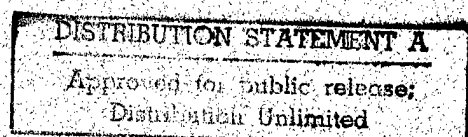


**Final Report to the U.S. Army Research Office
for**

RAPTECH-ACM

**Rapid Placement Technology
for Affordable
Composites Manufacturing**

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(1) LIST OF MANUSCRIPTS submitted or published under ARO sponsorship during this reporting period, INCLUDING JOURNAL REFERENCES:

JOURNAL PAPERS AND BOOK CHAPTERS

Butler, C. A., R. L. McCullough, and A. R. Wedgewood, "An Analysis of Mechanisms Governing Fusion Bonding of Thermoplastic Composites," accepted for publication, *Journal of Thermoplastic Composite Materials*, 1997.

Heider, D., M. J. Piovoso, and J. W. Gillespie Jr., "Intelligent Control of the Thermoplastic Composite Tow Placement Process," accepted for publication, *Journal of Thermoplastic Composite Materials*, 1997.

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(2) SCIENTIFIC PERSONNEL supported by this project and HONORS/AWARDS/DEGREES received during this reporting period:

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Ankur Parekh

Ranga Pitchumani

Scott Quirico

Mark Scott

Joe Thiravong

John Tierney

Frank Wohrmann

Yuquaio Yang

(3) Report of INVENTIONS (By TITLE ONLY):

none

(4) SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS:

Executive Summary

The RAPTECH-ACM program yielded the following research accomplishments:

- Development of process models governing heat transfer, consolidation, crystallization, intimate contact, healing, and residual stress and warpage. These models have been incorporated into a real-time neural-network-based simulation.
- Incorporation of advanced model-based control on line and optimization to establish set-points for heat input, velocity, and pressure to achieve the desired quality (i.e., bonding, void content).
- Integration of infrared sensors for feedback control.
- Successful demonstration on lab-scale robotic workcell.
- Transition of technology to industrial partners.
- Mounting of RAPTECH/DuPont placement head onto Cincinnati Milacron's gantry tape layer (see Figure 1), where it is being used to make high-quality parts for HSR (less than 1% void content, mechanical properties approaching autoclave baseline).

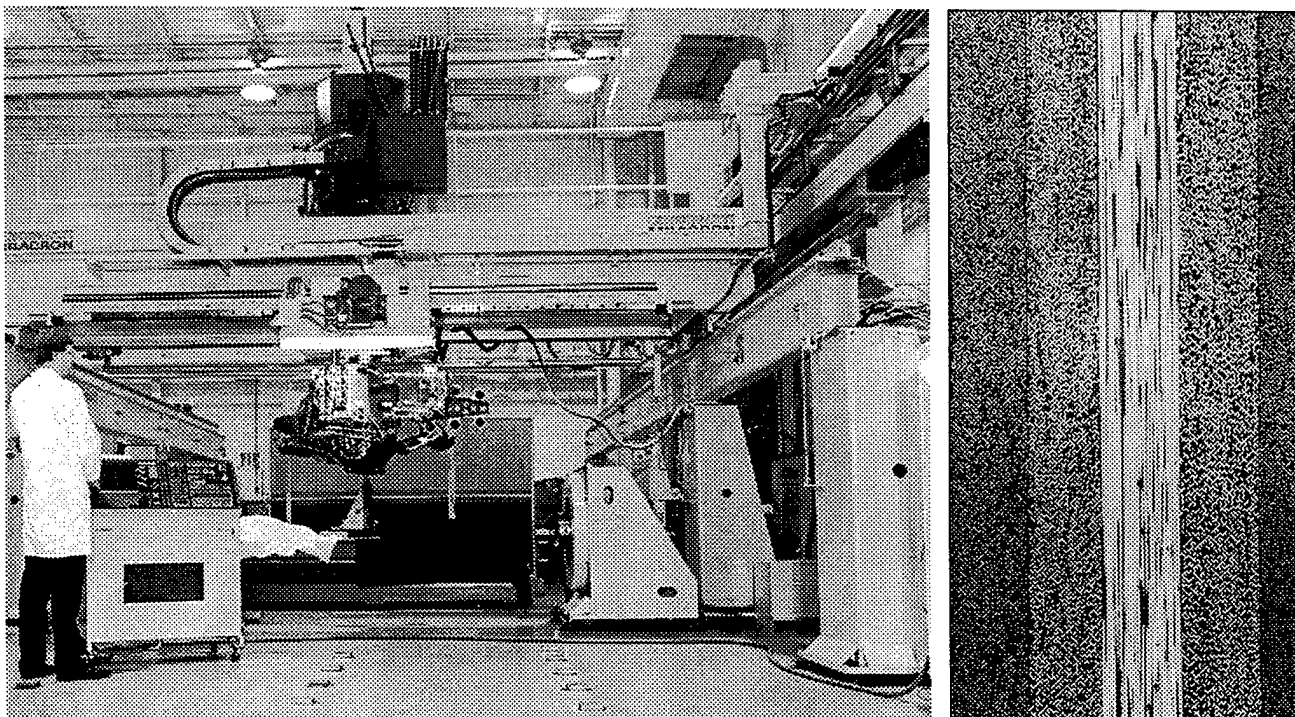


Figure 1: RAPTECH/DuPont placement head mounted onto Cincinnati Milacron's gantry tape layer (left), where it is being used to make high-quality parts for HSR—less than 1% void content, mechanical properties approaching autoclave baseline, as shown in the micrograph (right).

