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Process optimization of tape placement for thermoplastic composites

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Abstract

Despite the advantages of tape placement with its high production rate in manufacturing composite laminates, residual stress development and operation under non-optimum conditions remain as the drawbacks to be surpassed. The goal of this study is to develop a process optimization scheme for tape placement. Two objectives of optimization are separately considered; one is to minimize the peak tensile residual stress. The other is to increase the productivity by maximizing the processing speed. Two quality requirements act as constraints in the optimization procedure. First of all, the chosen process parameters should be conducive to good bonding between the tape and substrate; secondly thermal degradation should not be excessive. In order to determine temperature distribution, residual stresses, bond quality, and thermal degradation, previously developed process models were used. Nelder–Mead, a zeroth-order search algorithm, was employed to minimize the objective function. The numerical results showed that significant improvement could be achieved through optimization and a laminate with acceptable quality could be produced in situ.

Keywords: A. Laminates; B. Residual/internal stress; B. Thermomechanical; C. Finite element analysis (FEA); E. Prepreg; Nelder–Mead algorithm

1. Introduction

Thermoplastic composite materials are replacing many traditional engineering materials and are being demanded in areas with high production rates. This tendency may continue only if composites can be supplied at lower costs without any compromise of the quality. High costs are mainly due to inefficient labor intensive processing methods. It is therefore imperative to develop reliable, fast, and economical manufacturing techniques. The tape placement process is one of the few techniques that have the potential to continuously process thermoplastic composites in large-scale industrial applications. Nevertheless, one of the difficulties preventing this process from being used widely and adversely affecting its quality is the undesirable residual stress development; the other is low productivity associated with low processing speeds.

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

Placement process of thermoplastic composite tapes involves heating, melting, and cooling steps. Consequently, development of residual stresses is unavoidable due to disparate thermal characteristics of matrix and fiber materials and also due to non-uniform heating and cooling. From the product quality standpoint such as interlaminar strength, dimensional accuracy, etc. these stresses should be kept within allowable limits. As another quality requirement, a laminate should be void free and well consolidated for reliable use in a structure as a load bearing part. Achievement of good bonding between individual plies is therefore an important concern. Incomplete bonding results in high void content, which seriously degrades the mechanical performance of the composite. Another important concern is thermal degradation resulting from excessively high temperatures. Prolonged times at a high temperature may lead to degradation and decomposition

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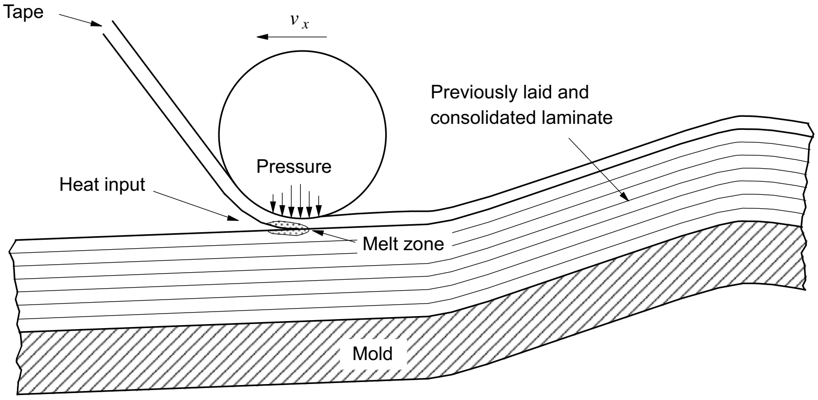

Fig. 1. The tape placement process.

of polymer matrix [1]. Applying inappropriate heat input may result in degradation of the matrix, which should not exceed the allowable limits. Thus, limited degradation is another requirement for satisfactory quality. Not only these three important quality requirements should be satisfied in the processing, but also the process should be optimized either to improve the quality of the end product or increase the productivity of the process.

In some of the previous studies of tape placement [2–7], suitable sets of process parameters were found by conducting experiments. Also, in a number of studies, a feasible process window was developed through process modeling. James and Black [8] developed a process window for filament winding. They used thermal degradation data and a diffusion model to determine the upper and lower limits on process parameters. Pitchumani et al. [9] considered thermal degradation, void content and dimensional change as product quality criteria to develop a process window for tape placement. Sonmez and Hahn [10] used the quality criteria for interlaminar bond strength, weight loss through thermal degradation, and crystallinity to find feasible sets of process parameters. Heider et al. [11] proposed a process optimization scheme for tape placement based on a neural network model to maximize output rate while maintaining the minimum quality. They considered void content and interlaminar bond strength as quality criteria in their optimization procedure. However, they did not take into account residual stress and thermal degradation.

The goal of this study is to develop a process optimization scheme first to determine the set of process parameters that will result in a laminate with minimum peak residual tensile stress, with the condition that all the other quality requirements are satisfied. The second objective of this study is to apply the optimization scheme to achieve the highest possible lay-down speed. As the main advantage of thermoplastics as opposed to thermosets, they can be manufactured in situ, i.e. without any need of post processing. However, current thermoplastic processing speeds in comparison to thermosets are so slow as to negate this advantage. Processing the thermoplastic composites at high speeds will significantly increase the productivity and their relative advantage. Accordingly, the other objective of this study is to find the process parameters using which one may place the tapes with the highest speed.

In view of the quality constraints, extensive process modeling is needed to determine the relationships between the process parameters and the quality parameters (peak tensile residual stress, the degree of degradation, and bonding). For this purpose, the process models developed before [10,12–14] were used. Since there is no closed-form expression relating the process parameters to the quality parameters, and considering the difficulty of calculating numerical derivatives of the objective function and the constraints, a zero-order numerical optimization algorithm called Nelder–Mead was chosen.

