In Situ Thermoplastic ATP Needs Flat Tapes and Tows with Few Voids

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SUMMARY

In thermoplastic automated tape/tow placement, prepregs are heated rapidly under pressure to processing temperature, then chilled as if autoclaved-processed, but with an application time period of only several seconds. Sponsored by NASA, University of Delaware Center for Composite Materials (UD-CCM) developed a model of Accudyne's patented thermoplastic tape/tow placement head to simulate the in situ process. The model reveals the detrimental effects of tape roughness and tape void content on laminate microstructure. Layer-to-layer intimate contact is hampered by a one-fifth power law applied to time, leaving behind *inter*ply voids in the laminate. *Intra*ply void removal is inhibited because the very compactors supplying the transverse pressure to the laminate eliminate the through-thickness escape route. Thus, the process needs flat, low void tape to place high quality laminates. Rough and smooth tapes were placed using the thermoplastic head, and the beneficial impact of placement-grade tape has been established in the new process model and by measuring laminate strengths.

1.0 THERMOPLASTIC ATP MODEL PREDICTIONS – QUALITY MODEL

In [1], Accudyne detailed the remaining developments required before thermoplastic ATP could be commercialized to fabricate large aerospace structures. One crucial need cited was to enhance process/quality models that correlate process physics with laminate microstructure to expose sources for the property gaps that exist. Sponsored by NASA, Accudyne and UD-CCM teamed to develop and validate a process and quality model of the Accudyne head, presented at this conference [2].

Figure 1-1 shows the quality model result for the head placing APC-2 AS-4 at 1.83 mpm. The head preheats the laminate until 12 seconds and the various compactors force the layers together until 24 seconds. The model then predicts the intimate contact, healing, and void content as the head passes over the process spot:

<u>Void Content</u> - The void volume reduces beneath and elevates between the compactors according to interplay between the pressure applied and the internal void pressure governed by PV=nRT. The incoming 5% voids elevate to 7% after preheating (no

pressure), then compress to 1% under the heated line compactor (high pressure). The voids soar to 10% between the heated line and area compactors, then retreat to 3.5% beneath the heated area compactor. The voids rebound to 10% between the heated area compactor and the chilled area compactor, fall to near 0% under the chilled line compactor, then increase to 3% under the chilled area compactor. If the laminate temperature does not drop below Tg, 145ºC for APC-2, the voids can and do rebound and reach values above the initial 5%.

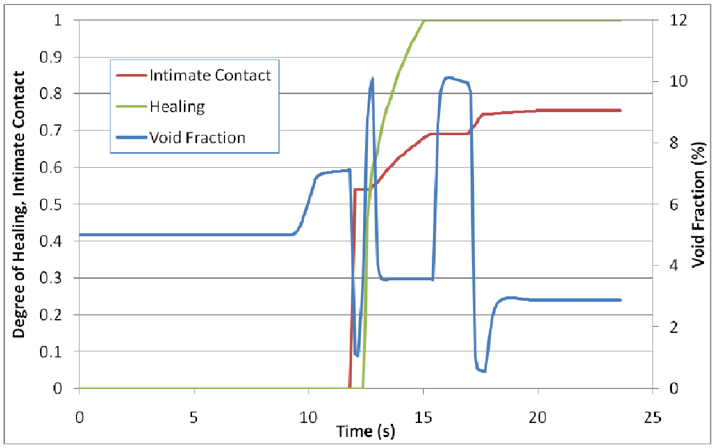


Figure 1-1 Quality model results when placing at 1.83 mpm show the void content starts at 5%, then rises and falls due to heating and compaction. The healing quickly achieves 100%. The intimate contact reaches only 76%.

Healing – Full healing is readily obtained with APC-2. The reptation times at processing temperatures are small compared to the dwell times beneath the heated compactors.

Intimate Contact – Only 76% intimate contact is achieved. The tape initial roughness is sufficiently high so that the newly contacted surfaces never fully come into contact, leaving interlaminar voids. Without full intimate contact, reptation/healing is limited, full bonding is not achieved, and neither are full mechanical properties.

