DEVELOPING A CONTOURED DEPOSITION HEAD FOR IN SITU TAPE LAYING AND FIBER PLACEMENT

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ABSTRACT

A conformable compaction system employing three individual compactors has been designed for integration into fiber placement and tape laying deposition heads for out-of-autoclave fabrication of thermoplastic contoured parts. The compactors are intended to perform against two geometry specifications: (1) a general minimum radius of curvature limit of 180cm (71-in), and (2) a pad-up specification with a maximum height of 2.5mm (0.1-in) and a minimum ramp of 25mm (1-in). The mirrored specification is applicable to a pan-down. The three designs include a hot line compactor capable of a 1000N (400-lb) force at 450°C over a 114mm (4.5-in) width, a hot area compactor capable of a 400N (100-lb) force at 450°C over a 114mm width by 76mm length (4.5-in by 3-in), and a cold compactor that combines the features of a line and an area compactor. The cold compactor's line segments act with a 2800N (700-lb) force across a 127mm (5-in) width, while the cold compactor's area segments act with a 1000N (250-lb) force over a 127mm by 102mm (5-in by 4-in) area. Two of the designs, the hot line and hot area compactors, have been constructed, developed, and proven out in hot mode to compact actual thermoplastic composite plies over undulating geometry. IM-7/PEEK [0/90/0/90]s pan-down and IM-7/PEKK [0/-45/90/45]2s pad-up laminates have been fabricated and photomicrographs show good microstructure.

KEY WORDS: Conformable Compaction System, Thermoplastics, In Situ Consolidation, Automated Fiber Placement, Fiber Placement Head, Tape Placement Head

1. INTRODUCTION

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.

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 [4,5], 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 [6]. PEEK, PIXA, PIXA-M, and PETI-5 placement grade tows and tapes were developed and laminates fabricated.

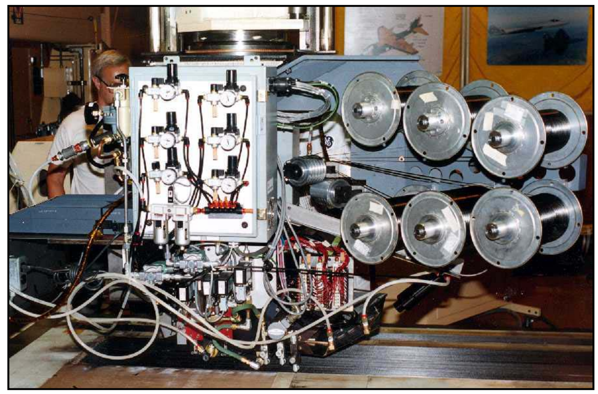


Figure 1 In-situ deposition head consolidating 12 IM-7/PEEK tows on a laminate up to 5mpm (20fpm)

Real aerospace laminates are not flat, however, and a thermoplastic automated tow or tape placement head must be able to provide a uniform compaction force over the process spot in order to in situ consolidate the placed layer. A conformable compaction system has been developed to be integrated into heated ATP heads for thermoplastic in-situ fiber and tape placement of curved parts and even flat panels with pad-ups or ply details [7,8]. Heated line and area compactors have been fabricated and pan-down and pad-up laminates have been fabricated. This paper reports on the compactor design and features, then details the laminate microstructure produced in the contoured laminates that have been fabricated.

2. OUT-OF-AUTOCLAVE FABRICATION PROCESS USING CONFORMABLE COMPACTION SYSTEMS

Figure 2 illustrates the integration of a process concept for a generalized deposition head that employs heated and chilled zones, and requires high forces over a small area or modest forces over a larger area. These process zones correlate to three compactor concepts, and are described in the context of thermoplastic in situ consolidation. However, a number of out-of-autoclave processes can be arranged by employing some or all of the compactors in any order. In the Figure, a feeder provides accurate deployment, starting, and cutting of tows or a tape. There may be a material or substrate heat source. In this process, 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. Three conformable compactors alternately heat and chill the composite. The first hot 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 those locations where intimate contact has been achieved. The second hot area compactor maintains the temperature long enough to complete healing of the longest polymer chains to develop interlayer strength. The third 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 the voids before the force is removed.

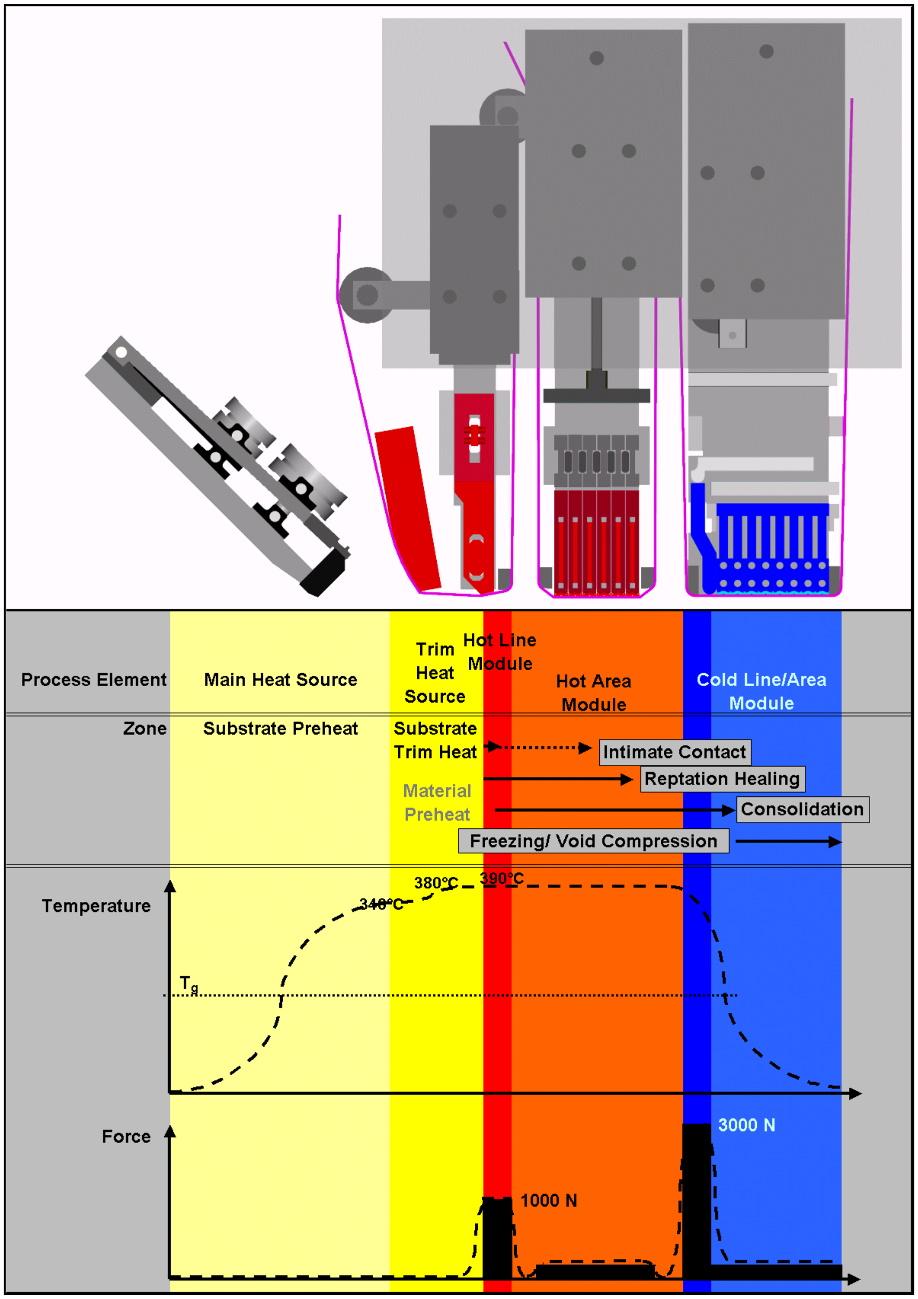


Figure 2 Fiber placement process zones and process parameters

3. CONFORMABLE COMPACTION SYSTEM DEVELOPMENT

The current NASA SBIR II program is directed towards developing both line and area conformable compactors. The designs were completed prior to the SBIR phase II and were guided by the following specification:

Specifications Two different surfaces over which conformance must be achieved have been defined. They are a general contour and a pad-up, which must both be fulfilled simultaneously.

