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Analysis of the On-Line Consolidation Process in Thermoplastic Composite Tape Placement

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ABSTRACT: The main objective of the present study is to establish the relationships between the process variables and the quality of thermoplastic composite laminates fabricated by tape placement. The quality parameters considered in the process modeling are interlaminar bond strength, weight loss through thermal degradation, and crystallinity. Stress, heat transfer, crystallization, degradation, and bonding models are developed. These models relate the process parameters (e.g., roller velocity, roller pressure, heat input) to temperature, stress, and crystallinity distributions, degradation weight loss, and degree of bonding within the composite. These relationships are used to develop a process window to ensure product quality. The process parameters are then optimized to reduce the lay-up time.

1. INTRODUCTION

A MAJOR STUMBLING block to large-scale use of thermoplastic composites is the lack of efficient manufacturing techniques. Composite structures are normally made from prepreg plies by lamination. Hand lay-up is the basic processing step. Using a hot iron solder or an air gun, tapes are manually spot welded to create a loosely connected stack of plies. The laminate is then vacuum bagged or transferred to a hot press or autoclave and allowed to consolidate under applied heat and pressure. With a large number of plies to be oriented in different directions, the process is subject to human error, and gaps and laps are easily introduced due to imprecise tow placement.

The tape placement process is one of the few techniques that have the potential to continuously process thermoplastic composites in large-scale industrial applications. This process holds the promise of increasing productivity by reducing labor costs and producing more repeatable, better quality products [1]. While the tra-

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ditional tape placement process for thermoset composites involves a curing step after the placement operation, thermoplastic tape placement offers the additional advantage of on-line consolidation.

In the thermoplastic tape placement process, an incoming composite tape is bonded to a previously laid and consolidated laminate under heat and pressure locally applied to the interface (Figure 1). By laying additional layers in different directions, a part with the desired thickness and properties can be fabricated.

The mechanical performance of a laminate depends on a number of factors. It should be void-free and well consolidated for reliable use in a structure as a load-bearing part. Thermal degradation induced during processing should be minimal in order for the material to retain its properties. Its crystallinity should be within the recommended range for the material to attain the optimal properties. It should meet the required dimensional tolerances in order to be assembled with other parts. Warpage and residual strains should also be eliminated.

As some experimental studies indicate [2–4], the overriding problem in the application of tape placement is either thermal degradation of the matrix due to excessive heat intensity or high void content as the result of incomplete consolidation. It was difficult to find a process window that represented a compromise between these two conflicting requirements. Consolidation of the tape has been achieved at laydown rates slower than 1.5 cm/s. These consolidation speeds are below the desired values for commercial applications. Also, void contents as low as 1% are required by the industry [5]. Higher production rates could be achieved if the correct combination of processing parameters is applied.

In the previous studies [6–11], conducting experiments was the usual method for determining a suitable set of process parameters. There are also a few studies that use a theoretical approach. James and Black [12] developed a process window for filament winding. They used isothermal thermal degradation data and a diffusion model to determine the upper and lower limits on processing. However, it should be noted that only by using a degradation kinetics model, it is possible to realistically determine the upper limit on heat input. Isothermal thermal degradation data may lead to misleading results. Pitchumani et al. [13] considered thermal degradation, void content and dimensional change as product quality criteria to develop a process window for tape placement. None of these studies included crystallinity as a product quality criterion in developing a process window.

Process modeling offers a means of establishing the relationships between process variables and the material behavior in a given manufacturing environment. In actual practice, determination of the optimum processing parameters is usually done by trial and error. Processing parameters are chosen based on experience, the part is fabricated, and its properties are determined. The parameters are then modified, and the experiment is repeated until the desired properties are achieved. The procedure is time consuming and costly. Furthermore, the processing parameters thus obtained are meaningful only for the given set of material, tool geometry and part dimensions. Experiments should then be repeated whenever a different material is used or a different part is fabricated. The difficulty becomes more evident when the process involves a large number of process variables (applied pressure, heat input, roller velocity, etc.) and geometrical constraints (laminate thickness,

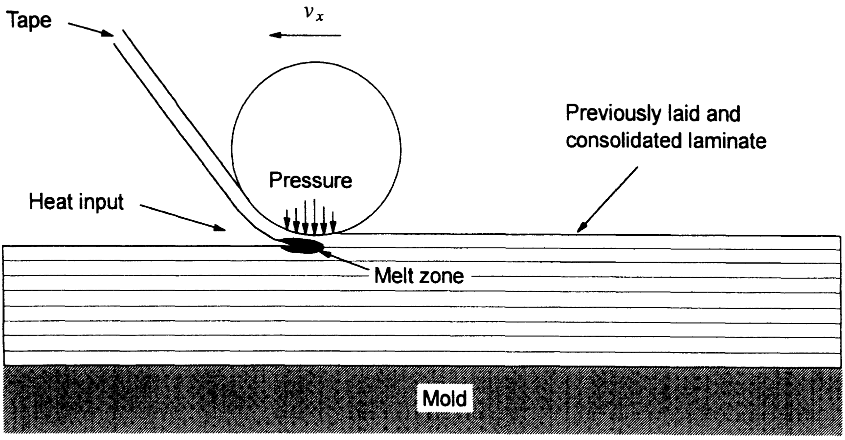

Figure 1. *The thermoplastic tape placement process.*

roller radius, heated length etc.) as in the case of tape placement. In this study, therefore, process models are developed to identify the process parameters that will result in a laminate satisfying the quality requirements. The product quality criteria were chosen to be thermal degradation, interlamnar bond strength, and crystallinity.

Figure 2 presents an outline of the process model. Double arrows indicate full coupling. Since the thermomechanical history experienced by the material during

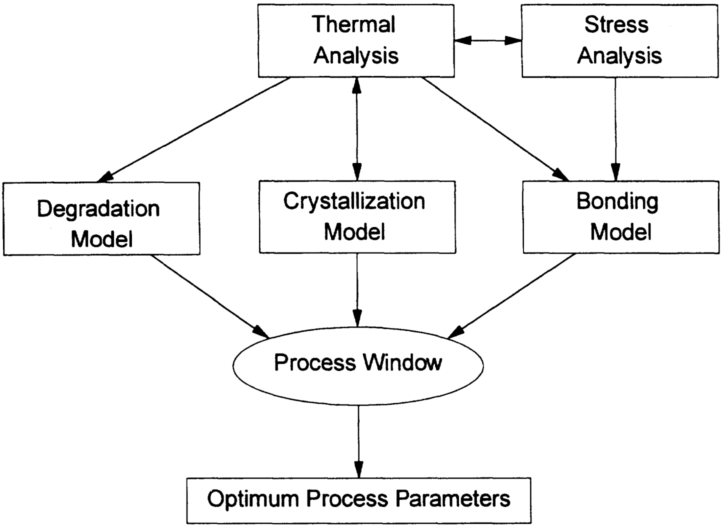

Figure 2. *A schematic of the tape placement process model.*

processing determines its microstructure, and hence the mechanical performance of the resulting part, thermal and stress analyses are carried out. The stress analysis predicts the stresses developed under consolidation roller pressure. The temperature and stress fields thus obtained are used in the crystallization, degradation, and bonding models to develop a process window. Finally, optimum processing parameters are determined by a parametric study to achieve high productivity. Models for heat transfer, stress, crystallization kinetics, and degradation kinetics were previously reported [14–16]. In this paper, only the bonding model is described.

2. MODELING OF BONDING

Consolidation in thermoplastic composite manufacturing processes is accomplished by applying heat and pressure to the system to squeeze the air out of the composite structure or dissolving it into the melt. It is a very complex phenomenon involving heat transfer, resin flow, wetting, and molecular diffusion. The main goal of consolidation is to produce a monolithic structure by inducing intimate contact and adhesion between individual plies and minimizing the void content within the composite.