2.0 INVESTIGATION OF ACTUAL TAPE AND LAMINATE SURFACE ROUGHNESS

Accudyne investigated the actual APC-2 tape and laminate roughness further. Figure 2-1 shows a tape surface profilometry scan exhibiting 35 micron peak-to-peak roughness. Figure 2-2 shows a 76 mm wide APC-2 AS-4 tape photomicrograph (folded over) with excessive roughness and high void content. Accudyne then measured the finished laminate roughness, shown in Figure 2-3, to determine if the head can smooth out the tape following heating, placing, and compacting.

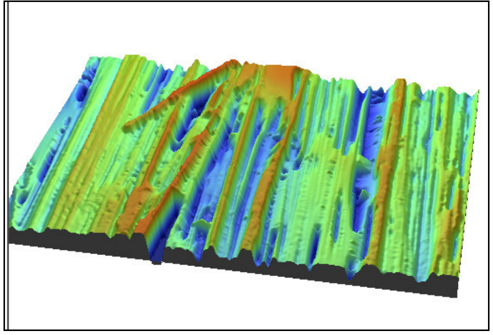


Figure 2-1 Michigan Metrology measured the surface profilometry on many tapes, with a 35 micron average roughness on 12 samples.

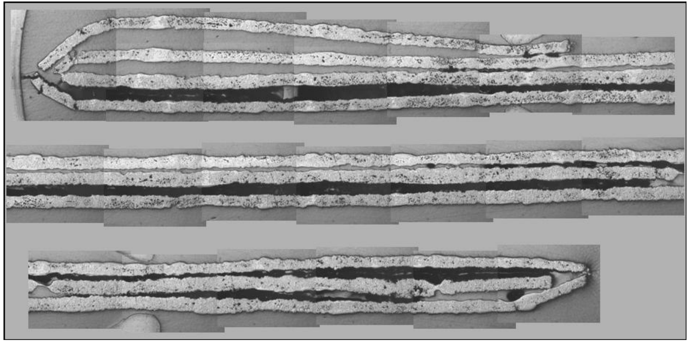


Figure 2-2 A photomicrograph of one folded-over 76 mm (3 inch) wide APC-2 AS-4 tape shows excessive tape roughness and excessive void content.

The average roughness amplitude diminished from 35µ on the tape to 17µ on the laminate. This proves that when placing commercial APC-2 AS-4, the ATP head is effective but unable to eradicate the tape surface roughness, and presumably is unable to achieve intimate contact in the laminate interior. Figure 2-4 shows the laminate photomicrograph corresponding to the Figure 2-3 profilometry. Now knowing what to look for, the upper laminate surface roughness is unmistakable.

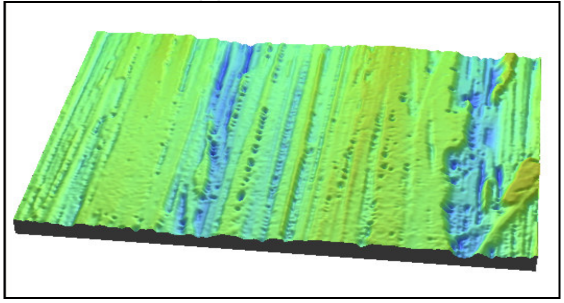


Figure 2-3 The surface profilometry on two laminates indicated a 17 micron average roughness.

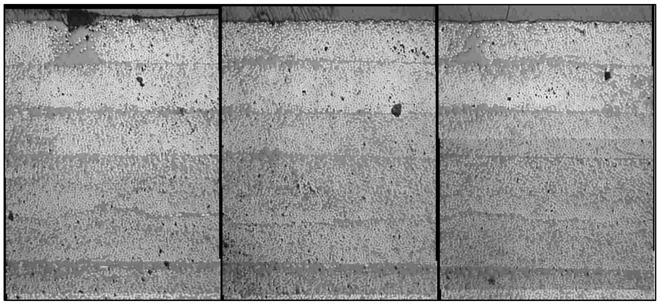


Figure 2-4 Tape roughness, evident on the upper surface of this 16-ply APC-2 AS-4 laminate, is not fully removed by the head.