2. Process modeling of tape placement

A process model provides the input–output relation between the process variables and the product quality. The process variables are the controllable variables that affect the quality of the product. In the previous studies [2–33], researchers identified the process parameters of tape placement and investigated their effects. The parameters that had a determining effect on quality were mainly temperature of the hot gas exposed to the tape-substrate interface (T_{hg}), velocity of the roller pressing tape onto the laminate (v_r), preheating temperature of incoming substrate (T_o), heated length on tape (hl), and the ratio of the heated length on substrate to the length on tape ($hlr = hl/hls$). Fig. 2 shows the process variables under consideration. Although roller force is also a process parameter, its magnitude is not varied during optimization. Because increasing this force is always conducive to consolidation, for optimum performance the maximum value that will not cause fiber-bed spread or resin starvation was chosen as in Ref. [10]. We assume that the whole lay-up process is achieved using the same process parameters during the placement of each layer. A more comprehensive problem would be the optimization of the whole lay-up, where a

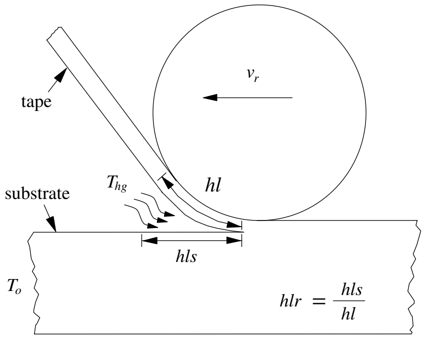

Fig. 2. Process variables of tape placement.

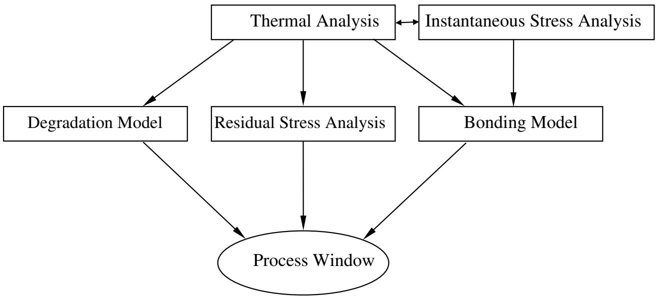

Fig. 4. A schematic of the process modeling for tape placement.

separate set of processing variables is chosen for the placement of each layer. In this case, the number of optimization variables would be $5n$, n being the number of layers. Considering the computational time for simulating the placement of one layer, the large number of variables, and possibly high number of local minimums, obtaining a globally optimum solution for this problem would be a formidable task.

Fig. 3 illustrates the schematic representation of the input–output relation in the process model. A process optimization algorithm uses this input–output relation to improve the quality of the product or increase productivity. Such a relation between the inputs and outputs of the tape placement process was established before through numerical models simulating the process [10,12–14], and the developed models were verified by comparing the numerical results with analytical and experimental results.

Fig. 4 shows a schematic of the process modeling for tape placement. Since thermomechanical history experienced by a material during processing determines its microstructure, and hence the mechanical performance of the resulting part, thermal and instantaneous stress analyses were carried out. Temperature and stress fields thus obtained are used in the residual stress, degradation and bonding models.

2.1. Residual stress development

Residual stress analysis using a thermoviscoelastic finite element model was carried out according to the method explained in Ref. [14]. However, a larger domain of analysis and a more refined mesh were chosen during optimization in order to ensure accuracy for all values of process variables generated by the optimization algorithm. In order to ensure convergence, the length of the analysis domain was chosen to be 5 m, and the finite element mesh to be 160×30 as shown in Fig. 5.

Placement of each layer partially destroys already existing residual stresses in the substrate because of locally induced high temperatures, but also contributes to them during cool down. Already existing residual stresses are accounted for by taking them as initial stresses in the analysis carried out for the placement of the current layer. In order to account for the relaxation of residual stresses in previously laid layers during the current placement, the following approach was adopted: In the previously laid layers experiencing temperatures exceeding the stress free temperature of the thermoplastic material, residual stress is assumed to be fully relaxed and set to zero; because experiments show that unbalanced laminates become flat when the temperature of the material is raised close to its melting point [34]. On the other hand, residual stresses in the layers experiencing lower temperatures continue to exist, but their magnitudes change. Considering that there is no externally applied load and equilibrium is to be satisfied, average stress at the cross section of the laminate should continue to be zero. Accordingly, the following formula is adopted to calculate initial stresses.

$$\sigma^i_{\text{ini}} = \begin{cases} \sigma^i_{\text{res}} - \sum_{k=1}^{n} \sigma^k_{\text{res}} \frac{b_k}{b_r} & \text{if } T^i_{\max} < T_{\text{free}} \\ 0 & \text{if } T^i_{\max} \geqslant T_{\text{free}} \end{cases} \tag{1}$$

where, σ^i_{res} is the resulting residual stress after the placement of the previous layer in ith finite element counted from the bottom in the vertical direction; σ^i_{ini} is the initial stress in that element to be used in the analysis of the placement of the current layer; $T^i_{\max}$ is the maximum

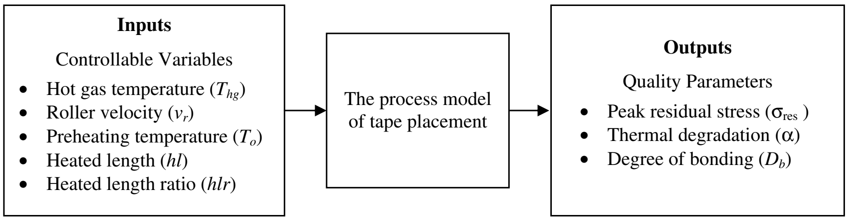

Fig. 3. Inputs and outputs of the process model.

