Modeling the Accudyne Thermoplastic In Situ ATP Process

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SUMMARY

Sponsored by NASA, Accudyne teamed with the University of Delaware Center for Composite Materials (UD-CCM) to develop simulations of Accudyne's patented thermoplastic ATP head and process. The model captures the relevant physical mechanisms involved, including heat transfer to calculate the distributed temperature field in the laminate, intimate contact to examine interply void creation/elimination, reptation/healing to build interface strength, crystalline melting and recrystallization, consolidation, void compression, and void rebound following the process. Each layer's temperature history is catalogued throughout laminate fabrication so the heating effectiveness to depth is observable. The model accommodates the tooling heat conductivity and heat capacity and tracks the tooling's influence throughout the lamination. The microstructural quality is estimated throughout the process. The model underwent significant validation. The model reveals the impact of heating and compaction on laminate microstructure. Head, process, and control system modifications dictated by the model are responsible for improvements in APC-2/AS-4 laminate mechanical properties.

1.0 THERMOPLASTIC IN SITU PROCESS, EQUIPMENT, AND PROPERTIES

Accudyne has developed and patented a thermoplastic tape and tow placement head, process, and control system for fabricating composite laminates without an autoclave [1-4]. The head, shown in Figure 1-1, is conformable to 10:1 slopes with a 12 mm height [5-7] and places one 75 mm tape or twelve 6.35 mm tows. The head has fabricated laminates that achieve 89-97% of various strengths measured from autoclaved laminates, as shown in Figure 1-2. If the strengths generated by thermoplastic in situ consolidation would rise to levels measured from post-autoclave cured

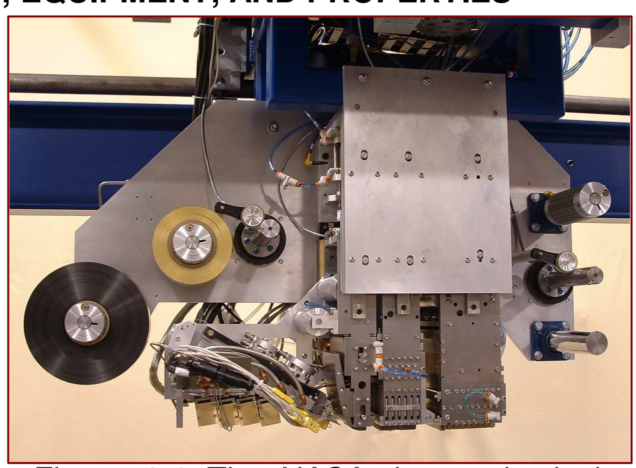

Figure 1-1 The NASA thermoplastic in situ consolidation tape deposition head on the NASA-LaRC gantry.

laminates, the most significant barrier blocking the adoption of the thermoplastic process and equipment would be eliminated. Achieving the last 10% of property translation is elusive [8], so the team sought to fully model the process to identify the important physical and material mechanisms controlling microstructure and properties.

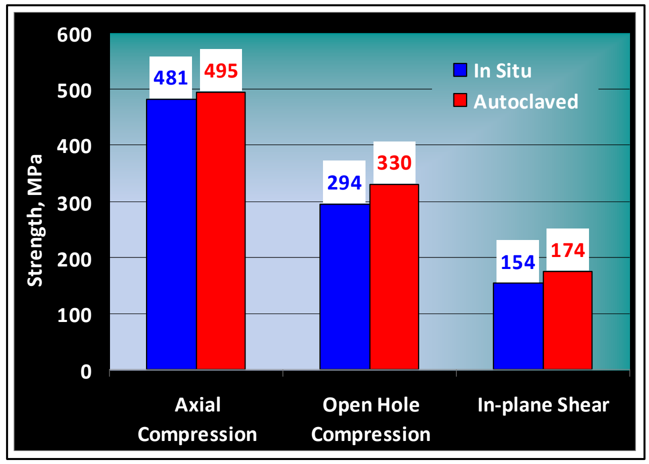

Figure 1-2 APC-2/AS-4 laminate strengths resulting from the in situ consolidation and autoclave process.