- Contour: The surface will have a minimum radius of curvature of 180cm (71-in).
- Pad-up: This is a rectangular pad on the surface of the part. The pad is a maximum of 2.5mm (0.1-in) tall and is blended into the surface using a ramp that is a minimum of 25mm (1-in) long (10:1 slope). A similar specification is applicable to a pan-down of identical dimensions.

Three modules were designed to incorporate the four process zones shown in Figure 2. The modules are the hot line compactor, the hot area compactor, and the cold compactor, comprising the cold line region and the cold area region. Two of the three compactors are being fabricated and developed in the SBIR program: a line compactor and an area compactor.

There is also an overall head system design consisting of a frame, vertically articulating drawers that extend the geometry limits of the compactors to conform to the tool or part, and a shim drive apparatus to manipulate all of the shims, thereby achieving the process motions. Their conformance is being evaluated by placing tape in hot and passive modes. The line and area compactors are shown on their frame in Figure 3. These compactors will be described below.

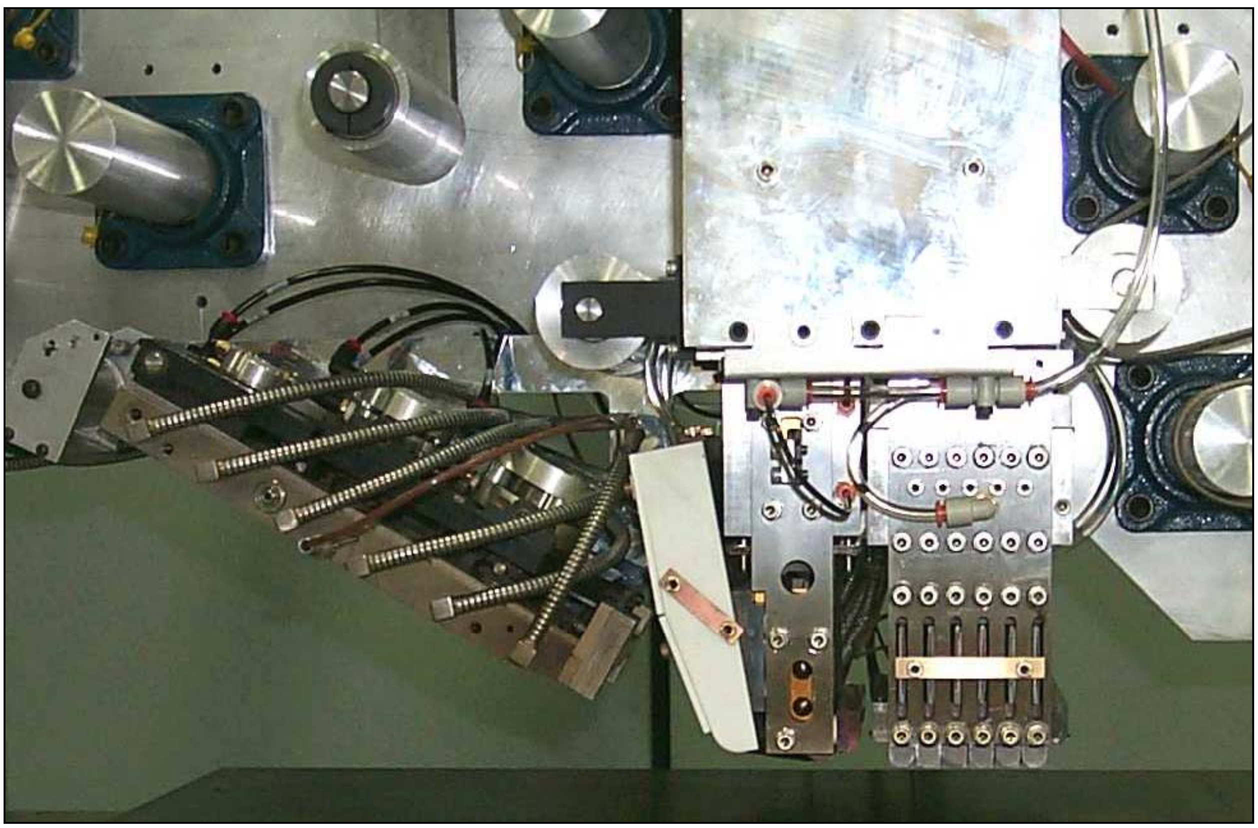


Figure 3 The hot line and the hot area compactors are integrated together with a feeder on an evaluation frame so that their conformability can be evaluated while placing composite tape.

The Line Compactor - The line compactor is designed to provide a uniform short duration high force to the laminate. When heated, the “hot line” compactor provides a high temperature to initiate the in situ consolidation process. When chilled, the “cold line” compactor is designed to provide a high force and low temperature. Both versions feature a multiplicity of segments to allow the force to conform to the geometric details of the tool or laminate. The heated or chilled compactors have a different number of segments, as shown in Table 1. In the hot line compactor shown in Figure 4, there are seventy-six segments covering a 114mm (4.0-in) width, and the head is capable of compacting a 76mm (3-in) width. Thus, the hot line compactor is compatible with heads placing twelve 6.35mm (0.25-in) tows or one 76mm (3-in) tape. In either hot or cold mode, the segments are covered by a shim to protect the individual fibers in the tape or tow and also to integrate the segment forces. Shim thicknesses were chosen after substantial evaluation experiments proved the thickness requirements for robustness and conformance. A shim transport system is in place to index the shim so that it can be refreshed after each course, or less often, as required. Experience has shown that indexing is not required often.

The internal detailed parts of the line compactor enforce a constant pressure across the segments.

