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Rapid Automated Induction Lamination (RAIL) for High-Volume Production of Carbon/Thermoplastic Laminates

by Nicholas Shevchenko, Bruce K. Fink, Shridhar Yarlagadda, John J. Tierney, Dirk Heider, and John W. Gillespie, Jr.

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Rapid Automated Induction Lamination (RAIL) for High-Volume Production of Carbon/Thermoplastic Laminates

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Abstract

An innovative Rapid Automated Induction Lamination (RAIL) process has been developed that can fabricate fully consolidated 8-ply AS4/polyetherimide (PEI) laminates in high volumes. The process relies on induction-based rapid volumetric heating for multilayer consolidation at very rapid rates (less than 30-s cycle times), while maintaining high quality (<1% voids). Full translation of mechanical properties has been achieved in comparison to baseline processes, such as autoclave and vacuum debulk with an order of magnitude increase in throughput. The RAIL process has the potential to be integrated with thermoforming for high-volume production of net-shape carbon/thermoplastic parts.

Acknowledgments

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1. Introduction

Carbon fiber-based composites are being used today in a wide range of structural applications in aerospace and defense systems. Material and manufacturing costs have been traditional barriers for use in the automotive and consumer industries. Low-cost carbon fiber is now available that may open markets for these high-volume applications. Carbon fiber-reinforced thermoplastic composites offer economic and performance advantages in terms of low-cycle times, rapid multistep processing (e.g., consolidation, stamping, welding) and high-specific stiffness and strength. Carbon-thermoplastic composites offer the potential for significant weight reduction and recycling benefits.

A key concern in the economics of carbon fiber composites is manufacturing costs, especially for thermoplastic systems. The search for cost-effective manufacturing has led to the study of induction heating for processing of carbon fiber-reinforced thermoplastics. Induction processing offers a potential solution by enabling rapid volumetric heating of the thermoplastic laminae leading to multilayer consolidation. This technology enables reduction in cycle times, while maintaining quality, compared to conventional compression molding processes.

A review of the literature in the area of induction heating and processing of carbon fiber-based composites reveals that the majority of work has focused on heating of preconsolidated laminates. Several efforts [1–9] have focused on using induction as a means for bonding and repair of composites with metal-mesh susceptors or heating elements. Some work has been done [10, 11] on the use of composites on metallic substrates for generation of Joule-loss energy. Little research [12–17] has focused on the use of the inherent conductivity of the carbon fibers for susceptorless heating and bonding.

Border and Salas [12] studied bonding of carbon fiber-reinforced thermoplastic composites by heating the adherends at the joint through the thickness and applying consolidation pressures. Miller et al. [13] and Lin et al. [14] examined induction heating of carbon fiber-reinforced thermoplastics for applications such as die-less forming. They also developed theoretical heating models, with the conclusion that good electrical contact is required between crossed plies, and Joule heating in the fibers is the heat source. Their work has primarily focused on heating preconsolidated carbon-thermoplastic laminates. An alternative heating mechanism was proposed by Fink et al. [15–18] who observed that, in laminates in which the fibers in adjacent plies do not come into direct electrical contact before or during consolidation, heat generation is caused by dielectric losses in the polymer at the junctions of overlapping fibers from adjacent plies. They also developed theoretical models for unconsolidated laminates, based on the predominate dielectric heating mechanism.

Tests by Miller et al. [13] on cross-ply prepreg stacks resulted in nonuniform heating and consolidation. As their objective was to study induction for forming operations, they concluded that preconsolidated laminates are a better choice of starting material for induction-based thermoforming. Fink et al. [18] extensively tested AS4 carbon fiber/polyetheretherketone-based APC2 consolidated and unconsolidated laminates verifying their models [15–17] for the dominate dielectric heating mechanism in those materials under varying stacking sequences and coil geometries.

The motivation of this work arises from the need to develop an economical and high throughput, carbon-thermoplastic-lamination process capable of obtaining uniform heating for any carbon fiber-based thermoplastic prepreg laminate stack. This requires developing an understanding of the additional mechanism of contact resistance in laminates exhibiting fiber-fiber contact before and during consolidation as developed by Yarlagadda et al. [19] and Kim et al. [20] and incorporated into this work. It also requires developing a manufacturing process that achieves uniformity in heating in the plane and takes advantage of the through-thickness volumetric heating potential of induction. In addition, induction offers internal non-contact heating; the possibility of a moving heat source (the coil); high efficiency; control of the heat generation by coil design; and powerful, portable, and easy-to-operate induction generators.