3.0 DETAILED MODEL RESULTS – TEMPERATURE PROFILE, VOID CONTENT, AND INTIMATE CONTACT

Figure 3-1 shows the through-thickness temperature profile for the 16th ply in a laminate placement, along with the tape preheat temperature trace. Generally, the surface APC-2 AS-4 tape is heated to 430°C and chilled to 130°C over a 30 second period. Each interior layer is also reheated, about 25°C less for each layer near the surface, and about 15°C less for each layer near the tool. All but layer 1 exceeds Tg at least for some time during the process. The top four layers reach the melting temperature, 343°C. The heating sources assert considerable depth influence.

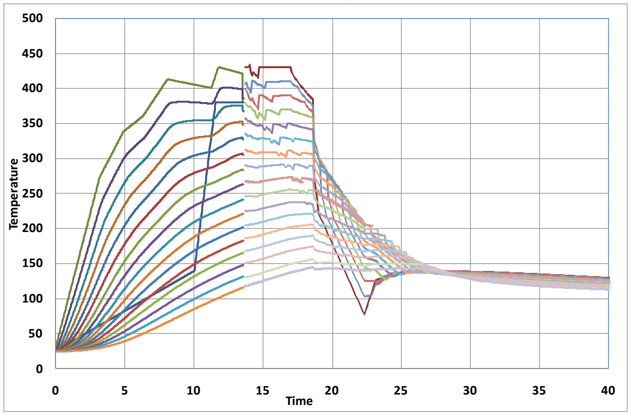


Figure 3-1 The through-thickness temperature profile for the 16th placed layer shows four layers reaching melt and all but layer 1 reaching Tg. All layers cool below Tg.

Figure 3-2 shows a cascade of layer void contents as the model simulates a 16-ply placement. Layer 1 voids are compressed from 5% to 3.6% after one layer, reach 0.9% after the 2nd, and so on until being fully compressed, taking advantage of the laminate reheating shown in Figure 3-1 and the re-compression. Layers 1 to 9 reach 0% voids, but layers 9 - 16 do not acquire the full advantage of reheating and recompacting.

Figure 3-3 shows a cascade of layer intimate contact during the 16-ply laminate simulation. Layer 1 achieves 76% intimate contact after one layer is placed. With more placed layers, it achieves full intimate contact as do layers 2 to 11. Layers 12 to 16 fail to achieve full intimate contact, as they do not each experience continual recompacting.

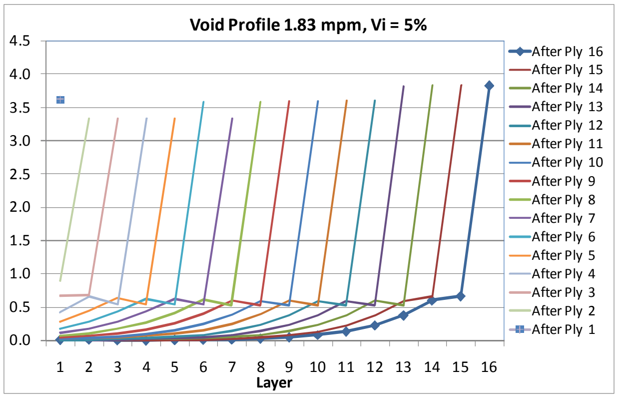


Figure 3-2 A cascade of layer void contents shows a 16-ply laminate should achieve 0% voids in the base layers, but not near the surface.