Incomplete consolidation results in high void content, which seriously degrades the interlaminar shear strength of the laminate [7,17–20]. Considering that laminates are very susceptible to failure by delamination, degradation of shear strength renders a laminate useless for a structural application. Although loads are significantly large only in the fiber direction, very small shear loads may cause failure of a composite part due to its inherent weakness to this type of load. Voids act as initiation sites for crack formation and propagation [21]. They thus have a strong detrimental effect on the fatigue life of composite structures [18]. Other phenomena such as warpage and residual stresses may also occur due to improper consolidation [21,22]. Therefore, accurate modeling of the consolidation process plays an important role in ensuring the quality of the resulting composite structure.

Several consolidation models that mathematically attempt to incorporate the physics of the process have been proposed for prepregs [23–32] and commingled [32,33] and powder-impregnated tows [32,34].

Dara and Loos [24,25] developed a model to describe intimate contact and bond formation between plies in the processing of amorphous thermoplastic composites. The model considers that irregular surfaces of the plies can be represented by a wave of rectangular elements having different sizes. Lee and Springer [23] followed the model of Dara and Loos but considered elements of the same size. They also verified the model for a semi-crystalline thermoplastic composite in isothermal process conditions. While these studies try to model interlaminar bond formation, others modeled intralaminar void reduction, dimensional change, and compaction [26,35]. Ranganathan and Advani [26] considered the laminate as a compressible viscous fluid and modeled intralaminar void reduction in the tape placement process.

During the tape placement process, interlaminar bond formation occurs at the tape-substrate interface under nonisothermal conditions. As the roller traverses its path, pressure applied to a point at the interface changes. During the placement of subsequent layers, if the same interface is raised to process temperatures again, the consolidation process may continue. Most of the available models for interlaminar bond formation [23–25, 36–38], however, are based on constant pressure and temperature process conditions. Therefore, models for intimate contact and autohesion cannot be applied directly to the tape placement process, and a more general formulation of the consolidation process is needed. The model reported by Pitchumani et al. [40] includes nonisothermal and variable pressure conditions. However, in their model pressure was assumed to be constant through the thickness.

There are several studies on the consolidation behavior of thermoplastic composites processed by tape placement. Mantell and Springer [39] used the model developed by Lee and Springer [23] to model the development of intimate contact in the tape placement process. They assumed that temperature and pressure under the roller were constant. Also, they neglected autohesion. James and Black [12] examined consolidation of plies during the filament winding process both experimentally and numerically. They used the relation for autohesion of polysulfone plies reported by Dara and Loos [24,25] and assumed that the same relation was valid for APC-2. Also, they neglected intimate contact in their bonding analysis. Ranganathan and Advani [26] modeled intralaminar void reduction. Pitchumani et al. [13,40] used the same intimate contact model as Mantell and Springer [39] but included nonisothermal effects. They also adopted the nonisothermal healing model developed by Bastien and Gillespie [27] to describe autohesion.

The proposed bonding model in this study describes interlaminar bond formation. Voids could also be present within the plies, which may grow or shrink depending on the temperature and pressure states. However, in the present study, interlaminar bond formation was assumed to take longer than intralaminar void reduction. Therefore, interlaminar bond formation was chosen to be the controlling mechanism in determining the consolidation quality of the final part. The intimate contact model of Lee and Springer [23] was adopted. However, temperature and pressure were allowed to change during the bonding process. In order to model autohesion under nonisothermal process conditions, the reptation model [41] was modified. Progression of the bonding process during the placement of subsequent layers, which was neglected in the previous studies, has been taken into account in the present bonding analysis.

2.1 Modeling of Autohesion

The mechanism controlling inter-ply bond formation during processing of thermoplastic composites is recognized to be autohesion or self diffusion [36]. Once the two surfaces come into contact, diffusion of macromolecules across the interface starts due to random thermal motions. After sufficient time has passed, some of the chains will have diffused across the interface and entangled with molecular chains on the other side of the interface, so that the interface is no longer distinguishable from the bulk polymer.

The motion of a chain in an amorphous polymer has been modeled by the reptation theory. This theory was first developed by de Gennes [41] and then modified by Wool and his coworkers [36–38]. De Gennes considered the movement of a single chain in a fixed network. In order to model the dynamics of this fixed network, De Gennes made the following assumptions:

- The chain is moving in a fixed isothermal network and therefore is not allowed to cross any obstacles.
- The chain is able to move between obstacles by a snake-like motion.

Consequently, the chain is confined in a tube of length L. As the chain moves in the tube, its extremities exit the tube. The chain ends are then free to move. The reptation theory predicts that the length, l, of the chain ends (called minor chain, Figure 3) varies with the square root of the time. The reptation time T_r is defined as the time at which the chain has totally exited its original tube ($l = L$). Diffusion of molecular chains across an interface is a temperature-driven process. The tube renewal time T_r therefore, is a strong function of temperature. For this process, the following relation holds:

$$\frac{l}{L} = \left(\frac{t}{T_r}\right)^{1/2} \tag{1}$$

Researchers have attempted to relate the extent of diffusion to the degree of bonding through a structure-property relationship [38,41,42]. The time dependence of the interfacial bonding strength was found to be

$$\frac{S}{S_\infty} = \left(\frac{t}{T_r}\right)^{1/4} \tag{2}$$

where S is the bond strength at time t and S_∞ is the ultimate bond strength. The relation given in Equation (2) also holds for polyetheretherketone (PEEK) films and prepregs [23,43].

Equation (2) needs to be generalized to nonisothermal processes. Following an

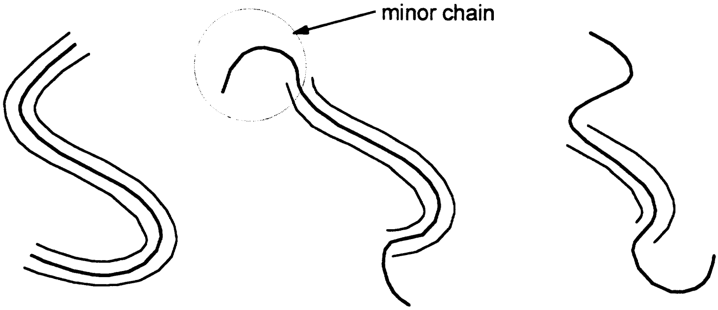

Figure 3. Minor chain.

approach similar to Bastien and Gillespie [27], the temperature history is divided into infinitesimal time intervals during which the temperature is assumed constant. In each isothermal step, the healing theory can then be applied. Differentiating Equation (1), we obtain

$$\frac{dl}{L} = \frac{dt}{2\sqrt{tT_r}} \tag{3}$$

Integrating Equation (3)

$$\int_0^l \frac{ds}{L} = \int_0^t \frac{d\eta}{2\sqrt{\eta T_r}} \tag{4}$$

yields

$$\frac{l}{L} = \int_0^t \frac{d\eta}{2\sqrt{\eta T_r}} \tag{5}$$

Since

$$\frac{l}{L} = \left(\frac{S}{S_\infty}\right)^2 \tag{6}$$

we obtain

$$\frac{S}{S_\infty} = D_{au} = \left(\int_0^t \frac{d\eta}{2\sqrt{\eta T_r(\eta)}}\right)^{1/2} \tag{7}$$

2.2 Modeling of Intimate Contact

Resin flow may be required for the autohesion process to start. Ideally, if the prepreg surfaces were perfectly flat and parallel, autohesion could proceed immediately. However, thickness through the width of the tape is not uniform. The molecules cannot move across open space. When two plies, particularly plies of different orientation, are brought into contact, the roughness of their surfaces will leave spaces to be filled. Since the viscosity of thermoplastics is too high even at elevated temperatures, application of pressure is essential in achieving the required resin flow. Pressure is applied to smooth out the prepreg surface and to squeeze the entrapped air out or dissolve it into the melt. As this process continues, the thickness of the composite decreases [10]. As a previous study indicates, there is a threshold pressure below which consolidation is not possible and a limit pressure beyond which an increase in pressure hardly affects consolidation [44]. When high pressures are applied, it is also possible that fibers migrate across the interface at low roller speeds (fiber bridging) [9]. It should also be noted that very high stresses could cause the fibers to wrinkle and spread [45]. Therefore, excessive pressures should be avoided. In cooling, it is important to maintain the applied load until the resin has sufficient strength and stiffness to suppress deconsolidation and warping [46]. Besides, some of the entrapped air dissolves in the polymer during the consolidation. If the pressure is released prematurely during cooling, voids will form in the composite due to condensation of the air predissolved in the polymer matrix [47]. The applied pressure can be reduced during the solidification; however, it should be maintained until the material cools down to the glass transition point [48,49].