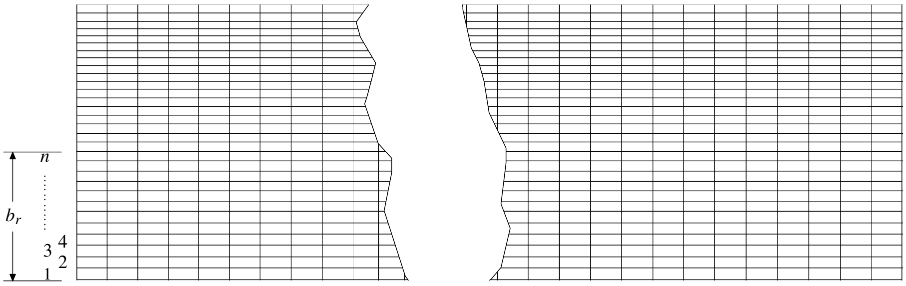

Fig. 5. Mesh structure used in the residual stress analysis. Horizontal and vertical dimensions are not to scale.

temperature experienced by the material occupying *i*th finite element. T_{free} is the stress free temperature beyond which material may not sustain any residual stress; b_k is the length of the kth element in the vertical direction, b_r is the thickness of the portion of the laminate that experiences temperatures less than T_{free} (Fig. 5); n is the number of finite elements across the section in this portion.

2.2. Degradation model

Thermal degradation can be quantitatively characterized through the associated weight loss. In the optimization procedure, a degradation kinetics model was used to calculate the percentage of weight loss due to degradation, α. The degree of degradation, α_d, is given by the ratio of the current weight loss to the ultimate weight loss [37]:

$$\alpha_d = \frac{M_0 - M}{M_0 - M_f} \tag{2}$$

where M, M_0 and M_f are the current, the initial and the final weight of the polymer, respectively. The degradation rate for PEEK is given by the following equation [37]:

$$\frac{d\alpha_d}{dt} = k[w_1(1-\alpha_d) + w_2\alpha_d(1-\alpha_d)] \tag{3}$$

where w_1 and w_2 are weight factors and k is a rate constant described by an Arrhenius relation, $k(T) = A\exp(-E/RT)$, which indicates that at high temperatures the rate of degradation increases dramatically. The ultimate weight is $0.64M_0$ for PEEK [37]. Reduction in the weight of the polymer as the percentage of the ultimate weight loss is then expressed as

$$\alpha = 36\alpha_d\ (\%) \tag{4}$$

2.3. Bonding model

Degree of bonding, D_b, is a measure of interlaminar bond strength. In order to determine D_b, a model [38,39,17] adapted before for tape placement [10] was employed. D_b is calculated using the following equation:

$$D_b(t_b) = \int_0^{t_b} \left[\int_0^{t_b-\tau} \frac{d\eta}{\sqrt{\eta T_r(\eta)}}\right]^{1/2} \frac{dD_{ic}}{d\tau}\, d\tau \tag{5}$$

where t_b is the bonding time during which the material at the interface experiences temperatures above the processing temperature. T_r is a parameter depending on temperature.

$$T_r = t_r \exp\left[\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right] \tag{6}$$

D_{ic} is the degree of intimate contact given by [17]

$$D_{ic} = a^* \left[\int_0^{t_b} \frac{P_{\text{app}}}{\mu_{mf}}\, dt\right]^{1/5} \tag{7}$$

Here P_{app} is the pressure at the interface and μ_{mf} is the viscosity.

3. The optimization scheme

3.1. Minimization of residual stress for in situ processing

The optimization algorithm should find the optimum set of process parameters by searching among the feasible sets, which result in a laminate satisfying the quality requirements. Limited thermal degradation and full consolidation act as the constraints in the residual stress minimization process.

The maximum allowable weight loss α_{all} for APC-2 was estimated to be 0.01% [12], below which degradation in mechanical properties was assumed to be inconsequential. The degradation constraint may then be expressed as

$$\alpha \leqslant \alpha_{\text{all}} \tag{8}$$

Another quality requirement is achievement of full bonding during in situ processing; in that case, post processing will not be needed. When full bonding is achieved bulk properties are restored at the interface. This means that when the degree of bonding, D_b, is equal to one, the interlaminar shear strength, S, attains its maximum value, S_∞. Therefore, we only need to consider D_b. Thus,

$$S = S_\infty \tag{9}$$

or

$$D_b = 1 \tag{10}$$

The aim in the optimization process is to find the set of process parameters (controllable variables) that will result in the minimum value of the objective function and, at the same time, satisfy the constraints. The objective function may be chosen as the peak tensile residual stress to maximize the load capacity of the produced laminate. Accordingly, the problem may be stated as

$$\begin{aligned} &\text{Minimize} && \sigma_r \text{ (peak tensile residual stress)} \\ &\text{subject to} && D_b = 1 \\ &&& \alpha_d \leqslant \alpha_d^{all} \end{aligned} \tag{11}$$

It should be noted that peak residual stress, σ_r, degree of bonding, D_b, degradation weight loss, α, corresponding to the given set of process parameters are not closed-form functions of the process parameters, yet calculated through a series of numerical analyses. Therefore, it is not possible to benefit from the analytical optimization techniques. Although stochastic optimization techniques seem to be appropriate candidates for this case, they require excessive numbers of iterations to reach the global minimum. Considering that numerical analyses require considerable computational time, utilization of stochastic optimization techniques such as simulated annealing or genetic algorithms is not feasible. At this point, local optimization techniques shine as the most convenient alternatives though they converge to one of the local minima not necessarily to the global optimum. For this reason, they have to be employed several times starting from different values of optimization variables and the resulting lowest objective function value should be chosen as the best solution.