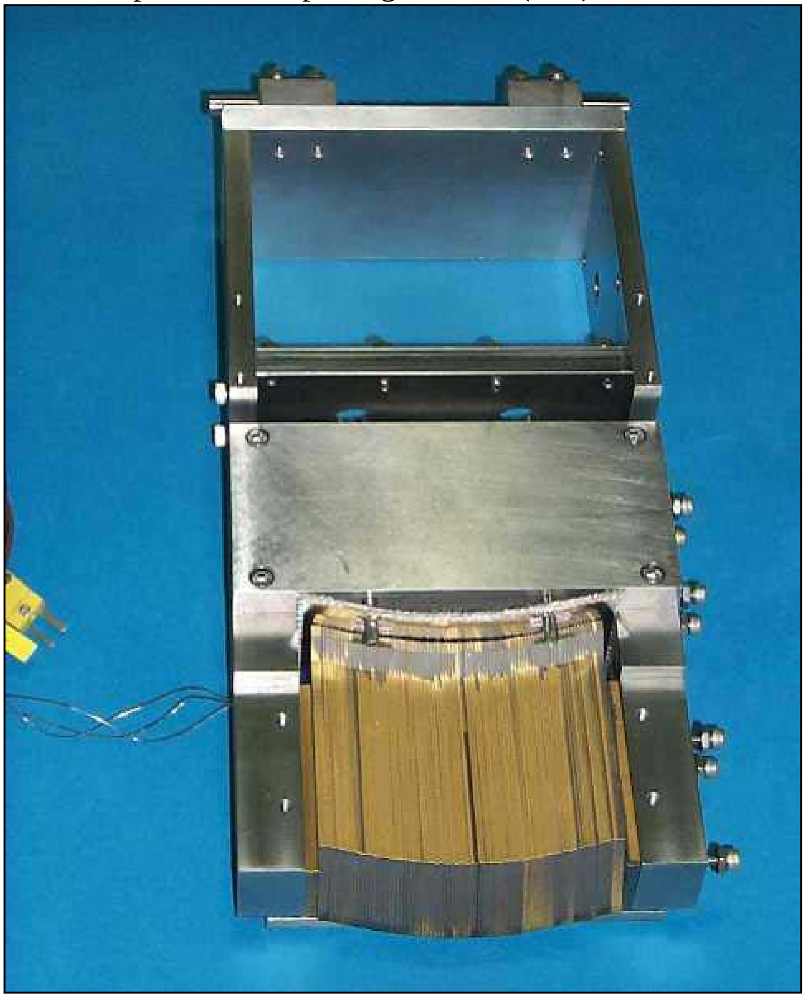


Figure 4 The hot line compactor features 76 heated segments. It is capable of transmitting a 1000N (250-lb.) conformable force at 450°C across a 102mm (4.0-in) width.

	Segments	Active Width, mm (in)	Active Length, mm (in)	Maximum Force, N (lb)	Temp, °C	Vertical Segment Conformance, mm (in)
Hot Roller		102 (4.0)	6 (0.25)	1000 (250)	450	0
Hot Line	76	114 (4.5)	6 (0.25)	1000 (250)	450	12.7 (0.5)
Hot Area	240	114 (4.5)	76 (3.0)	400 (100)	450	12.7 (0.5)
Cold Roller		127 (5.0)	6 (0.25)	2800 (700)	10	0
Cold Line	50	127 (5.0)	6 (0.25)	2800 (700)	10	12.7 (0.5)
Cold Area	400	127 (5.0)	102 (4.0)	1000 (250)	10	12.7 (0.5)

Table 1 Design features of hot line, hot area and cold line/area conformable compactors compared with rigid compactors used in the Cytec Engineered Materials thermoplastic ATP head

Figure 5a shows the ability of the line compactor to conform to a ball peen hammer. Figure 5b shows the line compactor in a drawer that allows air-pressurized cylinders to press the hot line compactor against the laminate, effectively increasing its stroke to 38mm (1.5-in).

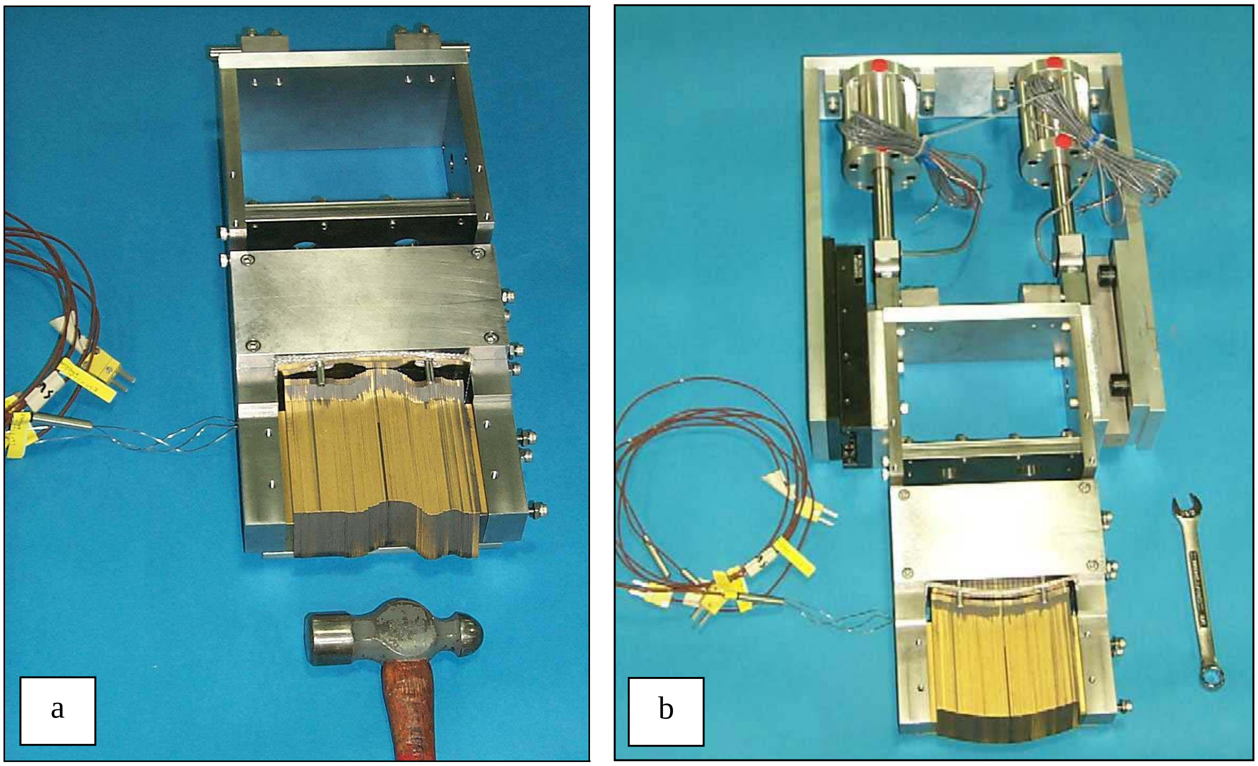


Figure 5 Hot line compactor has 76 segments, and can accurately conform to the shape of a ball-peen hammer. The hot line compactor is mounted in a drawer that provides an extra vertical articulation axis. When pressurized by air cylinders against the composite layers, the stroke is increased from the 6mm (0.25-in) available from the compactor itself to 38mm (1.5-in) overall.

The Area Compactor The area compactor is designed to provide a light force over a longer process distance than the line compactor. As such, it has multiple rows of larger segments covered by a shim. All segments in the area compactor are tipped with remote center compliance feet. Table 1 shows that the area compactor has 240 segments if designed as a hot device and 400 segments if designed as a cold device. The segment widths are actually the same in the cold and the hot design.

In the hot area compactor actually developed, there are six rows of forty segments, and the compactor is able to heat an area 114 mm wide by 76mm long (4.5-in by 3-in) while pushing with a 400N (100-lb.) force at 450°C. In the cold area compactor, there are eight rows of fifty segments, and the compactor is able to chill an area 127mm wide and 102mm long (5-in by 4-in) while pushing with a 1000N (250-lb.) force at 10°C. Thus, the area portion of the cold compactor is essentially an extended version of the hot area compactor, with two extra rows of segments. In the hot area compactor, the shim can index after each course.

