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AN INVESTIGATION INTO SCIENCE-BASED AUTOMATION IN COMPOSITES MANUFACTURING

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ABSTRACT

Significant success has been achieved in the manufacturing of commercial aerospace composite structures over the past several decades. Automation stands out as a crucial technological platform that has paved the way for this success. This work investigates Automated Fiber Placement as one of the cutting-edge lamination technologies in composites manufacturing. A small Automated Fiber Placement simulator (dubbed the µAFP) has been developed to scientifically study the underlying physics in this process. A material- and process-centric sense-think-act framework is used, where critical process parameters related to fiber placement are identified and measured. To achieve this, smart compaction rollers for AFP processing are developed that can measure local pressure at the process nip point. The local data is then systematically analyzed, using physics-based simulation to develop insight into process control. A preliminary application is demonstrated through a case study.

1 INTRODUCTION

Automation has emerged as a key enabling technology in composites manufacturing significantly enhancing material handling, lamination processes and inspection. In particular, Automated Fiber Placement (AFP), has been instrumental in the aviation industry, facilitating the production of high-quality, large-scale, complex components with consistent quality at high production rates.

With the increasing use of composite materials in aircraft structures, there is a pressing need for even higher production rates to meet market demands. Currently, the rate of production of composite aircraft (10-14 per month) is a quarter of that of metal aircraft and it needs to increase six-fold over the next two decades [1]. The current utilization of these systems typically ranges from 20 to 50%, indicating that a significant portion of their capacity remains untapped. Considerable time and resources are dedicated to downtime, offline (ex-situ) process inspections, error recovery, and rework, highlighting areas for potential efficiency improvements.

1.1 Automated Fiber Placement

Simply, an Automated Fiber Placement system consists of an automated motion platform, such as a cartesian gantry or an articulated robotic arm, that is carrying an AFP head. The motion platform orients and translates the AFP head with respect to tooling, over predefined trajectories, while the AFP head is responsible for depositing several narrow strips of prepreg (called tows) on the tool surface. On the AFP head, individual prepreg tows are pulled from bobbin spools, the tow release film is removed and the tow is transferred to the compaction roller under controlled tension. All available tows are collimated under the roller to form a course, and are precisely placed on tooling with application of heat and force under a controlled deposition rate.

1.2 Prepreg Tack Characterization and Modeling

Prepreg tack is a critical material parameter during AFP processing, as it is the primary force preventing deviation of fibers from the designed orientation and thereby resisting formation of defects [2]. In 2021, the first standard method of characterizing prepreg tack was released by ASTM International (D8336 [3]). This test method involves characterization of tack between two prepreg plies, while they are simultaneously consolidated and peeled in a single stage.

Forghani et al. [4], [5] developed a physics-based model for prepreg tack. The model is comprised of a cohesion and a decohesion module. The cohesion module takes into account material viscosity and processing conditions to determine the Degree of Intimate Contact achieved at the end of material deposition. This value, representing quality of contact between prepreg plies, is then used in the decohesion module along with the material viscoelastic response to predict a traction-separation law describing tack. An open-literature calibration of this model was develop [5] using ASTM peel tests and probe tack tests [6] and is used in this study.

1.3 Structure of the Paper

This paper first introduces the developed µAFP simulator system and smart rollers for AFP processing in sections 2 and 3. Section 4 develops a material- and process-centered Sense-Think-Act framework towards an integrated approach for managing material deposition and consolidation in AFP. Then, a case study is presented that investigates the use of smart rollers in the µAFP for tow consolidation and application of in-situ nip point pressure measurements in a physics-based modeling framework to predict process tack outcomes. Finally, the paper is concluded in section 5.

2 µAFP: A Table-top AFP Simulator Platform

When investigating the manufacturing chain from material characterization to AFP processing, a significant gap was identified between the state-of-the-art in tack characterization methods (e.g. ASTM D8336-21 [3]) to even the smallest research AFP systems in terms of technology representation and range of processing parameters such as rate [7]. To address this gap, a table-top AFP simulator system was developed (Figure 1) that can deposit a single prepreg tow under representative AFP condition. Furthermore, the µAFP can perform peel tests immediately after the deposition process enabling in-situ characterization of tack at various independently controlled deposition and peel rates, temperatures, forces and substrate fiber orientations that are much closer to what is observed in industrial AFP systems [2], [7].