A comparison between zeroth, first, and second order local minimization algorithms should be made to choose the best technique that can serve for this purpose. A zeroth order method, although not very efficient regarding computational time, does not require calculation of the derivatives of the objective function and the constraints. Despite the fact that the speed of convergence of the higher order methods is higher, the values of the derivatives are needed. However, their numerical calculation poses a great difficulty. In the light of these facts, Nelder and Mead [35], a zeroth order algorithm, was chosen for the optimization process. Because this algorithm is suitable for unconstrained optimization problems, penalty functions are added to the cost function in order to cope with constraint violations. The constrained optimization problem is thus transformed into an unconstrained one. Accordingly, the cost function for residual stress minimization is formulized as follows:

$$f = \frac{\sigma_r}{\sigma_{ref}} + p_1 \langle \alpha_d - \alpha_d^{all} \rangle + p_2 \langle 1 - D_b \rangle \tag{12}$$

where p_1 and p_2 are suitable penalty coefficients. The bracketed terms yield the value of the inside term if it is positive, or zero otherwise. In other words, if the quality constraints are violated, the cost is increased proportional to the extent of violation; if they are satisfied, the cost is not affected. Also, the peak tensile residual stress, σ_r, is normalized by dividing by a reference value σ_{ref} (75 MPa).

The optimization procedure for residual stress minimization is illustrated in Fig. 6. First, one should choose initial values for the process parameters. These should result in a laminate satisfying the quality constraints, i.e. the initial point should be within the feasible region. Otherwise, the optimization process may converge to a minimum outside the feasible region. For this reason, randomly generated values for process parameters are tried until a feasible set can be found. The generated values of the process parameters are used as inputs in the process models. The temperature distribution determined by the heat transfer model is used in the degradation, instantaneous stress, bonding, and residual stress models. If there is any violation of quality constraints, the associated penalty is calculated. The new set of process parameters is determined through the Nelder–Mead algorithm. In some cases, the algorithm may generate such values that processing may not be possible (e.g. negative roller velocity or heated length.) or practicable (e.g. very large heated lengths). In that case, model calculations are not carried out; instead a penalty is calculated proportional to the extent of violations of these side constraints.

Because Nelder–Mead is a local search algorithm, optimization process may end up in a local minimum, rather than globally minimum point. In order to ensure convergence to the globally minimum value of residual stress, the optimization process was repeated many times, starting from randomly chosen sets of process parameters within the feasible region. Then, the lowest value was taken as the globally minimum value of the objective function.

3.2. Maximization of roller speed in case of post processing

In situ processing has the advantage of better dimensional accuracy, and also lower cost, because achievement of full consolidation during lay-down does away with post processing. However, if the lowest achievable residual stress is too high, or the highest achievable lay-down speed is too low in in situ processing, then one may consider laying down the tapes at the highest possible speed that enables achievement of consolidation just sufficient to keep the integrity of the part. The optimization problem then becomes

$$\begin{aligned} &\text{Maximize} && v_r \text{ (roller speed)} \\ &\text{subject to} && D_b \geqslant D_{b.min} \\ &&& \alpha_d \leqslant \alpha_d^{max} \end{aligned} \tag{13}$$

here $D_{b.min}$ is the minimum allowable degree of bonding that ensures integrity of the part and allows placement of tapes along nongeodesic paths. In this study 80% bonding was assumed to keep the part from delamination under the effect of gravitational and processing forces. Because, residual stresses relieve during post processing, we do not need to introduce a constraint on residual stresses. The maximum allowable weight loss, α_{all}, should be the same in all optimization problems, because thermal degradation cannot be recovered by a post processing. The optimization

