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In-Situ Thermography of Automated Fiber Placement Parts

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Abstract. Automated fiber placement (AFP) provides precision and repeatable manufacturing of both simple and complex geometry composite parts. However, AFP also introduces the possibility for unique flaws such as overlapping tows, gaps between tows, tow twists, lack of layer adhesion and foreign object debris. These types of flaws can all result in a significant loss of performance in the final part. The current inspection method for these flaws is a costly and time intensive visual inspection of each ply layer. This work describes some initial efforts to incorporate thermal inspection on the AFP head and analysis of the data to identify the previously mentioned flaws. Previous bench-top laboratory experiments demonstrated that laps, gaps, and twists were identified from a thermal image. The AFP head uses an on-board lamp to preheat the surface of the part during layup to increase ply consolidation. The preheated surface is used as a thermal source to observe the state of the new material after compaction. We will present data collected with the Integrated Structural Assembly of Advanced Composites (ISAAC) AFP machine at Langley Research Center showing that changes to the temperature profile is sufficient for identifying all types of flaws.

INTRODUCTION

Automated fiber placement (AFP) is the process by which fibers, pre-impregnated with resin, are placed layer by layer by a robotic system to build up a composite laminate. The composite laminate is then cured, usually in an autoclave. AFP aims to reduce fabrication time, scrap waste, and variability in part quality by automating the process. AFP uses discrete tows of carbon fibers that are pre-impregnated with epoxy resin to build up a composite part, either on a flat table or some sort of tool. The tows are delivered and stored on spools that are mounted on the AFP machine. Multiple tows make up a course and are placed concurrently in a specific orientation. Each layer of multiple courses is called a ply. The spools are loaded onto the AFP head and then tows are gathered by the head and placed on a substrate. The resin becomes tacky when heated so a heat source, often a lamp, is used to heat the substrate prior to a new course being placed over it. The new course is then pressed into the substrate with a compaction roller. Figure 1 shows a diagram of the AFP process.

The current process for composite part fabrication by AFP can result in a number of potential flaws, the simplest being gaps (unintended space between tows), laps (tows overlapping), and twists (tows that twist so that a portion does not lie flat). In addition to these AFP flaws, which are likely to be found by time intensive visual inspection, an AFP part might also contain flaws that are much more difficult to detect visually, such as insufficient adhesion between plies or tow peel-up in the presence of complex geometry. Finding flaws and correcting them prior to placing another layer or prior to cure saves material and time as correcting flaws post cure is much more complicated.

Thermography provides a visual representation of the surface temperature of the part. The fundamental aspect of thermography is that information about volume can be obtained or deduced by observing the surface temperature of volume over time in the presence of known heating conditions. The AFP process already utilizes a heat source to aid with compaction and adherence. By observing and analyzing the time history of the surface temperature after a new course is applied, we can assess part quality using established thermography nondestructive evaluation techniques and image processing algorithms. This type of assessment allows for repairs to be made during fabrication, reducing

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the risk of curing a part of unacceptable quality. This paper describes the work performed to demonstrate the viability and value for thermographic inspection to the AFP process.

In most cases, a course has a constant fiber orientation and all the courses in a ply have the same fiber orientation but when a course is "steered," meaning the AFP machine is changing fiber orientation during a course, it is referred to as tow-steered. The data presented in this paper was collected for a part that contained normal plies and tow steered plies.