The technology outlined in this effort arose from the need to fabricate thermoplastic sheets in high volumes for munitions. The sheets are currently fabricated from AS4/polyetherimide (PEI) by conventional technology, starting from the raw material (prepreg) to the final product. One of the critical steps during the fabrication process is the lamination of 8-ply prepreg sheets, which is currently being done by vacuum-debulk tables with 300-s cycle times. Full-scale factory production demands cycle times of less than 20 s with equivalent quality and mechanical properties. For this application, throughputs of 10 ft/min are required. The primary objective of this work was to develop a Rapid Automated Induction Lamination (RAIL) process for high-volume production of carbon fiber-reinforced thermoplastic laminates. Process development, optimization, and hardware design was performed using simulation models accounting for all potential heating mechanisms. A lab-scale machine was fabricated to demonstrate the RAIL process and has successfully fabricated 8-ply laminates from AS4/PEI prepreg at high throughputs. Full translation of mechanical properties was achieved for laminates fabricated using the RAIL process compared to autoclave baselines.

2. Material System and Process Requirements

The RAIL process was developed to fabricate fully consolidated 8-ply laminates of AS4/PEI from prepreg supplied by Cytec Fiberite. Symmetric angle-ply laminates (i.e., $[0/\text{theta}/0/\text{-theta}]_s$ where theta can range from 15° to 90° were investigated. The prepreg material has an average thickness of 0.0052 in and a fiber volume fraction of approximately 60%.

The requirements of the RAIL process for this specific application were:

- laminate with dimensions of 3 ft (length) and 1 ft (width),
- throughput of 1–10 ft/min,
- void content <1%,
- laminate thickness tolerance ±2 mil,
- dimensional tolerances (±35-mil length, ±25-mil width),
- minimal warpage (symmetry),

- maintain fiber orientation and negligible fiber damage or distortion,
- temperature and pressure controls to within desired ranges, and
- automated machine operation.

This criteria was determined such that laminate quality was similar or better than baseline vacuum-debulk or autoclave laminates.

3. Process and Hardware Design

Several process schemes were evaluated as candidates for the RAIL process. The typical design is shown in Figure 1. All of the evaluated schemes had heating and cooling zones; the differences were the heating and cooling mechanisms. In all cases, consolidation was achieved using roller pressure due to the high amplification factor and the short residence times at high throughputs. Process simulations were used to evaluate each process scheme and the design was down-selected based on the desired process requirements.

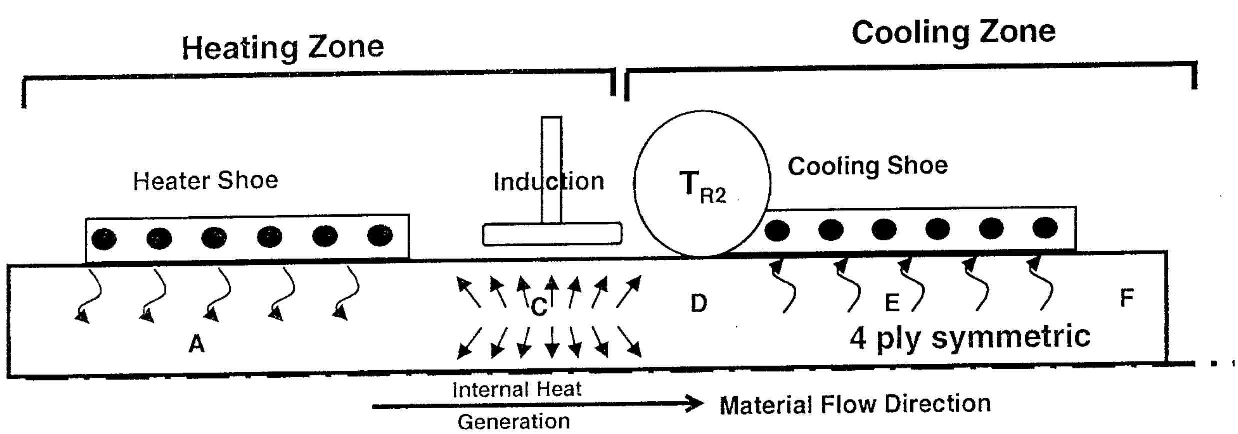

Figure 1. Process Schematic for RAIL.

