AFP Automated Inspection System Performance and Expectations

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Abstract

In AFP manufacturing systems, manually inspection of parts consumes a large portion of total production time and is susceptible to missing defects. The aerospace industry is responding to this inefficiency by focusing on the development of automated inspection systems. The first generation of automated inspection systems is now entering production. This paper reviews the performance of the first generation system and discusses reasonable expectations. Estimates of automated inspection time will be made, and it will be shown that the automated solution enables a detailed statistical analysis of manufactured part quality and provides the data necessary for statistical process control. Data collection allows for a reduction in rework because not all errors need to be corrected. Expectations will be set for the accuracy for both ply boundary and overlap/gap measurements. The time and resource cost of development and integration will also be discussed.

Introduction

Inspection of composite plies is an important step in AFP manufacturing. To ensure quality, the current industry standard is to have dedicated personnel visually inspect each ply before the next ply is deposited. Each part has specific inspection requirements, which typically include accuracy of tow end placement (ply boundary), control limits on overlaps and gaps between tow lanes, foreign object debris (FOD) detection, and detection of defects such as puckering and bridging. Presently, tow end accuracy is verified by visually comparing location to a laser line projected onto the surface by laser projectors. The other requirements are inspected by using human eyes to scan the surface. This type of manual inspection is time consuming and vulnerable to human error. Studies have shown that manual inspection can consume more than 20% of total production time, and many defects escape detection [1].

To reduce manufacturing time and improve quality, the latest generation of AFP equipment automates the inspection of ply boundaries and overlaps/gaps. The Electroimpact inspection system integrates cameras, laser projectors, laser profilometers, and a user interface. These technology solutions are described briefly in this paper, and explained in detail in a previous paper by Cemenska et al [2].

The first generation of automated inspection systems is currently in use on 4 large-scale AFP cells making production parts for commercial aircraft.

Inspection time depends heavily on ply complexity, and increases with the number of tow ends marked for inspection. For 0.5” width tow, the inspection system measures 15 tow ends per second. On large parts with over 1000 inspected tow ends, the measurement system takes a few minutes to inspect the part. Tow ends that the system is unable to measure are presented to the user, who inputs these measurements using the user interface. This semi-automated user input adds additional time to inspection.

Automated ply boundary inspection is able to correctly identify and measure 92% of tow ends on a standard ply. The remaining 8% is comprised of 7% non-identified tow ends and 1% identification of the wrong feature. Tow ends that are not automatically identified are forwarded to the user interface for input.

Automated ply boundary population accuracy has a mean error smaller than 0.005” and a standard deviation of 0.020”. Semi-automatic measurements have a standard deviation of 0.016”.

Overlap/gap measurements happen in parallel with material lay down. Out of tolerance lap/gap data is displayed after each ply for the user to acknowledge and repair manually.

Gap measurement data has been qualified to have a mean error smaller than 0.003" and a standard deviation of 0.005".

Overlap measurement data has been qualified to have a mean error smaller than 0.010" and a standard deviation of 0.013".

Inspection Process Overview

The inspection system uses multiple hardware systems to gather raw data. Then, a suite of software programs processes the data to create meaningful measurements for the location of ply boundaries and widths of overlaps and gaps.

The processed data is stored in a database which acts as the interface for the suite of software programs for interaction and data sharing.

An extensive user interface ties all of the data together and displays the results.

Ply Boundary Inspection

Ply boundary inspection is achieved using a camera that comes equipped in LASERVISION projectors from Assembly Guidance (now Aligned Vision). The LASERVISION hardware is dual purpose with two independent mirror sets. Half of the unit is a standard laser projector. The other half is a camera system that captures accurately located photographs. Images from the camera system are processed to identify the location of tow ends that comprise the ply boundary. Figure 1 illustrates the LASERVISION hardware. In stationary applications, camera images of ply boundaries have been qualified to be within +/- 0.030" of the true position and +/-0.060" in mobile (gantry mounted) setups.

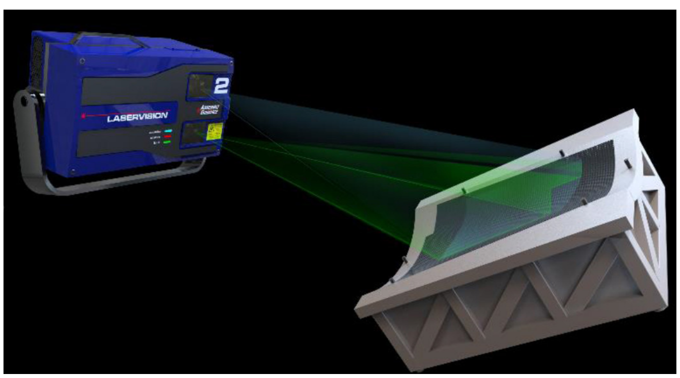


Figure 1. LASERVISION Hardware

Overlap/Gap Inspection

Overlap and gap data between AFP tow lanes is gathered using laser profilometers. A laser profilometer is a device that projects a laser line onto a surface and measures the distance to points along that laser line. The array of distances creates a profile of the surface, which can be evaluated to identify and measure surface features, specifically overlaps and gaps between lanes. Figure 2 illustrates the concept of a profilometer.