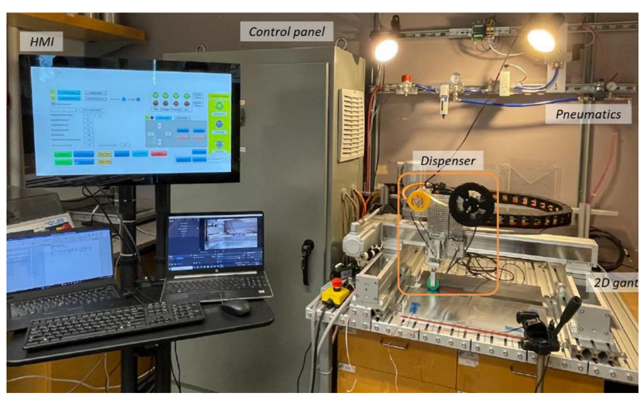

Figure 1. µAFP system conducting an in-situ peel test.

3 Smart AFP Compaction Rollers

Smart compaction rollers have been previously developed for AFP processing using flexible capacitive sensors [8]. The smart rollers are made up of two layers of electrodes that are separated by a pillar-based dielectric layer. The top electrode layer is made of four rectangular strips of conductive fabric running along the roller perimeter and placed at equal distances across the roller width. The bottom electrode layer is made of thirteen rectangular patterns etched on a flexible PC board, that run across the roller width and are placed along the roller perimeter at equal intervals. Each location where a top and a bottom electrode crossover forms a sensing point, called a taxel. As pressure is applied to taxels, the dielectric layer deforms, reducing the distance between a taxel's electrodes, thus changing the mutual capacitance between them. A preliminary characterization has been conducted to relate the change in normalized mutual capacitance to local pressure applied [8].

4 Integrated Analysis Framework

4.1 An Integrated Material- and Process-Centered Sense-Think-Act

The Sense-Think-Act (STA) framework has long been the dominant paradigm in robotics, originally established within the fields of robotics, control, and automation [9]. This framework states that a robot first 'senses' its location relative to its surroundings, 'thinks' about potential strategies for carrying out the intended task, plans, and finally, 'acts' and executes the planned motion using its actuators. In the AFP industry, substantial research has been conducted on robotic trajectory planning, which considers the actuation of motion platforms axes, to accurately produce the desired layup path on complex tool geometries.

A material- and processing-centered Sense-Think-Act framework is presented here. It is fundamentally of interest to understand what process or material parameters are essential to measure (sense) during the AFP processing for effective prediction and control of quality outcomes. The decision to measure a particular parameter should be made through a systematic and science-based framework that is based on transformation of the material during the process. Then, the data measured from the process should be analyzed in a physics-based framework (think) developed for understanding the process, in order to finally determine how we can establish the AFP process window scientifically, effectively, and efficiently (act). It is proposed that through an integrated and balanced development of sensing, acting, and thinking technologies, an effective and efficient approach to automation in composites manufacturing can be achieved.

When considering the process through the lens of the sense-think-act framework, it is often observed that one of these elements has progressed significantly while the other ones are lagging. For example (Figure 2, a), very advanced sensor technology may be used to monitor the process. But what if the available physics-based frameworks are unable to offer accurate interpretations or insights into the process and relevance of the measured parameter to material processing? This necessarily leads to inability to act or control the process efficiently, resulting in untapped capacity in the system. This work posits that the most effective and efficient approach to automation is a balanced integration of sensing, thinking, and acting within an automated manufacturing system (Figure 2, b). This concept is applicable to all composites manufacturing, especially more modern technologies with high potential for automation, including but not limited to, AFP, forming and Additive Manufacturing.

