REMAINING DEVELOPMENTS REQUIRED FOR COMMERCIALIZING IN SITU THERMOPLASTIC ATP

Mark A. Lamontia and Mark B. Gruber,
Accudyne Systems, Inc., 134 Sandy Drive, Newark, DE, 19713

ABSTRACT

Thermoplastic automated tape placement (ATP) process developers now "glimpse the light at the end of the tunnel." The ratio of mechanical properties between 1) laminates fabricated by thermoplastic ATP with in situ consolidation and 2) laminates autoclaved following placement has surpassed 90%. Thus, real promise exists for in situ processing with thermoplastic composite material systems to supplant thermoset fiber placement and tape laying for some large primary aerospace structure. However, several developments remain to be completed. Thermoplastic technology lacks process models validated with heating/cooling rates associated with the actual in situ process; yet models are required for process control design and to guide placement speed increases. The process and equipment must improve to accommodate complex aerospace geometry and realistic tooling, and deposition head robustness must improve for daily factory operation. Placement grade thermoplastic composite material is needed. Mechanical testing must reveal part longevity. On-line and post-process NDE are required to generate confidence in part quality and to be able to enact corrective measures to remedy a defect. Finally, demonstration of the more articulate fiber placement process with more complex part geometries is required. This paper describes the development that remains for deposition head and process developers, and for materials companies commercializing thermoplastic materials.

KEYWORDS: Automated Tape Laying/Tape Wrapping, Fiber Placement/Automated Tow Placement (ATP), Resins/Materials – Thermoplastics

1.0 INTRODUCTION

Thermoplastics composite materials systems are generally considered as substitutes for thermoset materials in aerospace and defense applications to take advantage of

- beneficial resin properties such as thermal stability and toughness, and/or
- capital and fabrication cost reductions afforded by consolidating without an autoclave [1].

Out-of-autoclave cost savings using thermoplastic in situ consolidation are proportional to the laminate size to be fabricated, since the largest thermoset matrix composite laminates and tools require the largest autoclaves. Thus, thermoplastic process development programs are usually linked to the fabrication of large aircraft skins or space vehicle tanks [2]. The desire for out-of-autoclave fabrication of high performance composites continues to fuel thermoplastic composite development [3].

In the 1990's, hand lay-up was replaced with fiber placement and tape laying as the preferred routes to prepare thermoset parts for autoclave consolidation. Accudyne Systems designed, assembled, and developed the placement head shown in Figure 1.1, along with the associated process and controls to compete with this thermoset ATP technology [4,5,6]. The heated deposition head, capable of gentle contour, operated on a Cincinnati Machine gantry tape placement machine modified to coordinate the polymer process with course deposition. The in situ consolidation process fabricated aircraft-quality composite structure from dry, boardy tape or tow.

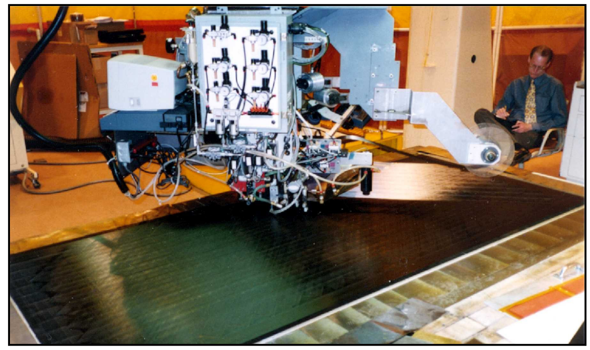

Figure 1.1 In-situ deposition tape-laying head consolidating 75mm APC-2/AS-4 tape on a laminate at speeds up to 5mpm (20fpm)

NASA Langley Research Center contractually assigned a team to demonstrate the in situ process by fabricating flat laminates and skin stringer and honeycomb built-up structure that meet aircraft thickness, weight, and mechanical property specifications [7]. PEEK, PIXA, PIXA-M, and PETI-5 placement-grade tows and tapes were developed and laminates were fabricated and tested [8]. Laminate quality is exemplified by the excellent IM-7/PIXA laminate photomicrograph in Figure 1.2, showing well-consolidated resin interfaces, few voids, a uniform fiber/resin distribution, and no ply waviness.

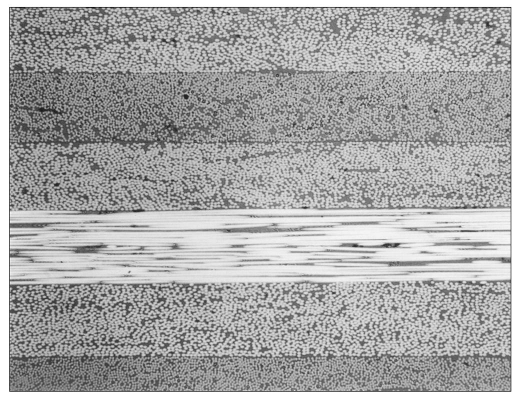

Figure 1.2 Photomicrograph of high quality IM-7/PIXA laminate from TP-ATP and placement-grade tape

Figure 1.3 exhibits compression strengths and moduli plus Open Hole Tensions (OHT) and Open Hole Compression (OHC) strengths for PEKK, PEEK, and PIXA quasi-isotropic laminates [9,10]. Properties are included for laminates fabricated by three processes:

- in-situ ATP,
- in-situ ATP followed by autoclave consolidation, and
- hand lay-up followed by autoclave consolidation.

The compression moduli for in-situ processed laminates range from 84 to 99% of the moduli from in-situ placed post-autoclaved laminates. The compression strength ratios of in-situ laminates to in-situ post-autoclaved laminates range from 84 to 103%. The OHT strengths closely compare for both in-situ and in-situ post-autoclaved laminates. The OHC strength values for in-situ placed laminates were 76 to 92% of autoclaved laminates, averaging about 85 percent. Autoclave treatment clearly furthers consolidation.