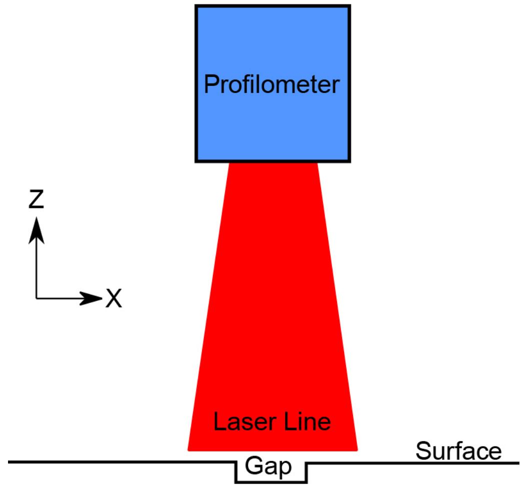


Figure 2. Profilometer Diagram

Inspection User Interface

Inspected Part Model

The inspection user interface uses an interactive 3D model with the in-process part images overlaid in real time. The interface allows an inspector to view images as they are obtained and review previous images in an intuitive manner. The interface can display an entire ply, or be zoomed in to show an arbitrarily small window of the ply. Figure 3 shows a 3D model view with several overlaid images.

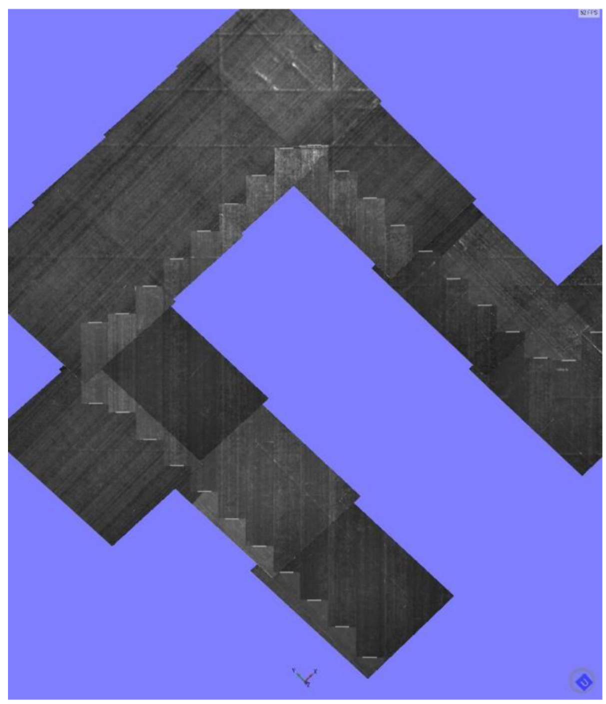


Figure 3. Conjoined Ply Image.

For a unified inspection experience the interface also shows:

- Overlap/gap measurements and errors
- Ply boundaries
- Tow end tolerance bands
- Tow errors indicators
- Part coordinates

- Course and tow numbers
- Part program model
- Tool model

The interactive inspection screen is shown in Figure 4. It shows inspection data for one ply at a time. The inspection UI contains a 3D image of the ply constructed from multiple camera images. Overlap/gap inspection data and ply boundary inspection data can be overlaid on top of each image.