3.1 Process Simulation. A complete process simulation was developed that enabled evaluation of various heating and cooling techniques for process design. The simulation was based on and adapted from earlier work on automated tow placement [21, 22] and determined relationships between input process parameters, such as temperature and pressure profiles and output quality like void content and degree of bonding. A schematic of the process simulation is shown in Figure 2. The temperature solution is generated by a two-dimensional (2-D) transient finite-difference scheme that can handle various types of heat input sources such as infrared (IR), platens, internal heat generation, etc. Transient solutions are necessary since the process is discontinuous and has start/stop zones and process velocities of up to 10 ft/min. Possible boundary conditions include free convection, forced contact (platens), adiabatic, impinging gas, and infrared radiation. The internal heat generation term is based on induction heating in the carbon-fiber prepreg stack.

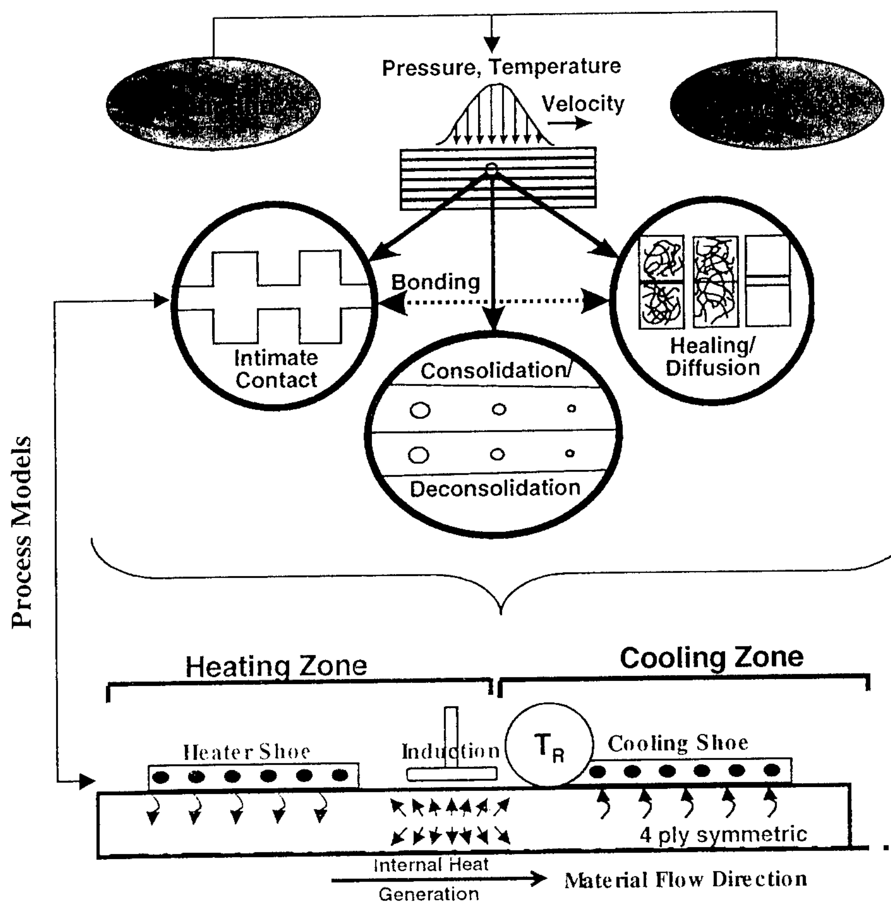

Figure 2. Simulation Scheme for Parametric Studies, Process, and Hardware Design.

