THE FABRICATION AND PERFORMANCE OF FLAT SKIN STRINGER AND HONEYCOMB PANELS MANUFACTURED BY A THERMOPLASTIC AUTOMATED TAPE PLACEMENT PROCESS

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ABSTRACT
An automated thermoplastic tape placement head and process have been demonstrated via successful fabrication of flat laminates and skin stringer and honeycomb built-up structure. The process uses a third-generation heated head on a modified gantry tape placement machine. Tape material included AS-4/PEKK, AS-4/PEEK, IM-6/PEEK, IM-7/PEEK, IM-7/PIXA, IM-7/PIXA-M, and IM-7/PETI-5. Tooling, processes, and property data are described that demonstrate the potential benefits of thermoplastic automated tape placement (ATP).

1. BACKGROUND
Thermoplastics are generally considered over thermosets to take advantage of one or both of the following: (1) a special resin property such as thermal stability or surface toughness and (2) cost saving during processing. For example, the NASA High Speed Civil Transport (HSCT) Program was especially interested in the thermal stability, toughness, and fabrication costs of thermoplastics, while thermoplastic surface toughness was paramount for the inside of missile launch barrels. Cost savings are commonly linked to a sizable fabrication cost reduction promised if a large panel can be fabricated out-of-autoclave [1,2] as with HSCT wings and fuselage panels or Reusable Launch Vehicle liquid hydrogen or oxygen tanks. Also, low cost aircraft structure fabrication has been recently reported successfully employing thermoplastic welding [3]. The desire for out-of-autoclave fabrication of high performance composites continues to fuel TP-ATP development.

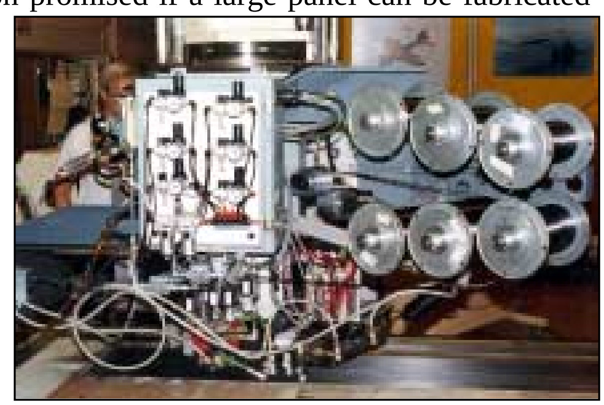


Figure 1 In-situ deposition head consolidating 12 IM-7/PEEK tows on a laminate up to 5mpm (20fpm)

In the 1990's, fiber and tape placement accelerated in replacing hand lay-up as the preferred route to prepare thermoset parts for autoclave consolidation. To compete with this thermoset technology, a working thermoplastic process and heated deposition head was required that could fabricate aircraft-quality composite structure from dry, boardy tape or tow and be operable on current ATP machines. Cytec Engineered Materials and Cincinnati Machine teamed with Boeing (BCAC) to develop a working thermoplastic placement head, shown in Figure 1, and associated processes. Accudyne Systems was the equipment subcontractor. The head, described previously [2], operated on a Cincinnati Machine gantry tape placement machine modified to execute in-situ commands. NASA Langley Research Center contractually assigned the team to demonstrate the process by fabricating flat laminates and skin stringer and honeycomb structures that would meet aircraft thickness, weight, and mechanical property specifications. PEEK, PIXA, PIXA-M, and PETI-5 placement grade tows and tapes were developed and laminates fabricated. This paper explains misconceptions about heated steel tools, describes optimum tooling required for TP-ATP, describes skin/stringer and honeycomb thermoplastic processes, and provides data to show the panels equaled, nearly equaled, or exceeded requirements.

2. FLAT LAMINATES

In addition to the deposition head, a working thermoplastic ATP process requires tooling that provides for effective first ply contact and assists in controlling laminate warpage. Steel tools work poorly as they heat sink the first ply temperature and that of subsequent plies until the lay-up is built-up. The head speed must slow for these layers, complicating heat control. Heating a steel tool accomplishes little, since even a 100°C tool is chilly compared to the 400°C PEEK placement temperature. An insulated tool is an improvement since it retains the heat in the composite laminate. Optimal tooling minimizes the job of the heat controller and thus is constructed from a material having a thermal conductivity and heat capacity equaling that of the plies being placed. Avimid® N is perhaps the ideal material; it has the desired thermal properties and heat resistance.

