STRINGER-, HONEYCOMB CORE-, AND TIGR -STIFFENED SKINS, AND RING-STIFFENED CYLINDERS FABRICATED FROM AUTOMATED THERMOPLASTIC FIBER PLACEMENT AND FILAMENT WINDING

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ABSTRACT

Two in situ thermoplastic processes, automated fiber placement and filament winding/tape-laying have been developed and deployed to fabricate carbon-fiber thermoplastic stiffened parts. This has been supported by the development of a number of polyimide and polyetherketone placement-grade tows (sometimes called ribbons) and tapes. Both processes integrate deposition with a polymer process that combines preheating, generation of layer-to-layer intimate contact, interlayer bond development by reptation healing, consolidation/squeeze flow, and freezing/void compression in the laminate. The in situ filament winding process combines sequentially with tape laying to fabricate [0°/90°] and [0°/90°/±θ°] monocoque and ring-stiffened cylinders from polyetherketone composite material systems with outstanding property translation. Finished parts and systems have been commercialized, especially those loaded in external hydrostatic compression. The automated fiber placement process has been developed for flat skins with twelve 6.35mm (0.25-in) tow or one 76mm (3-in) tape placement capability. Both composites and coated metal foils can be placed. Many demonstration parts have been fabricated including flat laminates with and without padups, stringer-stiffened skins, honeycomb-stiffened skins, and TiGr (interleaved Titanium and graphite/thermoplastic layers) skins alone or sandwiching Titanium-honeycomb core. Parts were fabricated with polyimide, cross-linking polyimide, and polyetherketone placement-grade tows and tapes. In general, 85% to 100% property translation is available with in situ processing, and 100% if post-autoclaved cured, for example to advance a cross-linking polyimide resin (1).

KEY WORDS: Automated Fiber Placement, Automated Tape Placement, Automated Tape Laying, Filament winding, In Situ Consolidation, Polyetherketones, Polyimides, PEEK, PEKK, Avimid®, PETI-5, Skin-stringer, Honeycomb, TiGr

1. INTRODUCTION

From the middle 1980's, thermoplastics were touted as the next great family of composite materials due to several advantageous resin properties and the claim of easy processibility. The fabrication claim has proven elusive, however, and most high-performance composite parts are still thermosets consolidated in the autoclave. In that context, a pair of realistic in situ processes was developed: automated fiber placement (ATP), and filament winding combined with tape laying. This paper will cover their process concept, how that concept was manifested in equipment, the materials, and the process capability in terms of cylindrical and flat stiffened parts that can be fabricated.

2. THERMOPLASTIC IN SITU CONSOLIDATION PROCESS CONCEPT

2.1 In Situ Process Fundamentals

The thermoplastic in situ consolidation process first applies energy to heat the incoming tow or tape and the already deposited substrate to its resin melt temperature. A normal compaction force is applied to the molten heat-affected zone and the layers are fused together. The laminate then re-freezes. An in-process quality sensing system, if achieved, could view the re-frozen area to measure some parameter related to the defects in the layer just deposited.

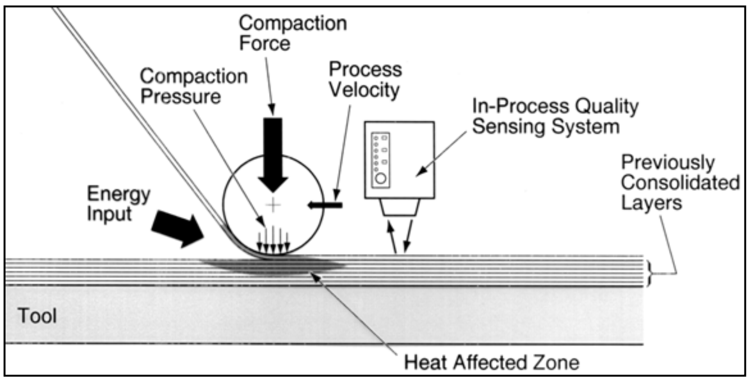


Figure 2.1 The in situ consolidation process applies heat and pressure to weld the layers. A conceptual in-process sensing system monitors layer quality.

2.2 Heat Transfer Induced Temperature Field

The coupling of the energy input determines the temperature field in the process spot. At the maximum process speed, a z-direction temperature gradient exists where the highest temperature is at the nip inlet top surface. For best quality, it must be no higher than the resin degradation temperature, T_{deg}. Because of the gradient, the lower surface just reaches T_{melt}. The equipment transfers enough heat to the composite so that the upper surface of the deposited layer is just cooled to T_{debulk}, the temperature were the laminate spontaneously debulks or unconsolidates. T_{final} depends on process dynamics.

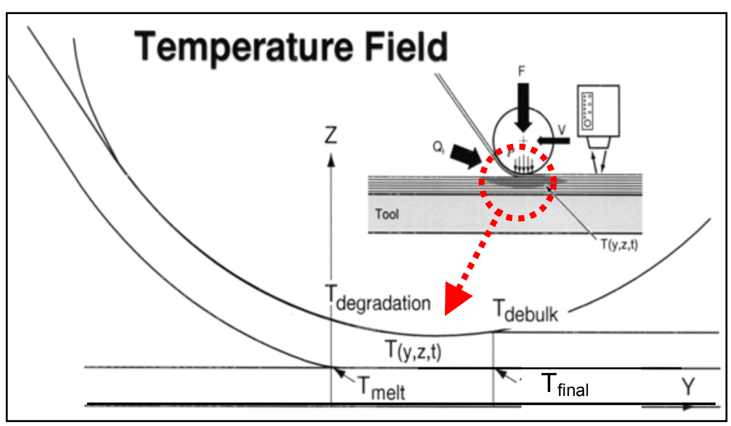


Figure 2.2 At maximum placement speed, the incoming composite layer lower interface reaches T_{melt} without overheating the resin at the upper surface.

