Dry Ribbon for Heated Head Automated Fiber Placement[1]

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ABSTRACT

Ply-by-ply in situ processes involving automated heated head deposition are being developed for fabrication of high performance, high temperature composite structures from low volatile content polymer matrices. This technology requires (1) dry carbon fiber towpreg, (2) consolidation of towpreg to quality, placement-grade unidirectional ribbon or tape, and (3) rapid, in situ, accurate, ply-by-ply robotic placement and consolidation of this material to fabricate a composite structure. In this study, the physical properties of a candidate thermoplastic ribbon, PIXA/IM7, were evaluated and screened for suitability in robotic placement.

Specifically, towpreg was prepared from PIXA powder. Various conditions (temperatures) were used to convert the powder-coated towpreg to ribbons with varying degrees of processability. Ribbon within preset specifications was fabricated at 3 temperatures: 390, 400 and 410°C. Ribbon was also produced out-of-spec by purposely overheating the material to a processing temperature of 450°C. Automated placement equipment at Cincinnati Milacron and NASA Langley was used to fabricate laminates from these experimental ribbons. Ribbons were placed at 405° and 450°C by both sets of equipment. Double cantilever beam and wedge peel tests were used to determine the quality of the laminates and, especially, the interlaminar bond formed during the placement process.

Ribbon made under conditions expected to be non-optimal (overheated) resulted in poor placeability and composites with weak interlaminar bond strengths, regardless of placement conditions. Ribbon made under conditions expected to be ideal showed good processability and produced well-consolidated laminates. Results were consistent from machine to machine and demonstrated the importance of ribbon quality in heated-head placement of dry material forms. Preliminary screening criteria for the development and evaluation of ribbon from new matrix materials were validated.

KEY WORDS: Fiber Placement, Quality Assurance, Wedge Peel

1.0 INTRODUCTION

The quality of composites processed by in-situ methods such as automated fiber placement is highly dependent on the quality of the tape or ribbon which is supplied to the placement machine. Many specifications can be placed on such materials in an attempt to have some control over the final part quality. These specifications include ribbon width and thickness tolerances, resin content, and residual solvent content [1]. The following is given as an example of a set of requirements for dry ribbon and tape:

DRY TAPE AND RIBBON REQUIREMENTS

Width:	0.635 +/- 0.0254 cm (ribbon) 7.62 +/- 0.0254 cm (tape)
Nominal Thickness:	0.015 cm
Thickness Variation:	Less than 25% of total thickness
Resin Content:	35 +/- 5% by weight
Void Volume:	Less than 3% (when measured by “The Water Immersion Method for Determination of Void Content of Thermoplastic Fiber Impregnated Tow”.)
Tensile Strength:	Measure and report only (ribbon only)
Product shape:	Rectangular cross-section (when inspected by photo micrograph)
Tow Splits:	Less than 0.076 cm wide, less than 7.62 cm long
Tow Alignment:	Less than 0.076 cm deviation in any linear foot
Residual Solvent:	Less than 0.01%

Incoming material that has an excess of voids will produce a laminate that also has an excess of voids, assuming that the part is not post-processed. Additionally, the thermal history of tape/ribbon during manufacture is important in the final part quality. Material which has been manufactured at temperatures above which thermal degradation begins will produce laminates having weak interfaces and thus poor mechanical properties.

Since automated fiber placement equipment differs greatly from machine to machine, an attempt was made to determine whether ribbon quality could be assessed by placing the same materials at two different automated fiber placement facilities. Four ribbon batches were processed by varying the ribbon processing temperatures. The fourth batch of ribbon was processed at 450°C to purposely produce material that had received excessive thermal treatment and suffered possible thermal degradation. These four ribbon batches were fiber-placed at both the Cincinnati Milacron and the NASA Langley fiber placement facility. The placement machine at Cincinnati Milacron is a gantry-type machine with a large placement head [2], and is capable of fabricating large composite structures. The

NASA Langley machine is a much smaller, fully articulating-arm machine and is used to assess novel resin systems and address placeability issues [3] . A correlation of mechanical property data between specimens fabricated at the two facilities would then eliminate the placement equipment as a source of discrepancy in assessing ribbon quality. Additionally, positive results would also validate screening criteria of materials for suitability in automated placement.