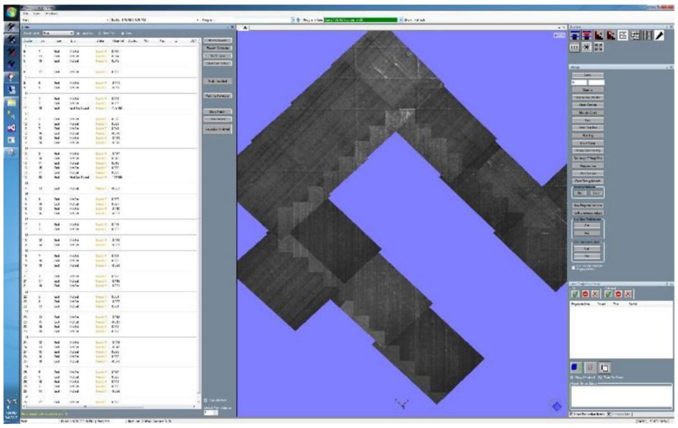
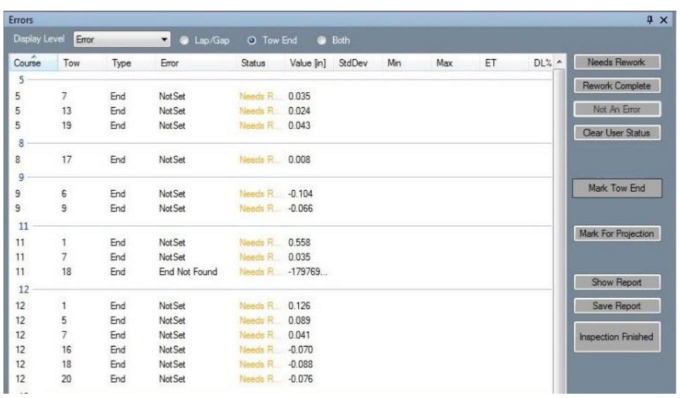


Figure 4. Inspection User Interface.

The control interface for each is located on the left hand side of Figure 4 as a list of items. These display a list of automatically detected defects and out of tolerance conditions. The end user inspects defects using a combination of the list view and the overlay on the ply image. A closer view of the list box is shown in Figure 5. The user can choose to display all data or just errors and sort the data by Course, Tow, Type of Data, Error Description, Status, and Value.



Course	Tow	Type	Error	Status	Value [in]	StdDev	Min	Max	ET	DL%
5										
5	7	End	NotSet	Needs R...	0.035					
5	13	End	NotSet	Needs R...	0.024					
5	19	End	NotSet	Needs R...	0.043					
8										
8	17	End	NotSet	Needs R...	0.008					
9										
9	6	End	NotSet	Needs R...	-0.104					
9	9	End	NotSet	Needs R...	-0.066					
11										
11	1	End	NotSet	Needs R...	0.558					
11	7	End	NotSet	Needs R...	0.035					
11	18	End	End Not Found	Needs R...	-179769...					
12										
12	1	End	NotSet	Needs R...	0.126					
12	5	End	NotSet	Needs R...	0.089					
12	7	End	NotSet	Needs R...	0.041					
12	16	End	NotSet	Needs R...	-0.070					
12	18	End	NotSet	Needs R...	-0.088					
12	20	End	NotSet	Needs R...	-0.076					

Figure 5. List View of Errors.

Should inspection or rework at the part need to occur, the inspector/operator has the ability to control the laser projection system directly from the interface to project the location of features or defects on the part.

Overlap/Gap Interface

Automated overlap/gap detection measures the overlap/gap between every tow in parallel with process layup. The 3D position of each measurement is recorded, and this ties each measurement to its location on the part.

Lanes of overlap/gap data can be overlaid on the display of the ply in the interactive 3D model user interface. After selecting a lane in the list box, as shown in Figure 6, the overlap/gap data is illustrated in the 3D model, as shown in Figure 7. The user can find the overlap/gap value of any of the data points in Figure 7 by hovering over it with the mouse.

3	9.5	L/G	None	OK	5.295	0.005	0.013	0.033	0	0	0
3	10.5	L/G	None	OK	0.059	0.002	0.000	0.010	0	0	0
3	3.5	L/G	None	OK	0.086	0.002	0.000	0.019	0	0	0
3	4.5	L/G	None	OK	-0.236	0.007	-0.058	0.014	0	0	0
3	5.5	L/G	None	OK	1.722	0.006	0.000	0.018	0	0	0
3	2.5	L/G	None	OK	2.123	0.003	0.000	0.023	0	0	0
3	7.5	L/G	None	OK	-0.286	0.005	-0.021	0.000	0	0	0
3	8.5	L/G	None	OK	3.131	0.006	0.000	0.030	0	0	0
3	6.5	L/G	None	OK	-0.195	0.013	-0.191	0.011	0	0	0
4	12.5	L/G	None	OK	-0.593	0.006	-0.026	0.000	0	0	0
4	19.5	L/G	None	OK	5.056	0.005	0.000	0.034	0	0	0
4	18.5	L/G	None	OK	0.519	0.004	-0.028	0.020	0	0	0
4	17.5	L/G	None	OK	4.191	0.012	0.000	0.037	0	0	0
4	16.5	L/G	None	OK	-0.150	0.003	-0.021	0.010	0	0	0
4	15.5	L/G	None	OK	4.238	0.006	0.000	0.030	0	0	0
4	14.5	L/G	None	OK	0.001	0.003	-0.022	0.011	0	0	0
4	13.5	L/G	None	OK	2.988	0.006	0.000	0.021	0	0	0

Figure 6. List View Data Select for Display.