To model the formation of intimate contact, Lee and Springer [23] considered that the irregular surfaces of the plies can be represented by a wave of rectangular elements (Figure 4). These rectangular elements spread along the ply contact surface under the applied pressure as shown in Figure 5. This leads to reduction in the overall height of the composite.

In their model, the worst stacking sequence $[0,90]_N$ is chosen, so that no nesting of the tows occurs as in the case of unidirectional laminae $[0]_N$. The degree of intimate contact (D_{ic}) is a measure of the amount of surface that is in contact, defined as

$$D_{ic} = \frac{b}{w_o + b_o} \tag{8}$$

where b_o and b are the initial and the instantaneous width of each rectangular element, respectively, and w_o is the initial distance between two adjacent elements. The plies are in complete contact when the degree of intimate contact reaches unity.

Assuming laminar flow and applying the boundary conditions, the following expression for the degree of intimate contact can be derived [23]:

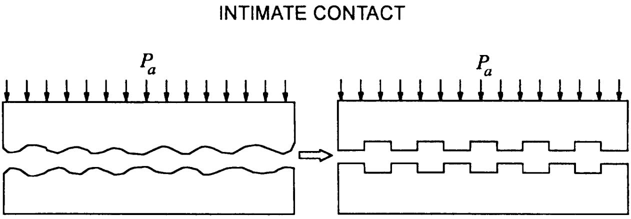

Figure 4. Schematic of the rectangular elements representing the uneven surface of the tows.

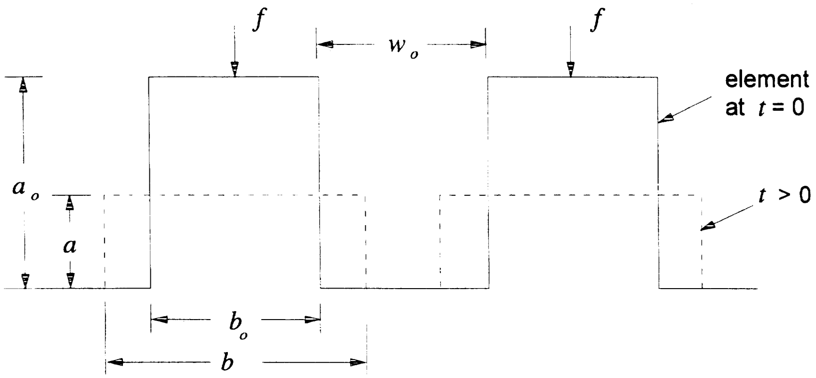

Figure 5. Deformation of the elements during the formation of intimate contact.

$$D_{ic} = \frac{1}{1 + w_o/b_o}\left[1 + \frac{5P_{app}}{\mu_{mf}}\left(1 + \frac{w_o}{b_o}\right)\left(\frac{a_o}{b_o}\right)^2 t\right]^{1/5} \tag{9}$$

If the applied pressure P_{app} and the interface temperature are changing during the process, Equation (9) should be modified to accommodate nonisothermal and inconstant pressure conditions.

$$D_{ic} = \frac{1}{1 + w_o/b_o}\left[1 + 5\left(\frac{a_o}{b_o}\right)^2\left(1 + \frac{w_o}{b_o}\right)\int_0^{t_b} \frac{P_{app}}{\mu_{mf}} dt\right]^{1/5} \tag{10}$$

where t_b is the bonding time. Equation (10) contains geometric parameters (a_o, b_o, w_o) that may be difficult to measure. Following Mantell and Springer [39], Equation (10) is simplified as follows:

$$D_{ic} = a^*\left[\int_0^{t_b} \frac{P_{app}}{\mu_{mf}} dt\right]^{1/5} \tag{11}$$

Now, the constant a^* can be determined by just fitting the model to experimental data.

2.3 Degree of Bond

Once intimate contact is established at a point along the interface, autohesion and thus the bonding process starts. The degree of bonding, D_b, can be defined as the area average of bond strengths calculated for each of the incremental areas that come into intimate contact throughout the duration, t_b, of the bonding process. D_b can be expressed mathematically as

$$D_b(t_{au}) = \int_0^{t_b} D_{au}(t_{au} - \tau)\frac{dD_{ic}}{d\tau}d\tau \qquad (12)$$

Bonding is complete when D_b becomes unity. This allows one to calculate the time required to achieve complete bonding.

Substituting Equation (7) into Equation (12), the degree of bonding becomes

$$D_b(t_{au}) = \int_0^{t_b}\left[\int_0^{t_{au}-\tau} \frac{d\eta}{2\sqrt{\eta T_r(\eta)}}\right]^{1/2} \frac{dD_{ic}}{d\tau}d\tau \qquad (13)$$

Equation (13) can be written in numerical form as

$$D_b(t_{au}) = \sum_{i=1}^{t_b/\Delta t}\left[\left(\sum_{j=1}^{(t_{au}/\Delta t)-i} \frac{\sqrt{\Delta t}}{2\sqrt{jT_r(j\Delta t)}}\right)^{1/2}(D_{ic}(i\Delta t) - D_{ic}((i-1)\Delta t))\right] \qquad (14)$$

where

$$D_{ic}(i\Delta t) = a^*\left[\sum_{k=1}^{i}\left(\frac{P_{app}(k\Delta t)}{\mu_{mf}(k\Delta t)}\Delta t\right)\right]^{1/5} \qquad (15)$$

3. THE SOLUTION PROCEDURE

Based on Equation (14), a solution procedure was developed to determine the degree of bonding in the tape placement process. Figure 6 shows the solution procedure used for the bonding analysis. First, the temperature and stress profiles at the tape-substrate interface and the location of the nip point are determined using the coupled heat transfer and stress analyses. Nip point location is important because after the tape and the substrate merge at the nip point, ply surfaces come into contact, and it is only then that bonding starts. The bonding process continues as long as the temperature is high enough to allow molecular mobility. Bonding below 270°C was reported to be very slow for PEEK [43]. Accordingly, if the temperature at the interface falls below 270°C, bonding calculations are discontinued. During the placement of subsequent layers, the same interface may experience high temperatures and compressive stresses. In this case, bonding calculations are resumed. However, as the layers are laid down, the temperature at that interface

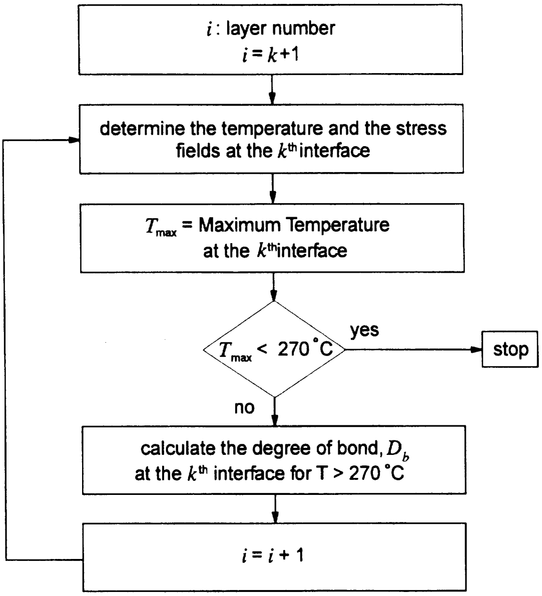

Figure 6. *The solution procedure for the bonding analysis. The degree of bond is calculated at the kth interface.*

will gradually decrease. If the maximum temperature at that interface becomes lower than 270°C, bonding calculations are stopped.