2.3 Evolution of Intimate Contact and Healing (2)

The tow or tape mating surfaces are initially rough, but their surface asperities disappear as they heat, melt, and deform during contact. As intimate contact evolves, surface healing can originate and progress. Four stages of intimate contact and healing are shown depicting the development of an interface weld. Healing occurs by migration of polymer chains at any location of intimate contact. Elevated temperature, not pressure, drives healing, which is predicted to occur whereever $T>T_g$, even after the compaction roller. High temperature, up to the degradation temperature, drives quicker healing. Thus, if at t_1 only short chains begin reptating across, longer chains have extended by t_2 at the initial areas of intimate contact and short chains start across at the fresh areas. After t_2, the normal pressure is removed but more chains move across the interface until the temperature reaches T_g. The "degree-of-bonding," integrates intimate contact and healing together, coupling the incremental additional area coming into intimate contact and the degree of healing.

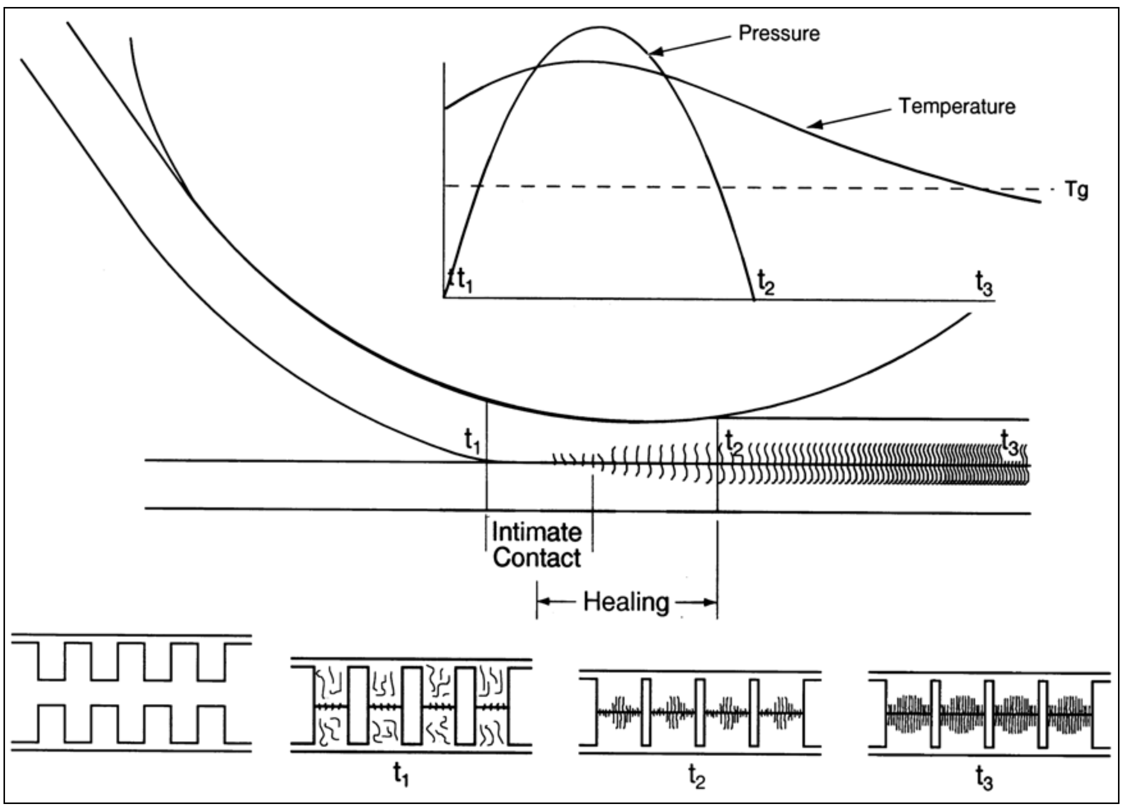


Figure 2.3 Layer-by-layer polymer healing occurs whenever surface intimate contact is established and the temperature is maintained

2.4 Consolidation Squeeze Flow/Void Reduction (2)

Squeeze flow describes the transverse flow of the fiber/resin/voids mixture as a function of the pressure distribution across the tow to yield the reduction in height and the increase in width. This is accompanied by a reduction in void content. While the major mechanism of interply void reduction is increased intimate contact, the major mechanism of intraply void reduction is gas compression under the pressure roller, although coalescing, migration, and bubbling may also occur.