2.0 EXPERIMENTAL

2.1 Ribbon Production Facility The ribbon used in the study was fabricated at Cytec Fiberite's Thermoplastic Intermediate Forms Facility (TIFF) [2,4]. Three specific products are manufactured at this facility; 7.62 cm wide placement grade tape, 0.635 cm wide filament-winding and placement grade dry ribbon, and dry impregnated towpreg. Many fiber types and matrix resins, including some thermosets, have been processed by TIFF. These include PIXA, PIXA-M, PEEK, PEKK and numerous others. The facility has achieved ISO 9001/9002 certification.

2.2 Ribbon Fabrication Towpreg for the ribbon was produced from dry PIXA powder and IM7 fiber. All processing variables were held constant except for process temperature. Table 1 provides processing information of the various ribbon lots. It should be noted that all ribbons with the exception of QC-D were made with polymer of the same lot number.

Table 1. Processing temperatures and lot numbers of ribbon.

Ribbon Lot Number	Process Temp. (°C)	Polymer Lot Number
QC-A	390	89-626
QC-B	400	89-626
QC-C	410	89-626
QC-D	450	26-685

2.3 Cytec Fiberite Specimen Fabrication and Testing The Cytec Fiberite placement head, located at Cincinnati Milacron, is part of a gantry-style placement facility. The machine has been used to fabricate both honeycomb and skin-stringer composite laminates. The placement head is capable of depositing simultaneously, twelve 0.635 cm wide ribbons, or one 7.62 cm wide tape. The head features the ability to control individual ribbons of material. Figure 1 below shows the Cytec placement head and associated hardware.

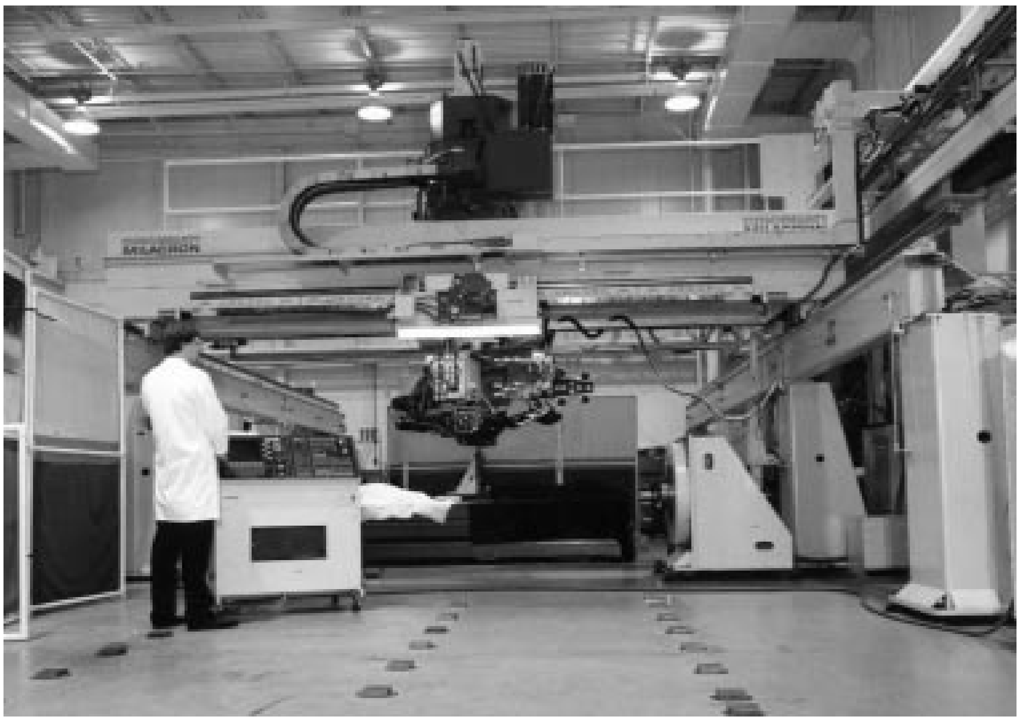

Figure 1. Cytec Fiberite placement facility at Cincinnati Milacron.