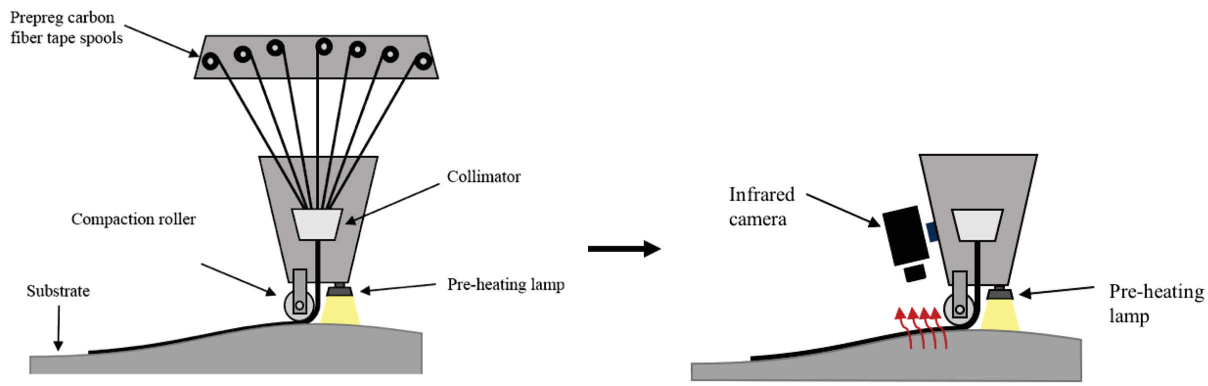


FIGURE 1. The automated fiber placement process.

FIGURE 2. Example of actual visual inspection of a composite AFP part.

Automated fiber placement has become a critical component of aerospace composite manufacturing. Ideally an automated process can repeatedly and dependably be performed quickly. Part quality becomes more difficult to maintain during fabrication when geometry becomes more complex. Flaws, such as laps, gaps, and twists have been demonstrated by Croft to result in reduction of part strength by up to 13 percent [1]. Inspecting for these and other types of flaws during fabrication can prevent waste of a part post-cure or failures during service. Current inspection is performed by manual visual inspection. Figure 2 shows a visual inspection being completed on a new ply that was placed on a complex contour part.

The problem of in-situ inspection during fabrication was researched as early as 1996 when Boeing company patented a method for detecting laps, gaps and twists using laser profilometry [2]. Laser profilometry continues to be the most mature method for flaw detection during AFP with recent developments in the form of machine learning and big data analytics to use the large data sets that are being acquired [3,4]. One limitation of laser profilometry is that it does not detect areas of insufficient ply adhesion.

In 2009 Boeing patented the concept of using a thermal camera to inspect AFP parts during fabrication. This method did not include specifics for holistic data analysis [5]. Thermography for process monitoring has also been developed by Denkena, Schmidt and others to observe any foreign object debris, laps, gaps, and tow misplacement using computer vision techniques on the collected frames, along with a priori knowledge about the planned path of

the AFP head [6,7]. However, these tools do not utilize the physics of thermal heat flow to analyze the thermal signal. Thermography theory goes well beyond observing temperature contrasts, to enable localization and characterization of flaws.

Thermography has long been a useful method for nondestructive inspection and evaluation of composite structures. The foundational mechanism of thermography is that heat flows through a homogeneous material in a uniform manner. By observing variation in surface temperature, we can deduce information about the underlying structure. Thermography provides more information about thin materials as discontinuities located far away from the surface being observed have a reduced effect due to heat diffusion. Shepard demonstrated that a quantitative analysis of time dependent thermographic data can yield specific information about the depth and size of embedded defects [8]. He then extended this theory to include composite (layered, anisotropic) material [9].

Two data acquisition methods for theromographic inspection are used for our *in-situ* evaluation. One method is observing the surface of a new ply as it is placed over a pre-heated substrate. Figure 3 shows general signals that would be expected for an ideal (defect-free) layup, where heat is conducted up from the heated substrate. Laps, overlapping tows, or tows with poor adhesion will show up as colder because the material is thicker; gaps will show up as hot because the camera will be seeing the heated substrate. After plies are placed it is possible to use the AFP robot as a moving heat source and camera. This method consists of heating the surface of the laminate and observing the heat diffusion. This method for analysis has been used at NASA previously by Winfree [10].

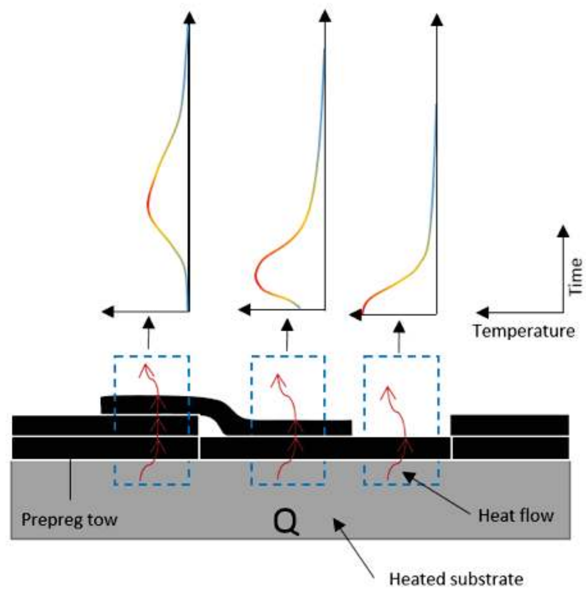


FIGURE 3. Model of heat transfer in the AFP process.