3.2 Induction Design. When directional carbon fiber-based composites are subjected to an alternating magnetic field, volumetric heating of the composite occurs and volumetric heating rates on the order of ~100 °C/s have been demonstrated [14–20]. Initial efforts focused on identifying coupled heating mechanisms and induction parameters for uniform heating in the prepreg feedstock [19, 20]. Based on these studies, a rectangular coil design was identified that generated uniform temperature profile across the width of the prepreg stack. Motion of the stack along the feed direction causes the stack to heat up to temperature as it passes through the induction zone.

Based on the temperature solution and pressure profile in each stage of the process, material void content, and degree of bonding were calculated (Figure 2). Details on the process simulation will be published at a later date.

3.3 Hardware Design. For the selected process scheme (Figure 2), parametric studies were performed to identify desired process setpoints and hardware requirements (rollers, platens, etc.) to obtain the desired material quality. Examples of design parameters that were determined using process simulations are shown in Table 1. Note the different setpoints for changing throughput velocities.

4. Experimental Laminator

Based on the simulation models and hardware design, an experimental "proof-of-concept" laminator has been designed and fabricated (Figure 3). The experimental laminator was then rigorously tested to meet the desired requirements. Modifications were made to the stages as required; however, the overall design concept has remained the same.

The laminator is comprised of six stages: (1) infeed, (2) preheat, (3) induction, (4) consolidation, (5) cooling, and (6) outfeed. The infeed rollers align the spot-welded laminate perpendicular to the coil and outfeed rollers. The preheat stage establishes intimate contact

Table 1. Examples of Process Setpoints and Hardware Parameters Determined by Simulation

Hardware Station	Hardware Specification	3 ft/min	6 ft/min	12 ft/min	20 ft/min
Heater Shoe $T_1 = 482\ °F$ $T_1 = 625\ °F$	6 in length Resistance Heaters	505 °F 482 °F	610 °F 792 °F	939 °F 1180 °F	1454 °F 1788 °F
Induction Power $T_{max} = 716\ °F$	1 in wide	3.2 KW	5.7 KW	9.1 KW	12.3 KW
Cooling Shoe	6 in length water cooled	257 °F	140 °F	77 °F	77 °F
Consolidation Roller Force $F_{roller} = 3{,}200$ lb	D_b (F_{shoe} = 3,200 lb)	81.08%	89.91%	82.71%	81.60%
	D_b (F_{shoe} = 1,600 lb)	80.01%	89.02%	80.40%	77.52%
	D_b (F_{shoe} = 800 lb)	79.74%	88.61%	79.24%	75.30%
	V_f (F_{shoe} = 3,200 lb)	0.74%	0.76%	1.91%	3.13%
	V_f (F_{shoe} = 1,600 lb)	0.79%	1.24%	2.21%	3.13%
	V_f (F_{shoe} = 800 lb)	0.80%	1.77%	2.47%	3.14%
Consolidation Roller Force $F_{roller} = 3{,}200$ lb	D_b (F_{shoe} = 3,200 lb)	70.55%	79.61%	75.53%	72.88%
	D_b (F_{shoe} = 1,600 lb)	70.54%	78.14%	72.08%	71.12%
	D_b (F_{shoe} = 800 lb)	70.53%	77.43%	70.26%	67.87%
	V_f (F_{shoe} = 3,200 lb)	0.82%	0.76%	1.91%	3.13%
	V_f (F_{shoe} = 1,600 lb)	0.86%	1.24%	2.20%	3.13%
	V_f (F_{shoe} = 800 lb)	0.88%	1.77%	2.47%	3.14%
Consolidation Roller Force $F_{roller} = 3{,}200$ lb	D_b (F_{shoe} = 3,200 lb)	61.20%	71.63%	70.31%	68.52%
	D_b (F_{shoe} = 1,600 lb)	61.18%	69.34%	65.51%	66.42%
	D_b (F_{shoe} = 800 lb)	61.17%	68.18%	62.74%	61.96%
	V_f (F_{shoe} = 3,200 lb)	0.93%	0.76%	1.91%	3.13%
	V_f (F_{shoe} = 1,600 lb)	0.98%	1.24%	2.21%	3.13%
	V_f (F_{shoe} = 800 lb)	1.01%	1.77%	2.47%	3.14%

between plies by heating the outer plies, which aids in heat generation in the induction stage; this is necessary, as intimate contact (surface quality of prepreg) drives the heat-generation capability in the induction stage, and prepreg quality can vary widely. The induction stage generates volumetric heating at high rates (~100 °C/s) and raises the temperature of the material to within the desired process window. An IR-sensor-based feedback control loop is used to maintain temperature to within ±10 °C of the setpoint. The consolidation stage consists of chilled rolls that apply pressure to obtain the desired degree of bonding and void content. The cooling stage reduces the temperature of the laminate to below the glass transition temperature of the polymer.