In this program, two vacuum tools were successfully used: an Avimid ® N tool and a G-7 fiberglass tool supported by steel. Both were covered with porous Armalon®. Start and stop strips comprised of the tape to be placed were added in the run-on and run-off areas, as shown in Figure 2.1. This tooling was very effective in reducing panel curvature, with the best IM-6/PEEK panels exceeding a 760cm (300in) radius and the best IM-7/PIXA laminates exceeding a 1300cm (500in) radius, far better than the 500cm (200in) minimum requirement.

Figure 2.1 Skin stringer tool ready for ATP processing. Porous Armalon® covers the Avimid® N tooling. Start/stop strips are used.

Laminate quality was critically dependent on tape quality. In one year, 32 laminates were tape placed, as shown in Figure 2.2. Laminate quality, tracked by C-scan attenuation, depended more on the improving tape quality (developed by the then competing material suppliers) than anything else. This highlights the importance of using placement grade tow or tape with uniform width and thickness, few/no voids, and no volatiles [2]. With placement-grade tapes, quality laminates resulted. For example, an excellent IM-7/PIXA laminate photomicrograph in Figure 2.3 shows well-consolidated resin interfaces, almost no voids, a uniform fiber resin distribution, and no ply waviness.

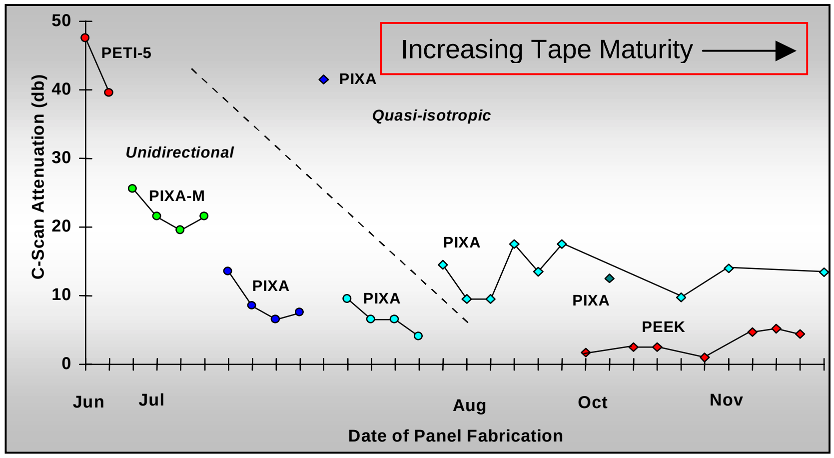


Figure 2.2 Trend in the improvement of laminate quality over time. This shows the importance of using placement-grade

Some developers use short beam shear (SBS) data to screen process effectiveness. Improvements in SBS strength are notable, but compression modulus, open hole tension (OHT) strength, and especially open hole compression (OHC) strength are much more useful for aircraft panel design. Table 2.1 shows compression strengths and moduli plus OHT and OHC strengths and moduli of PEKK, PEEK, and PIXA laminates. Properties on laminates fabricated by three processes, in-situ ATP, in-situ ATP followed by autoclave treatment, and hand lay-up followed by autoclave treatment, are included. These same data are charted in Figures 2.4 and 2.5 to better compare the OHC and OHT values, respectively. Table 2.2 shows those and additional properties for PIXA-M laminates made by the same three processes: in-situ ATP, two batches of in-situ ATP/autoclave, and hand lay-up/autoclave. Finally, Table 2.3 shows a comparison of OHC strengths of PETI-5 laminates generated from two types of prepreg: (1) solvent-free ("dry") tape processed via in-situ ATP with a post autoclave treatment, and (2) wet IM-7/PETI-5 tape processed by hand lay-up/autoclaving. PETI-5 is a lightly cross-linked polyimide that requires an autoclave post-cure for chain extension and final cure.