In addition to the signal reconstruction proposed by Shepard, Ibarra-Castanedo also applied principal component analysis techniques to the thermal data sets to better isolate the location and size of defects [11]. Many of the same techniques used for image or video analysis and computer vision can also be applied to thermographic data. Zheng focused on image segmentation and minimum spanning tree clustering to automate the identification and localization of defects in thermal data [12].

INTEGRATED THERMAL NDE SYSTEM

NASA Langley Research Center has acquired an AFP system named the Integrated Structural Assembly of Advanced Composites system (ISAAC) [13]. This was the system used to generate all the data included in this paper. ISAAC is used for prototyping of parts as well as AFP technology research and development. Figure 4 shows the integrated thermal camera and its location on the ISAAC AFP head.

The thermal camera used in this study is the FLIR A65, which uses an uncooled microbolometer sensor to capture 14 bit linear temperature data in 640 x 512 resolution and at a rate of up to 30Hz. It is powered and communicates with the controller via gigabit Ethernet connection using the industry standard GigEVision protocol. The thermal camera is mounted near the existing visible light camera, which is used by the operators to monitor the roller. The cameras point to a region directly behind the compaction roller to observe the material right after lay up as it passes underneath the roller. The placement of the camera coupled with the installed 50 mm lens enabled the capture of approximately 3-inch by 4-inch region behind the roller, giving a 100 pixel/inch density.

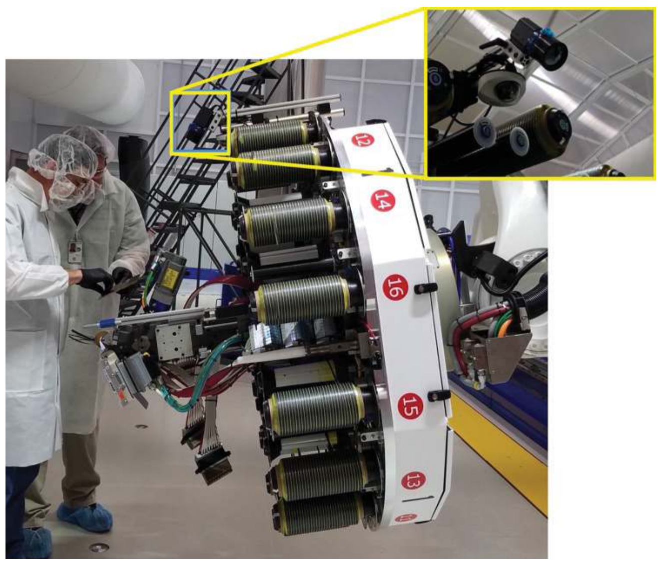
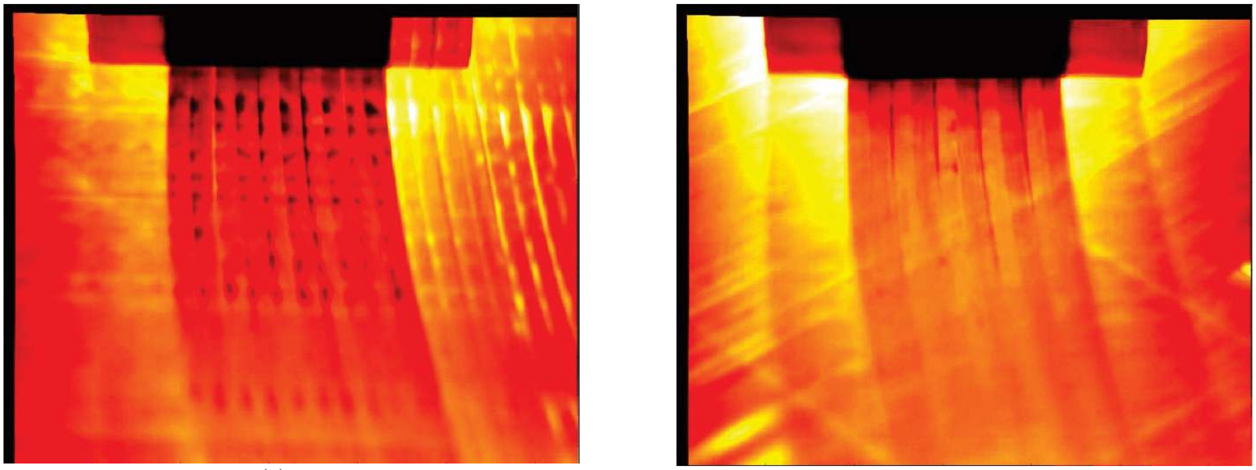