2.0 PROCESS MODEL DESCRIPTION

A set of models for the in situ Automated Tow/Tape Placement (ATP) processes that capture the important process phenomena were developed by UD-CCM. The models, shown in Figure 2-1, were used to improve the head and process and demonstrate final laminate quality gains through hardware upgrades. The process models are integrated into two parts:

1. The heat transfer solution that generates the temperature field in the material, and
2. The quality models that calculate laminate microstructural quality.

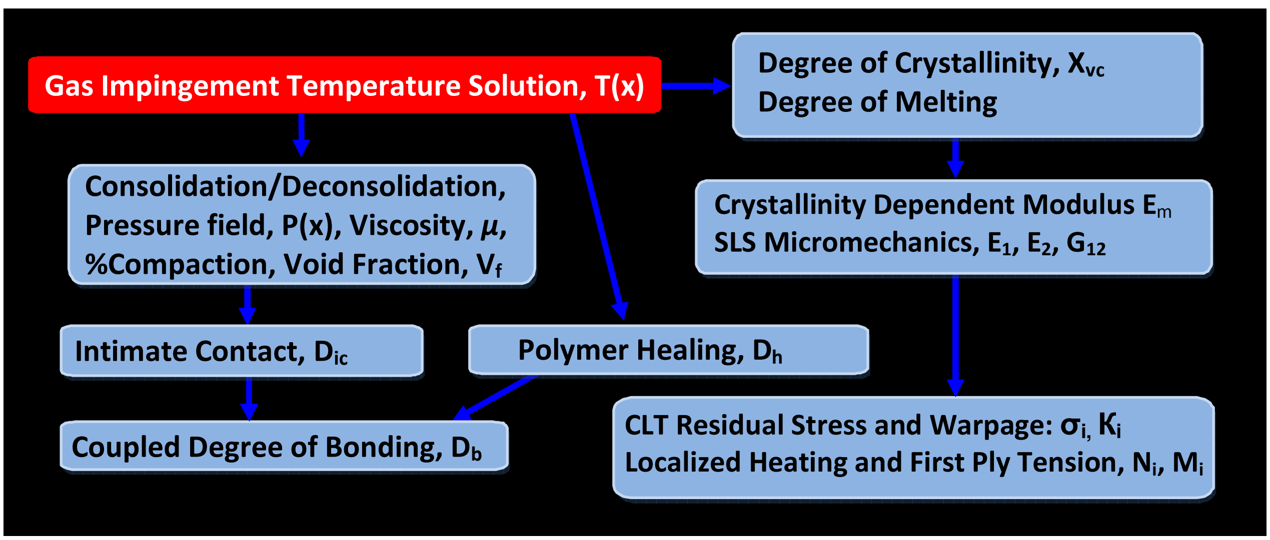

Figure 2-1 The thermoplastic tow/tape placement models developed at UD-CCM simulate the heat transfer in the laminate and then calculate the microstructural quality.

The temperature field is simulated [9] with a gas impingement temperature solution since the head employs five combustion gas torches as laminate heat sources. Energy input from the heated and chilled compactors is also accurately captured by the model. With the heat transfer solution in place, the quality model determines the laminate microstructure with several submodels:

1. A consolidation model for each head compactor tracks the pressure field within the laminate and applies the pressure to incoming voids so that the void content is monitored throughout and after the process [9].

2. The intimate contact between the mating surfaces of the incoming tow/tape and the previously placed laminate is monitored based upon process conditions and the initial roughness [10].
3. The polymer interdiffusion that heals the interfaces that have achieved intimate contact and builds during multiple passes is calculated based upon the heating from each head compactor.
4. The degree of bonding is computed anywhere there is intimate contact and healing so the interlayer strength can be estimated [11, 12, 13].
5. Based upon heating and polymer physical properties, the degree of crystal melting is monitored entering the process spot beneath the heated line compactor [14].
6. Based upon the cooling rate of the chilled compactors, the laminate cooling following the process, and the crystalline kinetics, the degree of crystallinity in the final laminate is calculated [14].
7. The degree of crystallinity is used to calculate the resin modulus achieved, and through laminate micromechanics, the composite properties are estimated [11].
8. The residual stresses and warpage are calculated to determine the final laminate shape [15, 16, 17].