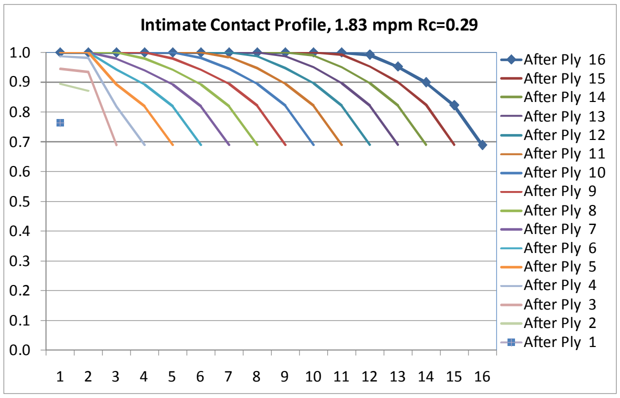


Figure 3-3 A cascade of layer intimate contact shows a 16-ply laminate achieves full intimate contact only after recompacting layers 1-11.

The void content and intimate contact analyses were completed for a number of conditions. The intimate contact conditions are the most varied and are repeated here. In Figure 3-3, the final intimate contact reaches 100% for layers 1-11, but falls after that for layers 12-16, ultimately to 68% at the surface. The ultimate intimate contact forms an envelope of the cascaded intimate contact plots, and of the laminate. Figure 3-4 shows three such envelopes. The familiar final intimate contact envelop from Figure 3-3 is shown in red. When placing slower at 0.9 mpm, the laminate reaches full intimate contact for all layers but 15 and 16. When placing faster at 3.0 mpm, no layer reaches full intimate contact. Figure 3-4 clearly shows that tape initial roughness specifications will be a function of placement speed to achieve autoclave part quality and properties.

Figure 3-5 asks the question – what initial roughness is required? Must the tape be perfectly flat with an Rc = 1 [2]? In the Figure, the envelope with 1.8 mpm placement

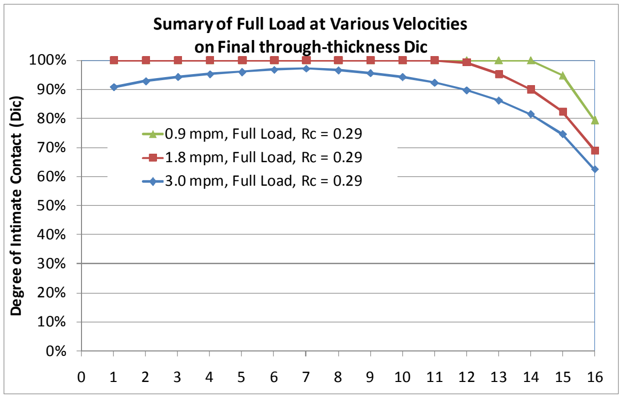


Figure 3-4 An envelope of intimate contact cascades for 0.9, 1.8, and 3.0 mpm placement speeds shows intimate contact is almost fully achieved when placing slow, but is never achieved when placing fast.

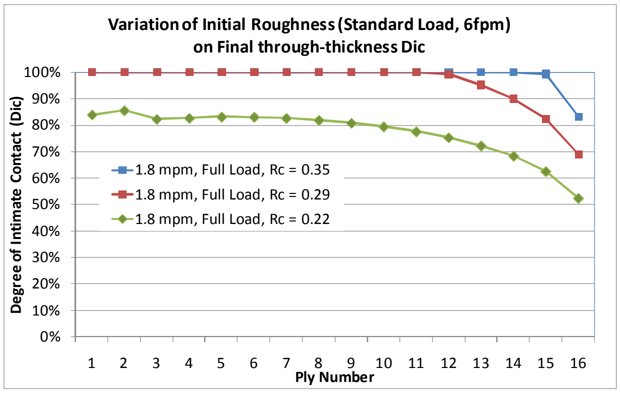


Figure 3-5 An envelope of intimate contact cascades shows tape roughness need not be perfect (Rc = 1) to achieve full intimate contact, but an improvement to Rc = 0.35 from Rc = 0.29 would pay handsome dividends.

speeds is again plotted with Rc = 0.29. A much rougher tape with Rc = 0.22 degrades the laminate. But if Rc = 0.35, the laminate achieves almost perfect intimate contact, even at 1.8 mpm placement speed.