Built-up structure was also fabricated. Skin stringer laminates were manufactured by placing directly over embedded preconsolidated thermoplastic stringers (or thermoset stringers coated with a thermoplastic film layer) into an IML tool and then tape placing over them using the in-

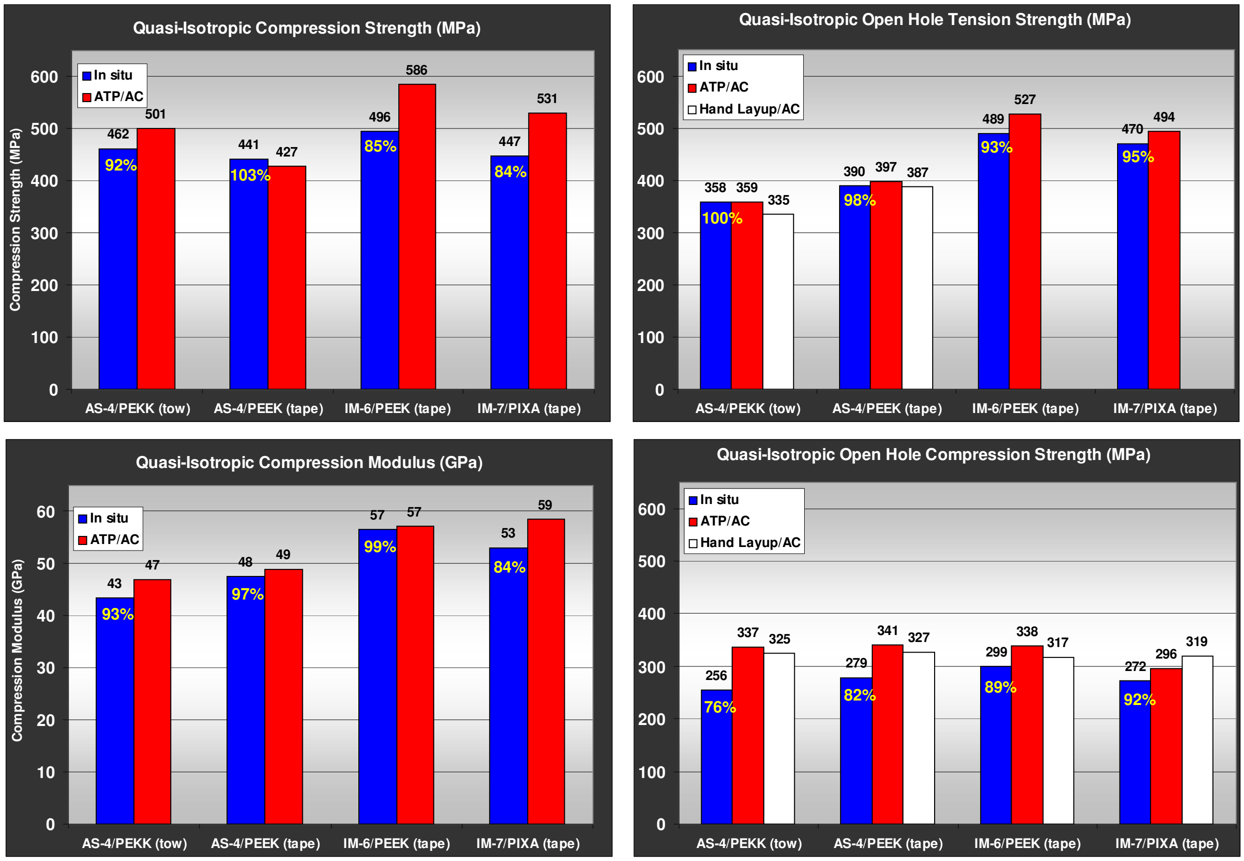

Figure 1.3 Compression strength and modulus, OHT, and OHC for AS-4/PEKK tow placement, AS-4/PEEK tape laying, IM-6/PEEK tape laying, and IM-7/PIXA tape laying using three consolidation processes, in situ ATP, ATP/post-autoclaving, and hand-layup/post autoclaving.

situ consolidation process to produce a stringer-flange skin weld. This process is known as primary (1°) bonding, as opposed to secondary (2°) bonding of preconsolidated laminates and stringers, or co-bonding where an autoclave is used to consolidate the stringers while at the same time bonding them to a pre-finished skin laminate. ATP skin stringer laminates were made by 1°, 2°, and co-bonding. A completed thermoplastic skin stringer laminate is shown in Figure 1.4.

Figure 1.4 In situ placed three-stringer laminate

Thermoplastic in-situ consolidation was also used to fabricate 1° and 2° bonded honeycomb panels. In 1° bonding, facesheets were tape placed directly over titanium core precoated with roller-coated BRX-5® paste adhesive, FMX-5® film adhesive, and PEEK or PIXA-M film, as shown in Figure 1.5 with the head placing a laminate directly over titanium core. Run-on and run-off tooling surrounds the core so it is hidden in the photo. In 2° bonding, in-situ consolidated facesheets were bonded to core with BRX-5® under light autoclave pressure.

Actual aerospace structure is contoured, however, and programs were completed demonstrating heated and chilled conformable compaction systems for the deposition head [11,12]. These compactors allowed process heating and resin re-solidification while accommodating a 6 mm tall ply detail over a 10:1 slope. An APC-2/AS-4 joggle laminate is shown in Figure 1.6. The ensuing contoured deposition head, shown in Figure 1.7, features heated line and area conformable compactors to establish intimate contact and reptation healing between the pre-consolidated laminate and the tape being placed, followed by chilled line and area conformable compactors to consolidate the laminate [13].