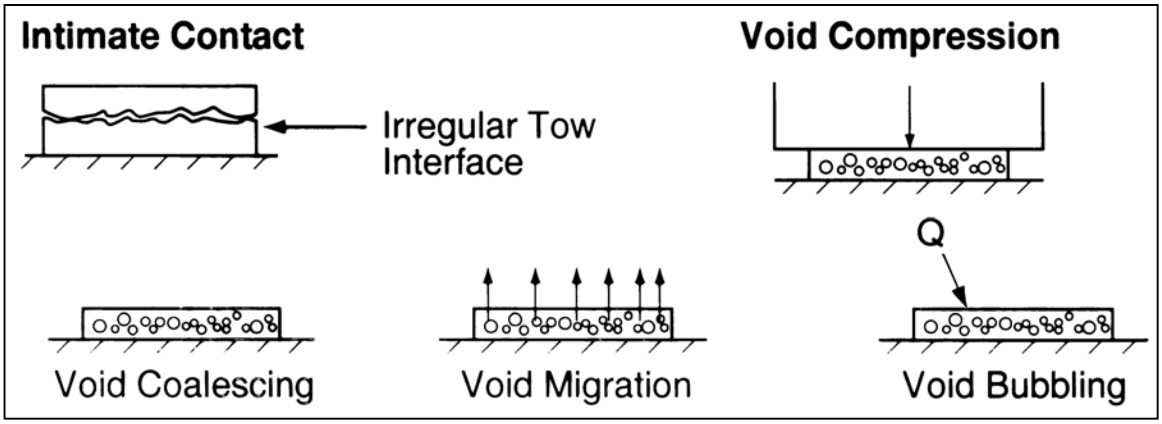


Figure 2.4 Mechanisms of void elimination in thermoplastic placement processes

3. THERMOPLASTIC IN SITU PROCESS

Figure 3 integrates the equipment developed with the process concept detailed above. A feeder provides accurate deployment of twelve 6mm (0.25-in) tows or one 75mm (3-in) tape. A nip roller provides for accurate feeding while the clamp and cut capability allows for tow and tape cuts with a 100mm (4-in) material free-length. The head is capable of starting tows and tapes on-part on-the-fly to a within 0.75mm (0.030-in).

Two torches direct heated air to the material. The first heats the bare tool or previously laid composite, while the second trim heats the substrate and material feedstock. Two rollers alternately heat and chill the composite. The first roller establishes the initial intimate contact between the lower surface of the incoming composite and the upper surface of the substrate, and initiates healing in those locations where intimate contact has been achieved. Consolidation also begins under the heater roller. A heated shoe maintains the temperature long enough to foster further intimate contact and complete healing of the longest polymer chains to develop interlayer strength. The second roller consolidates and chills the material, re-freezing it in place and compressing the voids. A chilled shoe extends the freezing process. A photograph of this head is in Section 6.

The filament winding head is similar, but lacks a material feeder, as the rotating mandrel and the cross-feed carriage provide for material deposition during cylindrical winding of 90° and ±θ° layers. A dedicated tape laying head is integrated with the filament-winding machine on its own 0° axis to provide for the in situ deposition and consolidation of 0° plies so that [0°/90°/±θ°] cylinders can be fabricated.

4. THERMOPLASTIC TOWS AND TAPES

Cytec Engineered Materials has developed placement-grade tows and tapes. Figure 4 shows five cross-sections of high-quality tape in one photomicrograph mount. To be "placement-grade," the material must be of uniform thickness, and have a width variation under 0.15mm (0.006-in), and few or no voids. Tows and tapes have been fabricated from a variety of matrix resin systems. Tapes made from polyetherketones – PEEK and