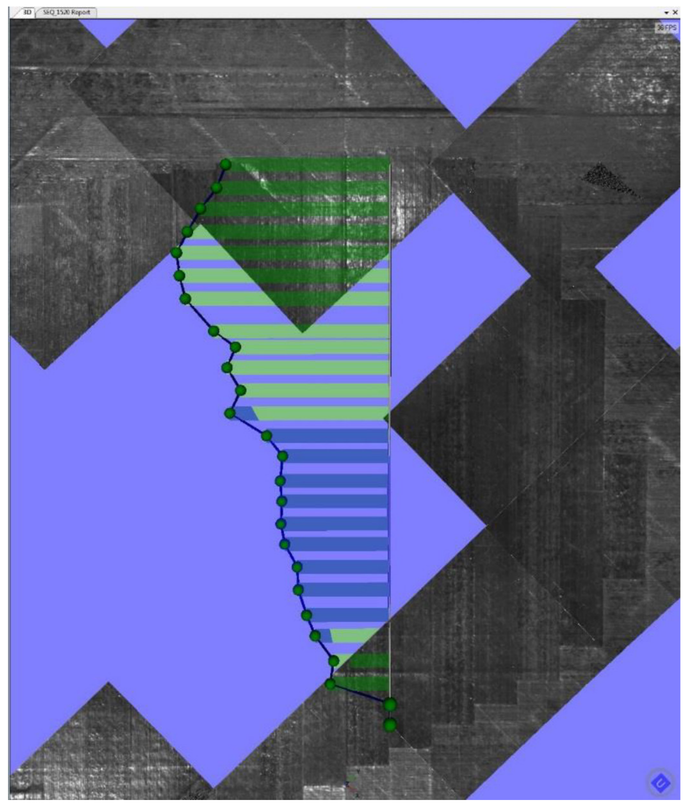


Figure 7. Overlap/Gap Errors Overlaid on 3D Model of Ply.

The end user is presented with information detailing the out of tolerance condition as shown in Figure 8. Out of tolerance conditions are configured per customer inspection goals.

Course	Tow	Type	Error	Status	Value [in]	StdDev	Min	Max	ET	DL%	OV%
Data Collection Error											
11	3.5	L/G	Data Collection Error	Needs Review	-0.648	0.009	-0.038	0.013	0	2	2
11	17.5	L/G	Data Collection Error	Needs Review	1.201	0.017	-0.161	0.030	0	5	2
11	18.5	L/G	Data Collection Error	Needs Review	1.585	0.013	-0.174	0.020	0	6	1
12	9.5	L/G	Data Collection Error	Needs Review	-0.363	0.014	-0.070	0.036	0	4	0
13	2.5	L/G	Data Collection Error	Needs Review	2.425	0.006	-0.017	0.020	0	6	0
13	4.5	L/G	Data Collection Error	Needs Review	-1.069	0.014	-0.113	0.015	0	4	0
13	6.5	L/G	Data Collection Error	Needs Review	-2.650	0.018	-0.138	0.016	0	5	0

Figure 8. List View of Overlap/Gap Errors.

Each measurement is logged into a database that includes the following information:

- Path distance from start of course
- 3D position in part coordinates
- Part number
- Program Name
- Ply/Sequence number
- Course number
- Tow number
- Time and date

All overlap/gap data is stored in a database, and it can be queried by position, program, ply, course, and tow. This allows the inspection software the flexibility to be tailored to custom inspection requirements.

Ply Boundary Inspection

Fully-Automatic

Using feature recognition software, the location of ply boundaries and tow ends can be automatically measured from ply images. Error is computed by comparing ply boundary targets (from the part program) to the locations measured in the images.

Figure 9 shows the UI displaying automatically measured tow ends as white lines.