4. PROCESS WINDOW DEVELOPMENT

A process window consists of feasible sets of process parameters that result in parts with the desired properties. Requirements on product quality impose bounds on the values of the process and design variables. Quality parameters considered in this study are interlaminar shear strength, weight loss through thermal degradation, and crystallinity. Because of its indirect effect on the product quality, maximum allowable process pressure is also used as a constraint. Other constraints that can be used for the development of a process window such as limitations of the equipment, product cost, dimensional tolerances, and distortion in the final part are outside the scope of the present study.

4.1 Interlaminar Shear Strength Constraint

The objective in on-line consolidation is to fully achieve consolidation during processing, so that bulk properties are restored at the interfaces at the end of the process. If this objective is met, no post-processing is needed. This means that the shear strength is supposed to reach its ultimate value or the degree of bond, D_b, unity at the end of the processing:

$$S = S_\infty \quad \text{or} \quad D_b = 1 \tag{16}$$

Since a relationship has already been established between the shear strength S and the degree of bond D_b, only the degree of bond will be considered.

4.2 Thermal Degradation Constraint

Unlike press molding, bonding at a ply interface in tape placement should be achieved in a very short time. This can be done only by raising the interface to high temperatures to lower the viscosity of the polymer and increase the rate of interply molecular diffusion. However, polymers are subject to degradation and decomposition at high temperatures. Prolonged times at high temperatures may also lead to crosslinking of polymer chains, which may retard crystallization [50,51] and increase the polymer viscosity [52]. However, in this study, the overriding degradation mechanism was assumed to be degradation weight loss rather than crosslinking or chain branching. The maximum allowable weight loss was estimated to be 0.01% [14]. The degradation constraint can then be expressed as

$$\alpha_d \le \alpha_d^{max} \tag{17}$$

where α_d is the degradation weight loss at the interface and α_d^{max} is the maximum allowable weight loss [14].

4.3 Crystallinity Constraint

The crystallinity of a semi-crystalline polymer is known to affect its mechanical properties. In order to avoid post-processing, the crystallinity of the final product should be within the recommended levels. Recommended levels of crystallinity for APC-2 are between 25 and 35% [53]. Then,

$$c_m^{min} < c_m < c_m^{max} \tag{18}$$

where c_m is the mass crystallinity, c_m^{min} and c_m^{max} are the minimum and maximum levels of recommended crystallinity, respectively.

4.4 Process Pressure Constraint

Excessive pressures applied during processing may cause fiber damage, fiber bed spread, or resin starvation. Therefore, excessive process pressures should be avoided. The maximum allowable normal stress for APC-2 in the transverse direction was taken to be 20 MPa. The pressure constraint is expressed mathematically as

$$\sigma_y \le \sigma_y^{max} \tag{19}$$

where σ_y is the normal stress in the laminate in the y-direction and σ_y^{max} is the maximum allowable normal stress.

5. PROCESS OPTIMIZATION

Processing times can be reduced by increasing the roller velocity as much as possible without violating any constraints. Therefore, the objective function to be maximized is the roller velocity (v_x):

$$\text{maximize} \quad v_x \tag{20}$$

The above optimization problem is subject to the product quality constraints given by Equations (16–19). Since there are too many constraints and variables, the optimization problem needs to be simplified.

Increasing the temperature is conducive to consolidation. Accordingly, for optimum performance, the temperature should be increased as much as possible without violating the degradation constraint. Degradation weight loss is controlled by the heat input. Increasing the heat input leads to higher temperatures as well as more severe degradation. Equation (17) for the optimization problem then becomes

$$\alpha_d = \alpha_d^{max} \tag{21}$$

This means that during the optimization process, heat input will be set to a value that provides 0.01% weight loss. The effect of pressure is similar to that of temperature. When higher stresses are applied, consolidation takes place sooner. Therefore, Equation (19) becomes

$$\sigma_y = \sigma_y^{max} \tag{22}$$

With the assumptions made in Equations (21) and (22), the optimization problem is simplified. Weak coupling between stress and temperature states allows us this simplification. A parametric study can then be used to determine the optimum parameters. In a previous study [14], we found that although roller velocity had an effect on crystallinity, the determining factor was the preheat temperature. Therefore, only preheat temperature is varied to satisfy the crystallinity constraint. Figure 7 presents the optimization procedure used for the tape placement process. Design variables such as roller radius r and heated length wq are preset. First, a preheat temperature T_c is chosen. Then, using degradation and maximum stress criteria, heat input and roller force are selected for a given roller velocity. Heat input and roller force thus become dependent variables. In other words, the degree of bonding is uniquely related to the roller velocity. The maximum allowable veloc-

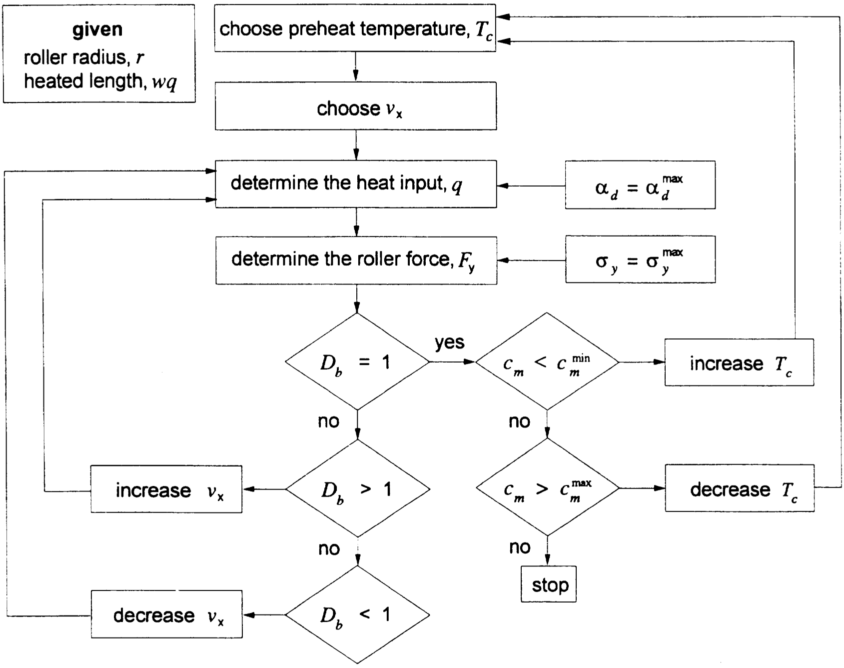

Figure 7. *Optimization procedure.*

ity is then found by an iterative technique using the relation that the slower the roller speed, the better the bond strength. Although degree of bonding D_b being greater than 1 is physically meaningless, it shows that there is leeway to increase the speed. After finding the maximum allowable velocity corresponding to the chosen preheat temperature, the crystallinity level is checked. If it is below the minimum required crystallinity, c_m^{min}, preheat temperature is increased. This process is iterated until the maximum allowable velocity is found without violating the crystallinity constraint.

6. RESULTS AND DISCUSSION

Computer codes for stress, heat transfer, degradation, and crystallization analyses were developed. A parametric study is conducted following the aforementioned solution procedure. Although each analysis models different mechanisms of material behavior, because of their interaction, the codes are run iteratively to develop a process window. The variables of the process are heat input, roller velocity, total force applied on the roller, preheat temperature of the substrate, roller radius, heated length, and ratio of the heated length defined as the ratio of the length of the heated area on the substrate to the length on the tape.