Background

The automated tow-placement (ATP) technology for thermoplastic composites is a non-autoclave process that offers the potential to significantly reduce fabrication costs for large-scale structures. ATP involves the continuous consolidation of thermoplastic composite tows on an already consolidated substrate material. This is achieved by the concurrent use of localized heat and pressure so that bonding is achieved at the newly formed interface and consolidation is achieved within the material. Figure 2 shows the laboratory setup of the automated thermoplastic tow-placement process at UD-CCM. The workcell enables validation of process models and advanced model-based control.

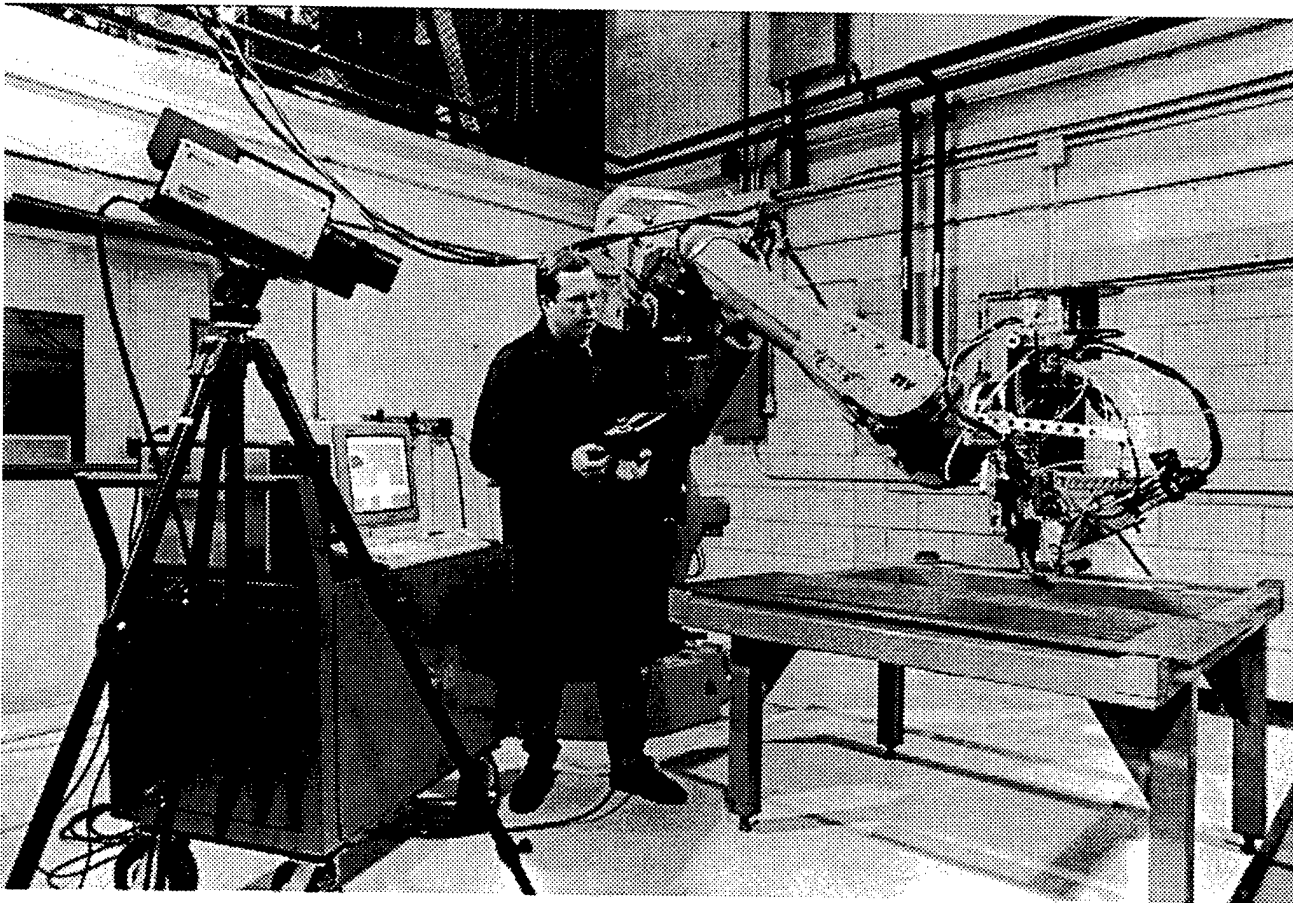


Figure 2: Laboratory setup of the automated thermoplastic tow-placement process at UD-CCM, which is used for validation of process models and advanced model-based control.