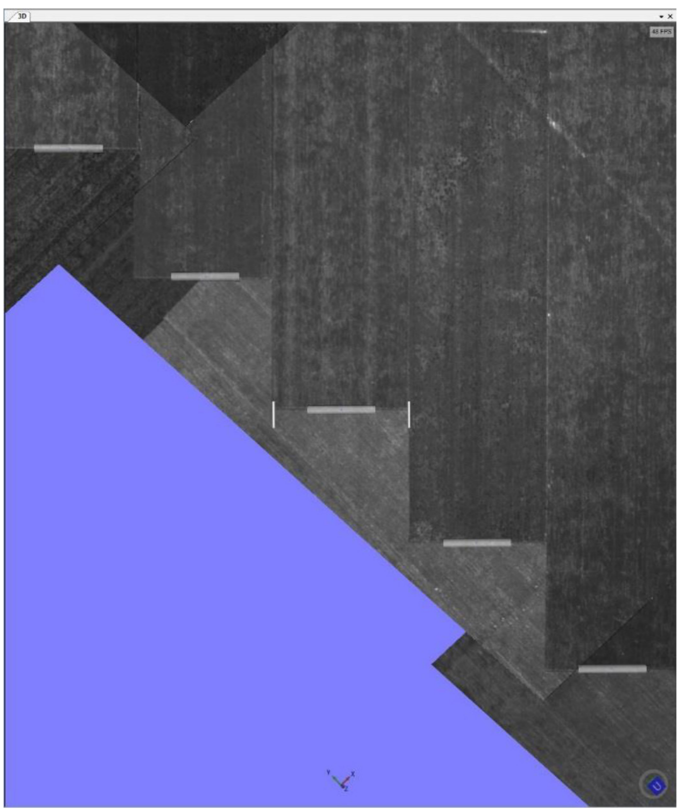


Figure 9. Example of Automated Edge Detection.

Automated ply boundary inspection is able to correctly identify and measure 92% of tow ends on a standard ply. The remaining 8% is comprised of 7% non-identified tow ends and 1% identification of the wrong feature. Tow ends that are not automatically identified are forwarded to the user interface for semi-automatic detection.

The ability of the system to measure tow ends varies by ply orientation. For plies with an underlying ply offset by 90 degrees the detection accuracy is significantly lower. Underlying 90 degree offset plies often contain features (lines) that mimic the appearance of a tow end, and these false features are sometimes identified as true features by the detection system. For these worst case plies the correct feature is determined 80% of the time, with 15% of features recorded as “not found” and 5% with the incorrect feature identified as the tow end. Figures 10 and 11 show examples of these difficult to identify features.

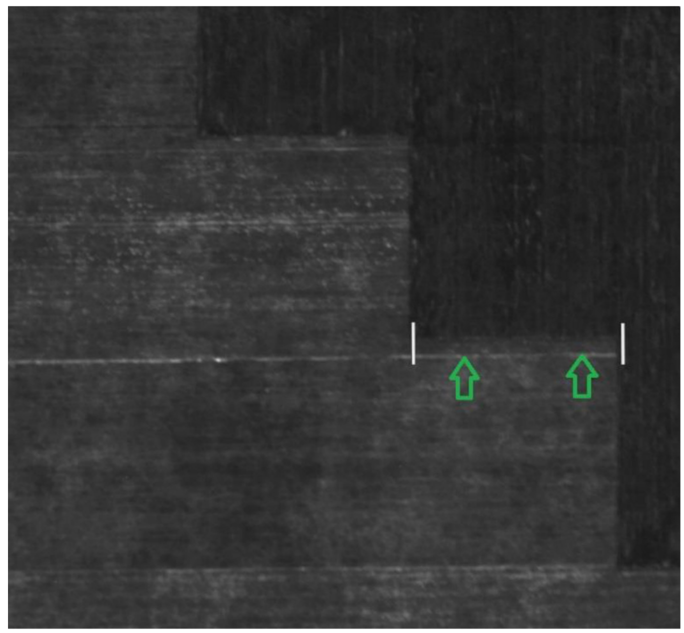


Figure 10. Problematic features.

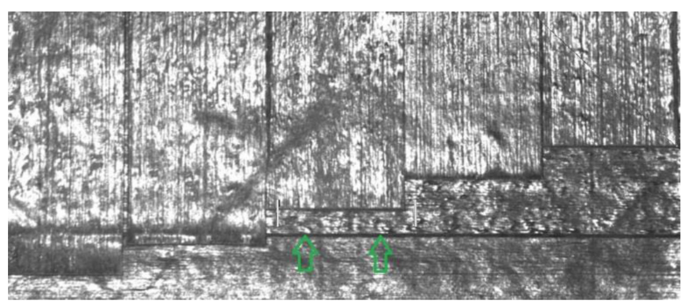


Figure 11. Problematic features.

Semi-Automatic

Tow ends that cannot be identified automatically are forwarded to the user interface for assisted manual detection. The UI lists tow ends that the system failed to find. Clicking on any error in the list focuses the 3D image view on that feature. The user can quickly mark tow ends as passing, or spend additional time to mark the location of the tow end, which provides a numeric location measurement. This measurement interface is shown in the 3D view in Figure 12. After selecting a tow end the user moves the mouse to align the green arrowheads with the tow end.