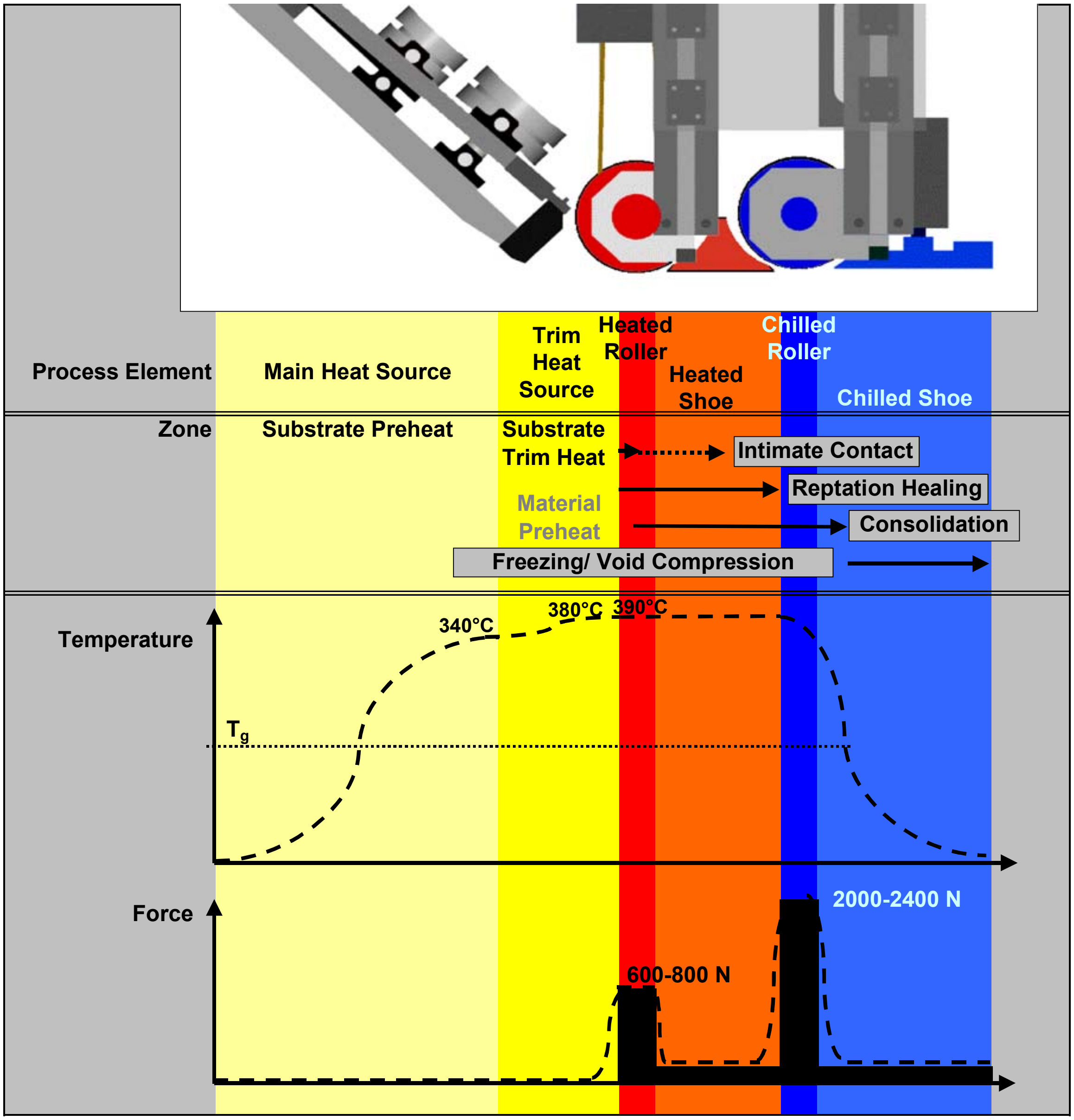


Figure 3 Thermoplastic fiber placement process zones and process parameters

PEKK – are available in slit tape form from Cytec's Anaheim facility and in slit tape and ribbon (boardy tow, never slit) form from Cytec's Havre de Grace facility. Similarly, thermoplastic polyimides - PIXA, PIXA-M, PIXA-M1, and Avimid® K3B are available from both sites. Lightly cross-linking thermoplastic polyimides, Avimid® R1-16, and PETI-5, are only available from the Cytec Havre de Grace facility.

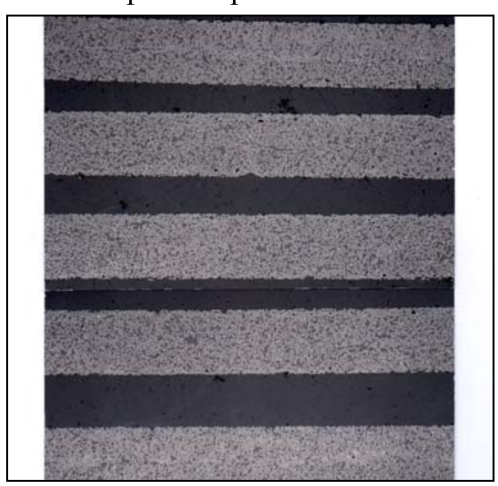


Figure 4 Photomicrographs of five placement-grade tape cross-sections

5. THERMOPLASTIC FILAMENT WOUND/TAPE LAYED PARTS

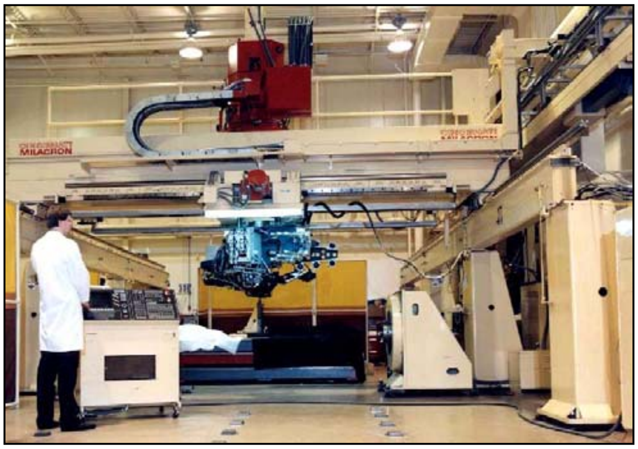
Thermoplastic filament winding/tape laying has achieved autoclave level properties in thin and thick right circular cylinders as shown in Figure 5.1. One AS-4/PEEK 61mm (24-in) OD, 16mm (0.629-in) wall thickness ring-stiffened $[90°_{2.27}/0°]_n$ cylinder achieved 37.9MPa (5500psi), one of the highest performing composite pressure hull scale models ever [3]. The largest cylinders are 152cm (60-in) in diameter. The technology was used to fabricate IM-7/PEEK cylinders for 53mm (21-in) diameter underwater pressure hulls as shown in Figure 5.2. The cylinders have thick walls with $[90°/0°]_n$ and $[90°_2/0°]_n$ laminate stacking sequences. These pressure hulls were built to a high laminate quality, with excellent consolidation and low circumferential layer waviness. Compression properties exceeded that available from thermoset autoclave processing.

Figure 5.1 Carbon and glass thermoplastic filament-wound cylinders up to 152cm

Figure 5.2 Filament wound/tape layed IM-7/PEEK underwater vehicle hull sections.

6. THERMOPLASTIC FIBER PLACEMENT EQUIPMENT AND LAMINATES

Figure 6.1 shows the Cytec Engineered Materials in situ consolidation head mounted to a Cincinnati Machine gantry tape layer. This deposition head was used to make hundreds of open-section flat laminates from carbon-fiber/PEEK, PEKK, PIXA, PIXA-M, PIXA-M1, Avimid® K3B, Avimid® R1-16, and PETI-5 tows or tape. It uses twelve 6.35mm (0.25-in) wide tows or one 76mm (3-in) tape, either way forming a 76mm (3-in) wide course. Typical laminates were 60cm x 60cm (2ft x 2ft) or 90cm x 90cm (3ft x 3ft) and included [45°/0°/-45°/90°], [0°/90°], and [0°] layups, with thicknesses up to 32 layers. The laminates were warpage free. The head can start and stop courses on-part to allow padups and ply details. The largest laminate produced was a tape placed 240cm x 90cm (93.2in x 34.5in) panel with tow-placed quasi-isotropic padups.