Table 1. Input parameters for the bonding analysis.

Intimate Contact Model		
a^*, geometric factor, Ref. [54]	0.29	
Viscosity, Ref. [39]	$\mu_{mf} = 132.95\left(\exp\frac{2969}{T(°K)}\right)$	Pa·s
Autohesion Model		
T_r, parameter	$T_r = t_r \exp\left[\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$	
t_r, constant	0.11 sec	
E_a, activation energy	57300 J/mol	
R, universal gas constant	8.31451 J K^{-1} mol^{-1}	
T_{ref}, reference temperature	673°K	

6.1 Inputs

The material chosen for the analysis is carbon-fiber-reinforced polyetheretherketone (APC-2). The input parameters for the bonding analysis are given in Table 1. The input parameters used in the other models are given in References [14–16].

Table 2 presents the development of bond strength at the 20th interface during the lay-up process, and Figure 8 shows the corresponding stress and temperature distributions. The following values are used as input: roller velocity, $v_x = 1.33$ cm/sec, temperature of the hot gas, $T_{hg} = 666°C$, total force applied on the roller, $F_y = 95$ N, and radius of the roller, $r = 16$ cm. As Table 2 shows, bond strength continues to increase during the placement of subsequent layers. Formation of intimate contact is slower than autohesion, partially because the stress distribution is much more concentrated than the temperature distribution (Figure 8). During the placement of subsequent layers, temperature levels at that interface become lower and the stress distribution becomes less concentrated.

Table 2. Development of bond strength at the 20th interface during the lay-up process.

Lay-up	D_b	D_{ic}	D_{au}
21st	0.79	0.79	1.00
22nd	0.84	0.84	1.00
23rd	0.95	0.95	1.00
24th	0.98	0.98	1.00
25th	1.00	1.00	1.00

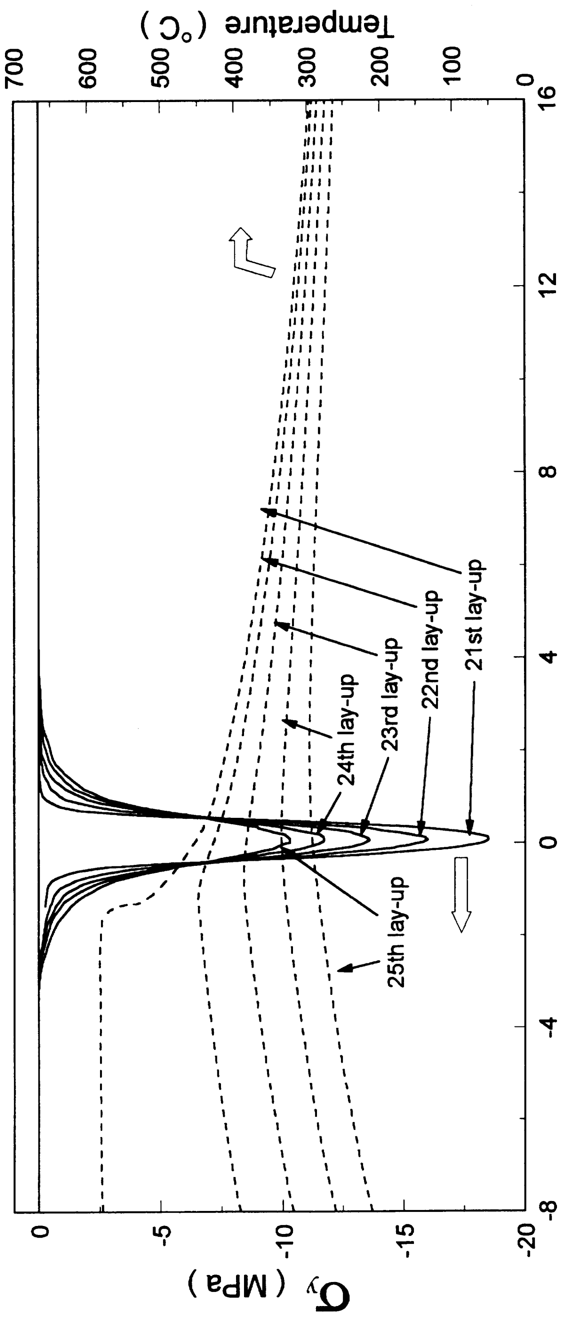

Figure 8. *Normal stress and temperature distributions at the 20th interface during the lay-up process.*

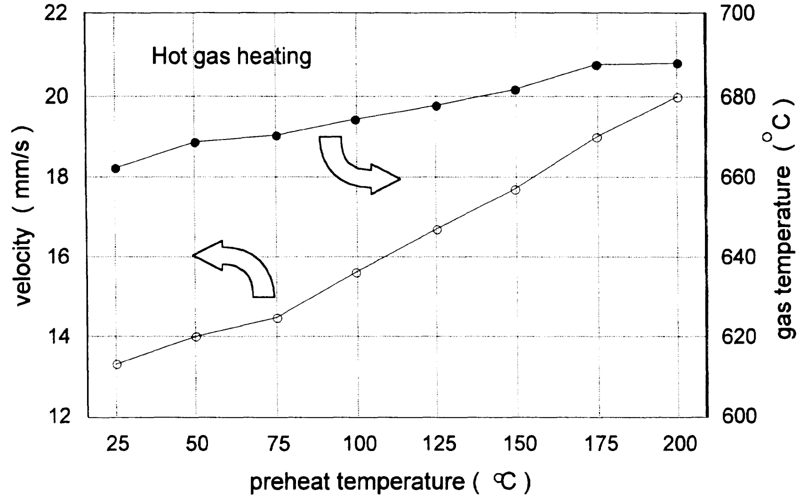

Figure 9. *Variation of the maximum achievable roller speed with the preheat temperature of the substrate.*

6.2 The Effect of Preheat Temperature

Figure 9 shows the variation of the maximum achievable roller speed with the preheat temperature of the substrate and the corresponding hot gas temperatures. The far-field mold temperature is also taken to be the same as the preheat temperature, but the incoming tape is at room temperature. For the results presented in this figure, crystallinity constraint is not observed. As the figure shows, preheating the substrate allows higher roller speeds. The relationship between the preheat temperature and the speed is almost linear. Therefore, the highest possible preheat temperature should be used for optimum performance. It should be remembered that high temperatures may result in delamination or void formation. Preheat temperatures above the glass transition point should then be avoided. The figure also indicates that with the increase in the maximum allowable roller speed, the laminate becomes less susceptible to degradation, and this allows higher hot gas temperatures. However, higher preheat temperatures are detrimental to the laminate through increasing degradation. Increase in gas temperature thus subsides as the figure indicates.

Consolidation becomes difficult at high speeds due to short dwell times. On the other hand, as the roller velocity becomes lower, the time spent at high temperatures increases. Therefore, the region below the curve in Figure 9 constitutes the feasible range.

Figure 10 explains the effect of preheating on consolidation. Preheating the substrate significantly increases the bonding time t_b by reducing the cooling rate. Therefore, increase in bonding time due to preheating offsets the decrease in bonding time due to higher speeds.