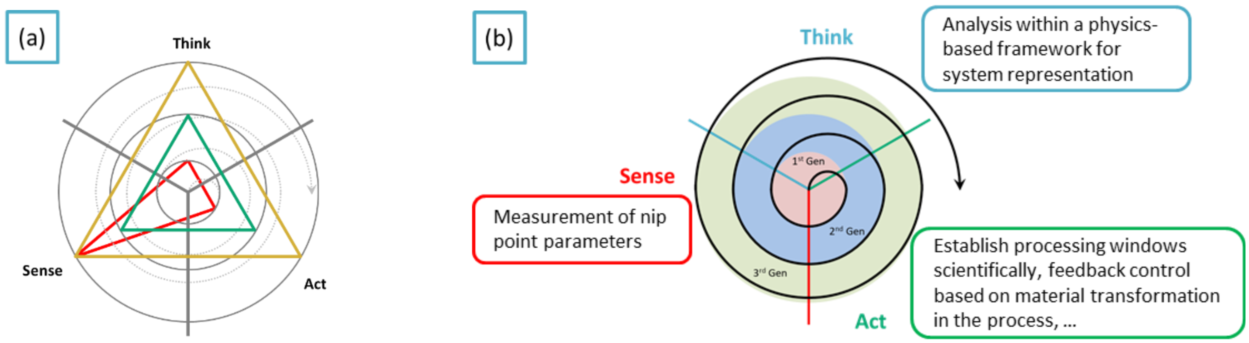

Figure 2. (a) Unbalanced vs balanced progression of sense-think-act and (b) Balanced STA integration concept.

4.2 A Case Study Toward On-line Tack Prediction

There are many scenarios in AFP processing where the roller is required to conform to a complex shape (for instance, convex/concave tooling, and ply drops). A case study is specifically designed such that the flexible tire of the roller needs to deform to three different height levels during the process. This necessarily creates pressure variations across the roller width that will directly impact development of tack and the quality outcomes of the process.

This case study investigates the application of previously developed smart rollers and physics-based tack models in the µAFP system, to evaluate tack during tow consolidation as a key material parameter during AFP and an indicator for potential layup outcomes. The smart roller is integrated with the rest of the µAFP's central control system to receive sensor data in realtime using a Python wrapper for Beckhoff's Automation Device Specification (ADS) communication protocol (PyADS) A workflow is developed to conduct in-situ pressure measurements at the process nip point using the smart roller, collect the data, and transfer the data to the central controller for further processing. An open-literature calibration of the physics-based tack model [4], [5] for the AS4/8552 material system is used to estimate tack levels developed in the process based on sensor data.

A single ply of prepreg is placed as a base substrate on top of the tooling. An 8-ply thick substrate is placed on the left, and a 4-ply thick substrate is placed on the right of the layup (Figure 3). A ¼" wide tow is placed on each substrate and a smart roller is used to consolidate all the tows with the application of 50 N force at room temperature, while the roller is traversing at 50 mm/s, while the roller response is recorded. Each taxel column is aligned with the position of a tow and they are identified in Figure 3, b. Unidirectional HEXCEL AS4/8552 prepreg [10] is used throughout the study.

The normalized change in capacitance for a row of taxels are presented in Figure 4, a. In each signal, the rising edge indicates the taxel column has entered the nip area, thereby applying pressure to the substrate, and the falling edge indicates the taxels have left the nip area. For this study, the average pressure applied at the process nip point in each taxel associated with a tow location is calculated. The open-literature tack model is exercised in the RAVEN simulation software [11] using the local pressure measurements, and other process conditions to simulate the traction-separation response of tack for each tow consolidated during the experiments.

Figure 4, b, presents the results of average nip point pressure measurements alongside the predicted Energy of Separation (EoS) of tack using the tack model. It is observed that even though all three tows were consolidated with a single roller pass under a constant compaction force of 50 N, the underlying layup geometry results in significant variations in the local pressure applied. Increased local pressure on a tow enhances the driving force for the resin to bleed into the interface micro voids, thus improving the quality of intimate contact. Consequently, this leads to stronger tack interactions, as reflected by a higher EoS, predicted by the tack model.

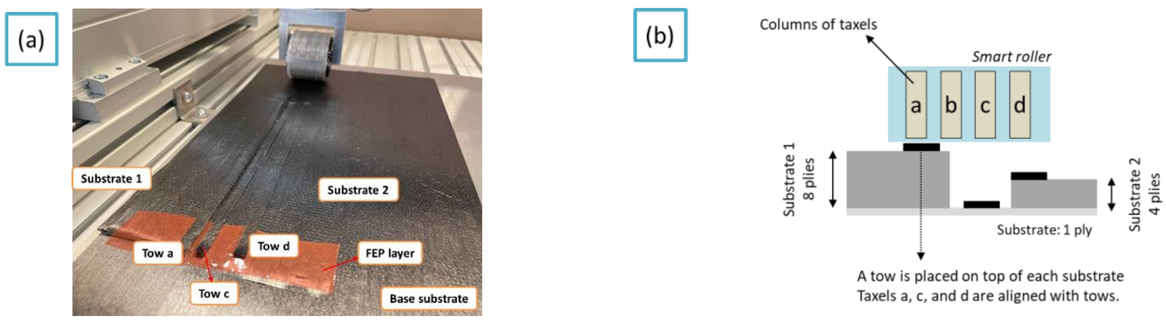

Figure 3. (a) tow consolidation case study using the µAFP and (b) roller position with respect to the layup.