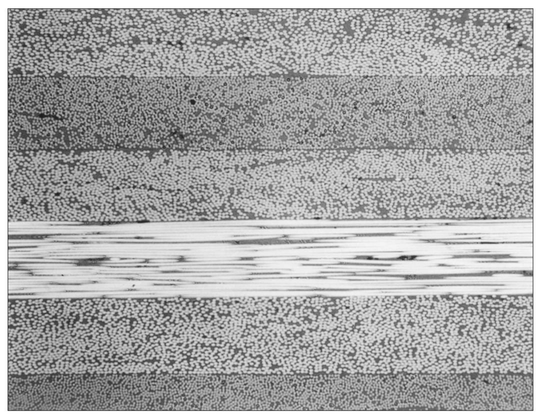


Figure 2.3 Photomicrograph of high quality IM-7/PIXA laminate from TP-ATP and placement-grade tape

From Table 2.1, the compression moduli for in-situ processed PEKK, PEEK, and PIXA quasi-isotropic laminates are 91-99 percent of the compression moduli from in-situ placed post-autoclaved laminates. The compression strength ratios of in-situ panels to in-situ post-autoclaved panels range from 84 to103 percent. The OHT strengths are essentially the same for both in-situ and in-situ post-autoclaved laminates. The OHC strength values benefit the most from an autoclave post-treatment. OHC values for in-situ placed laminates were 76 to 94 percent of those that were autoclaved, averaging about 85 percent. It appears autoclave treatment helps to further consolidation.

However, for PIXA-M laminates (Table 2.2), OHC strengths of in-situ placed panels were slightly better, about 88 percent of the values of autoclaved consolidated panels. OHT strength had almost full translation. Both the dry placed and wet hand-laid IM-7/PETI-5 laminates (Table 2.3) had to be autoclaved to achieve full cure. OHC strengths for the former slightly exceeded those of the latter showing that for flat lay-ups the automated in-situ process performed very well.

	AS-4/PEKK tow			AS-4/PEEK tape			IM-6/PEEK 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] Comp Strength, MPa	462	501		441	427		496	586		447	531	
[Quasi] Comp Modulus, GPa	43.4	46.9		47.6	49.0		56.5	57.2		53.1	58.6	
OHT Strength, MPa	359	359	335	393	397	387	490	527		470	494	
OHC Strength, MPa	255	337	325	276	341	327	296	338	317	272	296	319
OHC Modulus, GPa	40.7	44.1		44.8	47.6							