Summary of Current Process Simulation

A set of process models that capture the important process phenomena such as heat transfer, consolidation, coupled bonding, polymer degradation, and residual stresses and warpage has been developed. The models have the capability of operating in the critical, highly transient regions caused by process start-up or geometrically imposed velocity changes, where process quality must be maintained. These models have been incorporated into an on-line neural-network based predictive control system that allows interactive exploration of the process window by varying the control parameters. It is also used as a method for optimizing the final quality of the part by controlling the active processing window as well as utilizing the processing history as a method for continued improvement in final quality.

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Figure 3 is a flowchart of the current process simulation. The arrows indicate the direction of model outputs to subsequent process models. The CPU time required to determine the optimal processing parameters can be quite long. Thus neural networks have been employed as a method to determine the real time material response to various process changes. This methodology led to a separate study on PID control and optimization of the process. The following provides an overview of the models studied for this process.

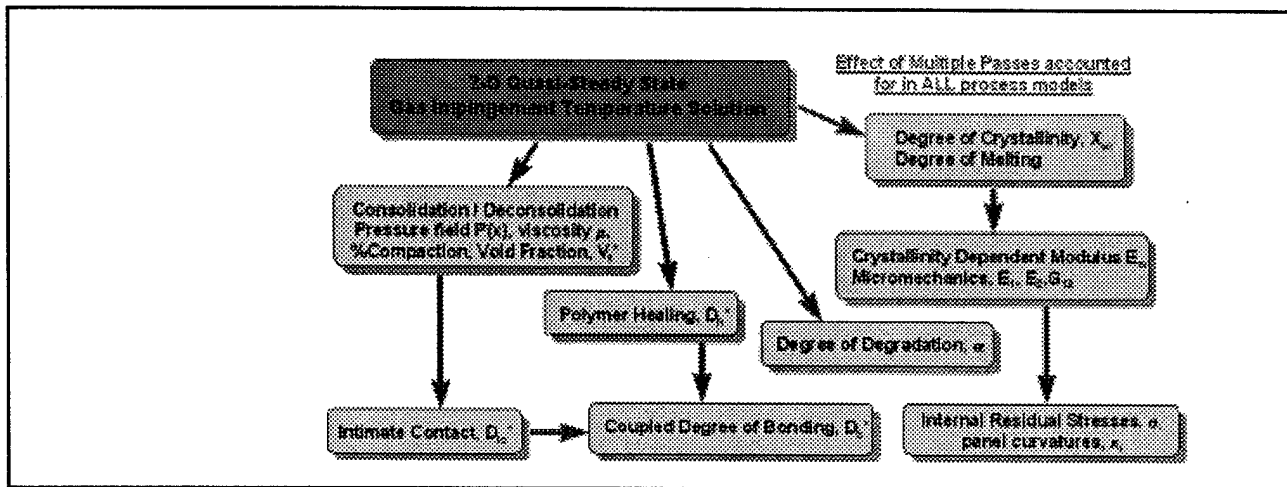


Figure 3: Flowchart of the current process simulation.

MODIFIED GAS IMPINGEMENT THERMAL SOLUTION

A modified two-dimensional quasi-steady-state thermal gas impingement solution was used to generate the temperature field used in the subsequent process models. The surface heat transfer coefficients are based on the compilation of results for forced jet impingement, conduction at the roller contact points, and free convection at the incoming tow and downstream region. The mandrel is included in the problem domain as it was found, through experiment, to act as a significant heat sink, especially during the start of the manufacturing process. The surface efficiency coefficients were modified in the model to account for gas disturbances introduced by the presence of rollers. Good agreement was obtained between heat transfer model predictions and experimental data gathered through an AGEMA thermal imaging system.

Figure 4 (next page) is a plot of through-thickness temperatures of a 16-ply composite lamina. The temperatures were taken at each ply interface. Also shown in the figure is the incoming prepreg tow surface temperatures as well as the substrate surface temperatures.

CONSOLIDATION/DECONSOLIDATION

The dominant void dynamics mechanism pertaining to this process is void compression due to the effects of cooling and compaction under the rollers. A compressible squeeze flow model of a Newtonian fluid in a two-dimensional geometry, developed by Ranganathan et al., is used to develop the pressure field under the rollers. Consolidation under the rollers is modeled as a squeeze flow continuum in which the rheological properties are dependent on the temperature, fiber volume fraction, and void content. A macroscopic flow model was developed to account for void transport, while a microscopic void dynamics model was used to account for void compression effects. A pressure distribution is generated and used to determine the degree of intimate contact.