Figure 6 shows the hot area compactor’s conformance to a basketball.

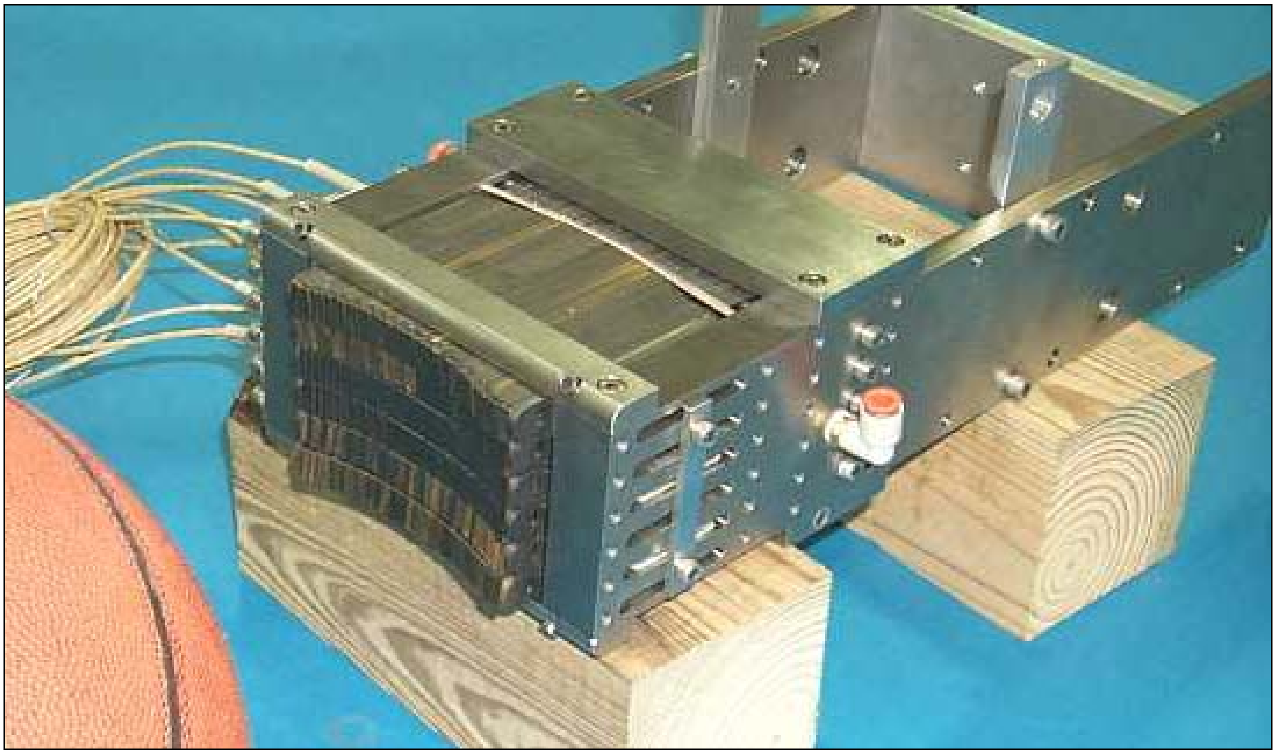


Figure 6 Hot area compactor's conformance to a basketball. The compactor pushes with a 400N (100-lb.) force at 450°C over a 114mm by 76mm area (4.5-in by 4-in).

4. FABRICATED PAN-DOWN LAMINATES

Figure 7 shows the hot line and hot area compactors assembled sequentially with a tape feeder and shim drive system into the deposition head used to develop the conformable compaction system. The head is placing IM-7/PEEK tape over a demonstration tool designed to mimic a pan-down with a maximum depth of 2.5mm (0.1-in) and 25mm (1-in) long ramps. A similar tool, not shown here, was fabricated to test a pad-up of identical dimensions. A [0°/90°]2s pan-down laminate is being placed.

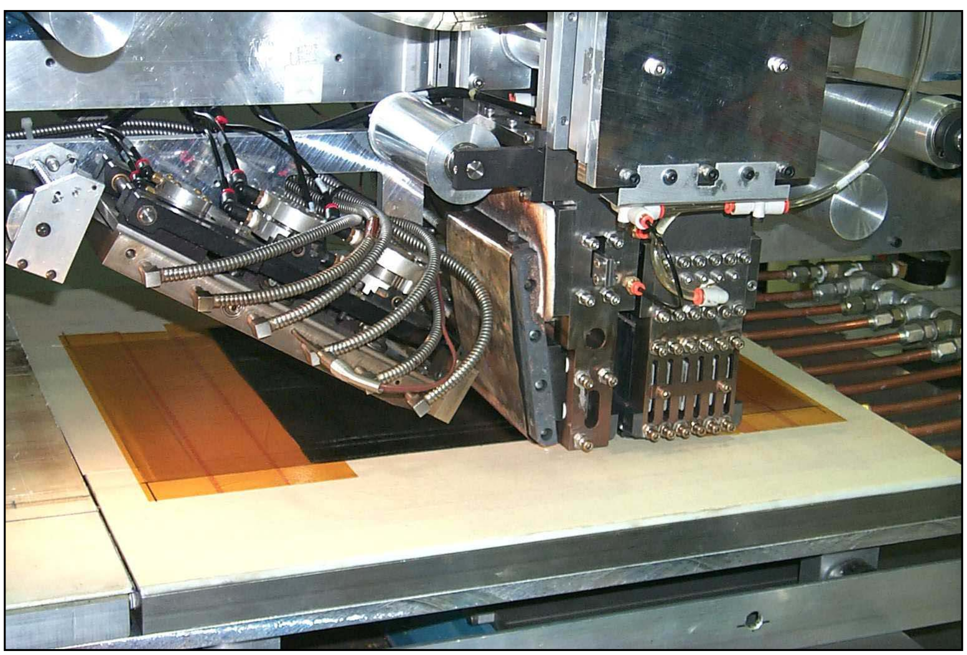


Figure 7 Conformable deposition head placing pan-down laminate with 2.5mm depth

Figure 8 highlights the conformability achieved by the hot line compactor. At the right, the shim is parallel with the outer upper surface of the pan-down. Moving from right to left, the shim drive system conforms faithfully to the ramp and levels out at the 2.5mm depth.

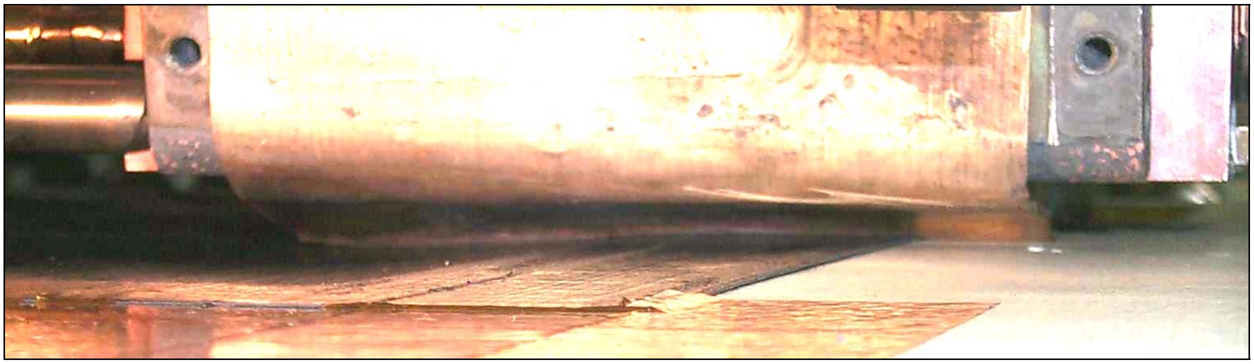


Figure 8 The hot line compactor conforms to the pan-down tool while laying PEEK tape.