3.0 PROCESS MODEL VALIDATAION WITH HEAT TRANSFER EXPERIMENTS

Along with model development, Accudyne and UD-CCM worked diligently to validate the heat transfer model upon which the quality model depends. The deposition head was used to place laminates with four embedded thermocouples to validate the heating model, as shown in Figure 3-1. Some placement runs were made by running one head module at a time to assure model accuracy for each compactor, as shown in Figure 3-2. The temperature profiles also show the effectiveness of the Accudyne head heating.

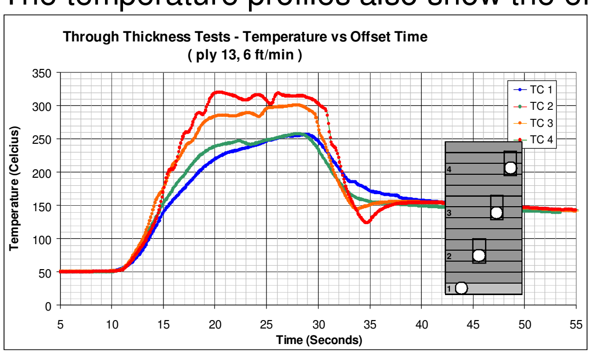

Figure 3-1 Temperature history for the Accudyne thermoplastic head placing at 1.83 mpm (6 fpm). Four thermocouples were embedded in the laminate, at the tool surface, and at the interfaces of plies 4-5, at plies 8-9, and plies 12-13.

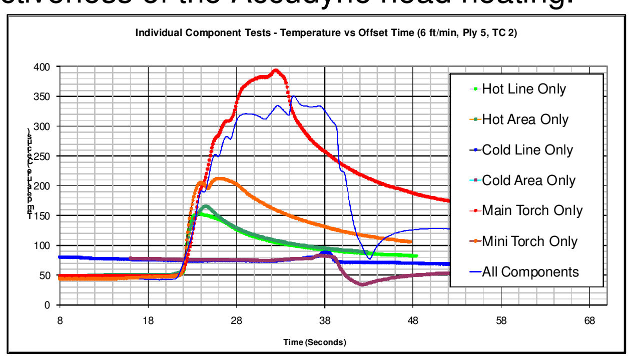

Figure 3-2 The Accudyne thermoplastic head placing at speeds of 1.83 mpm. The embedded thermocouple is one ply down into the unidirectional laminate. The effect of each heat source and individual compactor is measured.

Figure 3-3 shows the validated thermal profiles. The model reasonably predicts the transient heating, especially at the rapid heating and rapid cooling zones. The peak temperature appears less accurately predicted; however, recall the thermocouples are embedded one tape layer down, so the measured temperatures should be lower than the modeled surface temperatures. Figure 3-4 shows the heating color contour plot beneath a photograph of the head. The four combustion gas torches heat the underlying substrate from their initial temperature to near melt. The mini-torch trim heats the tape to $T_{process}$.

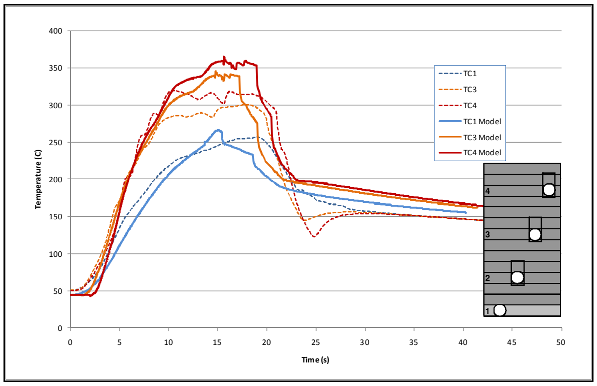

Figure 3-3 The thermal profiles were validated by comparing model predictions with experimental temperatures recorded from embedded thermocouple runs.