Away from the rollers, deconsolidation is the dominant mechanism. At high temperatures, the

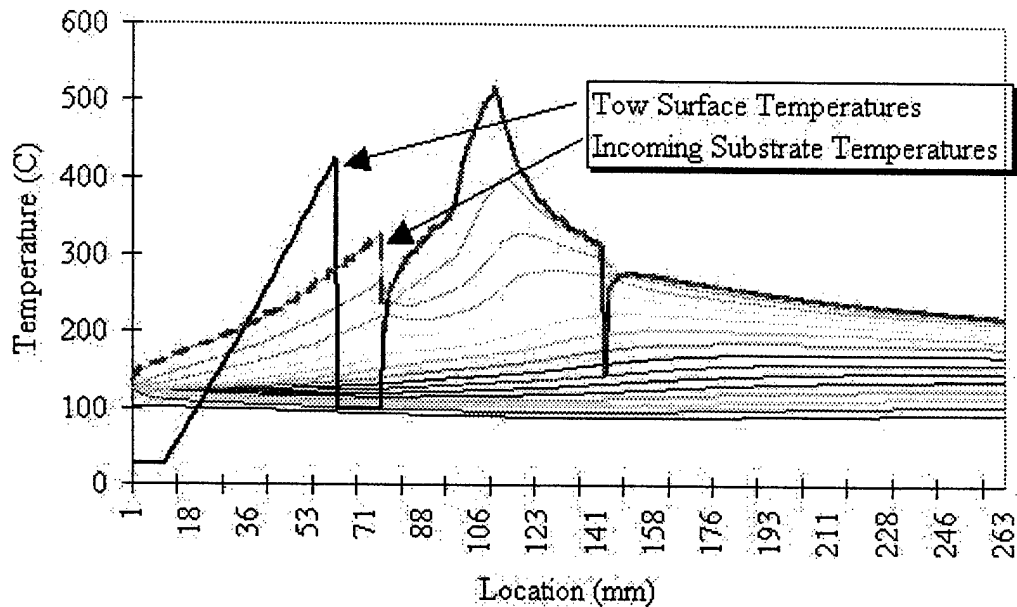


Figure 4: Plot of through-thickness temperatures of a 16-ply lamina.

material viscosity is low; as a result, voids are allowed to grow. The internal void pressure acts as a driving mechanism for this growth, with atmospheric pressure acting as an equilibrium pressure boundary condition. Through-thickness gradients in final void contact have been found as a result of both consolidation and deconsolidation as well as substrate cooling. These results have also been experimentally verified through photomicrograph measurements for various processing conditions.

INTIMATE CONTACT

The intimate contact model employed in this study follows that presented by Mantell and Springer. The degree of intimate contact is defined as the ratio of the instantaneous base width of an idealized rectangular asperity on the tow surface to the wavelength of an assumed periodic arrangement of the asperities. The mechanism of intimate contact is dependent upon the relative surface roughness, the interface temperature profile, and the pressure field at the tow interface. Intimate contact between the incoming tow and substrate material first develops at the tacking roller and continues to develop for a number of passes. Results have shown however that the development of intimate contact is usually limited to the first two plies from the surface. This model has also shown that it is possible to achieve significant intimate contact with repeated passes over the pre-consolidated material.

NONISOTHERMAL HEALING

Polymer healing is a temperature dependent phenomenon that is governed by the migration of polymer chains across the interfacial area in contact. The degree of healing is a function of both temperature and residence time at temperatures exceeding the glass transition temperature. The polymer chains are more mobile at these elevated temperatures, thus allowing for healing across the interface. Results from this process indicate that significant healing develops over multiple passes, and although residence times are low, significant healing can be achieved by annealing the interface.

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COUPLED BONDING

A coupled bonding model, which takes into account the mechanisms of polymer healing and intimate contact simultaneously, was developed and incorporated into the solution. This model gives a more realistic value of strength, as this process involves the concurrent development of both healing and intimate contact. The degree of healing for each spatial increase in intimate contact is integrated throughout the process history to give the final degree of bonding. Using a convolution integral, the net bond strength developed at the interface in dimensionless form can then be found. The residence time of the tows under the consolidation roller, which also represents the available time for intimate contact to develop, is small relative to the time available for healing to occur. As a result, the development of intimate contact under the roller is considered to occur instantaneously. The subsequent development of healing is tracked for each stepwise increase in intimate contact to give the final bond strength.

CRYSTALLIZATION KINETICS

The crystallization kinetics in semicrystalline thermoplastics play an important role in the development of residual stresses, due to the influence of the degree of crystallinity on the mechanical properties and volumetric shrinkage strain distributions. A nonisothermal crystallization kinetics model originally developed by Seferis et al. for a PEEK composite system was applied to this process to determine the through thickness gradients in crystallinity as a function of processing parameters. A melting model, originally developed by Maffezzoli et al. was also incorporated into the solution to determine the degree of melting. It was found that these competing models yielded significant through thickness gradients in crystallinity. The crystals were found to melt in a very short time interval, but could regrow due to the annealing effects within the laminate. Experimental results from DSC experiments are being carried out to validate these models.