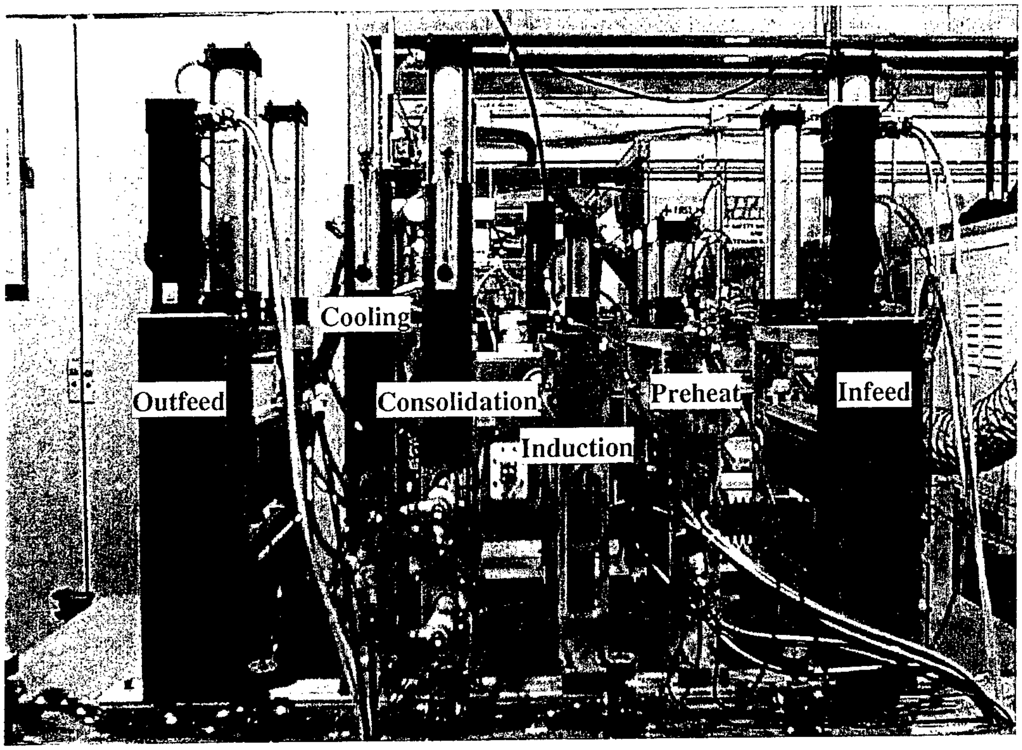

Figure 3. Lab-Scale Experimental Laminator to Demonstrate RAIL Process.

The outfeed stage is the drive system for the machine and pulls the material through, as well as controls the machine throughput. The laminator is fully automated; once the material feed is accomplished, the stages are automatically lowered and raised as the material goes through at the desired process velocity. A typical thermal profile in the heating zone is shown in Figure 4.

5. Laminate Performance and Quality

Laminator performance was quantified by measurements of void content and tensile properties of the laminate and compared to the vacuum-debulk baseline. Void content measurements for induction-processed laminates showed that voids were primarily in the outer two layers (Figure 5), with almost zero voids in the inner layers (also predicted by the process model). This is due to the chilled consolidation roller that "freezes" the outer two layers and locks in the voids. The inner layers are still at high temperatures and the roller pressure reduces