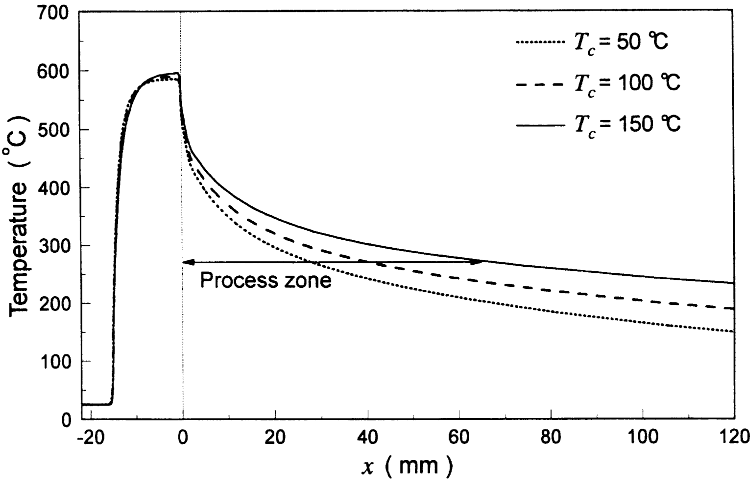

Figure 10. Temperature profiles at the tape-substrate interface for different preheat temperatures of substrate.

The effect of preheating the tape and the roller was also examined. Preheating the tape or the roller did not improve consolidation.

6.3 The Effect of Heated Length

The length of the heated area on the tape or the substrate is an important factor for process optimization. The beneficial effect of increasing the heated length on consolidation was reported by a previous work [55]. Figure 11 corroborates this finding. However, this effect subsides for heated lengths larger than 20 mm. The figure also indicates that gas temperature should be decreased for longer heated lengths in order to avoid degradation.

As shown in Figure 12, the effect of increasing the heated length is similar to the effect of preheating in slowing down the cooling rate and thus increasing the bonding time. However, the maximum temperature becomes lower as the heated length increases due to more severe degradation. We may conclude that after some point, further increase in heated length does not improve consolidation as Figure 11 implies.

Figure 13 provides the processing windows for two different hot gas temperatures. The processing windows are bound by the polymer degradation (lower limits) and full bonding (upper limit). Exceeding the upper limit results in incomplete bonding, and falling behind the lower limit results in degradation. As can be seen, increasing the heated length leads to increases in both upper and lower limits. However, for the higher hot gas temperature, T_{hg} = 600°C, increase in the lower limit is more substantial than the upper limit so that there is no feasible region for heated lengths above 15 mm.

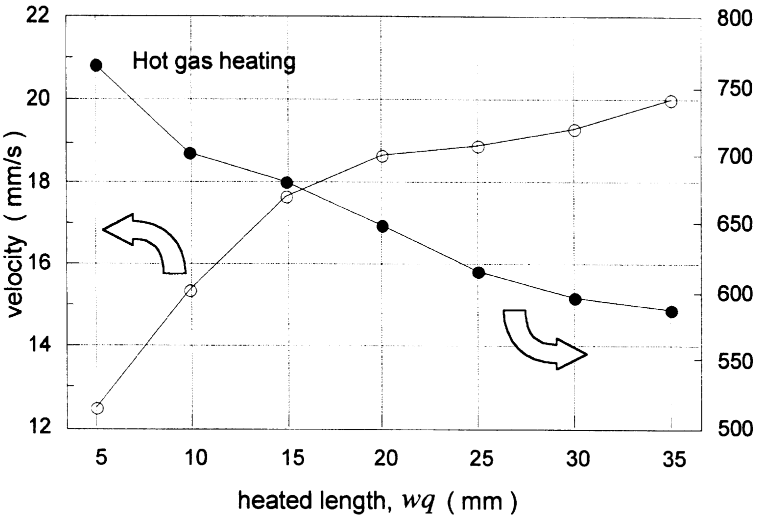

Figure 11. *Variation of the maximum achievable roller speed with the length of the heated region.*

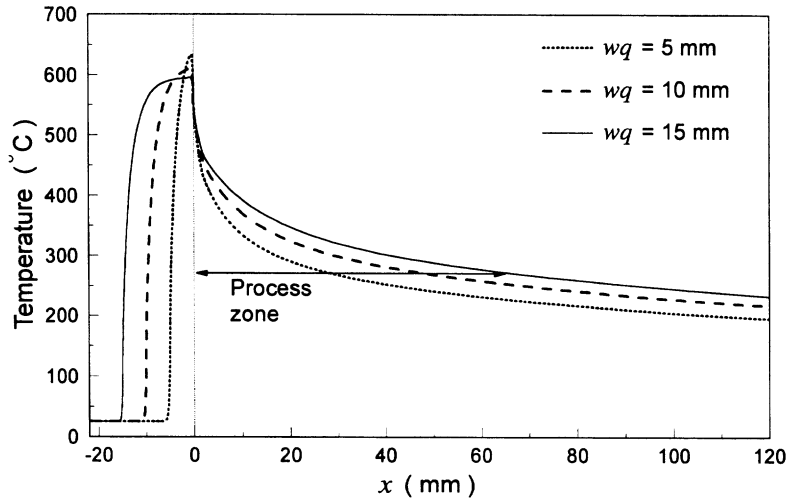

Figure 12. *Temperature profiles at the tape-substrate interface for different heated lengths.*

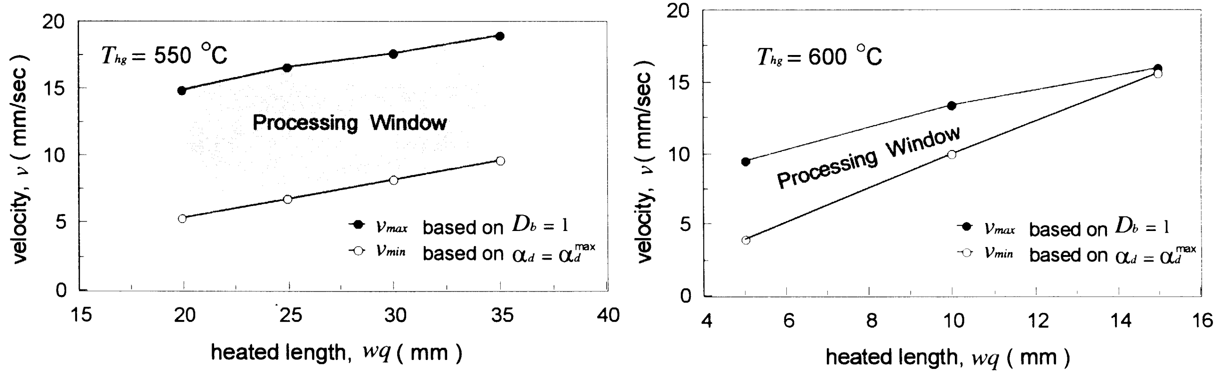

Figure 13. *Processing windows for two different hot gas temperatures. The processing windows are bound by the polymer degradation (lower limits) and full bonding (upper limit).*

6.4 The Effect of Roller Radius

As shown in Figures 14 (left) and 15 (left), larger roller sizes allow higher roller speeds for both hot gas and laser heating. For optimum performance, the largest possible roller radius or radius of curvature for a compaction shoe should be used. Lower speeds for laser heating may be attributed to the smaller heated length used as input. Laser provides too concentrated heating. The heated length for laser heating was taken to be 4 mm, while for hot gas heating it was 15 mm. Also, Figures 14 (right) and 15 (right) indicate that increasing the roller radius allows higher roller forces and heat inputs.

Figure 16 shows the stress distributions at the interface for various roller radii. As the roller diameter gets smaller, the stresses become more concentrated. The time spent under high stresses will then be shorter. Consequently, small roller sizes are not conducive to bonding. Another point can be made about the stress profiles. Maximum normal stress occurs at the contact surface. Stresses become lower below interfaces. As shown in the figure, stress degradation is highest for the smallest roller size. This situation may also contribute to the adverse effect of small roller size.

The differences in the temperature states for different roller radii are small compared to the stress states. The effect of roller size also attests to the significance of pressure in achieving consolidation. Even for very high speeds, reptation time (T_r) is smaller than bonding time. Therefore, bonding is controlled by the mechanisms involving resin flow as some experimental studies indicate [11].