DEGRADATION

Thermal degradation of the polymer system results from prolonged exposure of the tows to high temperatures during the process. Degradation deteriorates the properties of the material and can increase the glass transition temperature. A polymer degradation model developed by Nam and Seferis was applied to the ATP process. In this study, the term degradation refers to the material weight loss as a result of exposure to extreme temperatures at the gas nozzles.

Strength experiments of coupons which were reconsolidated in an autoclave were carried out to determine the degree of degradation of PEEK and PEKK composite samples. It was found from both model predictions and experiments that running the process at low speeds with the nozzles close to the surface yielded significant degradation on the surface. As a result, degradation was found to represent the upper limit of heat input to the system.

MODIFIED SLS VISCOELASTIC RESPONSE

The resin modulus within the composite plate was determined using a modified form of the standard linear solid (SLS) viscoelastic model. This model determines the stiffness of the matrix component as a function of both temperature and crystallinity. The results from this model are then applied to the Classical Lamination Theory solution through a doubly embedded self-consistent micromechanics field model to determine the internal stresses and resulting warpage.

RESIDUAL STRESSES AND WARPAGE

The residual stresses and resulting warpage are found using a simplified Classical Lamination Theory (CLT) model. CLT theory has been used extensively to describe the behavior of composite materials under mechanical, thermal, and hygrothermal loading conditions. In this study, thermal and mechanical loads are applied to a composite laminate to determine the response in terms of internal stress and resulting warpage. Figure 5 (next page) is a plot of the resulting warpage from a typical 8-ply [90/0]_{2s} laminate manufactured with the automated tow-placement process.

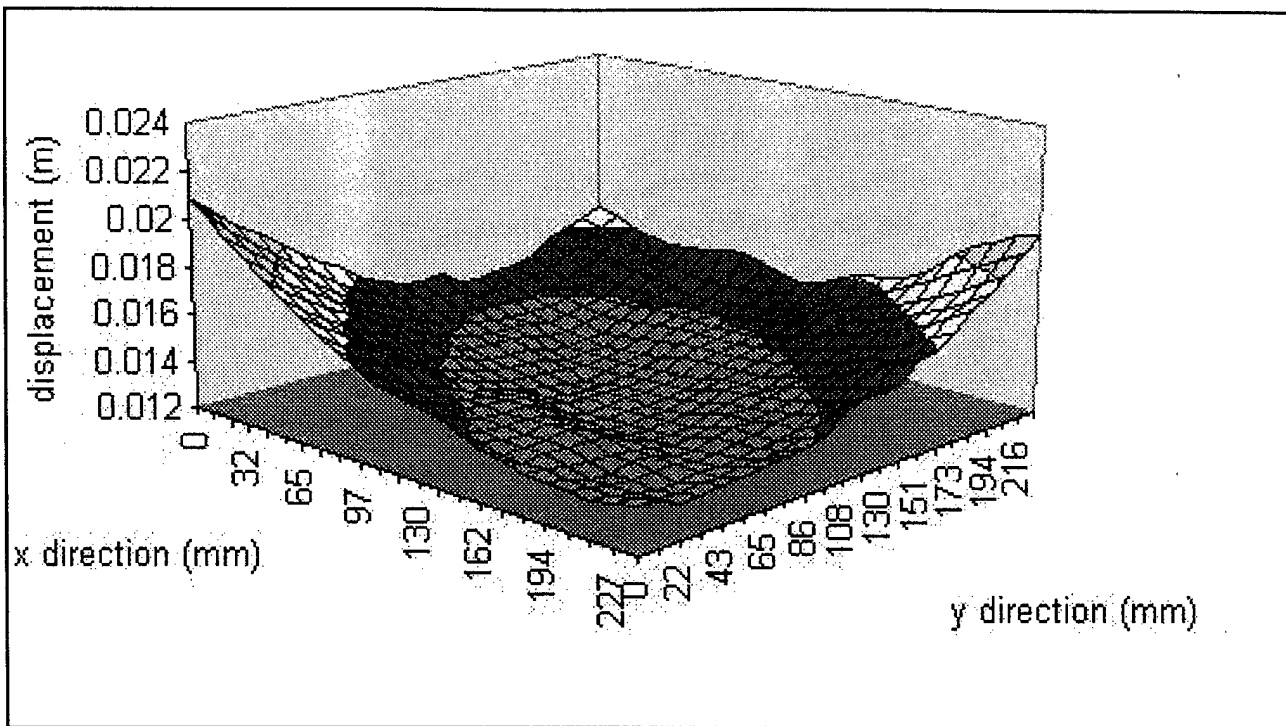


Figure 5: Plot of resulting warpage from a typical 8-ply [90/0]2s laminate manufactured with the automated tow-placement process.