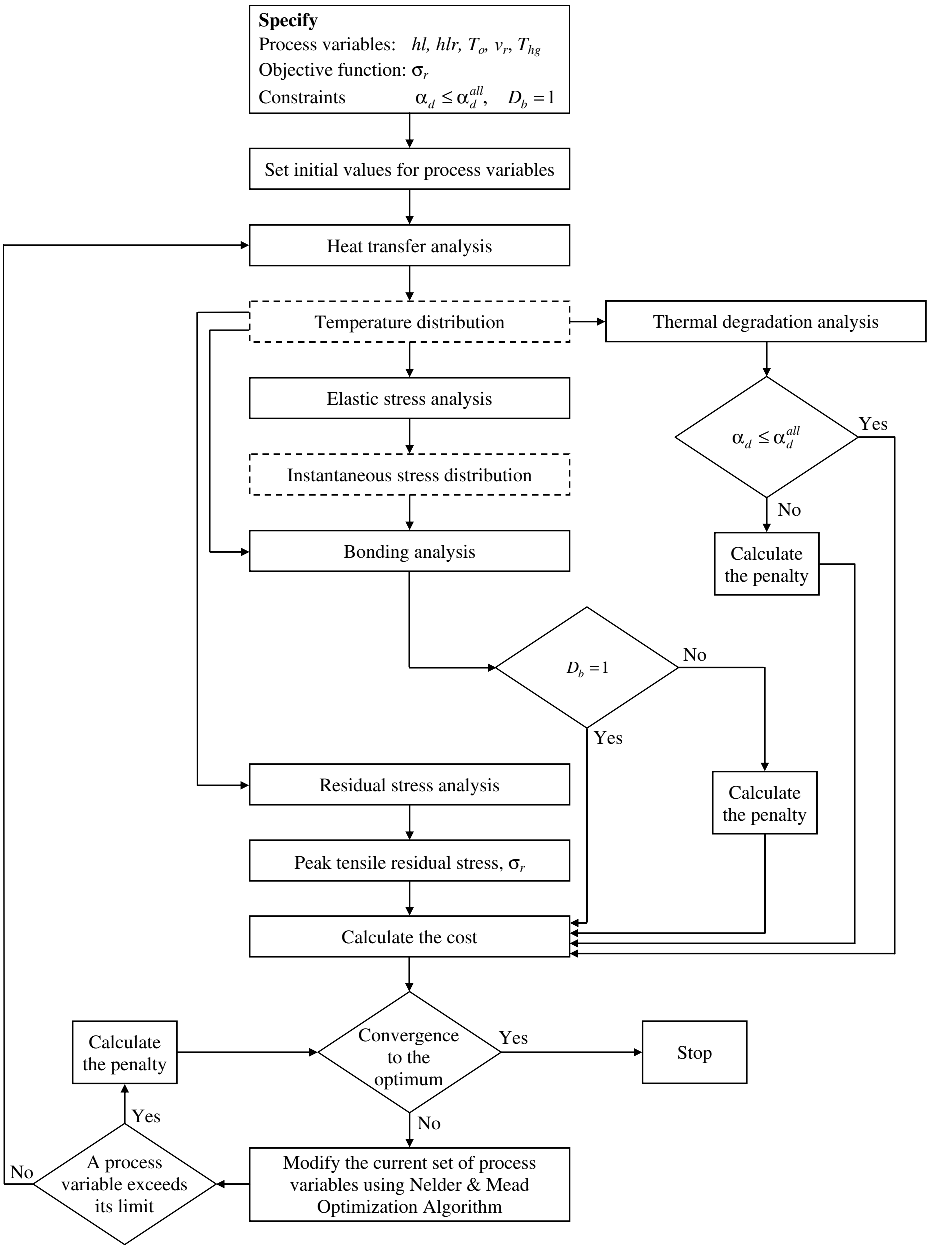

Fig. 6. The procedure for residual stress minimization.

procedure is similar to the one depicted in Fig. 6 with minor modifications.

4. Results and discussion

As mentioned before, for each process parameter there are limits as listed in Table 1 acting as constraints. They are either upper or lower bounds on the feasibility of the process. For instance, preheating temperatures below the room temperature or very high heated lengths are difficult to realize. There are also limits on the processibility of the material. Consolidation is difficult to achieve with hot gas temperatures lower than the melting temperature. Preheating temperatures exceeding glass transition temperature (135 °C for APC-2) may disrupt the dimensional stability of the part. Besides, some limits are set because optimum processing is not expected be possible beyond these limits, such as lower limits on heated length ratio and heated length on tape, and upper limits on velocity and hot gas temperature. A lower limit is set for roller speed because long processing times are undesirable.

4.1. Residual stress minimization for in situ processing

The processed material was chosen to be APC-2. The inputs for the heat transfer, bonding, degradation, instantaneous stress, and residual stress analyses were given in Refs. [10,12–14].

As shown in our previous study [14], residual stresses accumulate gradually during successive lay-down of layers;

Table 1
The limits on the process and quality parameters for APC-2 in residual stress minimization

	Lower limit	Upper limit
Process parameter		
Heated length on the tape, *hl*	0.5 cm	9 cm
Heated length ratio, *hlr*	0.1	–
Preheating temperature, T_o	20 °C	135 °C
Roller velocity, v_r	1 mm/s	25 mm/s
Hot gas temperature, T_{hg}	400 °C	750 °C
Heated length on substrate, *hls* ($hl \times hlr$)	–	20 cm
Quality parameter		
Degradation weight loss, α, (%)	–	0.01
Degree of bonding, D_b	1.00	–

they may reach excessively high levels especially in thick laminates. This is because every fresh layer is laid-down on a colder substrate through localized heating. Fig. 7 shows accumulation of residual stresses at the midpoints of the first and fifth layers in a cross-ply laminate, $[0_4 90_8 0_4]_T$, during the lay-down process. The values of the process parameters are $hl = 2.53$ cm, $hlr = 7.9$, $T_o = 135$ °C, $v_r = 6.0$ mm/s, and $T_{hg} = 531$ °C. No appreciable residual stress develops during the placement of the 2nd, 3rd, and 4th layers, where fibers in the tape and the substrate run in the same direction. This is because the main cause of residual stress is the discrepancy in the thermal expansion behavior along the transverse and longitudinal directions. When the substrate includes fibers oriented transverse to tape, significant residual stresses develop as in the case of lay-down of the layers 5th to 16th. Fig. 8 shows the final residual stress (σ_{xx}) distribution through the thickness of this cross-ply laminate. Ply numbers 1 and 16 indicate the bottom and top layers, respectively. As expected compressive stresses develop in the top and bottom 4 plies, while tensile stresses develop in the middle 8 plies due to much higher value of thermal expansion coefficient in the transverse direction. The distribution of residual stresses is uneven through the thickness of the laminate and they are high enough to cause undesirable distortions in the laminate. The maximum transverse tensile stress, which develops in the fifth layer, is 243 MPa. This value far exceeds tensile transverse strength of the material (≈78 MPa). We should expect transverse cracks to develop during processing, which surely weaken the composite part. Otherwise, the set of process parameters used for this particular case is expected to result in a laminate satisfying the other quality criteria, namely full bonding and limited degradation, according to our process model. Thus, a laminate processed by tape placement is liable to fail also due to excessively high residual stress levels. Just ensuring full bonding and limited degradation is not sufficient for quality assurance. Without optimizing the processing for minimum residual stress development, tape placement can not reliably be used for processing thermoplastic composites.