FIGURE 4. Integrated thermal camera on ISAAC AFP system at NASA Langley.

The camera communicates via Ethernet to an Ethernet switch on the AFP head itself, which then passes the ethernet through the slip-ring/tool changer assembly at the end effector of the robot. From there the Ethernet passes through several other networks before getting to the data acquisition computer. Though all network ports were rated to support gigabit (10/100/1000 Mbps) Ethernet communications, packet loss in the slip-ring reduces communication down to 100/10. This results in a lower rate of capture to about 15 to 17 frames per second when capturing full frames. Acquiring subframes can increase the capture rate back up to 30Hz, but this still may not be fast enough for adequate temporal resolution at high speeds of layup.

The initial system and proof of concept for this ISAAC *in-situ* system was completed at NASA Langley, in the nondestructive evaluation science branch where it was demonstrated that thermography, using a source similar to the integrated heat lamp, could be used to identify laps and gaps [14].

Figure 5 shows some the individual frames captured by the in-situ thermal camera. Subfigure a) shows examples of tows that are peeling-up due to the steering compared to subfigure b) that shows tows without the peel-up. The black corresponds to cooler areas so the tow peel-up appear as dark, cool spots.



(a) (b)

FIGURE 5. Example of a single frame of data collected by the integrated thermal camera on ISAAC AFP system at NASA Langley.

COLLECTED DATA AND ANALYSIS OF GO-1 TRIAL PANEL AND CYLINDER

NASA Langley Research Center, in collaboration with Generation Orbit Launch Services, Inc. (GO) is working to develop a single stage rocket to be launched from an aircraft platform [15]. As part of this effort NASA Langley was tasked with fabricating multiple manufacturing demonstration units (MDU) for a critical cylindrical, tow-steered component, referred to as the GO-1 cylinder. Traditional AFP layup consists of courses of tows that are laid up in a single orientation for each ply layer, varying the fiber orientation on each ply to tailor strength properties in the desired direction. Tow steering actively changes the fiber orientation of the tows within each course by steering the compaction roller for each course. This enables engineers to actively tailor how the intended load is distributed on the structure.

Each GO-1 cylinder is 73 inches in height with a diameter of 24 inches and contains constant orientation plies, tow-steered plies, and build-up patches tailored for specific load conditions. The process of tow-steering can lead to tow peel-up, where the changing angle causes insufficient tow adhesion. Engineers planned to counteract this phenomena by including one or more debulking cycles in the fabrication process. In the process of debulking, a laminate is placed in a sealed vacuum bag; the positive pressure of the atmosphere then presses on the bag and removes voids and increases ply adhesion, thereby removing “bulk” from the laminate. The primary goal of the GO-1 risk mitigation panel was to estimate the time it took for the tow-steered courses to begin peeling up; after that their secondary goals were to test their peel-up mitigation strategies.