A number of important assumptions are made in this simplified residual stress model in order to avoid the complexities associated with a moving localized heat source on a composite laminate. The first assumption in the model is that the panel undergoes the same thermal cycle across the panel surface. Since classical lamination theory is time independent (not including the effects of viscoelastic stress relaxation), this assumption is valid for a constant-velocity manufacturing process, since every point on the surface observes the same thermal processing cycle. So although this analysis cannot provide information about localized residual stresses during panel manufacture, it can predict the overall response based on this assumption. In this simplified model, the surface ply is the only ply that undergoes any thermal cycle. This leads to an overestimation of final warpage, as a thermal strain component is generated throughout the composite surface. To solve this problem, a series of partial constraints is applied in the material principal directions. The use of partial constraints greatly simplifies the analysis, and these constraints can be used as a series of empirical constraint vectors.

For the thermal input to this model, the surface plies are added sequentially at an initial processing temperature (greater than the glass transition temperature) and then cooled to room temperature. This step is repeated until the desired number of plies are bonded to the surface. Previous studies have indicated that the glass transition temperature is exceeded for up to seven layers beneath the surface, although the area above T_g on each ply decreases significantly with increasing depth from the surface. The effect of neglecting multiple ply cooling is an overestimation of the constraint vectors used in the model. The effect of multiple ply thermal gradients is presently under investigation and will be included in future studies on this topic. The inclusion of this effect will result in an increase in partial constraint, as more plies contribute to the development of residual stresses during each pass.

EFFECT OF MULTIPLE PASSES ON FINAL QUALITY

Sequential placement of the incoming tow can effectively anneal and improve the tow interface properties and help to reduce the bulk void content in the material, due to repeated compaction at the roller region. The effect of multiple passes on the response of the composite material can be obtained by applying the following solution technique to the heat transfer model:

- (1) The steady state solution is obtained for the placement of layer n. The temperature solution for the surface layer is then applied to the material models.
- (2) A new layer is added, and the model recomputes the temperature field for a lamina of n+1 layers. The temperature data for the second layer beneath the surface is extracted and applied to the process models.
- (3) This procedure is continued until the maximum ply temperature drops below the glass transition temperature, where high polymer viscosities inhibit the growth and/or reduction of voids within the laminate and constrain further development of intimate contact.

Optimization of Processing Parameters

The process models presented in this section have been incorporated into an on-line process simulator that allows interactive exploration of the process window by varying the control parameters and observing the model outputs. To reduce the time it takes to converge on a solution, an artificial neural network (ANN) version of the simulation has been developed. Preliminary trials on the ANN, which incorporates recently developed process models, show great promise in decreasing computation time while maintaining sufficient accuracy. A Labview interface (Figure 6) allows the user to determine optimal conditions either manually or through a series of optimization procedures. These procedures include optimization of surface properties and optimization of bulk properties through the use of multiple passes. Both procedures are then coupled to give the best overall processing cycle.