4.0 Varying Head Parameters to Eliminate Voids and Increase Intimate Contact

A number of parameters were varied to determine a set that would yield improved laminate microstructure and, thus, properties equivalent to that measured from autoclaved laminates. Four examples are included.

4.1 Change Forces on the Chilled Line and Chilled Area Compactors

What if the forces on the chilled compactors are redistributed from the chilled area compactor to the chilled line compactor? The baseline distribution is 62% to the chilled line compactor. Figure 4.1-1 shows that as the chilled area compactor gives up its share of the chilled compactor suite's loads, the intimate contact remains unchanged. Figure 4.1-2 shows that the voids would increase significantly, from 2.8% at standard conditions, to a staggering 7.2% if the chilled area force is given to the chilled line compactor. The chilled area compactor is significant in keeping pressure on voids until the laminate solidifies and gains strength at Tg.

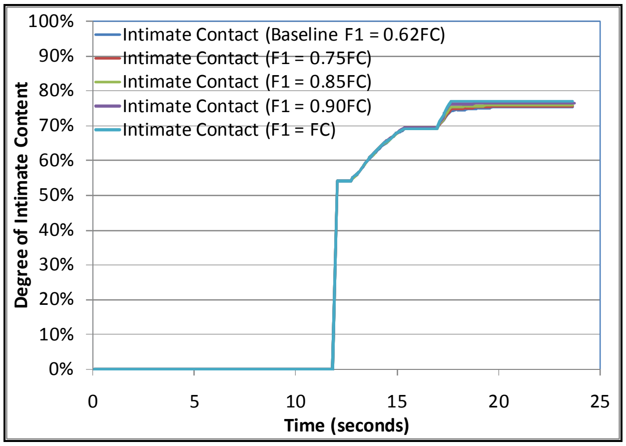


Figure 4.1-1 Transferring more load from the chilled area compactor to the chilled line compactor does little to change the layer intimate contact.

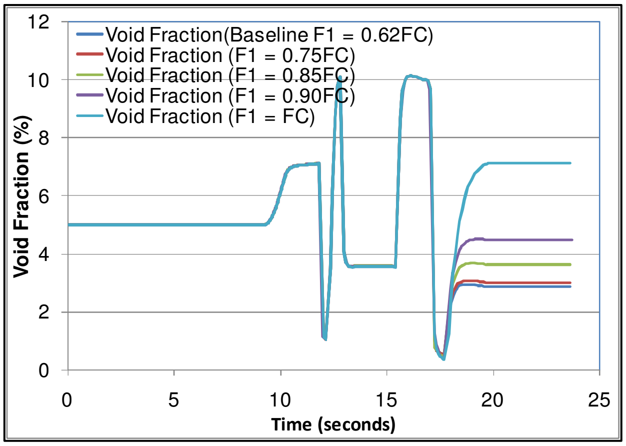


Figure 4.1-2 Transferring more load from the chilled area compactor to the chilled line compactor causes the layer voids to increase.

4.2 Change Forces on the Heated Line Compactor

What if the forces on the heated line compactor are significantly increased? The baseline load is 800 N, and Figure 4.2-1 shows the increase in intimate contact with an increase in heated line compactor load to 1600 N, to 3200 N, and finally to 4800 N, some six times the initial load. This option increased the final intimate contact from 75% to 86%, a modest improvement. Unfortunately for the actual equipment, no fiber placement machine or tape layer could exert such a large force. In addition, the head's shims could not withstand such a large compaction load. Thicker shims might last, but the head's ability to conform to complex curvature would be diminished.

4.3 Placing at Lower Velocities

What if the placement velocity is slowed? There would be extra time to improve the intimate contact. Figure 4.3-1 shows the result. Placement at 1.8 mpm yields a final intimate contact of 76%. Slowing to 0.9 mpm yields 87%. Slowing further to 0.46 mpm yields full intimate contact; an impressive improvement, if not economically viable.