HLU - Hand Layup *AC = Autoclave consolidation*

Table 2.1 Mechanical property comparisons for PEKK, PEEK, and PIXA laminates

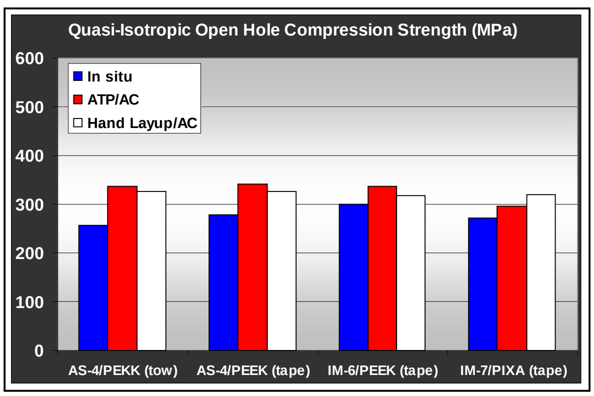


Figure 2.4 OHC comparison – in-situ, ATP/AC. and HLU/AC

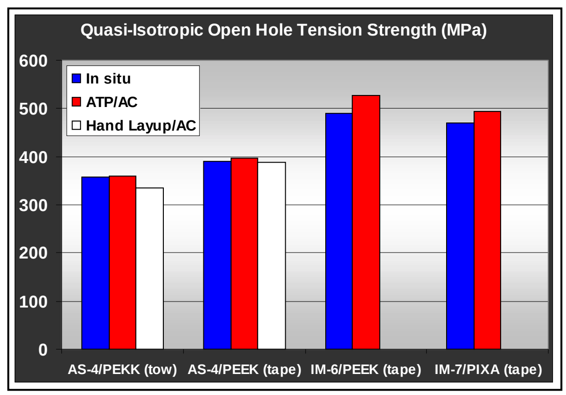


Figure 2.5 OHT comparison – in-situ, ATP/AC. and HLU/AC

Property		Units	In Situ ATP 76mm (3") Tape	ATP/Autoclave 76mm (3") Tape	ATP/Autoclave 76mm (3") Tape	HLU/Autoclave 305mm (12") Tape
Quasi Comp. Strength	RT	MPa (Ksi)	471 (68.3)	618 (89.7)	*not available*	*not available*
Quasi Comp. Modulus	RT	GPa (Msi)	51.7 (7.5)	55.8 (8.1)	53.1 (7.7)	*not available*
OHT	RT	MPa (Ksi)	483 (70.1)	502 (72.8)	492 (71.4)	480 (69.6)
OHC	RT	MPa (Ksi)	265 (38.5)	303 (43.9)	299 (43.4)	313 (45.4)
OHC	350°F dry	MPa (Ksi)	194 (28.1)	210 (30.4)	204 (29.6)	204 (29.6)
CAI	RT	MPa (Ksi)	*not available*	390 (56.5)	388 (56.3)	406 (58.9)
In-Plane Shear Modulus	RT	GPa (Msi)	*not available*	*not available*	5.6 (0.81)	5.7 (0.83)
CILS	RT	MPa (Ksi)	*not available*	83 (12.1)	97 (14.0)	96 (13.9)
Fiber Volume			58.6%	60.0%	61.5%	62.5%

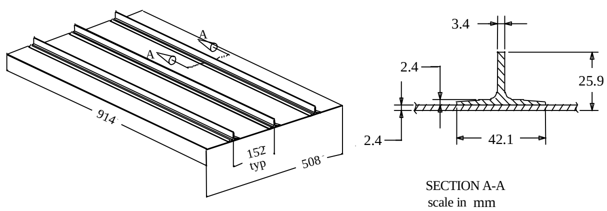
Table 2.2 Mechanical property summary for IM-7/PIXA-M laminates

		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 2.3 Open hole compression strength for autoclave-cured IM-7/PETI-5 laminates

3. FABRICATION OF THERMOPLASTIC SKIN STRINGER PANELS

Thermoplastic skin stringer panels can be manufactured by first embedding 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-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 panels were made by 1°, 2°, and co-bonding.



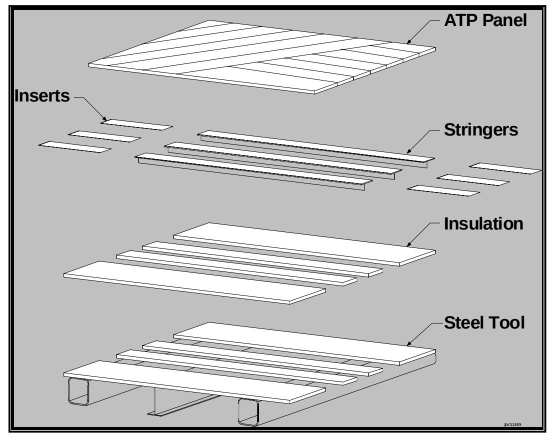


Figure 3.1 A steel tool covered with insulation accommodates prefabricated stringers, upon which a thermoplastic laminate can be in-situ tape placed.