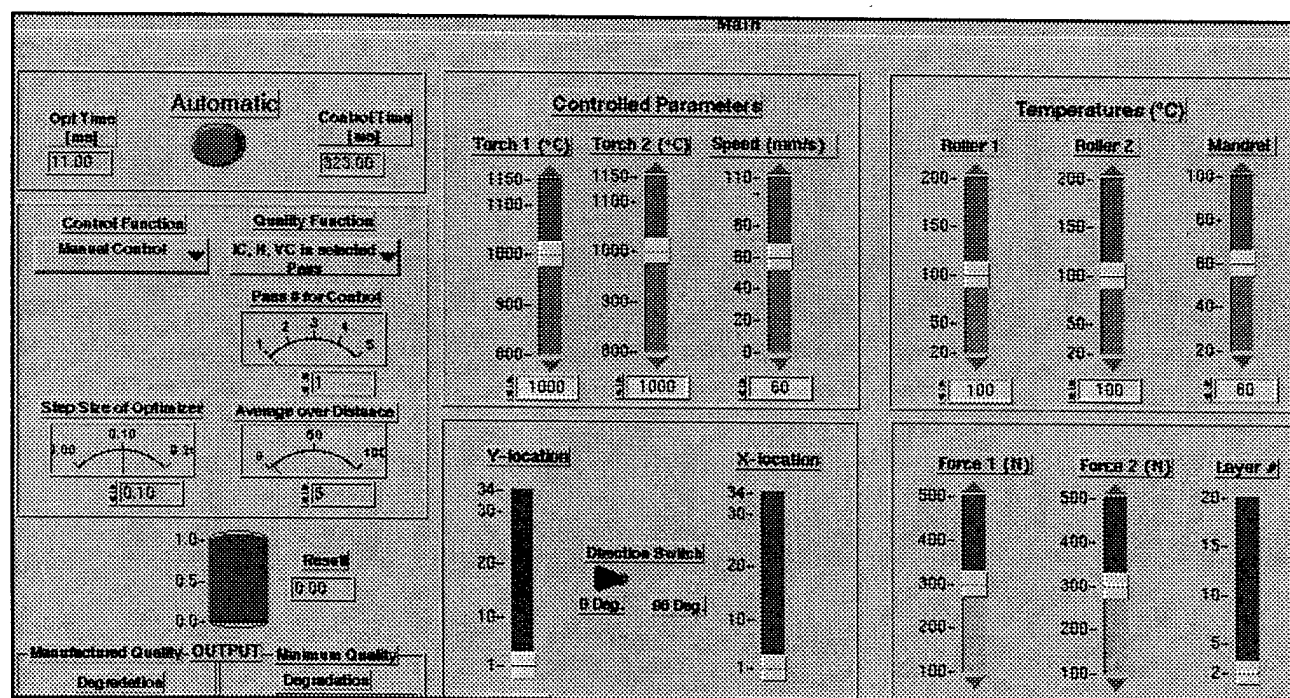


Figure 6: Labview output of neural-network-based process simulation.

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A neural network simulation with an optimized control system aimed at improving quality was developed and used to carry out a series of parametric studies for an AS4/PEKK material system (see Figure 7). Neural networks provide the capability for real-time data observation from highly nonlinear models. The neural network is adapted off-line with information from the tow-placement model and then substitutes the original model as the software sensor. As a result, a fast yet accurate model of the tow-placement process is obtained. This model can then be used for on-line control and serve as a model base for optimization techniques (see Figure 8). Frequently, quantitative nondestructive methods are not available for feedback control, and therefore a predictive controller is required. This nonautoclave process, with its on-line consolidation capability, incorporates an advanced controller that produces desired part quality at minimal cost. The control system combines a neural network based model, numerical optimization, and an infrared thermal imaging camera to sense the temperature profile on the part surface. Together, these methods provide a robust and stable control system for the process.

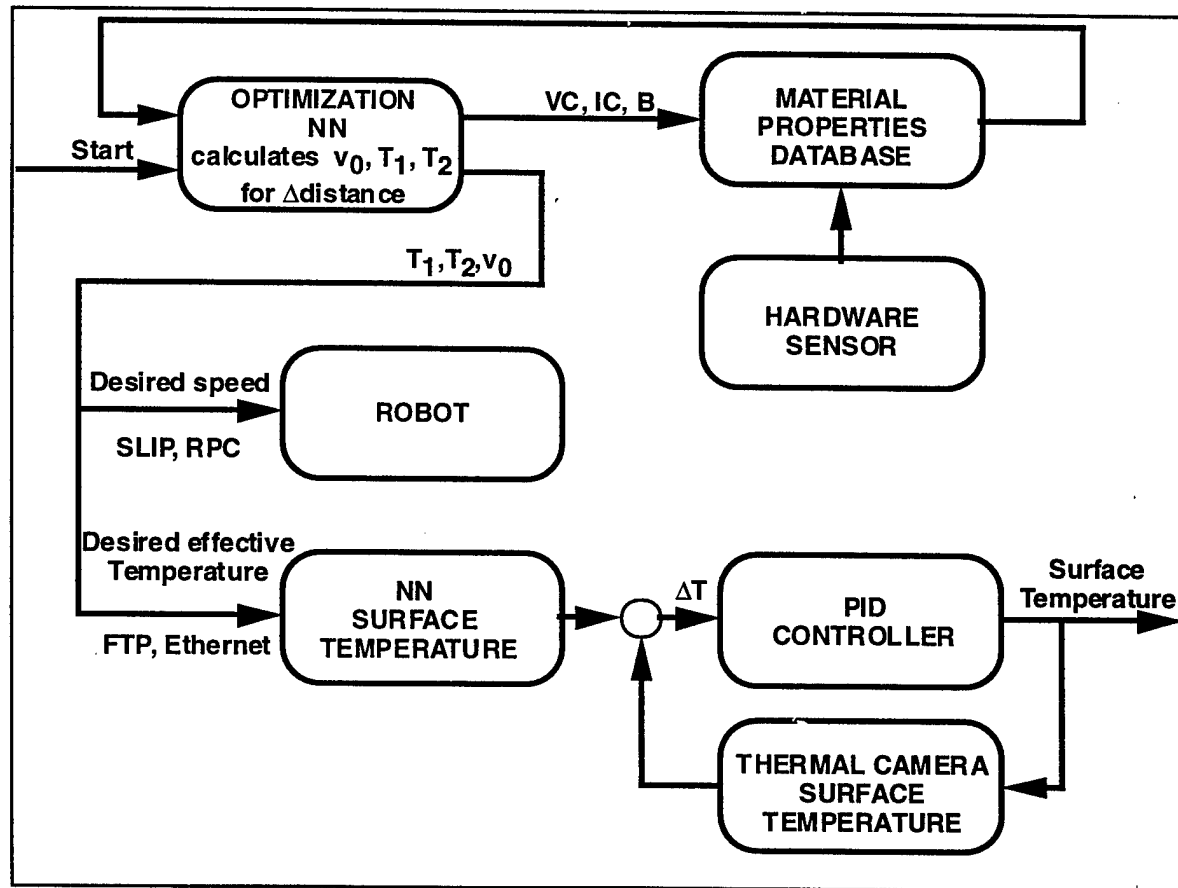


Figure 7: Neural network simulation with an optimized control system.