6.5 The Effect of Laminate Thickness

Figure 17 shows the feasible roller speeds for each layer during a 20-ply lay-up process. Since process conditions during the placement of a layer affect bonding at other interfaces, optimization of the whole lay-up time was not possible using a parametric study. This could be done by using a more sophisticated technique such as nonlinear optimization.

A significant portion of the bonding occurs during the placement of subsequent layers. For that reason, during the placement of the last layer, lower speeds have to be used. Using a lower speed leads to longer bonding times at the previous interfaces. This allows higher speeds at those layers as shown in Figure 17. Lower speeds should also be used during the first few lay-ups. As the main reason, the highly conductive steel mold leads to very high cooling rates (Figure 18). Accordingly, bonding times will be shorter. As a second factor, stresses are more concentrated for very thin layers. The time spent under high stresses then becomes shorter. After a number of plies are laid, the speed reaches its steady state value as shown by the dashed line in Figure 17.

6.6 Crystallinity

Figure 19 presents the final crystallinity levels after the lay-up through the thickness of a 20-ply laminate. The roller speeds used during the placement of

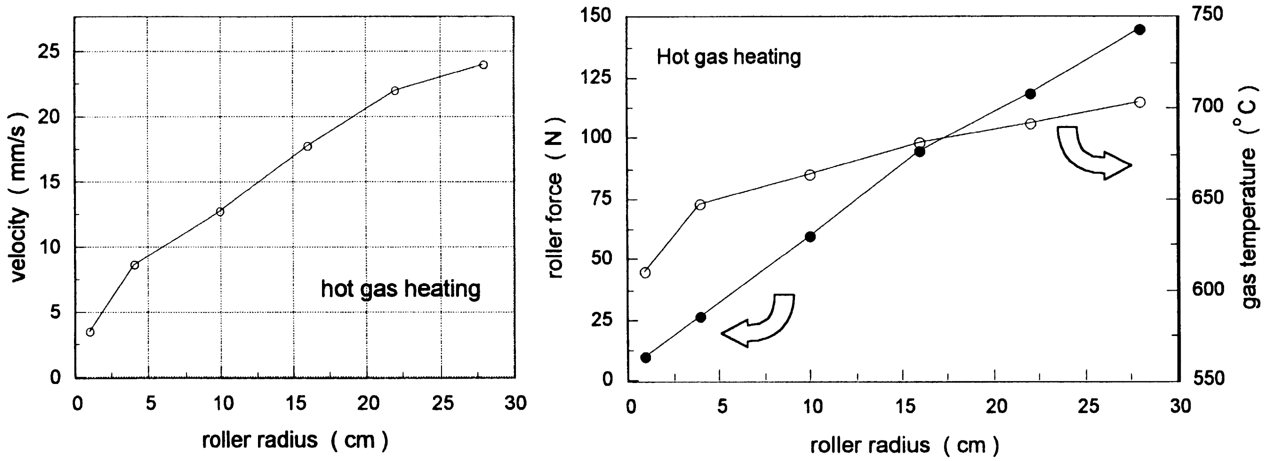

Figure 14. *(left) variation of the maximum achievable roller speed with roller radius for hot gas heating, (right) corresponding roller forces and hot gas temperatures.*

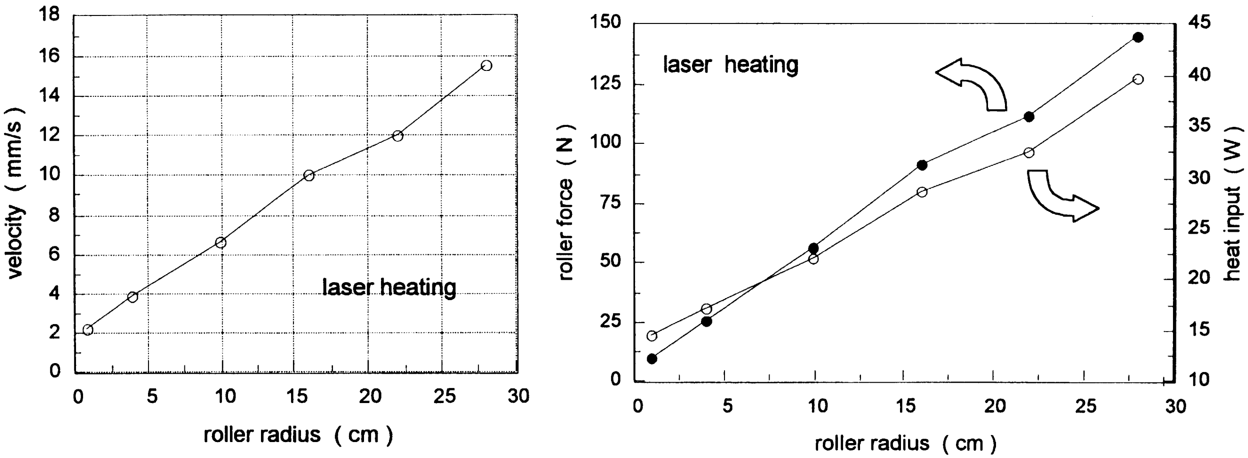

Figure 15. *(left) Variation of the maximum achievable roller speed with roller radius for laser heating. Preheat temperature,* T_c, *is 150°C, (right) corresponding roller forces and hot gas temperatures.*

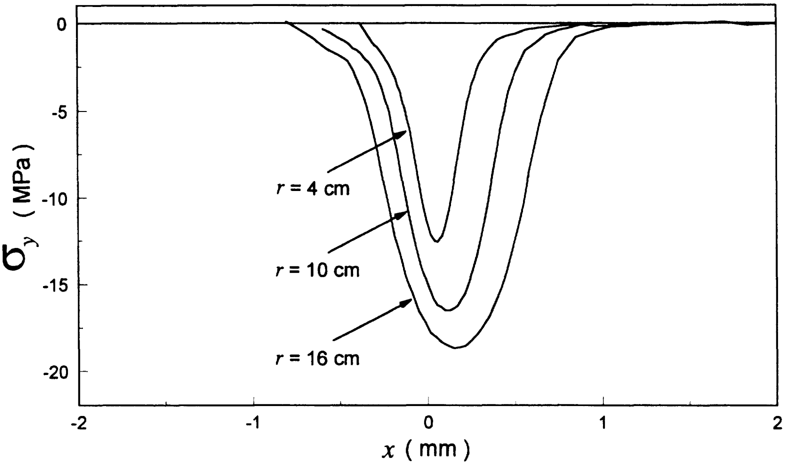

Figure 16. *The effect of roller radius on the stress distribution at the interface.*

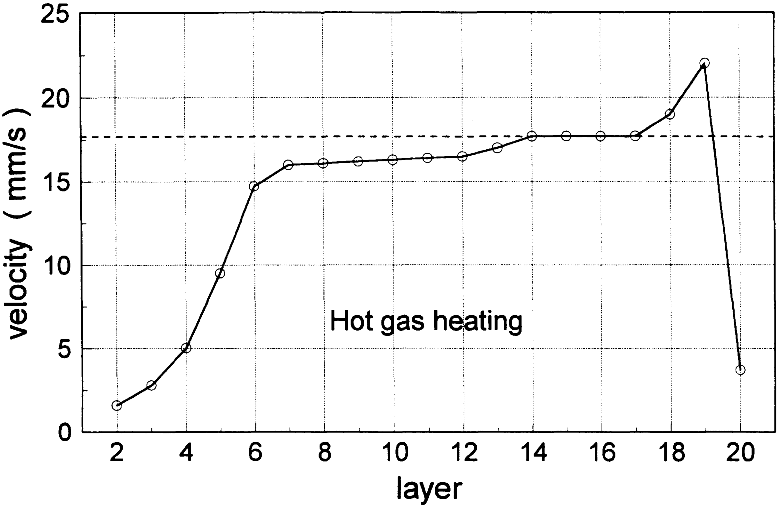

Figure 17. *Feasible roller speeds for each layer during a 20-ply lay-up process. The preheat temperature is 150°C.*