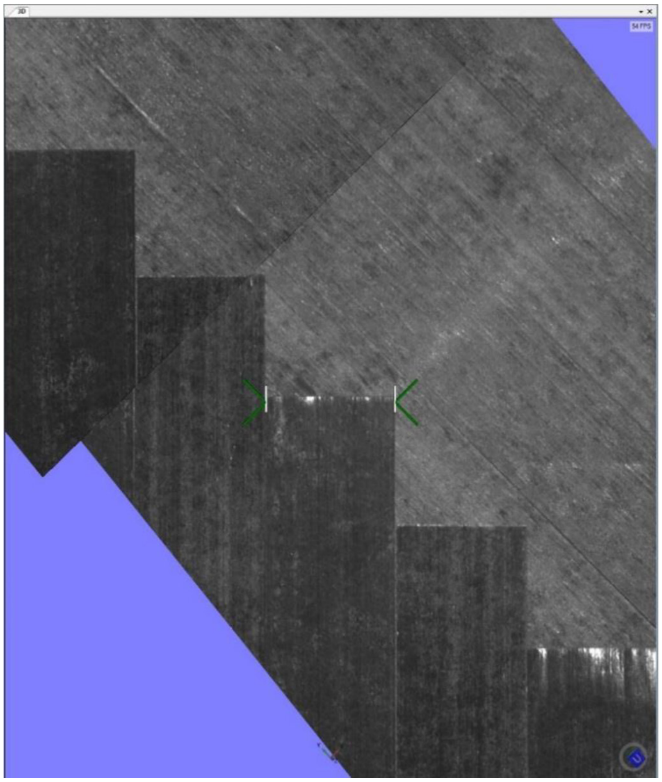


Figure 12. Semi-Automated Ply Boundary Inspection Measurement

Figure 13 displays tolerance bands to be used for quickly selecting pass/fail input. If the tow ends are visible between the blue and green lines the operator indicates they pass inspection. Otherwise a defect is flagged for rework.

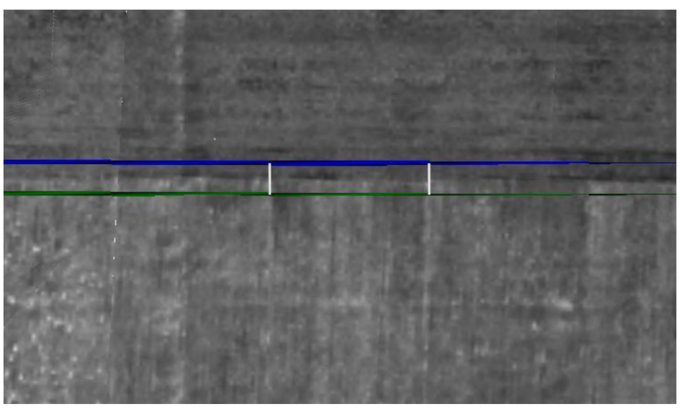


Figure 13. Semi-Automated Ply Boundary Inspection Pass/Fail

Pointing to Defects

The user interface is fully integrated with our laser projection system. An inspector can mark any defects from within the UI and have the laser projector project the location on the part surface for quick identification.

For stationary projectors, projected laser lines have been qualified to land within +/- 0.030" of the target on the part. Mobile lasers projections have been qualified to land within +/- 0.060" of the target on the part.

Inspection Time

Ply Boundary

The ply boundary inspection process consists of the following steps:

1. Process a part program to determine where tow ends are located on the part.
2. Build a list of commanded positions to take images.
3. Position a LASERVISION camera system such that its field of view encompasses the desired location.
4. Image (take a photo)
5. Image processing (tow end detection)
6. User display
7. User input (semi-auto)
8. User input (rework/ignore)
9. Ply report
10. User input (inspection complete, ok to start next ply)

In some machine cells imaging can begin during a layup to save time. Processing occurs for each image as soon as it is taken. The user may begin viewing processed images and inspection data while the system is still acquiring images, which also saves time.

Inspection time depends heavily on ply complexity. Inspection time increases with the number of tow ends marked for inspection. For 0.5" width tow, the inspection system measures 15 tow ends per second. On large parts with over 1000 inspected tow ends the measurement system can take several minutes to inspect the part. Missed tow ends add additional inspection time from user input.

Tow ends that subsequently get trimmed from the final part do not require a measured position. They do not get imaged and do not contribute to inspection time or statistics.