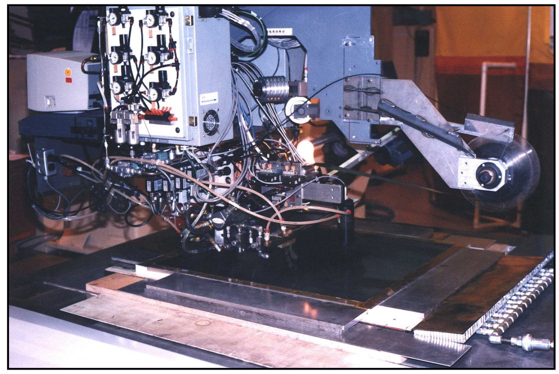

Figure 1.5 Primary bonding using thermoplastic in situ consolidation to place 76mm (3-in) tape on honeycomb core precoated with BRx-5 and FMx-5 adhesives.

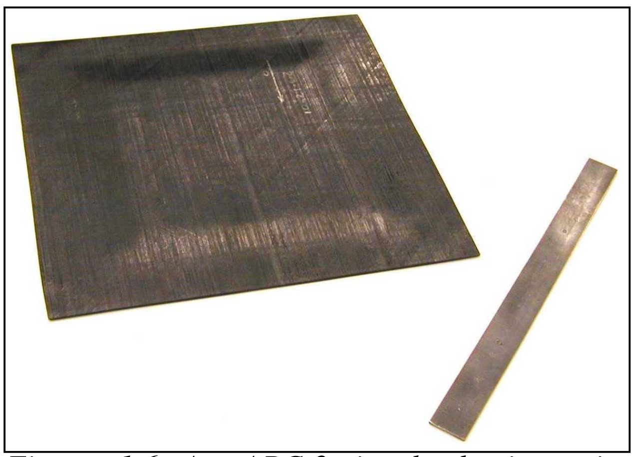

Figure 1.6 An APC-2 joggle laminate is successfully placed using heated and chilled conformable compactors on the head.

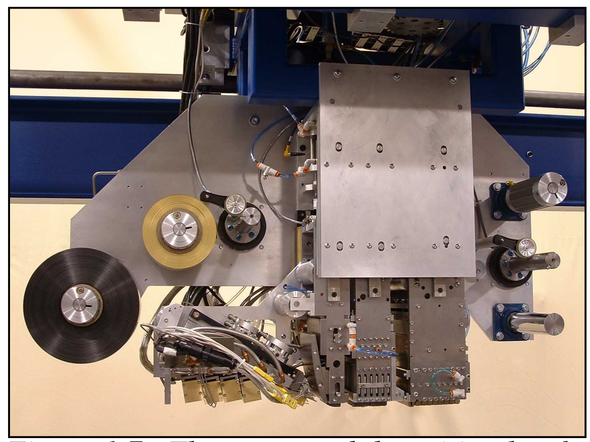

Figure 1.7. The contoured deposition head can place twelve 6.35 mm wide tows or one 75 mm wide tape by changing feeders.

2.0 PROCESS FUNDAMENTALS

A thermoplastic deposition head is multifaceted compared with its thermoset counterpart. Whereas thermoplastic and thermoset heads share the task of depositing tape or tow in specific tool or laminate locations, a thermoplastic head has the additional duty to furnish a polymer process to heat the incoming thermoplastic material feedstock and previously deposited laminate so as to weld them together, then resolidify them as an integral step in consolidating the layers. The thermoplastic process has one prime chance to produce a quality layer in a short time.

Figure 2.1 illustrates the process concept for the deposition head shown above [4,5,6,8]. A material feeder provides accurate deployment, starting, and cutting of tows or a tape. Two torches direct heated air to the process spot. The first torch heats the bare tool or previously laid composite, while the second trim heats both the substrate and material feedstock. Three conformable compactors alternately heat and chill the composite. The first, a heated line compactor, establishes the initial intimate contact between the lower surface of the incoming composite and the upper surface of the substrate and initiates healing in locations where intimate contact has been achieved [4,5,6,8,11,12]. The second, a heated area compactor, maintains the temperature long enough to complete reptation healing of the longest polymer chains to develop strength across the layer interface [14]. The third, a cold compactor, combines the action of a cold line and a cold area compactor, and chills the material, re-freezing it in place and compressing interlayer voids before the force is removed [4,5,15]. Figure 2.2 shows the temperature-time history achieved, with the compaction systems detailed for the heated head placing at 1.83 mpm (6 fpm). The temperatures achieved are slightly below those prescribed in Figure 2.1; being measured via a thermocouple buried one layer down in the laminate. The temperature ramps from 50°C to 360°C in 8 seconds, a heating rate of 39°C/second. The cooling rate is even faster. The laminate is above 350°C for 9 seconds.

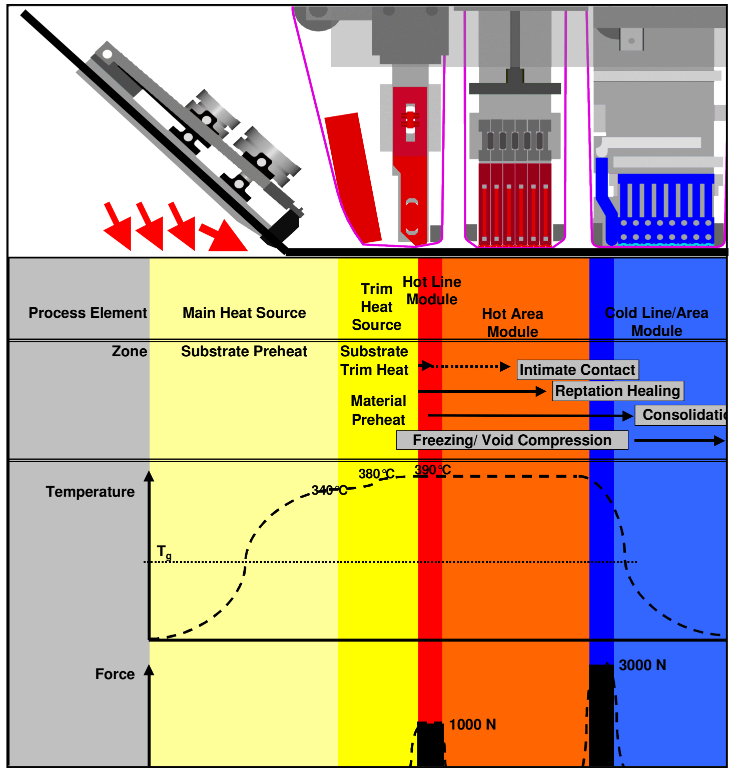

Figure 2.1 Deposition head process concept, process steps, and temperature and force parameters