When equipped with a tow feeder, the head is a "TCA" or Tow Cut and Add head and additionally allows variable deposition of tows for steering or placement on contoured geometry. The tow feeder uses a 12-position creel, and has a capacity of 54kg (120lb). The tow feeder can be replaced with the 76mm (3-in) tape feeder. Changeover from tow to tape mode takes about two hours.

Figure 6.1 Cytec Engineered Materials 12-tow in situ consolidation head on Cincinnati Machine gantry tape layer.

Figure 6.2 shows a close up of the deposition head placing tows. The head is also capable of depositing one 76.2mm (3-in) tape at speeds up to 5 mpm (20 fpm).

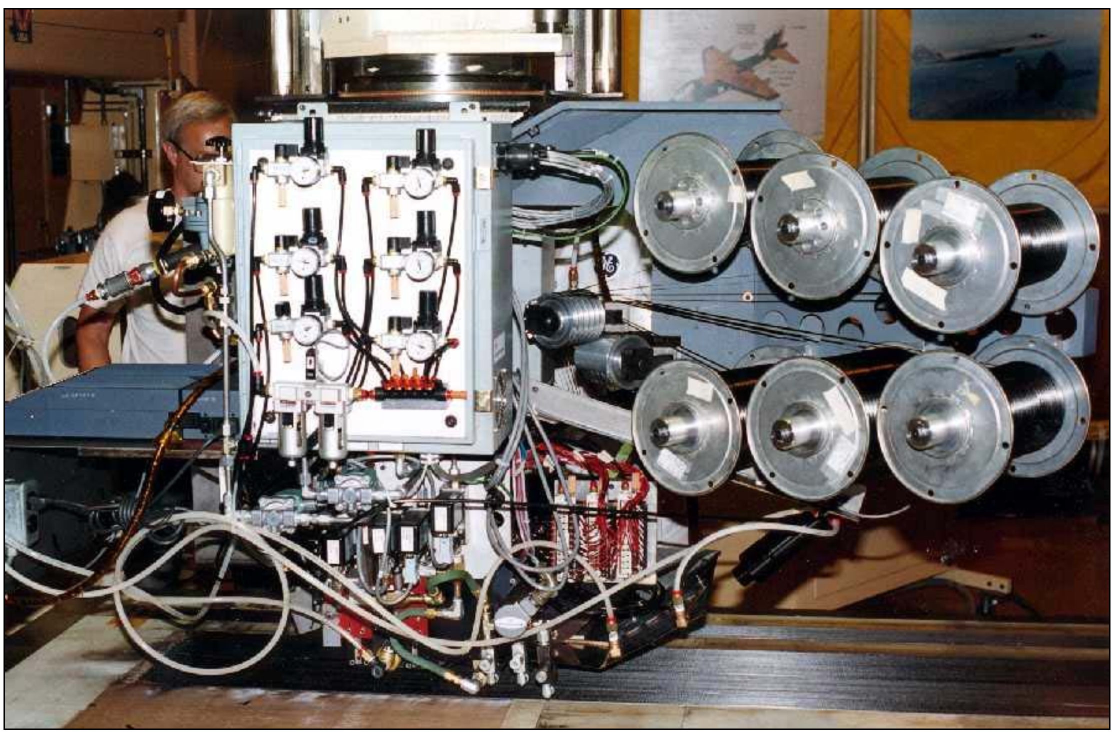


Figure 6.2 Deposition head in situ consolidating 12 thermoplastic tows.

Table 6.1 shows a property comparison for PEKK, PEEK, and PIXA laminates. Compression strength and modulus, open hole tension (OHT), and open hole compression (OHC) strengths and modulus were measured from tape and tow placed laminates. Laminates fabricated by in situ ATP, in situ ATP followed by autoclave cure, and hand-layup followed by autoclave cure are all included. Table 6.2 repeats the comparison for PIXA-M laminates made by in situ ATP, ATP/autoclave, and hand layup/autoclave cure. Finally, Table 6.3 shows a comparison of OHC strengths generated from solvent-free ("dry") laminates fabricated via in situ ATP plus a post autoclave cure, and wet IM-7/PETI-5 laminates fabricated by hand layup/autoclaving. PETI-5 is a cross-linking polyimide that requires an autoclave post cure to chain-extend the polymer.

	AS-4/PEKK ribbon			AS-4/PEEK tape			IM-6/PEKK tape			IM-7/PIXA tape		
	in situ	in situ AC	HLU AC	in situ	in situ AC	HLU AC	in situ	in situ AC	HLU AC	in situ	in situ AC	HLU AC
[Quasi] Compression												
Strength, MPa	462	501		441	427		496	586		447	531	
Modulus, GPa	43.4	46.9		47.6	49.0		56.5	57.2		53.1	58.6	
Open Hole Tension												
Strength, MPa	359	359	335	393	397	387	490	527		470	494	
Open Hole Compression												
Strength, MPa	255	337	325	276	341	327	296	338	317	272	296	319
Modulus, GPa	40.7	44.1		44.8	47.6							