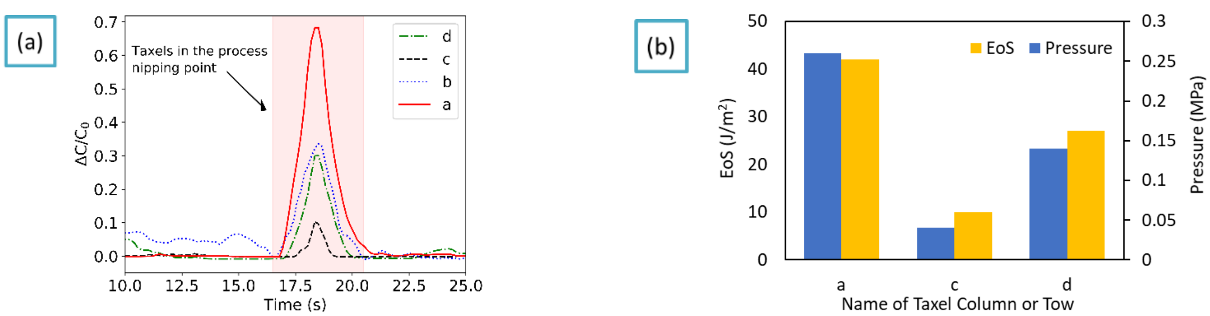

Figure 4. (a) change in normalized capacitance. (b) average nip point pressure measured in-situ and predicted EoS.

For this case study, the result of tow consolidation is qualitatively evaluated by manually peeling each tow off (Figure 5). It was observed that tow a, which experienced the highest local pressure and predicted EoS, is fully consolidated with a very high peel resistance, accompanied by fibril formation indicating cohesive failure in the resin and a high quality of intimate contact. Tow c, subjected to the lowest pressure, demonstrated minimal tacky resistance, while tow d, the intermediate case, required a moderate amount of force to peel off. Both these latter cases exhibited adhesive interface failure indicating lower quality of intimate contact formation. A parallel case study presented in [7], with similar substrate geometry, involved tows first being deposited using the µAFP and then peeled off in-situ. That study corroborates the observation that the in-situ measured tack EoS increases with increasing nip point pressure, as measured by the smart roller, further supporting observations in the current work.

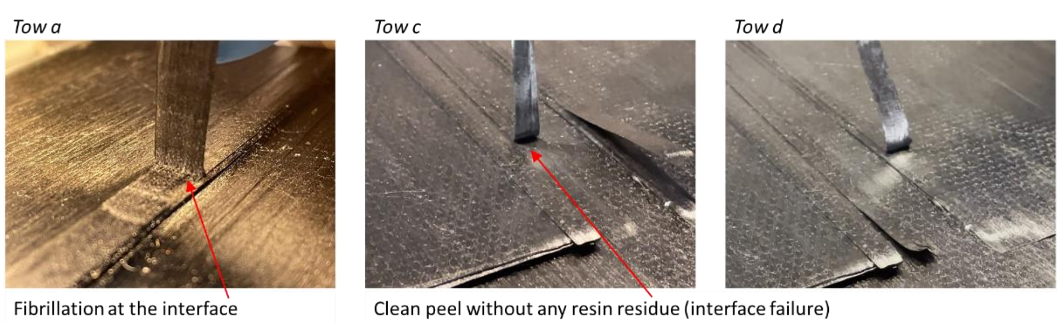

Figure 5. Qualitative assessment of tack through a manual peel test.

5 Conclusion

This work presents the efforts made to develop a tabletop AFP simulator system (μAFP) and in-situ peel tests, as well as smart rollers for AFP processing that can measure local nip point pressure in-situ. A material- and process-centered Sense-Think-Act framework is developed that posits highly effective and efficient development and control of an advanced processing technology, like AFP, can be achieved through a balanced integration of sensor technologies and a physics-based system representation framework. This framework is centered around the material's transformation in the process, enabling comprehensive understanding of the appropriate management of process parameters to achieve desired quality outcomes.

A case study is presented that integrates the smart roller into the μAFP's central controller. The sensor signal is received and processed to obtain local nip point pressure which is then used to predict tack outcomes using an open-literature physics-based tack model. Future work will focus on employing the systems described here, to investigate effects of various process parameters during AFP, on tack development and microstructure of intimate contact.

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