A series of eight test panels were fabricated in-situ with the Cytec Fiberite placement head. All processing conditions were held constant during placement with the exception of the laydown temperature. Half of the panels were placed at 405°C and the remaining half at 450°C. The as-placed panels were 20-ply unidirectional layups 7.62 cm wide and 91.44 cm in length. Panels were fabricated from each of the A-D material lots.

Double cantilever beam (DCB) specimens were prepared from the test panels. These specimens were prepared in accordance with established standards for mode I testing of unidirectional composites [5]. The lone exception to this was the absence of a crack starter at the specimen mid-plane. At one end of the panels however, the plies were not firmly bonded. From this end, a shim could be forced into the approximate mid-plane of the test specimen to begin a delamination. The value of the load required to propagate the crack was recorded as the wedge opening load. In the absence of friction, the force needed to wedge open the delamination at a constant speed is equivalent to a fracture toughness. Because of this, and to obtain more data, these tests were performed for the present study. The crosshead speed used in the wedge opening load tests was 1.27 cm/min. Tests using a driven wedge have been under investigation as a means of determining Mode I fracture toughness [6-8].

Loading blocks for DCB testing were then bonded to the specimens. The specimens were again tested, with *propagation* fracture toughness values being recorded. The delamination length of the specimens was, on average, over 5 cm in length. A crosshead speed of 5 mm/min was used during testing.

The absence of this crack starter did not allow the measurement of the critical fracture toughness, G_{IC}, associated with crack initiation.

2.4 NASA Langley Tow Placement Facility The NASA Langley Automated Fiber Placement Facility uses a fiber placement head designed by Automated Dynamics Corp. This head is attached to the arm of a six-axis, fully articulating industrial robot. Placement of flat, open-section laminates as well as cylindrical laminates are possible. The machine is capable of feeding five 0.635 cm wide fully consolidated ribbons, or a single 3.175 cm inch wide tape. Hot gas torches capable of 900°C are directed at both the upper surface of the substrate ply, and the facing side of the incoming tape. The material is fed underneath a heated compaction roller. This roller provides the load necessary to consolidate the laminate. Figure 2 below shows the NASA Langley fiber placement head and associated components [3]. The NASA Langley placement facility is shown in Figure 3. Flat panels may be fabricated on the table at the right and cylindrical parts on the spindle on the left in the figure.

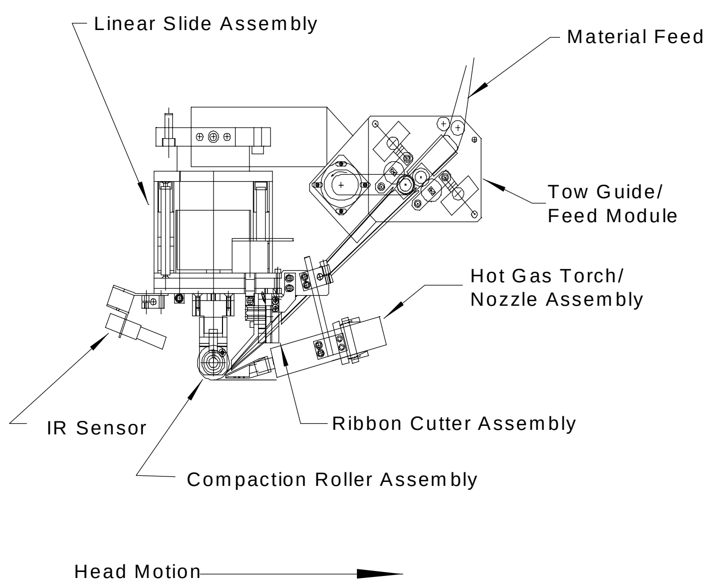

Figure 2. NASA Langley fiber placement head.