HLU - Hand Layup AC = Autoclave consolidation

Table 6.1 Property comparisons for PEKK, PEEK, and PIXA laminates

Property		Units	In Situ ATP 76mm (3") Tape	ATP/Autoclave 76mm (3") Tape	ATP/Autoclave 76mm (3") Tape
OHC	RT	MPa (Ksi)	265 (38.5)	303 (43.9)	299 (43.4)
OHC	350°F dry	MPa (Ksi)	194 (28.1)	210 (30.4)	204 (29.6)
Quasi Comp. Strength	RT	MPa (Ksi)	471 (68.3)	618 (89.7)	not available
Quasi Comp. Modulus	RT	GPa (Msi)	51.7 (7.5)	55.8 (8.1)	53.1 (7.7)
CAI	RT	MPa (Ksi)	not available	390 (56.5)	388 (56.3)
OHT	RT	MPa (Ksi)	483 (70.1)	502 (72.8)	492 (71.4)
In-Plane Shear Modulus	RT	GPa (Msi)	not available	not available	5.6 (0.81)
CILS	RT	MPa (Ksi)	not available	83 (12.1)	97 (14.0)
Fiber Volume			58.6%	60.0%	61.5%

Table 6.2 Mechanical property summaries for IM-7/PIXA-M laminates

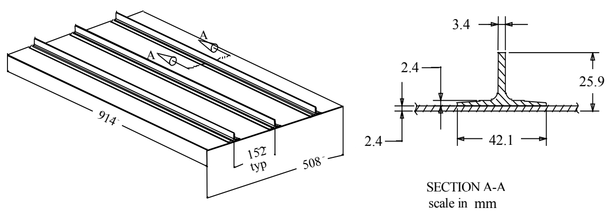
		Dry ATP	Wet Hand Layup
OHC MPa (Ksi)	RT	337(48.9)	326(47.4)
OHC MPa (Ksi)	177°C	234(34)	229(33.3)

Table 6.3 Open hole compression strength in IM-7/PETI-5 post-cured laminates

From the tables, the compression modulus for PEEK, PEKK and PIXA quasi-isotropic laminates is 91-99% of the equivalent modulus from post-autoclaved laminates, and the strength ratios range from 84-103%. The OHT strength is essentially the same for in situ laminates and in situ ATP/autoclaved laminates. The OHC strength, however, is 76-94% of the post-autoclave strength, averaging about 85%. For PIXA-M laminates, the OHC strength rises slightly to 88% of the strength value if the panel was autoclaved, and the OHT strength has almost full translation. The property values for dry and wet IM-7/PETI-5 are both post autoclave curing, and the values for dry ATP/autoclave slightly exceed the values for wet HLU/ autoclave.

7. STRINGER STIFFENED THERMOPLASTIC SKIN FABRICATION

A variety of structural panel concepts can be fabricated using thermoplastic in situ consolidation. One of those is to embed prefabricated thermoplastic stringers (or thermoset stringers coated with a thermoplastic film layer) into an IML tool and place over them, using the in situ consolidation process to produce a stringer-flange weld as an integral step in skin placement. Figure 7.1 shows a schematic of the tooling used for skin-stringer fabrication.



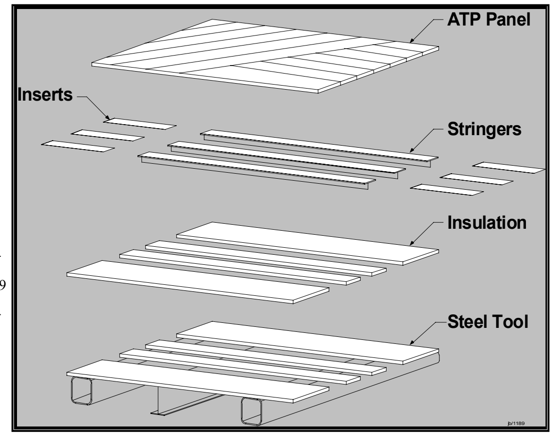


Figure 7.1 A steel tool covered with insulation accommodates prefabricated stringers, upon which a thermoplastic laminate can be placed.

Figure 7.2 shows an example of a first few courses being placed and in situ welded directly over three blade stringers along with the finished panel. The 51cm x 91cm (20-in x 36-in) skin has 18 plies in a [$\pm45/0_2/90/0_2/\pm45$]s configuration. Many IM-7/PEEK, PIXA-M, and PETI-5 panels have been made. PEEK or PIXA-M thermoplastic film matching the skin resin was co-cured to the blade surface for the skin to be placed on.

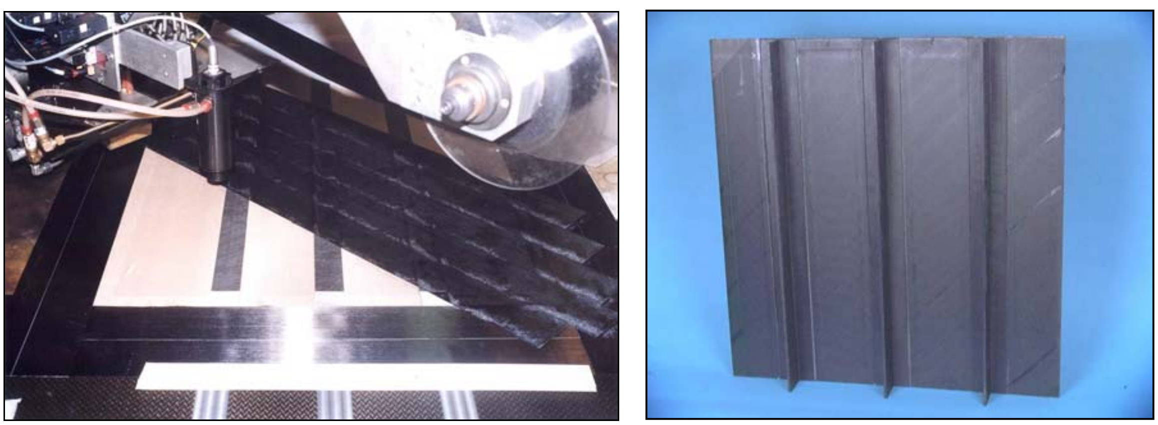


Figure 7.2 Placing the first few courses of a stringer-stiffened panel over embedded pre-cured thermoplastic stiffeners.

