP machines contain many control dependencies that cannot be easily changed, the hardware integration of an IPI system in an existing AFP machine is quite a challenge. Even for the design of new AFP machines, an IPI system must be adaptable since design priorities might be given to other critical components on the machine's head. A key aspect of a SS-OCT based IPI system is its modularity. As illustrated by Figure 2, since the optical scanner, located in the sample arm, is connected to the rest of the interferometer through an optical fiber, it is the only component which must be mounted on the AFP head. Some AFP system configurations might require that the optical scanner be located as far as 50 meters, in cable length, from the main interferometer unit. Figure 6 a) shows an IPI system based on the SS-OCT technology mounted on a Viper 4000 AFP machine (Fives Machining Systems). The grey box on the AFP head contains a galvanometer-based optical scanner with adjustable focus. The few optical components needed in the scanning head allow a design that integrates well with the AFP head, ensuring no collision with the part under fabrication. The interferometer, the swept-laser source and the computer (acquisition and processing) are contained in the black interferometer box attached to the side of the machine. There is an additional secondary box containing the controller for the galvanometer to respect the limit in the electric cable length set by the manufacturer.

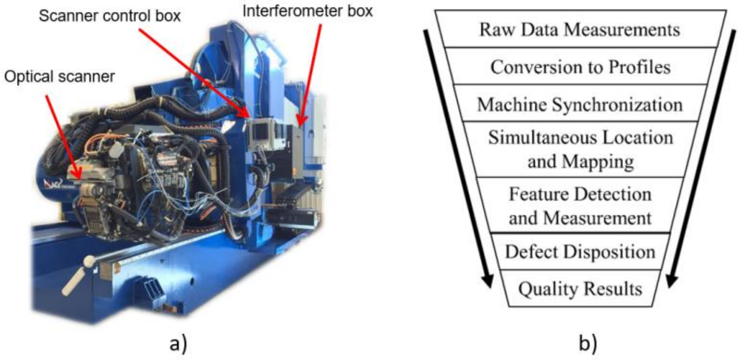

Figure 6. a) IPI system based on SS-OCT technology integrated in a Viper 4000 AFP Machine. b) Schematic representation of the data pipeline integrating both the IPI and AFP machine data.

The IPI system performs profilometry in its own coordinate reference frame. To locate the defects that are detected and to ensure that the fabricated part meets the requirements that were set when designing the part, the data from the IPI system must be integrated with the real-time position information provided by the AFP machine in a common reference frame. Fortunately, typical SS-OCT systems provide high fidelity synchronization capabilities from the swept laser or the scanning system to ease this integration. Figure 6 b) also provides a very simplified representation of the integrated data pipeline for the SS-OCT based IPI system presented in this paper.

5. CHALLENGE: IN-PROCESS INSPECTION

AFP IPI proposes challenges on multiple length scales. The AFP tows are on the order of 0.15 mm thick. Defects typically cover a thickness of a few tows and a length on the order of 1 to 10 mm depending on their type. The layup speeds of state-of-the-art AFP machines are on the order of 1000 mm/s. Manufacturing specifications require controlling process tolerances to within fractions of a mm in some cases. Thus, a perfectly optimized IPI system must have sufficient resolution in all three spatial dimensions. The optical and electrical hardware components of an SS-OCT system described previously (laser-source, acquisition system, scanning hardware) allow to meet this requirement.

Gaps and overlaps between adjacent tows are the most common defect type in AFP layup. An example of gaps and overlaps in an AFP laminate is shown in Figure 7 a). A typical manufacturing specification might allocate a permissible maximum gap size of 1.5 mm between adjacent tows and a maximum accumulation of 3 mm of total gap within any 25 mm wide segment of the layup. The lateral resolution of the system must be capable of capturing both edges of the gap with enough precision to not consume most of the manufacturing tolerance in the measurement uncertainty. If each measured edge of the gap has a +/- 1 mm positional uncertainty, in this example, the system would not provide sufficient accuracy to cover the manufacturers specification. The SS-OCT system used for AFP IPI has a lateral resolution better than 0.15 mm, therefore meeting the aerospace industry's requirements.

AFP tows have an as-deposited thickness of only approximately 0.15 mm. Furthermore, features in underlying layers can cause unevenness in the surface prior to layup and measurement, which adds more complexity to image analysis. Thus, in addition to a consistent and high depth resolution, an AFP IPI system also requires a rigorous method to perform real-time alignment of datasets captured in a moving referential in order to produce 3D point clouds of good quality [4]. An example of the reconstruction of the cross section of a part is shown in Figure 7 b). This digitized image of the part was obtained by combining multiple datasets obtained with the SS-OCT based IPI measurements of successive layers during the fabrication process. A small un-reworked overlap between two tows on ply 3 is aligned with a similar overlap defect in ply 5. As a result, the deviation from nominal observed in ply 5 is much greater than the deviation from nominal in ply 3, for the same category of defect. The SS-OCT system provides a depth resolution better than 0.05 mm, allowing accurate measurement of the thickness of each layer of material. It also uses a rigorous method to track the position of the SS-OCT scan head relative to the tool at all times during deposition. The combination of these features allows the IPI system to precisely align datasets and fully reconstruct complete 3D point clouds containing each layer of the part.

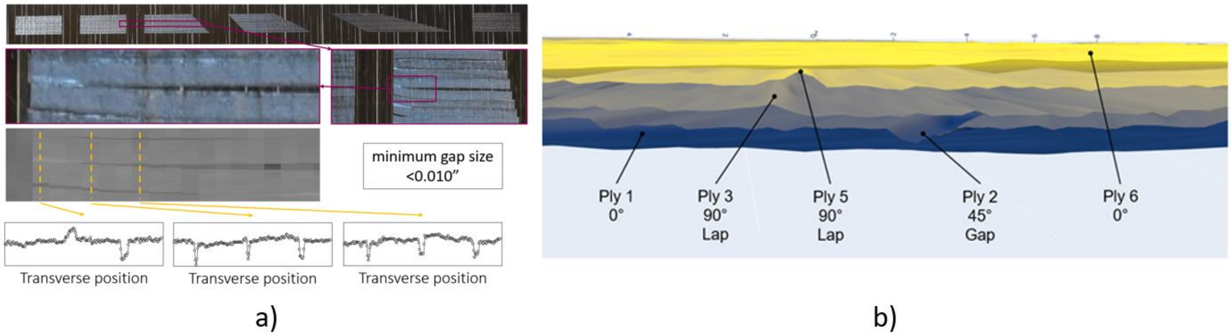

Figure 7. a) Example of an overlap turning into a gap in an AFP laminate. Profile data captured by the system (4 bottom images with yellow) matches the pictures (3 top images with purple) of this layup and provides a quantitative value on the minimum gap size detectable with the system. b) View of a cross section of located measurement data showing gaps and overlaps (labelled "lap") in a multi-ply laminate.

6. CONCLUSION

In this paper, we have demonstrated that an IPI system based on the SS-OCT technology overcomes all the challenges related to implementing in-process monitoring in an AFP manufacturing process. This high-fidelity imaging technology, developed for biomedical applications, has now been proven to be sufficiently robust, providing a long-sought solution to the aerospace manufacturing industry. SS-OCT is a technology that has reached the level of maturity and robustness to meet the requirements of an industrial application. Future developments of the IPI system will primarily focus on increasing its measurement rate to align with increased AFP fabrication speed. The technology will be developed for both new and existing AFP machines. Further developments on image analysis and defect recognition robustness will also be possible from the use of larger training datasets obtained with the IPI system.

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