Overlap and Gap

The overlap and gap inspection process consists of the following steps:

1. Process a part program to determine where tow lanes are located on the part.
2. Execute a part program to place tow.
3. Profilometers continuously collect overlap/gap data in real time and report the measurements to a database.
4. Process data to trim measurements based on part program
5. User display
6. User input (rework/ignore)
7. Ply report
8. User input (inspection complete, ok to start next ply)

Data collection occurs in parallel with material deposition, so inspection time is only affected by user interaction with the user interface. User input for overlap/gap data is limited to a button click that confirms the trouble regions have been reworked to tolerance. Other than the actual part rework, this process takes a negligible amount of time.

Inspection Data

Accuracy

Automated ply boundary population accuracy has a mean error better than 0.005” and a standard deviation of 0.020”. It has been qualified with a locational accuracy within +/- 0.060”.

Semi-automatic ply boundary population accuracy has a mean error better than 0.005” and a standard deviation of 0.016”. This number is influenced by image pixel resolution, which is approximately 0.008” per pixel.

Gap measurement data has been qualified to have a mean error smaller than 0.003” and a standard deviation of 0.005”.

Overlap measurement data has been qualified to have a mean error smaller than 0.010” and a standard deviation of 0.013”.

Ply Report

After each ply, the UI generates an inspection report that shows mean and standard deviation statistics for ply boundary and overlap/gap measurements for that ply. Ply reports can be saved to create an inspection history log for entire part builds. Figure 14 shows an example ply report of overlap/gap data. Figure 15 shows an example ply report of ply boundary data.

The ply reports can be tailored to meet end user inspection requirements.

The data presented in each report can be used to visualize and understand the distribution of defects on the part and take appropriate corrective action.

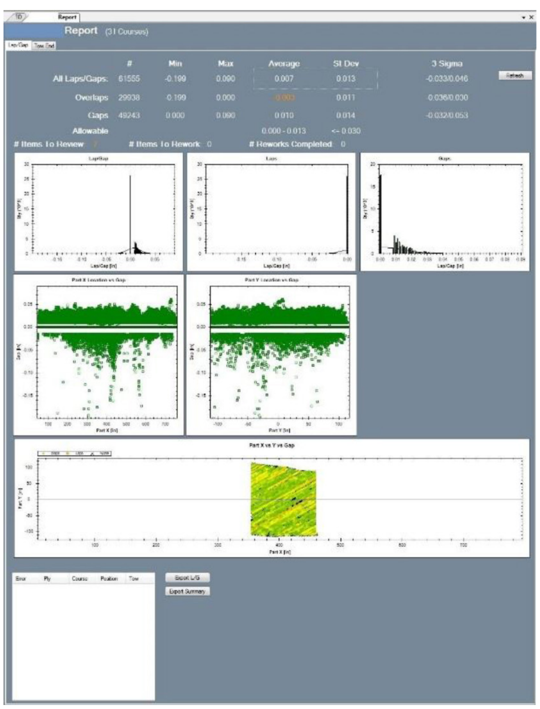


Figure 14. Overlap/Gap Inspection Report

Figure 15. Ply Boundary Inspection Report

Data Volume

Inspection data consumes a large amount of hard drive space. The data can approach 1 TB per part for large complex parts. To maintain space on the hard drive and database, old data is automatically deleted. End users who want to archive old data must make backups onto external media and devise a system of managing the archived data.

Data Value and Utility

The value of automated inspection systems is commonly associated with overall cell efficiency and elimination of inspection time. In addition to reduced inspection time, the system offers other benefits that are worth consideration.

The enormous volume of automated inspection data is not practical to gather manually. AFP inspectors do not gather lap/gap data every 1” along every tow interface. Doing so would take weeks per ply. In addition, inspectors nominally check ply boundary acceptance visually without obtaining measurements. Automated inspection data provides extensive opportunities to understand and improve upon AFP manufacturing processes.

Statistical process control, a dominant method used in other manufacturing processes, has until now not been possible for AFP due to lack of measurement data. By providing overlap/gap and ply boundary measurements, the inspection system makes it possible to apply statistical process control to the AFP manufacturing process.

Statistical process control can reduce rework by eliminating unnecessary fixes. With manual inspection operators rework every lane that violates ply boundary or overlap/gap tolerances. With automated inspection, instead of reworking every out of tolerance error, operators can rework only conditions that make the population out of tolerance. This can drive down rework time. Studies have measured that each repaired tow consumes 15 minutes of cell time [1]. By ignoring non-critical tow errors, manufacturers could see a much greater time savings than that gained by automating inspection.

By amassing large quantities of inspection data, manufacturers would be able to characterize their machines and processes to an extent that might provide sufficient confidence to reduce inspection and rework down to minimum statistically significant levels.

By monitoring inspection data, a process control engineer would be able to determine when process parameters are drifting out of compliance and pursue corrective action before negative results are seen on the part. As a simple example, out of tolerance or drifting measurements for a particular lane could be used to indicate that the feed or cut mechanisms for that lane should be investigated or tuned.