Figure 3.1 is a schematic of the tooling used for in-situ ATP skin stringer fabrication by a 1° bonding process. Figure 2.1 showed the tooling ready for placement after the stringers were added. Stringers were clamped in fixtures prior to insertion, as shown in Figure 3.2. Having the stringers just reach the tool surface while not sitting too high or too low was critical for creating a good 1° welded joint and was difficult to achieve. PEEK or PIXA-M thermoplastic film matching the skin resin was consolidated onto the stringer flange to act as a welding resin during tape placement. Figure 3.3 shows the first few tape courses being tape placed and in-situ welded directly over the flanges of three blade stringers. The 51cm x 91cm (20in x 36in) 18-ply skin had a [$\pm 45/0_2/90/0_2/\pm 45$]s stacking sequence. Over sixteen IM-7/PEEK, PIXA-M, and PETI-5 panels were made. A microstructure for a finished skin stringer panel is shown in Figure 3.4. The detail at the panel/stringer edge

Figure 3.2 Stingers are fixtured before inserting them into the tool. Accurate stringer height is critical to achieving a weld joint between the stringer and skin.

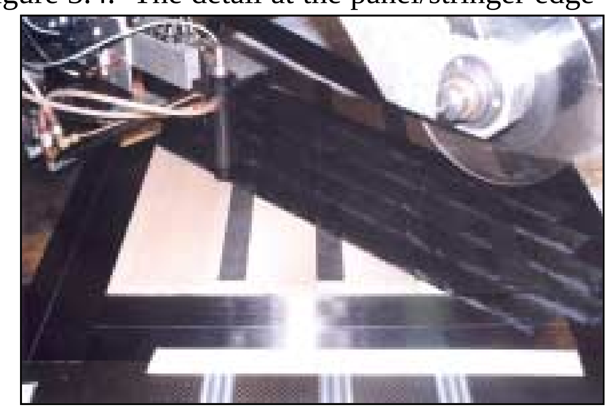


Figure 3.3 Placing the first few courses of thermoplastic tape over embedded pre-consolidated thermoplastic stiffeners.

was typical of the best achieved for a 1° bonded panel. Postmortem examination of tested flatwise tensile and OHC specimens showed no failures at the skin-stringer bond for either IM-7/PEEK or IM-7/PIXA-M 1° bonded panels. For comparison, in-situ placed IM-7/PEEK and IM-7/PIXA-M panels with no autoclave treatment had OHC strengths approximately 85 percent of the values of autoclaved panels. This improvement following autoclave consolidation was consistent with the trend observed for unstiffened quasi-isotropic panels (Tables 2.1, 2.2).

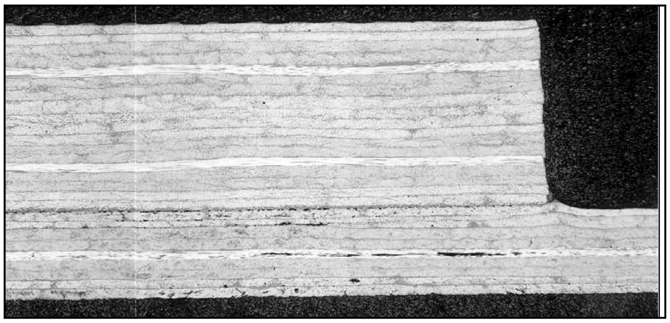


Figure 3.4 Microstructure and stringer/skin interface achieved with in situ skin stringer 1° bonding process

Figure 3.5 Co-bonded IM-7/ PETI-5 three-stringer panel

Figure 3.5 shows a finished IM-7/PETI-5 skin stringer panel made from the alternate co-bonding process. Since PETI-5 requires an autoclave cure to chain extend and fully cure the polymer, the three blade stringers were co-bonded to the pre-consolidated 24-ply quasi-isotropic skin with FMX-5® adhesive in the autoclave. These panels await compression testing.

4. PLACEMENT OF THERMOPLASTIC TITANIUM HONEYCOMB PANELS

Thermoplastic in-situ consolidation was 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. In 2° bonding, in-situ consolidated facesheets were bonded to core with BRX-5® under light autoclave pressure. Figure 4.1 shows a photograph of the head placing a laminate directly over titanium core. Run-on and run-off tooling surrounds the core so it is not seen in the photo but is detailed in Figure 4.2. Figure 4.3 shows two 1° bonded thermoplastic honeycomb sandwich panels; one was in-situ processed, the other in-situ processed and then autoclave consolidated.