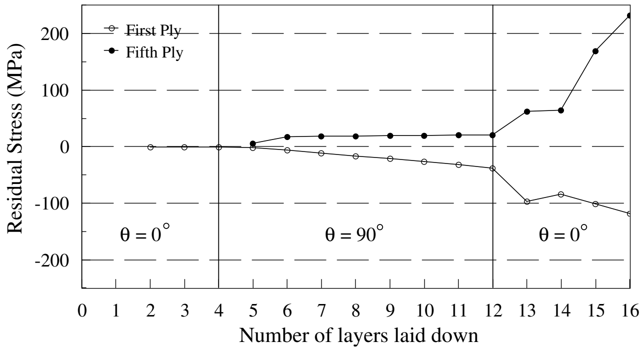

Fig. 7. Development of residual stresses in the first and the fifth layers during the lay-up process of a cross-ply laminate, $[0_4 90_8 0_4]_T$.

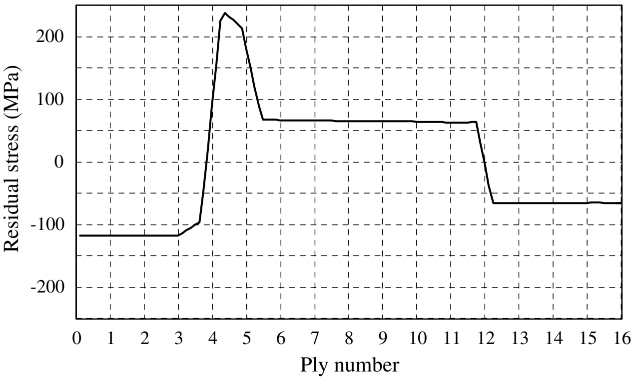

Fig. 8. Final residual stress (σ_{xx}) distribution through the thickness of a cross-ply laminate, $[0_4 90_8 0_4]_T$, after the lay-up process.

The optimization results for a lay-up sequence of $[0_4 90_8 0_4]$ were obtained using the optimization procedure described in Fig. 6. As expected, a number of local minimums were found after repeated runs. After 30 runs, we found three distinct local minima at which the maximum residual stress was around 70 MPa as given in Table 2. This magnitude is within the range obtained by the standard press molding process [36].

Of the side constraints listed in Table 1, the constraint on the heated length on substrate, *hls*, ($hl \times hlr$), is active or very close to its upper limit. This is because larger heated lengths on substrate lead to more uniform temperature distributions [12], which in turn tend to reduce residual

Table 2
Optimum process parameters for minimum residual stress

	Optimum sets		
	1	2	3
Process parameters			
Heated length, *hl* (cm)	2.9	6.4	3.1
Heated length ratio, *hlr*	6.7	3.0	6.3
Preheating temperature, T_o (°C)	135	135	135
Roller velocity, v_r (mm/s)	4.2	3.9	3.8
Hot gas temperature, T_{hg} (°C)	518	507	505
Quality parameters			
Peak residual stress, σ_r (MPa)	69.6	70.4	70.5
Degradation weight loss, α (%)	0.0082	0.0081	0.0052
Degree of bonding, D_b	1.00	1.00	1.00

stresses, as opposed to highly localized heating. The constraint acting as the upper limit on preheating temperature is also active for the same reason. The other side constraints in Table 1 are not active. Also, both of the behavioral constraints on bonding and degradation are not active. The degree of bonding reaches its limit, which is 1.0, before the processing ends. This is because the processing speeds are low, the highest being 4.2 mm/s. This allows sufficient time for bonding to take place. The reason why the algorithm found the optimum processing at low speeds is that when the roller moves slowly, significant portion of the laminate under the roller is heated, leading to low temperature gradients, thus more uniform cooling [12] and lower residual stresses [14]. As for the heated length ratio, *hlr*, if more heat is supplied to the substrate a more uniform temperature distribution is obtained. We may need to heat up a region on substrate six times as long as that on tape to achieve optimum conditions.

Fig. 9 shows the change in the maximum tensile residual stress. As seen in the first trials, arbitrarily chosen process parameters may result in exceedingly high residual stresses.

Fig. 10 shows accumulation of residual stresses in the first and fifth layers in a cross-ply laminate, $[0_4 90_8 0_4]_T$, during the lay-down process using the optimum values for the process variables. Fig. 11 shows the final residual stress (σ_{xx}) distribution through the thickness of this cross-ply laminate. Unlike the one shown in Fig. 8, residual stress distribution is symmetric with respect to the mid-plane. We should not expect the residual stresses to cause distortion of the laminate. Since the magnitude of the maximum residual stress is in the same range as obtained by press molding, we may expect that the quality of the parts produced by tape placement using the optimum values for process variables is as good as produced by press molding.