The ply inspection report provides data that can be used as a complete historical record of the part build.

When inspection data is measured automatically, it reduces human error in the system. In standard situations, the user's input is limited to just a go/no go for 7% of all ply boundary data. Users are not personally tasked with guaranteeing a 100% in-tolerance condition.

Gap data is difficult for human inspectors to manually measure. Overlap data is difficult and often impossible for human inspectors to measure. The automated inspection system provides accurate, repeatable measurements that would be difficult, impossible, extremely time consuming, or inaccurate for a human to measure.

Automated inspection systems are imperfect. Their imperfection should not detract from their utility. A system that measures 80%-90% of all data provides a sufficient data set to characterize the missing data, provided the missing data is random and not clustered.

Resource Burden

Because automated inspection is an entirely new technology, it requires special resources to develop and support. The extra resources are required of both the supplier and the customer.

The integration of a production inspection system requires 2 Electroimpact software engineers for 1 year. An additional 1 year of on-call inspection support is required to adequately adapt the system to unique production cells. The driving reason for the additional support is the parameters of the imaging system depend greatly on the parts being made. Part geometry and part programming greatly influence the effectiveness of the inspection system. An inspection system that works on one part will not necessarily work on a different part.

Special operator training is required for the inspection system. Experienced operators will take time to become familiar with the new system and run it efficiently. Much of this education happens in the beginning stages of production, and the additional 1 year of on-call support is intended to guide operators through the learning curve.

Manufacturing organizations are tasked with making decisions about how to use inspection data. They must decide what conditions are acceptable for overlaps and gaps as well as tow end placement accuracy. It must be decided whether to enforce acceptance criteria for individual tows, individual courses, individual plies, or individual parts. Other factors for manufacturers to decide are whether to place absolute values on acceptance conditions, or to apply statistical process control. The machine tool builder can supply functionality but requires the part manufacturer to make inspection decisions.

This emerging technology provides manufacturers with powerful data, but burdens them to adapt the manufacturing process to make meaningful use of the new data.

Hardware Cost

The LASERVISION, profilometers, and high-power PCs that comprise the inspection system are high cost units.

Ballpark costs are $5,000 per PC, $20,000 per profilometer, and $100,000 per LASERVISION unit.

A system comprised of several profilometers and LASERVISION units can approach $1,000,000 of hardware, which doesn't include the cost of engineering integration.

While appreciating the powerful data provided by automated inspection, is it important to recognize the high cost associated with the system, and to make an appropriate business case for pursuing an inspection system.

Summary/Conclusions

The first generation of AFP automated inspection systems was deployed in 2016 and is now providing production measurements of ply boundary location and overlap/gap width.

Inspection accuracy is sufficient to qualify parts.

More than 80% of desired data can be automatically measured quickly and reliably. Gathering missed data can be time consuming and require human interaction. It is important to recognize that the inspection data per ply is a single population, and that statistical analysis applied to the large majority of data which is automated also applies to the small percentage of missing data. This team's position is that small populations of missing data should not detract from the utility of the majority of data, nor should significant time be spent in attempts to recover small populations of missing data as defined as 20% or less of all data.

The system provides powerful data and benefits, but also requires significant investment to bring to production. When considering the purchase of an automated inspection system, manufacturing organizations should have a comprehensive understanding of the burden placed on their own resources. In preparation to use the system they will need to create plans for specifying inspection tolerance and system qualification. The organization will need to plan how to best use the inspection data. Statistical process control in AFP has value that warrants study by a dedicated process control engineer.

The data provided by this document offers much of the information necessary to begin the decision making process. Hopefully it raises awareness that the purchase of an automated inspection system is not simply a line item in a PO, but it is a complex system that demands buy in from machine tool buyers, the operations team, and the manufacturing engineering team.

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Definitions/Abbreviations

AFP - Automated fiber placement

Tow - A single strip of carbon fiber

Lane - The path for a tow

Layup - Deposited carbon fiber

Ply - A layer of layup

Feed-rate - Speed of layup

Inspection - Observe the as-made part surface and determine if rework is necessary

Rework - Manually or automatically correcting defects in the layup

Gap - A space between parallel adjacent tows

Lap - An overlap between parallel adjacent tows

Ply Boundary - Tow ends and edges of a ply

FOD - Foreign object debris

Defect - A misplaced tow or tow end, missing tow, FOD

Laser Projector - Hardware that projects laser lines onto the part

LASERVISION - A laser projector that can also capture camera images

Profilometer - A laser sensor that measures surface profile

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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