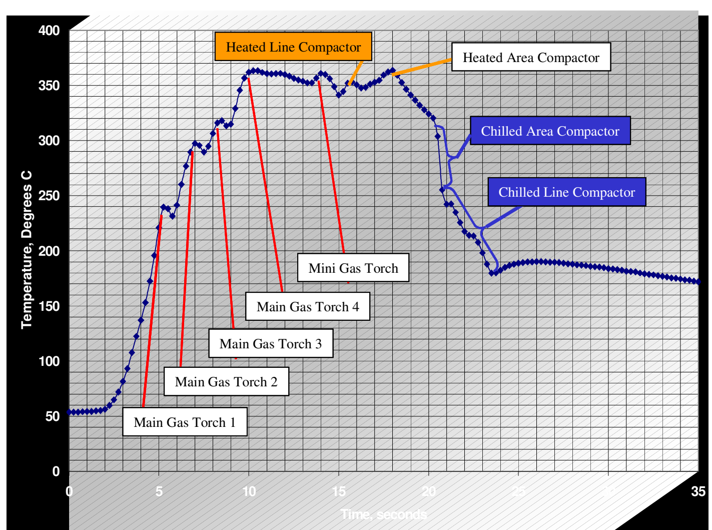

Figure 2.2 Temperature-time history for the deposition head and process, measured with an embedded thermocouple one layer down.

Is this process and equipment adequate to generate full mechanical properties in the laminate (equivalent to autoclave processing) with no post-processing required? On what basis? A head designer attempting to fulfill the process concept would seek to arrange subsystems to reproduce a process proven by R&D. How could that R&D demonstration be accomplished?

Consider the following hypothetical scenario. A picture frame mold is placed within a fast-closing press heated to 390°C, the processing temperature for PEEK. A single PEEK tape layer is placed at the base of the mold. A second PEEK tape layer is added to the mold, which is quickly closed, then opened, to mimic the 10-second heating times characteristic of the thermoplastic process. Imagine further that this layer-by-layer process is repeated “n-1” times until a full thickness quasi-isotropic laminate is a manufactured, "n" layers thick. Would this be adequate to define the thermoplastic process? If laminates made in this manner achieved 100% mechanical property translation (almost certainly not) compared with properties measured from autoclaved laminates, could the designer be confident that a heated deposition head that reproduced that process would generate laminates having those properties as well?

The answer is profoundly no. In this hypothetical example, composite tape in the mold is held at 390° for the entire process duration while an in situ consolidated laminate temperature cycles for each layer. In the compression mold, intimate contact and healing can occur gradually over a time period encompassing the "n" plies, as all "n" plies are heated following each mold closure. In the in situ process, intimate contact and healing are nurtured beneath the heated compactors one or a few layers at a time [4,5,14]. There is no first layer process in the picture frame mold, while actual in situ consolidated laminates have low force/temperature first layer consolidation processes. Finally, unless the picture frame is temperature cycled by active chilling (at slow cooling rates), the laminate remains soft and would not have integrity when the mold lid is removed following each cycle. The molded laminate in this example is not even chilled under pressure. An in situ process consolidates and chills following each head course, and the laminate is finished through "n" layers following every step. The laminate crystallinity from the two processes could be dramatically different [16,17,18]. It is clear from this comparison that the R&D molding process, however conducted, has little in common with the in situ process.

Another possibility would be to generate a model process using experiments run on a belt press. Appropriate temperatures can be achieved and experiments could be run mimicking a layered process. However belt press speeds are slow, heating times are long, and compaction pressures are low compared with those furnished by an in situ consolidation head.

There are at this point no examples of an experimental apparatus that could create an independent process window that would result in laminates with 100% autoclave properties. Deposition head developers are left without a proven R&D demonstration to base the head upon. It is possible that such an apparatus could not be achieved, unless it closely mimics an in situ head. However, if some researcher could create an independent process demonstration [15] that resulted in laminates with full property translation, it could instantly be employed to elucidate the important physical parameters to close the remaining 10% to 15% mechanical property gap.

3.0 PROCESS MODELING

Four papers [14,15,18,19] are cited from a dense field of papers describing thermoplastic in situ consolidation models. The four are current, excellent, and contain extensive references, highlighting process model development over the past 20 years. Tierney and Gillespie [15] developed heat transfer, macroscopic flow, and microscopic void dynamics models for the ATP process. The coupled models predicted void distribution through the tape based on various process inputs. Troublesome deconsolidation, elevated void content at the surface and substrate regions, heat sinking at the tool surface, and the struggle to simultaneously achieve consolidation and degree of bonding are highlighted. Tierney and Gillespie [18] also modeled the crystallization kinetics of PEEK composites exposed to highly non-isothermal heating and cooling. They validated models with innovative experiments to measure crystallization at high heating rates using single plies. Further work performed by them [14], coupled intimate contact and healing models to create a degree of bonding model. By applying their heat transfer model temperature field to the ATP process spot, they predicted the through-thickness Short Beam Shear Strength (SBSS) distribution following in situ consolidation, generating good agreement between predictions and experiments. Nicodeau [19] developed a process model of the "Drapcocot" process. She assumed that intimate contact time was negligible due to high compaction forces and calculated the interlayer diffusion and thermal aging kinetics occurring when processing APC-2 composites. She concluded, *"…there is no way to obtain, with the system under study, the theoretically maximum interfacial strength."*