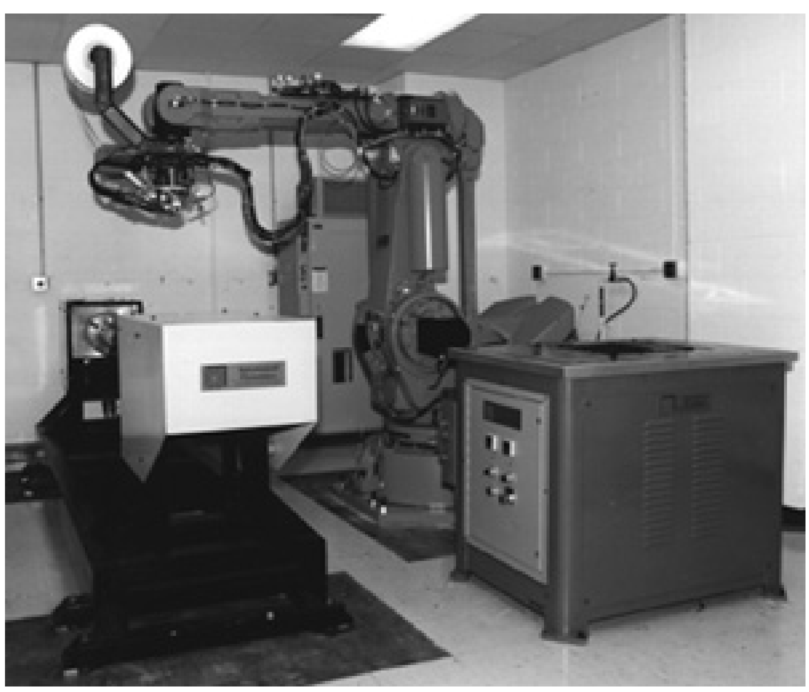

Figure 3. NASA Langley fiber placement facility.

Temperature studies performed on the NASA Langley fiber placement machine have demonstrated that the material temperature is most greatly influenced by the compaction roller temperature. It is therefore the compaction roller temperature which is varied between 405 and 450°C for this study. Hot gas torch temperature was held at 900°C and placement speed was 5.08 cm/sec. Tool temperature and compaction roller load were 75°C and 222 N, respectively.

Unidirectional, two ply wedge peel test panels were placed at the NASA Langley facility. Data from the wedge peel test have been shown to correlate with DCB fracture toughness [9]. The wedge peel specimens were 3.18 cm in width and 45.7 cm in length. A 0.05mm thick Kapton film was taped to the top of the first ply to initiate delamination for peel testing. Each as-placed two-ply panel provided tow wedge peel specimens. Each peel specimen yielded an average of 15.2 cm of peel length. Table 2 shows the number of peel specimens obtained for each ribbon lot and processing temperature.

Table 2. *Wedge peel specimen quantities*

Ribbon Lot	405°C	450°C
A	4	4
B	6	6
C	10	10
D	8	8

A wedge peel fixture incorporating a 0.15 cm thick stainless steel wedge was used in the peel testing. Figure 3 illustrates the method. A grip fixture attached to the crosshead was used to clamp the specimen plies. The crosshead was then actuated downward at a rate of 2.54 cm/min. Load data were recorded by the test software over an average of 15.2 cm of specimen length.