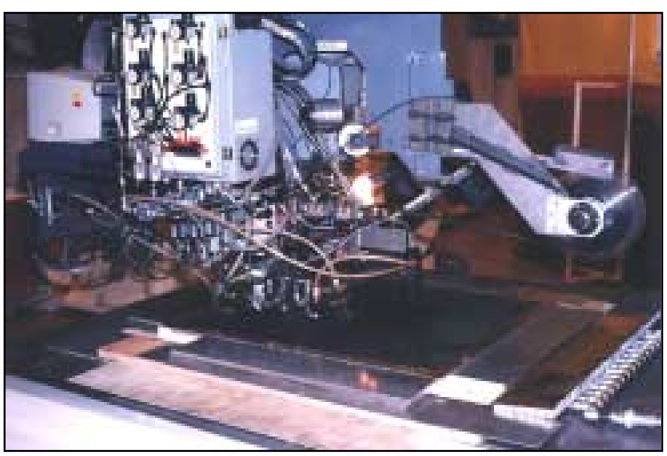


Figure 4.1 Primary bonding using thermoplastic in situ consolidation to place 76mm (3-in) tape on honeycomb core precoated with BRX-5® paste and FMX-5® film adhesives.

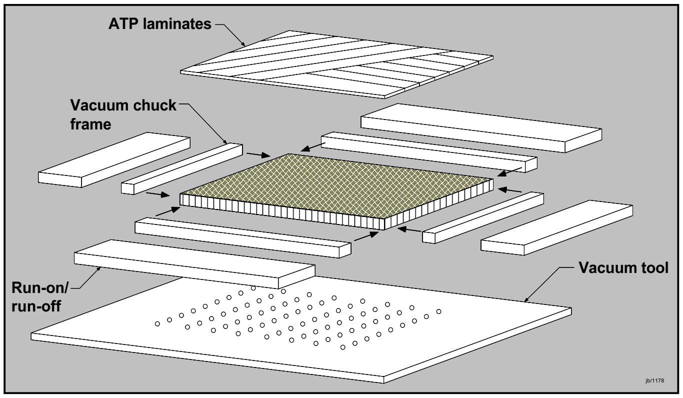


Figure 4.2 Exploded view of 1° honeycomb laminate and tooling components enabling placement over honeycomb core.

Figure 4.3 IM-6/PEEK honeycomb panels. The left made via thermoplastic in situ consolidation, the right post-ATP autoclave cured

Figure 4.4 shows three photomicrographs comparing the placement quality achieved via thermoset 1° bonded PMC honeycomb fabrication and thermoplastic in-situ fabrication using both 1° and 2° bonding. In the top photo, the use of a wet thermoset material causes substantial cell draping and core cell pinching due to volatile removal and ply thickness reduction in the autoclave. In the middle photo, thermoplastic in-situ consolidation was used with 1° bonding to dramatically lessen the amount of core cell drape. In the bottom photo, 2° bonded in-situ consolidation nearly eliminated core cell drape.

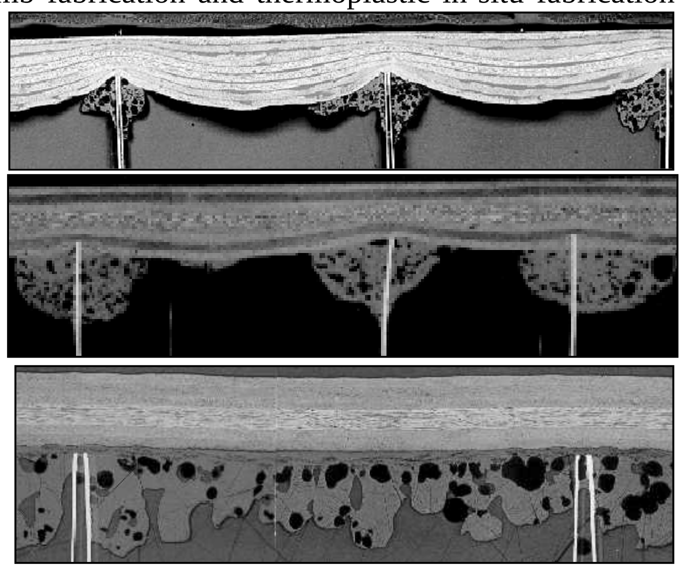


Figure 4.4 Photomicrographs of the edges of honeycomb panels fabricated by three separate processes: thermoset fiber placement followed by autoclave cure (top), 1°-bonded in situ consolidation on core (middle), and 2°-bonded TP-ATP laminate on core (bottom). Drape is diminished with 1°-bonding and almost eliminated with 2°-bonding.