The models well-describe the ATP process fundamentals, and have influenced head development [4,5,6,7,8,9,11,12,13]. However, to help commercialize ATP by closing the remaining 10% to 15% mechanical property gap to autoclave processed laminates, they are lacking. The papers assume a constant head configuration and constant input material. The head configuration cited in [14,15,18] was conceived of in the early 1990s. While appropriate at the time, industrial head configurations are now massively more complex, and feature multiple machine-controlled heating and cooling sources [4,5], and cascaded MISO process control based, in part, on the very papers cited. With respect to crystallinity, industrial experience is that full crystallinity is always achieved with APC-2 composites. Properties of interest to aerospace frame companies are not SBSS but instead $X_{11}c$, OHC, and CAI [4,5,6,7,8]. While previous work [14,15,18,19] have been successful at describing the process physics that occur in thermoplastic in situ consolidation, they generally describe how ATP suffers with incomplete properties and laminate microstructure, with (inadequate) heated steel tools [7], and with the (poor) material. A change in viewpoint is required. While outstanding at elucidating process physics, the focus of these papers would have to shift to feature head configuration and process control changes. Many of the heat source, control, and tooling problems have now been solved by industry, and to be helpful, models are required to guide laminate mechanical property increases from 90% to 100%. These models need to use constants appropriate to the configuration of the industrial head and processes, with actual process time constants, and with actual rates describing resin degradation, intimate contact, healing, and void elimination. If completed, a successful model would likely be the centerpiece for the feed forward portion of the head's dual MISO controllers.

Two further difficulties remain for process model development:

1. Constant idealized input materials are assumed. The authors have led several major thermoplastic development programs. Surprisingly, programs feature material development more than head, process, and control system development. For the process models to be useful to industrial head development, they must accommodate material defects such as thickness and width variation, uneven fiber resin distribution, and resin rich areas.
2. Universities have the requisite model development skills but must publish their results. An unresolved dilemma is to find a way for universities to team to work on the problem with companies that require results be kept proprietary unless they are patented.

4.0 DEPOSITION HEAD AND PROCESS

Our experience [4-13] with thermoplastic in situ consolidation is to tape/tow place flat and gently curved laminates with ply details. Several head/process features could be enhanced or added to augment process capability for commercialization with actual aerospace frame structure. While a comprehensive "wish list" would be extensive, five development areas are highlighted here.

4.1 Optimal Heating Adjustment with Computational Fluid Dynamics (CFD) – Several thermoplastic deposition heads developed since the early 1990s utilize heated gases for main composite substrate heating. Over this time period, fluid flow modeling capability has increased notably with impressive CFD software development. Directing heated gas into the nip between the laminate substrate and the incoming material is a geometrically complex flow problem, thus, heat source efficiency may not be optimal, limiting placement speeds. CFD could assess the heated gas flow to maximize the heat source effectiveness.

4.2 Heat Source Depth of Field and Articulation of Compactors for Fiber Placement – The deposition head in Figure 1.6 is effective for tape or tow placing flat laminates or laminates with mild curvature. The compactors and heat source are shortened to a single process spot for the automated fiber placement head used to fabricate parts with extreme curvature [20], as shown in Figure 4.2-1. A longer process spot is attainable with a long depth-of-field heat source. Then, heating would be independent of the distance to the composite substrate. Computer controlled laser heating could perhaps provide articulate heat source control and a very large depth of field required for fiber placement.

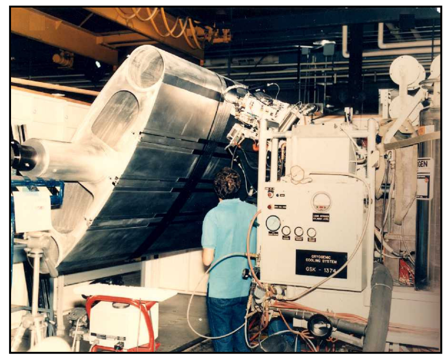

Figure 4.2-1 The ATP head has a single process spot to fabricate laminates with complex geometry

4.3 Conformance into Creases - Conformable compactors installed [11-13] have proven effective in placing slopes, joggles, ply details, and drop-offs on flat and mild contour laminates. However, when ply features intersect, a crease is formed. Compactors with ever more flexible conformance and articulate force application would always be desirable and may effectively place over or into the crease.

4.4 Scalability of First Layer Process/Tooling - It is important that current successful tooling methods be scalable to large tools for composite wing and fuselage skins that are the very parts that would drive adoption of the thermoplastic process.

4.5 Implement On-line NDE – The purpose of a composite lamination process is to situate the exceptional composite material properties into a useful shape, and to discern that those properties are present in the laminate. The thermoset ATP/autoclave process achieves this via coupling the fabrication process with nondestructive evaluation technologies like ultrasonic inspection. A large experiential knowledge base has been established by aerospace OEMs in using this scheme to successfully deploy large composite structure for mission-critical wing and fuselage skins.

Thermoplastic process developers have a chance to adopt and extend this technique with in-process NDE, as shown in Figure 4.5-1. Since a thermoplastic laminate is consolidated in situ, it is complete following the placement of each course of each layer. An effective in-process NDE technique used while placing each layer could

- Verify the course quality while the laminate was being fabricated, and

- Identify courses needing rework prior to processing the next course, the next layer, or to removing the laminate from the tool.

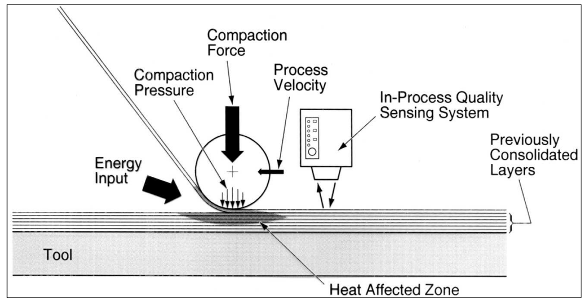

Figure 4.5-1 An effective in-process quality sensing system could be used to signal rework, to verify course quality, or in a process control system.