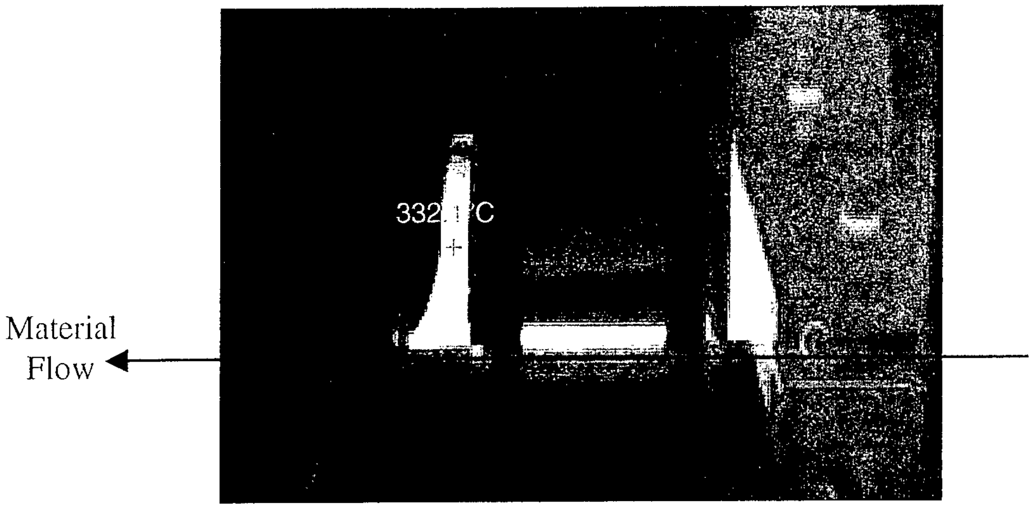

Figure 4. IR Temperature Profile of Heating Zones in the RAIL Process.

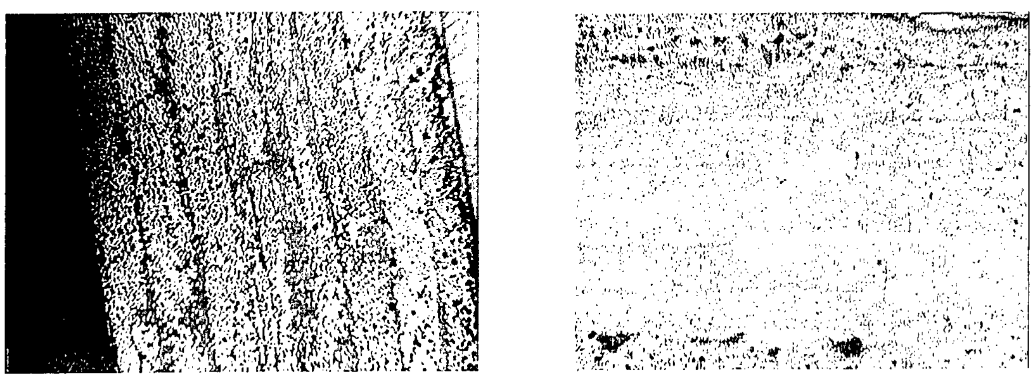

Figure 5. Micrographs Indicating Void Content Comparison Between Vacuum-Debulk Baseline (Left) and Induction-Processed Laminate (Right).

void content. Average void contents were less than 1%. Table 2 shows the measured material properties (American Society for Testing and Materials [ASTM] tests) for various laminates comparing the effect of different processing techniques and cycle times. The induction-processed laminates show identical properties to the vacuum-debulk baseline with an order of magnitude decrease in cycle time.

Table 2. Mechanical Performance of Induction-Processed Laminates

Process	Longitudinal Tensile Strength (ksi)	Longitudinal Tensile Modulus (msi)	Transverse Tensile Strength (ksi)	Transverse Tensile Modulus (msi)	Cycle Time (s)
Vacuum Debulk	191.7 ± 7.1	13.3 ± 0.5	16.3 ± 1.1	1.45 ± 0.04	300
Laminator at 5 ft/min	182.4 ± 2.8	13.6 ± 0.3	16.5 ± 0.3	1.50 ± 0.03	36

Technology developed and proven in the lab-scale laminator is currently being transitioned to a production line at Alliant TechSystems. Lessons learned during the laminator design, fabrication and prove-out have been implemented as part of the design criteria for the factory floor laminator.

6. Potential Applications of RAIL Process

The experimental laminator has demonstrated the high-volume lamination capability of the RAIL process, while maintaining material quality. The RAIL process can be modified to include a thermoforming station for high-volume production of molded parts (Figure 6). The forming station uses cooled dies to rapidly form the part as the material exits the heating zone of the laminator and also cool the part at the same time.