The reason why these sets of process variables resulted in minimum residual stress development became apparent when we noticed that high temperatures induced by local heating destroys the residual stresses in all of the 8 layers in the middle with 90° fiber orientation. During the placement of the last layer, residual stresses in the top 12 layers totally relax because they experience temperatures exceeding the stress free temperature, T_{free}, and the residual stresses in the bottom unidirectional 4 layers become insignificantly small according to Eq. (1). We may therefore conclude that if the layers that experience temperatures less than the stress free temperature of the material (280 °C for APC-2 [14]) during the placement of the last layer have fiber orientation in the rolling direction, then the residual stresses that develop have the minimum value, which is about 70 MPa for APC-2.

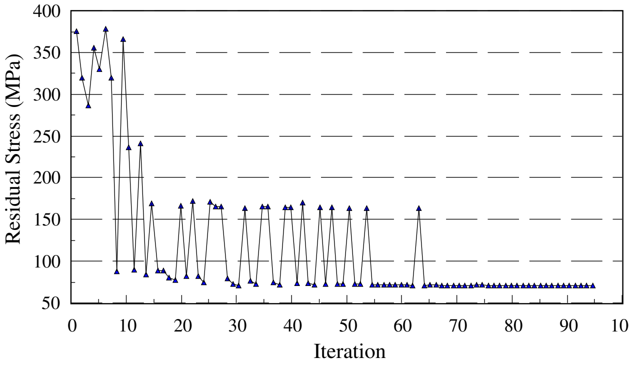

Fig. 9. Reduction in the maximum tensile residual stress.

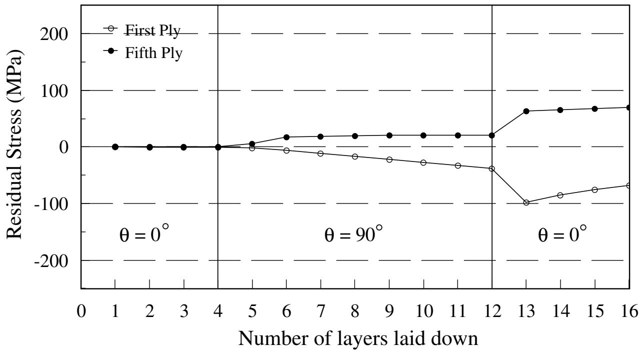

Fig. 10. Development of residual stresses in the first and the fifth layers during the lay-up process of a 16 ply cross-ply laminate, $[0_4 90_8 0_4]$ using the optimum process parameters.

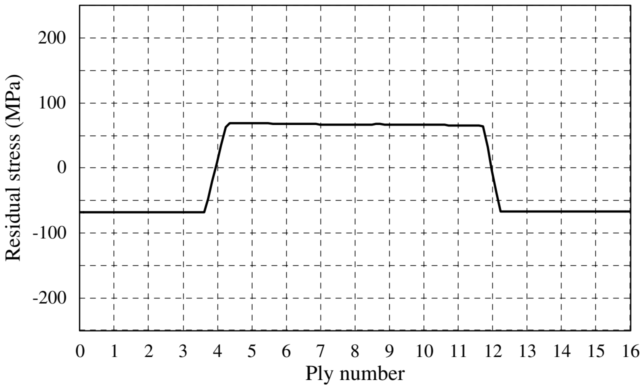

Fig. 11. Final residual stress (σ_{xx}) distribution through the thickness of a cross-ply laminate, $[0_4 90_8 0_4]_T$, after the lay-up process using the optimum process parameters.

We noticed that there were sometimes unexpected jumps in the residual stress levels through the iterations of optimization process as in Fig. 9 even though the changes in the values of process parameters are insignificantly small. These jumps are usually between 70 and 161 MPa, corresponding to differences between the values of process parameters less than 0.5%. Fig. 12 shows one of these cases resulting in high values of residual stress. If we compare Figs. 10 and 12, we notice that there is almost no difference in the residual stress development until the placement of the last layer. During the placement of the 16th layer, the residual stress at the mid-plane of the fifth layer jumps to a value of 126 MPa. The maximum stress, which again develops within the fifth layer, is 161 MPa. The reason is that the number of layers that experiences temperatures

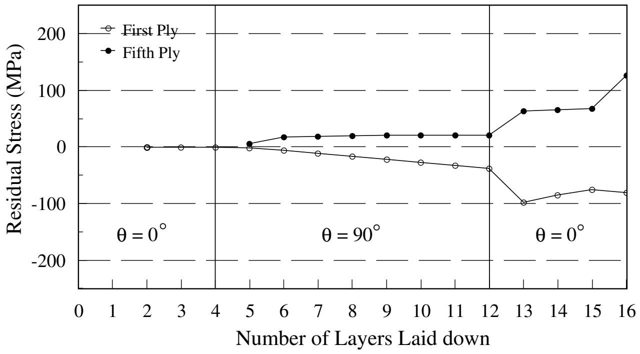

Fig. 12. Development of residual stresses in the first and the fifth layers during the lay-up process of a 16 ply cross-ply laminate, $[0_4 90_8 0_4]_T$ with an unexpected jump during the placement of 16th layer.

above T_{free} is 11.994 from the top. This means that residual stresses in a small portion of the fifth layer, which has 90°-fiber angle, do not relax. On the other hand, in the case shown in Fig. 9, number of layers subject to temperatures above T_{free} is 12.005. This means residual stresses in all the cross plies relax and the remaining plies are unidirectional and in the same direction as the tape.

One should note that crystallinity is a quality parameter that affects the mechanical properties. Normally, it should be included in the process optimization as a quality constraint. A previous study [12] found that using a low roller speed and preheating the substrate to a temperature close to the glass transition point resulted in uniform and recommended levels of crystallinity (25–35% for APC-2 [40]) throughout the thickness of the laminate. Considering the optimum values for the process variables given in Table 2, one may conclude that the resulting laminate should satisfy the quality requirement for crystallinity. Since the process conditions that minimize residual stresses also induce recommended crystallinity levels, there is no need to include a constraint for crystallinity in the process optimization procedure.