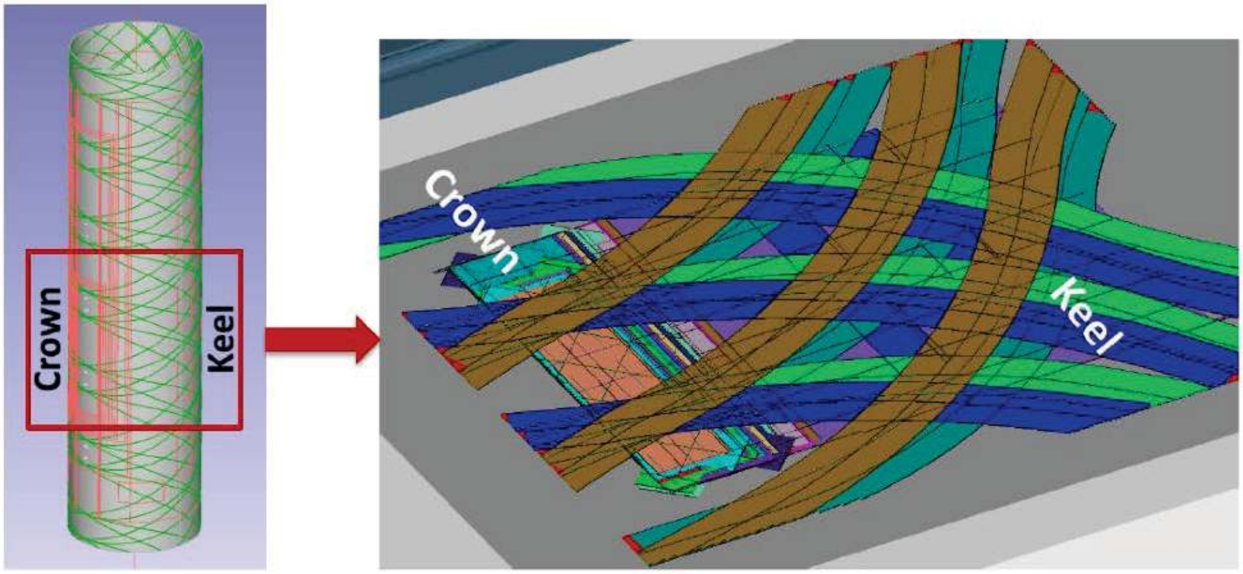
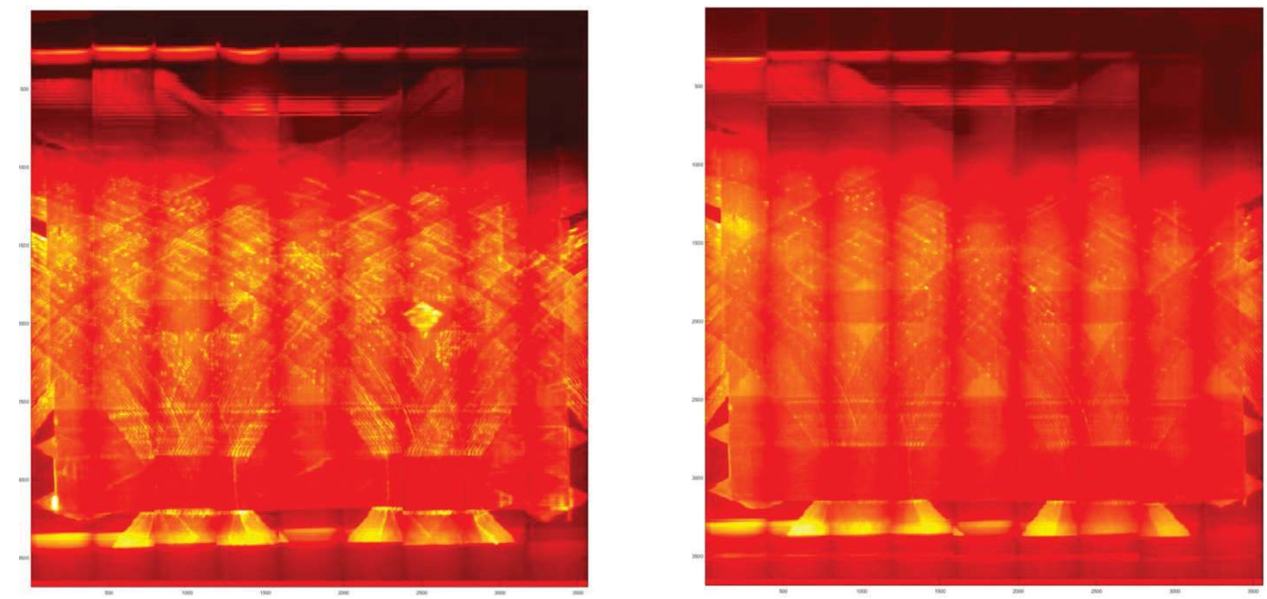


FIGURE 6. The risk mitigation panel for the GO-1 cylinder. This unfolded, flat panel included some of the features of main concern in the cylinder.