The IM-7/PEEK and IM-7/PIXA-M stringer-stiffened skins were fabricated in situ using a primary bonding process over IML tooling. A co-bonding process is also possible with OML tooling, and would yield the best aerodynamic surface. When IM-7/PETI-5 stringers and skins were fabricated and an autoclave cure was required to advance the resin, a co-bonding process using OML tooling was employed.

8. PMC/HONEYCOMB PANEL FABRICATION

Thermoplastic in situ consolidation was used to fabricate primary bonded and secondary bonded honeycomb panels. In primary bonding, facesheets were placed directly over core precoated with BRx-5 paste adhesive and FMx-5 film adhesive. Secondarily bonded facesheets were bonded with BRx-5 past adhesive under light autoclave pressure. Figure 8.1 shows the Cytec Engineered Materials in situ consolidation head placing a laminate directly over titanium core. Run on and run off tooling surrounds the core so it cannot be easily seen in the photograph.

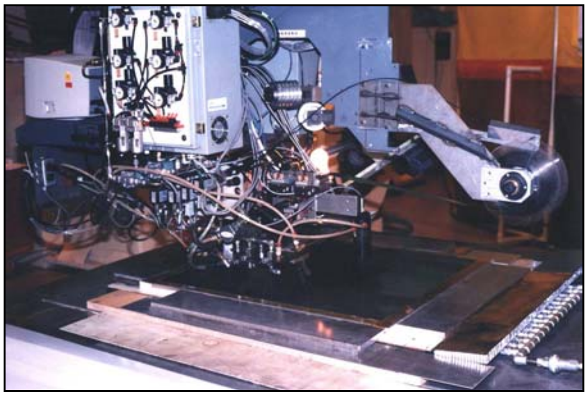


Figure 8.1 Primary bonding using thermoplastic in situ consolidation to place 76mm (3-in) tape on honeycomb core precoated with BRx-5 and FMx-5 adhesives.

Figure 8.2 shows two primary bonded thermoplastic honeycomb sandwich panels, one is situ processed, and the other post autoclave consolidated.

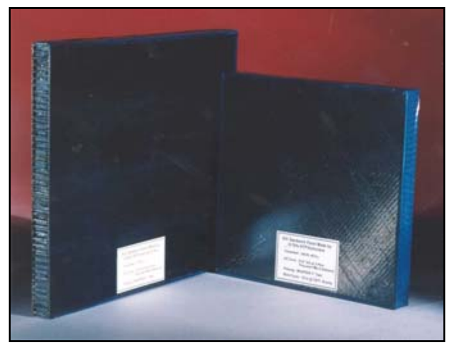


Figure 8.2 IM-6/PEEK honeycomb panels made via thermoplastic in situ consolidation, the second post-ATP autoclave cured

Figure 8.3 shows three photomicrographs comparing the placement quality achieved via thermoset primary bonded PMC honeycomb fabrication and thermoplastic fabrication both via primary bonding and secondary bonding. In the top photomicrograph the use of a wet thermoset material causes substantial cell draping and core cell pinching. In the second figure, thermoplastic in situ consolidation was used with primary-bonded honeycomb fabrication to dramatically lessen the amount of core cell drape. In the third photomicrograph secondary-bonded PMC/honeycomb fabrication almost completely eliminated core cell drape.

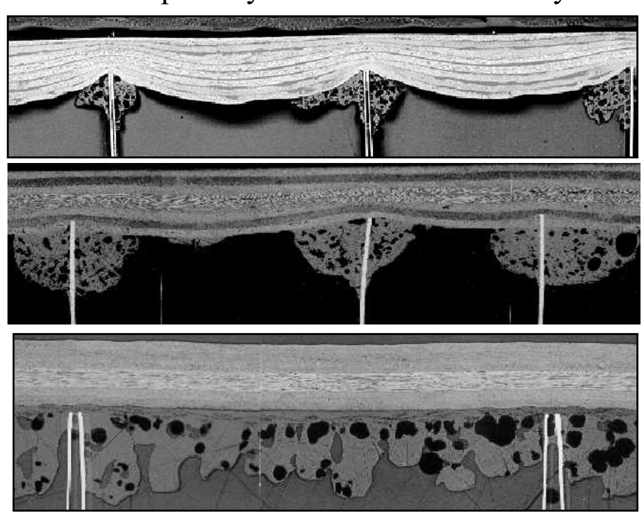


Figure 8.3 Three photomicrographs compare (top) thermoset fiber placement followed by autoclave cure, (middle) primary-bonded in situ consolidation on core, and (bottom) secondary-bonded honeycomb fabrication on core.

Table 8 shows excellent mechanical properties measured on the honeycomb-core stiffened ATP laminates. Almost all properties from primary and secondary bonded core stiffened laminates exceed that for traditional wet-thermoset processed co-cured panels. Of particular interest is the edgewise compression strength, which, at 421 to 486 MPa (61.0 to 70.5 ksi), far exceeds that from co-cured wet panels.