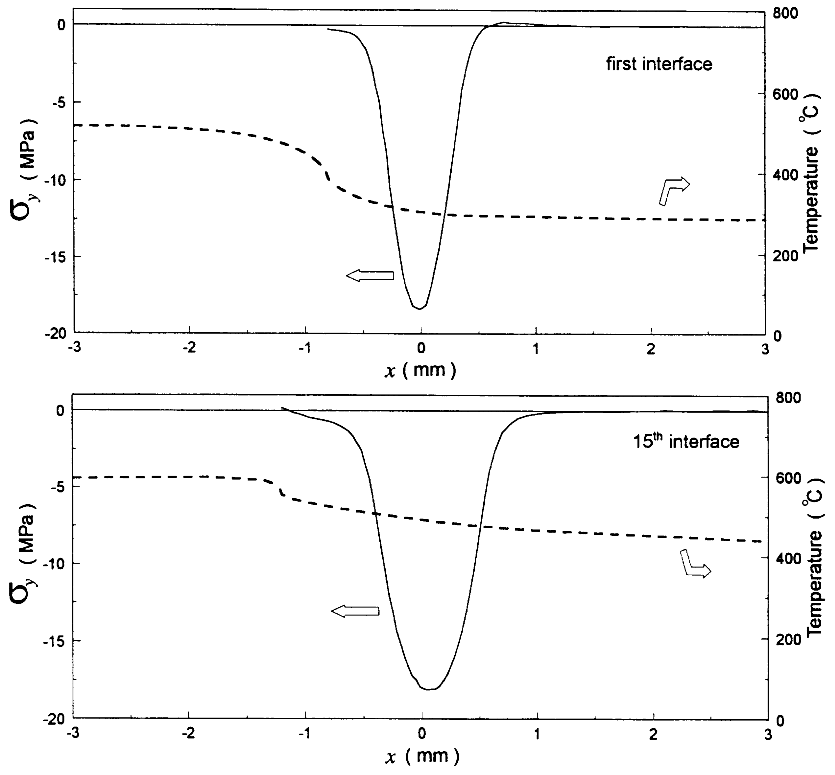

Figure 18. *Temperature and normal stress distributions during the placement of the first and the 15th interfaces.*

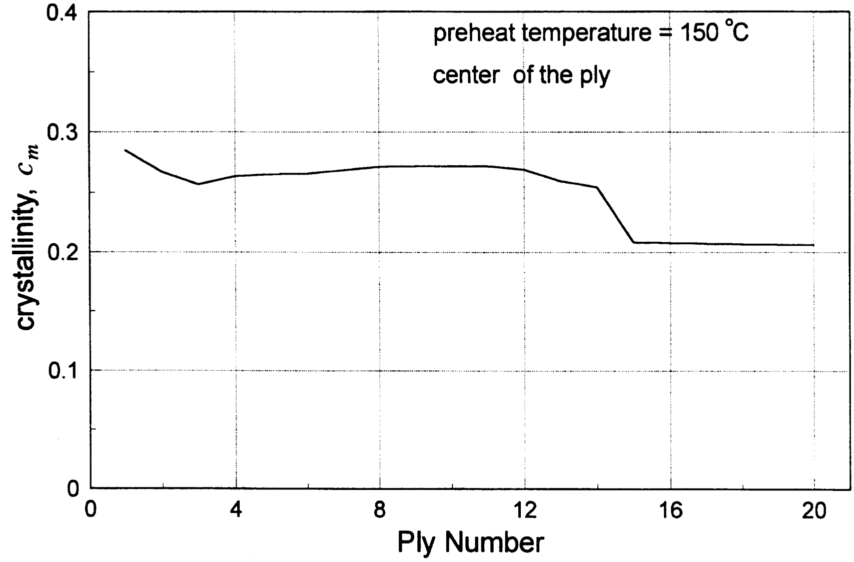

Figure 19. *The final crystallinity levels through the thickness of a laminate after a 20-ply lay-up process.*

each layer are given in Figure 17. The preheat temperature is 150°C, which is slightly above the glass transition temperature of the polymer matrix (145°C). As discussed in Reference [14], preheat temperatures higher than the glass transition temperature result in uniform and recommended levels of crystallinity through the thickness of the laminate. In this case, crystallinity levels are also uniform and close to the recommended range.

6.7 The Effect of Heated Length Ratio

The ratio of the length of the heated area on the substrate to that on the tape affects the temperature field and thus consolidation conditions. Since the tape is normally raised to higher temperatures than the substrate [2,14], supplying more heat to the substrate improves bonding as shown in Figure 20. However, increasing the ratio beyond 5 has a detrimental effect.

7. CONCLUSIONS

In the present study, process modeling of tape placement has been carried out. Tape placement is shown to be a viable technology for automated manufacturing of thermoplastic composites. The present study shows that, by using the optimum process parameters, roller speeds as high as 3 cm/s can be achieved. With some design changes such as adding a secondary roller, roller speeds can be increased to 5

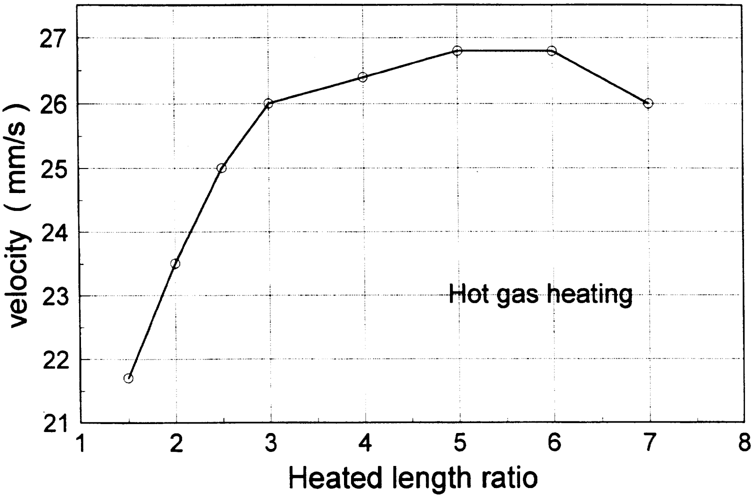

Figure 20. *The effect of heated length ratio. The preheat temperature is 150°C. The total heated length is (2 × wq) 40 mm.*

cm/s or even more. Although this range of processing speeds is still below the currently used speeds for thermoset tape placement, elimination of post-processing can be expected to offset the increase in the lay-up time.

The following conclusions can be drawn for optimum operating conditions of tape placement.

Preheating the substrate was found to be conducive to consolidation. Preheating the incoming tape or the roller did not improve consolidation.

Large heated lengths are more favorable to consolidation. However, the effect of heated lengths larger than 20 mm was small. Increasing the heated length ratio improved bonding. For the chosen material and design parameter, its optimum value was found to be 5.

Reduced roller speeds resulted in increased crystallinity levels as expected. However, preheating the substrate was found to be the major factor. Preheating the substrate above the glass transition temperature produced uniform and recommended levels of crystallinity throughout the thickness of the laminate.

Small rollers induced very concentrated stress distributions at the interface and thus led to shorter consolidation times. Therefore, larger roller diameters are more favorable to consolidation.

A significant portion of the bonding occurs during the placement of subsequent layers. For this reason, during the placement of the last layer, lower speeds have to be used. Lower speeds should also be used during the placement of the first few layers. As the main reason, the highly conductive steel mold leads to very high cooling rates. Accordingly, bonding times will be shorter. Also, stresses are more concentrated for very thin layers. The time spent under high stresses then becomes shorter.

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