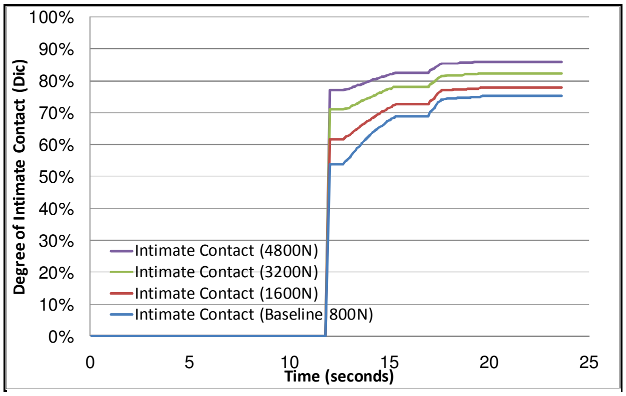


Figure 4.2-1 Increasing the heated line compactor load increases the intimate contact achieved from about 75% to 86% with increases in transverse compaction loading of 2X, 4X, and 6X.

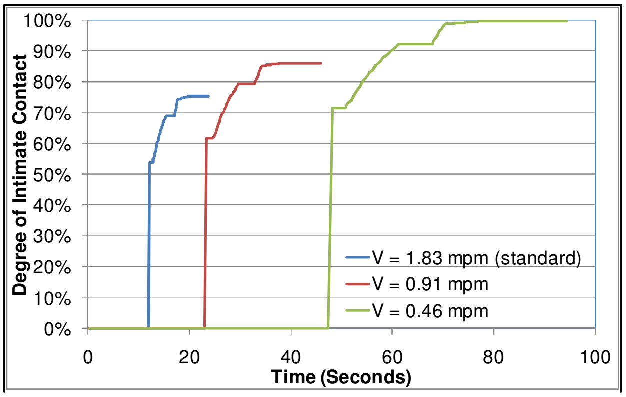
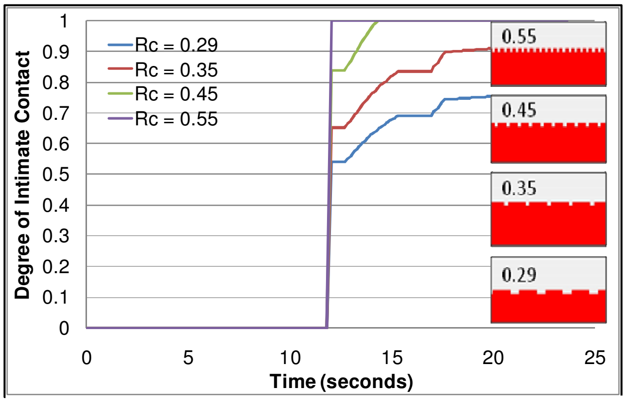


Figure 4.3-1 Decreasing placement speed from 1.83 mpm (6 fpm) to 0.91 mpm (3 fpm) to 0.46 mpm (1.5 fpm) increased the intimate contact from about 76% to 87% to 100%.

4.4 Placing Smoother Tape



By far the most effective route to increase intimate contact and thereby the degree of bonding is to place with flatter tape. Figure 4.4-1 shows the intimate contact achieved with different tape roughness values from Rc = 0.29 to Rc = 0.55. A schematic of tape roughness is shown as well. If Rc = 0.45 or higher, full intimate contact is achieved. Note that the tape does not need to be perfect.

Figure 4.4-1 The impact of tape roughness on the degree of intimate contact is shown along with four tape cross-section schematics. The higher the Rc, the more readily the head is able to achieve full intimate contact in the placed ply.