Since thermoplastics are remeltable, any troublesome course could be readily reprocessed or re-compacted prior to placing the next layer. In addition, the in-process NDE technique could continue to elucidate any potential problem area until it was adequately dealt with using the heated deposition head. A fully realized system could promote two additional benefits:

- Enable laminate quality-based process feedback control to regulate the polymer process and machine controls so as to minimize or eliminate delaminations and voids in the laminate, and
- Over time, as experience is gained with the head and process, promote a reduction in required in-process and post-process nondestructive evaluation and rework.

Three routes are suggested below as R&D areas ripe for development [21].

The first technique is to use "lock-in" optical thermography as shown in Figure 4.5-2. While traditional thermography is governed by laminate front surface emissivity, a lock-in technique differs. An Agema 900 thermal camera with a lock-in thermography option is used to detect the thermal radiation response following a sinusoidal thermal oscillation. Sub surface flaws like delaminations dominate the phase angle image of the lock-in thermography. The thermal waves can enable depth profiling by varying the modulation frequency.

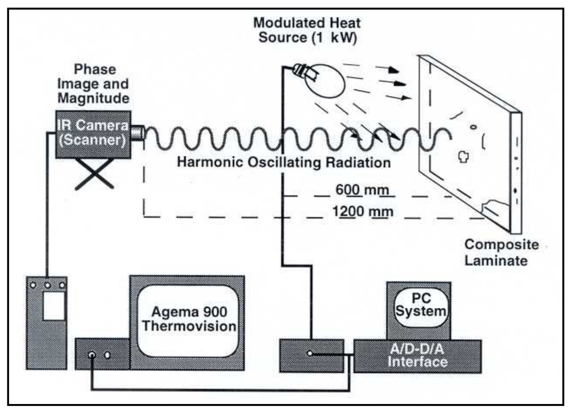

Figure 4.5-2 Agema Lock-in optical thermography system for in-process NDE

Figure 4.5-3 shows a comparison of two inspections. On the left is a traditional ultrasonic C-scan inspection of an IM-7/Avimid® K-3B tow-placed laminate. On the right is the thermographic inspection. This investigation shows that thermography is capable of elucidating delaminations with similar sensitivity to ultrasonic scans. The added advantages of thermography are (1) images are generated in real time, and (2) scans are completed without requiring direct surface contact.

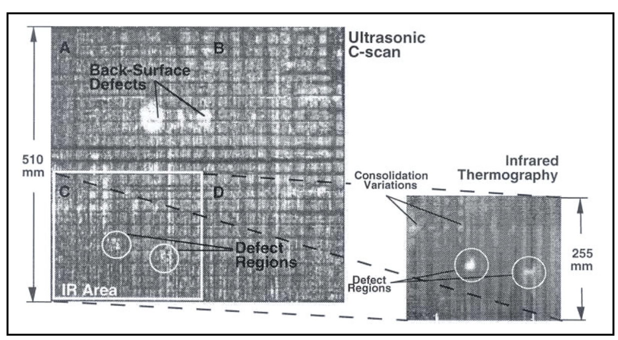

Figure 4.5-3 Thermography is capable of detecting delaminations in a thermoplastic laminate (right), similar to a C-scan (left)

The second method is to employ rolling contact transducers that introduce and receive ultrasonic waves in the composite as shown in Figure 4.5-4. While the propagation velocity of longitudinal and transverse stress waves is dependent upon the elastic modulus, material density, and Poisson's ratio, these waves are also influenced by voids. Comparison of void content with sound wave velocity measurements shows promising correlation, whereby propagation velocity drops linearly with void content increases [21].

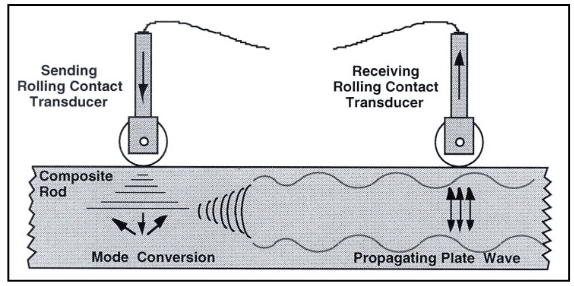

Figure 4.5-4 Rolling contact for void detection

The third method uses laser ultrasonics to inspect for delaminations. Generating and detecting Nd:YAG lasers were employed in a through-transmission mode with a confocal Fabry-Perot interferometer detection system to inspect for delaminations, as shown in Figure 4.5-5. Figure 4.5-6 shows a comparison between a conventional immersion-based ultrasonic C-scan and the laser-based ultrasonic C-scan. The sensitivity of the laser-based system would have to be significantly improved, and the system would have to be developed to run in pulse-echo mode to be suitable for the automated tape and tow placement lamination system. Still, the ability to detect consolidation variations similar to the ultrasonic C-scan shows that laser ultrasonics is a promising R&D technique.