Figure 9 shows the completed IM-7/PEEK pan-down laminate after it has been removed from the tool. The laminate stacking sequence is [0/90/0/90]s. Note that no autoclave consolidation was done; rather, the laminate is shown after trimming, just as it was in situ processed. Photomicrographs of the center and ramp areas of the laminate are shown in Figures 10 and 11, respectively.

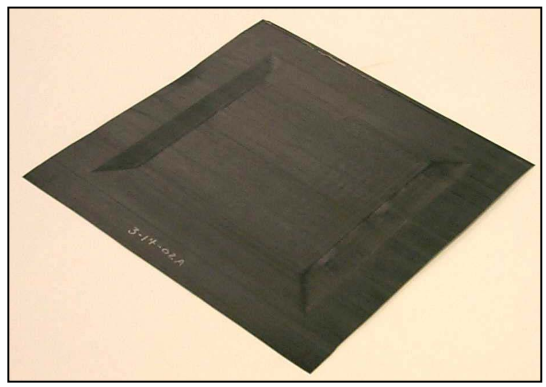


Figure 9 The completed IM-7/PEEK pan-down laminate, with a [0/90/0/90]s laminate stacking sequence

There are two polishing scratches in Figure 10. The figure shows that the interlayer welding that has taken place is excellent. There are no apparent voids at the interface between the 0° and 90° plies, and between the 90° and 90° plies. Some dark spots exist at the bottom 0° ply due to polishing. Note also the void reduction that has taken place in the IM-7/PEEK tape. There are few interlayer voids left.

Figure 10 Photomicrograph taken from center of in situ consolidated IM-7/PEEK pan-down laminate.

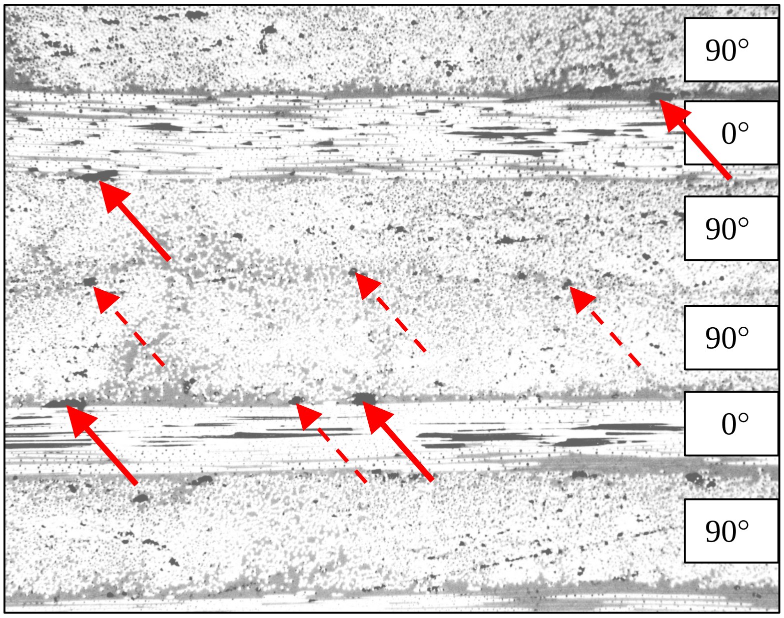


Figure 11 shows that the laminate quality in the ramp area is slightly worse than the quality in the center of the pan-down laminate. There are some very small interlaminar voids between the two center 90° plies. There are one small and two larger interlaminar voids between the lower-middle 90° ply and the 0° ply below it. There is also one void between the top-middle 90° ply and the 0° ply above it. The voids are labeled with arrows. The rest of the interfaces are well healed.

Figure 11 Photomicrograph taken from ramp of in situ consolidated IM-7/PEEK pan-down laminate

5. FABRICATED PYRAMID LAMINATES

The second padup tool is a mirror image of the pan-down tool described in Section 4, allowing placement of a pad-up or pyramid shaped laminate. A number of pyramid laminates were placed using the IM-7/PEKK material system in a 76mm (3-in) tape width. Figure 12 shows the upper surface of the resulting 16 ply [0/-45/90/45]2s laminate produced. Figure 13 shows the underside that rested against the tool. The underside shows the creases that form as the tool outside edge transitions to the ramp region.

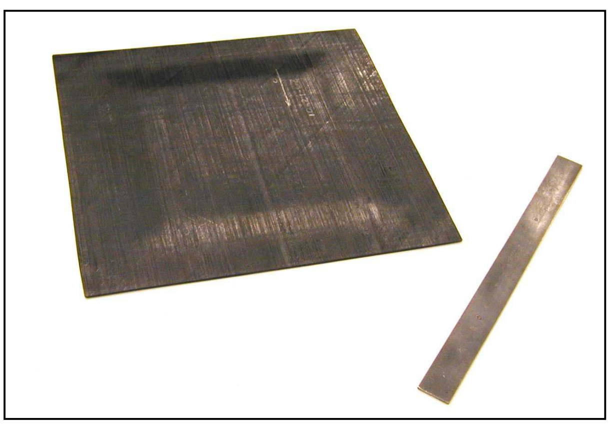


Figure 12 Top surface of [0/-45/90/45]2s pad-up laminate produced on pyramid shaped tool

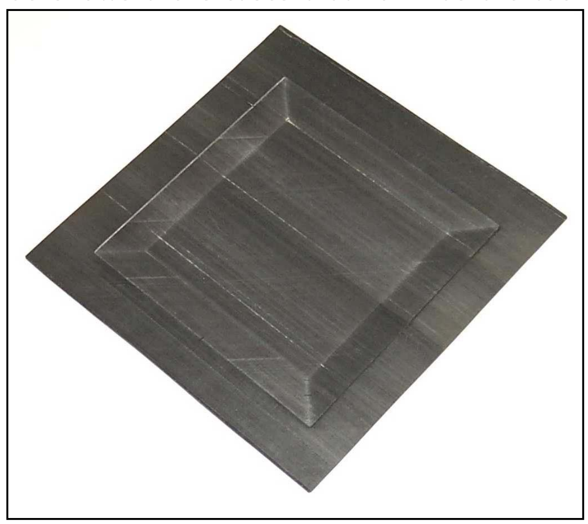


Figure 13 Tool surface of [0/-45/90/45]2s pad-up laminate produced on pyramid shaped tool

Figure 14 shows the conformance of the heated deposition head compactor on the edge region of this new pyramid laminate. In the photograph, the left side of the shim has ridden up the pad-up ramp and plateau while the right side is 2.5mm (0.1-in) lower on the laminate flange. The head is placing in the 0° direction in the figure. Figures 15 and 16 show the head placing in a 45°-course direction over the center of the laminate, where two ramps come together to form a 45°-crease. In Figure 16, the shim was removed to reveal the shim conformance against the laminate from the back side.