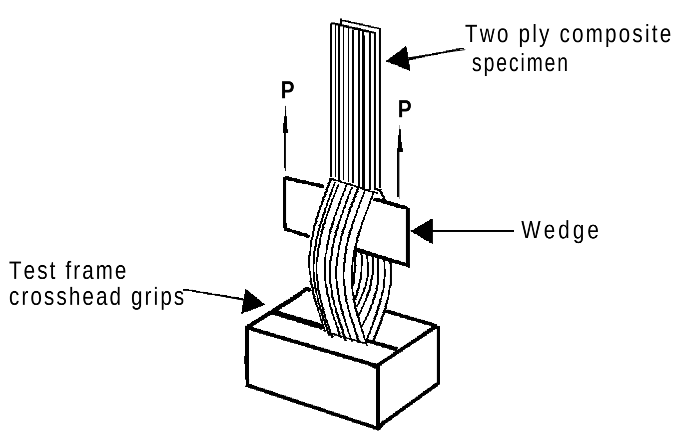

Figure 3. Wedge Peel Test Schematic

3.0 Results and Discussion

Presented in Table 2 below are the results of the study. Figures 3 and 4 display the test results for specimens made at each placement temperature and illustrate trends for the three methods.

Table 2. *Test results from specimens placed at Cincinnati Milacron and at NASA Langley.*

Placement Temperature (°C)	Process Temperature (°C)	Cincinnati Panel DCB Propagation Fracture Toughness (kJ/m^2)	Cincinnati Panel Wedge Peel Opening Load (N)	NASA Langley Wedge Peel Strength (kN/m)
405	390	0.64	105	0.99
405	400	0.75	95	0.91
405	410	0.73	113	0.15
405	450	0.48	67	0.15
450	390	0.75	88	1.14
450	400	0.67	104	1.59
450	410	0.55	89	0.20
450	450	0.45	72	0.22

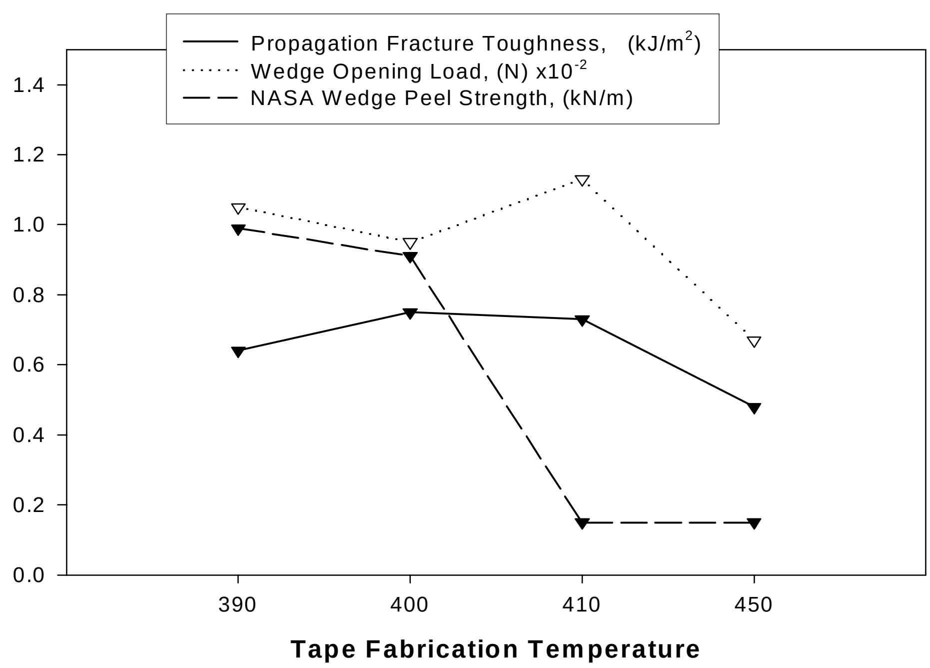

Figure 3. Cincinnati and NASA Property Data vs. Ribbon Lot.
Placement Processing Temperature - 405 C.