4.2. Maximization of roller speed

Our attempts to minimize residual stress showed that one may in situ produce a thermoplastic composite laminate having satisfactory quality using the tape placement process, but only with low processing speeds. Another approach would be to fabricate the laminate by tape placement as fast as possible without any regard to full bonding, then by post processing in an autoclave to achieve full bonding. During the fabrication stage, the degree of bonding between individual layers should be high enough to preserve integrity of the structure and to allow laying down over nongeodesic paths. However, one should avoid thermal degradation, because this is an irreversible damage. During post processing because of controlled heating and cooling, full bonding and satisfactory residual stress levels as well as desired crystallinity levels can easily be achieved.

Table 3
The limits on the process and quality parameters for APC-2 in speed maximization

	Lower limit	Upper limit
Process parameter		
Heated length on the tape, *hl*	0.5 cm	9 cm
Heated length ratio, *hlr*	0.1	–
Preheating temperature, T_o	20 °C	135 °C
Hot gas temperature, T_{hg}	400 °C	1000 °C
Heated length on substrate, *hls* ($hl \times hlr$)	–	20 cm
Quality parameter		
Degradation weight loss, α (%)	–	0.01
Degree of bonding, D_b	0.8	–

The constraints used for speed maximization are listed in Table 3. The upper limit on hot gas temperature was increased, because much more heat should be supplied in order to melt the interface under the roller at high speeds. No limit was set for maximum tensile residual stress. Even if residual stresses that develop during the placement process are very large, matrix cracks that they may cause can be eliminated during post processing. The upper limit on weigh loss due to thermal degradation was retained, because of its unrecoverable adverse effect. The minimum degree of bonding was chosen to be 0.8. This was assumed to provide sufficient strength for laying down tapes over nongeodesic paths.

Table 4 lists some of the results of speed maximization. Again, there are many local optimums. The results show that thermoplastic composite tapes can be laid-down at speeds up to 8 cm/s over nongeodesic paths. This is very close to the lay-down speeds of thermoset composite tapes, which can only be laid over geodesic paths because of insufficient bonding. Of the side constraints, only the upper limit on heated length on substrate is active or close to its upper limit. Of the quality constraints, the constraint on degree of bonding is always active as opposed to the bonding constraint in the residual stress minimization, because while the speed is increased, a smaller part of the region under the roller is melted leaving a shorter time for bonding to take place. The quality constraint on thermal degradation is either active or close to its upper limit. This is

Table 4
Optimum process parameters for maximum speed

	Optimum sets			
	1	2	3	4
Process parameters				
Heated length, *hl* (cm)	3.9	2.8	3.0	3.6
Heated length ratio, *hlr*	4.85	6.85	5.61	4.86
Preheating temperature, T_o (°C)	102	95	119	112
Roller velocity, v_r (mm/s)	82	80	81	81
Hot gas temperature, T_{hg} (°C)	679	674	687	680
Quality parameters				
Degradation weight loss, α (%)	0.01	0.0099	0.01	0.0096
Degree of bonding, D_b	0.8	0.8	0.8	0.8

because when speed is increased, more heat is needed to achieve bonding, but when hot gas temperature is increased for this purpose, the rate of degradation increases. Nevertheless, the results of velocity maximization should be verified through experiments. This is because very high temperatures develop on the surfaces exposed to heat and for this reason extrapolated data need to be used in degradation and bonding models, which may yield unreliable results.

Even though residual stress was not chosen as a quality parameter in velocity optimization, for the optimum sets it was calculated to be 326 MPa, 323 MPa, 363 MPa, and 347 MPa, respectively. These are quite large magnitudes. Development of cracks in the matrix is unavoidable. However, assuming that the fibers will not be damaged, these cracks can be healed during post processing.

Despite the existence of quite a number of local minimums in the process optimization of tape placement, use of Nelder–Mead as a search algorithm in this study turned out to be a viable approach. This was because the laminate was to be processed using the same process parameters; i.e. the number of design variables was small. However, if one chooses roller velocity, heated length, heated length ratio, preheating temperature, and hot gas temperature as a separate set of design variables for each layer, the only feasible approach to locate the global optimum among countless local optimums is to use a global search algorithm rather than a local search algorithm like Nelder–Mead.

5. Conclusions

The results of the process optimization of tape placement demonstrate that the maximum residual stress in the produced laminate can be reduced significantly. Residual stresses can be as low as 70 MPa for a cross-ply laminate, which is in the range obtained by press molding and at the same time full bonding without excessive thermal degradation can be achieved in situ. The condition for this is that all the layers having fiber orientation transverse to rolling direction should experience temperatures above the stress free temperature of the material during the placement of the last layer. We may conclude that in situ thermoplastic tape laying is a viable alternative to press molding.

Process optimization showed that satisfactory quality can be achieved by tape placement only at slow lay-down speeds. This may be considered as against the requirements of productivity. Accordingly, the roller velocity was also maximized using the same optimization procedure, but this time only partial bonding was considered to be sufficient for keeping the integrity of the part and laying down over nongeodesic paths leaving achievement of full bonding to post processing. It was demonstrated that the roller velocity can be as high as 8 cm/s, which is close to the lay-down speeds of thermoset composite tapes. Therefore, we may conclude that non in situ thermoplastic tape laying is a viable alternative to thermoset tape laying.

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