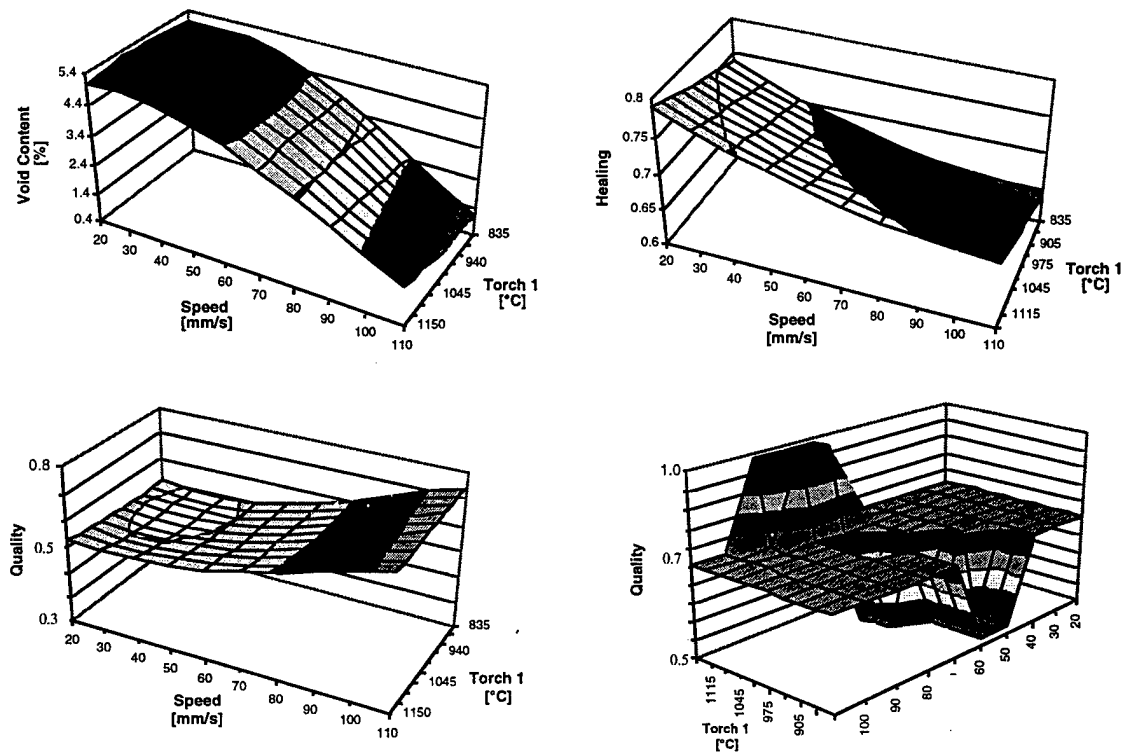


Figure 8: Incorporation of models into an on-line neural-network-based predictive control system allows interactive exploration of process window by variation of the control parameters and optimization of final part quality via controlling the active processing window.

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(5) TECHNOLOGY TRANSFER

University/industry collaboration via the RAPTECH program has contributed to the development of a TCA (tow-cut-and-add, 3-in. bandwidth) head in place at Cincinnati Milacron on a production gantry. It is now being used to make parts of <1% void content for the HSR program with mechanical properties approaching autoclave baseline. This successful partnership among government, academia, and industry of how research can be transitioned to industry for commercialization.

Other tech transfer activities include the following highlights:

- 35+ publications during the program.
- Physical process models transferred to industry (DuPont/Cytac Fiberite).
- Process setpoints optimized to achieve desired quality (degree of intimate contact, healing, void content).
- DURIP equipment grant for robotic fiber placement—equipment purchased, operational, and being used to validate process models developed under RAPTECH.
- ARO/URI link—via K. D. Tackitt's fundamental research on ultrasonic techniques to validate intimate contact models.
- ARL-WMRD interaction—via Dr. B. K. Fink in residence at UD-CCM full-time.
- TARDEC briefing on RAPTECH technology for CAV crew capsule fabrication.
- HSR Meeting at UD-CCM (May 1996):
 - Organized by N. Johnston, NASA.
 - 25 representatives of UD-CCM, NASA, Boeing, DuPont, McDonnell Douglas, Lockheed, Northrop Grumman, and Old Dominion University met to review and coordinate modeling activities for ATP process.
 - UD-CCM presentations included an overview by Technical Director J. W. Gillespie Jr. as well as discussions of reptation studies (R.P. Wool), warpage studies (R. F. Eduljee), and process dynamics and quality (J. J. Tierney).