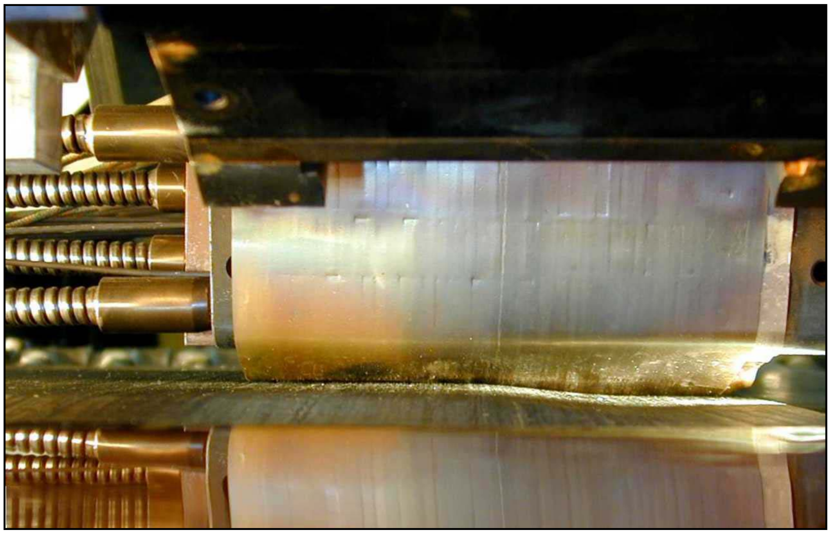


Figure 14 The conformance of the heated deposition head compactor on this new laminate is shown. The left side of the shim has ridden up the pad-up ramp and plateau while the right side is 2.5mm (0.1-in) lower on the laminate flange. The head is placing in a 0° direction.

Figure 15 The head is placing in a 45° course direction over the center of the laminate, where two ramps come together to form a crease.

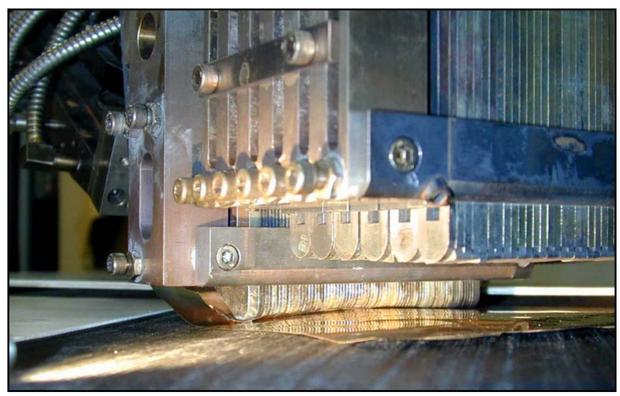
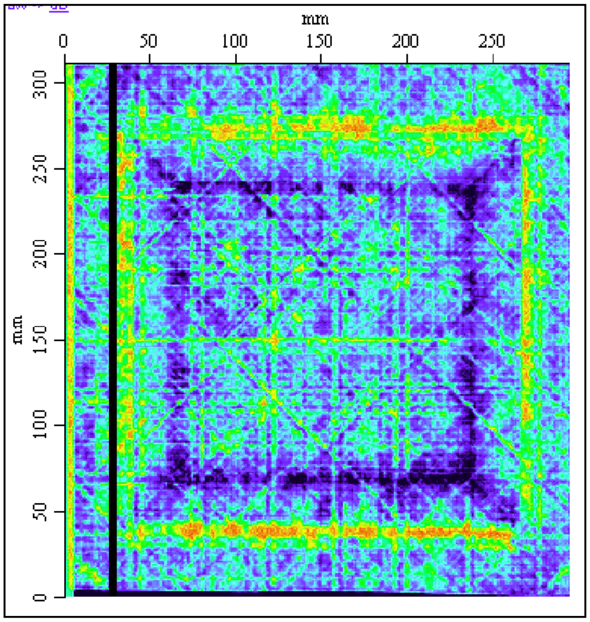


Figure 16 The shim was removed to show the shim conformance against the laminate from the back side.

Figure 17 is an ultrasonic through-transmission C-scan of the laminate at 5 MHz and 35 dB gain. It was taken at a 50.8mm focal length with a 0.6mm ultrasound beam diameter and a scanning resolution of 1mm. Figure 18 shows the dimensions of the laminate, allowing for easier interpretation of the C-scan plot. Much of the panel is a medium blue, indicating a C-scan loss of 6dB loss. The best quality appears to be at the ridge of the upper land, and areas of nearly 0dB loss are found. The angle of the 45° and –45° plies can be readily seen in the interior regions of the panel. The lowest apparent quality is at the re-entrant corner near the intersection of the outside lower land and the ramp region. The angel of the incident beam is being changed by the angle of the laminate in this region, but it may be that there are indeed areas of unconsolidated laminate at this transition.



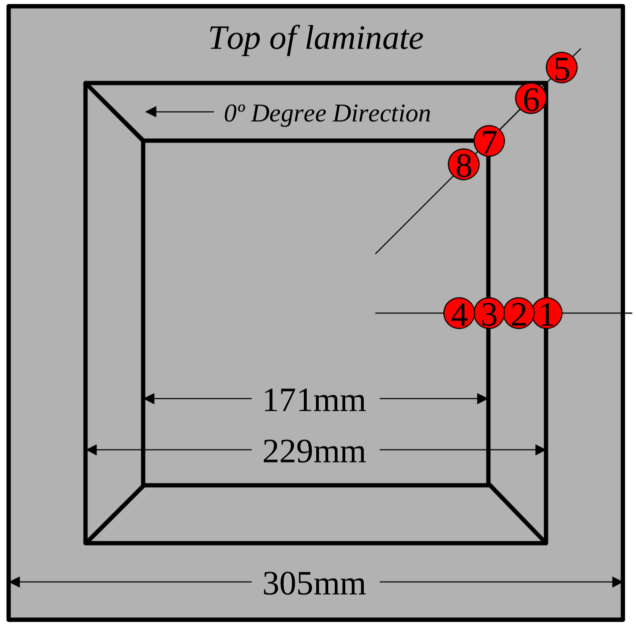


Figure 17 Ultrasonic C-scan of the pyramid-shaped laminate taking at 5MHz.

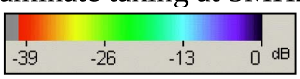


Figure 18. Laminate dimensions for the 16 ply [0/-45/90/45]2s IM-7/PEKK laminate. The numbered circles indicate the locations where photomicrographs were taken.

Figure 19 shows the photomicrograph of the laminate microstructure at the side ramp. The section is cut perpendicular to the edge transition line between the lower flange and the 10:1 ramp, looking from the top of the laminate. Conformance is very good away from the crease area. However, the compactor is unable to fully conform to the severe curvature in the crease area and some elevated void content is observed, especially in the second layer above the tool.

Figure 20 shows the photomicrograph of the laminate microstructure in the ramp region along the side of the tool. Here, the microstructure is very uniform, with even fiber/resin distribution, low intraply porosity, and almost no interply voids. This is a high quality laminate.