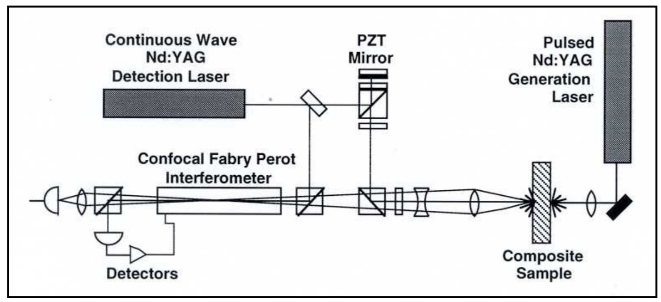

Figure 4.5-5 A Nd:YAG laser-based measurement system to detect laminate quality

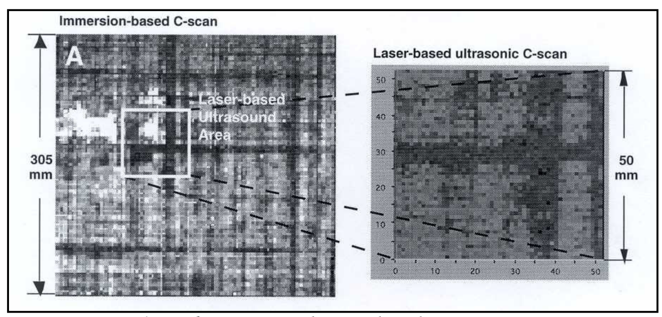

Figure 4.5-6 Laser based ultrasonic C-scans required development, but is capable of indicating laminate quality to some degree.

5.0 THERMOPLASTIC COMPOSITE TAPES AND TOWS

At least two important materials issues exist for thermoplastic ATP:

1. *Placement-grade* tows and tape are required to achieve full mechanical properties.
2. Lower cost thermoplastic tows and tapes are required to gain process adoptions.

5.1 Placement-grade Composite Tows and Tape - The need for *placement-grade* materials for thermoplastic tape and tow placement cannot be overstated, as processability, laminate quality, and ultimately, laminate mechanical properties depend directly upon material quality. Cytec Engineered Materials APC-2 composite tape, by far the most proven aerospace thermoplastic composite, was developed for autoclave processing. Additional developments are required on APC-2 or any other material supplier's tapes to be successfully used for ATP. Figure 5.1 shows an APC-2 tape photomicrograph. The cross-section's microstructure varies significantly from point to point. It reveals several large and many smaller voids, dramatic thickness variation, uneven fiber/resin distribution, pockets of high fiber volume fraction or resin weight fraction, and a resin-rich bottom surface.

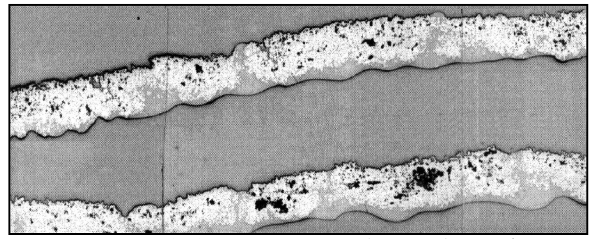

Figure 5.1-1 Two APC-2/AS-4 carbon thermoplastic tape photomicrographs.

APC-2 tapes are successfully utilized for autoclave processing because the gradual temperature and pressure ramp rates combined with extended autoclave processing times allow for void removal, macroscopic resin flow, and polymer inter-diffusion through the fiber network. APC-2 tapes are also employed for thermoplastic in situ head and process development and laminate demonstration, but the material requirements for in situ placement are more demanding than those for autoclave processing. Figure 2.2 confirms that only a scant 10 seconds are available for polymer flow during placement. Therefore tape dimensional tolerances and microstructure must be closer to that desired when the material is consolidated in the final part:

- Dimensional Variation - Tape width variation is preserved when placed because of exceptional gantry or fiber placement machine accuracy. Tape thickness variation prevents uniform head compaction, as shown in Figure 5.1-2, and even worse, manifests interlaminar voids in the final laminate from adjacent tape surface valleys. Interlaminar voids are very difficult to eradicate because filling them requires lateral flow of the highly viscous resin/fiber mixture, not just lateral resin flow.

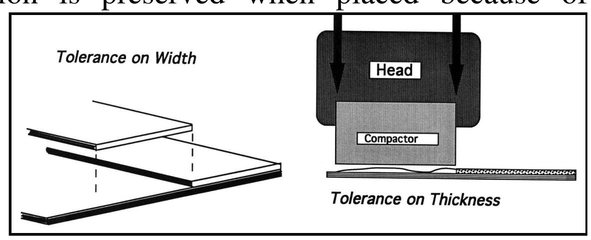

Figure 5.1-2 The head cannot uniformly compact tape with variable thickness, and thickness variation causes interply voids. Width variation is replicated in the tape or tow course by the placement head.

- Intralaminar void content - Excessive tape void content is preserved as intralaminar voids in the final laminate. Void removal from the thermoplastic polymer process is limited because of (1) short processing times, and (2) the very compactor used for consolidation acts as a boundary. In autoclave processing, the laminate is enclosed with a vacuum bag, but a bleeder ply beneath the bag fosters D'Arcy flow through the laminate. This mechanism for void removal is absent with thermoplastic in situ processing since compactors are solid and occupy space directly above process spot. The main void reduction mechanism for in situ placement is void compression.
- Uneven fiber/resin distribution - results in resin-starved regions that are less capable of transferring inter- and intra-laminar shear forces, and fiber-starved regions that do not carry in–plane loads. A more uniform fiber resin distribution like that shown in Figure 5.1-3 is desired, with nearly ideal tape cross-sections.
- A resin rich surface is lacking in Figure 5.1-3, but is excessive and non-uniform in Figure 5.1-1. We

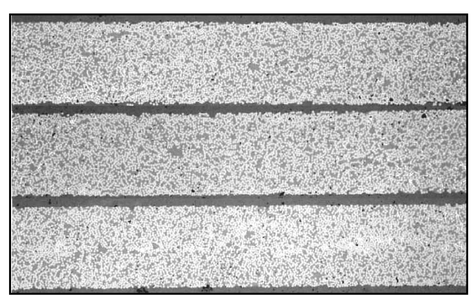

Figure 5.1-3 Tape with no thickness variation, few voids, and uniform fiber/resin distribution. The tape also lacks a resin-rich surface.

propose that a small but closely controlled (one fiber diameter) resin rich surface is desired for quick and effective interply welding.

Accudyne has developed a thermoplastic composite material specification with dozens of attributes; the most important of those attributes [17] are shown in Table 5.1.