In this design, speed of the forming step determines final throughput. As an example, at 12 ft/min, a 3-ft-long laminate "blank" can be produced in 15 s and if the stamping or forming process is just as fast, throughputs of 4 parts per minute (parts/min) can be achieved. The cycle time of 15 s compares favorably with metal-stamping operations, where times are on the order of 5 s/part. Stamped or formed parts can be fabricated for a variety of process conditions and low-cost carbon preforms, such as woven fabrics, comingled fabric, etc. Of particular interest are

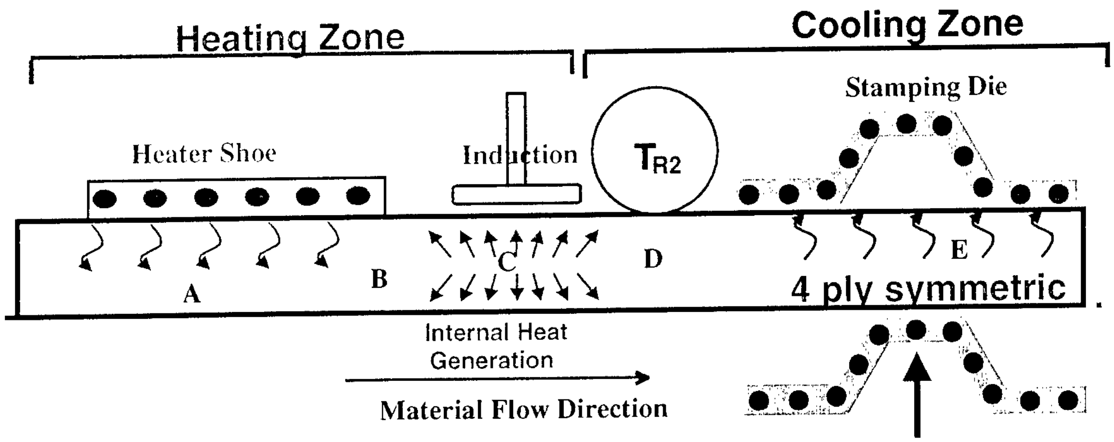

Figure 6. Process Schematic for an Integrated Laminating and Thermoforming System.

fiber preforms that have some axial extendibility since these are well suited for rapid forming of complex shapes. Key parameters are forming die temperatures, die pressures required during forming, and cycle times. It is expected that this design can reduce cycle times and costs of the final part significantly compared to conventional thermoforming.

The experimental laminator currently operates in the discontinuous feed mode where the input material is a 36-in-long × 12-in-wide 8-ply prepreg stack. The laminator can also operate in a continuous mode, where the 12-in-wide prepreg stack is fed continuously and cut into the desired lengths after laminating. However, preform-handling issues differ significantly for both cases and need to be addressed.

7. Conclusions

An innovative RAIL process has been developed and demonstrated for high-volume production of 8-ply AS4/PEI laminates. The process takes advantage of susceptorless induction heating to generate the volumetric heating necessary for rapid multilayer consolidation for high throughputs. Process models were developed and used for hardware design and fabrication of a proof-of-concept laminator. High-quality laminates have been fabricated at rates from 3–10 ft/min. Cycle times of 20 s have been demonstrated that represents a 15-fold reduction over the baseline technology. Full translation of mechanical properties has been demonstrated. The RAIL process can be adapted for use with thermoforming technology for high-volume production of net-shape parts. Higher rates can be achieved and will require higher power-induction generators and suitable redesign of hardware elements using the process models.

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An innovative Rapid Automated Induction Lamination (RAIL) process has been developed that can fabricate fully consolidated 8-ply AS4/polyetherimide (PEI) laminates in high volumes. The process relies on induction-based rapid volumetric heating for multilayer consolidation at very rapid rates (less than 30-s cycle times), while maintaining high quality (<1% voids). Full translation of mechanical properties has been achieved in comparison to baseline processes, such as autoclave and vacuum debulk with an order of magnitude increase in throughput. The RAIL process has the potential to be integrated with thermoforming for high-volume production of net-shape carbon/thermoplastic parts.

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