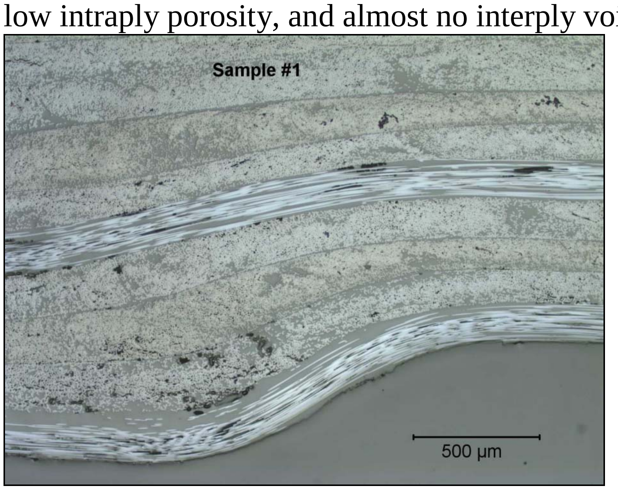


Figure 19 Photomicrograph of the laminate in the transition region #1 between the lower outside flange and the ramp.

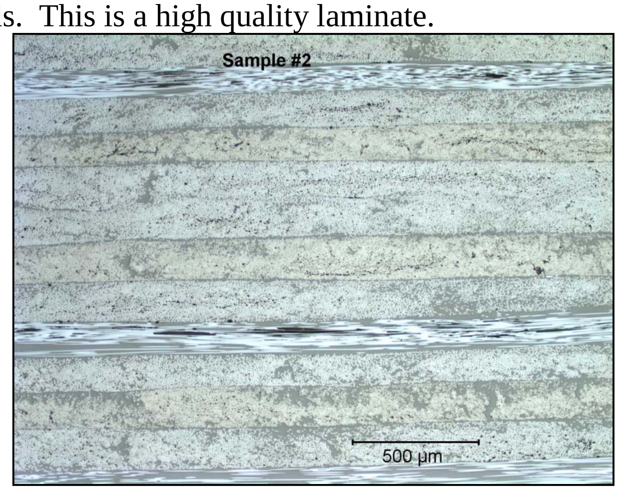


Figure 20 Photomicrograph of the laminate in the ramp region #2 between the lower outside flange and the plateau.

Figure 21 shows a photomicrograph of the transition between the edge ramp and the upper land of the pyramid. Again, the microstructure is high quality with the exception of some intraply voids in the center layers and some ply distortion. The ply distortion is in two areas. First, the ply nearest the tool is pinched at the exact point of the tool ramp to land transition. Second, the thicknesses of the 7th, 8th, and 9th plies vary substantially, trading off thickness with each other in the region just above the transition.

Figure 22 shows the photomicrograph of the laminate in the center. Here, the laminate microstructure is high quality, with good welds between plies, and very low intraply and interply void content. The ply consolidation between the 2nd and 3rd ply from the top is a particularly good example of excellent in situ consolidation. There is some non-uniform fiber/resin distribution in the laminate, creating a resin rich area.

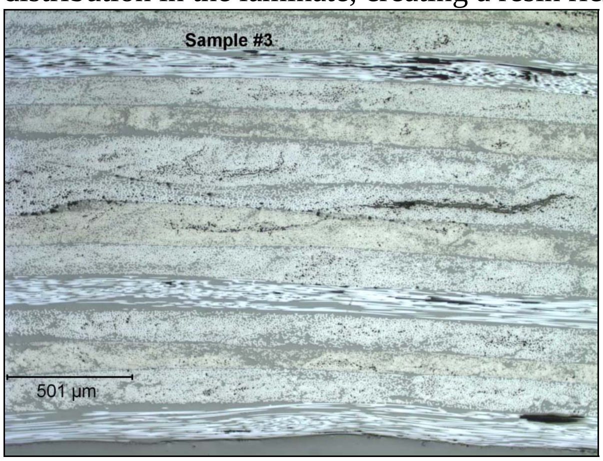


Figure 21 Photomicrograph of the laminate in the transition region #3 between the ramp and the upper land.

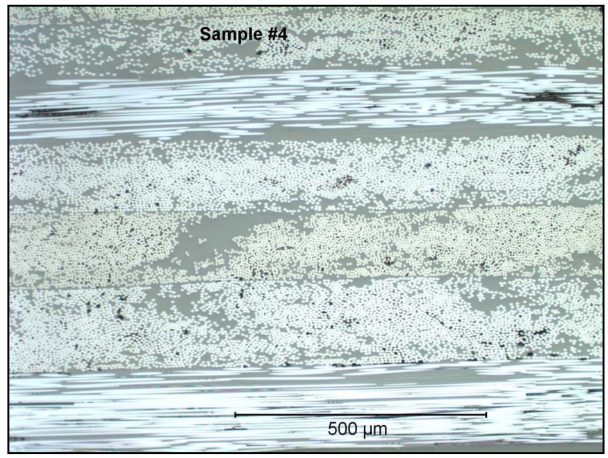


Figure 22 Photomicrograph of the laminate in the upper land region #4.

Figures 23 through 26 show the photomicrographs of the 45° crease between the top and side ramp regions. It was more difficult to locate the exact edge of the edges in the laminate with this series. Figure 23 shows the photomicrograph of the upper land. This photomicrograph shows the

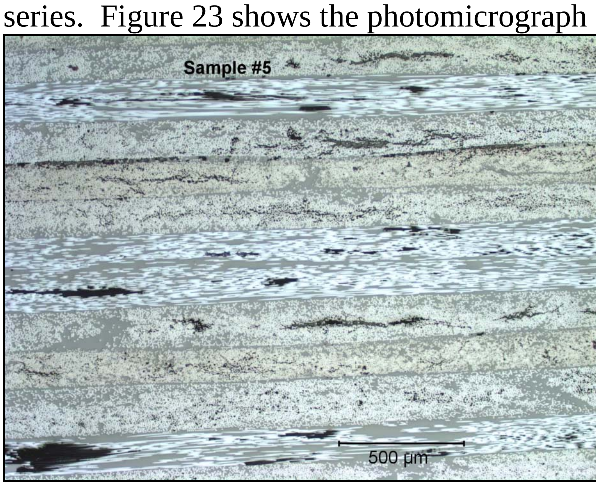


Figure 23 Photomicrograph of the laminate in the lower flange region #5 outside of the crease between the top and side ramps.

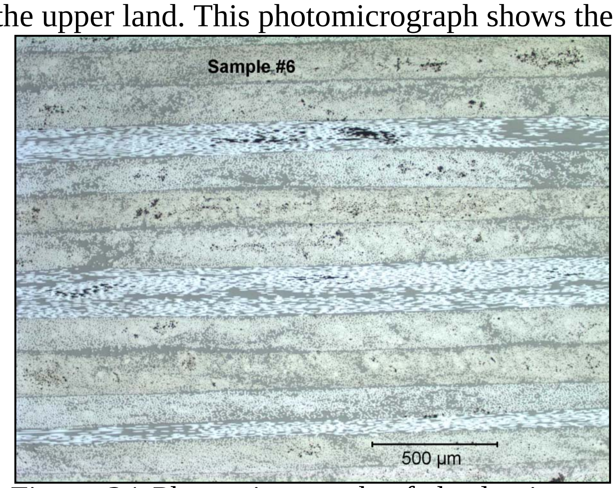


Figure 24 Photomicrograph of the laminate in the 45° crease region #6 between the top and side ramps.

laminate quality is not as uniform as in the other locations. There are pockets of voids in five of the plies. During the placement of this panel, the absence of significant run-on and run-off areas in the corner contributed to the lower quality in this area. This shows the difficulty in placing into the corner of the laminate near its outside edge, particularly when placing a 45° ply all the way into the corner.