			Primary Bonded IM-7/PIXA-M	Secondary Bonded IM-7/PIXA-M	Co-cure Wet IM-7/PETI-5	Secondary Bonded dry IM-7/PETI-5
Flatwise tension		MPa	11.6	7.8	12.4	
Edgewise Compression		MPa	477	421	306	486
1-inch Notched Compression		MPa	179	187	161	
CAI	*24.8 N-m impact*	MPa	332			
CAI	*8.5 N-m impact*	MPa		347	332	

Table 8 Mechanical properties measured from honeycomb core stiffened panels

9. TIGR (TITANIUM-GRAPHITE) FABRICATION

Titanium-graphite laminate fabrication is considered for use on wing and fuselage skins in order to raise the specific strength and specific stiffness of laminates. Titanium and composite plies are alternatively interleaved to form a composite and metal laminate. In the case of thermoplastic fiber placement, 76mm (3-in) wide titanium foil was pre-coated with PEEK polymer film and cut into 91cm (36-in) long strips. These strips were then placed right through the deposition head used for placing 76mm (3-in) PEEK tape. A number of TiGr laminates were fabricated in this manner as shown in Figure 9.1.

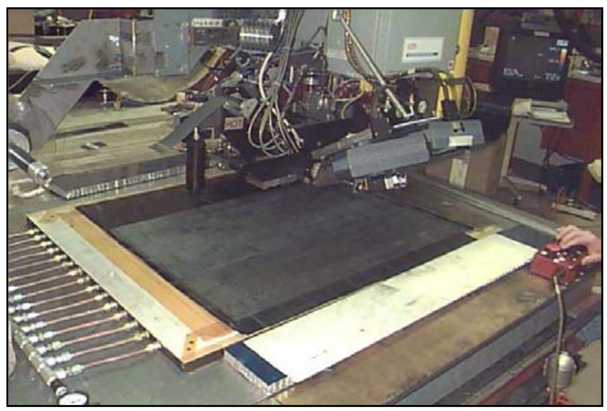


Figure 9.1 Cytec Engineered Materials 76mm (3-in) deposition head used to place Ti foils and IM-6/PEEK tape into a TiGr laminate with in situ consolidation

Figure 9.2 shows two TiGr honeycomb laminates. The laminates were made by placing the bottom TiGr laminate, adding core and then placing the top TiGr laminate to complete the panel. One of the laminates was post-autoclave consolidated and tested. Its photomicrograph is shown in Figure 9.3.

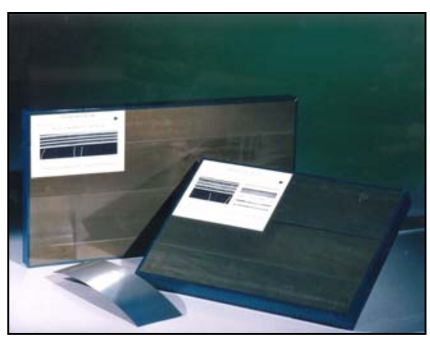
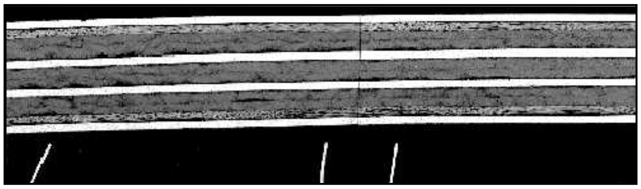


Figure 9.2 TiGr honeycomb laminates made by interleaving titanium and IM-6/PEEK plies using the primary bonded honeycomb process.

A portion of the final autoclaved laminate was tested for longitudinal and transverse un-notched compression and the results are in Table 9. These results compare favorably with strengths measured from hand laid-up TiGr honeycomb sandwich panels that were



61cm (24-in) wide foil and had no seams. As would be expected, transverse values for the ATP laminate were lower due to the presence of seams in the foil.

Figure 9.3 Photomicrograph of TiGr in situ ATP/autoclaved panel

	Longitudinal EWC, MPa (KSI)	Longitudinal Strain (μstrain)	Transverse EWC, MPa (KSI)	Transverse Strain (μstrain)
Laminate 97-6-3-1	896 (130)	8700	427 (62)	6500

Table 9 Un-notched Compression of TiGr ATP Autoclave 1° Bond Laminate

10. SUMMARY

A thermoplastic in situ fabrication filament winding/tape laying process has been demonstrated via the fabrication of many ring-stiffened thermoplastic cylinders from a variety of resin systems. Cylindrical laminate properties rival or exceed those from thermoset autoclaved cylinders, especially for thick sections. The process is well-suited for cylinders loaded in external hydrostatic compression.

Thermoplastic fiber placement has been used to demonstrate primary-bonded, co-bonded, and secondary-bonded skin-stringer fabrication, primary-bonded and secondary-bonded PMC honeycomb fabrication, and primary-bonded TiGr honeycomb fabrication, all in flat structure. Laminates have been made from carbon-fiber/PEEK, PEKK, PIXA, PIXA-M, PIXA-M1, Avimid® K3B, Avimid® R1-16, and PETI-5 tows or tape, and are warpage-free. Honeycomb panels fabricated with in situ ATP have negligible facesheet drape. Some mechanical properties from honeycomb and TiGr thermoplastic ATP panels fabricated in this study yielded superior performance over thermoset counterparts.

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