Excellent mechanical properties were obtained with the honeycomb core-stiffened ATP laminates (Table 4). Almost all properties obtained from both 1° and 2° bonded core-stiffened laminates exceeded those from traditional wet thermoset-processed co-cured

			1° Bonded IM-7/PIXA-M	2° Bonded IM-7/PIXA-M	Co-cure Wet IM-7/PETI-5	2° 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	1236			
CAI	*8.5 N-m impact*	MPa		347	332	

Table 4 Mechanical properties measured from titanium honeycomb core stiffened panels

panels. Of particular interest is edgewise compression strength, which varied from 421 to 486 MPa (61.0 to 70.5 ksi). These values far exceeded those from co-cured wet panels.

5. CONCLUSIONS

Thermoplastic flat laminates as well as skin stringer and honeycomb built-up structure were successfully in-situ tape and tow placed using newly developed heated head automated placement technology. Panel quality was excellent; many mechanical properties of in-situ placed panels equaled values measured from laminates post-autoclave consolidated after in-situ placement. However, OHC values still need some improvement; OHC strengths following in-situ placement were 76 to 94 percent of those from in-situ placed autoclaved panels. Skin stringer fabrication showed the viability of in-situ placement concomitant with 1° bonding of skins to pre-fabricated stringers inserted into an IML tool. OHC strengths of in-situ placed skin stringer panels were 85 percent of the values from in-situ placed autoclaved panels. Thermoplastic placement on titanium honeycomb was effective and did not cause core crush with either 1° or co-bonding. Superior properties resulted primarily due to the lack of ply drape, especially when compared with data and photomicrographs from panels made with wet thermoset prepreg. The authors urge further development of placement-grade prepreg tape, conformable compaction devices [4], the ability to add and drop tow or tape at constant speed to ease heat control, and the ability to start and stop on part so that ply drops and pad-ups can be achieved.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the engineers and technicians at Cytec Engineered Materials, Boeing, Cincinnati Machine, DuPont, NASA, and The University of Delaware - Center for Composite Materials who worked to create the materials, equipment, processes, laminates, and test results. NASA and DARPA supported some of the work via the High Speed Research Project and the RAPTECH-PMC and ACM programs, respectively.

REFERENCES

1. Gruber, M. B., M. A. Lamontia, and B. J. Waibel, “Automated Fabrication Processes for Large Composite Aerospace Structures,“Proceedings of 46th International SAMPE Symposium and Exhibition, SAMPE 2001, May 6-10, 2001, Long Beach, California.
2. Lamontia, M. A, and R. D. Cope, M. B. Gruber, B. J. Waibel, and J. F. Pratte, “Stringer-, Honeycomb Core-, and TiGr-Stiffened Skins, and Ring-Stiffened Cylinders Fabricated from Automated Thermoplastic Fiber Placement and Filament Winding,” Proceedings of the 23rd SAMPE EUROPE Conference, Porte de Versailles, Paris, 9-11 April, 2002.
3. Ruckert, Christian, S. Pearce, R. Avila-Dominguez, J-M. Bergerat, J-L. Garcin, L. Rubio-Garcia, P. Bertin, “Thermoplastic Processing at Airbus – Realized Components and Future Approaches,” Proceedings of the 34th International SAMPE Technical Conference, Baltimore, MD, November 4-7, 2002.
4. Lamontia, M. A., M. B. Gruber, B. J. Waibel, R. D. Cope, S. B. Funck, and A. Bruce Hulcher, “Contoured Tape Laying and Fiber Placement Heads for Automated Fiber Placement of Large Composite Aerospace Structures,” Proceedings of the 34th International SAMPE Technical Conference, Baltimore, MD, November 4-7, 2002.