Figures 24 and 25 show photomicrographs of the laminate quality in the crease, a challenging part of the laminate to place. The sloping angle of the plies is seen, looking from the top of the laminate as a reference point. Void content is only slightly higher than in Figure 20 for the side ramp, still low. Also, the ply-to-ply welding is uniform and there are almost no interply voids.

Figure 26 shows the photomicrograph of the laminate in location #8, the upper land. The transition to the upper land is shown in the lower left of the figure, as seen from the top. The laminate quality is about the same as in the crease locations.

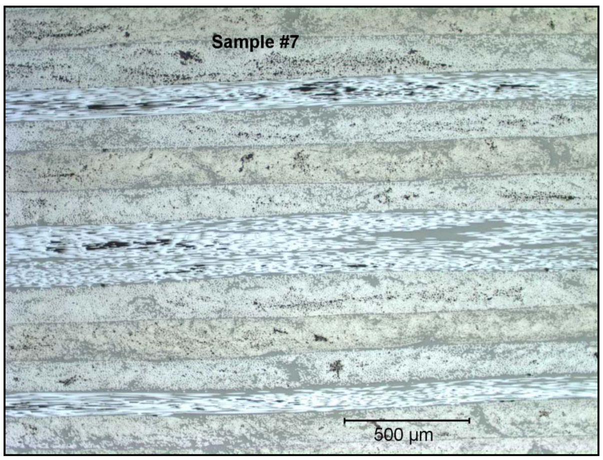


Figure 25 Photomicrograph of the laminate in the 45° crease region #7 between the top and side ramps.

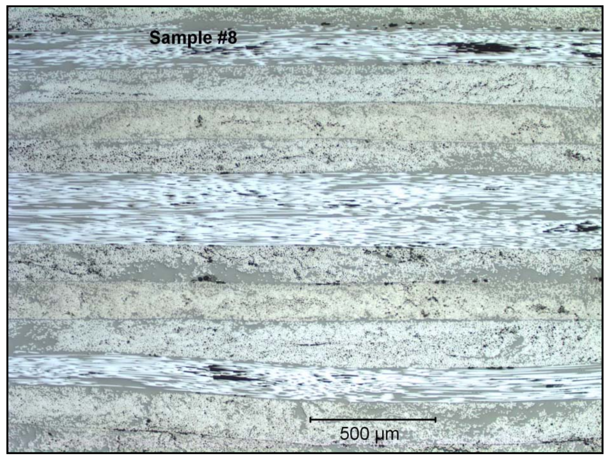


Figure 26 Photomicrograph of the laminate in the upper land region #8.

6. SUMMARY

The design of three conformable compactors has been completed. They include a 450°C hot line compactor capable of a 1000N (400-lb.) force over a 114mm (4.5-in) width, a 450°C hot area compactor capable of a 400N (100-lb) force over a 114mm by 76mm (4.5-in by 3-in) area, and a cold compactor that combines a line and an area compactor. The cold compactor's line segments act with a 2800N (700-lb) force across a 127mm (5-in) width, while the cold compactor's area segments act with a 1000N (250-lb) force over a 127mm by 102mm (5-in by 4-in) area.

The hot line and hot area compactors have been constructed and tested in hot mode to compact actual thermoplastic composite plies over undulating geometry. Resulting photomicrographs of completed IM-7/PEEK [0/90/0/90]s pan-down and IM-7/PEKK [0/-45/90-45]2s pyramid laminates show good quality. In particular, the head successfully consolidated laminate ramp and transition regions. Further development is required to assure adequate panel quality into the laminate corners. The head was unable to compact the laminate in the crease area on the underside near the tool, however this curvature at the crease was far more severe than anticipated by the conformance specification and the compactor designs. Further process development will aim at optimizing quality and throughput, and on quantifying the mechanical properties available by placing with a conformable deposition head.

ACKNOWLEDGEMENTS

The developments described herein required and benefited from the active participation of a number of highly talented engineers from several organizations. The authors are indebted to each of them. From The Boeing Airplane Company, Rick Evans had the vision to stimulate the initiation of compactor development. Many others worked to design them, including Al Schiede, Don Borisch, Ralph Rust, Rick Curry, Ron Hennies, Mike Grimshaw, and Chris Hamilton from Cincinnati Machine, Norm Johnston from NASA, Jim Pratte from Cytec Engineered Materials, Nan Gopez and Ross Hutter from Accudyne Systems, and Eric Venskytis from Enser. The University of Delaware Center for Composite Material Systems completed the ultrasonic C-scan.

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BIOGRAPHIES

Mark Lamontia, MSME - Mark spent 15 years of his 23 years at DuPont developing composite process and equipment and finished parts for the underwater vehicle and aerospace industries, especially using out-of-autoclave processing. He was Program Manager of the DARPA Advanced Submarine Technology Program, the ARPA/ARO RAPTECH program, and the NASA HSR Dry Materials Team to develop non-autoclave processable dry materials for fiber placement and tape laying. Mark has published 54 papers and reports in the field of composite process and equipment development.

Mark B. Gruber, MSME, P.E. - Mark has 20 years experience in DuPont and as a principal at Accudyne Systems. He was lead technical for several key thermoplastic in situ consolidation programs including the DARPA Advanced Submarine Technology Program, the DARPA/ARO RAPTECH programs, the NASA HSR program, and the Pratt & Whitney Advanced Composites for Propulsion (ACP) Program. Mark has also been active in thermoplastic ribbon and tape development. He holds eight patents for processing equipment for the manufacture of thermoplastic composite parts and has published 14 papers in the field of composites processing.

Steve B. Funck, BSEE – Steve has fifteen years experience in composite process manufacturing equipment. This included several assignments in the DuPont tow impregnation facilities. Steve was the principal investigator for in situ tow and tape placement on the DARPA RAPTECH-PMC and RAPTECH-ACM programs. In the NASA High Speed Research Program, he developed the processes to manufacture in situ consolidated skin stringer, honeycomb, and TiGr thermoplastic laminates. Steve joined Accudyne Systems, Inc in 1997, working on TIF and APC-2 line upgrades, redesign, and startup. Steve is the lead process engineer for the SBIR II Conformable Compaction System program.

Brian J. Waibel, MSME - Brian is a Senior Partner and a co-founder of Accudyne Systems. He developed the process and machine control systems for thermoplastic in situ deposition heads, especially DuPont's thermoplastic deposition head system developed under the RAPTECH programs and the NASA's High Speed Research program. Brian focuses on systems requiring the integration of machine control, process control, and process models.

Ralph D. Cope, PhDME – Following 2 years at Hewlett Packard Labs developing automation technology, Ralph became an Assistant Professor in the Mechanical Engineering Department at the University of Delaware. He started his own Engineering Company in 1993, then became a founding partner at Accudyne Systems, Inc, serving as President. His expertise includes creative problem solving and design, automation, biomechanics, composites, and system integration. Ralph designed the Generation 3 tow and tape placement head and led the design of the conformable compaction system.