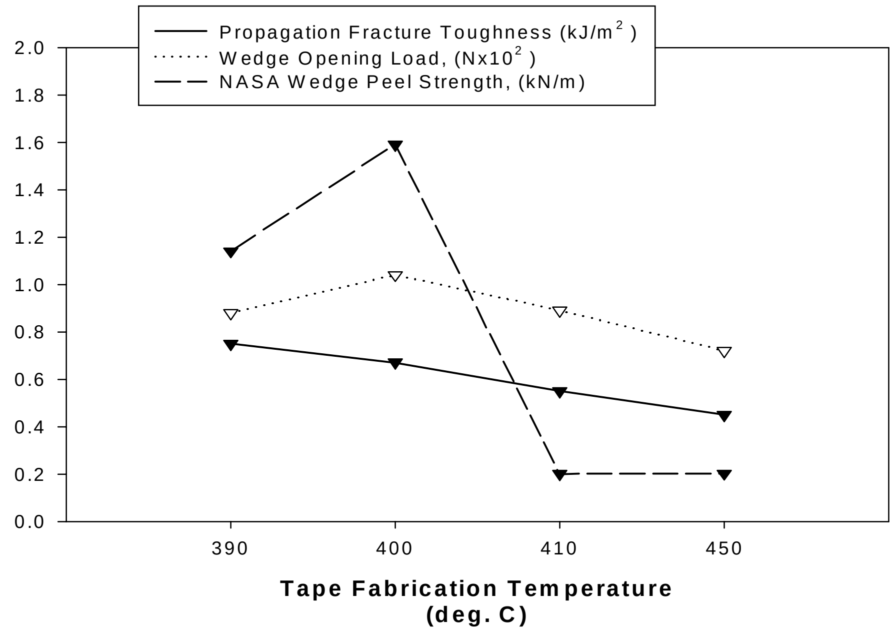

Figure 4. Cincinnati and NASA Property Data vs. Ribbon Lot Placement Processing Temperature - 450 C.

Test specimens placed at both Cincinnati Milacron and at NASA Langley showed consistent results. The 20-ply panels placed at Cincinnati at 405°C indicated that the ribbon made at 390 and 410°C had the strongest bonds. At NASA, the ribbon processed at 390°C produced the strongest weld. Placement at 450°C resulted in very nearly identical trends. The Cincinnati specimens made from ribbon processed at 390 and 400°C had the highest fracture toughness and wedge opening load, respectively, while the B ribbon gave the highest value of wedge peel strength when placed At 450°C at NASA.

Ribbon quality decreased rapidly beyond a ribbon processing temperature of 410°C. The processing of ribbon at 450°C clearly damages the material. The 450°C processed ribbons gave consistently low interply strengths after placement at both 405 and 450°C. Because the same result was obtianed on quite different placement equipment and at two different placement conditions, it is clear that the efficiency of consolidation depends on the state of the resin in the ribbon.

4.0 CONCLUSIONS

In this study a series of PIXA/IM7 thermoplastic ribbons was evaluated for suitability in robotic placement. The quality of composites processed by in-situ methods such as fiber placement is dependent on the quality of the tape/ribbon which is supplied to the placement machine. Ribbon/tape specifications include at a minimum, ribbon width and thickness tolerances, resin content, and residual solvent content. This study dealt with the thermal conditions under which the ribbons were produced.

Thermoplastic ribbon for automated tape placement was manufactured by Cytec Fiberite by processing at four different conditions. One ribbon batch was purposely produced out-of-spec by processing the ribbon at elevated temperatures. DCB specimens were placed on the Cincinnati Milacron machine. Wedge peel test specimens were placed by the ATP facility at NASA Langley. All of the mechanical testing was performed at NASA.

Ribbon made under conditions expected to be non-optimal resulted in poor placeability and composites with weak interlaminar bond strengths, regardless of placement conditions. Ribbon made under conditions expected to be ideal showed good processability and produced well-consolidated laminates. Results were consistent from machine to machine and demonstrated the importance of ribbon quality in heated-head placement of dry material forms. Preliminary screening criteria for the development and evaluation of ribbon from new matrix materials were validated.

5.0 ACKNOWLEDGEMENTS

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