Table 5.1 Critical specifications for placement-grade *composite tows and tapes*

Attribute	***Value***
Thickness variation	Within 6% including the ends
Tow width	6.35 mm, +0.00 mm, – 0.10 mm
Tape width	75 mm or 150 mm, +0.00 mm, – 0.10 mm
Resin weight fraction	35% ± 1%
Void content	Less than 1%
Fiber resin distribution	Uniform throughout thickness except for surface
Surface resin content	Pure resin at surface equivalent to one fiber diameter

5.2 Lower cost thermoplastic material forms – Cytec announced the development on an alternative lower cost PEKK material [22], but not yet as *placement grade* tape or tow. With this PEKK grade an advantage over PEEK would be lower processing temperature. A fundamental limitation with PEKK is crystalline kinetics too slow for in situ ATP. If full crystallinity, required for full mechanical properties could be achieved with PEKK matrix composites, they could perhaps be commercialized at lower cost than APC-2 composites Researchers are trying to speed the PEKK crystallinity development rate and amount by the compounding of POSS nanoparticle or Aerosil® nanosilicas [23,24] with some success. Cytec may also achieve a faster crystallizing PEKK via chemistry change and may be commercialized without using additives.

6.0 LAMINATE EVALUATION

Process models (Section 3.0) indicate how process heating and compaction affect the temperature and pressure field in the process spot and, therefore, the laminate microstructure Extended microstructural/macrostructural models coupled to the process models are required to assist in bridging the gap in mechanical properties to those properties exhibited by autoclaved laminates. Laminate models would need to allow for explicit description of in-laminate material defects and features like intraply voids, interply voids, resin rich and resin-starved areas, layer waviness, and ply nesting. Important questions to be addressed by the models are:

- What compression, OHC, in-plane shear strength (IPSS), and other properties would the models predict? What process parameters are required to achieve autoclave level properties?
- What is impact of the actual fiber/matrix interface adhesion of an incoming tape or in a final placed laminate on mechanical properties?
- What residual stresses are induced via the ATP process, and how do they affect the ultimate mechanical properties and laminate curvature that is achieved from in situ ATP?
- What is the effect of in-plane fiber marcelling in the laminate on mechanical properties?
- Would a laminate with mechanical properties that are 90% of the properties generated from autoclaved laminates confer acceptable durability to cyclic loading?
- APC-2/AS-4 composite cylinders have been fabricated from a filament winding/tape laying process that uses deposition heads and heat sources closely related to thermoplastic ATP.

Why do these cylinders produce full compression strength and shear strength properties following in situ consolidation [25] when ATP does not?

7.0 INDUSTRIALIZATION ISSUES

A number of industrialization issues exist to transition the thermoplastic process and equipment to mainstream production of aerospace wing and fuselage skins. They include:

- Reliability and Maintainability - the deposition head must be capable of operating multiple shifts per day for most of the days of the year. The head should be as well packaged as today's thermoset automated fiber placement heads, offering ease of maintenance and repair.
- Maximum Transverse Force - the maximum transverse force imparted to the laminate is higher for a thermoplastic deposition head than for a thermoset head, especially as tape width increases from 75 mm to 300 mm. This places imposing stiffness requirements on gantry motion mechanisms, and extreme rigidity requirements for automated fiber placement machines with respect to the maximum compaction force that can be applied to the laminate.
- Head weight - a gantry motion mechanism can carry a deposition head of substantial weight but an automated fiber placement machine cannot. Deposition head weight should be minimized to allow the adoption of the head and process to the widest variety of applications.
- Cost - comparing the cost of a thermoplastic head and process with a thermoset head and process should be kept in mind. The thermoplastic head will be more costly because of the onboard polymer process. However, thermoplastic in situ consolidation avoids the need for costly autoclave while fabricating large composite structure. If the thermoplastic head cost is too far in excess of the thermoset head, this will prevent adoption at aerospace OEMs.

8.0 CONCLUSIONS

Thermoplastic ATP is nearly ready for out-of-autoclave fabrication of wing and fuselage skins. Complex mechanical properties such as compression strength and modulus, open hole compression strength, in plane shear strength, and compression strength after impact are achieving properties that are nearly the same as those measured from autoclave consolidated laminates. Developments areas required to bridge the remaining gaps are (1) mechanical properties, (2) process and equipment performance, (3) equipment reliability, and (4) equipment cost. The most worthwhile development would be *placement grade* thermoplastic tows and tapes with tight control of thickness and width variation, low intra and inter ply void content, uniform fiber/resin distribution, and a thin but finite resin rich surface. Achieving *placement grade* material is the most important technology bridge because its success will be carried through all thermoplastic composite developments.

The thermoplastic deposition heads need more highly tuned heat sources and more articulate conformable compactors. A fundamental discovery would be the demonstration of in-process quality sensors that could reveal microstructural course defects while they were still accessible for reprocessing. Together with in-process NDE, thermoplastic re-melting would allow laminate defects to be repaired as an integral step in completing the laminate.

With the enhanced material and deposition head, process and laminate demonstrations would continue to strive for mechanical properties equivalent to that produced by autoclave processing.

Analytical modeling could significantly improve guidance. Micro- and macro-mechanics models that elucidate the impact of fine microstructural details on mechanical properties are needed. Particularly important are the impact of intra-ply voids, inter-ply voids, layer waviness, fiber rich and resin rich pockets in the laminate, ply nesting, and layer waviness on inadequate mechanical properties. This laminate microstructure is the result of the process. Therefore process models that detail the impact of process heating on process spot temperature, the evolution of intimate contact and reptation healing, the cooperative effects of intimate contact and healing on the degree of bonding, the degree of laminate consolidation, process-induced residual stresses, the degree of laminate degradation that occurs following heating to excessive temperatures, and the mechanism of void evolution and compression are crucial to understanding routes to achieve the same properties as achieved by thermoplastic lamination and autoclave processing.

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