The GO-1 team required a method to tell if the debulking process was successful and requested that we collect *in-situ* thermography data before and after the debulk cycle to assess the part. Prior to fabricating the GO-1 cylinder the team fabricated a flat panel with similar constant orientation plies, tow-steered plies, and build-up patches to test the debulking process. This GO-1 panel was not cured and served merely as a risk mitigation tool. Figure 6 shows an outline layup for the cylinder and how that layup was unwrapped for the risk mitigation panel. The cylinder has one side with significant build-up; this area is referred to as the *crown*. The opposite side has the most extreme tow-steered orientations and a few build up patches; this is referred to as the *keel*.

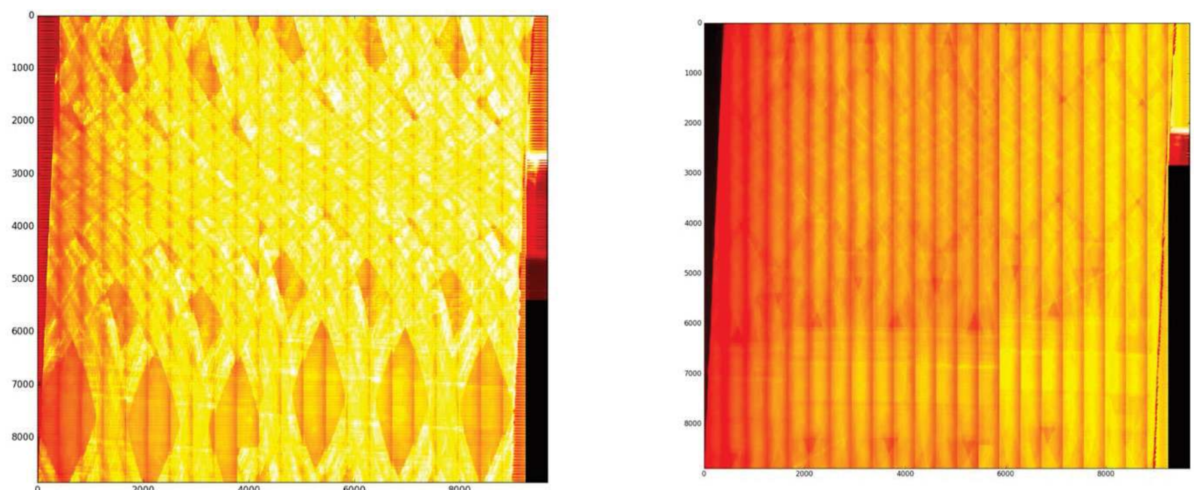
For both the cylinder and risk mitigation panel, data was collected in two ways. First, data was collected while fiber was being placed; then, additionally, the program for a constant orientation ply that fully covered the part (referred to as an acreage ply) was repeated with no fiber being placed, no variation in speed, no compaction force on the roller, and the heat lamp at maximum power. This second process for data collection was referred to as a *scan*. In the scan process the laminate is being heated from the top surface as opposed to the *in-situ* process where the new ply is being heated from the substrate. As a result of these different heating configurations, delaminations would appear colder *in-situ* but hotter in a scan.

For this particular investigation, the scan data was much more useful for two reasons. Currently, we do not have specific position data from the robotic head so position must be inferred based on part geometry. This is easier and more accurate when velocity and tow orientation are constant, which allows us to collect data in a raster scan pattern.



(a) (b)

FIGURE 7. Temporally aligned *in-situ* Thermography data for the Go-1 risk mitigation panel before (a) and after a debulking cycle (b).



(a) (b)

FIGURE 8. Temporally aligned *in-situ* Thermography data for the Go-1 Cylinder before (a) and after a debulking cycle (b).