5.0 Placing with Commercial and Experimental APC-2 AS-4 Tape

Accudyne has published a placement grade tape and tow specification [1]. The most important features are:

- Fiber areal weight: 145 g/m^2
- Resin weight fraction: 35% ± 1%, uniform fiber/resin distribution
- Thickness variation: less than 6% across entire width
- Width variation: +0.00, -0.10 mm
- Void content: less than 1%

Cytec Engineered Materials is developing a tape to meet the placement-grade specification, as shown in Figure 5-1. Cytec supplied tape to Accudyne to characterize the benefit compared with commercial APC-2 AS-4, intended for autoclave processing.

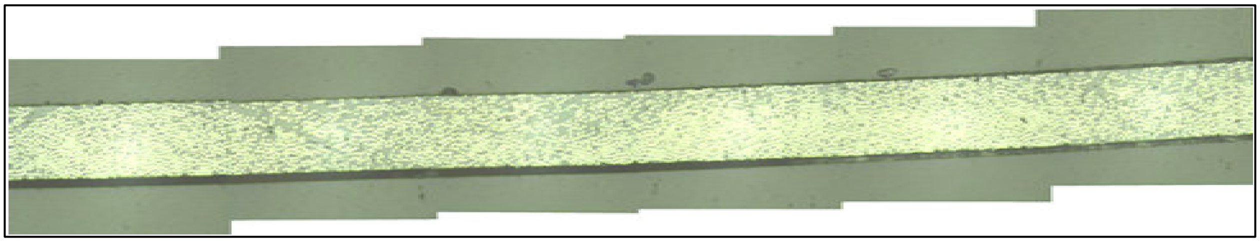
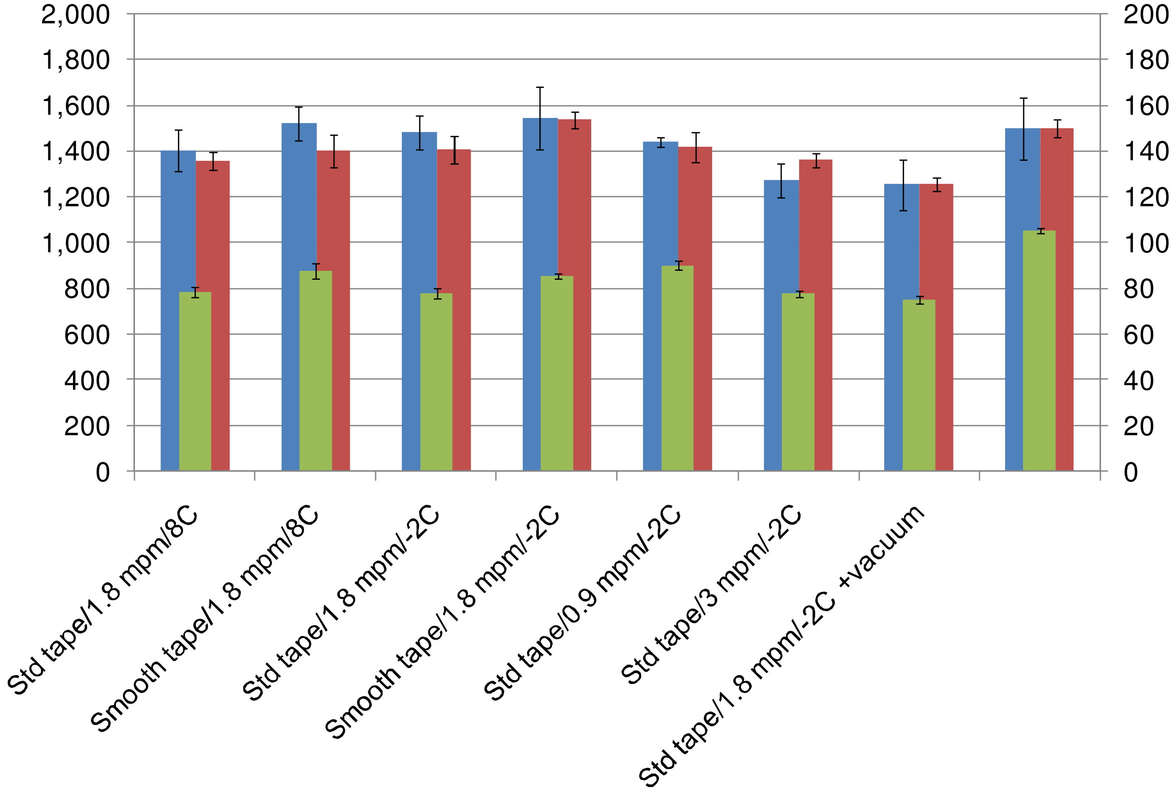