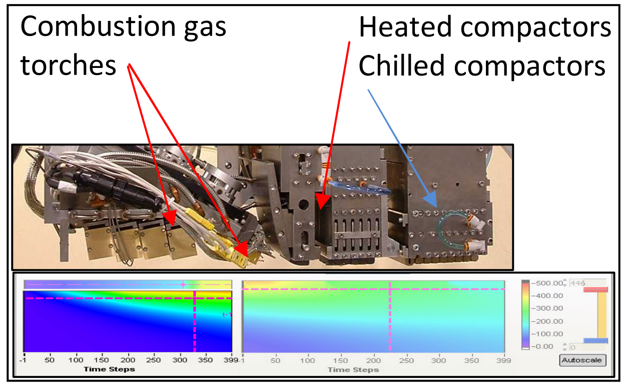

Figure 3-4 The head heating/chilling sources effectively increase the tape temperature to melt, maintain it, and then chill it to near Tg. The heating is effective several layers down.

The laminate temperature is accurately captured in the color contour plot and shows the heating is active to a significant depth into the laminate. Then, the compactors force the layers together under heat and pressure. The temperature is maintained until the chilled compactors reduce it. From the right color contour plot, the thermal heating diffuses throughout the laminate, and the surface becomes chilled.

4.0 PROCESS QUALITY MODEL RESULTS

Figure 4-1 shows the quality developed in the laminate. Figure 4-1a shows the void content under the head. Figure 4-1b shows the Intimate Contact, IC, the Degree of Healing, DoH, and the Degree of Melting, Xvc. Figure 4-1c shows the increase in healing during a ply placement, and Figure 4-1d shows the melting.

Void Content - In 4-1a, the incoming voids are 5%. Without any mechanism to evolve voids from the tape to the atmosphere, the void volume reduces under the compactors and elevates between the compactors according to the pressure applied at any point in the process and the ideal gas law that translates the applied pressure to the void volume. Following the trace, the 5% voids elevates to 7% after heating, only to fall to near 0% under the heated line compactor. The voids jump to 9% between the heated line and area compactors, then falls back to 3% under the heated area compactor. The voids jump to 9% between the heated area compactor and the chilled area compactor. The voids then fall to near 0% under the chilled line compactor, then increase to about 2% under the chilled area compactor, and also visibly fall as the compactor pulls internal energy out of the layer. Since the temperature does not fall to Tg, 145°C for APC-2 composites, the voids rebound and reach 7%, higher than the initial 5% due to the elevated temperature. The head needs a more effective chilling system.