Secondly, the major concern of the GO-1 risk mitigation panel build was tow peel-up that occurs over time after the course is placed, allowing time between when fiber placement and scanning optimizes the opportunity to observe tow peel-up. Figure 7(a and b) shows the thermographic scan data that has been spatially registered and temporally aligned.

The same process was completed for the GO-1 cylinder. The scans were completed by running the program for a full coverage ply that was one continuous helical without placing any fiber. Due to time constraints, the scans were completed at a higher than ideal speed, which resulted in less heat being transmitted to the part overall and less data being collected.

Figures 8a and 8b show the spatially registered and temporally aligned data for the GO-1 cylinder. The areas of concern observed in the data collected prior to the debulk cycle are the edges of the tows in the tow steered courses. The change observed after debulking is dramatic as shown in subfigures b) of Figs. 7 and 8.

CONCLUSIONS

In-situ thermographic inspection can provide critical information on laminate quality of AFP parts. It is apparent from raw thermal data that laps, gaps, and twists create significant relative temperature indications to be identified. Additionally, areas of reduced adhesion can be identified with some data processing. This information has already proved useful for one program at NASA by demonstrating that efforts taken during fabrication to reduce risk and increase laminate quality were successful.

REFERENCES

1. K. Croft, L. Lessard, D. Pasini, M. Hojjati, J. Chen, and A. Yousefpour, Composites Part A: *Applied Science and Manufacturing,* **42**, 484-491 (2011).
2. L. Kitson, D. Rock, and J. Eder, Composite Material Laser Flaw Detection, U.S. Patent 5,562,788, (1996).
3. F. Shadmehri, O. Ioachim, O. Pahud, J. Brunel, A. Landry, V. Hoa, and M. Ho-jjati, "Laser-vision inspection system for automated fiber placement (afp) process," 20th International Conference on Composite Materials, *ICCM20 Proceedings,* 4217-2, Copenhagen, (2015).
4. J. Cemenska, T. Rudberg, and M. Henscheid, *SAE International Journal of Aerospace,* **8**, 2015-01-2608 (2015).
5. J. Ritter and J. Sjogren, Real-time infrared thermography inspection and control for automated composite marterial layup, US Patent 7,513,964, (April 7, 2009).
6. B. Denkena, C. Schmidt, K. Vo,ltzer, and T. Hocke, *Composites Part B: Engineering,* **97**, 239-243 (2016).
7. C. Schmidt, B. Denkena, K. Voltzer, and T. Hocke, "Thermal Image-based Monitoring for the Automated Fiber Placement Process," *Procedia CIRP*, Vol. **62**, pp. 27-32, (2017).
8. S. Shepard, AeroSense, *International Society for Optics and Phot*onics, **4710**, 531-535, (2002).
9. S. Shepard, "Flash Thermography of Aerospace Composites," *IV Conferencia Panamericana de END Buenos Aires*, 7 pages, (2007). http://www.ndt.net/article/panndt2007/papers/132.pdf
10. W. P. Winfree, D. M. Heath, and K. E. Cramer, "Thermal diffusivity imaging with a moving line source," *Thermosense XXIII*, **4360**, pp. 606-615, (2001).
11. C. Ibarra-Castanedo, N. P. Avdelidis, M. Grenier, X. Maldague, and A. Bendada, "Active thermography signal processing techniques for defect detection and characterization on composite materials," *Thermosense XXXII,* **7661**, p. 76610O, (2010).
12. K. Zheng, Y. S. Chang, K. H. Wang, and Y. Yao, *Polymer Testing*, **49**, 73-81, (2016).
13. K. C. Wu, B. K. Stewart, and R. A. Martin, "ISAAC—A Testbed for Advanced Composites Research," *The American Society for Composites 29th Annual Technical Conference,* San Diego, California, 1395-1404 (September 2014).
14. P. D. Juarez, K. E. Cramer, and J. P. Seebo, "Advances in *in situ* Inspection of Automated Fiber Placement Systems," SPIE Thermosense Conf.: Thermal Infrared Applications, *Proceedings*, **9861**, 8 p. (2016).
15. R. Grenoble, J. McKenney, A. Przekop, T. Nguyen, P. Juarez, G. Gregory, and D. Jegley, "Fabrication of a Tailored Cylinder for Launch Vehicle Applications," 59th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, *AIAA SciTech Forum,* (2018).