Figure 5-1 Cytec is developing a placement grade APC-2 AS-4 tape, with uniform thickness, few voids, and a more uniform fiber/resin distribution.

Accudyne and UD-CCM fabricated and tested ten laminates under a number of conditions [2]. Some evaluated a new chilling system to prevent void rebound. Some evaluated the new experimental Cytec tape. Other laminates evaluated process conditions such as changing compaction forces and process speeds. Figure 5-2 shows the short beam shear strength and flex strength from the tested laminates.



Significant conclusions based on the models and the above data are listed below:

- **Flat Tape** – The experimental Cytec flat tape was effective compared with the rough commercial APC-2 AS-4. The improvement can be observed in flexural strength and short beam shear strength for both the less-effective chilling system (cool to 8ºC) and the more-effective chilling system (chill to -2ºC). While placing with experimental flat APC-2 AS-4 tape at standard speed, 1.8 mpm, SBSS increased by 11% and flex strength increased by 7% compared with standard APC-2 AS-4.
- **Flat Tape and Improved Chilling** - With flat tape and improved chilling, flexural strengths reached autoclave levels, although SBSS did not.
- **Decreasing Placement Speed** – Placing standard APC-2 tape at ½-speed (0.9 mpm), increased SBSS by 14% and increased flex strength by 3%.
- **Increasing Placement Speed** – Placing standard APC-2 tape at a 3.3 mpm rate decreased SBSS by 1% and flex strength by 7%, even with better chilling conditions.
- **Post Compacting with Vacuum Bag** – Due to the relatively high compactions pressures, post-processing under vacuum pressure resulted in significant void growth and deconsolidation.

6.0 CONCLUSIONS AND FUTURE WORK

UD-CCM developed a model of the Accudyne ATP head and process, which was validated from 0.9 mpm to 3.0 mpm process velocities. UD-CCM's quality model predicted the harmful impact of incoming tape voids and roughness on final laminate microstructure. The team searched for head/process parameters to remedy the microstructural defects, but only discovered impractically low placement velocities or huge compaction forces. The best remedy is to improve tape quality. An experimental Cytec APC-2 AS-4 proved this hypothesis, scoring flexural and short beam shear strength gains rivaling the gap between in situ ATP and autoclave properties.

The team plans model updates to develop a better intimate contact model to use actual tape profiles, an intraply void model, a MW distribution/crystal melting model, head modifications, and placement of test laminates more of interest to aircraft manufacturers. Further, the team is highly interested in experimental Cytec tape. Finally, the team plans to investigate head and process modifications to make the process more robust even with commercial tape.

7.0 ACKNOWLEDGEMENTS

The Accudyne/UD-CCM team acknowledges the fine work of Michigan Metrology in profilometry and heartily recommends them. We especially acknowledge Cytec for their supply of experimental APC-2 AS-4 tape, and encourage their continued development.

8.0 REFERENCES

1. M. A. Lamontia and M. B. Gruber, "Remaining Developments Required for Commercializing In Situ Thermoplastic ATP," Proceedings of the 2007 SAMPE Conference and Exhibition, Baltimore, MD, June 3, 6, 2007.
2. M. A. Lamontia, M. B. Gruber, J. J. Tierney, J. W Gillespie, Jr., B. J. Jensen, and R. J. Cano, "Modeling the Accudyne Thermoplastic In Situ ATP Process," 30th International SAMPE Europe Conference, Paris, March 23-25, 2009.