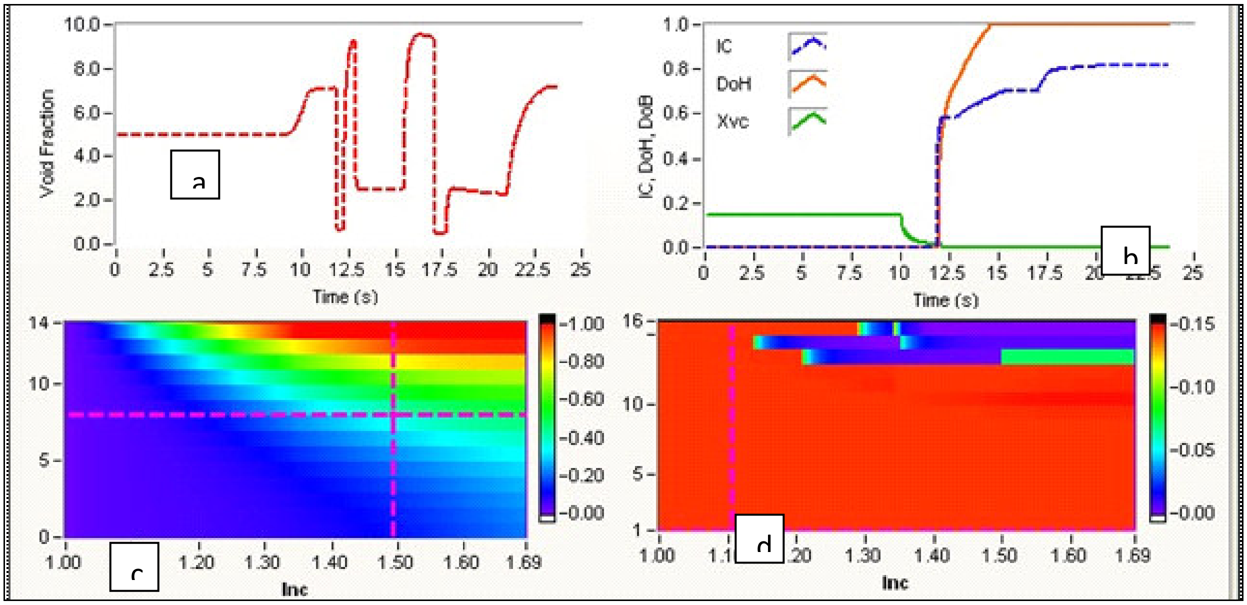

Figure 4-1 (a) Surface void fraction through the process, (b) Degree of melting (Xvc), Degree of Healing (DoH), and Intimate contact (IC) on the surface ply, (c) Degree of Healing through the thickness and (d) snapshot of internal crystallinity and the melt pool (shown in blue) on the surface.

Melting, Healing, Intimate Contact – Figure 4-1b shows that the degree of crystallinity falls to zero as the tape travels beneath the process spot, indicating that the resin has fully melted. The degree of healing quickly achieves 100% beneath the compactors; a general result over a wide range of process conditions. However, the degree of intimate contact achieves only about 80% in this simulation. The tape's initial roughness is too high, and the surfaces never fully come into contact, leaving interlaminar voids[18]. The degree of bonding, defined as the integration of the degree of intimate contact and the degree of healing, is never fully achieved, and neither are full mechanical properties. A flatter tape is needed, or the head must be redesigned to place rough tape[18].

Healing Development – Figure 4-1c shows the increase is healing as the tape is placed. To the left, there is no increase in healing. As the head heats the laminate and moves over the process spot, full healing is readily obtained, as was also shown in plot (b). In this plot, the effectiveness of through-the-thickness healing is shown, Even one layer down, full healing is readily obtained, and partial increases in healing are readily available by the head, even over 40%/pass half way down the laminate.

Melt Front – Figure 4-1d shows the melt front as indicated by the degree of crystallinity. When the crystals are all fully melted, the plot layers are blue. Thus the molten resin extends 2 to 3 plies down into the laminate at the 1.83 mpm (6 fpm) placement speed.

5.0 TEST LAMINATES

Motivated by model predictions, Accudyne and UD-CCM fabricated ten laminates under a number of conditions, and measured short beam shear strength and flex strengths, as shown in Figure 5-1. Significant conclusions are:

- **Better Chilling** - A more effective chilling system was evaluated to reduce the placed layer temperature below Tg so as to steer clear of void rebound. Laminates were placed with the less-effective chilling system (cool to 8ºC) and the more-effective chilling system (chill to -2ºC). Placing standard tape while using improved head chilling maintained SBSS and increased flex strength by 1 – 5%.
- **Flat Tape** - Cytec supplied Accudyne with an experimental flat APC-2 AS-4 tape. Placing with experimental flat tape at standard speed, 2 mpm, increased SBSS by 11% and increased flex strength 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*, (1 mpm), increased SBSS by 14% and 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.
- **Lowering the Compaction Load** - Placing standard APC-2 tape with ¼ of the normal compaction load maintained SBSS and decreased flex strength by 7%

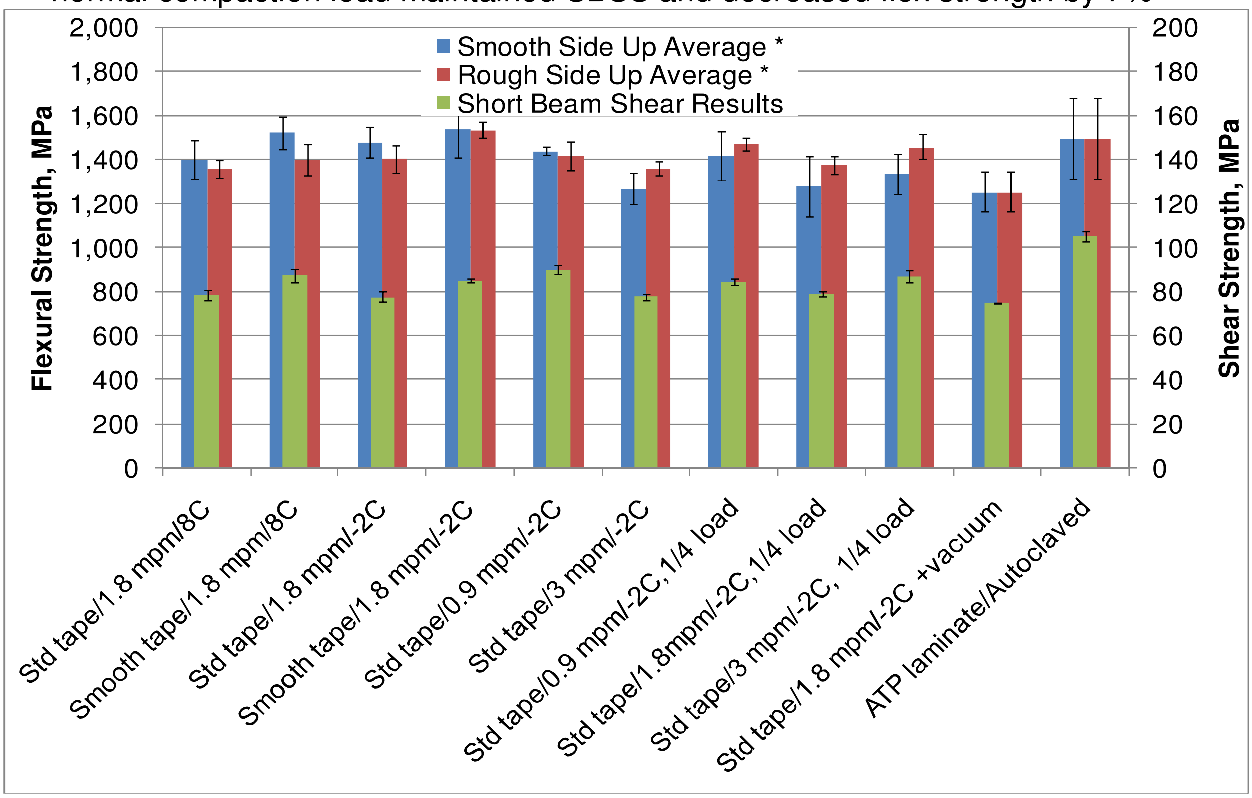

Figure 5-1 The short beam shear strength and flexural strength test on ten placed laminates is shown. Placing with flat tape and using improved head chilling increases mechanical properties, including the flexural strength to autoclave values, although SBSS lags. Compacting with only a ¼ load reduces properties. Using a vacuum bag oven reconsolidation is ineffective, and even reduces mechanical properties.

6.0 CONCLUSIONS

A summary of the results of Phase 1 is shown in Table 6-1. The process model was effective in dictating head improvements. Heat transfer, reptation/healing, crystalline melting, crystallinity generation, and avoiding degradation all work well. However, the tape roughness and void content cannot be eliminated by the head. Increasing placement speed or reducing placement compaction loads are detrimental. Flat, void-free tape is preferred for the process. Alternatively, a more robust head, able to successfully place commercial tape, is needed.

Table 6-1 Results of the STTR Phase 1 program show benefits and liabilities of the head, process, and material.

	Head and Process	Tape/Tow
Pre-heating tape	Works well	
Pre-heating laminate	Works well	
Heating Process Spot	Works well	
Intimate Contact	Head does not eliminate all tape thickness variation	Excessive thickness variation
Healing	Achieved	APC-2 well suited
Consolidation	Achieved	
Degradation	Avoided	APC-2 well suited
Crystallinity	Achieved	APC-2 well suited
Intralaminar Void Elimination	Head cannot remove all the tape's incoming voids	Excessive internal void content
Interlaminar Void Elimination	Head cannot accommodate tape's thickness variation	Excessive thickness variation
Cooling	Inadequate cooling solved	Excessive internal void content
Rebound	Inadequate cooling solved. Rebounds eliminated	Excessive internal void content.
[green] = head/tape works	[aqua] = Successful R&D	[red] = planned R&D

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